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DEVELOPMENT AND EVALUATION OF LOW-LEVEL TURBULENCE ADVISORY DISPLAY FOR AIRCRAFT OPERATION

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Abstract

Low-level turbulence, including windshear, can reduce landing rates and cause aircraft accidents. The Japan Aerospace Exploration Agency (JAXA) has developed a prototype graphical display for its Low-level Turbulence Advisory System (LOTAS) that uses low-cost Doppler radar and Doppler lidar sensors and supports aircraft approach planning and landing timing decision-making. The proposed display shows not only the presence of windshear on the landing path but also the "estimated landing difficulty" in real time. Flight crews can obtain LOTAS information from ground operations staff by radio voice communications and/or a newly-designed ACARS (Automatic Communications Addressing and Reporting System) text message. To verify the effectiveness and usability of the LOTAS display and functions, evaluations by flight crews and operations officers were carried out during actual operations at Shonai airport. The results of the evaluation confirmed the effectiveness of the LOTAS display, and identified further topics of research to support aircraft operations.

1 Introduction

Low-level turbulence in the vicinity of airports can cause reduce landing rates and cause aircraft accidents. While conventional turbulence information systems, e.g. [1], [2], provide alerts on hazardous significant windshear (e.g. a change of headwind/tailwind component of 20 knots or more) and microbursts (e.g. a headwind/tailwind component change of 30

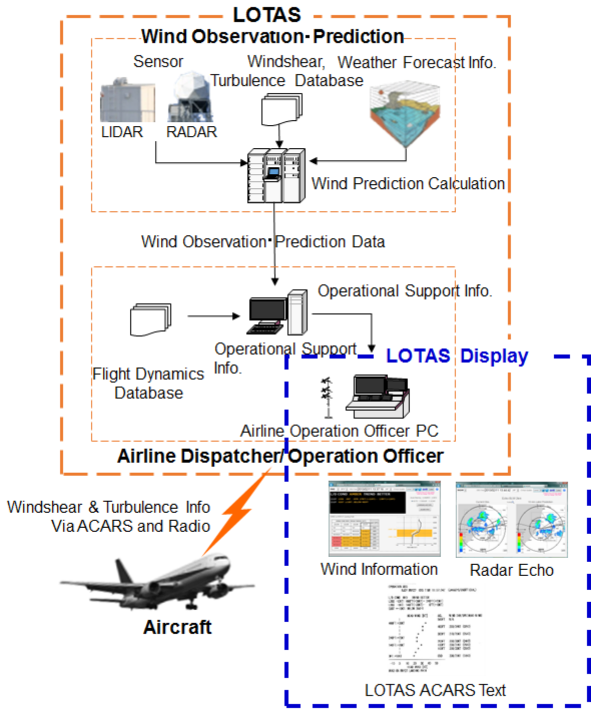


Figure 1 LOTAS Overview

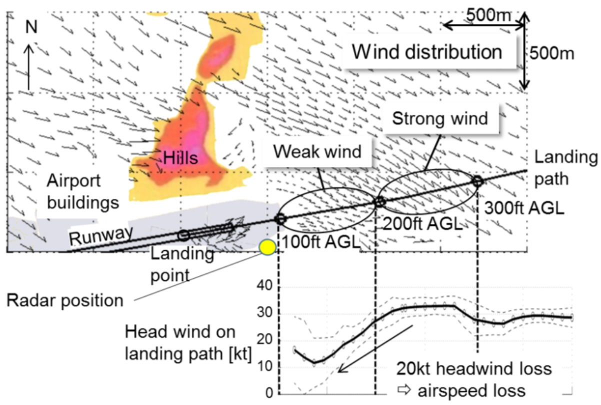


Figure 2 Example of Low-Level Turbulence Occurring at Shonai Airport with Strong Northwesterly Winds (observed by a weather radar of LOTAS))

knots or more) that are directly related to accident risk, this alert information by itself is insufficient as changes of airspeed and attitude due to less severe turbulence encountered just before touch down can also lead to accidents and go-arounds, even if the gain or loss of wind speed in the low-level turbulence does not reach hazardous significant windshear alert level. Additionally, conventional systems do not provide information to support landing timing decisions in dynamic weather situations. It is hypothesized that a landing timing decision support tool will help both flight crews and dispatchers/operations officers, especially when conditions change rapidly. Flight crews will be able to time their approaches to give lower landing difficulty, while airport-based operations staff may contribute to approach planning by advising crews of conditions and landing timing under strong winds and low visibility.

