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DEVELOPMENT OF LOW-LEVEL TURBULENCE ADVISORY SYSTEM FOR AIRCRAFT OPERATION

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Abstract

The Japan Aerospace Exploration Agency has developed the LOw-level Turbulence Advisory System (LOTAS) together with Osaka University. LOTAS introduces new features such as low-cost Doppler radar/lidar, landing difficulty estimation, short-term prediction of radar echo distribution and text message uplink using ACARS to resolve issues related to existing low-level windshear detection and warning systems. Operational evaluation results indicate that LOTAS is an effective aid for alerting aircraft operators to low-level turbulence and also for making decisions on the appropriate timing for landing.

1 Introduction

Wind disturbances at low altitudes, such as windshear and turbulence, can be major hazards to aircraft take-off and landing operations since they disturb aircraft flight paths and attitudes. In the 1970s and ’80s there were several tragic accidents due to strong windshear caused by extreme localized weather phenomena such as microbursts [1]. The International Civil Aviation Organization therefore requires airport meteorological services to provide windshear warnings for aircraft flying below 1600 ft above the runway elevation [2]. In Japan, the Japan Meteorological Agency (JMA) provides windshear warnings at Japanese major airports when a headwind change of more than 20 kt is observed by an airport-based Doppler radar/lidar. The warning threshold of 20kt was determined to detect a strong windshear severe enough to pose a high risk of accident even if pilot takes corrective actions on encountering the phenomenon.

Although the present low-level windshear detection and warning system fulfills its original purpose of preventing accidents, it is not so effective at providing information on wind disturbances which are not so severe but still serious enough to force a go-around and other air service disruptions. At Narita International Airport (Japan’s largest international airport), for example, more than 90% of go-arounds occur due to wind disturbances such as windshear, turbulence, and strong headwinds or crosswinds (Fig. 1). In some cases, the existing alerting system issued no warning even when pilots were reporting such wind disturbances.

The Japan Aerospace Exploration Agency (JAXA) has identified the following issues with existing low-level windshear detection and warning systems.

1) Content of information

- The current system does not provide information on wind disturbances with small spatial structures (on the order of 100 m), such as topographically induced turbulence and building wakes, that are a leading cause aircraft attitude disturbances that may lead to

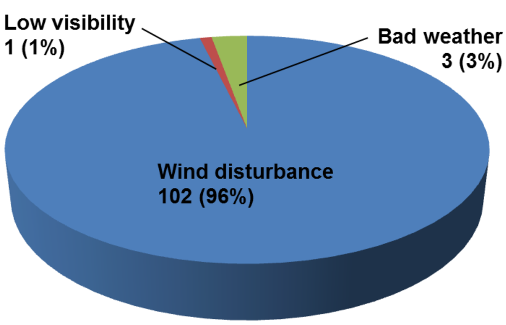

Fig. 1. Cause of go-arounds at Narita International Airport (2008)

go-arounds.
- The current system does not provide information to support the landing timing decision during turbulent conditions.

2) Transmission of information
- Quantitative and visual information on wind disturbances are not available to pilots in flight, who otherwise could utilize the information for planning and performing aircraft control maneuvers.

3) Cost
- The high procurement costs of Doppler radar/lidar systems prevent their installation at regional airports.

To resolve these issues, JAXA has developed the LOw-level Turbulence Advisory System (LOTAS) together with Osaka University. LOTAS detects low-level wind disturbances, even those with small spatial structures, in all weather conditions using the latest Doppler radar/lidar which have high spatial resolution but are less expensive than conventional systems. LOTAS then provides quantitative and visual information on wind disturbances together with severity information (estimated impact on flight) to pilots in flight via an existing datalink system. This paper discusses the LOTAS architecture, especially the estimation of the impact of wind disturbance on flight, and its performance in an operational evaluation conducted together with an airline.

2 LOTAS Architecture

2.1 Features of LOTAS

The features of the LOTAS are described below in the order corresponding to the issues with existing low-level windshear detection and warning systems presented earlier.

1) Content of information
- LOTAS automatically detects wind disturbances on approach flight paths, including those with small spatial structures. In particular, LOTAS is capable of providing severity information considering the flight characteristics of specific aircraft types and pilots' subjective decision-making processes.
- LOTAS assists pilots to decide an appropriate time of landing by offering short-term predictions (10 minutes in advance) of radar echoes (areas of precipitation) that are frequently associated with wind disturbances.

