Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-98616 / GARTEUR-TP-118

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by

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Abstract

This paper presents some specific results of a piloted windshear investigation performed by the members of the GARTEUR Flight Mechanics Action Group FM-AG(07) at the end of 1994.
The main objectives were to investigate the effect of forward-looking windshear detection systems on flight operation, flight safety and Human-Machine Interface (HMI) aspects. As a by-product the Flight Director (FD) performance for assistance during go-around and windshear recoveries was evaluated. Two different types of FD go-around modes were compared with each other. Also having no FD-assistance at all was compared with having a fixed pitch FD-mode. Some main results will be presented.
Furthermore, two similar, but different forms of windshear icon presentations on the EFIS/NAV-display were evaluated. These icons were derived by means of a scanning laser in real time. A few main results will be given. Unexpectedly, some crashes occurred during the experiment. To learn of these, two of them will be analyzed. Some of the conclusions drawn were that, in case of a windshear recovery, having a fixed pitch FD mode assistance during the windshear recovery was found slightly better than having no FD assistance. Furthermore the windshear icon displays improved situational awareness and reduced flight safety risk significantly.

Background

Following ongoing developments in the area of windshear detection system technology being performed by a NASA/FAA/Industry Team[1], the international collaboration organization GARTEUR (=Group for Aeronautical Research and Technology in EURope) installed Flight Mechanics Action Group FM-AG(05) in 1991. In this group participated the research institutes ONERA (of France), DLR (of Germany) and NLR (of The Netherlands). A work program was defined that consisted of three objectives:

- To acquire more knowledge about the relevant atmospheric perturbations, their probability of occurrence and about modeling these effects.
- To have a better understanding of the behavior of transport aircraft in windshear conditions.
- To evaluate the benefits of forward-looking windshear detection sensors using offline and piloted simulations.

These first two objectives were met by Action Group FM-AG(05)[2,3].Numerical simulations were performed to investigate the effect of forward-looking wind-shear detection systems on flight safety.[4,5,6]
At the end of 1993 a follow-on Action Group was installed. This Action Group FM-AG(07) consisted of the same members as the preceding one and would prepare and execute a piloted windshear flight simulator investigation.

To avoid duplication of work, the GARTEUR Action Group activities where harmonized in early 1994 with an ongoing national research program (named WINDSTREAM) carried out by NLR. This program was supported (co-funded) by the NIVR (the Netherlands Agency for Aerospace Programmes) and the RLD (the Netherlands Department of Civil Aviation). As part of the WINDSTREAM project a preparatory piloted experiment was held at the end of 1993[7] and a follow-on experiment was already in the phase of preparation. The harmonization resulted in the execution of a combined piloted windshear experiment in November/December of 1994.

Introduction

The main aim of the 1994 piloted GARTEUR windshear experiment was to investigate the effect of forward-looking windshear detection systems on flight operation, flight safety and HMI aspects.
This paper reports parts of this work and has been organized such that the experiment setup will be addressed briefly first. More details can be found in the Testplan[8], and also in a paper in the public domain[9]. Although in fact not a main aim but a by-product of the overall study, flight director aspects will be addressed. Specifically, as generally little has been reported on this, two different flight director pitch steering modes used for the go-around phase of flight will be commented on. Furthermore, some final results related to the windshear icon concepts evaluated will be presented. Full results can be found in the final report of FM-AG(07)[9]. Two unexpected

fatal experimental runs (crashes) will be reported and analyzed. Finally, the conclusions, a future outlook and the references are given.

Brief description of the 1994 experiment

Crews

Six international flight crews of the GARTEUR nations involved participated in the experiment and flew 54 approaches each, of which 12 were training runs. So 252 measurement runs were obtained in total. Averaged over both crews members, their flight experience varied from "very much" (over 15000 hrs) to "little" (about 2100 hrs).Crews were instructed to apply the Manual Crew Coordination Procedure (MCCP) as listed in the Pilot Briefing guide sent out to them before the experiment.

Sub-experiments

First sub-experiment

The total experiment was split up in two sub-parts. In the first sub-part a reactive and a forward-looking windshear detection system were tested separately. Also the effect of adding a flight-director guidance during a go-around or windshear escape was evaluated:

- two different types of FD-assistance were compared with each other when flying with the onboard laser windshear detection system only.
- when flying with the reactive system, having no FD-assistance was compared with having one.

However, in this sub-experiment no special windshear icon information was presented on the EFIS/NAV-display, only EFIS/PFD windshear labels and accompanying aural alerts were presented to the crews.

A non-scanning laser was evaluated at two different fixed look ranges of 1600 and 2400m, based on the FM-AG(05) numerical simulations[4,5] and in order to be able to compare them with the piloted simulations. These distances equate to a warning lead time of 20-30 seconds based on an approach speed of 80 m/s.

Second sub-experiment

In the second part of the experiment the effect of two different types of presenting windshear icons on the EFIS/NAV-display was evaluated. All runs were flown with one (viz. the modified) type of FD-guidance during the go-around.

To be able to derive the windshear icons, a scanning laser model was used and operated in real time. The laser beam tilt was automatically aligned with the inertial flight path vector and could not be controlled by the pilot. The laser scanned in a plane at this elevation within±45 degrees either side of the vector, assuming a wings-level stabilization. The laser look range *varied* from a minimum of 300 m to a maximum of about 8 km. The maximum range could degrade when precipitation (rain) was included in the windshear cells presented.

Flight and evaluation task

The crews were asked to execute the approach and land the aircraft safely on runway 06 of Amsterdam Airport, or to perform a go-around and stabilize the aircraft at 2500 ft above ground level (AGL). Crews performed manual approaches assisted by the FD, and with the Autothrottle (AT) engaged.

After every run both pilots had to fill out a questionnaire, for instance to evaluate their satisfaction with the flight director performance during the go-around. They also had to rate the usefulness of the windshear icons presented to them, if any, and to individually rate the effort and mental workload required for the conduct of the whole flight.

Research Flight Simulator

The GARTEUR experiment was conducted on NLR's moving base Research Flight Simulator (RFS). The RFS consists of a side-by-side transport cockpit mounted on top of a four-degrees–of-freedom (4DOF) motion base. Outside view was generated via a TV modelboard and a Singer-Link Miles MkV system. The cockpit has been equipped with six CRTs and three fully programmable CDUs. Noteworthy is to mention that this RFS facility will be upgraded in the coming three years. A computer-generated vision, an advanced civil transport cockpit and a 6DOF motion base will be installed.

Some models used

Aircraft model

In the experiment use was made of a fully nonlinear model with the characteristics of the Boeing 747-200. Aircraft parameters were based on the Maximum Landing Weight of 285,500 kg. Reference speed in the standard final approach configuration (flaps 30, gear down) was 151 kts. Maximum (Gross) Thrust over Weight was about 0.27.

Windshear models

Earth-fixed ("time frozen") microburst models of the ring vortex type were used[11]. Multiple cells with multiple vortices each could occur. Furthermore the Earth's boundary layer effect was included. The wind components were calculated at each aircraft position and used in the aircraft equations of motion and by the reactive windshear detection sensor. In case the onboard forward-looking laser windshear sensor was operated, use was made of a pre-stored three-dimensional windgrid.

Turbulence model

The standard turbulence model available at NLR's RFS facility was applied[12]. It generates non-Gaussian turbulence and features intermittency, patchiness and influences of altitude and windspeed on turbulence scale lengths and intensities. In case of windshear, a special anisotropic effect was included by adding a fraction of the calculated wind from one axis into the turbulence intensity of another axis.

Windshear alerting

Both visual and aural windshear alerts were presented in the cockpit.

Visual alerts were presented on the EFIS/PFD and related to a *sensor-based* concept, i.e. showing alert labels every time a sensor detected a windshear. The top label belonged to the reactive sensor alert and the bottom label to the forward-look sensor alert. Both labels could appear at the same moment, see Fig.1. Blue, amber and red labels could appear, corresponding to increasing hazard levels.

For the aural alerts a special *threat-level based* concept was devised. To minimize the amount of voice alerts, only alerts of a higher hazard level than the one given before, would be passed on to the crew. Then the computer voice would speak out the label text of the highest windshear threat twice.

In the second sub-part of the experiment, windshear areas where also visualized on the EFIS/NAV-display by showing icons, based on information derived from the scanning-laser.

Furthermore, as an experimental variable, crews were sometimes allowed to apply a *speed increment* after a windshear alert and sometimes they were not.

Go-around flight procedure aspects

During the pilot briefing, the flight crews were thoroughly briefed about the MCCP and were instructed to apply normal operation safety standards related to the initiation and execution of a go-around. To distinguish a windshear go-around from a normal go-around, the Pilot Flying (PF) had to call "Windshear Go-around" instead of "Go-around".

Windshear flight procedure aspects

It was stated in the experimental flight procedures that in case of any windshear alert of the WARNING type, i.e. red labels on the PFD, a go-around had to be made.

Due to the fact that a forward-looking sensor is able to give lead time before entering a shear, a normal go-around instead of a windshear type of go-around was allowed to be made. However, in case of a reactive system warning alert a Windshear Training Aid (WTA)[13] type of go-around always had to be made. This was because flight crews are mostly trained to act and react according to the standards defined in the WTA and the Pilot Windshear Guide[14], in case of a windshear occurrence.

