Trial of a Slant Visual Range Measuring Device

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ABSTRACT

Each year fog at airports renders some landing operations either difficult or impossible. In such instances, visibility is the most important information for the pilot of a landing aircraft. Visibility may be constant, decreasing, or increasing with respect to the altitude; however, it is not possible to distinguish this with existing airport sensors. This paper describes a new technique for measuring slant visual range that makes use of a slant scanning device, an eye-safe laser radar.

This device has been tested by the German Meteorological Service in Quickborn, Germany, over a period of one year. A comparison with commercial visibility sensors shows that it is possible to measure visibilities with the slant-looking laser radar in the range from 50 m up to 2000 m and to even distinguish inhomogenities like ground fog. Statistics of the Quickborn measurements show that the atmosphere in that region is not homogeneous in 38% of fog situations, which would at the present lead to a restriction of the air traffic.

The first installation of this instrument at the Hamburg airport is described.

1. Introduction

One of the most complicated phases of flying an aircraft is the landing approach. The ground staff therefore provide the pilot with the most important weather parameters in the vicinity of the airport. One of these parameters is the visibility—the runway visual range (RVR). The RVR is composed from the meteorological visual range (MOR) measured with visibility sensors, the brightness of the background, and the illumination of the airstrip. The MOR is generally measured with ground-based transmissometers—a flash lamp with an optical receiver at a fixed distance (B) as shown in Fig. 1.

The received light is proportional to the transmission (through the distance B), which leads to the MOR:

$$A_E = A_0\tau,$$

$$\tau = e^{-\sigma B},$$

$$V_{\text{MOR}} = \frac{\ln(\eta)}{\ln(\tau)}, \qquad (1)$$

with

- τ: transmission of the measured path B,
- A_E: received amount of light,
- A_0: transmitted light,
- B: distance between the flash-lamp source and the receiver,
- σ: extinction coefficient,
- V_{MOR}: MOR in meters, and
- η: contrast threshold—for the MOR defined as 5%.

The visibility estimated in this way does not always correspond to the actual visual range of the pilot in a landing approach: low-lying clouds give a better apparent visibility, while ground fog produces smaller apparent visibilities to the ground staff with the situations reversed for a pilot. The second case may even lead to the worst situation—the closing of the airport.

The problem of measuring the real slant visual range is well known; a technical solution was proposed by the German Aerospace Research Establishment (DLR) by Werner (1981) and has been tested in practice in conjunction with Impuls Physik GmbH (now Hagenuk GmbH) (Streicher et al. 1988). The principle is similar to the measurement of the RVR—the goal being the

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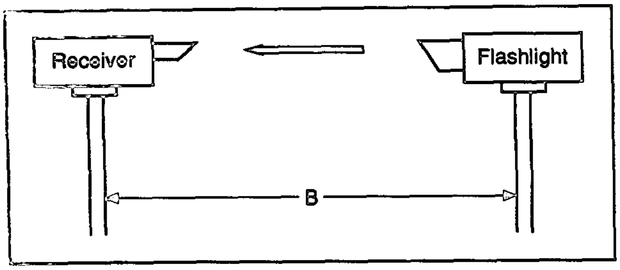

FIG. 1. Principle of a transmissometer.

determination of a transmission but in this case on a slant path.

The device has to be placed close to the airstrip; thus, it is impossible to put the receiver on a tower. Instead, it is fixed adjacent to the transmitter—a laser diode. This configuration is called a laser radar or, in short, lidar. The atmosphere can then be scanned at different elevation angles to detect vertical layers as shown in Fig. 2.

The main requirement of the laser in this application is therefore the eye-safety criterion. Such a laser was installed in a cloud ceilometer manufactured by Impuls Physik GmbH. The commercial cloud ceilometer has been modified with the addition of a turnable mirror to direct the emitted laser radiation into the investigated section, which includes the glide path of the aircraft. The receiver is identical to the former one except for the transient recorder and the photodiode.

It is now possible to give the pilot additional information about the visibility at the height level where he must decide whether to continue the approach or not—the decision point.

The pilot is thus kept informed of critical visual conditions allowing him to avoid hazardous go-around maneuvers: a decisive step toward increasing aviation safety. In the case of ground fog, the runway can be kept open for a longer period of time because it is now possible to determine, accurately, the slant visual range.