2) Transmission of information
- LOTAS converts wind disturbance data including graphs into a text message format for uplink over existing datalink

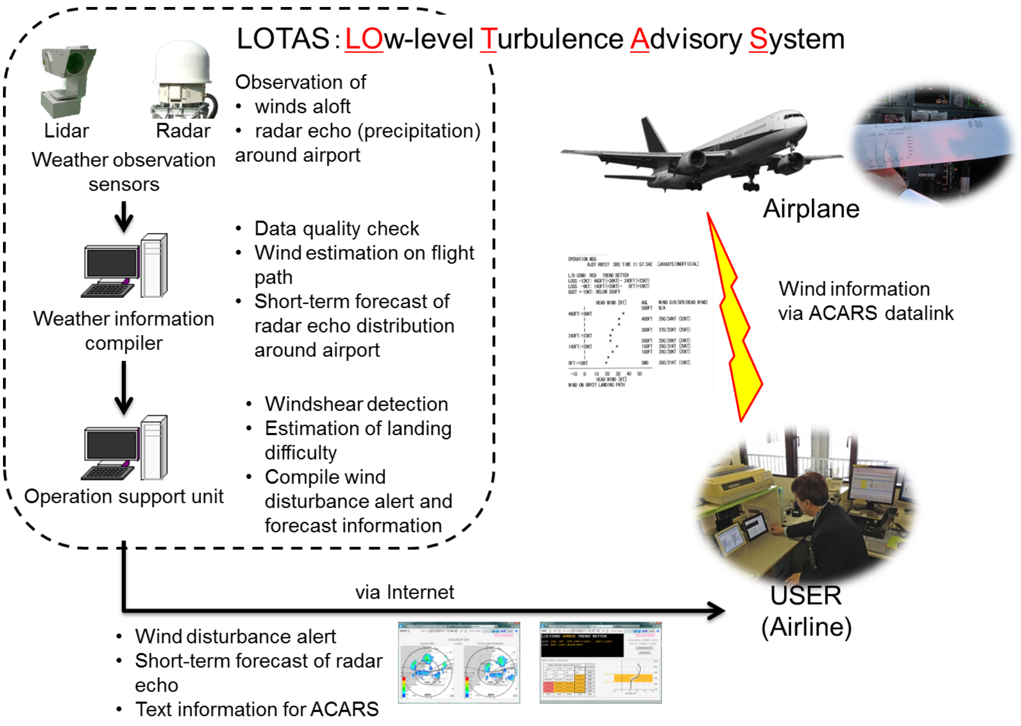

Fig. 2. LOTAS architecture

infrastructure (ACARS), thus supporting the ground-to-air transmission of quantitative and visual wind disturbance information.

3) Cost

- A LOTAS deployment costs less than half of a conventional system, thanks to the use of the latest low-cost Doppler radar/lidar technology.

2.2 Components and Functions of LOTAS

Figure 2 shows the LOTAS prototype. Its major components and functions are described below.

2.2.1 Weather Observation Sensors

Winds and radar echoes around an airport are detected by a Doppler weather radar developed by Osaka University and a Doppler lidar for all-weather observation (Figs. 3, 4 and tables 1, 2) [3]. The observation cycle is about every 90 seconds. These units have spatial resolutions equal or greater than conventional systems but are much less expensive, although their range is limited.

Fig. 3. Doppler radar used for LOTAS prototype

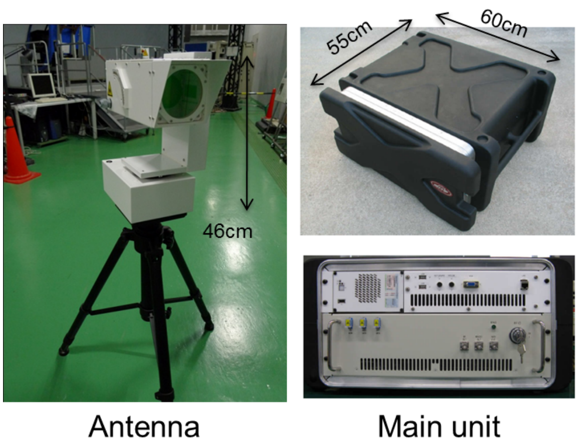

Fig. 4. Doppler lidar used for LOTAS prototype

2.2.2 Weather Information Compiler

1) Estimation of winds on approach flight path

The compiler calculates horizontal wind vectors along approach flight path from observed wind data by the VVP (Volume Velocity Processing) method [4]. Wind vectors are calculated at 10 ft height intervals from ground level to 500 ft. The

