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DEVELOPMENT AND CALIBRATION OF THE FORWARD SCATTER VISIBILITY METER

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13. ABSTRACT

A new visibility instrument, the forward scatter visibility meter, has been developed. This report describes the development of the instrument, including the various field tests. Some thirty instruments have been operationally deployed in a network of automatic weather stations near L. G. Hanscom Field in Bedford, Mass. Comparisons between field instruments and transmissometers yield differences of about ± 19 percent. Comparisons with visual observations show differences of ± 34 percent and greater. Analyses of individual cases uncovered difficulties with the response time of observers and with ability to diagnose spatially varying visibility. The accuracy of visibility measurements is assessed and the report concludes by looking at the future of visibility instruments.

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Development and Calibration of the Forward Scatter Visibility Meter

1. INTRODUCTION

A new visibility instrument, the forward scatter visibility meter (FSM), has been developed. The instrument operates on the principle of determining the extinction coefficient (visual range) by measuring the amount of light scattered in the forward direction by atmospheric particulates. This report describes the development of the FSM, including the various field tests, problem areas, and resulting modifications. Approximately thirty instruments have been operationally deployed in a network of automatic weather stations in the vicinity of L. G. Hanscom Field, Bedford, Massachusetts. Data obtained from these instruments are shown in comparison with transmissometer measurements and with visual observations. The report concludes with a general discussion of the accuracy of visibility measurements and the outlook for the future of visibility instruments.

2. BACKGROUND

A variety of activities of modern man become hazardous under conditions of restricted visibility; for example, operating aircraft during landing and take-off, navigating boats, or even driving a car. The first of these examples has always

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(Received for publication 13 March 1974)

been very important to the Air Force, for typical aircraft operations can be made safer and more effective through knowledge of present and future visibility conditions at airports.

Visibility, or more precisely, visual range is defined as the maximum distance at which one can recognize an object. As noted by Middleton,[1] the determination of visibility is a complex problem. Visibility depends on the particulates present in the atmosphere, such as fog droplets, haze or dust particles, raindrops or snowflakes. In addition, it depends on lighting conditions and characteristics of the object such as contrast (daytime) or brightness (if a light). Finally, visibility depends on the visual acuity of the observer, his perception, training, and familiarity with surroundings.

Traditionally, the weather services have used an observer to determine visibility. In this procedure, the observer periodically scans the area about him to note which of prechosen targets (lights at night) of known distances he can see; following prescribed guidelines, he arrives at a value for the visibility. Over the years, a set of rules, together with guidelines, has evolved with the intent of making measurement dependent only on atmospheric conditions. Further, there are standards for contrast of daytime targets and brightness of nighttime lights. However, there are several practical difficulties with the foregoing procedure:

1. It is not practical to construct ideal daytime targets to obtain fine resolution in every direction, and, as a compromise, a small number of available targets (hills, buildings and trees) are used, many of which are far from ideal.
2. At night, available lights are used. Often these lights are of unknown emission.
3. The press of other duties prevents the observer from allowing his eyes to adapt to outdoor darkness before making nighttime observations.
4. The nighttime background illumination varies greatly from airport to airport, making the compatibility of measurement difficult to achieve.
5. Measurements of the threshold contrast, related to visual acuity and training, show large variations indicating incompatibility between observers.

For these reasons Middleton[1] (page 228) concluded "...there is only one way in which meteorological observations of this element can be rescued from complete futility: abandon the entire scheme of marks and estimates, make good instrumental measurements of the extinction coefficient and then calculate something which will be of interest to the user of the datum."

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[1] Middleton, W.E.K. (1952) Vision Through the Atmosphere, University of Toronto Press, Toronto.

At the time Middleton made this recommendation in 1952, there were several experimental visibility instruments that had been proved, but they did not meet the requirements of an instrument for general usage. An ideal instrument must be capable of operating in both daylight and darkness (seven orders of magnitude difference in background illumination). Again, it must be accurate throughout the range from 50 m to 50 km.* Also, an ideal instrument must operate equally well over the spectrum of particulate sizes from 0.5 μm haze particles to 15 μm fog droplets, to 2000 μm raindrops, and 10,000 μm snowflakes. Finally, the instrument must be reliable, inexpensive and simple to operate; it must have an adequate response.

One instrument of that period, the Douglas-Young transmissometer,[2] was found to be very useful at airport sites for determination of visual range when values were close to a critical threshold—the lower limit for safe landing and take-off of aircraft. The transmissometer system is shown schematically in Figure 1. A focused projector lamp shines directly at a photodetector across a nominal path of 150 meters. The receiver produces an output proportional to the light received, which is decreased by the presence of visibility restricting phenomena. The extinction coefficient σ can be determined by the relationship $\sigma = 1/X \text{ Ln } (I_0/I)$, where X is the path length, I_0 the intensity of the unattenuated beam, and I the

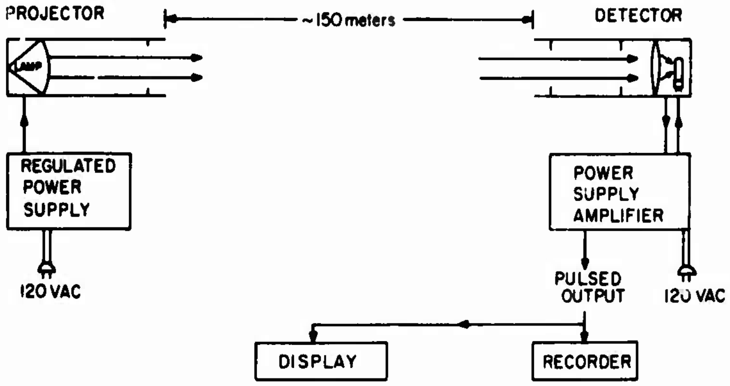

Figure 1. Schematic Diagram of Transmissometer GMQ-10

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*We will be using metric units in this article; the reader is reminded that 100 meters is very close to 1/16 mile, a frequently used increment in the low visibility range.

[2] Douglas, C.A. and Young, L.L. (1945) Development of a Transmissometer for Determining Visual Range, Technical Development Report No. 47, U.S. Dept. of Commerce, C.A.A., Washington, D.C.

measured intensity. For this instrument σ was determined to be related to visibility by Koschmieder's law* and a variation of Allard's law.† Charts were constructed to convert the output of the transmissometer directly to runway visibility (RVV). When high intensity runway lights became operational, conversion was made to the distance at which these lights could be seen; this was called runway visual range (RVR). (Allard's law is used for RVR computation.)

The received light I is measured continuously, but I_0 is considered a constant. When the visibility is excellent (15 km or more) the instrument is adjusted so that I is at a prescribed value. Optical alignment of the projector and detector is maintained by taking the precaution of mounting the projector and detector on rigid steel towers and bolting the towers to concrete pads. Lamp brightness I_0 is stabilized by using a regulated power supply.

The transmissometer is designed to be used for visibility in the range of one-half path length to thirty path lengths. Near the lower end of this range, I becomes very small and difficult to resolve. Near the upper limit, small changes in alignment or lamp brightness lead to large errors in visibility. Within these limits, the transmissometer is a very fine instrument for measuring extinction coefficient and visibility.

3. DEVELOPMENT OF THE FORWARD SCATTER VISIBILITY METER

During the 1950's and 1960's, transmissometers were deployed at more and more airfields throughout the United States, where they became the primary basis for determining whether conditions on a runway were above or below landing and take-off minimums. However, limitations of the transmissometer were causing concern:

1. The introduction of sophisticated electronic landing aids required better accuracy and more representative measurement of visibility.

2. The frequent attention required for maintaining alignment and calibration was not desirable,[3] particularly at remote sites.

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* The weather services use 0.055 for threshold contrast in Koschmieder's law, and 0.055 is also used in this study.

† The U.S. Air Force uses Allard's law for both RVR and RVV.

[3] U.S. Air Force (1966) T.O. 31M1-2GMQ 10-61 Technical Manual, Operating and Service Instructions, Transmissometer Sets, AN/GMQ-10B and AN/GMQ-10C.

3. Outages due to component failure do occur and recalibration is not possible during periods of restricted visibility.

4. The transmissometer system itself (based on electronics and optics of the 1940's) was approaching obsolescence.

In the late 1960's, AFCRL initiated the development of an improved visibility meter for provision of more accurate and representative measurement of runway visibility. An instrument using a backscatter measuring technique was constructed. The instrument responded well, with good agreement to transmissometer measurements. However, the calibration was not stable. An important result of this work was that the visibility determined from a scatter measurement of a relatively small sampling volume correlated well with the transmissometer.

Rather than pursue the back-scatter technique, AFCRL turned its attention to a forward scatter method with distinct advantages; for example, a measurement at a 30-degree scattering angle has a much better theoretical relationship to total scattering coefficient than a measurement at 180 degrees. Also, the scatter at 30 degrees is greater than at 180 degrees, and hence easier to measure. During the 1940's, Waldram had investigated this technique by having a shipboard visibility instrument constructed[1] (page 203). The results were surprisingly good for nighttime operation. The instrument had to be operated in a light-tight chamber in the daylight in order to avoid background illumination. It was felt by using current light modulation techniques and electronics, an improved compact visibility meter could be constructed, based on the forward scatter measuring method.

In 1969, Cambridge Systems of EG&G under direction of Arthur Bisberg and David Beaubien, began work on the construction of a forward scatter visibility meter through a development contract with AFCRL. Shortly thereafter, there developed an urgent requirement within AFCRL for a number of short-path visibility instruments. These instruments were needed in an investigation for the improvement of short-range aviation terminal forecasts. A test network of 26 stations was to be set up in the vicinity of L.G. Hanscom Field, and it appeared that the forward scatter visibility meters could provide the necessary information. This additional requirement greatly accelerated the development of the instrument.

