White Paper

The Case for Forward Scatter Sensors for IRVR

Ian Clark and Jonathan Abbott

May 2012

Aeronautical & General Instruments Limited
Fleets Point
Willis Way
Poole
Dorset
BH15 3SS
England

Tel: **01202 685661**
Fax: **01202 685670**

Introduction

A number of papers have been published comparing forward scatter instruments (FSIs) to transmissometers (TMXs) for the purposes of determining Meteorological Optical Range (MOR). This paper focuses on the application of these devices to automatically determine Runway Visual Range (RVR). It will be of special interest to airport operators looking to automate RVR measurements.

To determine RVR requires a measurement of the atmospheric clarity and other visibility-related parameters. This paper sets out the case for using forward scatter instruments for these calculations. It shows that there are errors in calculating the visibility related parameters that are common to transmissometers and forward scatter systems, and the assumption that a transmissometer is always the best instrument to determine RVR can be an expensive one.

The paper describes in straightforward terms the ways in RVR may be assessed. It also sets out specific data gathered from a comparison trial of a transmissometer and a forward scatter instrument in determining RVR. The final section is a comparison in the costs of typical transmissometer and forward scatter systems.

Methods of Observation

Runway Visual Range (RVR) is defined by the International Civil Aviation Organisation (ICAO) as:

"The distance over which the pilot of an aircraft on the centreline of a runway can see the runway surface markings or the lights delineating the runway or identifying its centre line."[1]

Because it is not possible to measure RVR directly (as instruments would have to be somehow sited actually on the runway), an *assessment* is made. The reliable and accurate assessment of RVR is essential if airport operations are to run as safely and efficiently as possible.

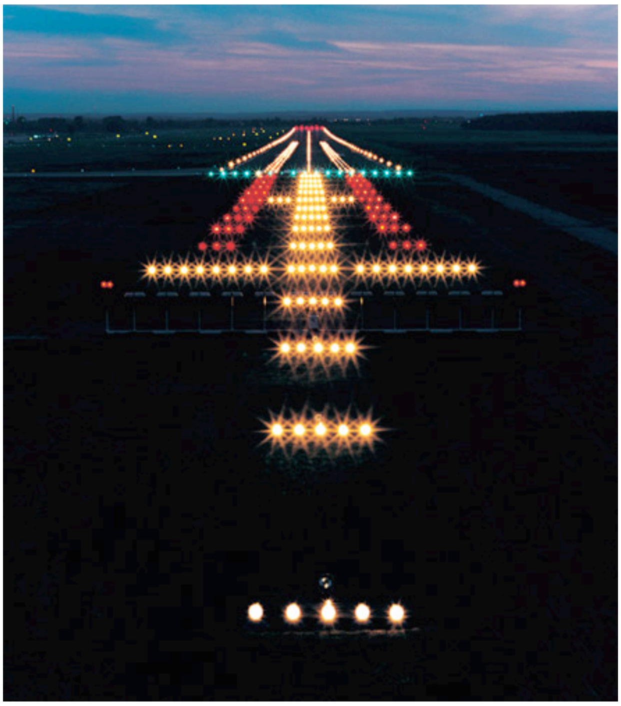

Figure 1: Runway Approach Lights at Dusk

To provide an RVR assessment, three methods may be used:

- Manually using human observers
- Automatically using transmissometer measuring instruments
- Automatically using forward scatter measuring instruments

Human observation techniques involve a trained Met observer standing at a pre-determined position adjacent to the runway touchdown zone and counting the number of edge lights visible along the opposite side of the runway. This observation is relayed to the ATC personnel, with RVR determined from a look-up table. The table is typically generated by a qualified meteorologist who produces the table and updates it every three years for the specific airport. As air traffic has dramatically increased over the last 25 years, with aircraft flying in all sorts of conditions and times of day and night, human observers are in general no longer efficient or cost effective. There are also accuracy concerns regarding human error in the system.

Where either transmissometers or forward scatter sensors are used, the resulting assessments are referred to as Instrumented Runway Visual Range (IRVR). Such automated systems eliminate human error and achieve much better repeatability of measurements. They can also provide RVR readings 24 hours a day without requiring the presence of dedicated Met personnel.