Without having advanced flight guidance systems available during a windshear escape, the flight crew will fall back from FD-assisted flight during the ILS tracking, to an unassisted flight while executing the missed approach. According to the WTA the near-optimal way of performing such a missed approach is to apply full (TOGA) thrust and to fly away with a constant pitch attitude, leaving the aircraft configuration (flaps, gear) unchanged until out of the shear, above 1000 ft AGL and not below the reference speed. The WTA-recommended pitch angle is 15 degrees, however for this experiment 12 degrees was chosen as is recommended in the Aircraft Operations Manual (AOM) of the particular aircraft type used in the experiment.

Flight Director aspects

Flight director go-around pitch steering modes

During a normal flight director (FD)-assisted approach the FD pitch bar showed a signal to minimize deviations from the ILS glide slope. The moment the crew would select TOGA thrust, either via the Flight Mode Panel or by pressing the TOGA switches on the throttle levers, the ILS tracking mode reverted to the go-around mode under evaluation. The FD roll channel was coupled to the heading (select/hold) mode and was not explicitly evaluated.

Flight director go-around aspects investigated

Two FD aspects investigated, related to a missed approach, were:

- Unassisted versus the FD-assisted go-around
- The standard versus the modified FD mode

In case the FD was not to be used (i.e. the unassisted go-around) the pitch and roll command bars were

stowed out of sight whenever the TOGA switch was pressed. These situations will be referred to as NO-FD to distinguish them from the FD assisted go-around.
For the latter, two different types of go-around pitch steering modes were evaluated:
- The standard mode (STD)
- The modified fixed pitch mode (MOD)
These modes will be described in more detail next.

Standard FD mode

The standard (STD) flight director pitch steering logic for the go-around represented a conventional go-around mode without any kind of windshear guidance or advanced stall protection, see Fig.2. The logic was such that after mode activation it would calculate two pitch error signals:
-The first error signal (Delta_1) prevented the actual climb rate from becoming lower than a minimum desired (reference) climb rate of 500 feet/min.
-The second error signal (Delta_2) tried to reduce the error between the momentary calibrated airspeed (V_c) and the regulated speed (V_reg). The value of this regulated speed used by the logic, depended on the AT-selected speed (V_sel) and was limited by the maximum and minimum speed belonging to the flap setting chosen by the crew.
Both pitch error signals were compared to one another and the one with the highest absolute value was passed on to the pitch steering needle. Note that in this way the regulation of one parameter (i.e. either speed or climb speed) implicitly took into account the regulation of the other parameter.

The logic of the STD-FD mode tried to prevent the aircraft's speed from deviating more than 15 kts from the regulated speed. However, it did not provide signals to prevent the pilot from stalling the aircraft.

Modified, fixed pitch FD mode

The fixed pitch, or MODified mode, see Fig.3, tried to overcome this latter problem and when activated, would indicate a constant pitch attitude (θ_ga) to the pilot while performing the missed approach. Furthermore, a protection angle of attack logic was available. It was always engaged, but not necessarily active. The value of the go-around pitch angle used would depend on the flap setting operated. With a final approach configuration (30 deg. flaps, gear down), the angle to be flown was 12 degrees, in accordance with the AOM recommended target pitch angle for an unassisted recovery. Offline simulations were performed to derive the associated FD go-around pitch angles for the other flap settings, see Table 1 below.

Table 1 FD reference pitch angles in the go-around

	Flap setting (deg)					
	1	5	10	20	25	30
θ_{GA} (deg)	15	17	17.5	17.5	17	12
α_{PROT} (deg)	8.5	13	12.5	12.5	11.6	11.6

Since a constant pitch angle may lead to aircraft stall in case of a severe windshear, a protection logic was devised and incorporated. The protection logic would only become active if the following two conditions were met:
1) The go-around mode had been engaged
2) The actual, but filtered angle of attack (α_f) exceeds the predefined protection angle of attack (α_{PROT})

When the protection logic intervened a FD pitch down command would be given equal to the dif-ference between the actual filtered and the protected angle of attack. This protected alpha was chosen to be 1 degree below the stick shaker angle of attack belonging to a aircraft flap setting, see Table 1.

Pilots were made aware of the pitch margin to stall by a so-called Pitch Limit Indicator (PLI) on the Primary Flight Display (PFD) pitch ladder, see Fig.1. If the actual pitch was below this PLI, the FD needle would indicate a positive pitch margin with respect to the stick shaker angle of attack. A stick shaker signal was given the moment the PLI and the FD pitch bar needle coincided.

FD mode switching-dynamics

A rate and amplitude limiter and a low-pass filter prevented a fast FD-bar jump when switching from the ILS-tracking to the go-around mode.

FD objective data recording

Various parameters, e.g. (FD) pitch angle, (vertical) speed, angle of attack etc, were recorded from the moment the go-around was initiated until the moment of altitude capture. Statistical properties like the mean, minimum, maximum and standard deviation were calculated immediately after every run. Results will be given per sensor type, but for the extreme windshear cases only, because only this way a reasonable comparison was possible.

Analysis of FD results

For the statistical analysis a significance level of p 0.1 was used. Because the experimental design was a fractional factorial one, the data of the first sub-experiment was not sufficiently well balanced to make a valid comparison possible. Therefore sometimes also data from the second sub-experiment had to be added and/or cases with and without an allowed speed increment had to be mixed.

Pilot opinions about STD versus MOD-FDmode

The pilot opinions obtained via the run-by-run questionnaire are presented in Fig.4. It shows that in the majority of cases the crews were satisfied with the behavior of each FD type. To find out the reason why pilots sometimes disliked the FD-behavior, and indicated “no” or “may be”, Fig.5 shows the answers given. With the STD mode the commanded pitch was found to be too low most of the time, while the opposite was true for the MOD mode. “Other” stands for a lack of FD-smartness, e.g. not including an altitude /stall margin dependency in the logic.

When comparing both FD types statistically by applying the non-parametric Kruskal-Wallis test, no significant difference was found (p=.3147).

Based on these results both FD modes should be judged to be equally satisfactory, but oddly enough afterwards crews stated they were generally dissatisfied with both of them (see pilot comments).

Comparison of stall margin performance

Fig.6 shows the overall effect of the FD type on the stall margin during the go-around. Comparison of the minimum or maximum values were found not to be significantly different, but the mean values of the stall margin were. In case of the measurement runs with the reactive sensor it reduced about 1.5 degrees when comparing NO-FD with the MOD-FD. This was due to the fact that without a FD lower pitch angles were flown than with the MOD-FD mode present. However, also the use of a possibly applied speed increment may have played a role, since sometimes crews were allowed, (or even advised) and would have set a higher speed before entering the go-around. With the laser sensor a significant ($p<0.025$) increase in mean stall margin occurred for the STD-FD mode when compared to the MOD-FD mode.

Comparison of pitch angles

Fig.7 presents the overall result for the actual pitch angle. It is shown in the middle box that there was a significant overall effect of the pitch steering mode on all pitch parameters (i.e. on maximum, mean and minimum angle). Going from the unassisted, manual WTA (NO-FD) to the FD-assisted WTA (MOD-FD) when having the reactive sensor, the mean and maximum pitch angle increased significantly by several degrees. When having a laser on board, the STD-FD mode led to significantly lower max and mean pitch angles than with the MOD-FD mode. Furthermore, it should be noted that the difference between the maximum and minimum pitch angle is the smallest for the NO-FD situation (e.g. about 10 degrees).

In comparing NO-FD presence with the FD-assisted flight, also the standard deviation (std) for the pitch angle was evaluated against the root means square (rms) of the FD pitch angle. As Fig.8 shows, the overall pitch steering mode available was statistically significant on the pitch angle std ($p<0.0200$), but not on the FD pitch rms! Therefore control with the FD was almost equally easy (or difficult) for both modes. Observe that the std in pitch for the NO-FD case has the lowest value of all three std values presented.

Finally, although not shown in a figure, there was a statistically significant interaction effect between the pitch steering mode and the experimental *speed increment* parameter. Without such an increment there was hardly an effect of FD mode, but with the speed increment applied, there was a significant increase in FD rms from about 2.5 to 4.1 when going from the MOD to the STD mode.

Comparison of flight safety risk

The flight safety risk model[9,9,18] set up for the go-around segment was used for analysis. As can be observed from Fig.9, the effect of adding FD-assistance had no statistically significant effect in case of the reactive sensor. Also in case of a laser sensor, there was no meaningful difference in flight safety between the MOD or STD type of FD.

Comparison of subjective pilot workload

The workload rating was given for the entire flight, and it may therefore not relate to a particular flight segment or FD-mode. Still when doing so, Fig.10 presents the result. From other studies performed in the past[15,16] it was learned that a flight director generally decreases workload and improves the accuracy of control when tracking the ILS. However, for the go-around or windshear escape, the effect of adding a FD turned out not to be statistically significant on the PF’s workload. In case of the reactive sensor, the trend even suggests a lower workload without FD assistance. For the laser sensor the differences between both FD-modes were nearly significant and suggest a lower workload for the STD FD mode than for the MOD-FD mode.