Two feasibility instruments were delivered in July of 1970 for field testing. A series of tests[4] demonstrated their suitability as visibility instruments. A modified version was constructed to overcome deficiencies discovered in the feasibility model, and also to facilitate production. This instrument became the prototype model, and upon successful testing, orders were placed to equip the 26 mesonet stations.

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[4] Hering, W.S., Muench, H.S., and Brown, H.A. (1971) Field Test of a Forwar Scatter Visibility Meter, AFCRL-70-0315.

Figure 2 shows the production model of the EG&G FSM 207. Its operation is illustrated schematically in Figure 3. A regulated power supply (operating on 120 volts, 60 Hz) operates a halogen projector lamp. The light beam is mechanically chopped before entering an optical system that projects a cone of light, with an inner cone masked out. A photodiode monitors the light, providing a feedback to the power supply and timing information to the receiver circuitry. About 120 cm (48 in.) from the projector is the receiver, with a photodiode that receives light from a cone-shaped volume similar to that of the projector. The masks in the projector and receiver prevent direct transmission of light. The intersection of the projection and viewing cones forms a sampling volume of 0.05 m^3 (1.8 ft^3); particulates within this volume will scatter the projector light into the detector at a forward angle between 20 and 50 degrees.* Synchronous modulation is used for detection of the scattered light.

The instrument has a linear and two log outputs, with zero to five-volt range. Most of the test data and all of the operational data were obtained from the log output channels. The positive log output covers the range of extinction coefficients from 44×10^{-6} to $4400 \times 10^{-6} m^{-1}$ (6 km to 60 m daytime visibility) and the negative log covers 44×10^{-6} to $0.44 \times 10^{-6} m^{-1}$ (6 km to 600 km daytime visibility). The framework (see Figure 2) was designed to minimize the effect of heat plumes rising from the control unit and affecting the sampling volume.

The forward scatter visibility meter was subjected to a series of field tests prior to final installation in the AFCRL mesonet. Highlights of these tests are summarized in Table 1. Tests of the feasibility models were performed at special ranges at the U.S. Naval Radio Station in Cutler, Maine, and at Sudbury, Mass.[4] Tests of the prototype model were performed at Otis AFB, with subsequent tests carried out on instruments installed in the network.

The following description represents the more significant instrument deficiencies uncovered during testing and the subsequent corrective measures.

1. The operation of the feasibility model was seriously limited by background light modulation under broken cloud cover, or moderate winds and bright conditions. This deficiency was met by increasing the modulation frequency to 300 Hz from the original 12-Hz modulation rate. A more subtle modulation problem was uncovered in the production model: Under very bright conditions, thus high dc background level, low level 60-Hz pickup would be introduced into the

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* This range covers the 45 degree value found by Deirmendjian[5] and the 30 degree value found by Waldram, for scattering proportional to total scattering.

5. Deirmendjian, D. (1964) Scattering and polarization properties of water clouds and hazes in the visible and infrared, Appl. Optics 3(No. 2):194.

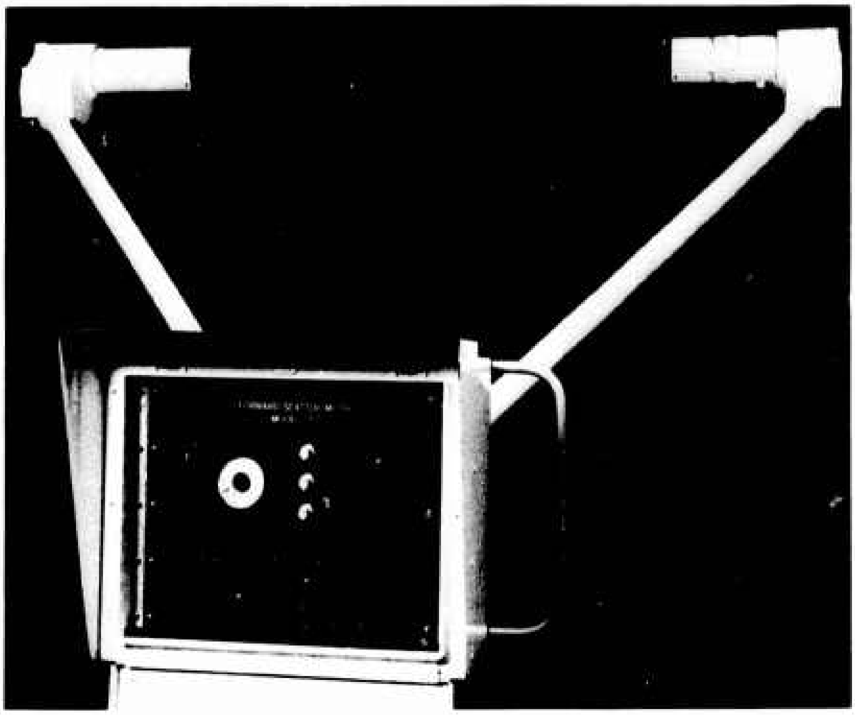

Figure 2. Forward Scatter Meter, EG&G, Model 207

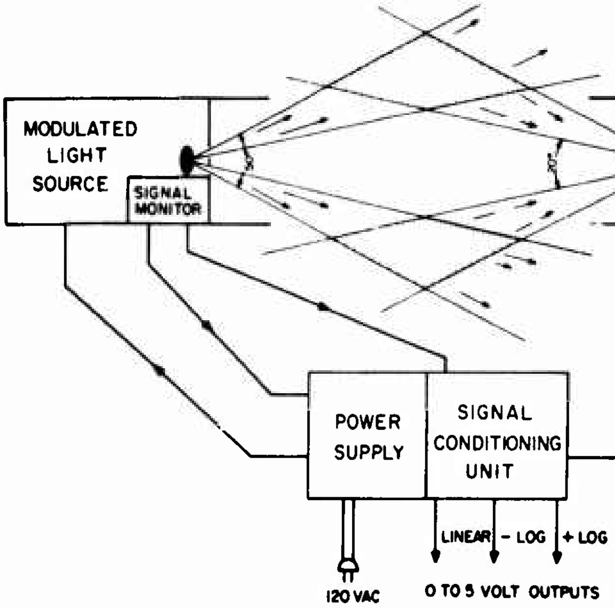

Figure 3. Schematic Diagram of the Forward Scatter Meter

Table 1. Summary of Forward Scatter Visibility Meter Tests

Location and Date	Instruments	Purpose	Weather	Standard	Comparability	Range[a]	Results
1. Cutler Naval Radio Facility Cutler, Maine August 1970	Two feasibility models	Response calibration	Coastal fog; rain	152 m transmissometer	± 24 to ± 28%	100 to 1500 m	Responded well except rain and bright daylight
2. AFCRL Visibility Test Site, Sudbury, Mass., Sept 1970-June 1971	Modified feasibility model	Reliability response in snow	Fog, rain; drizzle; snow	152 m transmissometer	~ ± 25 %	80 to 1500 m	Calibration stable; accurate in snow
3. Otis AFB Falmouth, Mass. June 1971	Prototype production model	Daylight response calibration	Coastal fog; rain	152 m transmissometer	~ ±20 to ±25 %	60 to 4000 m	Improved performance in rain and daylight
4. AFCRL Mesonet Northeast, Mass. Feb 1972 - Jan 1973	Production models	Stability, data gathering	Fog, rain; snow; drizzle	Three 60 m transmissometers	±16 to ± 22%	60 to 8000 m	Steady performance; some response decay and daylight problems
5. Cornell Aeronautical Lab Buffalo, N.Y. April 1972	Production model	Calibration	Cloud chamber	Short-path transmissometer; droplet counter	~ ± 20%	60 to 1000 m	Excellent calibration
6. AFCRL Mesonet Northeast, Mass. Jan 1973-present	Production model modified[b]	Mesonet operation	Fog, rain; drizzle; snow			60 to 15000m	Excellent unattended operation

a. Range of equivalent daytime visibility over which accuracy is better than 30%.
b. Modification included detuning, projection lamp baffle, and heating cable on hood.

amplifier as a signal. The problem was overcome by *detuning* the chopper motor off the 60-Hz harmonic to 290 Hz. Finally, excessive wear in the motor bearings caused mechanical vibrations which produced a modulation signal when background illumination was very high. A new motor with better bearing lubricant has significantly alleviated this problem.

2. Several months after installation, some of the scatter meters indicated a decaying sensitivity. An inspection revealed that an internal blackening of the halogen lamp was taking place. Further investigation showed that the difficulty was due to excessive cooling of the lamp by the mechanical chopper which inhibited the normal halogen reaction within. To correct this problem a cylindrical Pyrex shield was inserted over the lamp.

3. Three different photodiodes were tested before a suitable one was obtained. The original diodes were either not sufficiently stable, or not environmentally suitable. The present detector is extremely stable and long-lived.

4. During the first tests under wintry conditions, a problem did develop when there was a combination of strong wind and heavy, wet snow. Normally, the heat of the projector lamp was enough to keep the projector lens and hood free of snow. However, the detector would become clogged with snow and give false readings. This was corrected by placing a heating strap over the detector hood, a modification that has also been added to the projector hood.