Atmospheric Visibility

The most important factor in assessing RVR is to establish the atmospheric extinction coefficient or the related value for atmospheric transmittance. These measure horizontal visibility through the atmosphere. Light passing through air may be attenuated due to two effects:

- The scattering of light by airborne particles
- The absorption of light by airborne particles [2]

For light in the visible and near visible part of the spectrum scattering is the dominant effect in precipitating particles such as fog and snow, whilst absorption plays a larger (but still secondary) role for suspended particles, such as haze, dust and smoke.

Figure 2: Glare Due to Scattering of Light

The extinction coefficient is defined as:

"The proportion of luminous flux lost by a collimated beam, emitted by an incandescent source at a colour temperature of 2,700K, whilst travelling the length of a unit distance in the atmosphere (per metre)."[3]

The value for extinction coefficient is therefore high in conditions where a large number of airborne particles cause visibility to be low.

Assessment of IRVR

The ICAO mandates [4] that IRVR measurements should be updated at least every 60 seconds. IRVR systems perform IRVR calculations simultaneously using two different equations:

Koschmieder's Law

In 1924 a German meteorologist, Dr Harald Koschmieder, formulated what became known as Koschmieder's Law. This is a method of assessing visibility based upon the relative luminance of a black body against the luminance of the background it is viewed against. When calculated from the extinction coefficient (σ) using WMO assumptions the result is known as the Meteorological Optical Range (MOR) and may be approximated as:

$$MOR \approx 3/\sigma$$

Allard's Law

Koschmieder's equation is applicable for assessing visibility in daylight, but during night time a different method is required. In 1876 Emile Allard, engineer-in-chief of the French Lighthouses Commission, proposed a formula for calculating the visibility of a source of light. Since codified as Allard's Law, it is the ICAO-approved method for assessing the visibility of runway lights. It requires values for the extinction coefficient, the luminous intensity of the lights being viewed and the background luminance.

The value of background luminance is obtained from one or more background luminance meters (BLMs). These are photo-detectors with a photopic response similar to the human eye, to represent what the human observer would see. Each BLM is usually oriented so that it faces away from any nearby lighting that could distort readings, and also so that it is never exposed to direct sunlight.

The value of runway light intensity (RLI) is derived from the rated intensity of the runway lights at the airport where the IRVR system is installed. The nominal value for maximum intensity is usually reduced by a degradation factor (typically 20%) to allow for the loss of runway light performance through aging and any contamination. The value for RLI then used in calculations is varied in accordance with the percentage of the maximum nominal electrical current being used to drive the lights at the time the calculation is done. Set percentages of 100%, 30% and 10% are recommended by the ICAO [5], but some countries also use settings for 3% and 1%.

Calculations and Banding

IRVR calculations are usually carried out using a rolling 10 minute mean of extinction coefficient. Once calculations for both Koschmieder's and Allard's Laws are complete, the system selects the highest current IRVR value of the two, which is rounded down and reported in bands as per ICAO Doc 9328 (Manual of Runway Visual Range Observing and Reporting Practices).

Sources of Error in RVR Assessments

Each of the parameters used to assess RVR has an associated error attached to it. A respected meteorologist, Dr Alan Hisscott, has investigated the use of forward scatter instruments and carried out a number of trials in the early 1990s on the Isle of Man. Dr Hisscott has written and presented a number of papers to the Royal Meteorological Society concentrating on the scientific comparison of transmissometer and forward scatter sensor performance. From his trial results he has quantified the errors in each of the RVR parameters.

The background luminance parameter is certainly influenced by the ambient airport environment. From results of a trial of forward scatter sensors in 2001, Dr Hisscott had noticed a difference in luminance values between two BLMs located at different parts of the airport. With no change in visibility Dr Hisscott found that the difference in the two sensors was caused by the runway lighting.

It is evident that taking specific percentage values for the runway lighting intensity must introduce errors into the assessment and both Dr Hisscott and others estimate that the runway lighting value could be in error by 50% due to lamp aging and contamination.

Probably the most significant source of error in RVR assessments lies not with the ground systems but aboard the aircraft itself. Even setting aside differences in the eyesight and levels of alertness in individual pilots, the transmittance of the windscreen is a major factor and can vary greatly depending on the angle of incidence to the viewer, the number and types of layers of laminate and the condition of the glass.

