Measuring Visibility in Blowing Snow

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An electronic system that monitors visibility in blowing snow has been developed by the USDA Forest Service, in cooperation with the Wyoming Highway Department. The sensor for blowing snow is a photoelectric particle counter that produces a voltage pulse for each snow particle which passes through a 3 by 25 mm area normal to the wind. The sensor's pulse train is electronically processed to give voltages proportional to five-second averages of particle frequency and diameter. These voltages are combined with the signal from an anemometer in an analog computer which stimulates visual range according to the equation, $V = 5U/FX^2$ where V is the visual range in meters, U is windspeed in meters per second, F is the particle frequency in number per second through a 1 cm^2 area, and X is the particle diameter in centimeters. Field calibration was accomplished by comparison with closed circuit television recording of visual range targets during drifting. The correspondence between theory and observed visual range was very satisfactory, and two such systems are now in use for traffic control in Wyoming, having proved reliable and useful during three winters.

The Phenomenon

Becoming lost in a blizzard is one hazard that still threatens winter travelers in the Great Plains and western United States. To most, such an experience is certainly frightening, and for some, it has been fatal. This paper describes an electronic system developed by the USDA Forest Service, in cooperation with the Wyoming State Highway Department, to help travelers avoid being stranded in blowing snow storms, and to improve the safety of transportation under drifting conditions. The system consists of an anemometer, a blowing snow sensor, and a specialized analog computer designed to combine signals from the sensors according to an equation for visual range.

Some pertinent features of the blowing snow phenomenon are included to help the reader follow the assumptions in the development of a visibility equation. A description of the blowing snow sensor follows that derivation, and then the design of the electronic analog is presented. The procedure and results of field calibrating the system are explained, and an example of the strip chart record leads to a discussion of the usefulness and application of the system.

Blowing Snow Particles

Much of the quantitative information about blowing snow has been written by scientists studying the mass balance of water in Antarctica. Their measurements, and data obtained with the sensor described in this paper, show that particles of drifting snow are usually much smaller than the original precipitation crystals. The reduction apparently takes place by the crystal shattering, being abraded, and sublimated, during wind transport. At heights 50 to 100 cm above the surface, mean particle diameters are close to 100 µm. The distribution of size is skewed toward smaller diameters, so that log-normal or two-parameter gamma functions provide useful approximations (1). Mean size increases exponentially nearer the surface, approaching values of 200 µm at levels between 5 and 10 cm above the surface. At a given height, mean size increases with windspeed, once the threshold speed for wind transport is exceeded, but the function is conservative. Particle frequency, the number per second passing through a unit area normal to the wind direction, increases as a much higher power of windspeed, and also decreases exponentially with height, like particle size. Because of this strong vertical gradient in the density of blowing snow, truckers and snowplow operators usually enjoy better visibility than car drivers and patrolmen in the same drifting conditions.

Mean particle velocity at any height is equal to the mean wind velocity, except perhaps within a centimeter of the surface. Since particle frequency is such a strong function of wind velocity, natural wind gustiness produces a very large variation in particle frequency with time. At the 50 cm level, for example, particle frequency may increase from a few hundred to greater than 5,000 particles per second per square centimeter in less than 10 seconds. Careful consideration of averaging times is essential to assure that any measure of visual range approximates the ability of the human eye to form a persistent image with such rapid changes in visibility.

A Visual Range Equation

Liljequist (2) reports visibility in blowing snow and corresponding windspeed observed at Maudheim, in the Antarctic. Assuming constant particle size distributions, he argued that visibility is inversely proportional to the density of drifting snow. Data to test his hypothesis are provided by Budd, et al. (3), who show that visual range, V (m) is well predicted by $V = 100/n$, where n is drift density (in gm/m^3) at 2 m. These measurements were also made in Antarctica, at Byrd station.

The theory of visibility is covered completely by Middleton (4) and specifically for blowing snow by Mellor (5). Dr. R. D. Tabler first drew my attention to the derivation that follows (6). Attenuation of visible light by blowing snow should be proportional to the projected area of the transported particles, since particle diameters are large compared to the light wave lengths. If N represents the number of particles per cubic centimeter in the air stream, then for spherical particles of uniform diameter, the sum ϕ of all particle cross sections in this volume is

$$\phi = N\pi X^2/4 \qquad (1)$$

where X denotes the particle diameter (in centimeters).