4. ABSOLUTE CALIBRATION

A visibility meter must certainly be one of the most difficult meteorological instruments to calibrate. There are no *standard* fogs on which to base a calibration or use for periodic checks. Some large cloud chambers do exist, but the environment can hardly be measured or controlled with the precision of commonly used temperature baths (for thermometers) or pressure chambers (for barometers). Moreover, there is not even a laboratory instrument of recognized high precision that can be used as a standard in comparison tests. The transmissometer is adequate for calibration purposes over a limited range, provided one maintains careful optical alignment and makes corrections when drifts in I_o do occur.

When the contractor delivered the prototype forward scatter meters for the tests at Cutler, Maine, preliminary calibrations from Mie scattering theory had been made. Absolute calibrations of the instruments were obtained by comparison with the extinction coefficients computed from transmissometer readings, in general, verifying the original calibration. A similar calibration procedure was used during the winter tests at Sudbury, Mass., and we were pleased to find that the calibration obtained from comparisons in fog produced very good visibility values in snow.

5. CALIBRATION DEVICES

When the prototype production model was delivered, followed by initial tests at Otis AFB, Falmouth, Mass., in June of 1971, the first calibration device was constructed. In clear weather, a lucite rod was attached to the scatter meter such that part of the projector beam was directed into the receiver. This calibrator proved sufficiently stable for the making of gross adjustments to the instrument. Also, it worked in both daylight and darkness.

The contractor devised a large screen of netting placed between the detector and projector to act as a standard scatterer when the instrument was arranged in an environmental chamber. However, this device did not produce repeatable readings. Next, a polyvinyl chloride (PVC) tube was tested as a calibrator. It was placed between the projector and detector. The light transmission by internal reflection was sufficient to duplicate the light scattered into the detector by a dense fog. This calibrator proved adequate for the chamber tests.

Two similar tube calibrators were built and used as field calibrators. They are compact enough for use on instruments installed at the remote stations and capable of use under restricted visibility conditions. Repeatable outputs are obtained when the field calibrator is used on the same FSM. However, the separation between projector and detector varies slightly from instrument to instrument; this results in slightly different light transmission by the calibrator from one instrument to the next.

The contractor further pursued the idea of a large screen for a laboratory calibrator. A translucent plastic proved to be a very good scatterer. A plastic screen calibrator was constructed, which is shown positioned on an instrument in Figure 4. The screen of the laboratory calibrator extends beyond sampling volume, and therefore positioning is not so critical. The laboratory calibrator produces more reliable comparisons between instruments than the field calibrator. However, the laboratory calibrator can be used only in a clear atmosphere. All FSM's are calibrated by the laboratory calibrator indoors before being installed at station sites, in order to ensure compatibility between instruments.

The calibrators were placed on the calibrated prototype FSM, for the purpose of obtaining an extinction coefficient and equivalent output voltage.

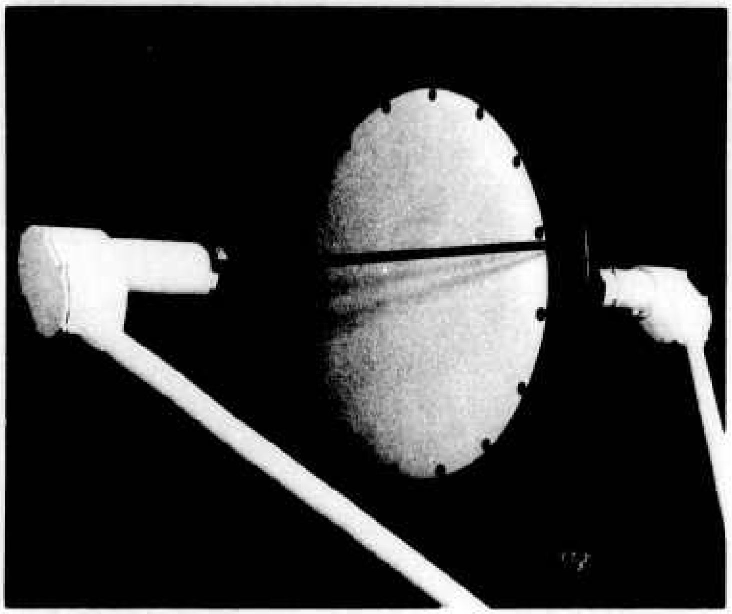

Figure 4. Laboratory Calibrator Mounted on Forward Scatter Meter

There was still concern that the accuracy of the laboratory calibrator might be altered by environmental factors during steady use; for example, collection of dust. For this reason, several similar sheets of translucent plastic were purchased, calibrated, and stored away for future use as standards.

6. COMPARISONS BETWEEN FORWARD SCATTER METER AND TRANSMISSOMETER MEASUREMENTS

In the calibration procedures previously described, the greatest emphasis was in achieving compatibility between instruments. When analyzing the network data, the forecasters had to be certain that the differences they observed between stations were real. In fact, the relative calibration was really more important than the absolute calibration. During the chain of events that led to the value finally assigned the laboratory calibrator, there were a number of steps where some small errors could have occurred; this could lead to an error in the absolute calibration that might be of importance in other applications, such as climatology. For this reason, an effort was begun to check the absolute calibration.

When the network was in the planning stage in 1969-1970, we were not at all certain what the performance of the visibility meter would turn out to be. There were worries that problems of calibration drift might arise, or that there might be difficulties with certain types of weather conditions, such as heavy rain or snow that might go unnoticed in the remote, automatic stations. As a safeguard, at three stations where additional space was available, GMQ-10 transmissometers were installed, with 60-m (200 ft) path lengths. In Figure 5, the letter <u>T</u> indicates stations with transmissometers. However, the geography of each station is quite different:

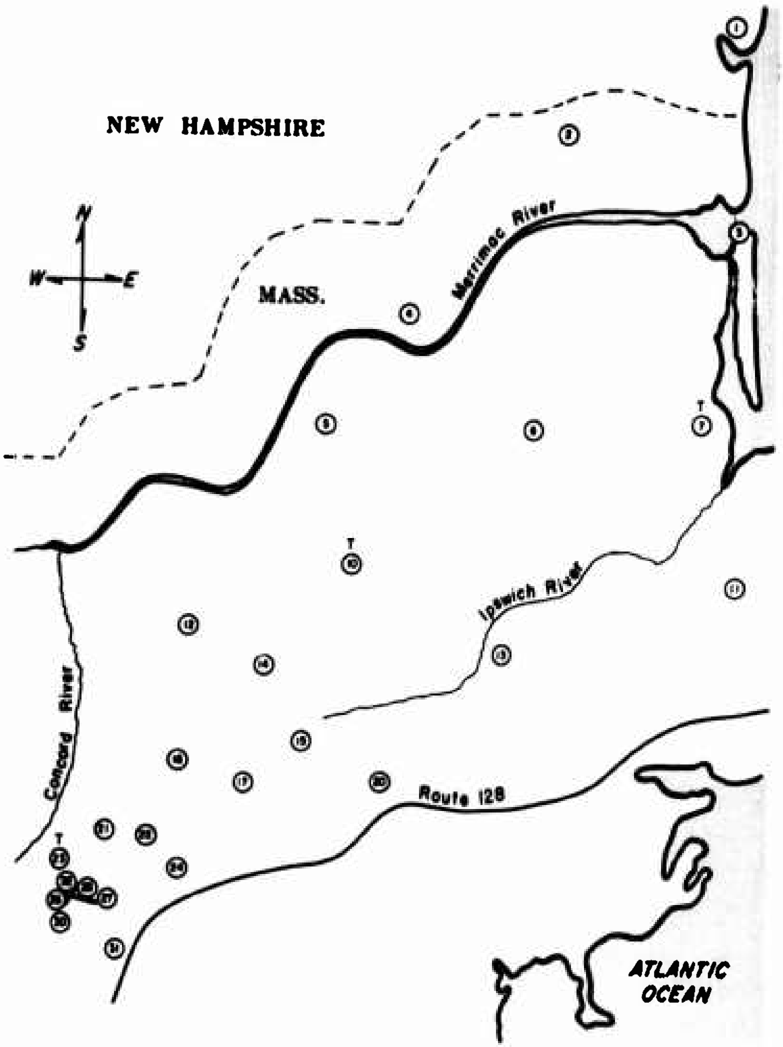

Figure 5. AFCRL Mesonet Stations, Fall 1972

The Bedford Nike site, 23, is on a small hill in the Concord River basin, which is very susceptible to ground fog; Station 10 is on the top of 385-ft high Boston Hill, and often in low cloud; to the east, the station at North Ipswich, 7, is but four miles from the open Atlantic and often affected by coastal fog.

The forward scatter visibility meters have performed far better than originally expected, and a dependency on the three network transmissometers never materialized. Nevertheless, there still remained the task of verifying the absolute calibration of instruments in the field. An attempt was made to use recorder charts from the Hanscom Field transmissometer for comparison to a nearby FSM, but only insufficient comparisons could be made owing to transmissometer outages as well as problems with calibration marks on the charts. We then turned to three transmissometer sites in the network for the purpose of obtaining comparative data from the growing library of magnetic tapes.

During the fall of 1972, our experience with the network transmissometers was not too favorable. Though there was not much urgency for the data, the technicians did make repairs and calibration checks about once per month, and still outage was nearly 25 percent. (In contrast, maintenance visits to the forward scatter meters were rare.) More serious was the problem of calibration drift, which became obvious from time to time during periods of fair weather. Two examples are shown in Figures 6 and 7. In the first, the drift represents a drift in I_o of about 8 percent, slightly larger than drifts that had been seen in data from Cutler, Maine, Otis AFB or Sudbury, Mass., but seen quite often in the Hanscom Field recorder charts. The drift appearing in Figure 7 represents a 27 percent change in I_o, as noted in data from Boston Hill on several occasions, particularly after a period of rain and fog, and always in the same direction. (This behavior is most likely to be attributed to moisture on the optics.)

