GARTEUR Open

FLIGHT IN WINDSHEAR CONDITIONS
(Phase 1)

by

FM (AG05)

GARTEUR aims at stimulating and co-ordinating co-operation between Research Establishments and Industry in the areas of Aerodynamics, Flight Mechanics, Helicopters, Structures & Materials and Propulsion Technology
Performance evaluation of airborne reactive and forward looking windshear detection systems on a simulated aircraft
Final report on Task 2 of FM (AG 05)

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Summary

This report has been prepared by the Flight Mechanics Action Group FM (AG 05) of the Group for Aeronautical Research and Technology in EURope (GARTEUR). The report describes various aspects associated with reactive and forward looking windshear detection systems.

The aim was to have a better understanding of the behavior of a transport aircraft under windshear conditions, and the improvement in flight safety that can be achieved by using an airborne windshear detection system.

A complete non-real time numerical simulation was set up in order to analyse the behavior of this aircraft during windshear encounters at approach/landing and take-off. The aircraft was assumed to be equipped with a fully automated flight guidance coupled to an airborne windshear detection system.

A parametric study has been performed on various factors such as specific characteristics of a forward looking windshear detection system of the Doppler-lidar type, severity factors, and intensity of windshear. This study shows the advantage of a forward looking windshear detection system, compared to a reactive system. With an advance alert-time of more than 20 s the fully automated system has the potential to improve aircraft safety, even in case of extreme windshear conditions.
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List of Symbols

a   aircraft lift gradient (rad⁻¹)
A   aircraft acceleration (m/s²)
\bar{c}  mean aerodynamic cord (m)
C_D, C_m, C_L  aerodynamic coefficients (§ 2.1)
C_D, C_L  constants of wind models (§ 2.2)
D  aerodynamic drag (N)
e  oswald factor (§ 2.1.1)
\bar{e}_L  unit vector along laser beam
F or F_w  F-factor, or averaged F-factor
F_{ht}  horizontal component of F-factor (§ 3.3.2)
F_{laser}  spatial mean value of F_{laser} between minimum and maximum range ;
\bar{F}_{laser}  time averaged maximum along beam laser F-factor
F_{laser}(R_i, t_i)  laser F-factor in beam point R_i at time t_i
(F_{laser})_{max}  maximum of along beam laser F-factor at time t
(F_{laser})_{min}  minimum of along beam laser F-factor at time t
\bar{F}_{max}  time filtering on the maximum value of the F_{laser} measurements
F_{Dp}  ideal Doppler-laser measure (§ 3.3.3)
g  earth gravitational constant, sea level (m/s²)
H or H_o  height above terrain (m)
H_E  energy height (m)
H^*  potential (predicted) height loss (m)
L  integral scale length (m)
L_s  windshear length (m)
m  mass (kg)
N  maximum number of laser beam grid points
q  pitch rate (rad/s)
r  radial coordinate (m)
R  radius of downburst shaft (m)
R_i  i-th laser beam point range (m)
R_c  range at which the laser scans (m)
R_{max}  maximum laser detection range (m)
R_{min}  minimum laser detection range (m)
R_{LS}  forward looking sensor measuring distance (m)
S  wing area (m²)
t  time (s)
t_0  start time (s)
t_X  filter time interval (s)
T  thrust (N)
T_c  pilot time-delay (s)
T_a  advance alert-time (s) (§ 3.3.2)
T_s  windshear duration (s)
u  velocity in x-direction (m/s)
\bar{u}_w  or \bar{u}_wo  horizontal wind speed (tailwind positive) (m/s)
u_k, \bar{w}_k  horizontal and vertical components of inertial speed (m/s)
U  magnitude of horizontal wind velocity (m/s)
V  airspeed (m/s)
V_c  controlled airspeed setting (m/s)
V_{Doppler}(R_i, t)  Doppler speed in beam grid point R_i at time t (m/s)
V_{u_r}  velocity of boundary layer portion (m/s)
V_k  inertial flight path speed (m/s)
\( \vec{V}_L \) inertial speed vector of on-board laser sensor (point L in Fig. 3.6)