Dr Hisscott has summarised the errors attributed to the runway lights and background luminance as well as the pilots view through the aeroplane's windscreen. These are set out below:

Parameter	**ΔRVR**
Runway light intensity	10%
Background luminance	6%
Windshield transmittance	10 to 30%

These errors are discussed further in the later section dealing with the comparison of trial data for a transmissometer and a forward scatter sensor.

Sensor Contamination

One of the other issues with assessing RVR is the build-up of contamination on the window surfaces of the sensor housings. This is a whole topic in its own right.

In this paper we limit our discussion to point out that IRVR systems have additional sensors and software to detect window contamination, and they can both compensate for it as well as sending warning messages to the operators. In this way contamination can be managed, but it is a factor that will be different with each installation and airport.

Transmissometers: Principles of Operation

Transmissometers measure the extinction coefficient by shining a light of known intensity through a specified distance onto a photo-detector.

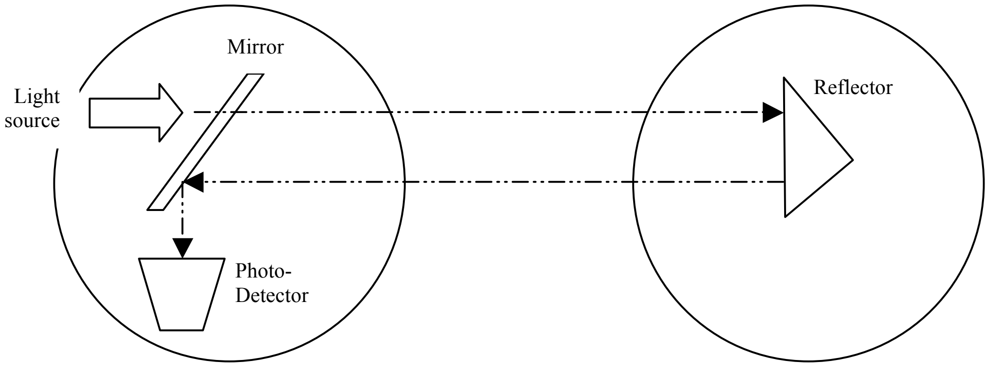

Figure 3: Simplified Reflecting Transmissometer

Many such systems operate as reflecting transmissometers, which means that the light beam is returned by a reflector back to the initial field site. This serves to double the baseline length along which the measurements are taken, increasing the system accuracy.

Transmissometers directly measure both the absorption and scattering of light through the volume of air sampled and the accuracy of the measurement does not depend on the type of weather phenomena occurring.

Figure 4: Transmissometer Installation

Transmissometers require accurate alignment of the transmitter and reflector, with stable foundations to ensure the alignment is maintained. They also need systems to keep the optics clear of contamination, and require periodic maintenance and calibration.

Forward Scatter Sensors: Principles of Operation

Scientifically called a nephelometer, a forward scatter sensor measures the amount of light scattered at angles less than 90 degrees by small particulates suspended in, or large particles passing through its sample volume. The amount of scattering is related to the quantity of particles in the volume of air being sampled. The sample volume is defined by the intersection of the transmitted beam of light and the receiver's field of view.