2. Lidar

Lidar is the abbreviation for light detection and ranging, the determination of the distance between the measuring device and a hard target—for example, a wall. In the case of visibility measurements, the targets are small water droplets, which reflect the transmitted laser radiation back into the receiver as shown in Fig. 3: the upper part shows the geometry of a slant measurement; the lower part the resulting detector signal. In this case the signal consists of two peaks: the first at approximately a 60-m slant range is caused by the water droplets or aerosols of the homogeneous atmosphere, which corresponds to the RVR; the second at approximately 90 m is caused by the higher density of scatterers—a layer or a cloud with a lower visibility. Without this cloud the signal would continue on as the dashed curve. The absence of a signal up to 30 m and the increase of the curve up to the first peak reflects the relation between the transmitter and the receiver—the geometrical overlap.

If one assumes that the particles (water droplets dominate, no molecular scattering) reflect the laser light with an angle of approximately 180°, the detector signal can be written with the formula known as the simplified lidar equation (Measures 1984):

$$U(R) = \xi(R)\frac{k}{R^2}K(R)\sigma(R)\exp\left[-2\int_0^R \sigma(r)dr\right], \quad (2)$$

with

$\xi(R)$: the geometrical overlap function,
k: the constant of the lidar system including the output power of the laser, amplification factors, the probability for backscattering, etc.,
R: the slant distance,
$K(R)$: the range-dependent backscatter–extinction ratio, and
$\sigma(R)$: the extinction coefficient of the particles.

The extinction coefficient, which includes the visibility, is extracted out of the lidar equation using the Klett algorithm (Klett 1981) and the assumption of a constant backscatter–extinction ratio, which is valid only for low visibilities (Klett 1985):

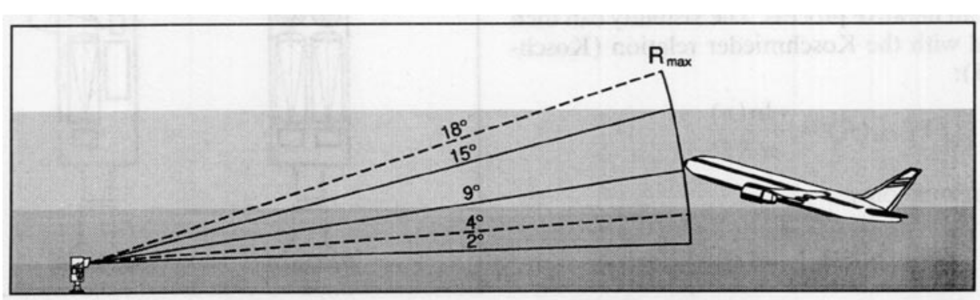

FIG. 2. Scanning procedure through a vertical layer.

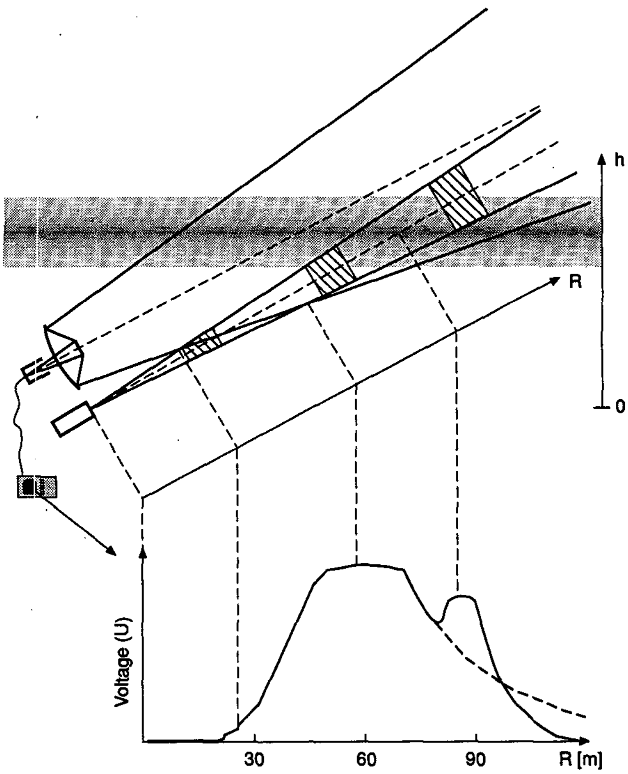

FIG. 3. Detection of a cloud with a laser radar.

$$\sigma(R) = \frac{S(R)}{\dfrac{S(R_m)}{\sigma(R_m)} + 2\displaystyle\int_R^{R_m} S(r)dr}, \qquad (3)$$

with

$S(R)$: the range-corrected signal $[U(R)R^2/\xi(R)]$, and

R_m: the maximum distance, mainly restricted by the signal-to-noise ratio.