\( V_s \) stall speed in stabilized horizontal flight (m/s)

\( V_{w}, V_{wo} \) wind speed (m/s)

\( V_{wa} \) magnitude of max. velocity of jet portion (m/s)

\( \vec{V} \) air speed vector (m/s)

\( \vec{V}_{at} \) turbulence vector (m/s)

\( w \) velocity in z-direction (m/s)

\( W \) weight (N) or magnitude of vertical wind velocity (m/s)

\( w_w \) or \( w_{wo} \) vertical wind speed (downdraft positive) (m/s)

\( x \) x-coordinate (parallel to center-line)

\( X, X' \) X-factor or X'-factor (see § 3.1.3.)

\( z \) z-coordinate (\( z = -H \))

\( z^* \) characteristic height (out of boundary layer)

\( z_o \) depth of outflow (m)

\( z_n \) height of half maximum \( u_W \)-velocity (m)

\( \alpha \) angle of attack (deg or rad)

\( \alpha_x \) inertial angle of attack (deg or rad)

\( \alpha_{prot} \) protected angle of attack (deg or rad)

\( \alpha_w \) wind angle of attack (deg or rad)

\( \gamma \) aerodynamic flight path angle (deg or rad)

\( \gamma_K \) inertial flight path angle (deg or rad)

\( \delta_e \) trim deflection (deg or rad)

\( \delta_e \) elevator deflection (deg or rad)

\( \delta_T \) throttle lever position as percentage of maximum thrust (%)

\( \Delta R \) beam increment range (range resolution) (m)

\( \Delta V_i \) speed increment (kt)

\( \Delta V_s \) measured wind speed difference (m/s)

\( x_f \) coordinate along x-axis of runway threshold (\( x_f = -286 \) m, see Fig. 1.2)

\( x_f \) horizontal position of aircraft at altitude \( H_r = 15 \) m (see Fig. 1.2)

\( \varepsilon \) characteristic height in boundary layer ; glide slope deviation (deg or rad)

\( \theta_l \) angle of laser beam with respect to aircraft reference x-axis

\( \theta \) pitch angle (deg or rad)

\( \lambda \) scaling factor

\( \Lambda \) aspect ratio (§ 2.1.1)

\( \rho_0 \) air density at sea level ISA (kg/m\(^3\))

\( \sigma \) standard deviation

\( \tau \) integration variable ; thrust time constant (s)

\( \chi_w \) flow direction (deg or rad)

\( \chi_{wl} \) magnitude of max. direction deflection of jet portion (deg or rad)

**Subscripts**

- max maximum
- min minimum
- ref reference
- W wind
- i indices
- L laser
- o initial
- f final
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Advisory Circular</td>
</tr>
<tr>
<td>AG</td>
<td>Action Group</td>
</tr>
<tr>
<td>AGL</td>
<td>Above Ground Level</td>
</tr>
<tr>
<td>AP</td>
<td>Automatic Pilot</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V.</td>
</tr>
<tr>
<td>FAS</td>
<td>Final Approach Speed</td>
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<td>FLS</td>
<td>Forward Looking System</td>
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<tr>
<td>GA</td>
<td>Go-Around</td>
</tr>
<tr>
<td>GARTEUR</td>
<td>Group for Aeronautical Research and Technology in EU Rope</td>
</tr>
<tr>
<td>GPWS</td>
<td>Ground Proximity Warning System</td>
</tr>
<tr>
<td>ISA</td>
<td>International Standard Atmosphere</td>
</tr>
<tr>
<td>NIMROD</td>
<td>Northern Illinois Meteorological Research On Downbursts</td>
</tr>
<tr>
<td>NLR</td>
<td>Nationaal Lucht en Ruimtevaartlaboratorium (National Aerospace Laboratory-The Netherlands)</td>
</tr>
<tr>
<td>ONERA</td>
<td>Office National d'Etudes et de Recherches Aérospatiales</td>
</tr>
<tr>
<td>RWDS</td>
<td>Reactive Windshear Detection System</td>
</tr>
<tr>
<td>SF</td>
<td>Severity Factor</td>
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<tr>
<td>TASS</td>
<td>Terminal Area Simulation System</td>
</tr>
<tr>
<td>TSO</td>
<td>Technical Standard Order</td>
</tr>
<tr>
<td>VMC</td>
<td>Visual Meteorological Conditions</td>
</tr>
<tr>
<td>YAG</td>
<td>Yttrium Aluminium Garnet (Y₃Al₅O₁₂)</td>
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1. INTRODUCTION

