INITIAL RESULTS OF A PILOTED SIMULATOR INVESTIGATION OF MODERN WINDSHEAR DETECTION SYSTEMS

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Abstract

A preliminary investigation has been carried out on the NLR Research Flight Simulator (RFS) concerning several aspects involving the use of modern windshear detection systems during landing approaches. Three windshear detection systems were evaluated together with three flight procedures. The systems evaluated were a reactive windshear detection system, a LIght Detection And Ranging (LIDAR) forward-looking windshear detection system, and a ground-based Terminal Doppler Weather Radar (TDWR) system. With the latter a simulated data-uplink connection to the aircraft cockpit was used.

Preliminary results of the experiments indicate that pilots perceived a greater windshear threat when making a go-around than when continuing the approach (at a higher speed). Although they accepted the "standard" flight procedure (i.e. to make a go-around at any alert) better, they had a lower workload when using a cautious penetration type of procedure. The laser sensor generally gave better timely alerts, but the TDWR was liked quite well. The best ground-air sensor combination seems to be the TDWR with the laser. It is recommended to carefully tune an integrated sensors and warnings concept with the flight procedure, and to add windshear displays in order to improve the situational awareness.

Abbreviations and Acronyms

AT	Autothrottle
CDU	Central Display Unit
CRT	Cathode Ray Tubes
EFIS	Electronic Flight Instrument System
EICAS	Engine Indicating and Crew Alerting System
FAS	Final Approach Speed
FD	Flight Director
GPWS	Ground Proximity Warning System
ILS	Instrument Landing System
LIDAR	LIght Detection And Ranging
LS	Laser Sensor system
KLM	The Royal Dutch Airlines
KNMI	The Royal Netherlands Meteorological Institute
MCCP	Manual Crew Coordination Procedures
MERS	Mental Effort Rating Scale
NIVR	Netherlands Agency for Aerospace Programs
NLR	National Aerospace Laboratory, the Netherlands
NM	Nautical Miles
PF	Pilot Flying
PFD	Primary Flight Display
PNF	Pilot Not Flying
POD	Probability Of Detection
RFS	Research Flight Simulator
RLD	Netherlands Department of Civil Aviation
RS	Reactive Sensor system
TDWR	Terminal Doppler Weather Radar (sensor system)
WTA	Windshear Training Aid

Notation

A_x, A_z	body linear accelerations
$\vec{e}_{laser}$	unit vector aligned with laser beam
F	windshear hazard F-factor
F_{av}	averaged F-factor
h_{RA}	Radio altitude
R_x	filter range
T_x	filter time
V	groundspeed
V_{TAS}	True airspeed
W_x	longitudinal wind component; tailwind positive
W_z	vertical wind component; downdraft positive
α	angle of attack
γ	flight path angle
ΔV	speed change
θ	aircraft pitch angle

Introduction

Windshear, defined as a deterministic change in wind velocity and/or wind direction, remains a concern in aircraft safety. Although the introduction of the Windshear Training Aid (WTA) Program in 1987(1) has reduced accident and/or incident numbers in which windshear played a role, it still remains a potential threat to aircraft safety, because there's no guarantee that aircraft performance will be sufficient to cope with the energy loss due to a windshear. Therefore new windshear detection systems and operational techniques are under development to enhance the safety of the aircraft during low-level windshear operations when speed is low(2).

To increase knowledge in the field of windshear, The National Aerospace Laboratory NLR in The Netherlands introduced a national windshear program in 1989. This program, abbreviated with the acronym WINDSTREAM (WINDShear Technology REsearch Advances Masterplan), tries to harmonize windshear activities amongst the Netherlands Agency for Aerospace Programmes (NIVR), the Netherlands Department of Civil Aviation (RLD), The Royal Netherlands Meteorological Institute (KNMI), and NLR(3),(4).

As a first step in the execution of this masterplan several windshear models where developed(5). Secondly functional windshear detection system models were defined and implemented in the moving base Research Flight Simulator (RFS) environment(6),(7),(8).

The goal of the implementation of these models was to be able to conduct a piloted experiment in order to test the models developed and to investigate the various operational and human factors aspects involved in the introduction of new, modern windshear detection systems on civil aircraft(9).

This paper shortly addresses the models used, the experimental design and set up, the way the investigations have been executed and the first initial results.

The Research Flight Simulator (RFS)

The evaluations were carried out on the moving-base Research Flight Simulator (RFS) of NLR. This simulator consists of a side-by-side cockpit mounted on a four-degrees-of-freedom motion system. The full-glass cockpit has a total of six cathode ray tubes (CRTs) and two central display units (CDUs) comparable with a level of sophistication of the Boeing 747-400 cockpit. Outside view is generated by a model-board television system with images collimated at infinity.

Models used

Aircraft model

A fully non-linear model of a four engined, heavy weight transport aircraft was simulated. The model includes delay in engine spool-up time responses, and effect of flap and gear setting on aerodynamic performance. The aircraft equations of motions are updated at 20 Hz. Aircraft parameters used in the experiment were based on the Maximum Landing Weight (MLW) configuration.

Windshear models

The windshear models that have been developed and were used during the experiments were a downburst (or microburst) model, a low-level jet model and another "neutral" shear model. Of each windshear model three versions were used, in order to prevent the crew from recognizing the windshear. All windshear models produce stationary (Earth-fixed) wind fields.

Low-level-jet. The low-level jet model has been based on the description given by Swolinksy(10).

Downburst model. The downburst model used is that of Schultz(11), in which several vortices can be added together. One version applied is the wellknown Fort Worth-Dallas case(12), another one is a downburst detected at Schiphol airport in February 1988. The 3 measured wind components of this downburst are given in Fig.1, together with the model-estimated wind components. The two vortex rings, which were identified to describe the phenomenon, are situated as shown in Fig.2. The strongest vortex ring, at 860 m height, had a vorticity of 48,800 m^2/s, the other one of 11,000 m^2/s. The Fort-Worth Dallas vortex-ring strength, for comparison, had a strength of 40,000 m^2/s. The pilot reported there was a "small CB-cloud (cumulonimbus) over the threshold of the runway". It looks as though the CB acted as a vortex generator, since the first vortex ring seemed to have been carried along with the prevailing wind. For the simulation trials the whole