Contrast C is defined as the difference in luminance between objects and background luminance, and liminal contrast C_e is that threshold value below which an observer cannot discern object against background. Contrast is reduced by blowing snow as an exponential function of distance and ϕ, the total cross section per unit volume. The threshold defines the observer's maximum visual range as

$$V = -\frac{\ln C_e}{\phi} \qquad (2)$$

Values of C_e are usually between 0.01 and 0.03, as determined by experiment. Assuming the mid-range value, $C_e = 0.02$, and substituting (1) in (2), the visual range for uniform spherical particles is estimated by

$$V = 5/(NX^2) \qquad (3)$$

If F denotes the number of particles per square centimeters area passing across the sight path each second, then $F = NU$, assuming the particles move with mean windspeed, U (cm/sec). Therefore, visual range in blowing snow might be estimated by

$$V = 5U/FX^2 \qquad (4)$$

where V is in meters if windspeed is in meters per second. The following assumptions have led to this greatly simplified equation:

a. the principles of geometric optics apply; particles are large enough that absorption of light may be neglected,

b. particles are spheres, all of the same diameter, and

c. wind velocity is equal to particle velocity and perpendicular to the sight path.

The first assumption seems to meet most conditions in blowing snow quite well, and should not lead to errors. Assuming that blowing snow particles are spheres instead of smoothed, but still irregular ice grains, is not likely to lead to much error either, because we wish to approximate scattering cross section, and it is quite possible to choose a diameter that will lead to the proper sum of projected areas. By the same argument, we should be able to minimize any error that is caused by approximating the scattering cross section of a skewed distribution of particle sizes with the areas of an equal number of uniform particles. However, the assumed diameter should be somewhat larger than the mean of the distribution. Measurements show that mean particle speed closely approximates mean windspeed. Since the particle number concentration in the sight path, which is computed by $N = F/U$, is the same regardless of wind direction, the equation (4) should apply even with oblique winds. Implicit in the derivation is an assumption that averaging times for all factors are properly choosen. As already noted, such an assumption is required by the physiological nature of the definition for visual range.

Comparison with Antarctic Data

If visibility is related to drift density, as in the empirical result, $V = 100/n$, then visual range must vary inversely as the cube of diameter, whereas (4) predicts an inverse variation according to diameter squared. Mellor (5) concludes from this contradiction that particle size must be nearly constant, as Liljequist had assumed. However, another explanation was suggested during review of this paper (7). It is possible that variance in estimates of both V and n is large enough that the coefficient, 100 in the empirical relation contains X as a factor. Let $V = BX/n$ represent this hypotheses. Data in table 1 are averages estimated from (3) for drift particles at 200 cm, by 10 m windspeeds that span the range of measurements. It appears a factor of X could easily be "hidden" in the coefficient, explaining the difference in functional form between (4) and $V = 100/n$.

The same date allow a rough calculation of the visibility predicted by (4). To do this, particle frequency must be estimated. Since $F = NU$, determining the volume concentration of particles will allow calculation of F, if U_{10} is reduced to the 2 m windspeed, using a standard wind profile. To estimate N, the drift density, n may be divided by the average particle mass. For the skewed size distribution, the diameter of a particle with average mass is estimated to be 1.2 times the mass of the particle with average diameter (1) or $\overline{M} = 1.2 (\rho\pi/6)X^3$ where density ρ is assumed to be 0.92 gm/cm^3 (ice). Dividing drift density by $\overline{M}$ determines N, and using a 1/7 power law wind profile gives $U_2 = 0.795\ U_{10}$. Visual range estimated by (4) is 2.2 to 2.8 times greater than values computed by $V = 100/n$.

The quantitative comparison will be left at this point, with the expressions agreeing in the functional relation of F, U, and X^2 and a factor of 2.5 difference in the coefficient. The empirical relation uses the value of drift density at 2 m because it was a drift measurement height; yet, the observer's line of sight probably was not this high, and the visual targets were poles, which represent a very small visual target, so that the value of liminal contrast assumed in the derivation of (4) may not apply. Most important, our experiments with the photoelectric sensor show that constant particle size is not a valid assumption for drifting in regions where the amount of snowfall available for wind transport is limited, or becomes so during a blizzard. In fact, incorporating particle size in visibility measurement leads to certain advantages discussed at the end of this paper.