In the past, several airplane accidents were identified to be caused by atmospheric perturbations associated with severe wind velocity gradients. Today, a number of warning systems are available providing means for this accident prevention. Nevertheless, within Europe there still remains concern about this topic and there is a need to acquire more knowledge and to provide appropriate tools to fulfill the regulation requirements for windshear warning systems and for defining and implementing proper windshear training.

Based on two meetings of a GARTEUR (Group for Aeronautical Research and Technology in EURope) Flight Mechanics Exploratory Group on "Windshear", the need for an Action Group related to this topic was clearly indicated and a coherent three tasks work program was identified with the following objectives [1.1]:

Phase I:

1. to acquire more knowledge of these atmospheric perturbations, of their probability of occurrence and to define characteristics of their models,

2. to have a better understanding of the behavior of transport aircraft in windshear conditions, by characterizing the windshear severity with respect to the aircraft considered using appropriate criteria related to on-board measurements,

Phase II:

3. to evaluate the benefits of forward looking windshear detection sensors using piloted simulation.

In 1991, formation of Action Group FM (AG 05) was approved by the GARTEUR Executive Committee to perform Phase I activities only. Phase II activities were to be performed by a follow-on Action Group.

The first task of Phase I, resulted in two GARTEUR reports [1.3] [1.4] concerning:

- a broad literature review of various existing models of windshears and associated turbulence for various applications (meteorological, mathematical, engineering, etc.) [1.3];
- an inquiry for setting up a data-base of windshear cases, with a special emphasis on Europe, since there is a lack of knowledge and/or data in this area, and the frequency of occurrence of windshear: some annotated cases of these occurrences are given in [1.4].

The present report finalizes the work of the second task which aims to provide some answers to the above defined objectives concerning airborne windshear detection systems.

Two classes of these systems can be distinguished:

1. "Reactive" windshear detection systems, based upon existing air data and inertial sensors, and which are able to identify the presence of windshear once the phenomenon is encountered and which provide suitable information (warning, flight guidance) to the pilot to cope with the danger. Minimum standard requirements are well defined by the FAA, through TSO-C117 [1.6], and most modern (heavy) civil transport aircraft are already equipped with such reactive systems. Nevertheless, these systems do not provide enough safety to the aircraft in the presence of very strong windshears caused for instance by extreme downbursts [1.4] [1.7].

2. "Forward looking" or "predictive" windshear detection systems, which are able to sense windshear conditions before the phenomenon is encountered and which provide suitable information to the pilot, well in advance, to improve aircraft safety.

Some studies have already been performed on these forward looking windshear detection systems, mainly by NASA [1.7], but several areas were still not completely covered, such as:
i) the benefits of "predictive" windshear detection systems compared to "reactive" systems;
ii) the minimum performance requirements of a forward looking windshear detection system;
iii) the various aspects associated with integration of a forward looking system on aircraft severity measures of windshears, guidance strategies, displays and man-machine interface.

The second task of Phase I aims to provide answers to the previous items i) and ii). Some contributions are hoped to be made related to item iii).

