OBJECTIVE AND SUBJECTIVE EVALUATION OF A NEW LIDAR-BASED SPEED PREDICTION AND ADVISORY DISPLAY

Jorg Onno Entzinger
The University of Tokyo (UTokyo)
Tokyo, Japan
Tomoko Iijima
Japan Aerospace eXploration Agency (JAXA)
Tokyo, Japan
Tsuneharu Uemura (UTokyo), Jun Matsumoto (JAXA),
Naoki Matayoshi (JAXA), Shinji Suzuki (UTokyo)

We evaluate a newly developed symbology that provides the pilot predicted and advisory airspeed information. This information is not only based on the current state of the aircraft, but also takes into account the wind field ahead of the aircraft measured by an onboard LIDAR system. Airline pilots flew landing approaches in wind shear scenarios that demanded careful consideration of whether to land on go-around in JAXA's full flight simulator. We obtained both subjective evaluations and objective data including flight performance, eye recoder data, electrocardiogram (ECG), electroencephalogram (EEG), and performance on a simple visual secondary task. The pilots considered all newly proposed systems useful during the landing approach, and reported better performance and lower workload compared to the conventional display, particularly in challenging situations. The objective data supported the subjective evaluation results.

The Japan Aerospace eXploration Agency (JAXA) is developing an onboard Doppler Light Detection and Ranging (LIDAR) system able to measure the wind velocity field up to several miles ahead of an aircraft when flying in clear air (Inokuchi et al. 2009, Inokuchi 2012). In a collaborative research between JAXA and The University of Tokyo we investigate how this information can be used to support the pilot’s situational awareness and to reduce accidents, incidents, or inconvenience caused by strong turbulence and wind shear.

Proposed Systems

Figure 1 shows how the wind data measured by the onboard LIDAR can be used. This paper focuses on the LIDAR-based predictive wind shear (L-PWS) warning system, the predicted airspeed indicator (L-PSPD) and the target airspeed indicator (L-TSPD). Figure 2 shows an impression of the current implementation. We assume manual operations. Readers interested in future connections to the autopilot and auto throttle systems are referred to the paper by Kamo et al. (2016).

LIDAR-based predictive wind shear (L-PWS)

Closest to the raw LIDAR data is the use of LIDAR as a clear air extension to the weather radar system. The LIDAR data is displayed on the navigation display (ND) and a LIDAR-based Predictive Wind Shear (L-PWS) advisory, caution, or warning is generated analogous and in addition to the current radar-based system. An addition to the radar version is that the higher accuracy of the LIDAR allows us to provide a countdown timer until the expected wind shear occurrence (“ETA 5sec” on the ND in Figure 2).

The LIDAR data display is intended to support situational awareness on the perception level, while the warning system should facilitate decision making (i.e., preparing for or initiating a Go-Around).

LIDAR-based predicted airspeed indicator (L-PSPD)

The higher resolution and accuracy of the LIDAR system makes it possible to provide the pilot with predictions of airspeed changes up to several tens of seconds or even a minute ahead. The L-PSPD consists of 3 ovals ("bubbles") between the speed tape and the artificial horizon (Figure 2). The oval centers represent the predicted average speeds, their heights are a measure for the speed variation (i.e., short in calm air and tall in strong turbulence).

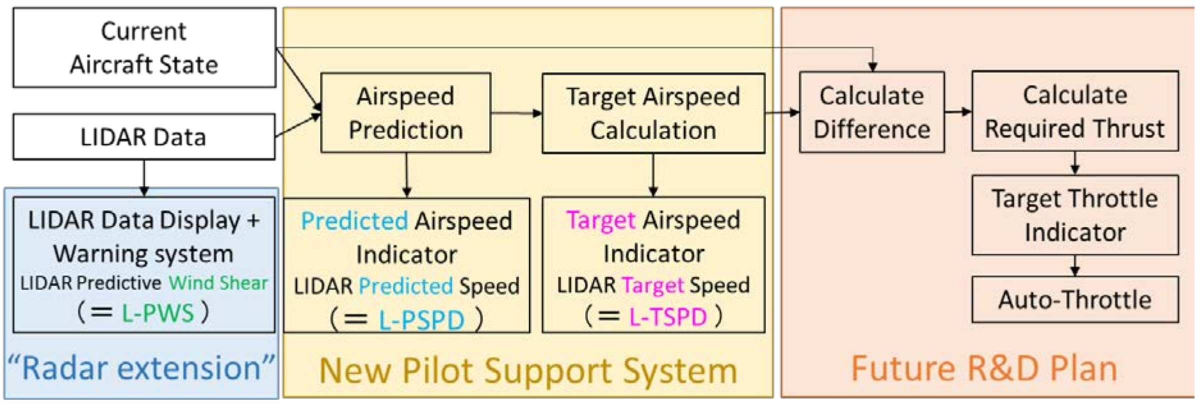

Figure 1. Overview of the proposed "SafeAvio" systems using data measured by the onboard LIDAR.