Table 1. Comparisons of visual range estimates[a]

	Windspeed U_{10} (m/s)		
	12	16	20
Factors estimated at 2-m			
drift density, n (g/m^2)	0.2	0.8	1.9
mean diameter, X (μm)	75	90	95
particle frequency, F (no./s/cm^2)	782	2,416	6,090
Visibility (meters)			
$V = 100/n$	500	125	53
$V = BX/n$ ($B = 1.1$)	412	124	55
$V = 5U/FX^2$	1,080	325	145

[a]Data from Budd et al., (3)

Sensing Blowing Snow

Research on blowing snow in the earth's polar regions generated two photoelectric sensors at about the same time. In Antarctica, Landon-Smith and Woodbury (8) tested a design that was improved by Wishart (9). Sommerfeld and Businger (10) used a different instrument for studies in the Arctic. Shortcomings in both devices were due primarily to calibration drift, quite understandable considering the temperatures. A new approach, based on the experience of the last authors, was undertaken at the University of Washington in Seattle. This development, directed by Dr. Walter Rogers, Department of Electrical Engineering, produced a blowing snow sensor with which individual particles could be counted in the air stream and which offered particle size and speed information as well (11). Further work by Sommerfeld streamlined the sensor (12), and both the electronics and mechanical design were revised in the version reported by Schmidt and Sommerfeld (13). A complete description of the device presently in use (Figure 1), including all circuit diagrams and shop drawings, is presented by Schmidt (14).

Figure 1. The snow particle counter (SPC) is usually positioned 50 cm above the surface, with the mounting arm and light beam (opening) normal to the wind direction most common during drifting.

The Snow Particle Counter

This sensor produces a bipolar voltage pulse for each particle that intercepts its light beam which is oriented perpendicular to the wind direction. Two phototransistors detect the shadow of the particle as it crosses the light beam (Figure 2). Each photosensor is positioned behind a narrow optical window, one-half mm wide and 3 mm high. An amplifier in the mounting arm connects the phototransistor signals in such a way that the particle's shadow generates a positive pulse on the first window and a negative pulse at the second window, 2 mm downwind. The sampling area is 25 mm long. Since the light from the miniature lamp is not so intense that the phototransistors are saturated, they respond to different particle sizes with different signal amplitudes. The windows are precisely dimensioned by photographic reduction on a stable film base, allowing particle speed to be estimated from the time interval between positive and negative portions of the pulse. Thus, information on size, frequency and speed may be obtained by processing the signal from the snow particle counter (SPC).

A small, battery-operated motor, which spins a 0.5 mm diameter wire through the center of the beam so that each window is completely shadowed, allows the sensor to be adjusted to produce a standard signal. Amplifier gain is compensated to minimize drift over the temperature range, -15 to 0°C. During adjustment, the signal is viewed on an oscilloscope so positive and negative peaks can be balanced to ± 3.0 volts.

Calibration of the SPC was complicated by a variation in sensitivity across the sampling area. Signal amplitude depends not only on size, but also on the location within the sampling area at which the particle intercepts the beam. Shadows that fall near the upper and lower ends of each window produce voltage pulses that may be less than 10% of the maximum amplitude which occurs when a particle crosses the center of the beam, near the sensor windows. This situation results from the overly simple optics, coupled with a variation in axial response of the phototransistors.

Particle size calibration was accomplished by rotating the sensor 90° from its usual position so that sieved particles could be dropped through the sensing area. A procedure developed to transform the distribution of pulse amplitudes into a particle size distribution, compensated for the nonuniform sensitivity across the sampling area. Average particle diameters can be estimated within 10 μm of means for known size distributions, by this method, but an electronic multichannel analyzer is required to make the measurement. Therefore, the technique

Figure 2. Light from the miniature lamp is received by each phototransistor through a separate window, 3 mm high and 1/2 mm wide. A differential amplifier combines the photocurrents so each particle shadow produces a pulse of positive amplitude at the first window and neagative at the second.