The principal problem with the Klett algorithm is with the knowledge of the boundary condition $\sigma(R_m)$, which needs to be determined now with the same algorithm (this corresponds to the visibility at the desired altitude—the decision point of the pilot). This contradiction is solved by scanning beyond the angle of sight of the pilot, which is about 9° as shown in Fig. 2. The evaluation algorithm then estimates the boundary condition in an iterative process. The visibility can then be calculated with the Koschmieder relation (Koschmieder 1925):

$$V_{\mathrm{MOR}}(R) = \frac{-\ln(\eta)}{\sigma(R)}:$$

With the transmission τ,

$$\tau = \exp\left[-2\int_0^R \sigma(r)dr\right],$$

one gets the same Eq. (1) for the MOR as for the transmissometer but this time for the slant path.

The problem of eye safety was solved by using the commercial cloud ceilometer from Impuls Physik GmbH: laser—GaAs laser diode array, wavelength—906 nm, pulse energy—1.6 μJ, pulse duration—50 ns, pulse repetition rate—2.5 kHz, optical diameter—14 cm, laser safety—conforms to IEC 825/VDE 0837 class 3A.

This device already has clearance to be installed at an airport. The very low pulse energy and therefore the small signal-to-noise ratio is improved by averaging over some hundreds of shots. This can be done very quickly because of the high repetition rate of 2500 shots per second. The averaging process has another positive effect in addition to smoothing; the transient recorder (specially designed for this device) digitizes every single shot with an 8-bit A/D converter. The shots are then summed up in a 17-bit sized array. The size of the digitizing steps can be reduced from 1/256 (least significant bit of an 8-bit converter) to 1/131 072 (17 bit) if the noise is greater than the least significant bit of the single shot converter, that is, noise level greater than 1/256. The total dynamic range of this fast (20 MHz) transient recorder is therefore 17 bits when averaging over many shots. This digitizer therefore provides an almost ideal lidar signal:

- very small digitizing steps, necessary for the range correction of the signal $[S(R) = U(R)R^2/\xi(R)]$, and
- a large dynamic range to follow the $1/R^2$ dependence signal especially for low visibilities, that is, small transmission of the atmosphere.

This technique makes it possible to measure visibilities between 50 and 2000 m MOR. Another modification in comparison to the standard cloud ceilometer is a turnable mirror, which is tilted to the vertical axis of the optics automatically when the cloud altitude becomes less than a suitable altitude. A rough sketch of the SVR sensor is shown in Fig. 4.

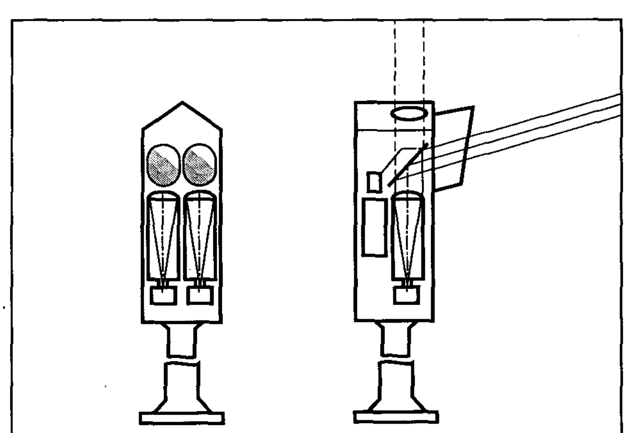

FIG. 4. Modified cloud ceilometer for SVR measurements and cloud height.