Considering this situation, the Japan Aerospace Exploration Agency (JAXA) has selected useful turbulence information which focuses not only on windshear to prevent accidents but also provides information to support normal operations, and has developed a low-level turbulence advisory system (LOTAS) which supports aircraft approach planning and landing timing decision-making as shown in Figure 1.

A new graphical and textual low-level turbulence advisory display (the “LOTAS display” in Figure 1) which provides strategic aircraft operational information on low-level turbulence and windshear has been developed as an aircraft approach planning support tool. The provision of LOTAS information is intended to increase operational efficiency (e.g. by reducing the number of go-arounds) and prevent aircraft accidents.

To verify the effectiveness and usability of the LOTAS display and functions, evaluation was carried out during aircraft operations by flight crews and airport-based operations officers from an airline, All Nippon Airways (ANA). The evaluation was carried out at Shonai airport from the end of December 2012 to the middle of February 2013. Shonai airport is known for low-level wind disturbances in the winter, when seasonal westerly winds from the Sea of Japan gain strength, which can lead to go-arounds and diversions to other airports as shown in Figure 2.

This paper presents the prototype LOTAS display, describes the evaluation of its effectiveness and usability, and discusses areas for improvement indicated by the evaluation.

2 Design Concept and System Overview

2.1 Selection of Information

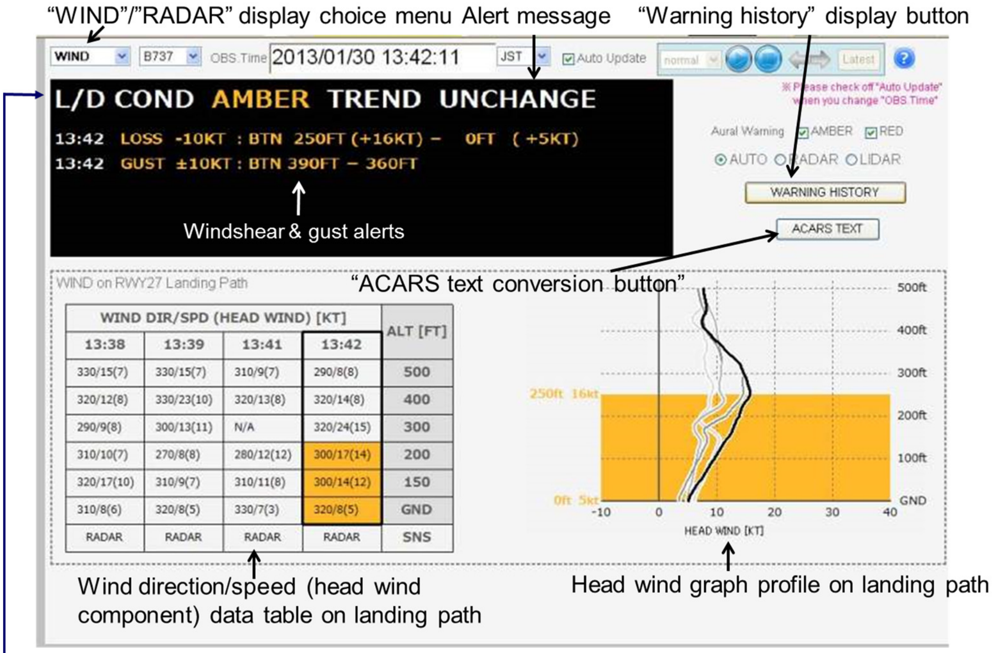
Information provided by the LOTAS display focuses on low-level wind disturbances (windshear, turbulence, etc.) and information to support approach planning. To detect atmospheric disturbances under all weather conditions and areas of low visibility due to rain and snow, wind speed and direction are derived from Doppler radar and lidar observations, and precipitation intensity is obtained from Doppler radar.

Since the altitude and airport distance ranges at which low-level wind disturbances occur differ for each airport due to factors such as local terrain, we survey the altitudes and distances for which low-level wind disturbances are judged to have a significant impact on flight operations based on wind observation data, aircraft flight parameters (e.g. airspeed) of specific aircraft types, and interviews with flight crews and airline operations officers. At Shonai airport, we determined that information on low-level wind disturbances below 500 ft and radar echoes below 2 km in altitude within a 10 NM radius of the airport should be provided.