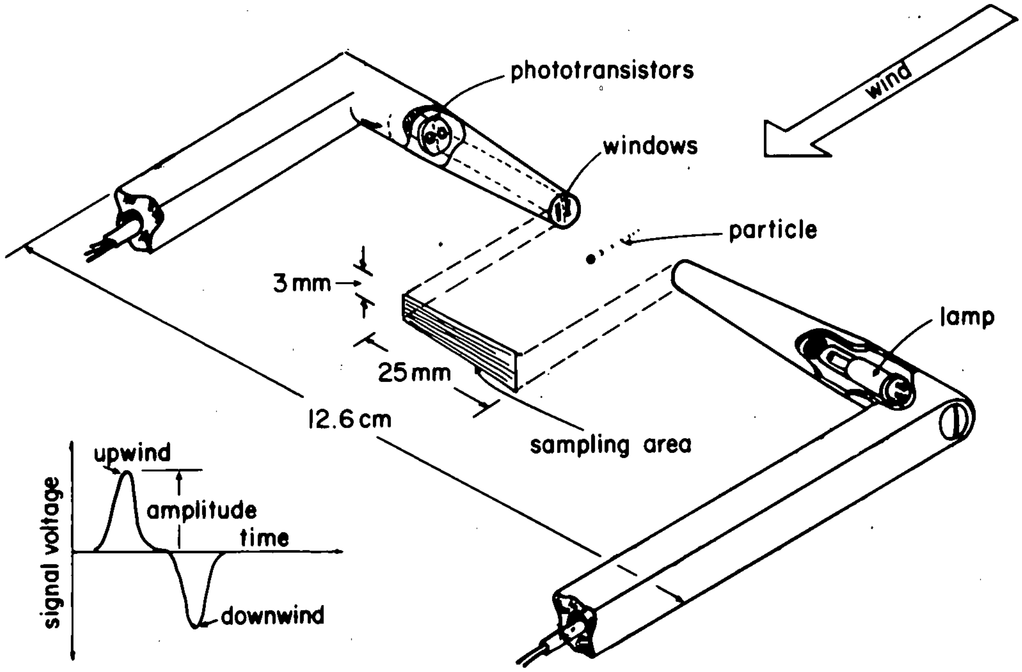
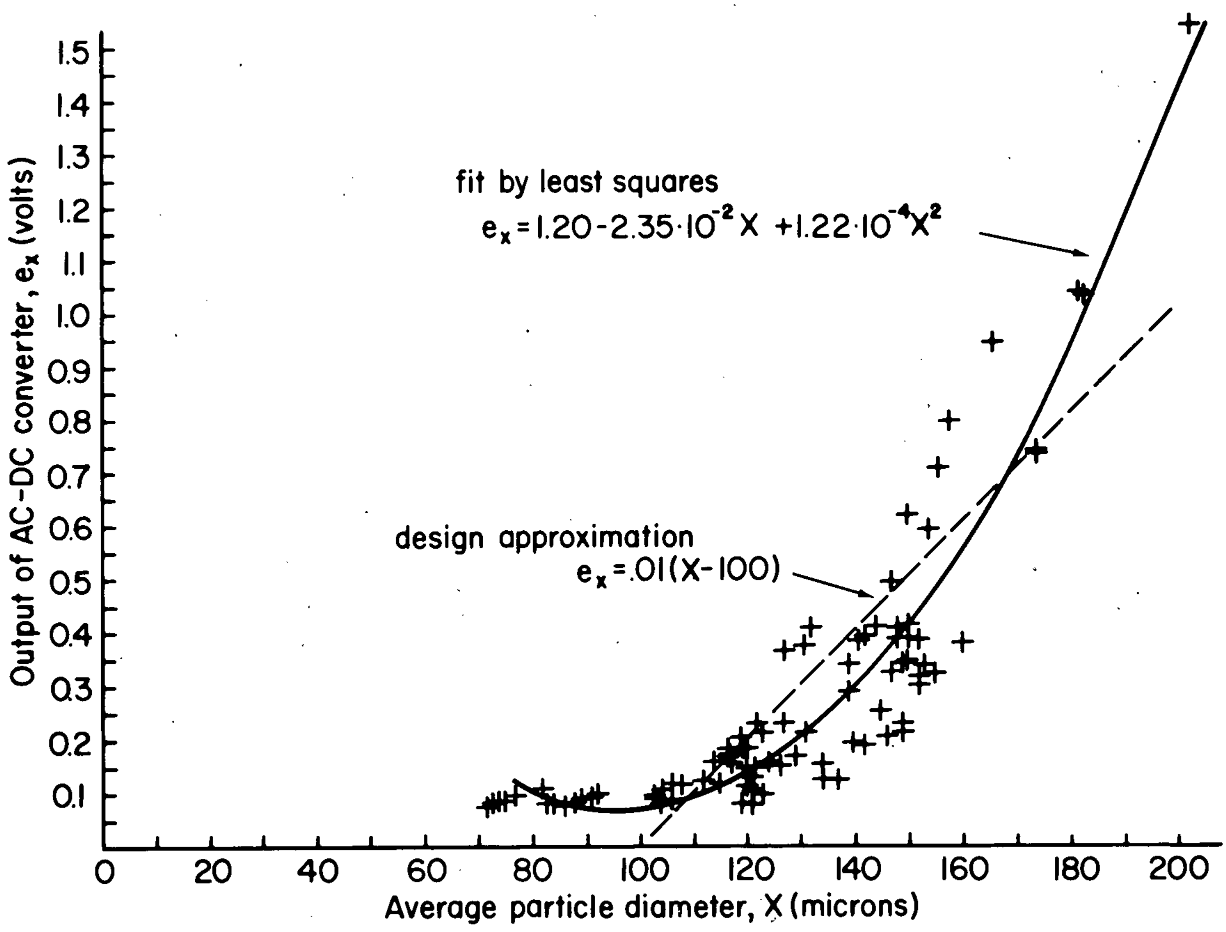