Table 1. Major specifications of Doppler radar used for LOTAS prototype

Item	Specification
Operational frequency	15.71-15.79GHz
Band width	80 MHz (max)
Transmission power	10W (max)
Beam width	3 degree
Range resolution	5 m
Range coverage	0.1-15km
Operation mode	spiral, conical, fix
Coverage Az/El	0-360 / 0-90 degree
Azimuth rotation speed	40RPM (max)
dimension, weight	1.5×1.5×1.6m, 500kg
Power consumption	4kVA
Output	received power, radial velocity, spectral width

Table 2. Major specifications of Doppler lidar used for LOTAS prototype

Item	Specification
Operational wave length	1.5 μm
Transmission power	Class 1M (JIS C 6802:2005)
Beam width	3 degree
Range resolution	30/75/150 m
Range coverage	0.6/1.5/3.0 km
Operation mode	PPI, RHI, fix
Coverage Az/El	-90-90 / 0-90 degree
dimension, weight	Main unit: 0.6×0.55×0.3m, 30kg Antenna: 0.23×0.16×0.46m, 8kg
Power consumption	200 VA
Output	radial velocity, spectral width, signal to noise ratio

maximum observation height is limited by the range of the radar/lidar.

2) Compilation and short-term forecast of radar echo distribution
The compiler produces the horizontal distribution of the strongest radar echoes below 2 km in altitude within a 10 NM radius of the airport. In addition, the compiler computes the movement vector of the radar echoes based on the differences between observations at different times, and extrapolates the radar echo distribution for 10 minutes in advance using the computed movement vectors. The prediction time is limited up to 10 minutes because the radar covers only up to 10 NM from the airport.

2.2.3 Operation Support Unit

1) Estimation of wind disturbance severity
LOTAS expresses the severity of an observed wind disturbance as an estimated landing difficulty classified into three levels:
RED: severe disturbance, high workload resulting into a go-around is expected.
AMBER: moderate disturbance, moderate workload is expected.
GREEN: slight disturbance, insignificant workload is expected.

The landing difficulties are probabilistically estimated for each aircraft type based on the type's flight characteristics and pilots' subjective decision-making tendencies as well as the wind vectors on the approach path. LOTAS outputs the most probable landing difficulty level based on the estimated probability of each difficulty level. Details of the estimation method will be discussed in the next section. The estimated landing difficulties of the recent observations are also monitored to detect any trends, which are then rated as BETTER (becoming less difficult), UNCHANGED or WORSE (becoming more difficult).

2) Advisory Display
Advisories to support aircraft operations are presented on displays: the radar echo screen and the wind information screen. These displays are implemented as web pages.

2-1) Radar echo screen (Fig. 5)
The radar echo screen shows the latest observation and a 10-minute prediction of the distribution of radar echoes below 2 km within a 10 NM radius of the airport.

2-2) Wind information screen (Fig. 6)
The wind information screen shows wind details on the approach path being observed. The top half of the screen shows the estimated landing difficulty and any detected low-level wind disturbances in a concise format suitable for verbal transmission to aircraft over the radio. The bottom half of the screen shows wind direction, velocity and headwind component on the flight path in a graph/tabular format. The screen also offers access to a text message format for transmitting over an ACARS datalink (Fig. 7), the history of alerts, and the records (in a time-series graph format) of winds on the flight path.

