The Vertical Structure of Fog Observed with a Lidar System at Misawa Airbase, Japan

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ABSTRACT

In order to improve airbase operations, vertical profiles of attenuation coefficients caused by fog are investigated with a mobile lidar system at Misawa Airbase in northern Japan. The results show that, when the ceiling is about 30 m (the decision height at Misawa Airbase), the attenuation coefficient near this level is generally larger than that near the surface. With higher ceilings, attenuation coefficients near the surface tend to be larger than those at the decision height. Moreover, it is shown that the attenuation coefficient in the upper levels increases slightly earlier than that near the surface when the ceiling is lowering; such a situation is frequently observed at Misawa on severe fog days.

1. Introduction

It has long been well recognized that slant-path visibility is important in aeronautical applications for landing operations especially in fog. Statistical relations between attenuation coefficients at the ground and slant attenuation-coefficient gradients were investigated using the tower observations at 30-m height by Puffett (1979); his results are very useful to estimate the slant visual range from the attenuation coefficients at the ground. He also tested the accuracy of on-line measurement systems for the actual initial visual-contact heights of aircraft and showed that the system provided a possible tool for improving landing regularity without prejudicing safety. The on-line system, however, requires a tower for measurements at some distance to the side of the runway, and the spatial separation of the measurements from the point of interest requires further investigations of the performance of this system. Furthermore, the on-line system is not so effective for shallow or patchy fog.

Comparisons of visibilities along slant and horizontal paths in foggy conditions using both a lidar system and a conventional transmissometer were carried out by Gaumet and Petitpa (1982). Lidar visibility was calculated by using the slope method (Collis 1966). Velocities obtained with the lidar technique agree well with the simultaneous transmissometer data, except for tendencies that the lidar measurements give greater values than the transmissometer data.

Misawa Airbase, which is one of the most prosperous airdromes in Japan, is famous for fog; the frequency of fog days amounts to about 50% or more in June and July. Since the airbase is located near the southern rim of the Okhotsk high during these months, operations are frequently interrupted by fog. In order to provide pilots with more useful information on visibility, based on meteorological data at the surface, vertical distributions of the attenuation coefficient caused by fog are investigated with a series of lidar observations from 1 June to 30 June 1988. Distributions of the attenuation coefficient are calculated by means of the Klett (1981) method and they are compared with other meteorological elements.

2. Observation site and characteristics of the lidar system

Misawa Airbase is located on Shimokita Peninsula facing the Pacific Ocean, as shown in Fig. 1a. Misawa city extends from the southern side of the airdrome. The seashore stretches from north to south and the direction of the runway is from 100° to 280°, it is about 3 km inland from the coast. The altitude is 39 m. The airdrome is surrounded by forests and paddy fields as well as Lake Ogawara and Ane Pond as shown in Fig. 1b. A wind rose of the foggy days at Misawa is
shown in Fig. 2. Because easterly winds prevail on these days, a lidar system is directed to the east. The elevation angle of the lidar is changed from 0° to 30° by 5° steps to obtain vertical cross sections of attenuation-coeffi-
cient distributions. An observation time is about 7 min for manual changes of the elevation angle. At Misawa, it is generally accepted that the fog is advected from the Pacific Ocean because of the predominance of east-
Fig. 2. Wind rose of foggy days at Misawa Airbase.

Fig. 3. The surface weather map at 2100 JST 13 June 1988.

Fig. 4. Results of radiosonde sounding. One full barb equals 2 m s⁻¹. Numerals and solid line in the figure represent air temperature.

erly winds and the sea fog on a large cold current, the Oyashio.

Fogs on only nine nights during the observation period are investigated. Measurements were limited because the 15-mW laser power is too weak to observe fog in twilight with the noise of background light. Air temperatures at 0.1-, 1-, 10-, and 20-m height are measured with thermocouples suspended from the 22-m radar tower. The ground surface temperature is defined with a thermocouple buried at a depth of about 1 mm, 50 cm away from the northern side of the tower. Accuracy of the thermocouples is ±0.05 K. A movable pseudorandom modulation continuous wave lidar sys-

tem (Takeuchi et al. 1983) was used in these observations.