<u>Some pilot comments</u>
During the debriefing pilots stated that the transient behavior, i.e. the dynamics while reverting from the glide slope tracking to the actual go-around mode, was not damped well enough and still too sudden. Furthermore, they disliked the behavior of both types of go-around modes of the FD evaluated, irrespective of the presence of a windshear and in fact in contradiction with the questionnaires filled out. They stated they could do better without.
Related to the STD mode they criticized it gave too little acceleration when having full power applied. Furthermore it should contain a more advanced windshear guidance logic. Related to the fixed pitch (MOD) mode, they found it difficult to fly. General damping was found too low and could easily lead to some kind of over-control. The stall protection mechanism, however was appreciated.
Moreover, most revealing was the statement that they tended to see and fly-through the FD needles instead of accurately following them. This explains somewhat why the pitch angles of Fig.7 deviate from the WTA-recommended, or FD-commanded 12 degrees.
In some situations the pitch needle interaction with the PLI symbol was found incorrect. Sometimes after the stick shaker had been activated the pitch bar gave an undesired momentary indication above the PLI. This problem, although serious enough, was most likely caused by the low-pass filtering in the PLI signal and did not specifically relate to the FD itself.
Finally, it was stated that more advanced windshear escape logic was already available and should be evaluated.

<u>The second sub-experiment</u>
The second sub-experiment evaluated the concept of presenting wind shear icons on the EFIS/NAV display, see Fig.11. The circular, colored icons would indicate the position and threat to the aircraft. Icon colors depended on the laser-derived along beam averaged F-factor (Fav) value. A red color would indicate a Fav [–.21 and a shear cell within alert zone A of Fig.12. An also circular shaped, but combined amber/red colored icon would indicate that a similar hazardous Fav-value exisited, but that the shear was detected somewhere in alert zone B but still outside alert zone A. Furthermore amber and blue icon colors could appear, indicating lower hazard levels (viz. -.21 [Fav > -0.10 and -.1 [Fav > –.04).

Two different forms of displaying windshear icons were investigated, viz. with and without *speed feedback*. Speed feedback means that the above indicated alert thresholds were modulated (increased in absolute sense) in case the pilot increased his AT speed after a windshear alert had occurred. This increase would be based on a blue and flashing speed advisory symbol on the speed tape of the PFD (See Fig.1) which would indicate a maximum additive of 20 kts to be set. If icon colors would modify (thereby indicating a lesser windshear hazard) after this advised AT-speed was set, this would give additional information to the crew about the possibility to overcome the shear with the speed increment applied. If the icon colors would not change then this would be an indication of a severe shear that should be avoided.

<u>Results of the second sub-experiment</u>
From all the data analyzed only the results related to derived Flight Safety Risk, the crew workload and the pilot display preference will be addressed.

<u>Results related to the derived Flight Safety Risk</u>
Fig.13 clearly shows a significant (p<.0867) improvement in the derived flight safety risk when having a windshear icon display. Adding a display reduces the flight safety risk. No significant difference was found between the two types of icon displays.

<u>Results related to crew workload</u>
Crew workload was considered (by combining the individual workload ratings given) since generally the PNF observed the NAV-display and the PF concentrated on flying the aircraft. The various display options had no significant main effect on crew workload. However, see Fig.14, there was a highly significant (p<0000) interaction effect with the weather scenario flown, whether or not the speed feedback mechanism was applied and whether an icon display was present. For the '*benign*' weather cases the workload significantly reduced with the normal display (no speed feedback). Also for the '*worst case*' weather scenario the workload significantly increased without speed feedback.

<u>Display preference of the pilots</u>
During and after the experiment the pilots were asked about there preference for a particular type of the windshear icon display. Although analysis of the run-by-run questionnaire results showed a slight preference for the icon display with the speed feedback

concept, the pilot debriefing questionnaire results given in Fig.15, when relatively ranked according to the Saaty method[17], showed the opposite. Together with the pilot comments made, see below, the icon display without the speed feedback mechanism was regarded the best option and clearly better than having no display.

Type of go-around made based on laser alerts

With a forward-looking windshear sensor the need for a windshear type of go-around, e.g. the WTA procedure, seems questionable. Therefore, if the crew decided to initiate a missed approach based on a WINDSHEAR AHEAD alert, it was left to them, as briefed, to decide to either apply the WTA or the normal (i.e. STD) go-around procedure. Fig.16 shows the collected results as a function of display type. As can be observed without a display there was an almost equal percentage of WTA and STD types of go-around made. Some crews motivated this by stating that they applied the rule “any windshear alert is WTA” since they did not know where the shear was exactly. However, when having a windshear icon display present this situation changed significantly and, as expected, the STD type of go-around was favored in 80% of the cases. This was motivated by that there was enough time to clean up the aircraft configuration and that it was better to climb away as soon as possible. However, a few crews were strongly opposed to not using the WTA procedure in case of a windshear alert.

Some pilot comments

The concept of presenting on the EFIS/NAV display one or more windshear icons, derived from a laser sensor, was found operationally feasible by all pilots. Still, it was advised to integrate such icons with a weather radar display. The icons definitely increased situational awareness compared to having aural alerts only. However, there was the danger of assuming that the icons presented all the existing windshear threat, i.e. that there would not be a windshear effect outside of these icon areas. Using this seemingly perfect information for close circumnavigation around icons could lead to unpleasant surprises in real life. Therefore the icon-indicated threats are required to be highly representative of the actual threats present.
Stability of the icon size and colors presented were also criticized, but this should be regarded a filtering problem. The threat-level based aural alerting concept was supported by all crews. However, with respect to the alerts presented, it was found that the blue labels and blue icons (i.e. lowest hazard level) should be left out to reduce the number of cockpit voice alerts.
The speed advisory (symbol) on the EFIS/PFD tape was not unanimously liked by all crews. Some were against it and some preferred a suppression below 500 ft AGL. The first level i.e. to increase speed with 5 kts was not found so useful, as crews would do it themselves already. Surprisingly 50% of the crews were not against automation of the strategy to increase the aircraft speed based on a forward looking windshear alert. Speed increases based on reactive system alerts was disliked by most crews.
As stated before, most crews disliked the tendency of the display with the speed feedback (i.e. with alert threshold modulation) as it drove them further into the shear. It was preferred to go-around earlier for such a once-in-a-life time experience.

Crashes

Unexpectedly, 7 measurement runs, out of a total of 252 measurement runs (excluding familiarizations) performed, resulted in a unsuccessful ending.
Before getting into details, it is remarked that all crews were strongly recommended during the crew briefing to apply normal safety standards, and not to pursue flight through windshear “because it is only a simulator experiment”, if they would not also do this in real life. Crews were informed that some very severe and dangerous windshears could be present, especially in the situations with a forward-looking detector and windshear icons present. Furthermore, there was no intention to let crews crash. The shear cases were expected to be recoverable for the situations where there was no windshear icon presentation in the cockpit. However, the other cases (i.e. with windshear icons present) were set up such that any flight through a red icon, representing a very heavy, e.g. potential “killer” shear, could result in a crash.
Crews were thoroughly briefed on this issue and the reasoning behind it was that a realistic threat impact and threat environment was created, such that their understanding of and reaction to the situation would be comparable with for instance the threat generated by severe weather radar indications (which sometimes also show red colored areas).
Therefore, it was not really expected that these accidents would occur. To learn from what happened this section will highlight two of them.

Crash case statistics

One of the seven crash cases was excluded from results afterwards, as it was found that the RFS

Operator had intervened with a crew's windshear recovery too early to correctly determine the successfulness of their action. Thus six valid crashes remained, implying an overall average of about 2.4%. In the first sub-experiment, one crash occurred, giving a "non-success rate" of 1.8 % (if based on the total of 57 go-arounds made for this part). The other 5 valid crashes happened in the second sub-experiment. Four of them were the outcome of a missed approach (or windshear recovery) and one of a very heavy landing. The second sub-experiment consisted of a total of 180 measurement runs of which 58 were landings and 122 missed approaches. Based on the latter, the five crashes resulted in "unsuccessful landing and go-around rates" of 1.7 % and 3.3 % respectively. These numbers can not be directly compared to normal operational practice, or safety standards, as all runs contained windshear(s) and therefore introduced a biased domain.

Crashes distributed over crews

Apart form the second and fifth crew who never crashed, the fourth and sixth crew crashed once and the first and third crew even twice.

Crashes distributed over windshear display presence

Four out of the six crashes occurred without windshear displayed in the cockpit and two with an icon display. In the latter case, although instructed not to do so, the crews challenged the windshear in the amber/red icons. After this crash they never went into it again. This clearly indicates the need for pilot training but also the benefit of having a display.

The two crashes described next in more detail relate to the situation with and without a FD assistance during the windshear recovery. In both cases no windshear icon display was present.

First crash

The first crash occurred with a repeated run of the third crew. The evaluation would consist of a missed approach without having a FD-assistance, i.e. a windshear recovery of the NO-FD type would be made and the crews were briefed about it. No forward-looking, but only a reactive windshear detection system was on board the aircraft, to force the crew to fly into, or though the shear. Go-around altitude was set at 2500 ft (762 m) AGL.
Fig.17 shows the height-to-distance relation along the ILS descent, for all six crews. It is remarked that the run of crew 3 contained a different and more severe windshear than the other crews encountered, because the wind case used the first time did not trigger a windshear alert in their situation, and also did not make them decide to perform a WTA type of go-around, the objective of the investigation. As can be observed from the figure, apart from the third crew all other crews performed a go-around and a safe escape. In Fig.18, it can be seen in more detail that at the moment the third crew triggered the TOGA thrust, they had already initiated the go-around by applying a pitch up and were ascending. Also it can be learned that they initiated the go-around no later (i.e. at a lower height) than most of the other crews.

Fig.19 shows the in-situ averaged F-factor per crew. As can be observed, crews 2 and 3 initiated the go-around in a positive energy situation (i.e. positive F-value), while the other crews prolonged the approach until a windshear alert, i.e. an alert due to a negative impact of shear on aircraft's energy state, went off.