The quantitative effects of this drift in the transmissometer on the computation of extinction coefficient lead to interesting results. The extinction coefficient, as stated earlier, is defined by

$$\sigma = \frac{1}{x} \mathrm{Ln}\left(\frac{I_o}{I}\right) .$$

In the AFCRL mesonet operation, the transmissometer pulse output (0 to 4000 pulses per minute) is converted to a zero to five-volt signal, and this voltage is in turn converted to an eight-bit binary number for input to the mesonet computer. If <u>K</u> is the eight-bit number received by the computer, then, to compute extinction coefficient we use

$$\sigma = \frac{1}{x} \mathrm{Ln}\left(\frac{K_o}{K}\right) ,$$

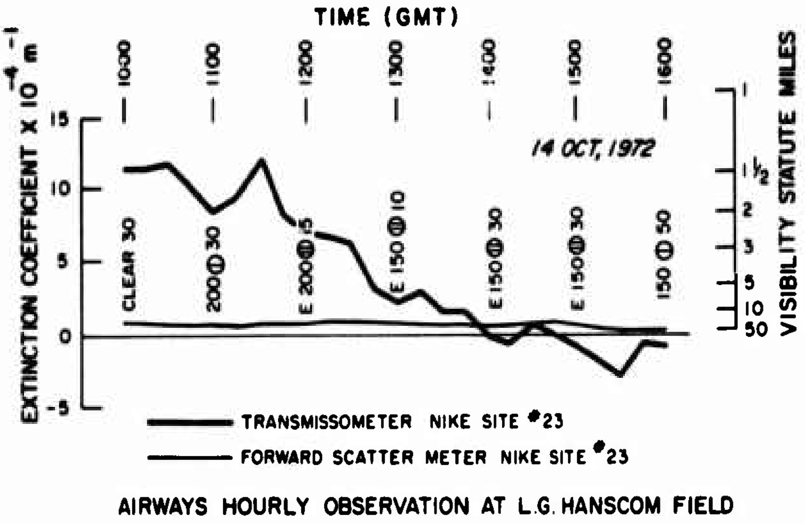

Figure 6. Transmissometer Calibration Drift in Fair Weather, Nike Site, 14 Oct 1972

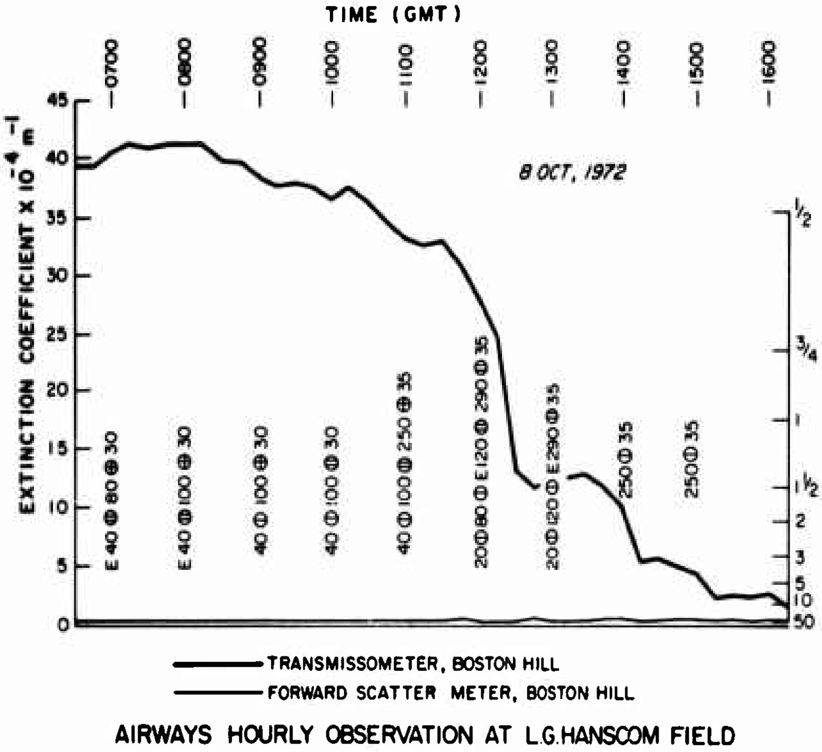

Figure 7. Transmissometer Calibration Drift, Boston Hill, 8 Oct 1972

where K_o is the binary equivalent to I_o. Eight bits allow a number as large as 255; however, we set K_o at 249, to allow for drift. Some upwards drifts of I_o have occurred, resulting in values of K that were pegged at 255. When the transmissometer is properly adjusted, we have

$$\sigma = \frac{1}{x} \, \mathrm{Ln}\left(\frac{249}{K}\right) .$$

If I_o shifts to a new value, one can write

$$\sigma = \frac{1}{x} \, \mathrm{Ln}\left(\frac{249}{K}\right) + \frac{1}{x} \, \mathrm{Ln}\left(\frac{K_o}{249}\right) .$$

The first term is the uncorrected extinction coefficient, or,

$$\sigma_u \equiv \frac{1}{x} . \mathrm{Ln}\left(\frac{249}{K}\right)$$

and the second term is the correction, or

$$\sigma_c \equiv \frac{1}{x} \, \mathrm{Ln}\left(\frac{K_o}{249}\right).$$

Therefore, $\sigma = \sigma_u + \sigma_c$. The correction term σ_c is not related to the prevailing extinction coefficient; a nonzero value represents a change in the instrument, such as optical alignment, light output, or photodetector sensitivity.

Since the measured extinction coefficient varies over three orders of magnitude, it is more realistic to consider percentage errors. The percentage error for the transmissometer, due to drift, is

$$\frac{\Delta\sigma}{\sigma} = \frac{1}{\sigma \, x} \, \mathrm{Ln}\left(\frac{249}{K_o}\right) .$$

Examples of the resulting percentage error for different path lengths, calibration drifts and extinction coefficients are shown in Table 2. Extinction coefficients of $2\times10^{-3}m^{-1}$ and $8\times10^{-3}m^{-1}$ correspond to daytime visual ranges of about 1600 meters and 400 meters, respectively. If the transmissometer is used primarily to determine whether visibilities are above or below a certain low threshold such as 400 m (1/4 mile), then it is easy to see that 5 to 10 percent drifts can be tolerated for the 152-m path length transmissometer. Our three transmissometers use 60-m path lengths; we are equally concerned about calibration when visibilities are 1600 meters. Clearly, 5 to 10 percent transmissometer calibration drifts would cause difficulties establishing the absolute calibration for the forward scatter

Table 2. Transmissometer Error as a Function of Path Length, Calibration Drift, and Extinction Coefficient

Path Length (In meters)	Calibration Drift (%)	Percentage Error in Extinction Coefficient $\sigma = 2 \times 10^{-3} m^{-1}$ (%)	$\sigma = 8 \times 10^{-3} m^{-1}$ (%)
152	5	16	4
152	10	32	8
60	5	41	10
60	10	79	20

meters. Further, they might also hide any systematic differences between the transmissometer and forward scatter meter measurements.

Fortunately, from experience we found the FSM's were very consistent and relatively stable in their readings during periods of low extinction coefficient, say $0.3 \times 10^{-3} m^{-1}$ and less (10 km daytime visibility and more). Comparisons between instruments and with visual estimates indicated the errors under these conditions were no more than $\pm 0.1 \times 10^{-3} m^{-1}$. We could not use transmissometer data for calibration purposes under these conditions as they are beyond the useful range of the transmissometer. However, we can use the FSM data to compute the transmissometer correction σ_c. Even an error of $0.1 \times 10^{-3} m^{-1}$ in σ_c would lead to a transmissometer error of 5 percent at 1600 m visibility.

A procedure was devised wherein the transmissometer corrections were determined immediately before and after a low visibility episode. The correction to be applied is simply the average of the two corrections. A linear trend correction was considered, but there was no way of knowing when or how abruptly the calibration drifts took place, and the simple average seemed a safe value. Even with this correction, there would still be some error in the transmissometer data and the percentage error would be worse at low extinction coefficient. To eliminate the poorest of the data, a threshold value of five times the difference in the two corrections (before-minus-after, absolute value) was determined; data with lower extinction coefficients were not used.

Next, the problem of sampling must be considered. To make a really valid comparison, the instruments must sense the same volume of the atmosphere at the same time. The forward scatter visibility meter measures a ring-shaped volume little more than a meter in any direction, whereas the transmissometer samples a 60-m long tube of air about 18 cm in diameter at the projector. At each of the three sites, the FSM is located several meters from the transmissometer projector and the centers of the two samples are approximately

30 m apart. The easiest method of minimizing the effects of inhomogeneity in fog is to take a time average of the data. The most inhomogeneous conditions we find are associated with ground fog, at which time we find winds of about one meter per second. When a five-minute mean is used, even in the ground fog case, about 300 m of air would pass each sensor during the averaging time, which is many times greater than the instrument separation, and this should greatly reduce the effects of inhomogeneity. This procedure, however, would not necessarily reduce differences due to stationary visibility patterns present in the wake of buildings, heat sources and wind obstructions, but the instruments were carefully placed to avoid such problems. As a last precaution, we excluded from the sample, periods when the RMS variations over five-minute periods were greater than ± 15 percent, in hope of eliminating the most inhomogeneous cases.