2.2 Display Overview

The newly-developed LOTAS display prototype introduces graphical Wind Information and Radar Echo displays, and a specific ACARS message text derived from a newly-developed severity metric (the estimated landing difficulty) [3] and headwind information, etc. as shown in Figures 3 and 4.

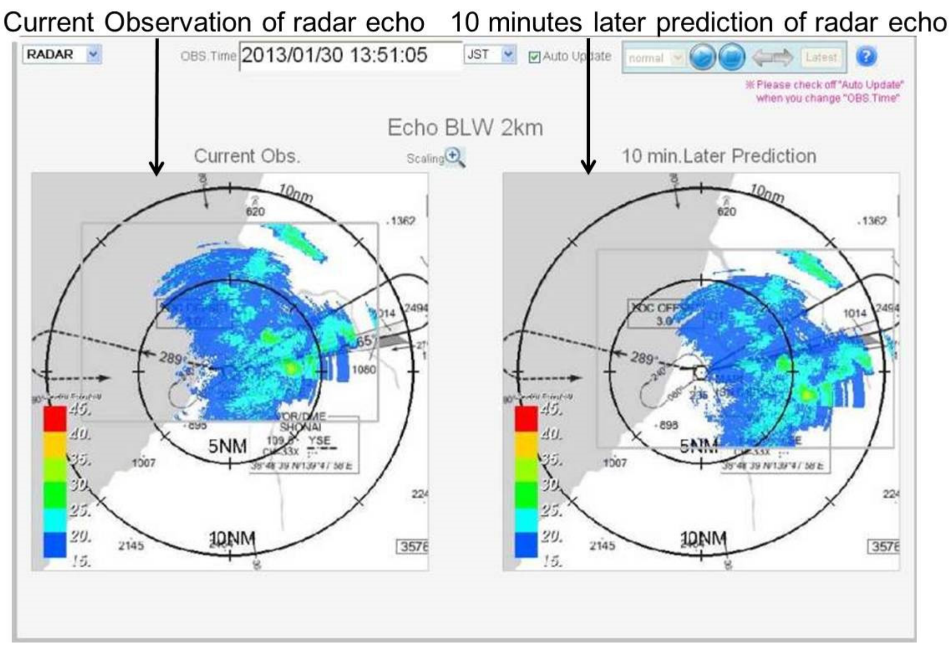
The Wind Information Display mainly provides alerts of low-level wind disturbances.



Severity information (Estimated Landing Difficulty)

RED	Severe disturbance, High workload (Go Around is predicted)
AMBER	Moderate disturbance, Moderate workload
GREEN	Slight disturbance, Insignificant workload

a. Wind Information Display



b. Radar Echo Display

Figure 3 Example of LOTAS Display

The Radar Echo Display, which shows precipitation intensity, is intended to be used for decision support to avoid areas of precipitation that will affect the aircraft's approach and to plan the landing timing when there are precipitation areas within 10 NM of the airport. The proposed ACARS message text, which provides low-level wind conditions to flight crews, could be used to improve wind situation awareness, prediction and approach landing planning in flight.