Fig.20 shows the windshear patterns encountered by all crews. Note that crew 2 recovered from a more severe downdraft then the unlucky crew 3.

Fig.21 presents the pitch angles and stall margins (alpha-max minus AOA) of both crews 2 and 3. Crew 2 was taken for comparison reasons as an almost similar flight path was followed.

Fig.22 shows the airspeed and Fig.23 the vertical speed of crews 2 and 3. Note that around 4500 m before TDP the major differences start to develop.

Case analysis

The stall margin of crew 2 and 3 was fairly similar during the recovery along the first part of the shear. It decreased while flying from around –4500 m to –3500 m Touch Down Point, but recovered after that again for crew 2, but not for crew 3.
After TOGA Selection, crew 3 initially tried to steer to and maintain 12 degrees of pitch angle. Then due to the downdraft the stall margin sharply decreased, observed by the pilots as the PLI on the PFD came down. The Pilot Flying (PF) initially tried to follow this PLI, but then focused on his negative climb speed and pulled pitch to stop the aircraft from descending. From Fig.23 it can be observed that this strategy seemed to succeed first, although angle of attack margin remained low. Note that the PF was flying with a pitch ABOVE the PLI during this portion of the recovery i.e. in the stick shaker! Suddenly the second shear (downdraft) hit the aircraft.The angle of attack margin decreased further. The moment the

stick shaker was activated, the PF pushed hard to reduce pitch back to about 10 degrees, but increased pitch again as he noticed that the aircraft was descending fast with about 2500 feet/ min. Being in the stick shaker constantly, now the PF reduced pitch sharply, close to 3 degrees. Although noticing the aircraft was stalling he pulled again to stop the sink rate, pushed pitch back to about 1.5 deg and finally in a last effort pulled pitch again.

At about 40 m AGL, the simulation was stopped (intervened manually) by the RFS Operator on command of the experiment leader although software protection mechanisms were available to stop and protect the TV-camera from impacting the ground (i.e. the model board). The windshear recovery was declared unsuccessful (i.e. a crash), because the aircraft's vertical speed of about 4000 feet/min was found unacceptably high, and the remaining altitude of 40 m was considered inadequate to be able to recover from the stall.

Case conclusion

Although it could not be proven, the outcome would most likely have been more successful, if the crew would have adhered to the recommended target pitch of 12 degrees as long as possible (like crew 2 did), because a non-recoverable situation was initiated the moment a larger pitch was pulled.
Furthermore, the PF seemed not able to perform precise pitch control during a windshear recovery as a result of the rapidly changing conditions and high workload in monitoring speed, height and climb rate. However, also a lack of confidence in the WTA-recommended fixed pitch (NO-FD) strategy played a role. Only with proper pilot training such confidence can be built up.

Second crash

The second crash occurred also in a run when no windshear information was visually presented to the crew. However, the aircraft was equipped with an onboard scanning laser, apart from the reactive system. For the go-around, the FD-MOD mode was present.

Fig.24 presents the height-to-distance during the approach and go-around. The fifth crew made a very early go-around high on the approach and has been left out of the detail Figure 25. There the black dots indicate the aircraft (crew) positions at the moment of TOGA selection. Note that the sixth crew initiated the go-around the latest and at the lowest position below the glide slope.

Fig.26 shows the in-situ averaged F-factor of all crews. As indicated, apart from crew 5, they all encountered almost the same, very heavy windshear severity irrespective of their flight path differences. Therefore Fig. 27 only presents the windshear pattern encountered by crew 6.

Fig.28 shows the actual pitch angle, the FD-commanded pitch angle, the protected angle of attack value and the AOA margin to stall.

Finally, Fig.29 indicates the aircraft velocities and vertical speed experienced by crew six only.

Case analysis

The first observation is that an earlier go-around not necessarily guarantees a better i.e. safer ground clearance, see trajectories of crew 2 and crew 3.
Crew 3 initiated the go-around about 2 seconds after a WINDSHEAR AHEAD WARNING alert was given. The crew was already alerted for windshear earlier on the approach by the scanning laser, because advisory (blue label on PFD plus voice) and caution (amber label on PFD plus voice) alerts had preceded the warning. The crews applied the AT-speed increments as indicated by the flashing speed advisory symbol on the PFD. Before this particular evaluation run the crew was again informed that the speed feedback (i.e. the alert threshold modulation) would be applied even though they had no windshear icon display. Knowing this, they should have been more cautions. After the warning alert came in there was clearly some cockpit confusion about which type of go-around to perform as the PF did not made a go-around call at all, but only shouted "yes". Flaps and gear were retracted.
Although the PF immediately pitched up after his "yes", the commanded pitch, see Fig.28, remained the opposite, because the FD system was still in the ILS/GS tracking mode as the crew had not yet selected TOGA thrust. After this selection was made, the FD commanded a fixed pitch of about 17.5 degrees instead of 12, because the flaps had been raised to 20 degrees due to the cockpit confusion as well. The audio track learned that the large peak of about 23 degrees actual pitch was the result of trying to stop the aircraft from sinking too fast.The large pitch down command of the FD that followed is the result of the reducing speed and rapidly increasing angle of attack due to the shear, such that the angle of

attack (AOA) exceeded its protection limit. Although initially the PF closely followed the FD pitch down command he biased it on the positive side, as if he hesitated to fly a negative pitch. The large deviation indicates a lack of confidence in the FD-logic.
Although the aircraft was only momentarily in the stall and airspeed and climb speed improved again, there was just not sufficient height available to recover form the very strong shear. At about 19 m AGL the aircraft still had a 3170 ft/min descent rate and the simulation was stopped.

Case conclusion

The crew encountered a very severe, probably non-survivable shear pattern. However, despite the alerts presented they waited the longest of all crews to decide to go around. From time recordings it was found that they actually had an amber, i.e. caution WINDSHEAR AHEAD label presented on the PFD all the time until it changed into a red i.e. warning label. Most probably the crew did not really understand the meaning of the alerts and the concept of speed feedback evaluated during that run. But the crash supports the observation that modulation of alert thresholds may be dangerous for crew decision making. Finally, whether the lack of procedural correctness, lack of confidence in the FD-mode, bad crew coordination and not changing the aircraft configuration would have prevented a negative outcome can only be speculated.

General conclusions

In view of the results obtained, lacking the element of surprise, and within all other (e.g. model) limitations of the experiment the following conclusions were made.
By weighting the element of flight safety risk improvement higher than the reduction in stall margin, having a fixed pitch flight director (FD) assistance during a windshear recovery was found slightly better than having no FD assistance at all.
With regard to the two different FD-modes evaluated no meaningful difference in pilot workload or flight safety could be observed, still they both need to be rejected based solely on negative pilot opinions. A more advanced logic should be designed instead.
Related to the crash cases analyzed it is concluded that the pilot's confidence in the WTA recommended or FD-assisted pitch control during a windshear recovery was decreasing under stressing and life-threatening situations and therefore should be better trained.
The concept of presenting windshear icons on the EFIS/NAV-display was found operationally feasible. It increased the crew's situational awareness and safety of flight. Two different icon concepts were tested, viz. the one with and the one without having the speed feedback mechanism. Based on pilot's preference, workload and flight safety considerations, the one *without* speed feedback is considered the best option. The best type of go-around procedure (viz. WTA or standard) to apply in case of a forward look windshear alert remains inconclusive. Finally, integration of the icons with a weather radar display should be considered.

Final remarks

Based on the conclusions of the 1994 experiment it was proposed to have a more advanced, or "better" FD logic in NLR's pre-planned 1996 experiment related to a weather Doppler windshear radar system. Although the lessons learned with that 'new' FD would not be part of it, some currently established results of the 1996 experiment, which also was not free of crashes, will be presented in September[18].

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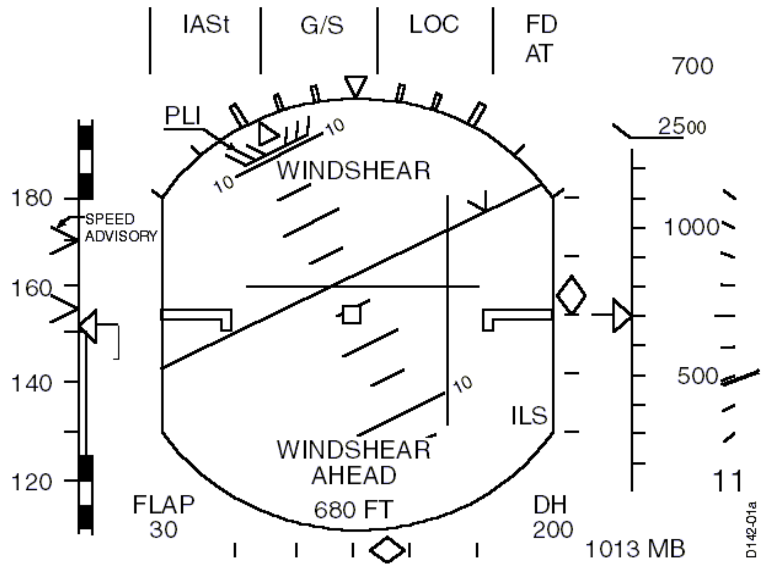

Fig. 1 EFIS/PFD showing windshear labels, the Pitch Limit Indicator (PLI) and the speed advisory.