The five-minute mean extinction coefficients from the transmissometers and forward scatter meters were computed and plotted on log-log scatter diagrams for each station (see Figures 8, 9, and 10). The 45 degree sloping line in each diagram represents the regression line that would be expected if the original calibration were correct. By inspection it would appear that the line fits very well, a deserving reward for those who worked diligently with the calibration procedure. A linear regression analysis was made based on the log of extinction coefficient (because data are uniformly scattered over two orders of magnitude.) The results are shown in Table 3.

Considering the scatter in the points plotted in Figures 8, 9, and 10, one would not be very tempted to make a refinement in the calibration. There are statistical tests that can be applied; for example, in Hoel,[6] there is a procedure for using the Student's distribution to compute confidence limits for a regression coefficient (slope). In Table 3, the largest departure from a slope of 1.00 is the 0.92 slope at Station 07. However the test would indicate this departure from 1.00 is significant only at the 25 percent level. The other departures are even less significant and hence we have no statistical basis for modifying the calibration.

The RMS differences are significantly lower than the ±24 to ±28 percent found for the two prototype instruments in the Cutler, Maine tests, indicating these are much improved forward scatter meters.

A rather interesting question is: What is the cause of the scatter in the points in Figures 8, 9, and 10 --- the ±16 to ±22 percent? Several possible answers come to mind. Certainly some of the scatter must be due to residual uncertainty in the transmissometer calibration. However, from the previous analysis, one would expect that percentage errors would decrease linearly with increasing

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[6] Hoel, P. G. (1947) Introduction to Mathematical Statistics, Wiley and Sons, New York, p. 147.

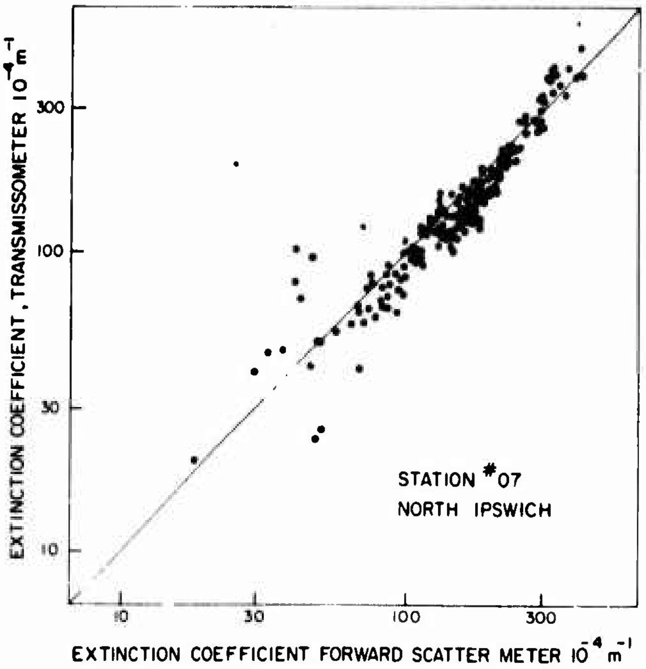

Figure 8. Comparison of Transmissometer and FSM Measurements, North Ipswich, Sept-Nov 1972

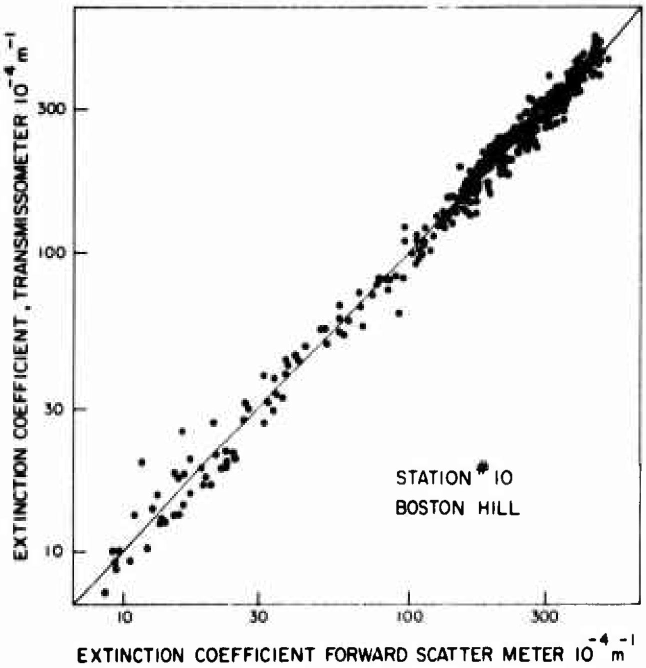

Figure 9. Comparison of Transmissometer and FSM Measurements, Boston Hill, Sept-Nov 1972

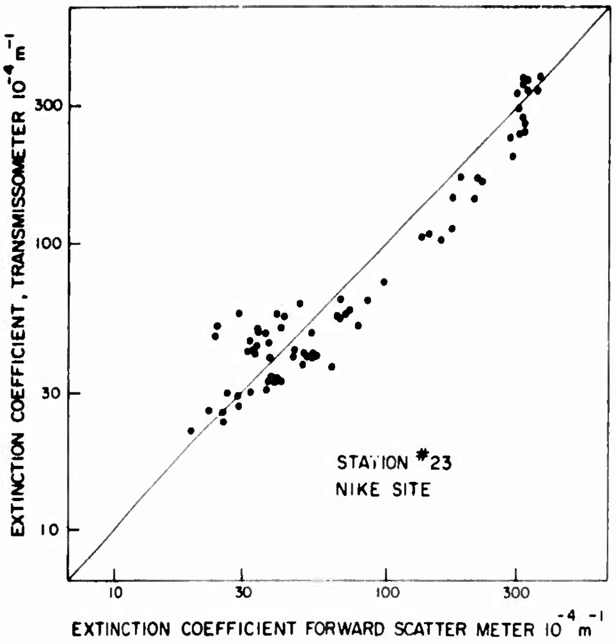

Figure 10. Comparison of Transmissometer and FSM Measurements, Nike-Site, Oct-Nov 1972

Table 3. Correlation of Extinction Coefficients from Forward Scatter Visibility Meter Against Transmissometer (based on logarithms)

Station Number	Station Location	Number of Comparisons	Correlation Coefficient	RMS Difference (%)	Slope
07	N. Ipswich	200	0.93	± 20	0.92
10	Boston Hill	435	0.99	±16	0.99
23	Nike Site	84	0.96	±22	1.00
All combined		729	0.98	±19	0.98

extinction coefficient, a factor of ten from 3 km^{-1} to 30 km^{-1}. In Figures 8 and 10, there is some reduction in scatter going towards higher extinction coefficient, but not a factor of ten, and in Figure 9 there is no discernible difference. Thus it would appear that transmissometer uncertainty is not a major factor.

Next, we might suspect that there is noise in the forward scatter visibility meter under foggy conditions, with high extinction coefficients. However, in July of 1973, we obtained evidence to the contrary. The laboratory calibrator was mounted on an FSM at a network station on two different occasions, a different instrument each time. In both cases the weather was fair, with very little atmospheric scatter; the calibrator was left in place for six hours in the first case and twelve in the second, both times including the sunset period. The readings from one instrument differed from the other by about 2.6 percent. Both instruments showed very small fluctuations during daylight hours, about ±0.7 percent and even less at night, ±0.3 percent! On one instrument there was a 1 percent shift going from day to night, and on the other it was 0.5 percent. The calibrator was producing a scattering of projector illumination equivalent to a fairly dense fog with extinction coefficient of 13.9 km^{-1} or 200 m daytime visibility. This exercise would certainly indicate that the noise level in the FSM is not an important factor in the scatter.

Further, we might consider some second-order effects such as absorption and secondary scattering that might create differences that would vary according to drop size distribution. However, Middleton[1] indicates that absorption by water drops is less than 1 percent of the total scattering even for drops as large as 5000 μm. Quantitatively, secondary scattering also does not seem a plausible explanation for the remaining disagreement between FSM and transmissometer. This leads us to question whether this could be atmospheric inhomogeneity. The instruments are effectively 30 m apart, and Chisholm and Kruse[7] found differences for FSM's with 4-meter separation of ± 12 percent in advective fog and ± 17 percent in radiation fog for one-minute means. At 1000 meters separation the differences rose to ± 27 percent and ± 103 percent respectively. The values for five-minute means would be a bit lower, but this is strong evidence that a major part of the variance found between FSM and transmissometer is atmospheric inhomogeneity.