Figure 3. Output voltage of the a.c.-d.c. converter is a function of mean diameter, for 1-minute samples at several heights in drifting snow. Particle size distributions were determined from the distribution of signal amplitudes accumulated by an electronic pulse height analyzer, using a transformation developed with sieved particles in the laboratory.

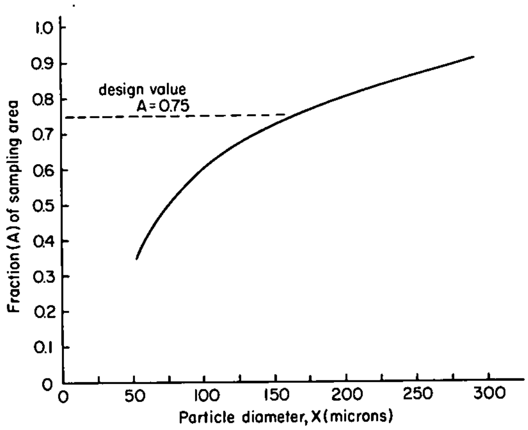


was used to find a relationship between average snow particle diameter and the root-mean-square value of the sensor pulse train (Figure 3), using 1-minute averages from signals recorded on magnetic tape during drifting events. If only mean particle diameter is required, an a.c.-d.c. converter contained on a small printed circuit card is then sufficient. A low pass filter on the card is designed to produce an output voltage e_x that represents the 5-second running average particle size. The linear relation e_x (volts) = (X-100)/100, where X is diameter in microns (X > 100), was used as a design approximation.

Particle frequency estimates are also affected by the variation in sensitivity across the sampling area, since some threshold of sensitivity must be specified to separate particle signals from electronic noise. If the light beam was perfectly collimated, the sampling area of the sensor would be equal to the distance between lamp and sensor windows (25 mm) times the sensor window height (3 mm) or 0.75 cm^2. However, the actual sensitive area is wedge shaped and closer to 1.0 cm^2. By mapping the variation in sensitivity across the sampling area, corrections for frequency estimates were determined as a function of particle size (Figure 4). If f is number of signals per second measured by the SPC, then the estimated particle frequency in number per square centimeter each second is F = f/A where A denotes the fraction of the total sensitive area (1 cm^2) which provides signals greater than the trigger level. Estimates of particle frequency are close for diameters between 150 and 200 μm, using the design value A = 0.75 and are low for smaller particles. No effort was made to correct this apparent error mainly because no independent measure of in situ particle frequency was available during the development. Another printed circuit produces a voltage e_f which is a linear function of the signal pulse frequency f and reaches 10 volts when f = 5000 per second, again with a filter which provides about 5-second averages. Thus, the transfer function is e_f = f/500, so F = 500 e_f/A, or F = 667 e_f, for A = 0.75.

In summary, the snow particle counter produces signal pulses corresponding to individual snow particles, and electronic circuits have been designed and calibrated to convert the sensor output signal into voltages proportional to particle size and frequency, with averaging times of about 5 seconds. Overall accuracy appears to be such that mean diameters are estimated within 10 μm, and frequency within 500/sec/cm^2, under natural drifting conditions, but no independent calibration standard was available.

Figure 4. Reduced sensitivity near the edges of the sampling area causes the frequency of smaller particles to be underestimated. The value, A = 0.75 was used for design.



Computing Visual Range

The electronic computer that provides a real-time solution of (4) uses analog techniques, primarily because the author had more experience with these methods than with digital computer design, at the time the design was begun (1972). Analog computation uses operational amplifiers and function modules to manipulate voltages that represent the parameters of the equation, and the solution is also a voltage. Part of the design problem is to scale amplifier gains in such a way that voltages remain within the limits of the amplifiers and modules.