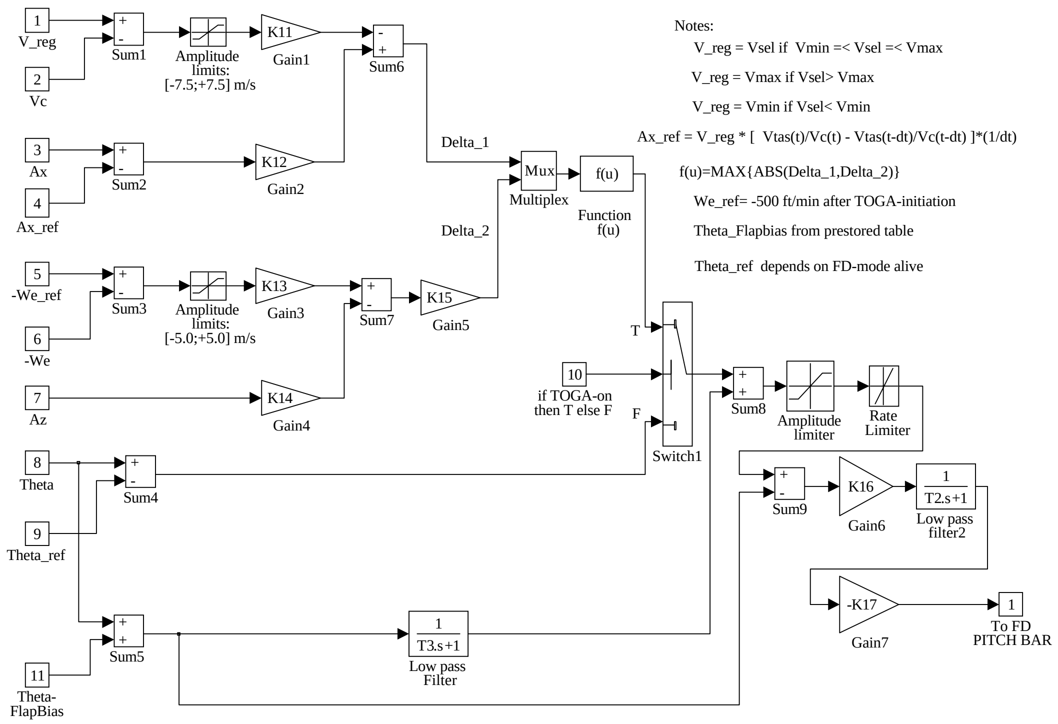

Fig. 2 Flight director standard (STD) pitch steering mode for the go-around.

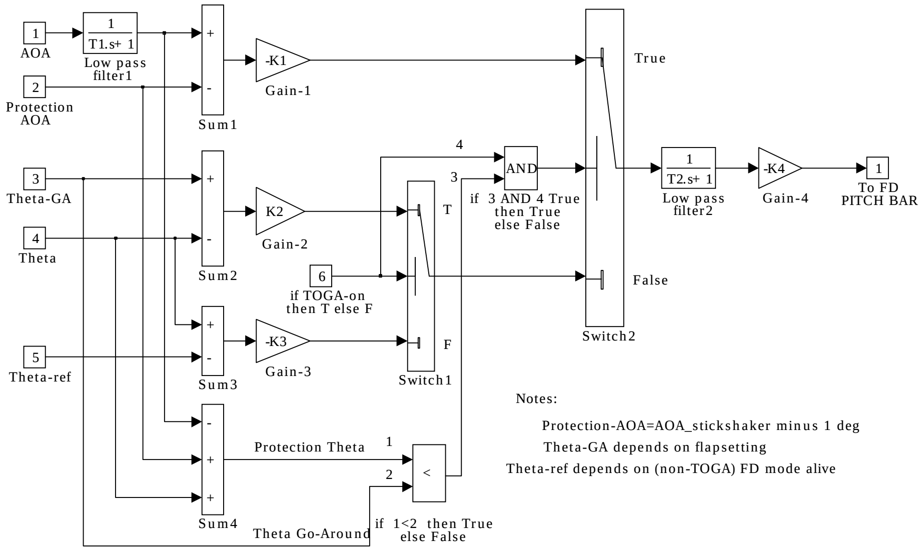

Fig. 3 Flight director MODified (fixed) pitch mode with angle of attack protection.

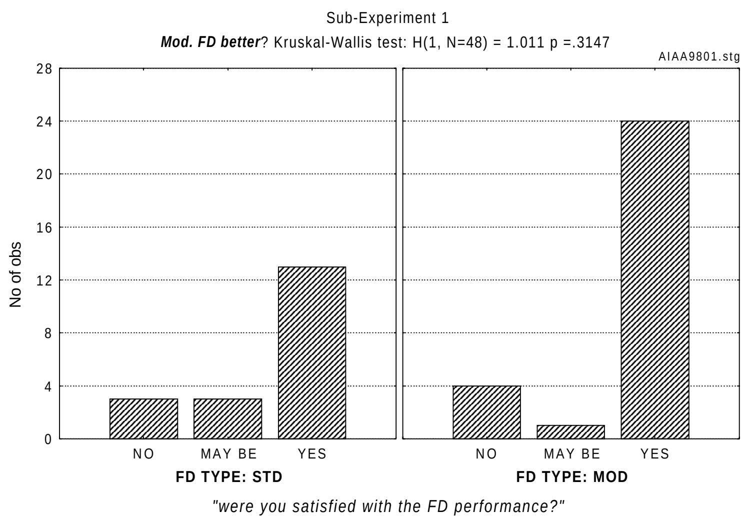

Fig. 4 Distribution of pilot satisfaction with the FD go-around mode.

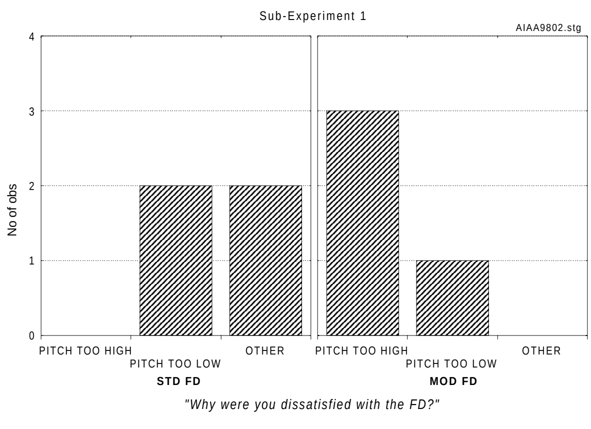

Fig. 5 Distribution of FD criticism over FD types.

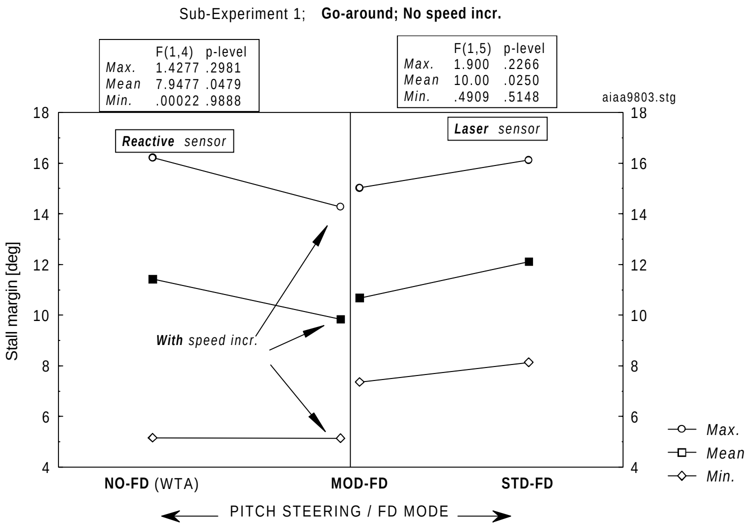

Fig. 6 Effect of pitch steering on the stall margin in the go-around.

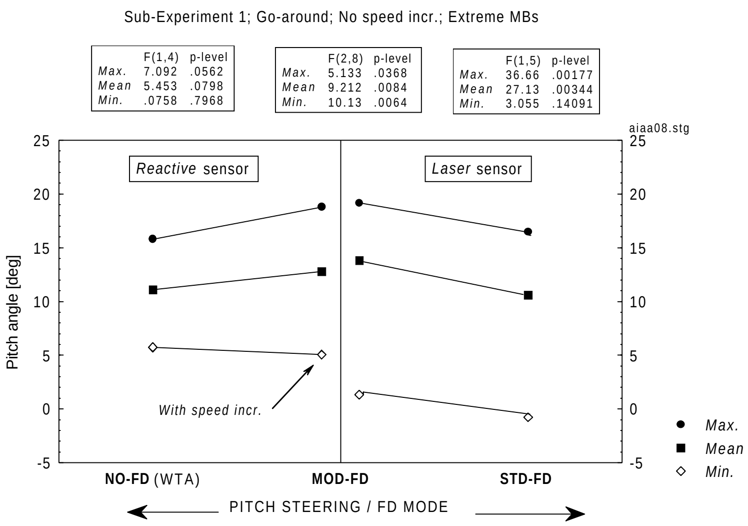

Fig. 7 Effect of pitch steering (FD-mode) on pitch angle in the go-around.