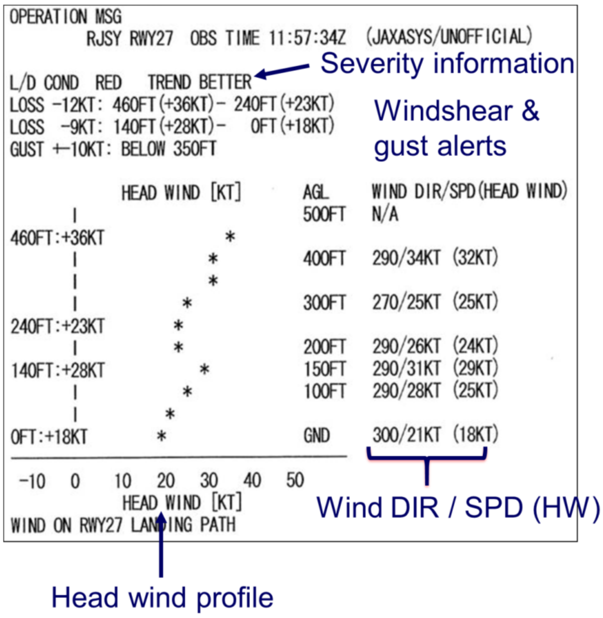


Figure 4 Example of LOTAS ACARS

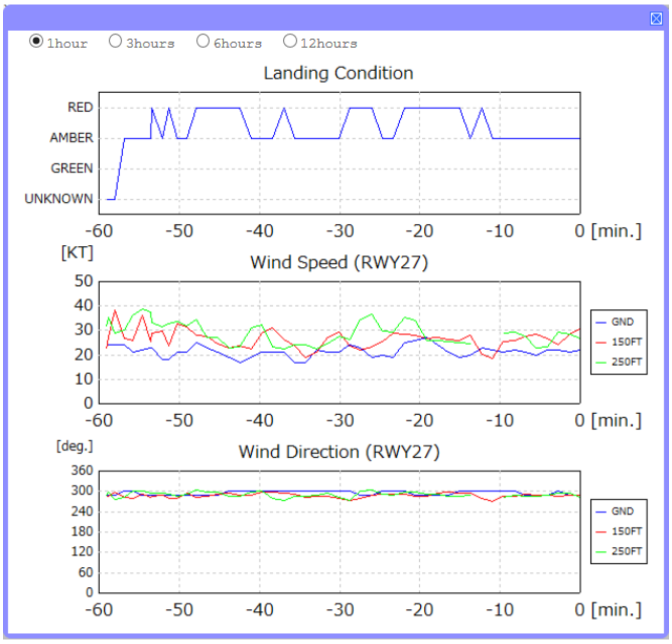


Figure 5 Example of Warning History in LOTAS

It should be noted that the displays provide information only for runway 27 at Shonai airport, because low-level wind disturbances frequently occur on the runway 27 approach side of the airport due to nearby terrain features as shown in Figure 2.

2.3 Wind Information Display

The Wind Information display presents the following information: Alert messages, landing path Headwind graph profile (“HW graph”) and Wind direction / speed (headwind component) data table (“Wind data table”), as shown in Figure 3-a. These are presented on the same screen simultaneously to enable users to easily assimilate the contents of alerts by the following flow: the user first obtains summarized information on alerts from the Alert Message area, then grasps the general wind situation from the graphical information presented in the HW graph, and finally confirms precise wind data from the numerical information in the Wind data table.

2.3.1 Alert Message

Although conventional wind disturbance alerts provides wind disturbance severity (e.g. Severe or Moderate turbulence) and headwind gain or loss (e.g. Windshear 15 knots on departure), there is no severity information related to the flight control actions necessary to deal with the wind disturbance; e.g. aircraft parameter changes, successful landing probability and landing difficulty for low-level wind disturbance. For example, even if wind disturbance alert information is provided, it might not directly help aircraft operations because the impact on the aircraft and on flight control (pitching, rolling, deviation from flight path and flight control difficulty) depends on the aircraft type and on the subjective judgment of pilots. Reference [4] recommends that currently provided information should be improved by accounting for the correlation between wind sensor observations and impacts on aircraft.

We therefore hypothesized that severity information which reflects the impact of wind disturbances on aircraft and on flight control difficulty is desirable, and proposed a new “estimated landing difficulty” metric [3] (L/D COND in Figure 3-a) for low-level wind disturbances to be presented in Alert messages. The ‘L/D COND’ for each aircraft type has three levels, ‘RED’, ‘AMBER’ and ‘GREEN’, as defined in Figure 3-a. Additionally, the Alert message provides landing difficulty trend information (e.g. TREND UNCHANGE) and head/tail windshear component (GAIN/LOSS) and altitude information.

2.3.2 Headwind Graph Profile on Landing Path

The display of headwind profile on the landing path (HW graph) provides information below 500 ft as shown in Figure 3-a. On the other hand, conventional wind information systems provide horizontal position information on existing low-level wind disturbances (e.g. WTWS [5]: ‘Microburst minus 30knots on final approach’, JMA (Japan Meteorological Agency) [6]: ‘MBA (Microburst Alert) 30KT-(30knots minus) 3nm FNL (Final approach)’). We assume that providing vertical profiles of headwind, especially for lower altitudes, will be more effective in supporting aircraft operations because the lower the altitude of the wind disturbance encounter, the harder it is for the pilot to continue the approach to make a successful landing.