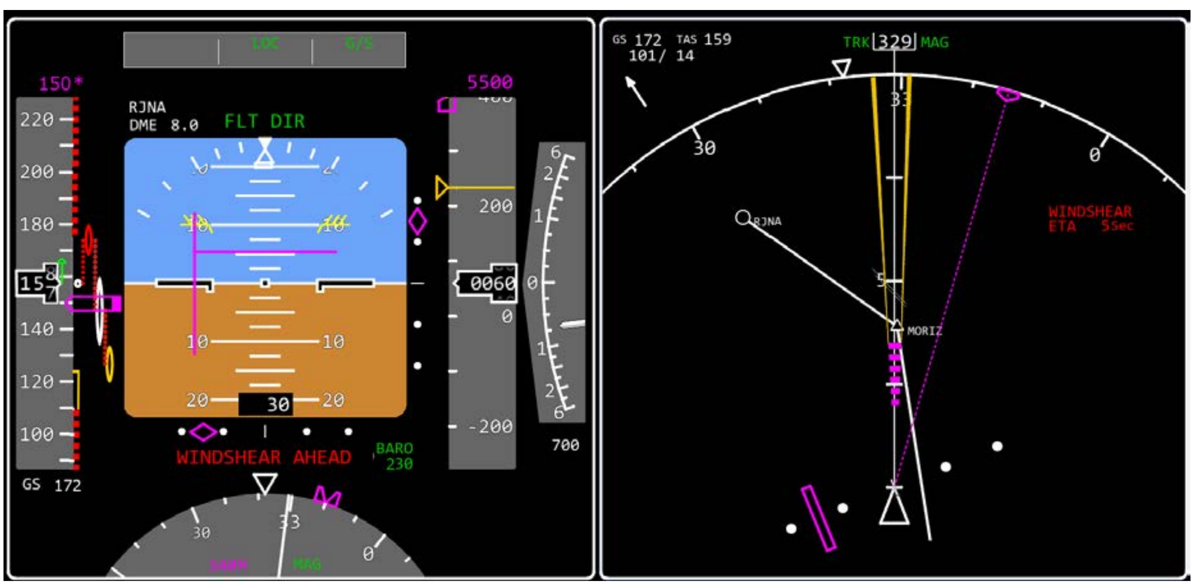

Figure 2. Impression of the L-PWS, L-PSPD ("Bubble") and L-TSPD ("Shell") additions to the Primary Flight Display (PFD, left) and Navigation Display (ND, right).

This indicator is similar to the speed trend vector on conventional displays, however:

1. it takes into account the future wind speed changes measured LIDAR (not only current wind),
2. it provides multiple predictions (e.g., 5, 10, and 20s ahead), (10s for the speed trend vector),
3. it shows the (in)stability of the airspeed through a variable height of each of the 3 "bubbles".

The predicted airspeed indicator is intended to support situational awareness on the (comprehension and) projection level. In particular, it is expected to be helpful for speed control, since the prediction could compensate the delays of several seconds the jet engines need to spin up and translate that additional thrust (acceleration) into speed.

LIDAR-based target airspeed indicator (L-TSPD)

In addition to the future airspeed predictions we propose a variable target airspeed (L-TSPD) that may temporarily deviate from the selected speed in order to prepare for large upcoming changes in wind speed. The symbology is similar to and replaces the "speed bug" or "selected speed" on conventional displays.

The predicted airspeed indicator is intended to directly support decision making, i.e., increasing or decreasing trust to keep following the advised target speed. It is expected to offer better protection of the minimum and maximum speed limits at all times.

Materials & Methods

To evaluate the proposed systems we carried out a series of simulator experiments with professional airline pilots. The experiment protocol was approved in advance by the ethics committees of JAXA and The University of Tokyo's School of Engineering. Each subject provided written informed consent before participating.