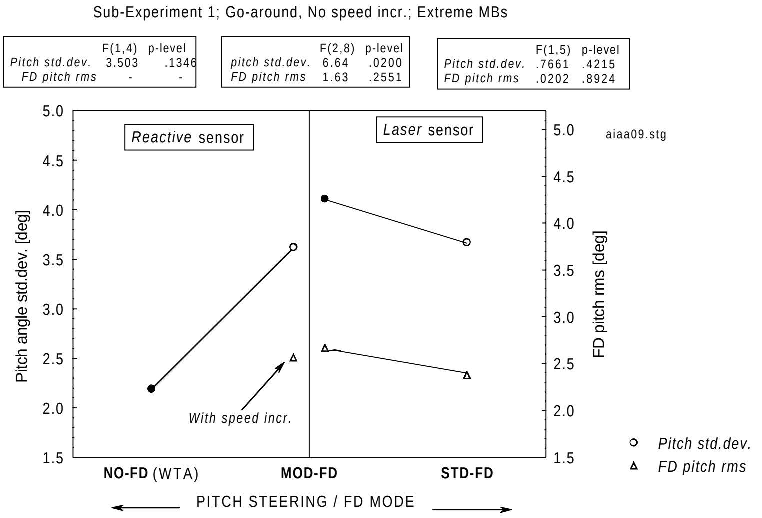

Fig. 8 Effect of pitch steering (FD-mode) on the pitch angle standard deviation and the FD rms.

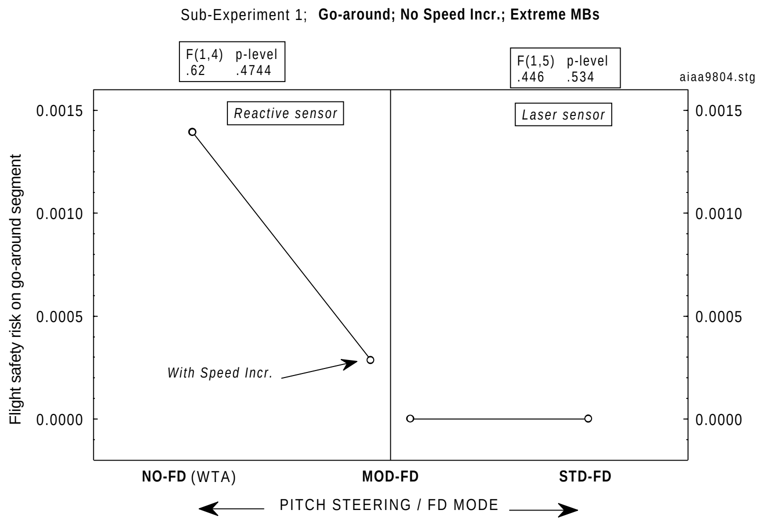

Fig. 9 Effect of pitch steering on flight safety risk in the go-around segment.

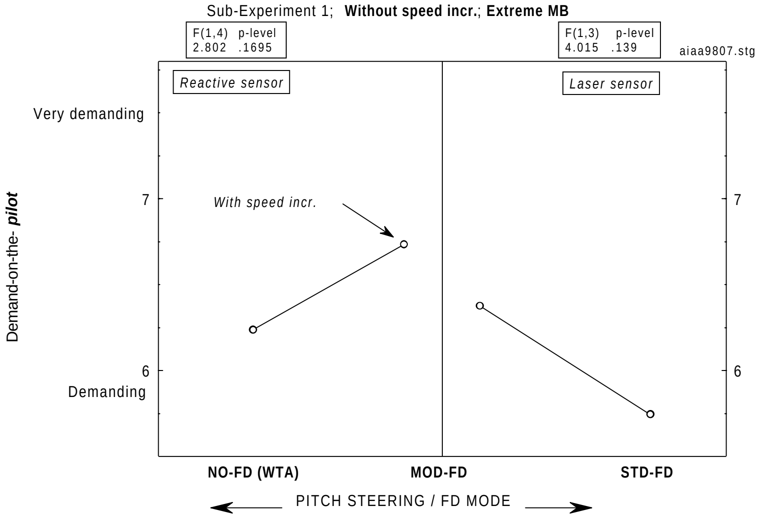

Fig. 10 Effect of pitch steering/FD mode on pilot workload.

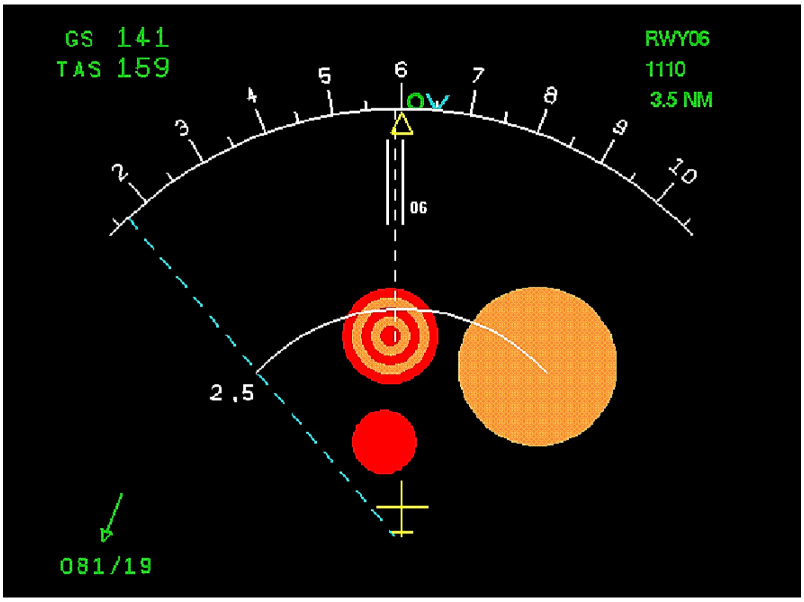

Fig. 11 NAV display presenting three colored windshear icons.

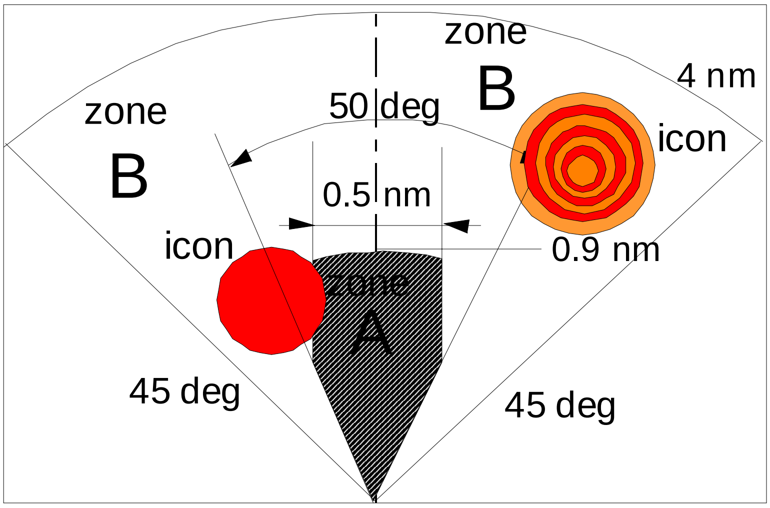

Fig. 12 Hazard zone A and B (relative to aircraft's longitudinal axis) and a red and an amber/red colored windshear icon.

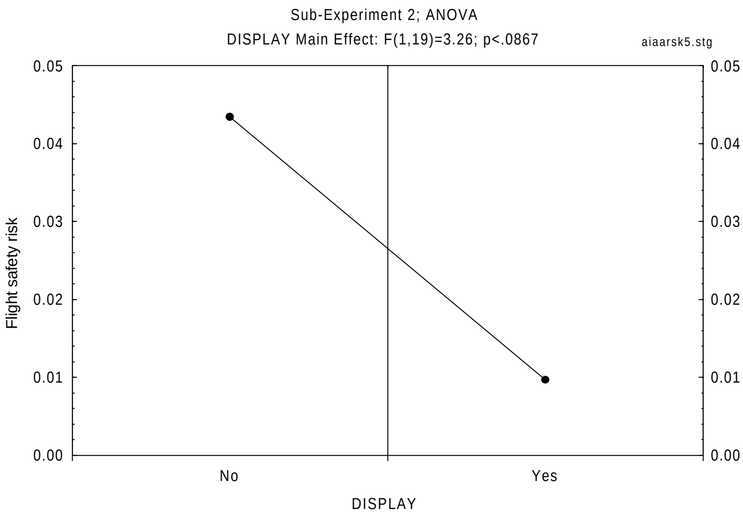

Fig. 13 Effect of icon display on flight safety risk.

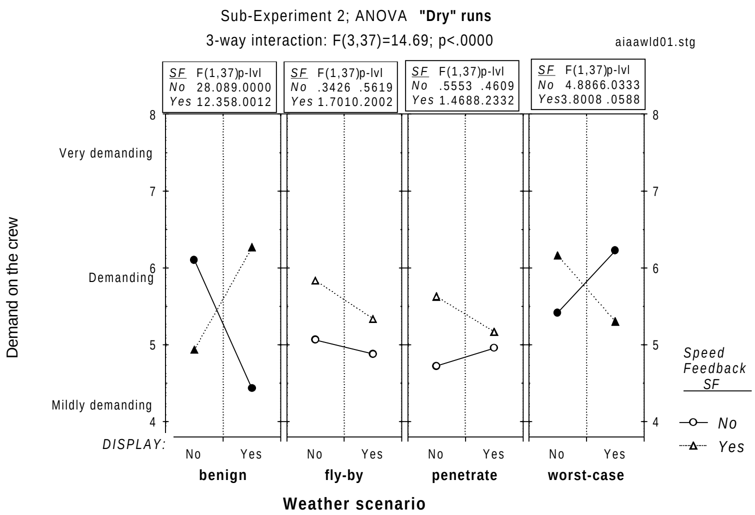

Fig. 14 Effect of icon display on crew workload per weather scenario, as function of speed feedback.