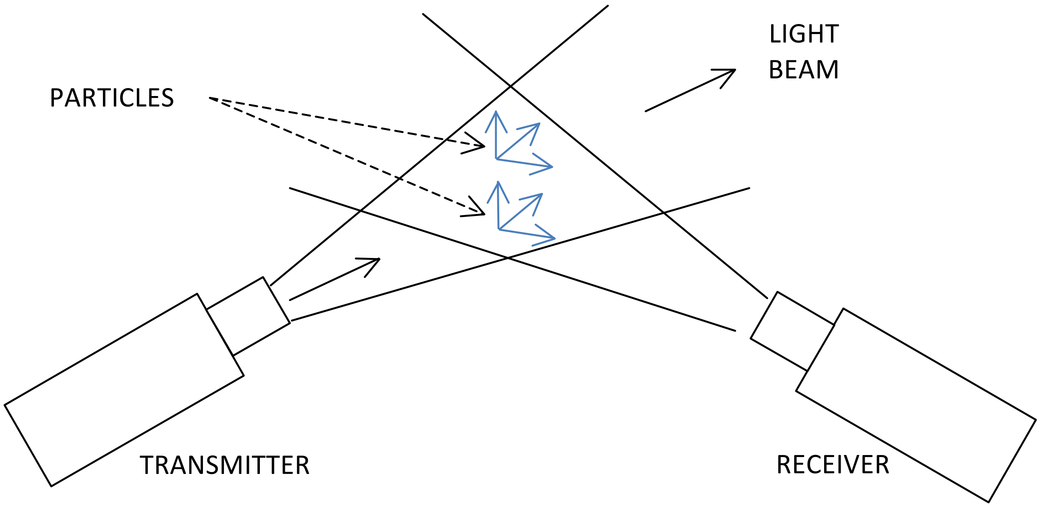

Figure 5: Principle of Forward Scatter Sensor

Forward scatter sensors cannot measure absorption directly. However, the relationship between the amount of absorption and the amount of forward scatter under different weather conditions has been determined by experiment. By adding a back scatter receiver and thermometer to a forward scatter instrument, present weather can be detected, and additional factors for absorption added into the extinction coefficient calculations. This results in a sensor that outputs what is sometimes known as a 'transmissometer-equivalent extinction coefficient'. Such sensors obviously also output present weather information, which is useful in its own right.

Figure 6: Forward Scatter Installation

Forward scatter sensors require accurate alignment of the transmitter and receiver(s) and also need systems to prevent or mitigate for optical contamination. Maintenance and calibration requirements are usually extremely low and they require simpler mounting foundations than transmissometers.

The ICAO mandates [6] that each individual sensor must be able to trace its calibration to a reference transmissometer.

Comparative Accuracy of a Transmissometer and Forward Scatter Sensor

AGI's transmissometer system, the AGIVIS 2000, has been in use for over 20 years. It has proved its accuracy and reliability both in bench mark trials and most importantly in operational use. The AGI forward scatter IRVR system (AGIVIS FSI) was developed in 2005, and in 2006 AGI ran a trial of an AGIVIS FSI system using the Biral VPF 730 sensor against an AGIVIS 2000 transmissometer at Birmingham Airport.

The trial data was analysed by mathematicians and meteorologists. Dr Hisscott was also sent a copy and his findings are set out below.

AGI Birmingham Trial Data

The following is an extract from the paper that Dr Hisscott produced for AGI:

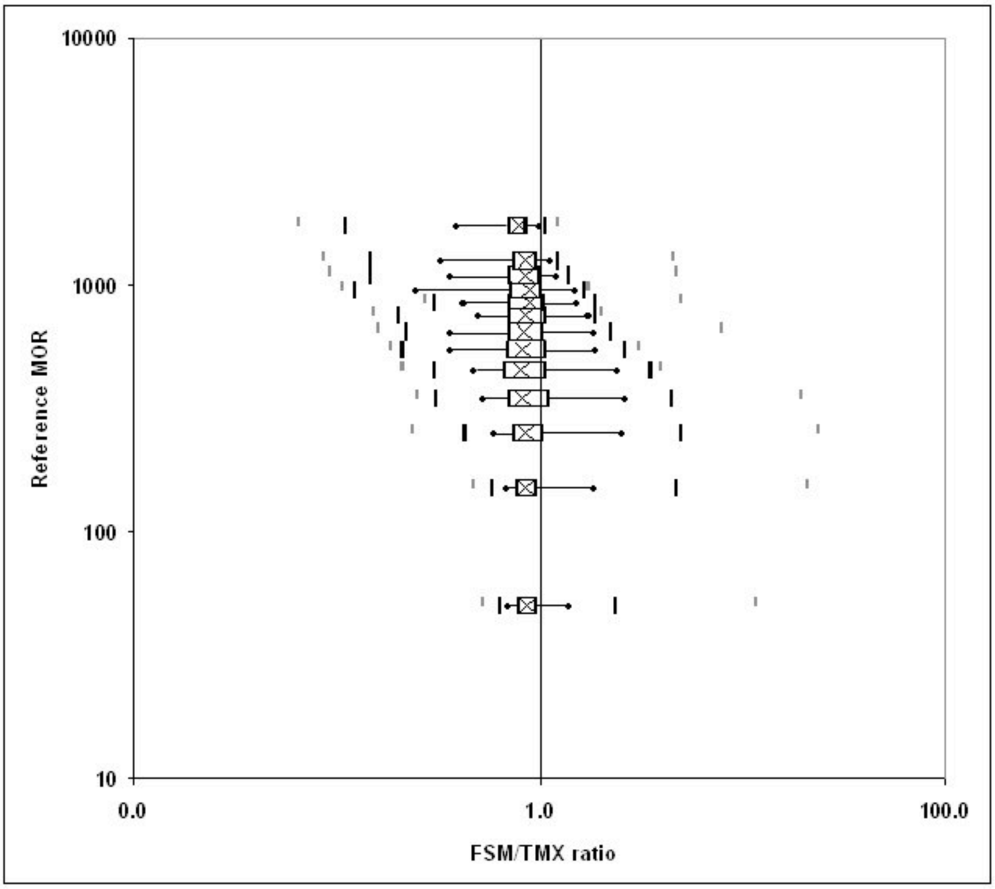

Figure 7: Transmissometer vs. Forward Scatter Trial Results

To remove extraneous information, the data set shown above was reduced to occasions when both the FSI and TMX were reporting valid RVR values.

Dr Hisscott commented on the results of the trail as follows:

"The difference between the complete set of values and the set analysed in [Figure 7] suggests that the apparent increase in FSI MOR in the region 1000-1500m arises from the instruments having a different response to transient conditions. MORs in this range often correspond to transition visibilities during fog formation and dispersal. The difference between the instruments is probably fundamental to their design. The volume of atmosphere sampled by a transmissometer (say 10m beam length x 0.05m^2 x-section = 500 litres) whereas FSI sample volume is usually around 3 litres. Also, the geometry of the sample volume is very different. During the formation/dispersal process of fog there are large spatial variations in droplet density over small ranges. The TMX beam has a higher probability of 'capturing' one or more 'wisps' of inhomogeneous fog during a measuring interval than the smaller sample volume of an FSI. However, it is likely that during such transient conditions neither instrument can measure an MOR sample which is truly representative of conditions along a runway."

"The most important part of the RVR range for Cat I operational decisions is around 400-800m and the average median ratio in this range is 0.83, i.e. the FSI reports MOR around 17% less than TMX in this range. Although it is possible to modify the calibration of FSIs to match the median of TMX, my view is that, at this stage of adopting FSI technology, it is probably better to retain the 'safe' bias where around 75% of the FSI MOR measurements are equal to or less than the equivalent TMX MOR."

For CAT II runway operations the runway visual range should not be less than 350 m. For CAT I it is 550m. The trial data shows the same median values at both these visibility ranges. The difference in the ICAO's recommendations is that a second sensor at the mid-point is required for CAT II runways.

Dr Hisscott's conclusions from the Birmingham trial data were as follows:

- A median difference in MOR between the transmissometer and the FSI sensor was -13%
- This is consistent in magnitude with other errors in IRVR calculations
- <u>The type of sensor used to measure the MOR does not contribute a more significant error than the overall error arising from the other parameters</u>

It is the transitory nature of fog, particularly during formation and dispersal that causes the major differences in output between a forward scatter system and a transmissometer. The actual comparative data when fog is well formed and thick is very similar. This was also proved in the German Meteorological Service trial as set out in their paper by Stefan Waas:

"In general measurements of forward scatter sensors and transmissometers match very well in homogeneous conditions especially at visibilities below 1000m which are most relevant for IFR approaches."

"During inhomogeneous visibility conditions even transmissometers can differ very strongly in direct comparison to each other." [7]

It should therefore be borne in mind that there are numerous sources of error common to both types of sensor. These include:

- Homogeneity and directionality of actual visibility
- Windshield transmittance factors
- Siting and direction of view of BLMs
- Actual performance of runway lights
- Alignment of sensor transmitters and receivers
- Pilot’s eyesight, alertness, etc.
- Optical contamination of sensors

Comparative Costs of Transmissometer and Forward Scatter Systems

For illustrative purposes, a simplistic cost comparison is presented between a transmissometer and a forward scatter system for a typical airport. In both cases this is for a two sensor, two BLM system. It includes the cost of ground works at each sensor location but assumes that wired or fibre optic comms back to the ATC tower are already available in the vicinity of each field site. The figures are presented in US dollars and are based upon market data from the end of 2011.