The Computer Design

Visual range can have very large maximum values and sometimes it is so small, "you can't see your hand in front of your face", but the values of most concern for surface travel are between 50 and 500 m. To emphasize this range, the computer produces a voltage e_v, that is proportional to the reciprocal of visibility. The full scale output, e_v = 10 volts was chosen to correspond to a 200 foot (61 m) visual range, because this is the standard distance between highway delineator posts, and might be used as a practical lower limit. Therefore, e_v = K/V, where K = 610 (in volt-meters).

Another important part of the design was to select a measurement height for the SPC that would provide representative data for solution of the visual range equation. The critical sight path of a motorist in blowing snow was judged to be the line from his eye to the road surface some distance in front of the vehicle, rather than a horizontal path. Because the drift density increases so rapidly near the surface, measurements at eye level were expected to overestimate visual range defined with respect to motorists. Experiments with the SPC at a height of 1 m demonstrated that the sensor output at this level was inadequate to detect either low intensity drifting, or the very beginning of snow transport. However, if the sensor is positioned below 10 cm, it tends to "saturate" at relatively low intensities, and the lower the height, the greater the effect of new snow depth on the measurement. These considerations led us to select 50 cm as the height at which to measure the particle parameters for the most useful monitoring of motorist visibility. It is possible to adjust the system for other measurement heights.

To stimulate the equation, $V = 5U/FX^2$, a voltage proportional windspeed is required, in addition to the particle frequency and size voltages already discussed. A windspeed signal is a desirable secondary output from the visual range computer since the hazard of high winds is, in itself, a real concern in traffic safety. For this reason, and to reduce the influence of local small scale obstacles in the visual range computation, a standard (NWS, FAA) anemometer was chosen, for use at the standard exposure height of 10 m. Output from this sensor is a d.c. voltage, e_u that increases as a linear function of windspeed, giving 4.0 volts at 44.7 m sec^{-1} (100 miles per hour). The 1/7 power law wind profile can be applied to estimate U at the 50-cm level chosen for SPC measurement. The relation $(U_{10}/U_{0.5}) = (10/0.5)^{1/7}$ gives $U_{0.5} = 0.652\ U_{10}$. From the anemometer calibration, U_{10} (m sec^{-1}) = 11.18 e_u (volts) so that the desired windspeed is U = 7.29 e_u. To summarize the design, the equation to be solved is

$$V = 5U/FX^2$$

and the desired computer output voltage is

$$e_V = K/V = KFX^2/5U \qquad (5)$$

where K = 610 (in volt-meters). Input factors are related to their corresponding voltages by

$$F = 667\ e_f\ (\sec^{-1}\ \mathrm{cm}^{-2}) \tag{6}$$

$$X = 0.01\ (e_x+1)\ (\mathrm{cm}) \tag{7}$$

$$U = 7.29\ e_u\ (\mathrm{m}\ \sec^{-1}) \tag{8}$$

Substituting in (5)

$$e_v = \frac{K}{5}\ \frac{(667\ e_f)(e_x+1)^2\ 10^{-4}}{7.29\ e_u}$$

or

$$e_v = \frac{C\ e_f(e_x+1)^2}{e_u} \tag{9}$$

For K = 610 (in volt-meters), the calculated value of C is 1.12. We consider the coefficient, C, as a scaling factor, the predicted value of which was subject to experimental verification.

Data flow through the VRM system is shown by the block diagram (Figure 5). The computer is contained in a 3.5-inch, standard rack-mounted case. An internal calibrator generates signals that simulate full scale values from the sensors, allowing a rapid field check of computer operation with the front-panel voltmeter.

Calibrating the Visual Range Monitor (VRM)

Two questions were of primary concern, once a prototype system was built. First, "Did the computer combine the input voltages in proper functional form to measure visibility?", and if so, "What value of the scaling factor, C gave the proper full scale value?"

Tabler conducted field experiments to answer these questions during the 1972-73 winter, at a location along Interstate 80, about 60 km west of Laramie, Wyoming. His initial method was to read the values of e_x, e_f, and e_u from strip chart recorders to the audio track of a video tape recorder which simultaneously recorded the image of a set of visual targets, from a television camera. The camera was mounted 1.8 m above the ground surface, in a small building with windows allowing a view perpendicular to the usual wind direction during blowing snow events. Flat black targets were positioned along the sight path, at distances that increased logarithmically, and the width of each target increased in proportion to its distance from the camera. By careful design, each target subtended a one-half degree horizontal arc and the image of each target was separated by the same amount.