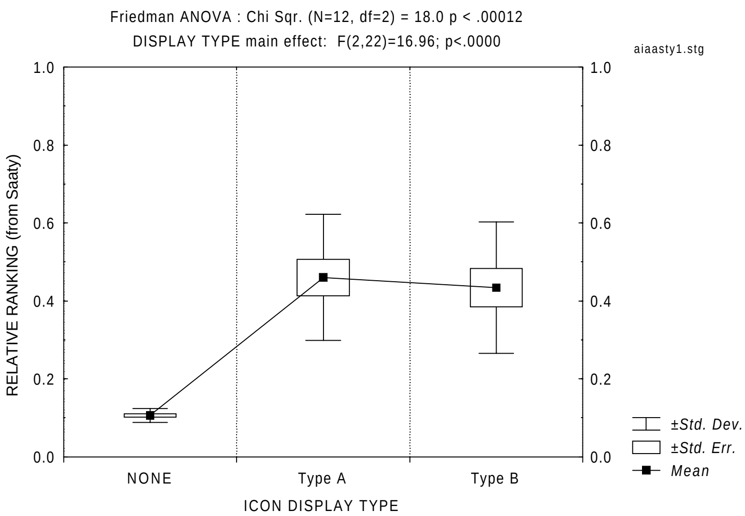

Fig. 15 Relative ranking of display preference according to Saaty[17].

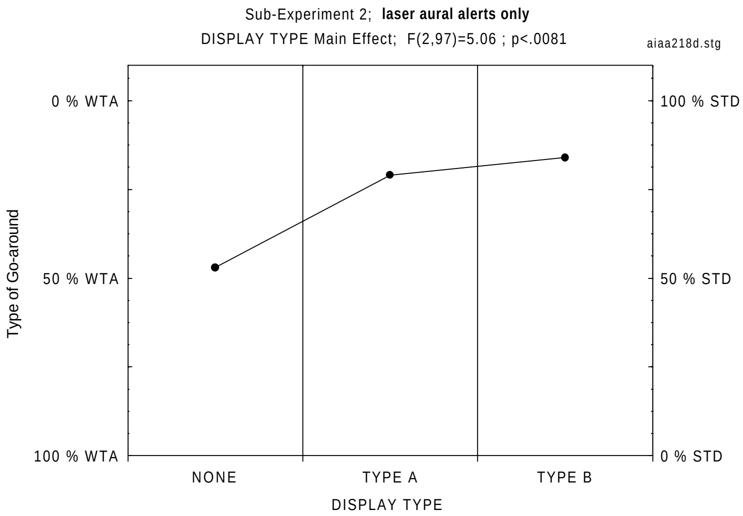

Fig. 16 Type of go-around as function of display type.

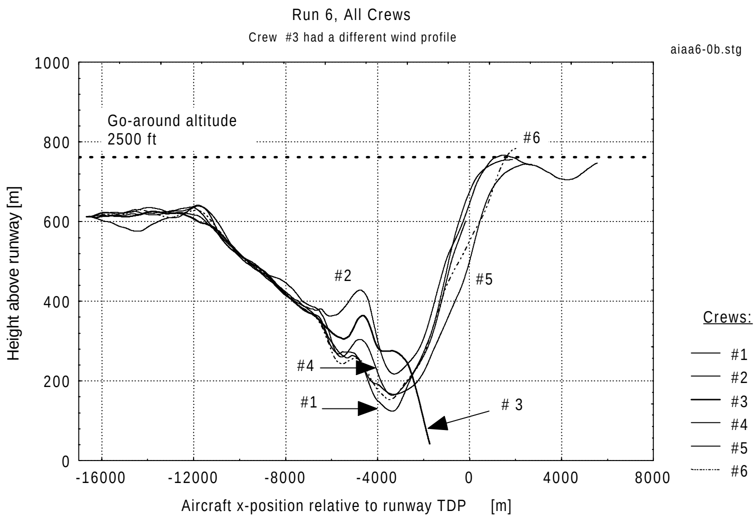

Fig. 17 Height versus distance time history for all crews.

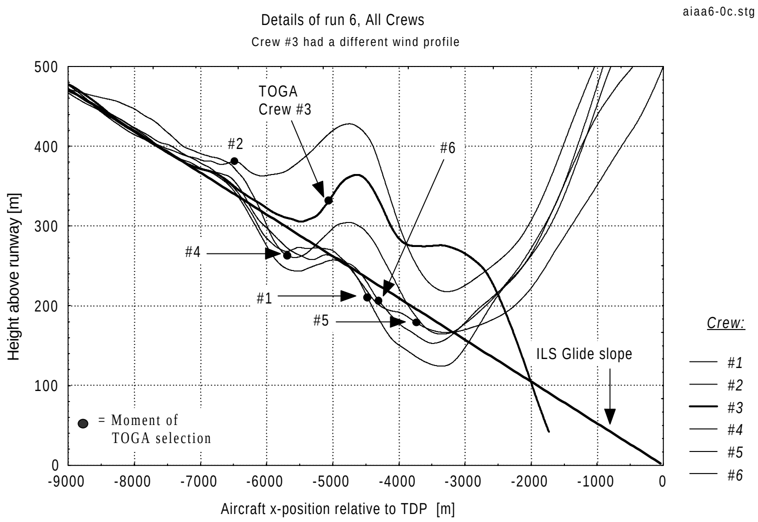

Fig. 18 Detail of height versus distance along the ILS glide slope and in the go-around.

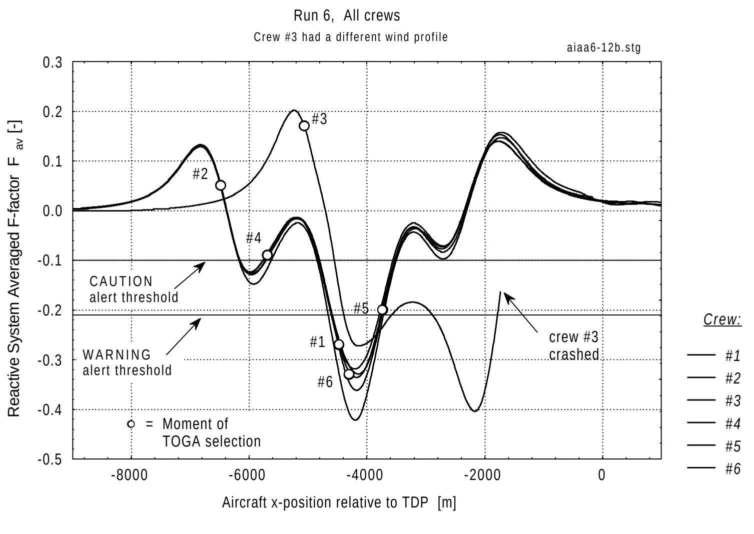

Fig. 19 Averaged F-factor of the reactive system as function of distance from touchdown.

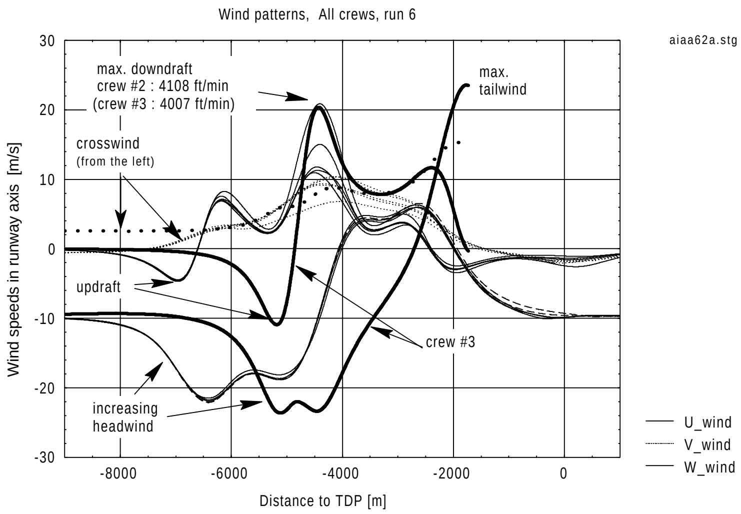

Fig. 20 Wind speeds encountered along the trajectory for all crews.

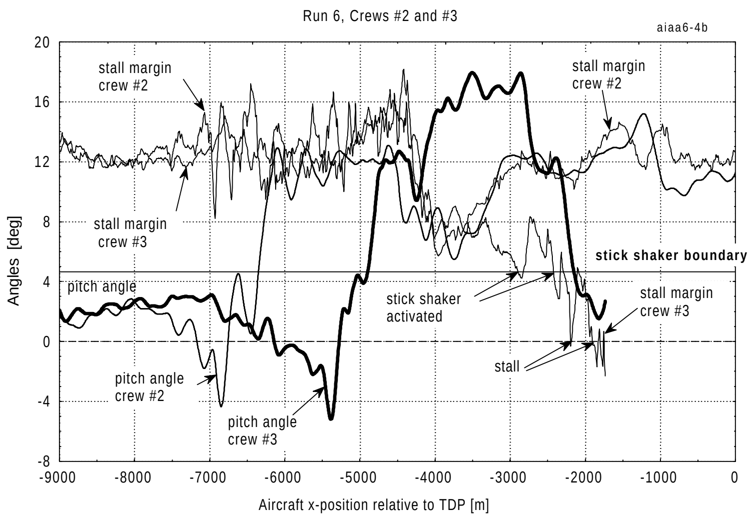

Fig. 21 Pitch angle and angle of attack time histories along the trajectory for crews 2 and 3.