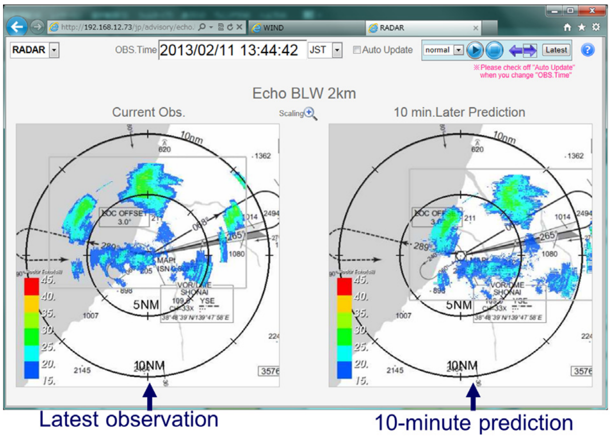

Fig. 5. LOTAS's radar echo screen

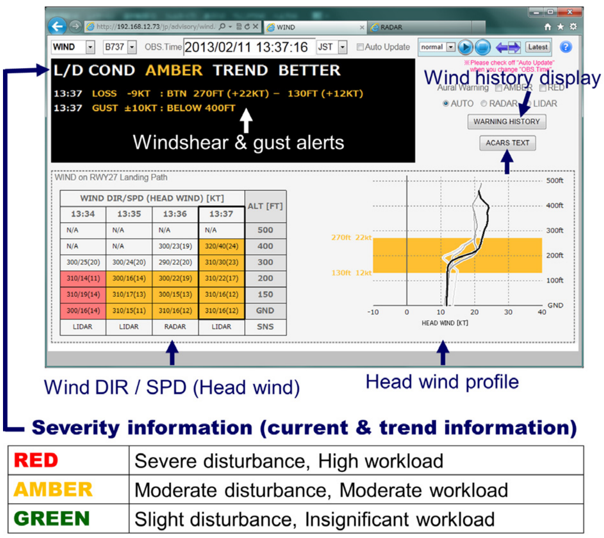

Fig. 6. LOTAS's wind information screen

2.3 Operational Concept of LOTAS

Figure 8 shows the LOTAS operational concept. LOTAS is considered especially useful for regional airports where there are fewer flights and so less chance of obtaining information on conditions from a preceding aircraft.

1) 10 to 20 minutes before landing
Ground operations support staff check on the trends of landing difficulty and 10-minute radar echo predictions to confirm that the wind on the approach path will be acceptable in 10 minute's time. These LOTAS information are then radioed to the aircraft along with the appropriate timing for initiating an approach.

2) Before final approach
Wind disturbance information on the approach path is uplinked to the aircraft over ACARS so that the flight crew can plan landing maneuvers in advance.

3) During final approach
If there is any change in wind conditions after the ACARS transmission, the flight crew will be notified over the radio (through one-way communication).

3. Estimation of Landing Difficulty in Turbulent Conditions

One of the unique features of LOTAS is providing severity information of wind disturbances as an estimated landing difficulty. Here, we describe the estimation method in detail.

3.1 Impact of Wind Disturbances on Flight

The main impact of wind disturbance on flight has traditionally been considered as flight path disturbance, especially height loss, due to windshear. Existing warning systems are therefore designed to detect excessive headwind changes on the flight path. However, there is another major impact: disturbance of the aircraft's attitude. This is especially important at low altitudes where attitude disturbance may easily lead to a hard landing or a go-around.

Figure 9 shows the relationship between pilots' subjective ratings of landing difficulty and flight parameter variations during approach derived from data on nearly 200 commercial transport airplanes provided by an airline. A strong positive correlation is clearly seen