The measuring range for cloud altitudes (dashed lines) is up to 5000 ft; the typical penetration depth for the slant path (solid three lines) is 1500 ft or in altitudes between 30 (2°) and 300 ft (18°). The slant measuring path has also an effect on low-level cloud monitoring: every lidar has a geometrical overlap function as shown in Fig. 3. The consequence of this is the absence of a signal in the range gates up to 30 m ≈ 150 ft. With a standard cloud ceilometer, one has not only an upper limit mainly caused by the output energy but also a lower limit caused by the geometry of the optics; the ceiling appears to be diffuse. The monitoring of the slant path overcomes this deficiency: a layer can be distinguished down to almost zero height with much better accuracy in height resolution than with a standard ceilometer.

3. Measurements in Quickborn

The slant visibility sensor has been tested by the German Meteorological Service in Quickborn, Germany, over a period of one year. Additional sensors were placed close to the SVR device to obtain comparable results. The installation of the different sensors is shown in Fig. 5.

One commercial transmissometer was set up in the usual way with a horizontal base to get the horizontal MOR, the other with a slant base of 9°. The receiver of the second transmissometer was fastened at a height of 20 m to a tower, on which three forward-scattering devices additionally measured the visibilities at different altitudes. All measured data were transmitted to a personal computer and recorded on a hard disk. The computer was also used to control the tilt angle of the mirror and to evaluate the slant visual range for a slant path of 9° four times a minute, after sounding three different angles (2°, 9°, 15°) and being averaged over one minute. A comparison of the horizontal, the slant transmissometer, and the SVR sensor is shown in Fig. 6.

Three different conditions of fog can be clearly distinguished:

(i) *Homogeneous fog.* The top diagram (a) shows vertical homogeneous visibilities ranging from 90 m (0700 LST) up to 1000 m (0730 LST): the three sensors produce values of the same order of magnitude. This demonstrates the applicability of the remote sensing technique with a lidar on the one hand and the stability of the evaluation algorithm on the other hand.

(ii) *Ground fog.* The middle diagram (b) represents the situation of most discrepancy between the real visibility of the pilot and the initially measured RVR: the horizontal MOR is about 200 m (dotted curve), which may lead to a refusal of the landing approach, whereas both slant visual range sensors (dashed and solid curve) indicate (by a factor of 5) greater visibilities. This demonstrated the need for the installation of this new visibility sensor: it is impossible to put up a tower with a slant transmissometer near the airport; therefore, remote sensing with a lidar is the only way to measure the actual visibility, directly.

(iii) *Low-lying clouds.* The bottom diagram (c) shows a lifting fog. At the beginning of this measurement all three sensors show the same visibility of about 200 m, whereas the horizontal transmissometer shows at the same time about two times better visual range than the slant sensors. The conformity of the slant sensors shows that the horizontal measured RVR may