The HW graph presents historical information for the previous few minutes in parallel with current information so that the user can easily grasp trends and tendencies. For a high estimated landing difficulty (L/D COND: RED or AMBER), the altitude band of the significant wind change relating to the landing difficulty is highlighted in same color as the estimated landing difficulty (i.e. RED or AMBER) to enable intuitive understanding of the alert information as shown in Figure 3-a.

2.3.3 Wind Direction and Speed (Headwind Component) Data Table on Landing Path

The Wind Direction and Speed (Headwind Component) Data Table (Wind data table) shown in Figure 3-a provides information on short-term wind change tendencies by tabulating wind direction, speed and headwind component information for the past few minutes for several heights below 500 ft. For a high estimated landing difficulty (L/D COND: RED or AMBER), the table cells of altitude and time in which the significant wind changes that relate to the estimated landing difficulty occur are highlighted in the same color as the estimated landing difficulty to enable intuitive understanding of the alert information.

2.3.4 Warning History (Long Term History Information)

Airline operations officers sometimes make forecasts of low-level wind disturbance based on a few hours of observations. The LOTAS display therefore has a function to provide past information (called “Warning history” in this paper) of “L/D COND”, wind direction and speed information for the previous several hours as shown in Figure 5. The information is accessed by the “Warning history” button shown in Figure 3-a.

2.3.5 ACARS Text Conversion

The ACARS message format proposed in this study (LOTAS ACARS), shown in Figure 4, provides not only the same critical microburst alert and windshear information as conventional systems [7], but also information that can support landing planning and decision making such as ‘PIREPs’ (Pilot Information Reports). A message is generated by LOTAS when the user clicks the “ACARS text conversion button” in Figure 3-a.

The LOTAS ACARS message is the world’s first trial of an ACARS message containing a spatial graph rendered as text. We hypothesize that this headwind graph will intuitively provide pilots with better windshear situation awareness of headwind changes with altitude. Moreover, we hypothesize that the automated message generation will reduce the workload of the operations officers by eliminating the need to collect and organize various wind and weather data (from e.g. the Internet and PIREPs) and summarize this in an ACARS message as is carried out manually at present.

2.3.6 Radar Echo (Precipitation, Snow intensity) Display

Preparation for landing requires not only information on low-level wind disturbances but may also require radar echo information on the intensity of rain or snow. At regional airports with only a few scheduled daily flights, aircraft are able to circle near the airport waiting for favorable landing conditions when there is rapidly changing weather with strong precipitation on the approach route, such as associated with thunderstorm cells or the passage of a front. However, conventional radar echo information, e.g. [8], is difficult to use for the landing timing decision because it has poor spatial resolution and a low update rate (e.g. 10 minutes); it is hard for flight crews to decide when to commence an approach from such ‘rough information’ in a rapidly changing weather situation.

In this study, we therefore present new radar echo information with a higher spatial resolution and update rate (e.g. 2 minutes) focusing on low altitudes (below 2 km) in the approach area. To further suppose landing timing decision-making, we propose a radar image that shows both the “Current Observation” and a “10-minute (10-min) prediction” of radar echoes superimposed on an approach chart as shown in Figure 3-b, since it takes approximately 10 minutes from the aircraft leaving the “high station” (initial approach fix) of the airport to starting the final approach and landing. By comparing the two images, a operations officer will be able to understand what the situation will be 10 minutes late, that is during the landing phase, before starting the approach, so enabling them better to judge the landing timing.

3 Operational Evaluation

3.1 Overview

The effectiveness of the proposed LOTAS display concept was investigated by an evaluation involving five operations officers and about thirty flight crews who landed at Shonai airport during the winter season of 2013 in actual operations. Participants were asked to rate the effectiveness and usability of the LOTAS display in a questionnaire, and also provided comments.

3.2 Results

3.2.1 Flight Crew Evaluation Results

(1) LOTAS ACARS Effectiveness

In this evaluation, 32% of flights (36/112 flights) were provided with information by ACARS message. ACARS messages were not provided for landings on runway 09 as explained earlier, or for mild wind conditions.

Figure 6 shows the result of the usefulness evaluation, revealing that 94% of flight crews considered the LOTAS ACARS message information to be useful. Figure 7 shows the evaluation results of the utility of the content of the proposed ACARS message. “Wind Direction and Speed on Landing Path (Wind Dir./SPD)”, “Headwind on Landing Path (Head Wind)” and “GAIN/LOSS Wind Information (GAIN/LOSS: Head/Tail Windshear Information) were rated as comparatively more useful than other items. Flight crew comments on how the ACARS messages were useful are summarized in Table 1.