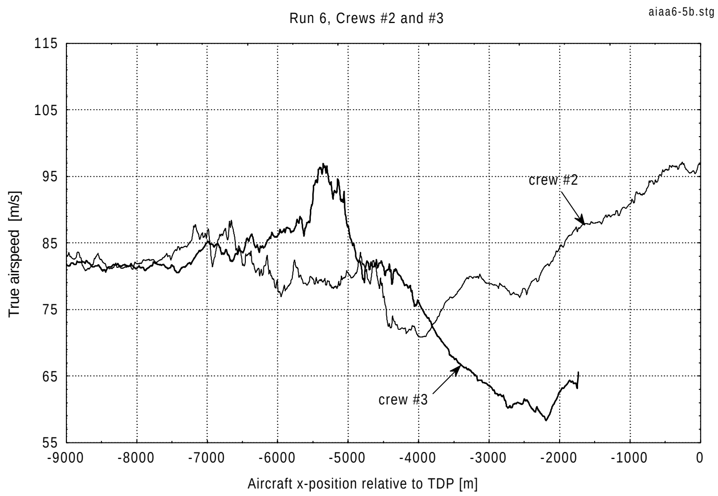

Fig. 22 True airspeed along the trajectory for crews 2 and 3.

Fig. 23 Vertical speed along the trajectory for crews 2 and 3.

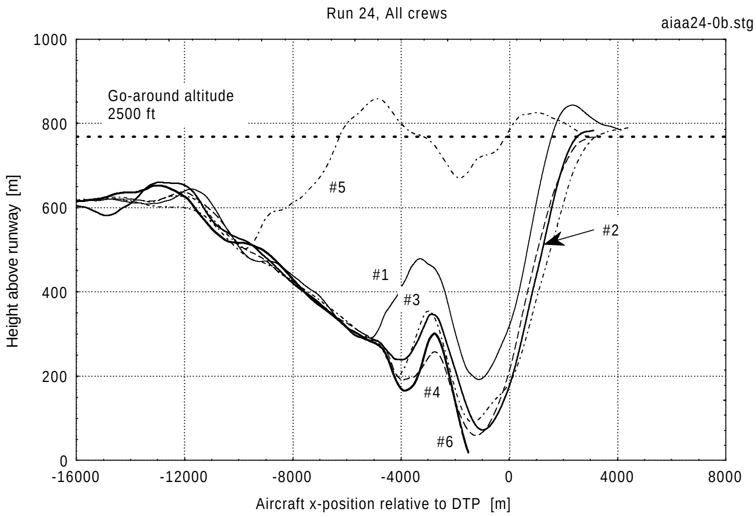

Fig. 24 Height versus distance path for all crews.

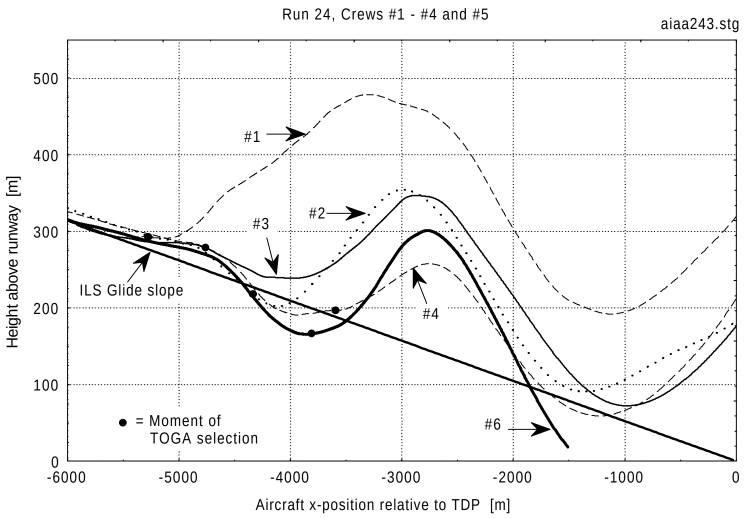

Fig. 25 Detail of height versus path along the ILS glide slope (crew 5 left out).

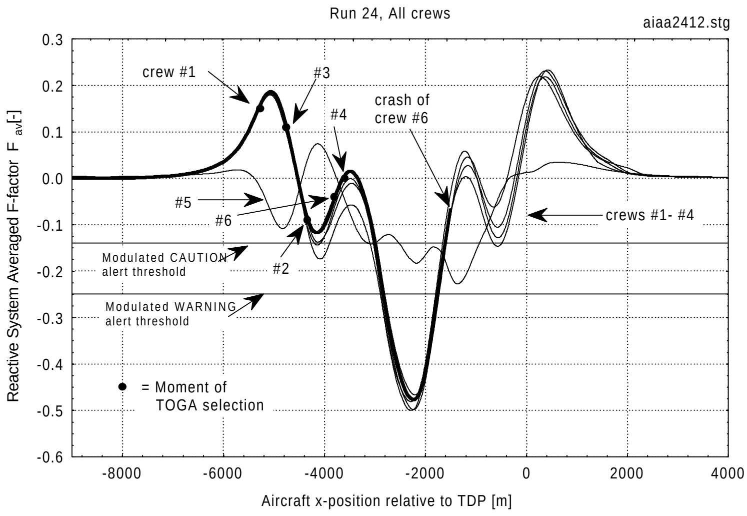

Fig. 26 Reactive system averaged F-factor during run 24 for all crews.

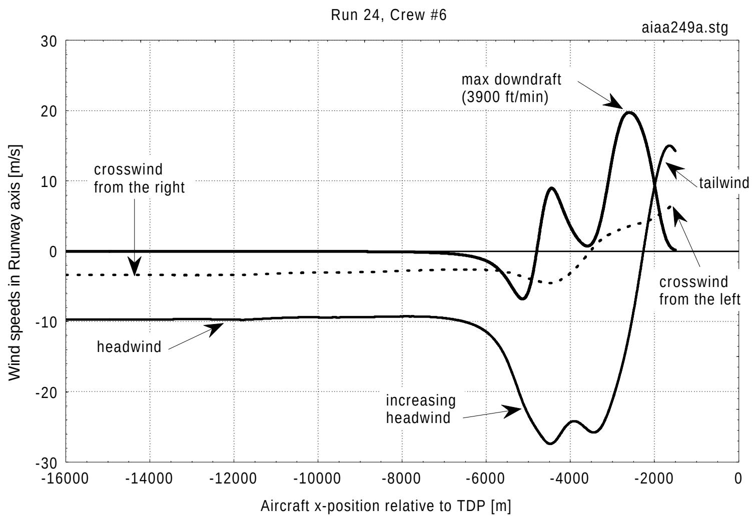

Fig. 27 Wind speeds versus distance for crew 6 on run 24.

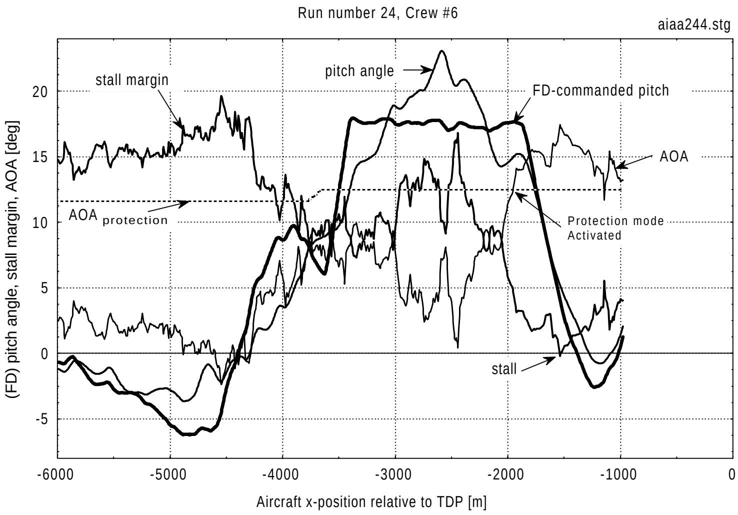

Fig. 28 Pitch angle, FD-commanded pitch, AOA and stall margin for crew 6 on run 24.

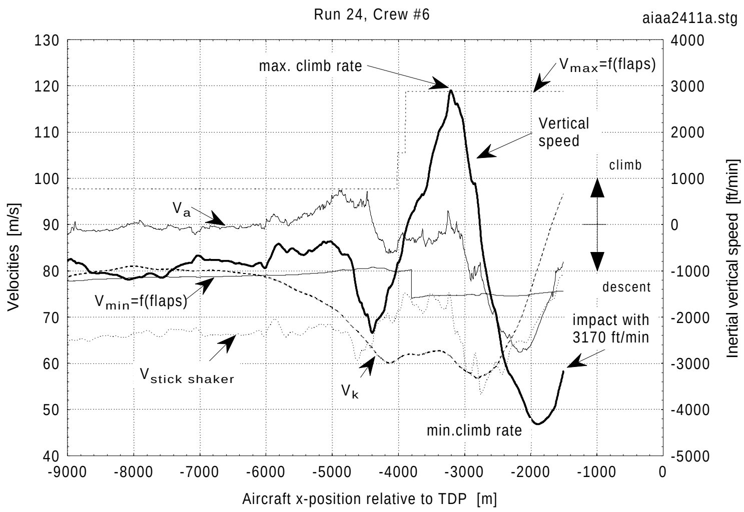

Fig. 29 Velocities experienced during run 24 with crew 6.