After verifying that an observer's visual loss of a target was simultaneous with the loss of the target image on the camera, values of the input voltages were tabulated by target distance, for those blowing snow periods when the video replay showed the threshold of target extinction. Averages of these voltages were used to compute $e_f(e_x+1)^2/e_u$, which was plotted (Figure 6) against the distance to the corresponding target, for the three targets that were most frequently obscured. The value $e_f(e_x+1)^2/e_u$ = 7.0 at a visual range of 61 m (200 feet) was chosen as a design point. Since the desired output at this range was e_v = 10.0 volts, the required value of C was computed as 10/7 = 1.43, by equation (9).

Figure 6. These initial calibration results determined the scaling factor, C. The design point was chosen to give a better fit of equation (9) to the lower visual ranges. Subsequent experiments showed the function was also accurate at greater visual range.

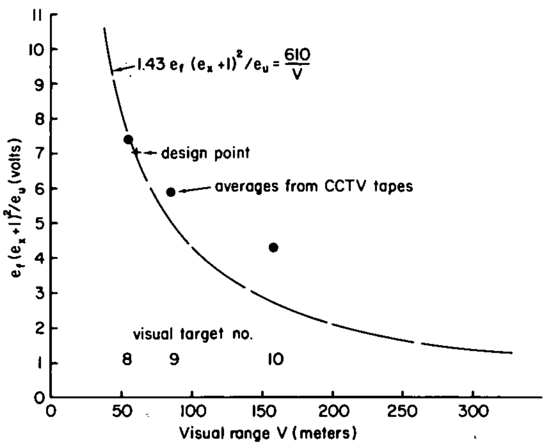
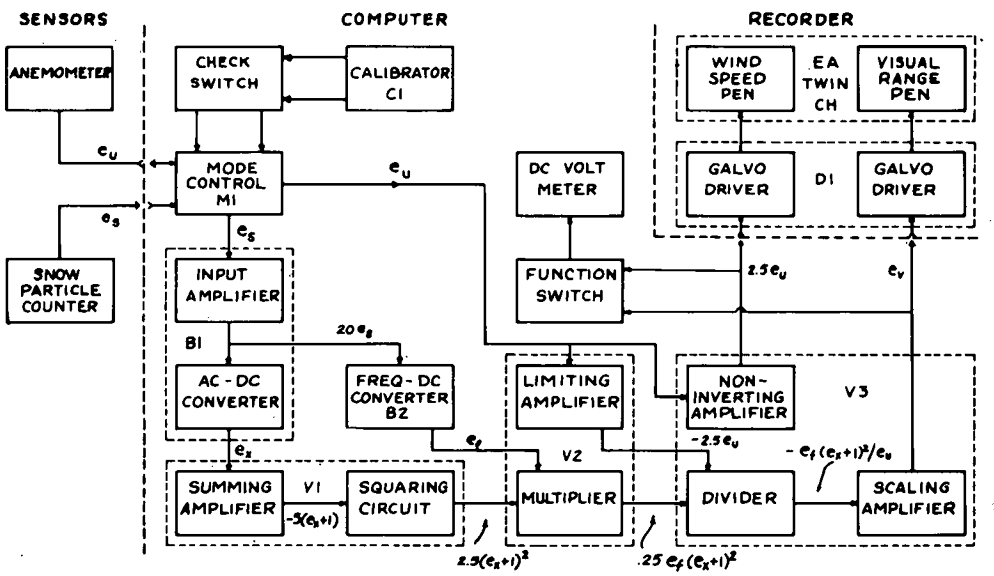


Figure 5. Functions and voltages in the VRM system. (Dashed enclosures designated B1, V1, D1, etc., are individual printed circuits.)



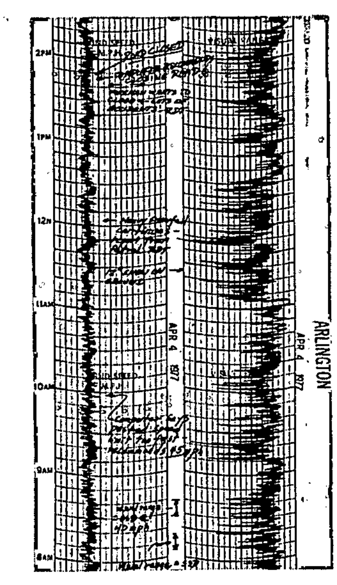
Once the VRM computer was adjusted for the empirical value, C = 1.43, Tabler used a split-screen technique to include a view of the VRM strip chart recorder above the visual range targets on the video image. These recordings convinced us that the computer estimated visual range in very close agreement with actual values. The under-estimation at greater distances, expected from the first experiments (Figure 6) does not occur, and we concluded that the error was due to the difficulty of determining the three separate voltages at the instant the target became obscured.