(2) Below 500ft Wind Information

Figure 8 shows flight crew subjective rating scores on a four-point rating scale. About 90% of flight crews responded “Effective” or “Slightly effective” regarding wind information below 500 ft. We obtained many comments regarding a choice of “Slightly effective” which indicated that although information on winds below 500 ft wind is sufficient for turbulence situation awareness, information on winds below 1000 ft is desirable to help decide the flap setting to use for landing.

3.2.2 Operations Officer Evaluation Results

(1) Alert Information

We obtained subjective rating scores on a four-point rating scale — ‘ineffective’, ‘slightly ineffective’, ‘slightly effective’ and ‘effective’ — regarding the effectiveness of alert information provided by the LOTAS display. All five operations officers responded ‘effective’.

Figure 9 shows the evaluation of the utility of the content of the alert information. “Radar Echo”, “10-min later prediction of Radar Echo (Radar Echo Prediction)”, “GAIN/LOSS Wind Information (Head/Tail Windshear Information) (GAIN/LOSS), “Wind Direction and Speed (Headwind Component) Data Table (Wind Data Table)” and “ACARS Text Conversion Function (ACARS)” were rated as relatively more useful than other items.

(2) Landing Timing Decision Support

Figure 10 shows the evaluation of the effectiveness of the LOTAS information for landing timing decision support. Although the effectiveness is confirmed from Figure 10, we obtained interesting comments from one operations officer who selected 'Slightly useful' as follows:

- If a 20-minute prediction of radar echoes is possible, it will be useful to decide whether or not aircraft should start their approach.
- The 10-min prediction of radar echoes is useful to decide whether or not aircraft should 'continue' their approach.
- Information on changes of "L/D COND" provided by the "Warning History" shown in Figure 5 might be applicable to deciding whether or not to start the approach, because past information on L/D COND may help the user to predict its future state.

Figure 11 shows the evaluation of the utility of the contents provided by the LOTAS display for landing timing decision support. All five operations officers rated the "10-min prediction of Radar Echo (Radar Echo Prediction)" and "L/D COND" as "useful", while "Wind Direction and Speed (Headwind Component) Data Table (Wind Data Table)" and "Warning History" functions were rated as "slightly useful". These results indicate the importance of predictive and historical information for landing timing decision support.

Regarding the appropriateness of the radar echo display area (distances of 5 or 10 NM from airport, altitudes below 2 km) for landing timing decision support, we obtained subjective rating scores on a four-point scale, 'inappropriate', 'slightly inappropriate', 'slightly appropriate' and 'appropriate'. All five operations officers selected "appropriate".

4 Discussion

4.1 ACARS Effectiveness and Usability for Flight Crew

Since flight crews mainly received LOTAS information by the proposed LOTAS ACARS

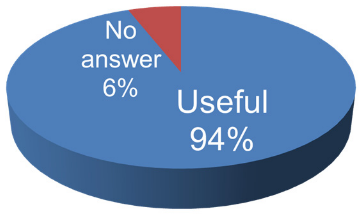


Figure 6 LOTAS ACARS Usability Results

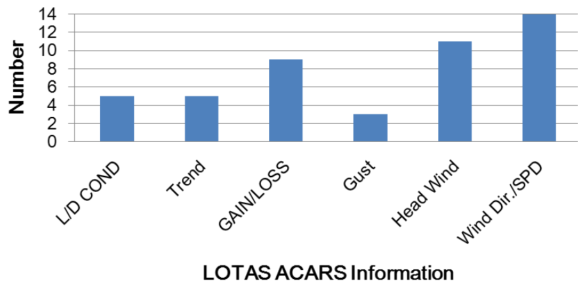


Figure 7 Useful Contents of LOTAS ACARS

Table 1 Summary of Comments for ACARS

Aspect	Comments
Improvement of Situation Awareness/ Prediction	It was possible for pilot to: - recognize headwind change and trend - predict course deviation - predict air speed reduction just before touch down - predict turbulence by wind direction and speed per altitude
Planning for flight control	Power Control Planning - It was possible for aircraft operation while prediction of windshear - Made use of difference information between wind below 200ft and surface wind for power control - It was possible for approach planning of path angle, air speed and power control. - Made use of ACARS Info. for approach briefing Ex. Common situation awareness of turbulence altitude by wind direction and speed changing point

message, we discuss the effectiveness and usability of the proposed message format.