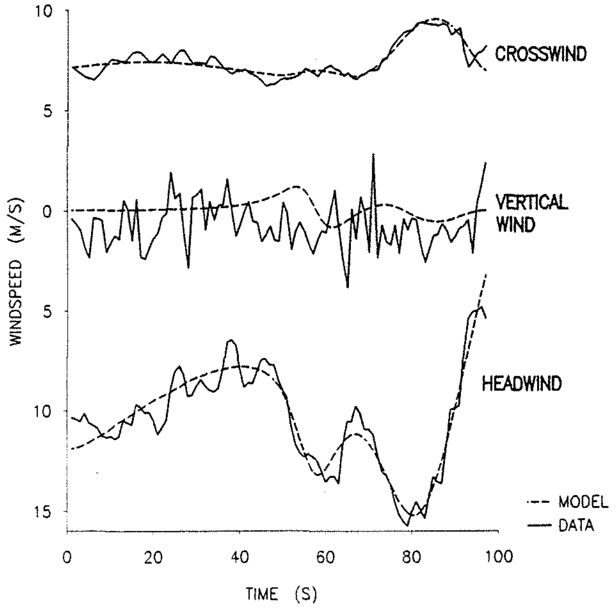

Fig.1 Wind components of downburst at Schiphol, February 1988

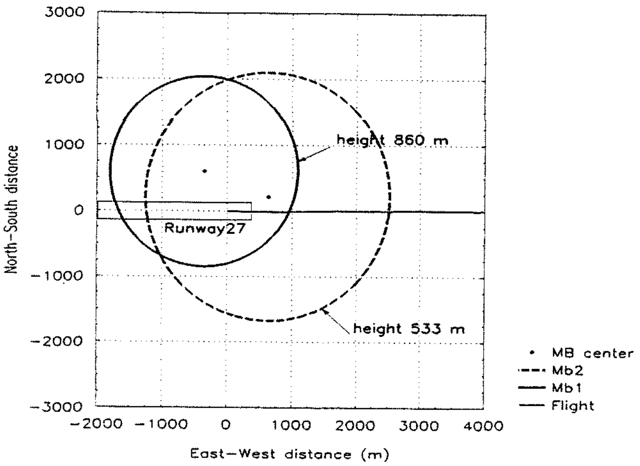

Fig.2 Situational sketch of microburst with 2 vortex-rings at Schiphol airport

vortex system was moved about 1 km towards the outer marker. Above a certain reference height the three dimensional windshear model-generated data is integrated with pre-stored tabled wind data. This table data only contains horizontal wind profiles as a function of height. To account for the atmospheric boundary layer effect, the windshear models are mixed with a boundary layer model. Due to real-time restrictions in the calculation process of the forward-looking windshear detection system, a three dimensional spatial grid in the area of the runway was developed on which the wind data generated by the above models were stored. In order to prevent the grid spacing algorithm from filtering wind variations due to windshear, a non-equidistant grid spacing (in three axes) was used, with the smallest grid size where the wind variation was greatest.

Turbulence model

To investigate the effect of turbulence on overall crew and system performance, the NLR Non-Gaussian turbulence model(13) was used and enhanced. The model features intermittency, patchiness, influences of altitude and windspeed on scale length and intensity, and "above/below clouds" effects. It is expected that an interaction exists between windshear and windshear-related turbulence. To account for this anisotropical effect, the suggestion by Woodfield and Woods(14) was followed to add a fraction of the absolute value of the vertical wind component into the various turbulence intensities.

Windshear detection system models

Reactive system

The reactive windshear detection system model developed has been based on information from a simple Sundstrand system(15). The reactive system will be engaged automatically below 1500 ft AGL or after rotation after take-off. The reactive system alert logic is based on an F-factor calculation in the aircraft wind axes, with the F-factor defined as:

$$F = \frac{A_x * \cos(\alpha) + A_z * \sin(\alpha) - \dot{V}_{TAS}}{g} * L_1 - \frac{\dot{h}_{RA}}{V_{TAS}} * L_2 \qquad (1)$$

where L_1 and L_2 are height-dependent scale factors to reduce nuisance effects at low altitude. This is a systems equivalent of the wellknown equation for F(2):

$$F = \frac{1}{g}\frac{dW_x}{dt} + \frac{W_z}{V_{TAS}} \qquad (2)$$

The instantaneous F-factor of Eq.(1) is used to calculate the averaged F-factor F_{av} (averaged in time), which is defined in the Technical Standard Order (TSO-117)(16) as:

$$F_{av}(t) = \frac{1}{T_x} \int_{t-T_x}^{t} F(\tau)\, d\tau \qquad (3)$$

with T_x being the filter time window. If the calculated averaged F-factor exceeds some prespecified limits a "CAUTION" or a "WARNING" alert will be generated in the cockpit and will remain present for at least three seconds. A "CAUTION" will be given in case of a performance *increasing* situation. A "WARNING" alert is given when the aircraft encounters a severe performance *loss*.

Forward-looking windshear detector

As forward-looking sensor a functional model of a CO_2 lidar was developed(6). The laser beam can be stabilized in three ways, viz. a) fixed in the airframe, b) pitch-stabilized, and c) flight path angle-stabilized. The mode of laser beam stabilization is an experimental variable. At the time of this experiment no scanning mode was provided, i.e. the beam is aligned within the longitudinal plane. To calculate the windshear hazard from the laser the laser F-factor derived by Bowles(2) was used:

$$F_{laser} = -\frac{V}{g}\frac{d}{dx}(V_{Doppler}) + \frac{W_z}{V_{TAS}} \qquad (4)$$

In its mechanisation the vertical wind component was deleted and not estimated by other means. The Doppler speed $V_{Doppler}$ includes horizontal as well as vertical wind components, and was calculated from the vector inner product

$$V_{Doppler} = \vec{e}_{laser}\cdot(\vec{V}-\vec{W}) \qquad (5)$$

where $\vec{V}$ is the inertial speed vector, and where $\vec{W}$ is the windspeed vector.

The F-factor for the laser also is averaged in a manner similar to F_{av}, by taking an equivalent spatial integration along the laser beam, as follows:

$$F_{laser_{av}}(r) = \frac{1}{R_x}\int_{r-R_x}^{r} F_{laser}(x)\,dx \qquad (6)$$

The distance variable r runs from a minimum range value R_{min}, determined by system parameters, to a maximum range R_{max}, where the maximum range is limited by precipitation and/or the presence of the ground.

The distance R_x and filter time T_x are related by:

$$R_x = V.T_x \qquad (7)$$

Three levels of filter time T_x, or distance R_x, were used in the experiments.

TDWR system

For the ground-based detection system a functional model of the Terminal Doppler Weather Radar (TDWR) was developed(7). The radar operates in the monitor mode but, when a hazard is detected, changes its scanning pattern to operate in the Hazard mode. The difference in scanning pattern between these two modes is described by Haverdings(7). Because of the functional principle of the radar, viz. it needs precipitation to detect weather, only in cases where there is precipitation will the radar possibly give a windshear warning. The functional model includes the radar signal-to-noise equation to detect whether the return signal is strong enough to produce a valid Doppler signal. Because of real-time problems with the simulator software this functional model could not be implemented in time, and hence the effect of this sensor on the warning was modeled. The TDWR was supposed to provide a windshear warning in case of a wet downburst only, but the time when the warning occurred was varied randomly. This variation is an experimental variable, discussed later.

Ground Proximity Warning System (GPWS) model

A reactive windshear detection system model will in general be incorporated within a ground proximity warning system (GPWS). To enhance operational realism a GPWS model has been defined, based on general information of SUNDSTRAND's Mark VII GPWS(15) including six modes out of the existing seven modes. The seventh mode, a windshear detection, annunciation and alerting mode, was replaced by an in-house-defined mode which regulates the priority between the six modes of the GPWS, the reactive windshear system alerting and the forward-looking windshear detection system alerting possibilities.

Windshear alerting and other aural alerts

Both visual and aural alerts were generated in accordance with the requirements of the FAA(16),(17), and were provided to the crew. Visual windshear alerts depended upon the type of windshear sensor detecting the windshear, and consisted of either a label "WINDSHEAR" presented on the lower part of a Primary Flight Display (PFD), or a label "WINDSHEAR AHEAD" on the upper part of the EFIS-PFD, or both labels simultaneously.