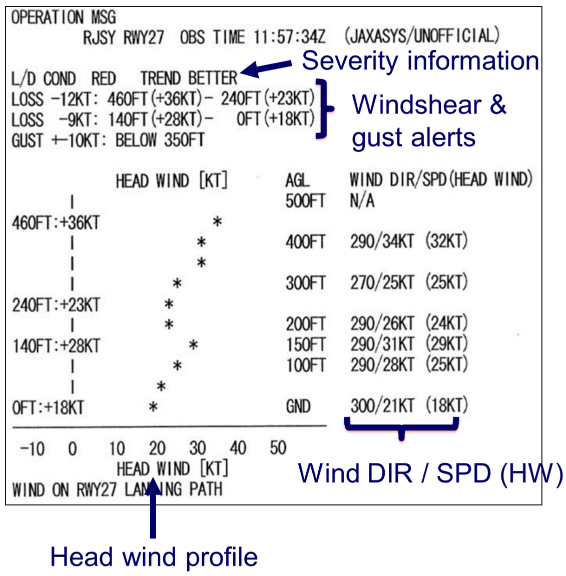

Fig. 7. LOTAS's text message format for ACARS

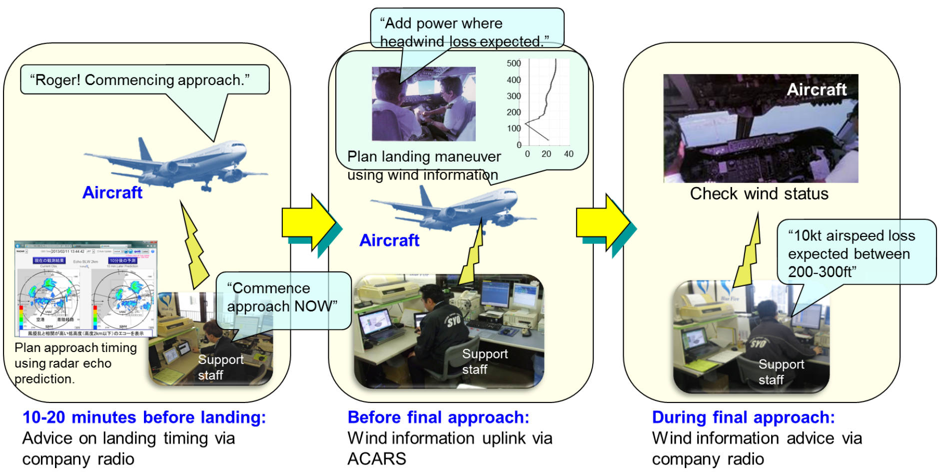

Fig. 8. LOTAS operational concept

between landing difficulty and attitude/acceleration variations. We also found that the highest correlation is expected when we calculate flight parameter variations using a moving average window of 2-4 seconds. In fig. 9, we use a 3-second window to calculate flight parameter variations. Since an aircraft's ground speed typically ranges over 50–70 m/s on approach, a 3-second time window corresponds to spatial window of about 150-210 m. This indicates that in order to estimate landing difficulty precisely we have to consider attitude/acceleration disturbance caused by small-scale wind disturbances (order of 100 m) as well as flight path disturbance.

3.2 Estimation Method of Landing Difficulty

The landing difficulty estimation process is composed of three units (Fig. 10). Each unit estimates wind disturbances, including those with small spatial scale, aircraft response considering type-specific flight characteristics, and pilots' subjective judgments, respectively. The details of each unit are described below.

3.2.1 Wind Disturbance Estimation Unit (WDEU)

The WDEU first calculates vertical windshear of headwind/crosswind components using the vertical profile of headwind/crosswind components estimated by LOTAS's weather information compiler. Vertical windshear may affect an aircraft's flight path and also produces sufficient turbulent energy to create small-scale wind disturbances. The WDEU then estimates the variations of the headwind/crosswind components. The estimated variations include the information of small-scale disturbances on the order of 100 m that may alter aircraft attitudes but are not directly measured by weather observation sensors due to resolution limitations.

To estimate the variations of wind components, we use a neural network which outputs variations of wind components using vertical wind profiles and vertical windshear. Since typical wind characteristics may differ for each runway, we have to train the neural network for each. We use flight data of aircraft landing on the target runway to build a training data set for the neural network. From flight data, we extract three-axis components of winds that contain information on small-scale disturbances because the spatial resolution of flight data is on the order of 10 m, much finer than the resolution of weather observation sensors (order of 100 m). We then decompose the extracted winds into a moving average and variation around the average. The moving average window is adjusted to simulate the weather observation sensor's resolution. The former corresponds to the neural network input and the latter corresponds to the neural network output.

3.2.2 Aircraft Response Estimation Unit (AREU)

The AREU estimates the effects on aircraft flight parameters due to wind disturbances. Parameters include attitudes (roll and pitch) and vertical/lateral accelerations which are considered to be closely related to landing difficulty (Fig. 9).

We again use a neural network to estimate

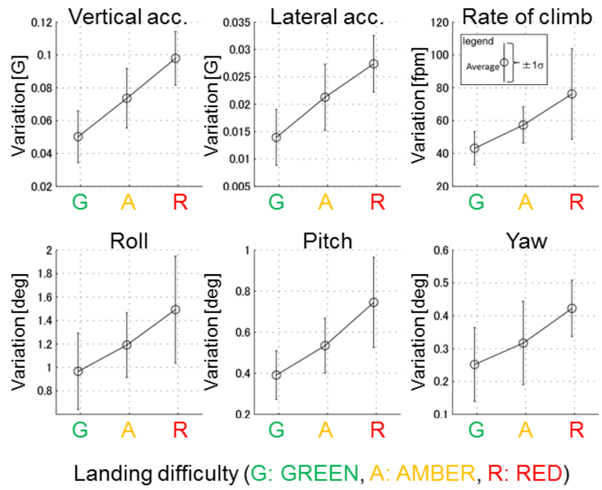

Fig. 9. Observed relationship between landing difficulty and flight parameter variations during approach