An important point is that these differences are not large when one considers that the extinction coefficient can rapidly vary over several orders of magnitude. To illustrate, Figure 11 shows a plot of two forward scatter visibility meters located about 3 meters apart during a period of highly variable extinction coefficient. The RMS difference is about ± 12 percent yet the individual traces are barely distinguishable. One of the two meters had been in the field (thus not

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[7] Chisholm, D. A., and Kruse, H. (1974) The Variability at Airfield Visibility: A Preliminary Assessment, AFCRL-TR-74-0027

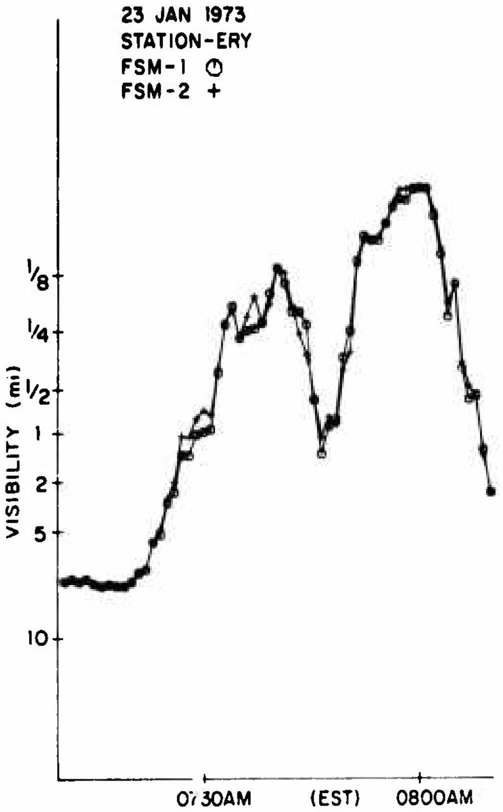

Figure 11. Time Sequence of Two Forward Scatter Visibility Meters at East Runway Site, 23 Jan 1973

calibrated) for six months, and whatever calibration error was present was certainly of no consequence.

7. COMPARISON OF FORWARD SCATTER VISIBILITY MEASUREMENTS TO VISUAL DETERMINATIONS

The previous tests have shown that the FSM measures extinction coefficient quite well within the limits of the <u>standard</u>—the transmissometer. To test the full <u>dynamic range</u> of the instrument and to be confident that we are indeed measuring visibility, the FSM measurements must be compared with visual observations. During the first two months of the mesonet operation, September and October 1972, regular weather observations were taken at Hanscom Field 24 hours a day by a team of AWS observers from a tower site labelled WX-OB in Figure 12.

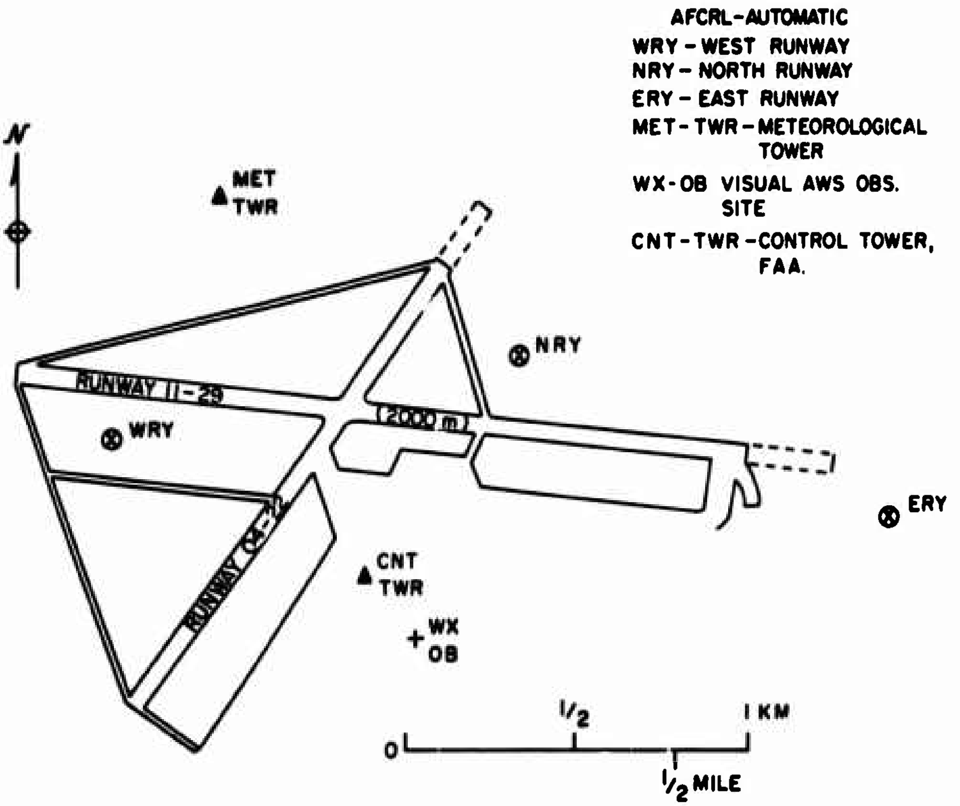

Figure 12. Instrument and Visual Observing Sites at L. G. Hanscom Field

In November of 1972, the observing function was turned over to FAA personnel, operating in the control tower (labelled CNT-TWR), 24 hours a day until cut back to 16 hours a day in the spring of 1973. The observed visibility was, of course, the prevailing visibility, taken in accordance with procedures described in Federal Meteorological Handbook No. 1.[8] To compare the FSM measurements to prevailing visibility a prevailing extinction coefficient should be derived from FSM data. Fortunately, there are a number of network stations located at Hanscom Field, as shown in Figure 12; three are along the principal runway and a fourth at the AFCRL mesonet tower somewhat to the north. Since both the AWS and FAA observers were located in towers about 25 meters above the runway and the runway FSM's were only 4 meters high, it would be well to include the mesonet tower FSM at the 40-meter level in the computations.

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[8] Federal Meteorological Handbook No. 1 (1972) Surface Observations, U.S. Government Printing Office, Washington, D.C.

With four instrumentally determined values of extinction coefficient a new problem arises: How should they be combined to form the prevailing extinction coefficient, that would be related to prevailing visibility? In the simplest case, in daytime with a black target against a light sky, the limit of visibility is the point at which the ratio of target brightness to sky brightness reaches a threshold ε (about 0.02 to 0.06 depending on illuminance, size of target, fatigue, etc.). Following Koschmieder's classical approach as described in Middleton,[1] at the point of maximum visibility in a given direction, or visual range -- V --

$$\varepsilon = 1 - \int_0^V \sigma e^{-\sigma} dx .$$

If the extinction coefficient is not a function of distance x this equation can be simply integrated and solved for V to yield Koschmieder's law

$$V = - \frac{\mathrm{Ln}\, \varepsilon}{\sigma}$$

In principle, even if σ does vary with x, the integral equation can be solved for V by finite difference techniques, but the effort would hardly be justified in this case with only four data points. A similar argument can also be made for the nighttime equation. The simplest solution to our problem is to take a straight average of the extinction coefficients. When the variations of σ are small, say 10 to 20 percent (and not correlated with distance) the average will be very close to the finite difference solution. When variations in σ are very large, as in the case of dense patchy ground fog, visibility is a function of position on the runway—it becomes the distance to the nearest fog bank—and the operationally most meaningful value might be the minimum visibility. Nevertheless, this averaging procedure will still yield a value approximately equal to the average visual range from all points on the runway, when we have three runway reports and no more than one dense patch of fog.

The observer's reported visibility was obtained for every hourly observation and special observation (taken when significant changes occurred), and the prevailing extinction coefficient was computed from one-minute means of the four FSM's at the time of the reported observation. The comparisons with AWS observations were kept separate from the FAA comparisons first, because different sites were used, and second, because there was a large difference between the two sets of observations.

A second separation was necessary because daytime and nighttime observations are not compatible. In a given fog, a bright light can be seen at considerably greater distance at night than could a black object be recognized in daylight. The meteorological agencies have adopted a 25-candela lamp as a standard and the resulting visibilities are at least twice as great when visibilities are 1.6 km (daytime) and less.

Figure 13 shows the comparisons between FSM prevailing extinction coefficient and prevailing visibility determined by AWS observers during daytime. The sloping line represents the conversion of visibility to extinction coefficient using Koschmieder's law,

$$\sigma = \frac{\mathrm{Ln}\,\varepsilon}{V_r}$$

and the standard threshold contrast ε of 0.055. Without question, the forward scatter visibility meters do measure visibility, and the response looks very good throughout the range from 60 m to 20 km (which is well beyond the upper design limit of the instrument—6 km). A somewhat higher value of ε than the standard 0.055 would actually produce a better fit, indicating either conservatism on the part of the observer or less than normal contrast in the targets; with ideal targets in the Cutler, Maine, tests, the AFCRL observers found ε to be as low as 0.02.

The corresponding comparison for AWS observers at night is shown in Figure 14. To convert nighttime visibility to extinction coefficient the weather services use as a standard (based on Douglas and Young[2])

$$\sigma = \frac{1}{V_r}\,\mathrm{Ln}\,\frac{I}{E_T\,V_r},$$

where I is the light source strength (25 candelas) and E_T is an illuminance threshold (0.18 lumens/km^2). The gently curving line represents the standard conversion. Two features are at once noticeable. First, the scatter is much greater than in the daytime diagram, Figure 13. Second, the visibilities are systematically lower than for the standard conversion, suggesting brighter than normal background illumination or else improper darkness adaptation by the observer.

Similar diagrams were constructed for the comparisons with FAA observers for the months of November and December of 1972, but the scatter in the points was very large (not shown here).

In either the daytime or nighttime case, the relationship could be represented by a straight line with 45 degree slope with about as much accuracy as any simple curve. This means we can express the relationship as $\mathrm{Ln}\sigma = \ln C - \ln V$, or $\sigma = C/V$, or $\sigma V = C$. Best fit values of C are shown in Table 4, along with the deviation of the points from the best fit line, expressed in percentage, so that we might make some comparisons between the sets of observations.