The labels were generated both for "caution" or "warning" alerts. Cautions were presented in amber colour, while warnings were presented in red colour, both for the airborne reactive and forward-looking windshear detection system.

A master caution/warning button/light in front of the pilot flying, located near the top of the instrument panel, was illuminated if an airborne windshear alert occurred. The light could be reset by pressing the button.

Aural windshear alerts were given by a computerized voice through the cockpit speakers calling out the words "WINDSHEAR" in case of an alert from the reactive system, or the words "WINDSHEAR AHEAD" in case of a forward-looking system alert. It was given in three subsequent cycles for warnings, but in only one cycle in case of a caution. If windshear alerts were generated by the simulated TDWR system a data-link message was presented on the lower EICAS panel. Three different formats (A, B, C) were used.

In format A only the warning message

"TDWR alert"

was displayed. With format B besides format A also an indication was given of the position of the downburst, in the form:

"TDWR alert"
"Position ..nm from threshold".

In format C in addition the max. windspeed change measured was displayed, e.g.:

"TDWR alert"
"Position ..nm from threshold"
"Max wind change ..kts"

The attention of the pilot was triggered by a simultaneous warning sound.

Other aural cues to the crew consist of engine sounds, protection warnings (like stick shaker), outer and middle marker beacon sounds, and callouts belonging to the six modes of operation of the GPWS.

An aural priority schedule was defined and implemented which gave overall priority to the windshear alerts. Due to the different types of windshear sensors involved, the alert of the sensor which came in first was executed first, while suppressing a possible second windshear alert from a different windshear sensor, until the first call-out was finished.

Procedures

Approach procedure

In this investigation only approaches were studied, although the take-off situation warrants attention. Take-offs may be studied at a later date. Each approach was initiated at a distance of 13 nm (24 km) from the runway threshold, 2 nm (3704 m) left of the extended centre line of the runway with heading 061 degrees at an altitude of 2000 ft (610 m). The aircraft was stabilized and trimmed in a horizontal flight condition at a heading of 090 degrees with an indicated airspeed of 205 kts, flaps set at 10 degrees and landing gear retracted. The pilots were instructed to perform Cat.I approaches (with a Decision Height of 200 ft) and to execute a normal landing approach, according to normal operational practice, thereby applying the Manual Crew Coordination Procedures (MCCP). During the approach the pilot had to adhere to the following procedure:

After intercepting the localizer, set the flaps at 20 degrees and reduce the speed to 172 kts. At 1 dot below glide slope lower the landing gear, select flaps at 25 degrees, and further reduce airspeed to 162 kts. After glide-slope intercept select full flaps (30 degrees) and reduce speed to Final Approach Speed (FAS) of 156 kts (Vref + 5 kts).

The pilot not flying (PNF) performed the ATC communication and assisted the pilot flying (PF) in his flying task, according to the MCCP the crew was briefed about. The crew had to fly the approaches manually, but use of the autothrottles was allowed. Furthermore the crew was assisted in ILS-tracking by a flight-director (FD). This FD, however, was not designed to give windshear guidance commands. Due to the latter the FD had to be disregarded if a Go-Around was initiated in case of a windshear situation.

Go-around procedures

The crew was given two options as to the type of go-around to perform, viz. the standard, normal go-around (normally involving configuration changes), or the Windshear Training Aid (WTA) go-around (no change of configuration). This latter type had to be adhered to whenever there was a reactive system windshear alert, or when the crew felt they were actually in a windshear. In other cases they were left free to choose which procedure they would follow.

Experimental design

Objectives

The specific objectives of the manned flight simulator experiment were:

1) To evaluate the windshear models, the windshear detection system models and the windshear warning logic(s),

2) to evaluate the practical implications of various windshear hazard factor definitions,

3) to establish the impact of simulated random atmospheric data, such as precipitation and turbulence, on the functional behaviour of the new windshear detection systems and their effect on operational procedures,

4) to obtain the subjective crew's acceptance and performance data during simulated flight flown in windshear conditions,

5) to evaluate the crew's ability to cope with possible conflicting aural and visual alert information coming from different windshear detection and warning systems,

6) to evaluate several experimental flight procedures, in comparison with the current Windshear Training Aid(18),(19) (WTA) procedures, when modern windshear detection sensors are being applied,

7) to evaluate the applicability of the proposed Technical Standard Order (TSO-C117(7)), which describes minimum performance standards for airborne windshear warning and escape guidance systems.

Experimental factors

In view of the objectives a number of experimental variables were defined in the manned simulation of windshear encounters, or which are considered to be important. These are:

a) flight procedures. Three flight procedures were tested. They consisted of applying some speed increment and to initiate a go-around, in case of one or more warnings, depending upon altitude, see Table 1. Each crew was given two out of three procedures to follow.
The following flight procedures were tested:

1) safety first: a go-around (GA) will be made at any time there is a RED alert (i.e. a WARNING).

2) cautious penetration: When there is a RED alert from any sensor the flight speed will be increased to $V_{ref}+15$ kts during the approach above 500 ft, or to $V_{ref}+20$ kts when below 500 ft, and the approach continued. If a second RED alert (from any other warning system) is generated above 500 ft, then the speed is increased further to $V_{ref}+20$ kts. If below 500 ft a second RED alert is generated then a go-around will be made.

Table 1. Speed increments and flight procedures

type of warning	speed increment above 500'	speed increment below 500'	flight proc.
single	GA	GA	safety first
	15	20	cautious
	15	20	daring
double/ multiple	GA	GA	safety first
	20	GA	cautious
	20	20	daring

3) daring penetration: the flight speed will be increased to $V_{ref}+15$ kts when there is any RED alert. If a second RED alert (from any other warning system) is generated then the speed is increased further to $V_{ref}+20$ kts. This procedure tends to drive the crew towards continuing the approach at a fairly high speed, rather than abort and make a go-around. Although in reality such a procedure will likely not be implemented, it is valuable to test such an extreme procedure in order to be able to compare the full scale of possibilities;

b) type of windshear detection sensors (reactive system, forward-looking laser, TDWR, or the combination of airborne with ground-based sensor);

c) the turbulence level. Turbulence was varied from none to light to moderate. Turbulence will effect the timeliness of the alerts coming from the airborne reactive system, since the system may be sensitive to turbulence and provide nuisance alerts;

d) critical F-factor level F_{crit}. When F_{av} exceeds this value an alert will be given. Three levels were used in the experiment, viz. 0.08, 0.10 and 0.15.

e) allowed speed change ΔV for the critical F-factor. This parameter is hidden within the algorithm for calculating F_{av}. The larger ΔV, the later the warning, since a larger speed change must have occurred before a warning will be given. Three levels were used in the experiment, viz. $\Delta V=10$, 20 and 25 kts.

f) type of laser beam stabilization. Three types were provided for, viz. fixed in the airframe, pitch-stabilized and flight-path angle stabilized;

g) precipitation. This will strongly effect the maximum effective range of the laser. The heavier the precipitation, the shorter the look range of the laser becomes. It may drop from about 8 km to as low as 1500 m when in heavy precipitation (~50 mm/h). Three levels of precipitation were used, viz. none, light-to-moderate (20 mm/h), and heavy (50 mm/h);

h) type of windshear. Three types of windshear were provided, as explained earlier;

i) TDWR probability of detection POD. Three "levels" were foreseen, viz. 'early', 'timely' and 'late'. These values, or labels, are associated with an altitude range, based on range from touchdown, where the TDWR alert occurs with a uniform probability of occurrence within the altitude interval, see Table 2.

j) the TDWR data uplink format. Three formats were defined, viz. A (only an alert), B (A plus location of downburst) and C (B plus max. wind change in downburst).