Perhaps the averaging time of the computer in processing the three input voltages also makes the predicted visual range more accurate. One interesting result of these experiments was that, apparently by the proper (and certainly in this case, fortuitous) choice of averaging times, a very short-path sensor was made to estimate visibilities up to 1 km. As a hypothesis, we suggest that the system compensates for the spatial variation in blowing snow intensity along the sight path by the way in which it averages the time variation due to natural gustiness. Demonstrating this mathematically requires assumptions about the nature of atmospheric turbulence and would prove an adequate subject for an entire paper. Foregoing this, it seems that the number of eddies transporting snow through the sight path vary with time in about the same way as the number passing the sensor during the averaging time interval.

Discussion

Data is recorded on a two-channel strip chart with windspeed on the left channel and visual range on the right (Figure 7). As visibility decreases, the pen moves to the left, and a special chart scale is used so that the left-hand margin of the visual range channel represents a 61 m (200 feet) value, and clear conditions are recorded at the right-hand margin. Very early in our experiments with the VRM, we recognized that the relationship between the two channels could be used to deduce whether travel conditions were improving or becoming worse. For example, if we noted that at some time during a blizzard, a gust of 20 m/s reduced visibility to 80m, but that

Figure 7. This example from an actual VRM record shows the large variation in visibility (right) associated with wind gusts (left). Handwritten notes relate to verification of an automatic analysis system (Tabler 1977).



an hour later a gust of the same magnitude only produced a minimum visibility of 200 m, we would conclude that the amount of snow available for transport was becoming limited. A marked reduction in visibility minimums without a corresponding increase in gust magnitude almost always indicated new snowfall. We began to pursue these new research leads as soon as the first system was placed on-line for operational testing.

In January 1974, the Wyoming Highway Department began testing the VRM as an aid for traffic control and maintenance decisions. The first monitor station was located near Arlington, on Interstate 80 between Laramie and Rawlins. Data from the system was telemetered by radio and telephone to a recorder in the dispatcher's room at the district office in Laramie. Field observations by patrolmen, plow operators, and other personnel were noted on the chart, to demonstrate the correspondence between the record and conditions on the highway. Enough confidence in the system developed during that first season of operation that this new source of information began to be used in traffic control decisions, especially those that involved closing or opening the road. A second monitor station near Elk Mountain began transmitting data to Laramie in 1975. Three years of experience has proven that these systems give reliable data from the remote locations, and that the data can be very useful for traffic and maintenance operations.

All personnel using the VRM were trained to recognize condition trends from correlations between the wind and visibility records, but our new research showed that more useful information is contained in the record than can be determined from routine visual inspection. By analyzing the data with automatic processing equipment, trends became obvious in a much shorter interval, and even estimates of the rate of condition change were possible. A processing system which carries out this data interpretation function was placed on-line at the district office in Laramie during late winter, 1977. The methods and decision logic used in this automatic analysis are reported by Tabler (15).

The snow particle counter has several advantages for application as a sensor in visibility monitoring. It is economical (costing less than $1,000) compared to transmissometers and other devices. Small size makes the SPC readily moveable and its position adjustable, compared to long path sensors which require more permanent mounting. Sensors are easily interchanged if maintenance becomes necessary. However, the instrument exhibits low drift, and requires little maintenance. Lamp replacement each month almost completely eliminates down time from burnout. Weekly checks of sensor gain and balance are recommended, but useable data is obtained with less frequent attention. The use of visible, rather than infrared or monochromatic light makes it easier to check the light beam, and makes the measurement more directly related to visibility. Finally, a signal which measures particle size and frequency rather than light attenuation, allows a visual range estimate based on the functional interaction with windspeed predicted from the theory of light scattering by particles.

Prominent among the factors which aided the rapid development of this system is the support of the Wyoming Highway Department, both financially and in testing the usefulness of the data, allowing us to see immediately what improvements were most needed. The author appreciates this cooperation.

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