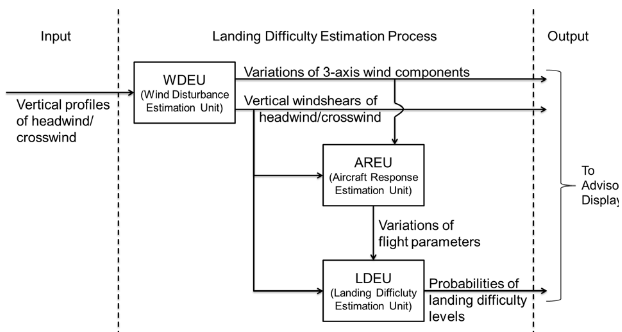

Fig. 10. Landing difficulty estimation process of LOTAS

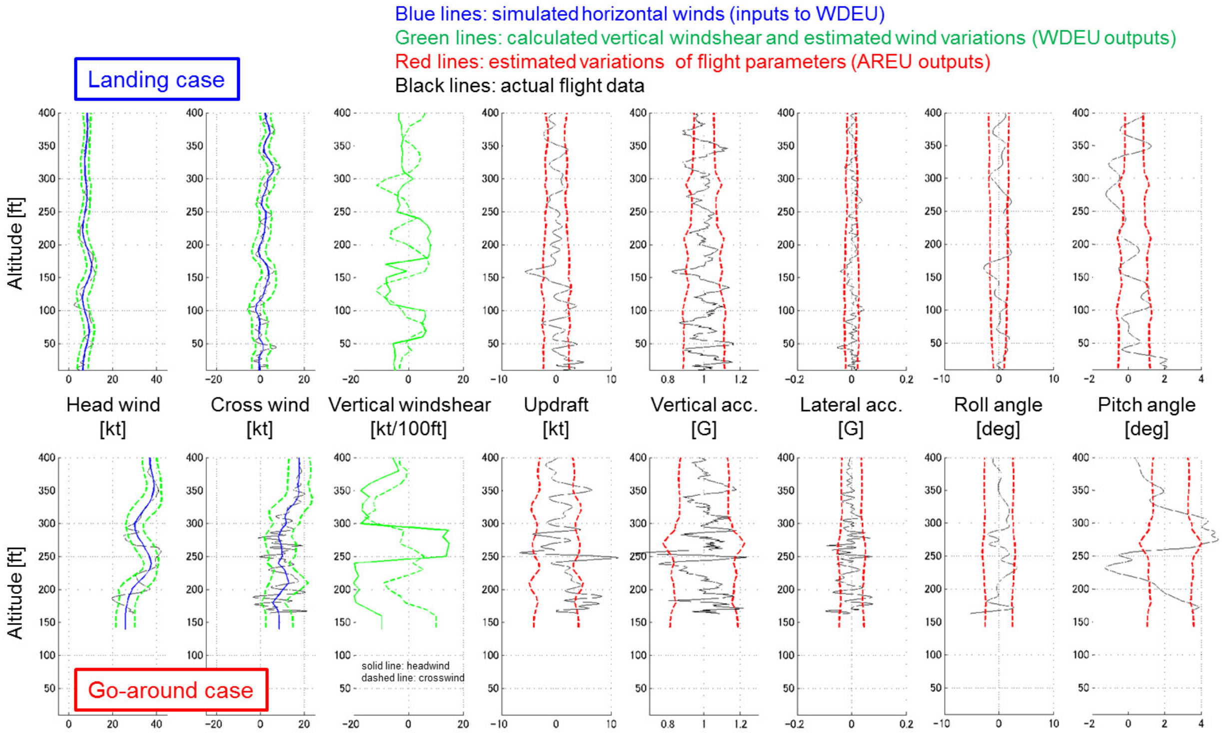

Fig. 11. Example of WDEU/AREU estimations of wind/flight parameter variations

the variations of aircraft flight parameters for a given magnitude of wind disturbance. The inputs to the neural network are the outputs of the WDEU. Since flight characteristics differ for each aircraft type, we have to train the neural network for each. We again use flight data of target aircraft types landing on the target runway to build a training data set for the neural network. The training data of the AREU's neural network input can be built in the same way as the WDEU. Regarding the training data of the AREU's neural network output, we calculate the flight parameter variations using a 3-second moving average window so that the calculated variations have high correlation with landing difficulty.