4.1.1 ACARS Text Information Contents

As mentioned in 3.2.1-(1), it is considered that the proposed LOTAS ACARS message is effective for supporting aircraft operations. The provided information is considered to be applicable to improving the situation awareness of low-level wind disturbance and enabling its prediction, and to flight control planning. There is therefore a possibility that the provided information might contribute not only to greater safety but might also reduce the number of go-around events that disrupt smooth operations, particularly because crews will be able to predict the reduction of air speed due to windshear and plan power control accordingly.

4.1.2 Effective Information of ACARS Text

As mentioned in 3.2.1-(1), we clarified that “Wind Direction and Speed”, “Headwind” and “GAIN/LOSS Wind Information (Head/Tail Windshear Information) are useful information items in the ACARS message.

Regarding the “Headwind Graph”, we obtained many comments that graph was helpful and effective because it gave flight crews an intuitive understanding of the wind situation and they were able to anticipate the wind during approaches. These results support our hypothesis in 2.3.5 that converting spatial information into a textual graph promotes intuitive understanding of headwind changes with altitude. It is considered that an intuitive understanding is highly important because a rapid but accurate situation assessment of wind disturbances is required during the high workload approach flight phase.

“L/D COND” was rated as effective information by fewer flight crews compared to another items. While the “L/D COND” status is accurate (agrees with actual conditions) nearly 70% of the time [3], it is possible that fewer crews regarded it as useful for aircraft operations because the information itself is novel and they had no experience as to how it could be applied. Moreover, it is possible that the meaning of “L/D COND” was not always sufficiently understood because some crews asked about it after landing.

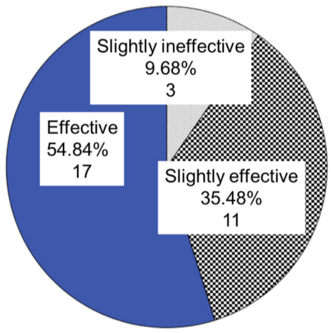


Figure 8 Altitude Range Effectiveness

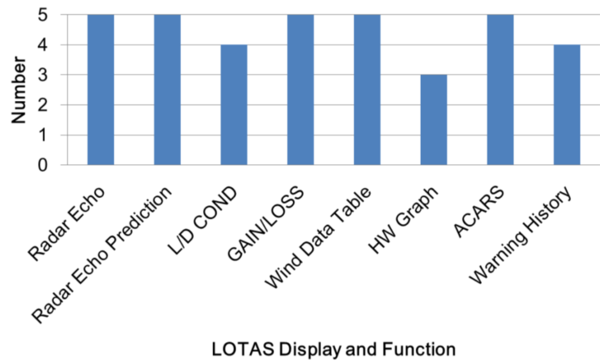


Figure 9 Useful Contents for Alert Information

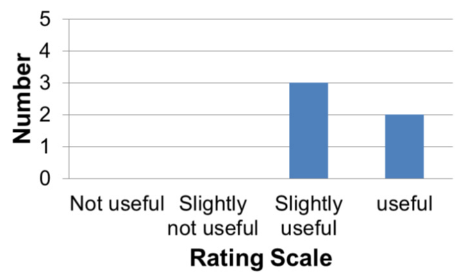


Figure 10 Effectiveness for Landing Timing Decision Support

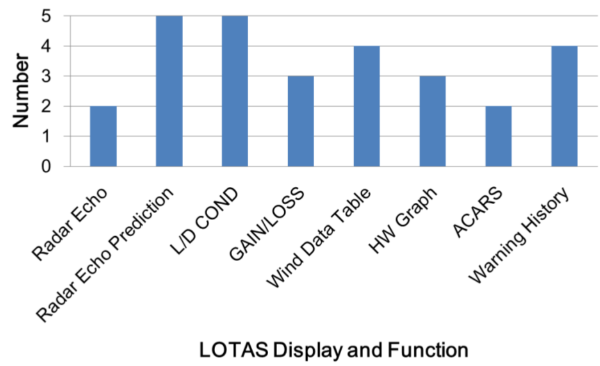


Figure 11 Useful Contents for Landing Timing Decision

4.1.3 Landing Timing Decision

In this evaluation, operations officers provided radar echo information to flight crews only by verbal radio communication, because it is difficult to convert radar echo information like Figure 3-b to a text message for transmission by ACARS.