3. Analysis of the lidar data

The lidar equation for random modulated continuous wave lidar is as follows:

\[ T(R) = \exp \left[ -\int_0^R \sigma(r) dr \right] \tag{1} \]

where \( P_0 \) is the laser emitted power, \( P(R) \) the power received at the distance \( R \), \( \beta(R) \) and \( \sigma(R) \) are, respectively, the backscattering and attenuation coefficients, \( Y(R) \) the crossover function, \( L \) one half of the pulse length, and \( K \) a constant depending the characteristics of systems. The crossover function is the correction
function for partial overlapping of the transmitted beam and receiver field of view in bistatic lidar systems; it is experimentally determined (Tmine et al. 1989).

It is shown by Fenn (1966) that the backscattering and attenuation coefficients can in fact be mutually related in a power law of the form

$$\beta(R) = (\text{constant}) \sigma^k(R)$$

where $k$ is assumed here to be unity. If this relation is adopted, (1) is transformed into (2) following Klett (1981). Here

$$\sigma(R) = \frac{\exp\{[S(R) - S_m]/k\}}{\sigma_m^{-1} + \left(\frac{2}{k}\right) \int_{r_m}^R \exp\{[S(r) - S_m]/k\} dr}$$

where $S(r) = \ln[r^2P(r)/Y(r)]$, $S_m = S(r_m)$ and $\sigma_m = \sigma(r_m)$. Collis (1966) determined $\sigma_m$, the boundary value of the coefficient at $r_m$, by the slope method. Distributions of the attenuation coefficient $r_m$ near the boundary are excluded from consideration in this paper because it is strongly influenced by the boundary value.
The influence of multiscattering can be avoided by narrowing the field of view of the receiving optics.

4. Vertical cross sections of the attenuation-coefficient distributions caused by fog

The fog on the night of 13 June 1988 is illustrated as an example. The surface weather map at 2100 JST on this day is shown in Fig. 3. The northern part of the main island was covered by a weak anticyclone and there was no front in the vicinity of Misawa. The wind was weak and no precipitation was observed in Misawa. The fog observed on that night was, therefore, not a frontal fog. Nine radiosondes were released at approximately 90-min intervals from 1830 JST on the 13th to 0900 JST on the 14th and the results of those are shown in Fig. 4. Above 1500-m height, a west wind prevails during the entire observation period, but near the surface east winds continued from 1800 to 2230 JST and after that the wind direction is variable. The surface wind speed becomes weak after 1900 JST. A stable layer, which is usually observed in foggy conditions at Misawa, is observed below 1500 m throughout the period.

Temporal changes of visibility, temperatures at the surface, and at 1- and 20-m heights are exhibited in Fig. 5. Visibility decreases with cooling in the evening to become less than 1 km at about 2200 JST and improves with increasing temperature in the morning. Surface temperature is always higher than air temperatures at 1- and 20-m heights. The fog is, therefore, not a radiation-type fog. After 1900 JST, Misawa Airbase is capped by stratus with its base lower than 60 m. This is a typical weather condition on foggy days at Misawa Airbase as described by Tomine et al. (1988).

A vertical cross section of the attenuation coefficient made by interpolation from the lidar data at the seven elevation angles in the fog from 2015 to 2022 JST is shown in Fig. 6. The areas of large attenuation coefficient above 50 m may correspond to low stratus. The distribution of attenuation coefficient in the figure may indicate a stratified fog. Temporal change of the vertical distributions of attenuation coefficient horizontally averaged at 5-m intervals is shown in Fig. 7, under the assumption that the average coefficient is representative of the level.