Table 2. TDWR probability of detection (POD)

TDWR POD	height range (ft)	distance from touchdown (nm)
'early'	1000 - 2000	3.1 - 6.3
'timely'	500 - 1000	1.6 - 3.1
'late'	0 - 500	0 - 1.6

Conduct of the experiment

In order to achieve the goals outlined before the total experiment was subdivided per crew into two sets of 5 trials each, executed successively within each set. The two sets were distributed over two days. The objectives and important experimental factors of these 5 trials are given in Table 3.

Table 3. Objectives and experimental parameters for the 5 trials

No.	Trial main objective	main experimental factors
1	basic configuration testing	windshears, turbulence
2	reactive system testing	system parameters (ΔV, Fcrit), flight procedures
3	laser system testing	system parameters (beam stabilization, ΔV, Fcrit), flight procedures
4	TDWR system testing	probability of detection, data uplink format, flight procedures
5	sensor mix	interactions, flight procedures

The mix of sensors consists of both a ground-based sensor (TDWR) and one or more airborne sensors (reactive and/or laser sensor).

Test matrix

For each trial described before an experimental test matrix was designed using the Taguchi design with orthogonal arrays. A more elaborate description of the Taguchi method is given by Phadke(20) and Barker(21). The advantage of the Taguchi method is that with a relatively large number of parameters a relatively small number of runs, or test cases, can be sufficient to determine main effects. In view of the number of factors to be tested and their levels, each trial test matrix was a fractional factorial (Taguchi) nested design, where flight procedures were nested within crews (i.e. each of the three crews only flew 2 out of three flight procedures).

Pilot questionnaire

After each run the crew had to fill out a questionnaire. Main questions concerned the timeliness and nuisance character of the windshear warning (if there was one), the situational awareness (where and which type of windshear was detected, how much was the improvement in awareness when having a windshear detection sensor), the severity of the shear, and acceptance ratings of the flight procedures.

Pilot workload and effort

The pilot flying had to answer questions related to piloting effort to maintain speed, track the ILS, etc., and also had to rate his (mental) workload using a subjective (ordinal) (mental) effort rating scale (MERS). This scale had been designed in cooperation between the University of Delft and the State University of Groningen, the Netherlands(22). To the knowledge of the authors this was the first time this mental effort scale has been applied to a national piloted experiment.

The pilot effort ratings, which were given on (5) non-adjectival free scales, with a scale value from 1 to 10, were normalized to Z-scores (per pilot) by subtracting the mean and dividing by the standard deviation. Afterwards they were transformed into EFFORT-scores by applying factor analysis to the Z-scores. The factor analysis showed there was only one dimension within these Z-scores, with almost equal loadings on all effort scales.

Preliminary results

A total of 240 approaches were flown, an average 1/3 through downbursts, but no crashes occurred. The results given in this paper are still preliminary and qualitative in nature, pending a full analysis. The results from the pilot questionnaires have been analyzed so far, but these will be indicative of the main results to be achieved. Therefore no statistics as to aircraft safety margins, angle-of-attack (stall) margins, etc. can yet be given in this paper. These will be reported in the near future.

Pilot subjective performance

The answers from the questionnaire were mainly ordinal data, or rank data. This type of data was analyzed using the non-parametric Kruskal-Wallis analysis of variance (ANOVA) on ranks(23), or, in several cases, using the Median test. For interval scale data the "standard" analysis of variance (ANOVA) was applied.

In the results given the "best" combination of answers from either the PF or the PNF is taken. If the answers from the PNF were statistically more significant than those of the PF then this is indicated in the figures by the notion (PNF). Although in most cases the results should be given in the form of histograms, in the associated figures it is assumed that the underlying

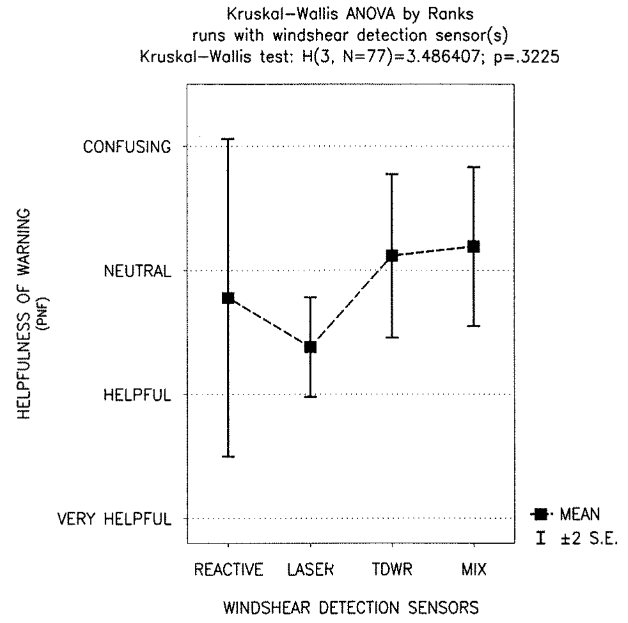

Fig.3 Effect of windshear detection sensors on helpfulness of windshear warning

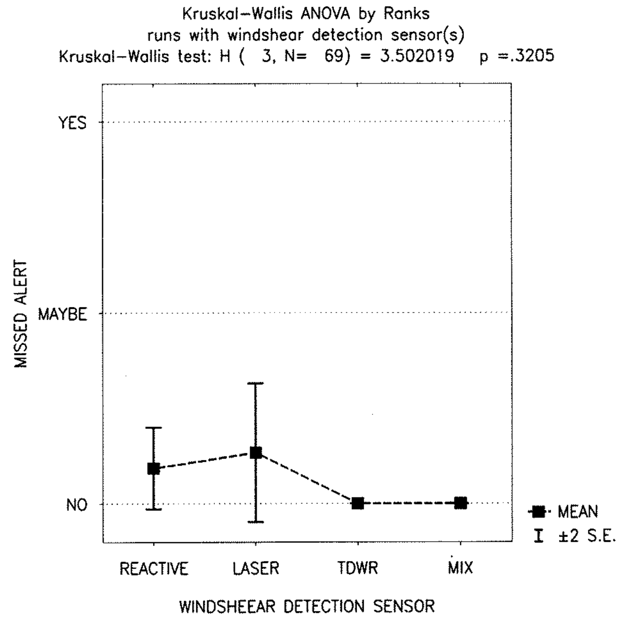

Fig.4 Effect of windshear detection sensors on missed alerts

dimension is a continuum, and hence means and standard errors are given instead. These are calculated, based on the assumption that the scales are linear.