Some crews commented that they would like to obtain radar echo information through other than verbal means to improve situation awareness. If it is difficult to convert radar echo information to a graphical text style, we are considering ways to present radar echo information using in-cockpit graphical displays such as EFB (Electronic Flight Bag) or MFD (Multi-Function Display) in the future.

Moreover, we will consider including previous “L/D COND” information from the “Warning History” in the ACARS message, since it may assist flight crews’ own decision making regarding the approach timing, if such information can be expressed successfully in an ACARS message as mentioned in 3.2.2-(2).

4.1.4 Low-Cost, High-Resolution Sensors in Future Installations

From the results mentioned in 3.2.1-(2), even if wind information is limited to below 500ft, 90% of crews regarded such wind information as “effective” or “slightly effective”.

Although the low-cost Doppler lidar and radar [3] used in this evaluation have only a tenth of the observation range of systems installed at major airports, they are proven to be effective as they can provide wind information up to 500ft altitude. The low-cost of these sensors and their effectiveness demonstrated by this evaluation might accelerate the installation of LOTAS on regional airports that are prone to severe low-level wind disturbances.

4.2 LOTAS Display and Function Effectiveness and Usability for operation officer

4.2.1 Effectiveness for Alert and Landing Timing Decision Support

The results in 3.2.2 indicate that the LOTAS display and functions are effective for low-level wind disturbance alerting and landing timing decision support.

Regarding landing timing decision support, it is possible that further effectiveness can be gained by increasing the radar echo prediction time 20 minutes because operations officers will then be able to advise crews as to when to start their approaches as mentioned in 3.2.2-(2). This will be possible if the radar observation range is increased.

4.2.2 ACARS Uplink Method

In this evaluation, operations officers manually “copy and pasted” the LOTAS ACARS message text into the company “Web ACARS” system to uplink the message. While this manual operation was feasible at Shonai airport due to the limited number of daily scheduled flights (four), it may be a significant workload at major airports with 30 or more arrivals per day.

We therefore require environment of an automatic ACARS text uplink regarding major airports that flight crew can obtain latest information at any time on request without manual uplink by operation officers.

5 Conclusion

This paper describes the prototype of a new graphical display for the Low-Level Turbulence Advisory System (LOTAS) that provides strategic aircraft operational information on low-level turbulence and windshear as an aircraft approach decision support tool. The results of an evaluation during actual airline operations and issues for future consideration are summarized as follows.

(1) We verified the effectiveness of the LOTAS display in improving the situation awareness of low-level wind disturbances and for landing timing decision support, both for flight crews and airline operations officers; 94% of participant flight crews judged the proposed ACARS text message information (LOTAS ACARS) to be effective, and all

participant operations officers considered the alert information from the LOTAS display to be effective.

(2) The provided information might contribute not only to greater safety but might also reduce the number of go-around events that disrupt smooth operations, particularly because crews will be able to predict the reduction of air speed due to windshear and plan power control accordingly.

(3) The results supported our hypothesis that converting headwind spatial information into a textual graph in the proposed ACARS message promotes intuitive understanding of headwind changes with altitude.

(4) The proposed 10-min prediction of radar echo with high spatial resolution and update rates and new severity information (estimated landing difficulty) contributed to landing timing decision-making by operation officers.

(5) Even if wind information is limited to below 500ft, 90% of crews regarded such wind information as "effective" or "slightly effective". The low cost and demonstrated effectiveness of high-resolution lidar and radar sensors which can detect wind disturbances below 500ft might accelerate the installation of LOTAS on regional airports that are prone to severe low-level wind disturbances.

(6) A method for presenting the new severity metric (estimated landing difficulty) in the LOTAS ACARS message and how to apply it are future issues, because the information itself is novel and participants had no experience of it.

(7) The provision of History information in the LOTAS ACARS message is a future discussion issue. Such information may assist flight crews' own decision making regarding the approach timing.

As the next phase of this research, a new wind information system (ALWIN) using a existing Doppler lidar has been developed in cooperation with the JMA (the Japan Meteorological Agency) and Japanese airlines aiming to implement LOTAS technologies in real operations. In this system, flight crews are able to obtain similar ACARS information to LOTAS at any time on request by using an automatic ACARS text uplink, solving the issues identified in this study. We have already obtained favorable feedback from flight crews of the airlines.

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