It is shown in this figure that although the attenuation coefficient is still small near the surface at 2000 JST, it rapidly becomes larger above 40 m. The ceilometer shows a ceiling (cloud-base height) of 60 m at that time. From 2030 to 2130 JST, the air temperature temporarily rises by about 2 K, wind direction is variable, visibility at the surface improves (see Fig. 5), and the attenuation coefficient from the surface to above 100 m becomes small. From 2130 to 2330 JST, weak easterly and southerly winds are alternately observed and the attenuation coefficient rapidly becomes larger. In the upper levels, the coefficient increases a little earlier than near the surface. Subsequently, weak and variable wind is observed, temperature decreases, and the coefficient near the surface gradually increases until about 0100 JST on the 14th. The attenuation coefficient in the lower levels is larger than that in the upper levels at that time. About 0330 JST, however, the coefficient decreases again with increasing temperature. Wind is weak and its direction is southwesterly. The warming is not a result of insolation because the sun has not yet risen. Temporal changes of the attenuation coefficient caused by fog are in phase with those of wind and air temperature. Relations among them will, therefore, be investigated in the next section.

5. Temporal variation of attenuation coefficient due to fog

At first, rapid fog thickening with a rapid change of wind (mentioned in the previous section) is investi-
gated. There were six examples of such fogs during the observation period. These fogs became more dense with rapid cooling as described by Nomoto (1969). The rapid cooling seems to be the result of cold air advection. In all but one of these examples, the attenuation coefficient in the upper levels becomes larger a little earlier than near the surface, similar to the fog at about 2200 JST on the 13th. The exceptional fog is observed.

Fig. 9. (a) Same as Fig. 7 and (b) same as Fig. 5, but for the fog from 1800 JST 27 June to 0600 JST 28 June 1988.
between 0300 and 0330 JST on the morning of 29 June. The vertical cross section of the attenuation coefficient of the fog is shown in Fig. 8. The coefficient above 50 m is small and stars are observed overhead. It is, therefore, certain that a very thin fog layer spreads only near the surface.

The next investigation is of fogs thickening slowly with constant wind direction. A fog from the evening of the 27th to the morning of the 28th is analyzed as an example. Temporal variations of the vertical distribution of the attenuation coefficient are shown in Fig. 9a; temporal variations of the temperatures and visibility are shown in Fig. 9b. Air temperatures slowly increase during this event. A slow change of air temperature is characteristic of a nearly constant wind direction. Visibility decreases from 2000 to 2300 JST. Temporal variations of the vertical profiles of the attenuation coefficient are also slow and at the upper levels the coefficient increases earlier than near the surface, this is similar to the fog with rapid changes of wind direction. Air temperatures increase slowly all through the foggy period but visibility starts to improve at 0500 JST due to insolation. The condition at fog dissipation cannot be observed by the lidar because of noise due to background morning light.

6. Inhomogeneity of attenuation coefficient in the vertical direction

When an aircraft is going to make a landing on the runway, the runway light must be in sight for the pilot at the decision height. The pilot on landing is advised by an air traffic controller of the weather conditions, e.g., visibility, ceiling, and others. However, in spite of the controller's clearance, sometimes a pilot cannot catch sight of the runway light at the decision height. This results in a landing failure. On the other hand, it is sometimes reported that the pilot at the decision height can see the runway light despite poor visibility on the surface. These phenomena are considered to be due to an inhomogeneous fog distribution.

The decision height at Misawa Airbase is 30 m. The vertical profile or inhomogeneity of the attenuation coefficient below this level is, therefore, important for operations of the airbase. Then, the magnitude of vertical inhomogeneity of the attenuation coefficient is evaluated by using a parameter $\Delta \sigma / \bar{\sigma}$, where $\Delta \sigma = \sigma_{30} - \sigma_5$, $\bar{\sigma} = (\sigma_5 + \sigma_{30})/2$, and $\sigma_5$ and $\sigma_{30}$ are the average values of the attenuation coefficient between the heights of 0–5 and 25–30 m, respectively.