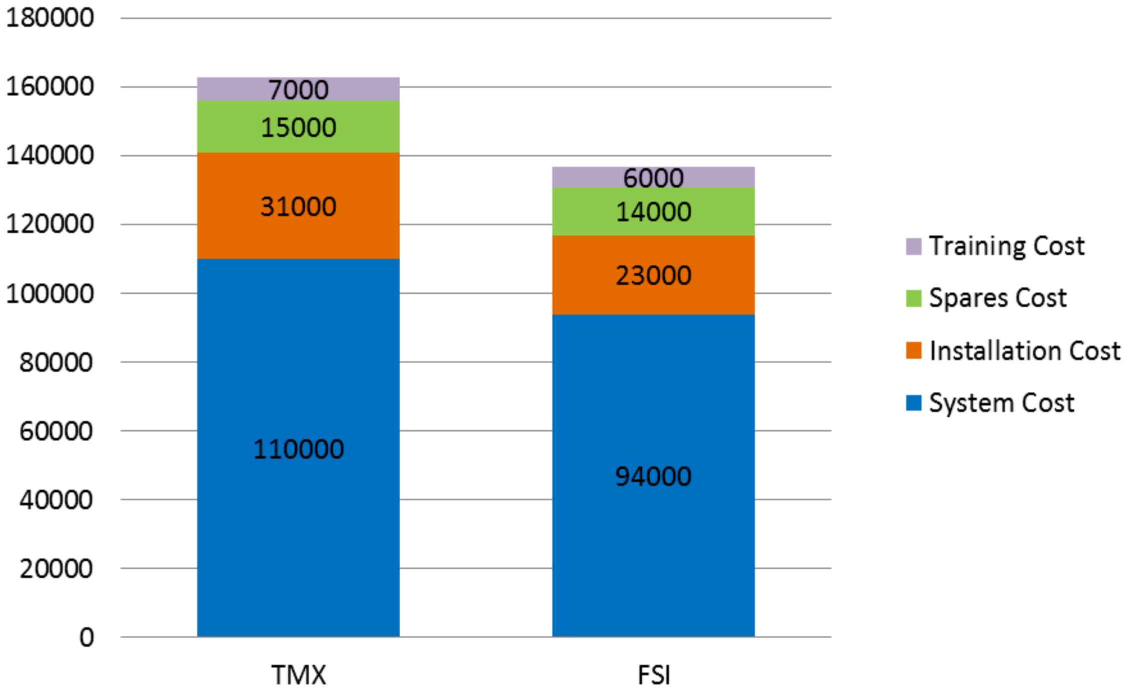

Figure 8: Transmissometer vs. Forward Scatter Cost Comparison, US$

The expected operating life is broadly similar for each, as are annual running costs although these are slightly higher for transmissometers.

It is interesting to note that, for a very similar cost to the two sensor transmissometer system, it would be possible to have a three sensor forward scatter system. Such a system would handle conditions of non-homogenous visibility and variations in background luminance better than the transmissometer system.

Conclusions

This paper shows that while the accurate assessment of IRVR is of central importance to the safe and efficient operation of an airport, such assessments are subject to many different sources of error. Although trials indicate differences between transmissometer and forwards scatter sensor accuracy, these differences are of no greater magnitude than the margins of error of several other parameters. The differences do in any case tend towards a safe bias.

A simplistic analysis shows that on a cost-for-cost basis, a forward scatter system with more sensors can be used; the increased number of sensors helping mitigate against major sources of overall system error.

Thanks to Dr Alan Hisscott for allowing us to use his research findings.

References

[1] ICAO Annex 3 (Meteorological Service for International Air Navigation): Chapter 1

[2] ICAO Doc 9328 (Manual of Runway Visual Range Observing and Reporting Practices): Chapter 6

[3] ICAO Doc 9328 (Manual of Runway Visual Range Observing and Reporting Practices): Chapter 3

[4] ICAO Doc 9328 (Manual of Runway Visual Range Observing and Reporting Practices): Chapter 11

[5] ICAO Doc 9328 (Manual of Runway Visual Range Observing and Reporting Practices): Chapter 6

[6] ICAO Doc 9328 (Manual of Runway Visual Range Observing and Reporting Practices): Chapter 8

[7] Field Test of Forward Scatter Visibility Sensors at German Airports, German Meteorological Service (DWD)