Figure 11 exemplifies the estimations of the WDEU and the AREU. The black lines indicate actual flight data: extracted three-axis wind components and flight parameters. The blue lines indicate the simulated input to the WDEU: the moving average of the extracted winds with corresponding spatial resolution of the weather observation sensors. The green lines indicate the output of the WDEU: vertical windshear and variations of headwind/ crosswind components. Finally, the red lines indicate the AREU's outputs: the variations of flight parameters. A normal landing case and a go-around case are shown in the figure. For both cases, the WDEU and the AREU successfully estimate the variations of actual flight data. Note that the variations of flight parameters clearly differ between the two cases, indicating that the flight parameter variations can be correlated with landing difficulty.

3.2.3 Landing Difficulty Estimation Unit (LDEU)

The LDEU estimates the probability of each classified landing difficulty level: RED, AMBER and GREEN. Since the landing difficulty depends on pilot subjective judgment, it cannot be derived deterministically. We therefore introduce a probabilistic output to express the variation of pilots' judgments.

We use a Bayesian network to estimate the probability of each classified landing difficulty level. Inputs to the Bayesian network are the outputs of the WDEU and the AREU. During flight data analysis, we found that acceptable flight parameter variations differ for each aircraft type. We therefore train the Bayesian network for each aircraft type. To make a training data set for the Bayesian network, we use flight data of the target aircraft type in the landing phase and pilots' subjective ratings of landing difficulty. The training data of the Bayesian network input can be built in the same way as the WDEU and the AREU. For the training data of the Bayesian network output, we can use the pilots' subjective ratings directly.

4. Operational Evaluation of LOTAS

4.1 Overview

A prototype of the LOTAS system was deployed and evaluated at Shonai airport (a Japanese regional airport) for about two months from late December 2012 to early February 2013. Shonai airport is known for low-level wind disturbances in winter when seasonal westerly winds from the Sea of Japan gain strength, sometimes resulting in go-arounds and diversions to other airports. Figure 12 illustrates an example of low-level wind disturbance observed at Shonai airport by LOTAS's radar. The evaluation was conducted with cooperation from the authorities of Shonai airport, the JMA and All Nippon Airways (ANA), an airline that operates scheduled flights at Shonai airport.

The approach path to the airport's runway 27, known for frequent occurrences of low-level wind disturbances, was monitored by the LOTAS radar/lidar installed at the east end of the runway (Fig. 13). LOTAS provided landing difficulty information for the two aircraft types mainly used for scheduled flights at the airport: Boeing 737 and Boeing 767. To estimate the landing difficulty, we trained the LOTAS neural networks and the Bayesian network using flight data of landings on runway 27 and the pilots' subjective ratings of landing difficulty collected before the evaluation with cooperation of ANA. Around 100 samples of flight data were used for training for each aircraft type.

For the evaluation, two tablet computers (Fig. 14) were installed in the ANA Dispatcher room at Shonai airport to present the LOTAS advisory displays (Figs. 5, 6). In addition, text information (Fig. 7) was uplinked to aircraft in flight via ACARS (Fig. 14).

4.2 Evaluation Results

As indicated in Fig. 15, more than 90% of the pilots who participated in the evaluation considered that the LOTAS information was useful for their flights, while 60% of the ground operations support staff answered that the information was useful when deciding on the

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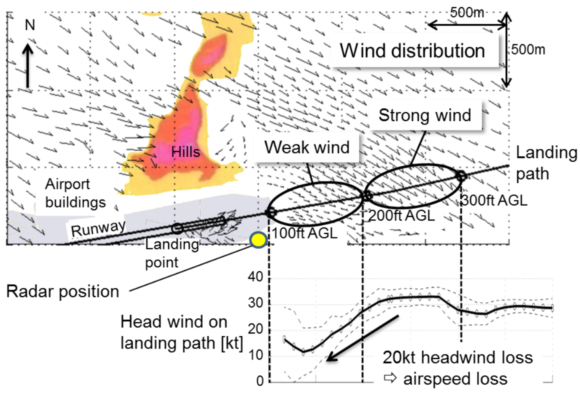


Fig. 12. Example of low-level wind disturbance observed at Shonai airport by LOTAS

Fig. 13. LOTAS installation at Shonai airport

Fig. 14. LOTAS operational evaluation by airline

appropriate timing for landing. These responses indicate that LOTAS is an effective aid for alerting aircraft operators to low-level turbulence that can have a significant impact on flight and also for making decisions on the appropriate timing for landing. Some of the key findings from the evaluation are summarized below. Details of the evaluation results are discussed in another paper [5].