General results

General questions answered are related to the helpfulness of the windshear warnings, nuisance alerts, missed alerts, safety of operation, situational awareness, acceptance of flight procedures and the effect of windshear detection sensor system parameters.

helpfulness of windshear warnings. The crew rated the helpfulness of the windshear warnings from 'very helpful' to 'nuisance'. The influence of windshear detection sensors is given in Fig.3. It seems that the laser sensor scores a little better than the other sensor types in terms of usefulness of the warning it generated. Especially the reactive system has a large "spread", indicating a large variability in usefulness of the warning from this type of system (sometimes even confusing).
Also it appeared that the usefulness of the warning in general was higher in case of a downburst than for the other types of windshear. Windshear warnings for the low-level-jet, or even the neutral shear, were considered more confusing or even a nuisance.

missed alerts. A missed alert is defined as an alert that, according to the crew, should have been given when it wasn't. This occurred more often with the reactive and the laser system than with the TDWR or mix of sensors, see Fig.4. Occasionally the crew thought the laser or the reactive system may have missed giving an alert, although the effect is not statistically significant.

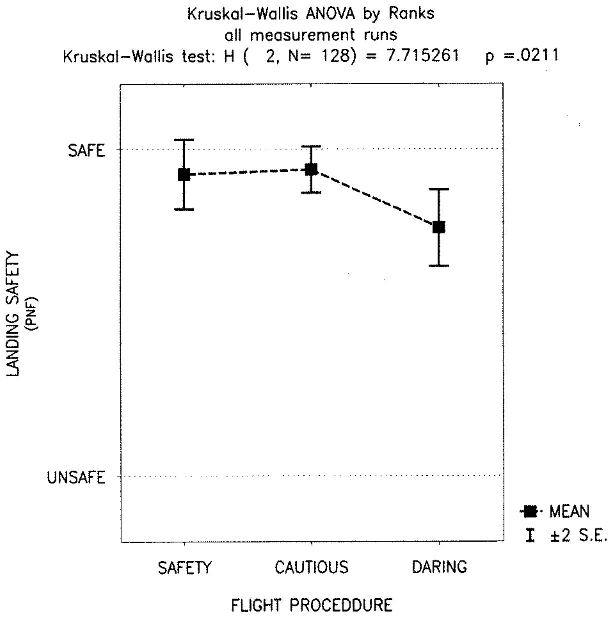

Fig.5 Effect of flight procedure on landing safety

safety of operation. Although the safety of operation under windshear conditions can only be analyzed after all the data have been processed, one of the questions was whether pilots thought the landing made was unsafe or not. Also they had to give a rating as to the windshear hazard perceived during the flight. This rating was given on a 10-point scale (from 0-10), with adjectives 'not at all hazardous' (0) and 'catastrophic' (10). In Fig.5 the effect of the flight procedure on landing safety is shown. Obviously, with the more "risky" flight procedures the landings made are judged unsafer, especially with the daring penetration flight procedure.

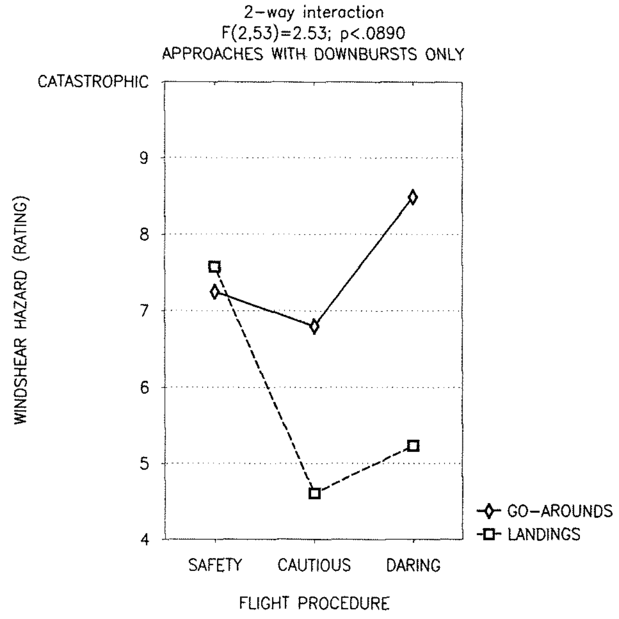

Fig.6 Effect of interaction between flight procedures and go-arounds on perceived windshear threat

In Fig.6 the interaction is shown between flight procedure and whether or not a go-around was made, for downbursts only. The perceived threat of the (same) windshear was rated significantly higher for go-arounds than when landings were made. Whether this is only a psychological effect can only be substantiated with aircraft performance data. This effect is strongest with the daring penetration flight procedure, i.e. that procedure where more landings than go-arounds are made through windshear. This result indicates that it was perceived to be safer to continue the approach than to go around. A probable contribution to this can be that due to the boundary layer the lower part of the downburst is "softened" and hence less dangerous to cope with than during a go-around, where the aircraft will traverse the higher part of the downburst, where large vertical wind components affect the flight path dramatically, especially because this component cannot clearly be observed by the crew.

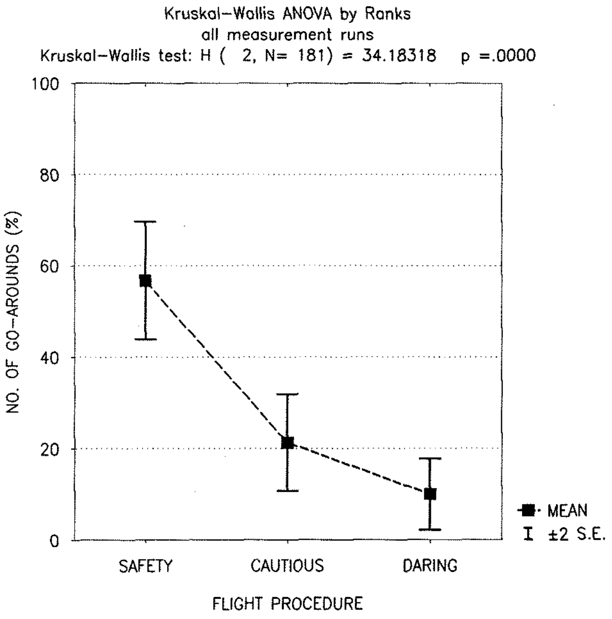

Fig.7 Effect of flight procedure on number of go-arounds

Go-Arounds. The presence of a windshear detector, coupled with a flight procedure to handle the alert, will in general result in more go-arounds, which is the price to pay for increased safety. In Fig.7 the effect of the flight procedure on the number of go-arounds is shown. The number of go-arounds dropped from about 60 percent for the "standard" safety-first procedure to as low as 10 percent for the riskiest flight procedure. Obviously the greatest number of go-arounds were made

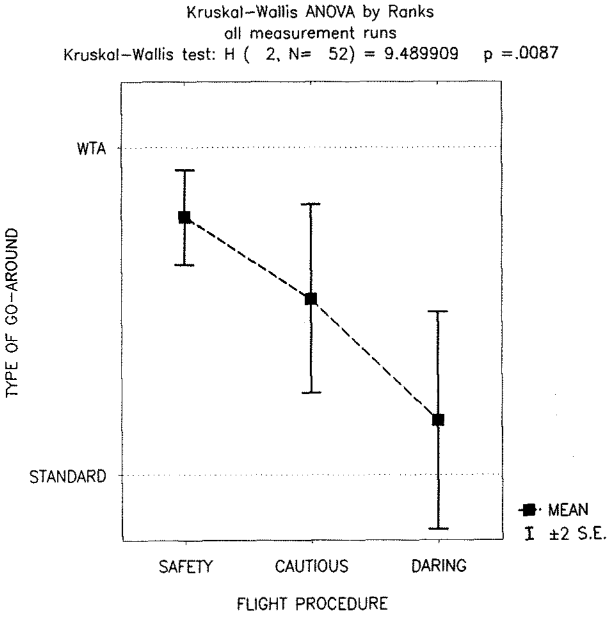

Fig.8 Effect of flight procedure on type of go-around

with the downburst, but even with the neutral windshears some go-arounds were made.