The temporal variation of $\Delta \sigma / \bar{\sigma}$ for the fog of 13–14 June is shown in Fig. 10. Comparisons of Figs. 10 and 7 reveal the following: the parameter $\Delta \sigma / \bar{\sigma}$ is negative from 2000 to 2200 JST except for one observation at about 2030 JST when cloud passes through at a lower level than before. Then, $\Delta \sigma / \bar{\sigma}$ takes a large positive value from 2230 to 2300 JST corresponding to the rapid increase of the attenuation coefficient in the upper levels slightly earlier than the lower levels. Then the parameter is relatively small, but it increases again at about 0300 JST coincidentally with passing cloud patches. This parameter is displayed for a fog with a constant wind direction in Fig. 11. It takes large positive values at about 2100 JST when the attenuation coefficient is increasing rapidly (see Fig. 9a), after that it turns small and positive. A common point of the two fogs is that the parameter takes large positive values when low cloud is passing through or there are areas of large attenuation coefficient in the upper levels.

In order to illustrate this common point more clearly, $\Delta \sigma / \bar{\sigma}$ is plotted versus $\sigma_{30}$ for all lidar data over the observational period (Fig. 12). Now, assuming that the attenuation coefficient derived from a transmissometer is correct, the ratios of the average and standard deviation of the errors of the attenuation coefficient derived from the slope method from the lidar data to
7. Discussions and conclusions

The vertical profile of the attenuation coefficient, which has positive $\Delta \sigma/\bar{\sigma}$, is inferred to be caused by low clouds as described previously. Negative $\Delta \sigma/\bar{\sigma}$ is considered to be caused by ground influences. The surface temperature is generally warmer than the air temperature during foggy periods at Misawa Airbase. It is, therefore, surmised that water vapor from the ground or grasses and trees is cooled by cold wet air near the surface to form steam fog. At least, it is certainly observed that the ground and trees are steaming at 2000 JST on the 13th and $\Delta \sigma/\bar{\sigma}$ is negative (see Fig. 10).

It is well recognized that vertical fog distributions are sometimes so inhomogeneous as to influence landing operations in fog at Misawa Airbase. It is urged that lidar be used for the detection of three-dimensional fog distributions. Moreover, it is noteworthy for an air traffic controller without a lidar at Misawa Airbase that, when the cloud ceiling is about 30 m, the visibility of a pilot at the decision height (30 m) is generally worse than that at the surface. Furthermore, when the ceiling

![Graph showing relations between $\sigma_{30}$ and $\Delta \sigma/\bar{\sigma}$](image)

![Graph showing vertical fog distributions](image)

![Graph showing temporal variation of vertical profile](image)

the correct ones are 18% and 16% (Takeuchi 1989), respectively. Therefore, in this paper, vertical profiles of the attenuation coefficient can be considered to be inhomogeneous when the parameter $|\Delta \sigma/\bar{\sigma}|$ is larger than 0.3. In Fig. 12, where $\Delta \sigma/\bar{\sigma}$ is larger than 0.3, $\sigma_{30}$ is larger than 6 km\(^{-1}\). This is because of low stratus clouds with bases below 30 m, or it is due to passing cloud patches as described before. Another notable point in the figure is that the data of $\Delta \sigma/\bar{\sigma}$ smaller than $-0.3$ have relatively small $\sigma_{30}$ (smaller than 11 km\(^{-1}\)). Since the parameter $\Delta \sigma/\bar{\sigma}$ is not independent of $\sigma_{30}$, the parameter $\Delta \sigma/\bar{\sigma}$ tends to be positive when $\sigma_{30}$ is large. Figure 12 also shows that, when the attenuation coefficient at 30 m is small, the coefficient near the surface is generally larger.

Conditions where $\Delta \sigma/\bar{\sigma}$ becomes negative are investigated. For example, $\Delta \sigma/\bar{\sigma}$ is negative slightly before the attenuation coefficient increases rapidly (see Figs. 7 and 10) at about 2100 JST on the 13th. The parameter also becomes notably negative after 0200 JST on the 13th. Temporal variation of vertical profile of the attenuation coefficient and the parameter $\Delta \sigma/\bar{\sigma}$ from 12 to 13 June are shown in Figs. 13a and 13b, respectively. The parameter becomes notably negative when cloud bases or areas of large attenuation coefficient rise a little.

![Graph showing same conditions](image)
is higher than 60 m, the visibility of a pilot at that height tends to be better than the visibility near the surface.

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