Primary Task

Subjects were asked to fly manual precision landing approaches to Tokyo Haneda airport runway 34L in JAXA's full flight simulator. The aircraft model was a generic model similar to the Boeing 737. Motion simulation was turned off. All experiments starting trimmed and on glide slope from 1400 or 2000ft altitude to 100ft altitude. Wind conditions were based on the longitudinal wind components from the FAA windshear database (Switzer et al., 1993) with additional light random turbulence. For the evaluation of the L-PSPD and L-TSPD the wind speeds were weakened to a level where a continued landing was possible, but a decision to go-around would not be unrealistic either.

Trials

In the morning subjects were given time to familiarize with the simulator, the various displays, and the various wind scenarios until they felt sufficiently familiar with them. They also practiced several trials with the secondary task.

Experiment 1A in the afternoon tested 4 different display combinations: the conventional display, and either or both the L-PSPD and L-TSPD display additions. All data except the secondary task were measured.

Experiment 1B was the same as 1A, but with a different wind profile. In addition, subjects performed the secondary task.

Experiment 2 compared the L-PWS system with a reactive windshear warning system under 2 different wind scenarios. For these trials only simulator data and subjective evaluations were recorded.

Some trials were duplicated to test for repeatability or by the subject's request (in order to develop a better basis for the subjective evaluation). After each experiment (1A, 1B, 2) the subjects filled out the corresponding subjective evaluation questions, followed by a short break.

Participants

8 male subjects participated in this experiment. 7 of them were captain pilots from 2 major Japanese airlines and 1 was a retired airline captain. The participants recruited through a contract with the airlines on the basis that they had significant flight experience and were able to provide a critical and detailed evaluation (e.g., have experience as instructor or examiner). The participants were compensated for their travel expenses.

Measuring Equipment

The simulator states were logged at 16.67Hz. Eye-mark data (pupil diameter, gaze direction, blink detection) was taken at 30Hz using the Takei TalkEyeLite. Electrocardiogram (ECG) data was recorded at 256Hz using the ParamaTech EP-301. Brainwave data (electroencephalogram, EEG) were recorded using the eMotiv EPOC+ at 128Hz.

In addition, a secondary task was administered in some of the trials. The task was a simple choice response time task, where the subject had to press one of two buttons attached to the control column depending on the change of either of two pictures displayed immediately left of the PFD within the pilot's peripheral field of view. The response time, error rate, and time-out rate were recorded.

The subjective evaluations consisted of a checklist based on the FAR 25.1301 and FAR 25.1322 Human Factors Considerations and a questionnaire focusing on perceived workload, situational awareness, and general usefulness or issues of each of the proposed systems.

Results

Experiment 1 (Conventional vs. L-PSPD vs. L-TSPS vs. LPSPD & L-TSPD)

Objective evaluation. Analysis of the simulator data showed that averaged deviations from the target airspeed (root of the mean square error, RMSE) were smaller when the L-PSPD indicator was present. This difference was significant at 5%-level compared to the conventional display and at 1% level compared to the L-TSPD only display. In particular deviations below the target airspeed were smaller. The addition of the L-TSPD indicator, on the other hand, significantly raised the all-time minimum airspeed throughout the trials. Also other flight performance parameters such as minimum and maximum pitch angles, pitch rate, and glideslope deviations showed small improvements, although differences did not reach the 5% significance level. In conclusion, the combination of both indicators helps the pilot to effectively stabilize the aircraft and guarantee a safe minimum airspeed.

From the ECG data we calculated the heart rate, which can be interpreted as a measure of arousal or stress, and an index of mental effort based on the heart rate variability (Vicente et al., 1987). The average and maximum heart rates were slightly lower for the L-TSPD only display. The mental effort, on the other hand, was slightly higher for the L-TSPD only display.

Mid-frontal brain wave activity in the theta band is said to correlate with the need for cognitive control (Cavanagh & Frank, 2014). The order from high to low activity was the conventional display, the L-TSPD, then the L-PSPD and finally the display with both L-PSPD and L-TSPD. However, the differences were not statistically significant. A more detailed analysis per phase (before wind, during wind, after simulation stop) may reveal clearer results, although the large measurement noise will still remain a problem.

The response times in the secondary task similar for the conventional, L-PSPD only and L-TPSD only displays, and only slightly slower for the display with both LPSPD and L-TSPD. For the L-PSPD display there were no timeouts, but the number of mistakes increased. One explanation could be that the subject sees the secondary task in his peripheral view when looking at the L-PSPD, noticing all changes, but not taking more effort to carefully check it.