Pilots were instructed to carry out the WTA go-around in case of a warning from the reactive system, or when actually in a windshear. If they felt otherwise compelled to execute a go-around, they were allowed to either execute a standard go-around, or the WTA. It turned out, however, that with the more risky flight procedures they made the standard go-around, while with the safety-first flight procedure the WTA-type of go-around was flown more often. This effect, shown in Fig.8, is unexpected and remarkable.

Also the type of windshear sensor was found to have a significant effect on the type of go-around made, see Fig.9. Between no sensor at all, or the reactive system, there is no difference. With the more advanced sensors (i.e. the laser, TDWR or mix of sensors) the WTA-type of go-around is used more and more. Because of the greater spread for the reactive system apparently that system gave rise to more confusing go-around situations than did the other sensors.

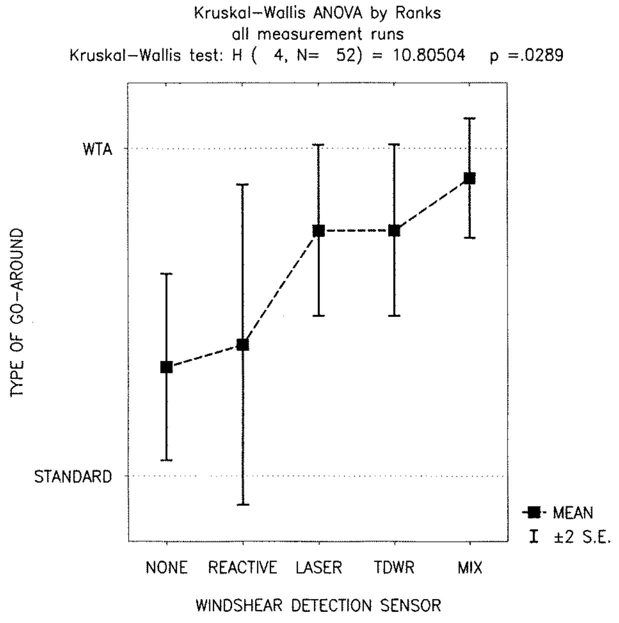

Fig.9 Effect of windshear sensors on type of go-around made

Finally also the type of windshear had an effect on the type of go-around flown, although again an effect not expected. Figure 10 shows that for the downburst the standard type of go-around was flown, rather than the WTA, whereas with the more benign low-level-jets and neutral shears the WTA was flown.

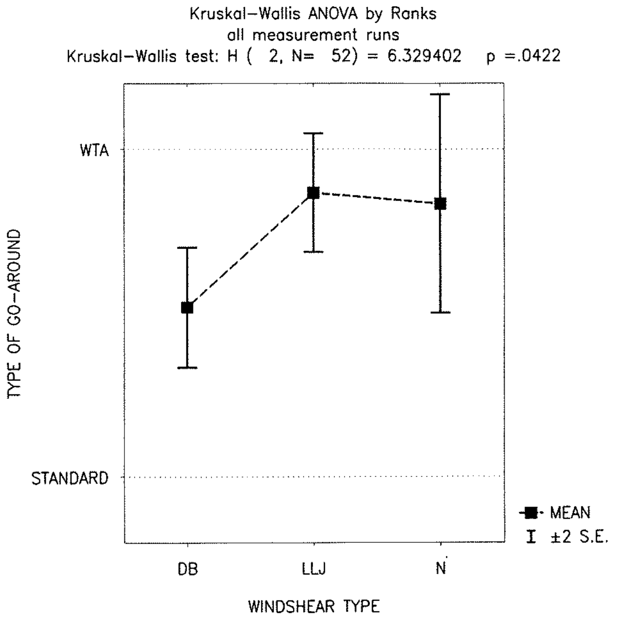

Fig.10 Effect of windshear type on type of go-around flown

situational awareness. Although situational awareness is quite a complicated matter, one of the questions asked related to the type of windshear detected by the crew. It turned out they consistently underestimated the type of windshear, see Fig.11. When having flown through a downburst they thought they had flown through a low-level-jet, etc. There is a small difference between

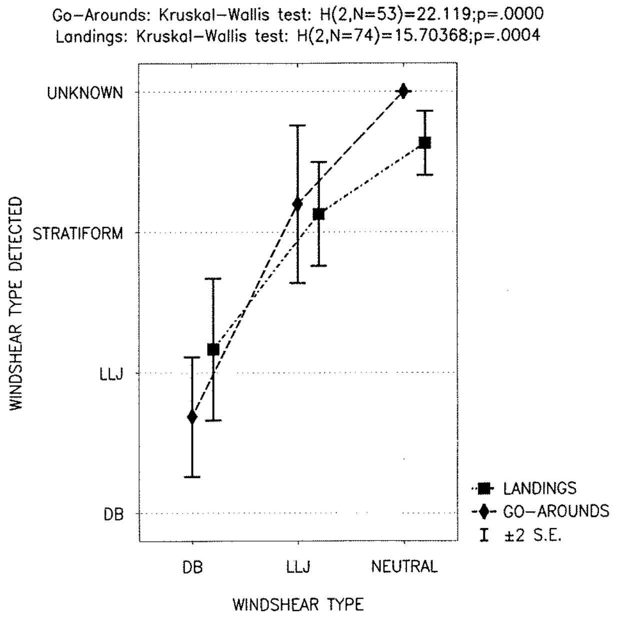

Fig.11 Effect of windshear type on type of windshear detected

whether or not a go-around was made, in the sense that during a go-around in a downburst they estimated the windshear a little better. One reason for this effect is again the boundary layer effect when flying low through a downburst, or the crew's inability to see the downdraft wind component when at the lower altitudes.

Acceptance of flight procedures. Whether the crews' accepted the flight procedure or not depended upon a number of factors. Acceptance was rated on a 10-point scale, with the adjectives "*un*acceptable" (0) and "acceptable" (10). Overall the safety-first procedure was accepted better, F(2,107)=2.29; p<.1061, than the other two flight procedures. There are, however, interactions with the type of windshear detection sensor, see Fig.12, such that e.g. the sensor mix, which has the highest acceptance with the safety-first and cautious procedure, has the lowest acceptance with the daring procedure. All this shows the importance of tuning the flight procedure with the windshear detection sensor combination to be used.