There was no change in the FSM instrumentation during this period and we know the instruments work as well, if not better, at night, so the differences in

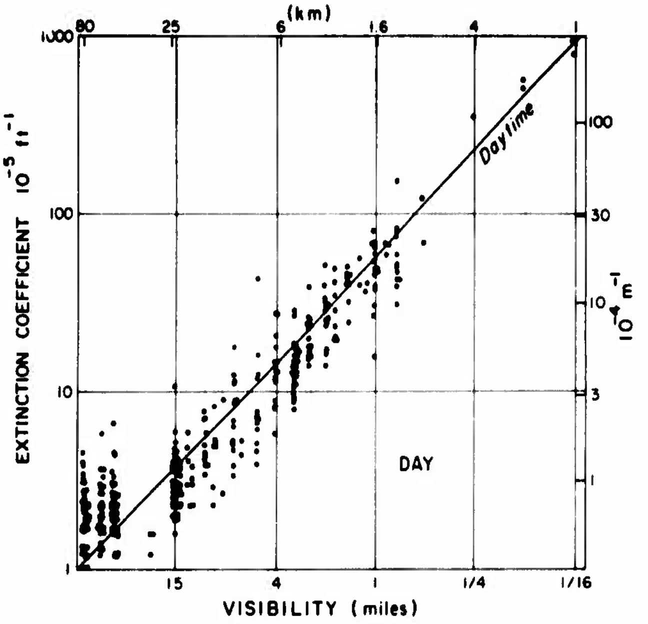

Figure 13. Comparison of AWS Prevailing Visibility to FSM Average Extinction Coefficient, Daytime, Sept-Oct 1972

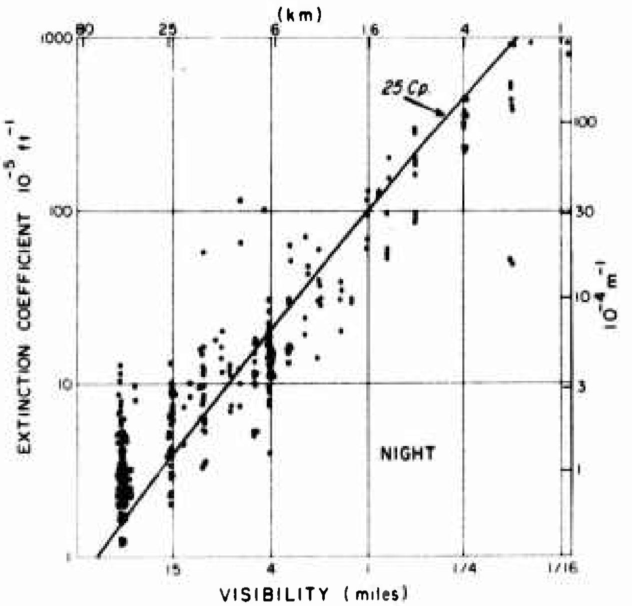

Figure 14. Comparison of AWS Prevailing Visibility to FSM Average Extinction Coefficient, Night, Sept-Oct 1972

Table 4. Summary of Comparisons of Forward Scatter Visibility Meter Observations to Prevailing Visibility

Type	Range	Day No.	Day C	Day Std. Dev. (%)	Night No.	Night C	Night Std. Dev. (%)
AWS	0-5km	123	2.64	± 34	76	3.80	± 53
AWS	all	435	2.80	± 51	448	4.17	± 82
FAA	0-5km	124	2.22	± 52	142	3.01	± 113
FAA	all	448	2.32	± 55	529	2.80	± 138

C between FAA and AWS seen in this table relate to the observers and not the instrument. We should pay closest attention to the 0 to 5-km range, for in this range the FSM's and observers are most apt to be sensing the same environment, and the observers have more and better targets, and the instruments have more scattered light to sense. Here the lower values of C mean that the FAA observers are even more conservative than the AWS, with visibilities about 16 percent lower by day and 20 percent lower by night for the same extinction coefficient.

The standard deviations are very hard to understand. In the tests at Cutler, Maine, a single prototype instrument agreed with visual determination within ± 27 percent. The values in Table 4 are much higher, yet they are based on four newer and clearly better instruments. The increase in the standard deviation for the FAA observations relative to AWS might be anticipated since the FAA observers had less training and experience as well as additional duties to perform. The increased standard deviation (scatter) going from day to night was not expected, although, when questioned, the AWS observers noted that intense foreground illumination from floodlights did give them problems at night, and they also had some difficulty with a building that partially blocked line of sight to the east end of the principal runway (where patchy ground fog has been detected by the FSM on more than one occasion). More explanations for the deviations will emerge as we examine some actual cases.

In Figure 15 the time variation of extinction coefficient from the four forward scatter meters located at Hanscom Field, during a period of rain showers. The solid line represents the reported visibility (right-hand scale). The agreement among the forward scatter meters is quite good, the calibration appears excellent, and close inspection shows the west runway site usually affected first and the east runway last, with a lag representing a translation speed of about 10 mps - a reasonable value. The observer was quite busy: not often does one see 12 special observations in a three-hour period. Yet he was still not able to keep up with

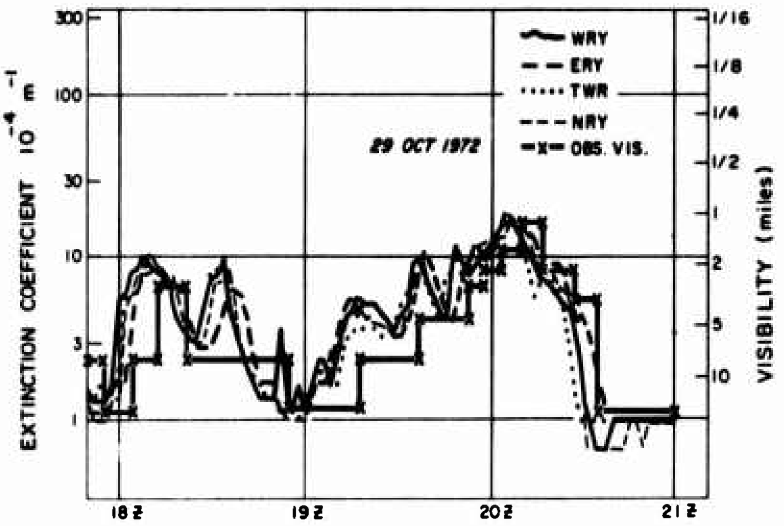

Figure 15. Forward Scatter Meter Measurements and Prevailing Visibility Reports in Showers, 29 Oct 1972

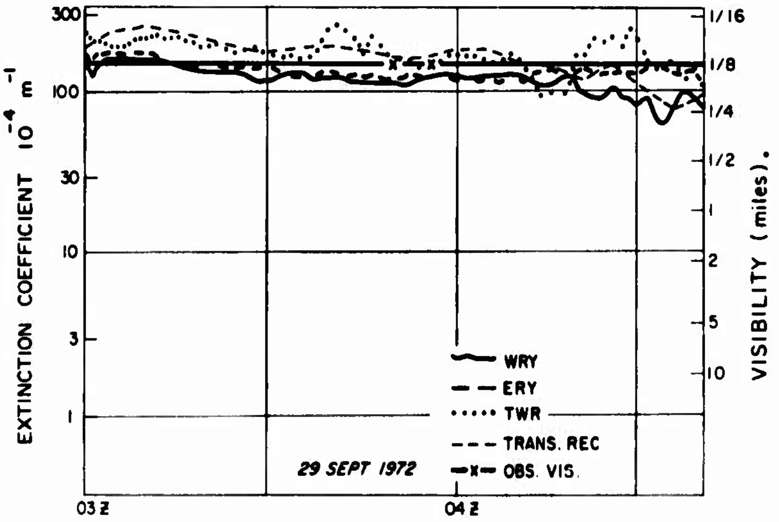

Figure 16. Forward Scatter Meter Measurements and Prevailing Visibility Reports in Dense Fog, 29 Sept 1972

the changes, he was generally five to ten minutes late, and completely missed some significant showers. Because of this delay, it is easy to see how many (if not most) of the observations were in error by 50 percent or more. Unless there is both an urgent need and rapid dissemination there is really no point in minute-to-minute response, as there is a risk the visibility will return before the user can be notified of the change. Thus, there is a motiviation for the observer to hold fire until he feels the change will last for, say, five minutes or more, and this feeling comes only by waiting and watching for a while.

In the next three diagrams (Figures 16, 17, and 18) we see examples of nighttime situations. Figure 16 represents a dense fog present at all sites, with some small perturbations and a small trend toward improved visibility. The observed visibility was justifiably constant, as the observer was limited to the reportable values of 1/16, 1/8 and 3/16 mile and could not in fact report the perturbations or trend. A few hours later (Figure 17), the fog broke up and the observer was able to follow the general trend, with some lag, but he was either unaware, or failed to report the large spatial variations and almost chaotic pattern indicated by the forward scatter meters. In the last of this series (Figure 18), there is a case of patchy ground fog that went virtually unnoticed by the observer. The base transmissometer (located near the west runway FSM) was inoperative that night. The meteorological tower and west runway sites appeared to be responding in unison, suggesting a fair size to the fog patches, perhaps 800 m or more, enough to give problems to landing aircraft.

The convincing feature of these cases is that the independent, widely scattered (800 to 1600 m apart) forward scatter meters were in many cases reacting almost simultaneously, and the observer was not. One is strongly tempted to believe that a large part of the scatter in Figures 12 and 13 was due to difficulty in making reasonable visibility estimates under these conditions, and not the instruments. Middleton[1] (p 227) remarked: "This distance is known as the visibility. The details of the technique were discussed in Chapter X, where it was shown that the datum which results from the observation has almost no relation to the optical state of the atmosphere at the time, so that nothing whatever can be predicted from it, except in the roughest sense." (Middleton in his Chapter X had discussed some of the difficulties in obtaining reliable estimates of visibility from observers.) Judging from visibility reports at Hanscom Field, particularly FAA reports at night, one concludes that the situation has not changed appreciably in the last 20 years.