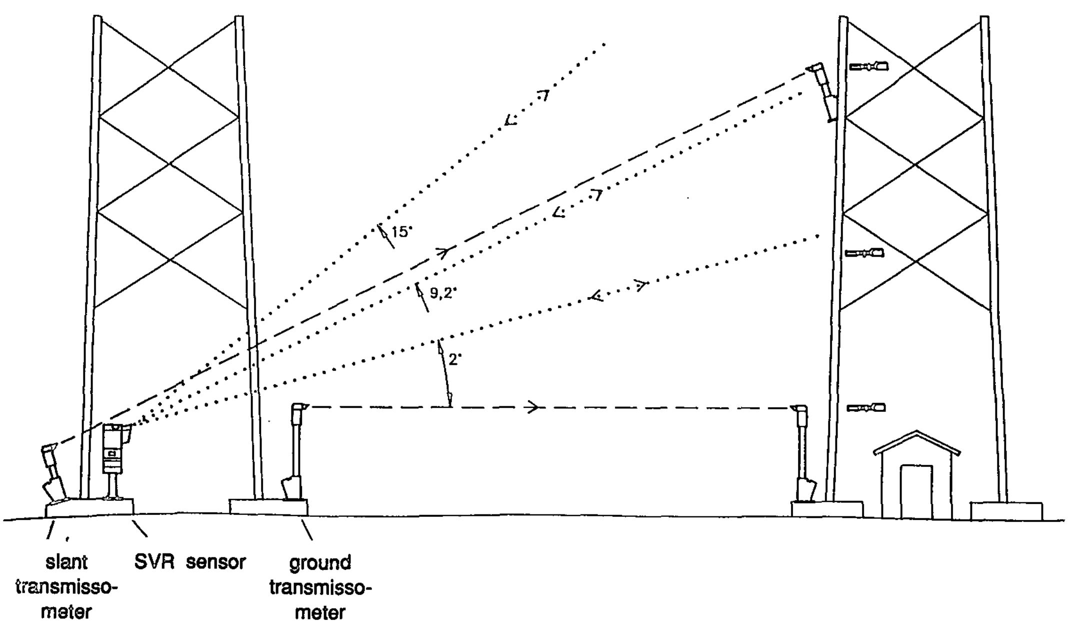

FIG. 5. Placement of the different visibility sensors in Quickborn.

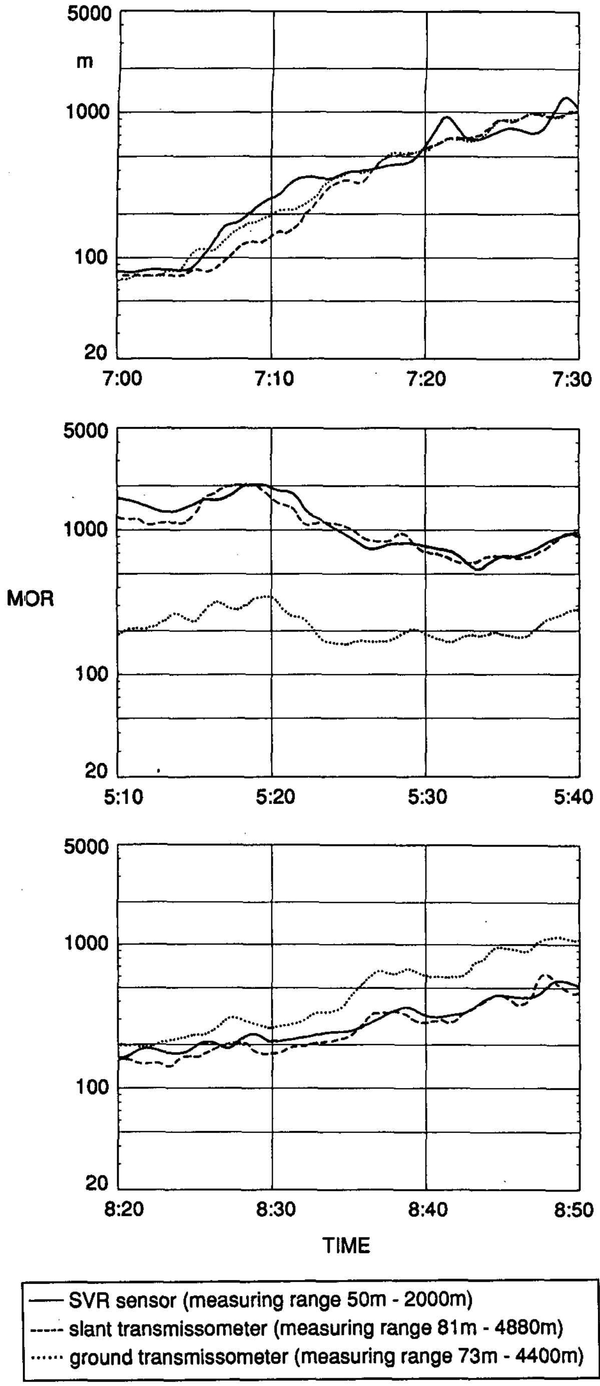

FIG. 6. Examples of three different fog conditions measured with different visibility sensors.

lead to a dangerous situation: the pilot will expect much better visibility conditions than he will really have on the approach. An additional application for the SVR sensor in this situation is the exact measurement of the cloud base. As mentioned in section 2, there is no information in the first 150 ft for a vertical measurement with a standard ceilometer.

The total amount of measurements taken in Quickborn from 1988 to 1989 is about 63 000 events with visibilities below 2 km. The differences between the slant and the horizontally measured visibility for these datasets is shown in Fig. 7.