4.2.1 Wind Information along Approach Flight Path

- The vertical profile of headwinds along the approach flight path helps pilots to enhance their situational awareness and plan maneuvers in advance.
- Although limited to 500 ft above the ground, the wind information was still useful. This justifies the use of a low-cost radar/lidar even with limited observation range.

4.2.2 Landing Difficulty Information

- The threat score of the 'RED' estimate of landing difficulty was 0.67 (table 3). This is much better than existing severity estimation methods which consider only the headwind component of windshear.
- For pilots, the landing difficulty information was not as effective as other LOTAS information. There might be two reasons for this: (1) The information was not well understood because it is novel and has not previously been available; (2) Pilots are trained to estimate the impact of wind disturbances on flight themselves from wind data.
- For ground operations support staff, the landing difficulty information was useful to understand impacts on flight and to determine the appropriate timing to provide information to aircraft.

4.2.3 Short-term Prediction of Radar Echo

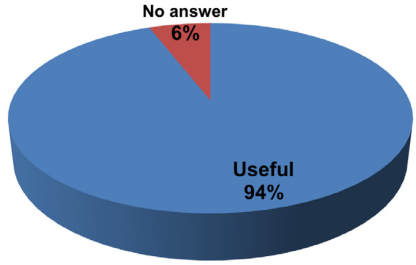
- The 10-minute prediction of radar echo distribution is quite useful to judge the appropriate timing for landing.
- The usefulness of the short-term prediction will greatly improve if can be extended to 20 minutes.

4.2.4 Information Transmission to Aircraft

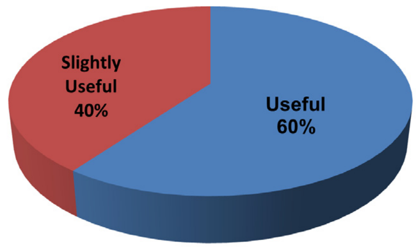
- The text information transmitted via ACARS is extremely useful as it can be used in the aircraft cockpit in flight. Most information transmitted to the aircraft was through the ACARS datalink.

5 Conclusion

This paper discussed the low-level turbulence advisory system (LOTAS) developed by JAXA together with Osaka University. LOTAS



(1) Evaluation of LOTAS text message via ACARS by pilots in flight



(2) Evaluation of LOTAS information for determining the appropriate timing for landing by ground support staff

Fig. 15. LOTAS operational evaluation results by airline

Table 3. Threat score of landing difficulty estimation at Shonai airport

(1) LOTAS method

Threat score of 'RED' estimate: 0.67 (= 20/30)

	Occurred	Not Occurred
Estimated	20	3
Not Estimated	7	113

(2) Existing method using a threshold of vertical windshear of headwind

Threat score of 'RED' estimate: 0.22 (= 6/27)

	Occurred	Not Occurred
Estimated	6	0
Not Estimated	21	116

introduces new features such as low-cost Doppler radar/lidar, landing difficulty estimation, short-term prediction of radar echo distribution and text data uplink using ACARS to resolve issues related to existing low-level windshear detection and warning systems. The results of an operational evaluation indicate that LOTAS is an effective aid for alerting aircraft operators to low-level turbulence and also for making decisions on the appropriate timing for landing.

To implement LOTAS technologies in real operations, JAXA has started a collaborative research program with the JMA to develop new low-level wind information system named ALWIN (Airport Low-level Wind InformatioN) using the JMA's Doppler lidar. ALWIN has similar functions to LOTAS except the functions related to the radar. A prototype of ALWIN has already been implemented at Narita International Airport and operational evaluation has started with the cooperation of airlines. The preliminary evaluation results have given us favorable feedback and encouragement to implement ALWIN in real operations.

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