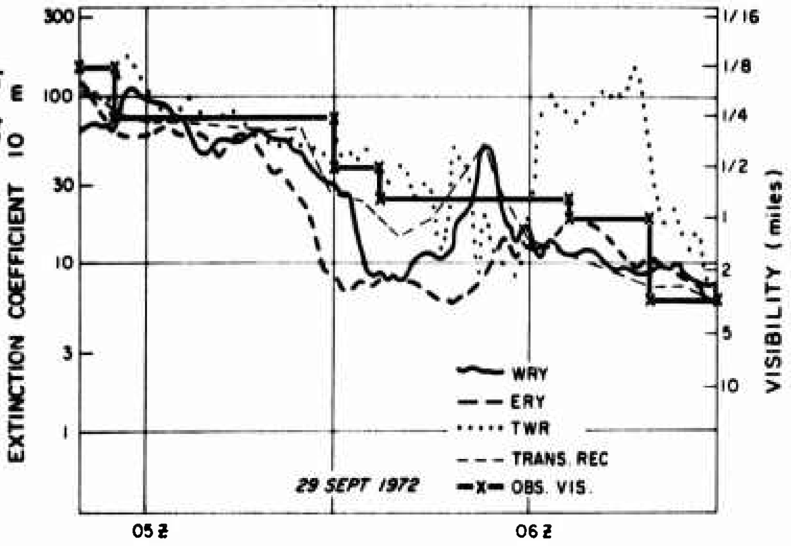

Figure 17. Forward Scatter Meter Measurements and Prevailing Visibility Reports in Clearing Fog, 29 Sept 1972

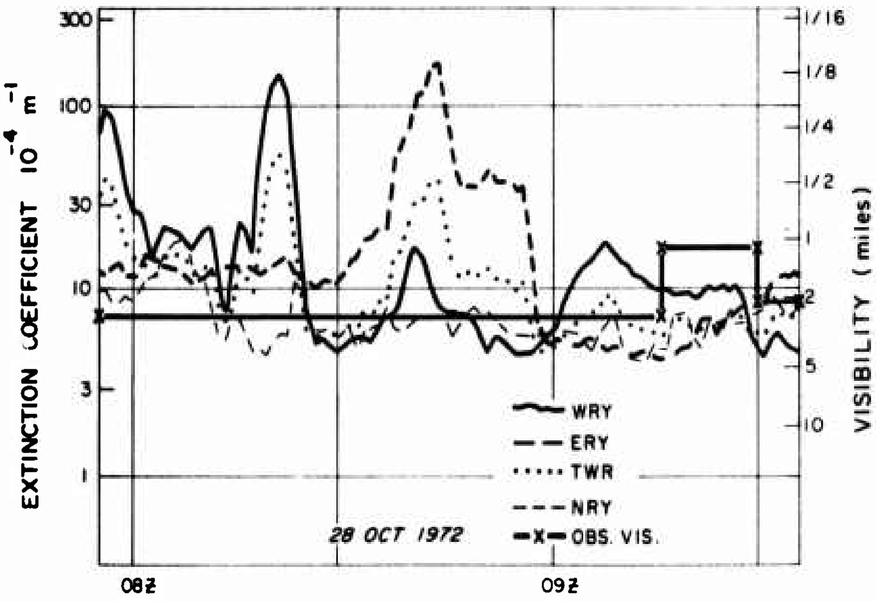

Figure 18. Forward Scatter Meter Measurements and Prevailing Visibility Reports in Patchy Fog, 28 Oct 1972

8. ESTIMATE OF THE ACCURACY OF VISUAL RANGE SYSTEMS AT AIRPORTS

A survey of the published literature of the past 30 years reveals that there have been very few experiments reported that would provide quantitative information on the accuracy of the reported runway visibility. Meteorologists can easily find information on the accuracy of measurement of such parameters as wind, temperature, humidity, and pressure, but there is virtually nothing on the accuracy of visibility. Yet, there are over 10,000 visibility observations taken by the weather services every day, stored on punch cards, magnetic tape and microfilm, and many are used in the dozens of forecast studies made each year.

The previous sections have shown convincing evidence that the forward scatter visibility meter represents a major advance in the measure of visibility. In overall range and stability, it is superior to the transmissometer, and it has obvious advantages over the human observer. Drawing on the extensive volume of mesonet data collected during the first year of operation and the experience with transmissometers and visual observations, we have assembled the following estimate of the errors in contemporary visibility observing systems, as shown in Table 5.

Table 5. Estimated Errors in Determining the Visibility Along the Runway with Different Observing Systems

System	Range	Threshold Variations[b] (%)	Noise, Drift (%)	Spatial Variations (%)		Net (%)
4 FSM(1 per km)[a] (1-minute avg.)	0-5 km	± 15	± 4	± 15		± 23
Transmissometer 1, 152m path	0-1.8 km	± 15	± 15[c]	± 35		± 40
Transmissometers 2, 152m path	0-1.8 km	± 15	± 11	± 25		± 31
		Threshold Variations[e] (%)	Systems Prob.[d] (%)	Time Lag (%)	Spat. Var. (%)	Net (%)
Prime duty observer, day	0-5 km	± 25	± 15	± 20	± 10	± 36
Prime duty observer, night	0-5 km	± 25	± 25	± 30	± 20	± 50
Secondary duty observer, day	0-5 km	± 25	± 25	± 30	± 10	± 47
Secondary duty observer, night	0-5 km	± 25	± 35	± 40	± 20	± 62

The following notes apply to Table 5.

1. We have assumed a typical jet aircraft runway of 3 km (10, 000 ft). A single FSM would have errors due to spatial variability of about ± 20 percent in rain and snow, about ± 40 percent in advection fog and ± 60 percent or more in radiation fog. A spacing of one instrument per kilometer would be able to account for most spatial variability; a tighter spacing might be needed where radiation fog is the predominant visibility restriction.

2. Even if a system perfectly specified the optical properties of the atmosphere, the indicated visibility would likely be different from what the pilot actually reported seeing. There are still physiological and psychological factors involved, which effectively mean that the threshold contrast and threshold illuminance vary not only from pilot to pilot, but even for a given pilot, they vary with time. In Chapter 10 of Middleton,[1] there are data on variations of threshold contrast which would indicate that uncertainties in visibility could be as high as ±25 percent. This is higher than the ± 19 percent difference found between observers and transmissometer in the AFCRL tests at Cutler, Maine, (the differences also included some transmissometer error and spatial variability). With visibilities about 100 m, experience at Cutler indicated that the uncertainty of when a target becomes visible is about ± 10 percent for an individual. While the observers at Cutler, Maine were probably more dedicated and concerned about accuracy than the observers reported by Middleton,[1] the pilot in a landing or take-off maneuver must also be highly motivated and concerned. In consideration of these factors, the figure chosen to express this variability was ± 15 percent.

3. During the first year of mesonet operation, the transmissometer drift was about ± 14 percent full scale, with maintenance and realignment limited to about one visit per month. When the transmissometer is maintained by trained technicians making daily and weekly checks described in T.O. 31M 1-2GMQ 10-61, the drift should be less than ± 2 percent of full scale. For Table 5 a value of ± 7 percent of full scale was chosen as a compromise between the two values and would likely represent what would be found at a typical airfield. This results in an overall visibility error of ±15 percent.

4. This includes such items as the use of poor targets, lack of darkness adaptation, operational pressures (to bias observations) and improper training and supervision. The values presented are lower than indicated by experience at Hanscom Field, but likely to be found at more active airfields.

5. The variability of threshold contrast (or illuminance) of both the pilot and the observer must be considered. As before, ± 15 percent was chosen for the pilot, but ± 20 percent was chosen for the typical observer in a routine operation.

A casual reader might be concerned at the magnitude of these values. For comparison, standard weather station temperature measurements are normally accurate to ± 0.5C, or ± 0.2 percent of absolute value, and pressure measurements are normally accurate to ± 0.1 percent of absolute value. The visibility accuracy values of ± 20 percent to ± 60 percent appear gross and may partly explain the apparent reluctance of meteorologists to publish figures of this type. There is some consolation if we look at the accuracy in terms of temporal variability. The temperature and pressure errors correspond to typical RMS changes (for temperate latitudes) in the 30 minute to one hour range. This is consistent with the practice of making new observations of these quantities every hour. However, RMS changes in extinction coefficient (when visibilities are 3km and less) are about ± 40 percent in 15 minutes! Actually these visibility systems are more capable, in that they can resolve changes occurring in much less than an hour. However, if the goal is to present credible values to the pilot, then ± 40 percent is not adequate and we must resort to a multiple instrument system.

9. CONCLUSION

It is clear that a new era of visibility measurement has begun. There are other instruments than the FSM that are either in or near the production stage, including back-scatter systems, integrating scatter devices, folded-path transmissometers, and laser systems. These instruments might not possess some of the features of the FSM such as wide dynamic range, but they may have other advantages such as sampling volume or cost, and may soon be brought into operational use. Besides the need for monitoring runway visibility, such instruments are needed to operate fog horns, beacons, highway warning lights, and monitor air pollution as well. With the recent introduction of reliable, low-cost solid-state electronic devices, communication and data processing costs have decreased to the point where networks of such sensors placed in problem areas are certain to come about in the near future. It is hoped that there will be a coordination of efforts between groups so that a maximum benefit will be gained from the coming era of automation.

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