The horizontal axis represents the true relative error between the horizontal (RVR) and the slant (SVR) visibility (both MOR):

$$\text{Difference} = \left(\frac{\text{SVR} - \text{RVR}}{\text{RVR}}\right) \times 100\%.$$

This leads to a positive difference for a better slant visibility (right side), and vice versa, negative values for a better horizontal visibility. The vertical axis shows the relative number of events; that is, all measurements added up (the integral over the surface of the light grey area) will lead to 100%. The different curves represent different kinds of visibility conditions:

- light fog with a visibility between 600 and 2000 m (light gray),
- moderate fog with a visibility between 200 and 600 m (dark gray), and
- thick fog with a visibility below 200 m (black).

The very sharp peak at 0% error shows that both sensors agree exactly with 24% of the measurements, or 41% if one accepts an error of ±10%. This demonstrates again that it is possible to compare a transmissometer with the remote-sensing technique. The second peak on the right side of the diagram reflects the frequency of ground fog: the SVR is over 100% better than the RVR (again both MOR), especially for thick and moderate fog conditions. Thirteen percent of the measurements with thick and moderate fog show over two times higher slant than horizontal visibility (see also Fig. 6b). In comparison with light fog (light grey curve) such a difference appears only in an order

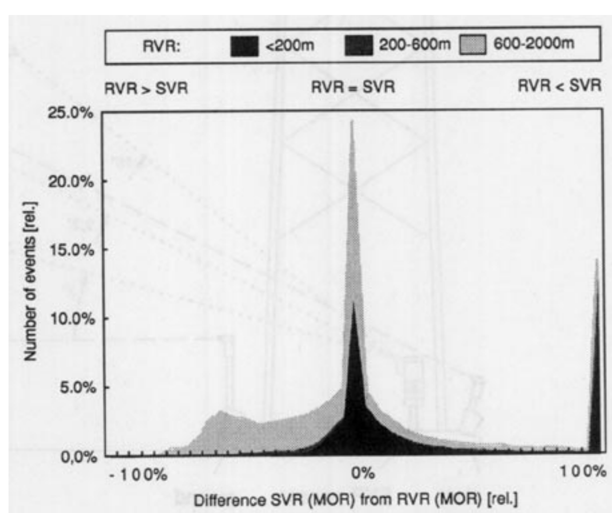

FIG. 7. Comparison of all fog measurements with visibilities below 2 km.

TABLE 1. Statistics of fog situations derived out of the measurements in Quickborn.

Fog	Events	RVR = SVR	±10%	±20%	Ground fog	Lifting fog
Thick	39.9%	11.4%	21.2%	25.1%	9.1%	0.6%
Moderate	9.1%	0.3%	1.3%	2.2%	3.7%	2.3%
Light	51.0%	12.6%	18.4%	24.4%	1.3%	21.3%
All	100.0%	25.3%	40.9%	51.7%	14.1%	24.2%

of 1%. On the other hand, light fog produces 20%–60% lower slant visibilities (third maximum on the negative side of the diagram) in 24% (now integrated because of the missing peak) of the measurements. This is the typical situation of lifting fog. An overview of the statistics is given in Table 1.

The three maxima in Fig. 7 (or Table 1) show the following.

- At 52% of the time of the measurements, the atmosphere in Quickborn was vertically homogeneous.
- A ground fog with very low visibilities was detected in 14% of the measurements.
- Lifting fog or low-lying clouds were detected in 24% of the measurements, especially for light fog conditions.

This shows again the need for an installation of the SVR sensor: a fictitious airport in Quickborn could be held open for a longer time in thick fog conditions. On the other hand, low-lying clouds or lifting fog, which both cannot be measured at an airport so far, increase the separation time (time between two consecutive airplanes). Both situations of a nonhomogeneous atmosphere lead at present to a restriction of air traffic at airports already working to capacity.

4. Installation at an airport

The SVR sensor was installed (after an additional test in Ahlhorn in 1991) in December 1991 at the Hamburg airport. The sensor was placed parallel to two transmissometers. At present, the SVR sensor is reporting only the horizontal visibility, which can be compared directly with the measurements of the two transmissometers. This kind of comparison is made as a first step to show again the conforming nature of the remote-sensing SVR device with a standard transmissometer (phase one of the Hamburg measurements).

A dataset of the three sensors for thick fog is shown in Fig. 8.