Subjective evaluation. Pilots ranked their subjective performance best and workload lowest for the L-PSPD in Experiment 1A. In Experiment 1B with the secondary task and different wind pattern, they found the L-TSPD and combined L-PSPD&L-TSPD displays equally good (with slightly lower perceived workload for the combined display). They concluded that any of the newly proposed displays would be a valuable addition to the conventional display during the landing approach, although the preference among the new displays differed per person. Pilots commented that the lack of future wind information in the conventional display case made them initiate a go-around, and that knowing the wind changes ahead made it easier to control the airspeed.

Some subjects liked L-TSPD because it is simple. Others did not like it for the same reason: they wanted more raw information (L-PSPD) and draw their own conclusions. In case of higher workload (more difficult wind, additional tasks, etc.) these pilots would fall back on the L-TSPD, therefore the combined system proved effective.

General comment. We found significant differences between Experiment 1A and 1B for a number of physiological parameters (in particular the ECG related parameters), some flight performance parameters, and the subjective evaluations. Unfortunately, the current experiment design makes it impossible to know whether this was due to the different wind profile, the presence of the secondary task, the fact that it was the second round of trials, or a combination of these.

Experiment 2 (L-PWS versus reactive wind shear warning system)

Objective evaluation. In this experiment no psychophysiological and secondary task data were recorded. The objective (simulator) data showed highly significant flight performance improvements when using the proposed L-PWS system (smaller airspeed and glideslope deviations, lower pitch rates and sink rates, less extreme pitch angles, etc.). This is not surprising, since the Go-Around is initiated much earlier (46s on average), before the large wind speed changes occur.

Subjective evaluation. Subjects indicated that the proposed L-PWS enables them to plan ahead, and therefore reduced their workload. They noted it was compatible with the current radar based PWS system (which would detect noting in clear air) with equivalent workload and equal or even better performance. The main point of criticism was that the size of the detected wind shear area is narrow and therefore difficult to confirm on the ND. We believe this is partly mitigated by the added “Estimated time of arrival (ETA)” indication which counts down the time in seconds until wind shear. Since there is also no outside visual cues to confirm the existence of the wind shear (such as a cloud front), a clear instruction manual and training will be needed (similar to for example the Ground Proximity Warning System).

Conclusion

The proposed systems proved effective in supporting the pilot to maintain safe airspeeds and generally resulting in more stabilized landing approaches or earlier go-around decisions. Additional workload measurements did not indicate any problems, and may even be interpreted as showing reduced workload in some cases.

Subjective comments were also positive. Pilots found the newly proposed systems useful and reported lower workload because they were better able to plan ahead. There seem to be personal differences in the preference for the L-PSPD and the L-TSPD. In some cases pilots reported confusion when both were available, but overall the combined display proved best in both the objective and subjective evaluations.

Acknowledgements

We like to thank all subjects for their participation in the experiments. This research is carried out in as a collaborative research project between the University of Tokyo and the Japanese Aerospace eXploration Agency (JAXA) under JAXA’s SafeAvio research program. The University of Tokyo received financial support from JAXA under their publicly funded research program.

References

Cavanagh, J.F., Frank, M.J. (2014). Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences*, August 2014, Vol. 18, No. 8. (pp 414-421). doi: 10.1016/j.tics.2014.04.012

Inokuchi, H., Tanaka, H., and Ando, T. (2009). Development of an Onboard Doppler LIDAR for Flight Safety. *Journal of Aircraft*, Vol. 46, No. 4. (pp. 1411-1415). doi: 10.2514/1.41738

Inokuchi, H. (2012). Detection of the Clear Air Turbulence by an Airborne Doppler LIDAR. In *Proceedings of the Asia-Pacific International Symposium on Aerospace Technology*, Jeju, Korea. (Paper #6.4.2).

Kamo, S., Entzinger, J.O., Uemura, T., Suzuki, S. (2016). Development of Control Advisory System Using Future Wind Information. *Asia-Pacific International Symposium on Aerospace Technology (APISAT)*, Toyama, Japan, Oct. 25-27.

Switzer, G.F., Proctor, F.H., Hinton, D.A., Aanstoos, J.V. (1993). *Windshear Database for Forward-Looking Systems Certification*. NASA Technical Memorandum 109012. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19940012810.pdf

Vicente, K.J, Thornton, D.C., Moray, N. (1987). Spectral Analysis of Sinus Arrhythmia: A Measure of Mental Effort. *Human Factors*, Vol. 29, No. 2. (pp. 171-182).