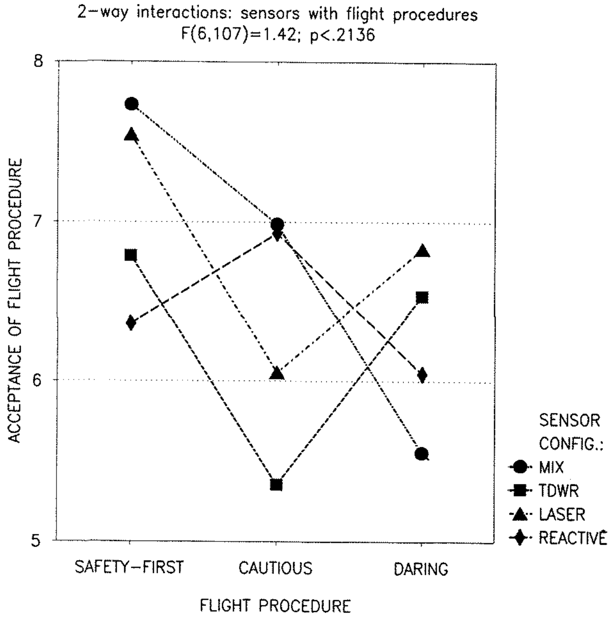

Fig.12 Effect of flight procedure and sensor type on acceptance of flight procedure

Workload/pilot effort. There is obviously an effect of windshear, flight procedure, etc. on pilot workload and/or pilot effort. For pilot workload the individual MERS-ratings described earlier were used. For pilot effort the EFFORT-scores were used, which normally vary between about +2 and -2. The effect of the windshear detection sensor is shown in Fig.13. There is a statistically significant effect of these sensor types on piloting *effort*, not on workload. The greatest piloting effort is required with the reactive system, and the least with the mix of detection sensors. In terms of workload the TDWR required the lowest workload instead. In rating 'workload' the complexity of interpreting multiple sensor alerts may have biased workload (mentally),

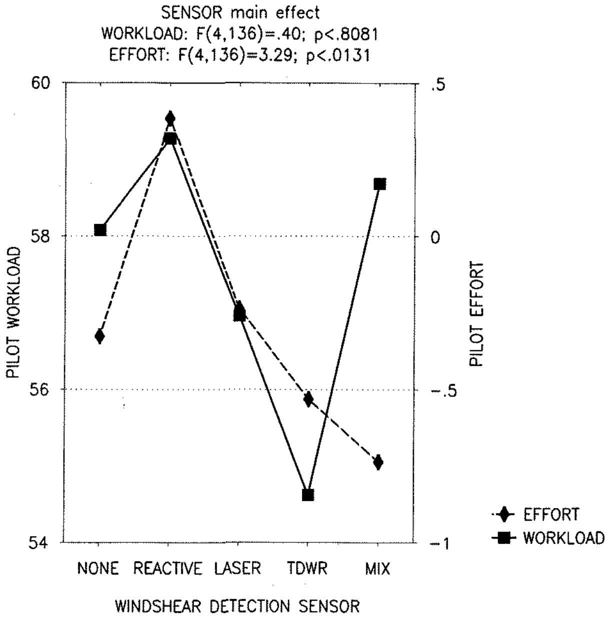

Fig.13 Effect of windshear detection sensor on workload and/or piloting effort

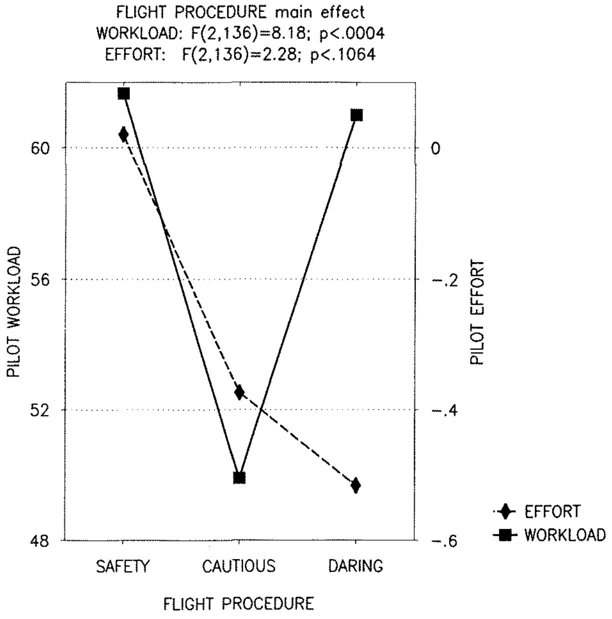

Fig.14 Effect of flight procedure on pilot workload or effort

whereas 'effort' only related to the control task (i.e. effort to *control* speed, glideslope, etc.). Hence the lowest workload was achieved for the TDWR, since the PNF primarily read the EICAS-displayed TDWR alert, while the PF performed his "normal" flying task as if he had no sensor. This effect may explain the dissociation between workload and effort for the sensors mix.
Furthermore there is a significant effect of flight procedure on pilot workload or effort, see Fig.14.
The cautious flight procedure required the lowest workload, or almost the lowest effort. Likely reasons are that no "nuisance" go-arounds were made or that no forced landings were made. Apparently the safety-first flight procedure was felt to be "too safe", whereas the daring penetration flight procedure was felt to be "too daring".

Windshear detection sensor parameters. A number of parameters were varied with the different detection systems. For the *reactive system* there was a weakly significant effect of the critical F-value F_{crit} on the helpfulness of the windshear warning, and a weak effect of the speed change ΔV on the missed alert rate, see Fig.15. The larger this value the greater the wind change must be before a warning can be given. Apparently a value of 25 kts is too high a threshold for the system to respond timely to windshear.

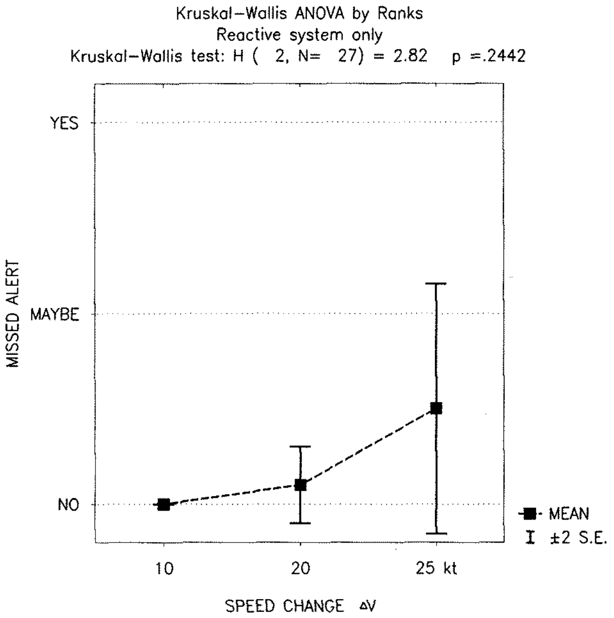

Fig.15 Effect of speed change ΔV on missed alerts

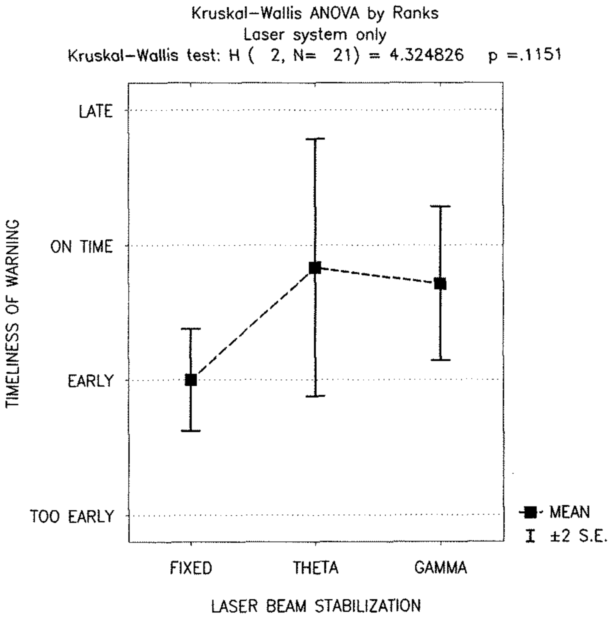

Fig.16 Effect of laser beam stabilization mode on timeliness of warning

For the *laser sensor* there is a (weakly) significant effect of the laser beam stabilization mode on the timeliness of the windshear warning, see Fig.16. With the beam fixed in the aircraft's frame there is an increased number of warnings which come too early. The best mode, in terms of timeliness and consistency of the windshear warning, seems to be the gamma-mode, where the laser beam is stabilized with the flight path angle.