The SVR sensor works in the normal scanning mode (see Fig. 2) and calculates the visibilities of the different altitudes with a height resolution of 1 m up to the largest detectable altitude. The output for this comparison is the visibility of the first altitude levels up to 3 m. The conformity of the SVR sensor with the transmissometers shows that it is even possible to replace a transmissometer with an SVR sensor.

The next step in the Hamburg campaign was the placement of the SVR sensor near the touchdown point of the airstrip. This phase 2 started in the summer of

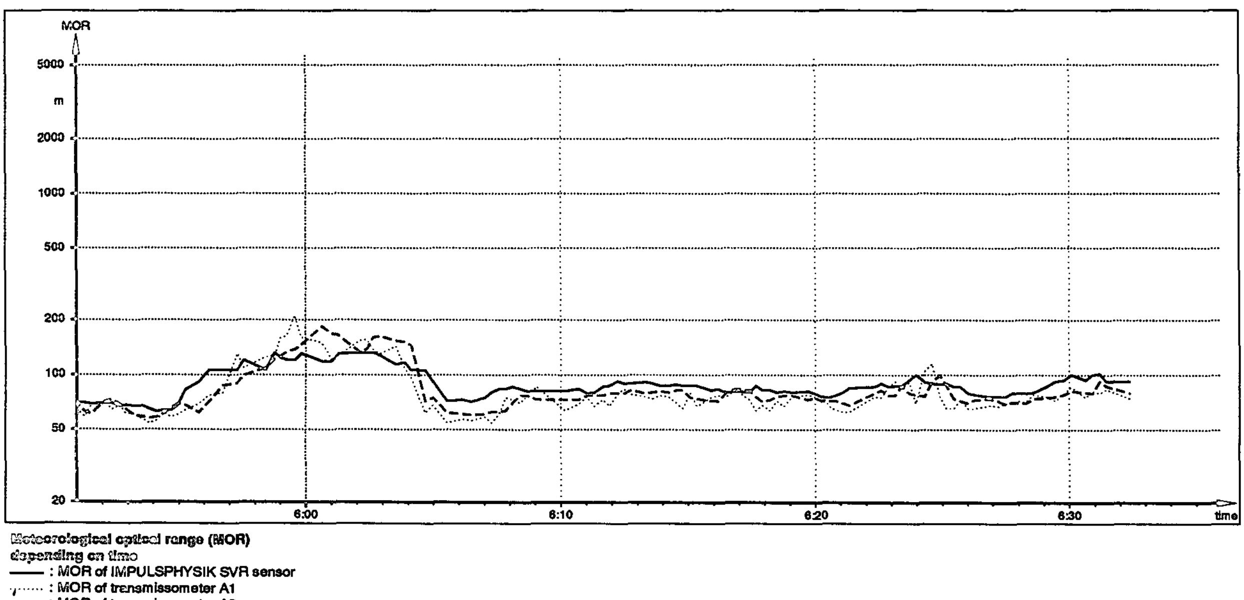

FIG. 8. Dataset taken at the Hamburg airport on 25 January 1992.

1992. Hamburg is the first airport providing pilots with an additional piece of information—the slant visual range.

5. Conclusions

It has been shown that it is possible to compare the results of a remote-sensing technique (an eye-safe laser radar) with an acknowledged visibility sensor (a transmissometer).

The principle of the lidar includes the advantage of determining the height dependency of the visibility up to 300 ft. With this new technique it is now possible to detect different atmospheric conditions:

- homogeneous fog,
- ground fog, and
- lifting fog or low-lying clouds.

The comparisons of the horizontal with the slant visibilities in Quickborn have shown that the atmosphere is only in 52% of the measurements homogeneous with the altitude. A pilot can expect 14% ground fog and 24% lifting fog in that region, which cannot be detected with a standard transmissometer.

Low-lying clouds, which so far have been detected vertically, produce, as a result of the geometrical overlap of the cloud ceilometer, a blurred ceiling. With this device, low-lying clouds can be detected much more accurately on the slant path.

This device is in addition designed to fulfill three tasks:

1) slant visual range measurements for low visibility conditions,
2) cloud ceiling measurements on either the slant or the vertical path, and
3) runway visual range measurements as replacement for a transmissometer.

The SVR sensor is presently installed at the Hamburg airport.

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