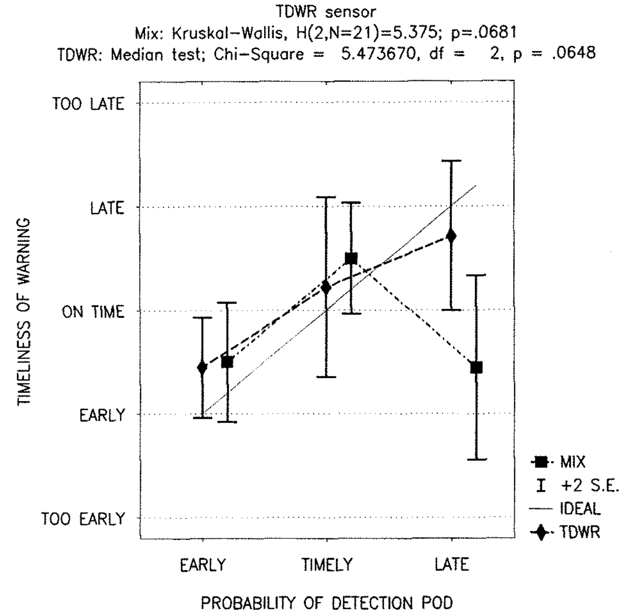

Fig.17 Effect of detection probability on timeliness of warning

For the *TDWR* there is obviously an effect of probability of detection on the timeliness of the warning, see Fig.17. In case of only having the TDWR there is almost an ideal relationship between POD and the perceived timeliness of the windshear warning. When adding more sensors, i.e. the condition 'mix' in Fig.17, then this relationship does not change, except for the condition where POD='late'. In other words, adding more windshear (airborne) sensors does not improve the perceived timeliness of the windshear warning, except when the TDWR detects the windshears late, i.e. when the aircraft is at or below 500' altitude. The effect of data uplink display format, although not statistically significant ($p<.2045$), is shown in Fig.18. Display format A (warnings only) is the least helpful one, sometimes confusing, and varied much in its rating. Display formats B and C did not differ in their average rating on helpfulness. Both rated between 'neutral' and 'helpful', but there was less variability (i.e. more consistency) in the helpfulness of display C (i.e. warning plus range of threat plus max. wind change are given).

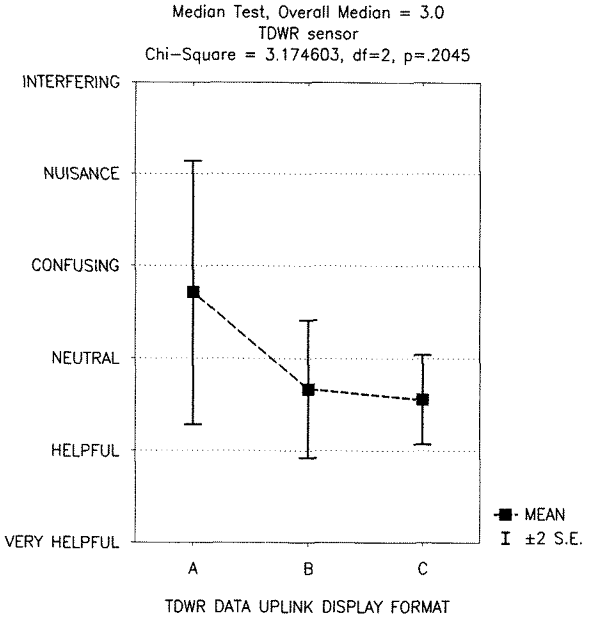

Fig.18 Helpfulness of data uplink formats

The overall variation of timeliness of the windshear warning per windshear sensor is given in Fig.19. It clearly shows the significant effect ($p<.0463$) of the laser having the best timeliness, as expected, whereas the reactive system has the worst timeliness.

Conclusions and recommendations

From the preliminary results obtained, one may conclude that pilots felt the windshear threat to be less when

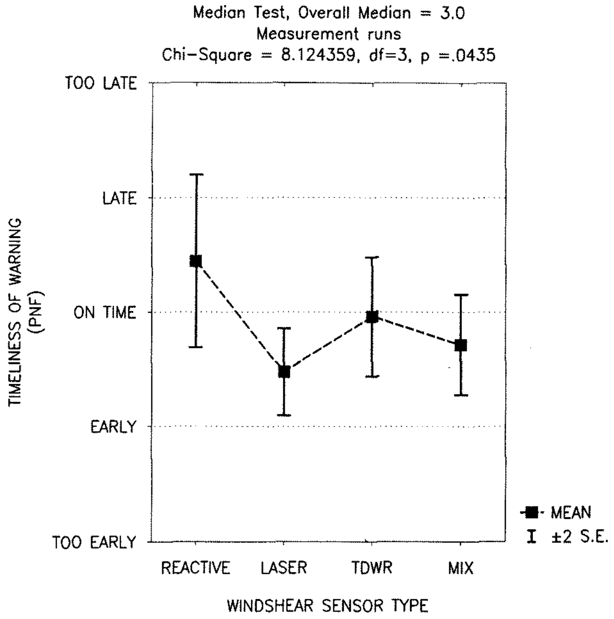

Fig.19 Variation of timeliness over windshear detection sensor(s)

continuing to land than when making a go-around. Although pilots accepted the safety-first flight procedure as the best one, they experienced a lower workload with the cautious penetration flight procedure (i.e. to continue at a higher speed when getting a windshear alert above 500'). In view of the lower workload, the frequency of go-arounds and relative perceived windshear threat the cautious penetration flight procedure is a good alternative. The TDWR alone was considered to give timely alerts; only in case the TDWR alerts came late the timeliness of the warnings could be improved by adding airborne windshear sensors. The best ground-air mix of sensors seems to be the TDWR, with data uplink format B or C, with the forward-looking laser. Pilots tended to prefer the standard go-around rather than the WTA when going around in a downburst because, with the aircraft's performance reserve available, they were reluctant to maintain the aircraft's configuration. They preferred to reduce flap setting and to accelerate to a higher energy level before "hitting the storm".

For future investigations it is recommended to integrate the warning concept with the EFIS displays and flight procedure to be used in order to reduce workload. Windshear hazard displays should be added in order to improve situational awareness. The type or mix of windshear detection sensor(s) should be carefully tuned with the flight procedure adopted in order to reduce workload also. Considering the reduction in workload, no. of go-arounds, etc. it is recommended to further study the cautious penetration type of flight procedure, or variants thereof. This means that on a first alert above some altitude the airspeed is increased rather than that a go-around is made. Finally it is recommended to check for windshear modeling effects as to why go-arounds were perceived to be less safe than when continuing the approach, and to study more closely the effect of the type of go-around on overall safety of operation.

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