For this purpose, it is necessary to take into consideration all the aspects which can influence the behavior of an aircraft during a windshear encounter, such as:

- aircraft characteristics and its flight conditions;
- type of windshear detection sensor (reactive or forward looking system);
- hazard criteria used for windshear detection decision;
- flight control system and guidance strategy associated with windshear detection system;
- man-machine interface and reaction time of the pilot.

A complete non-real time numerical simulation has been set up, simulating the behavior of an aircraft which is assumed to be equipped with a fully automated flight control system during the approach/landing and take-off phase.

The general architecture of the non-real time simulation is shown in Fig. 1.1. Approach/landing is illustrated in Fig. 1.2.

This report is structured as follows:

- Chapter 2 describes the main characteristic of different models for non-real time simulation: aircraft and engine model, windshear and associated turbulence models, windshear detection systems.

- Chapter 3 analyses several hazard definitions for characterization of the windshear threat during aircraft encounters and presents sensing algorithms which will be used for "reactive" and "predictive" windshear detection systems in non-real time simulations.

- Chapter 4 describes the flight control and the guidance strategies associated with the windshear detection systems to be used.

- Chapter 5 presents the experimental design and the results of parametric simulations and furthermore contains the analysis of the numerical results.

- Chapter 6 provides conclusions and recommendations for the piloted simulations which will be performed according to task 3 work program, with GARTEUR Action Group FM (AG 07) [1.2].

Man-machine interface issues and the pilot-in-the-loop evaluations will be taken into consideration during the second phase of the work program [1.2][1.5], that will be executed by the follow-on Action Group FM (AG 07).
2. MODEL DESCRIPTIONS

2.1 Aircraft model

For the non-real-time simulation studies a generic twin-engined heavy transport aircraft model is used. The data required for simulation of the landing approach and take-off are available according to [2.1]. This aircraft is very common to aircraft which are involved in windshear accidents, so that general statements can be made. It is not claimed that the employed data are complete; comparisons with the performance values for other aircraft is not the subject of the investigation.

2.1.1 Flight mechanics model

The main aircraft parameters (mass, wing area, wing aspect ratio) are given in Table 2.1.

A linear aerodynamic model is used. Drag, lift and pitch moment coefficients are composed as follows:

\[
C_D = C_{D0} + \frac{C_L^2}{\pi \Lambda} \\
C_L = C_{L0} + C_{La} \alpha + C_{Lq} \cdot \frac{c}{V} + C_{Lde} \delta_e + C_{Lde} \delta_\alpha \\
C_m = C_{mo} + C_{ma} \alpha + C_{mq} \cdot \frac{c}{V} + C_{mde} \delta_e + C_{mde} \delta_\alpha
\]

The derivatives and coefficients \( C_{L0}, C_{La}, \ldots, C_{mq}, \ldots, C_{mde} \) are given in Table 2.2.

The maximum aerodynamic angle of attack is limited to a specific value (Table 2.3).

The configurations and the speed settings are also given in Table 2.3 for the aircraft model during approach, landing, go-around and take-off.

2.1.2 Engine model

Maximum Thrust

The maximum thrust of high bypass engines depends on Mach number or true airspeed respectively and decreases when airspeed increases. Generally in parameter form the relationship is:

\[
T_{max} = 2 (C_1 V^2 + C_2 V + C_3)
\]

The thrust parameters are given in Table 2.4.

Dynamic Thrust Response

The modelling of the complete dynamic behavior of a jet engine is very complicated. Therefore, for the simulation of the total aircraft, a simple but sufficient engine model is needed to reduce the computation time. This model includes a low pass characteristic using different time constants for acceleration and deceleration with rate saturations depending on the thrust level (Fig. 2.1)[2.2]. Fig. 2.2 shows the dependence of the thrust rate saturation on the thrust level. Various engine model parameters are given in Table 2.4.

Fig. 2.3 illustrates different thrust responses of the engine model to throttle step inputs. These responses indicate the behavior of the thrust model compared with a low pass filter with or without rate limitations, as can be seen in Fig. 2.4.
2.2 Windshear models

The main objective of this study was the investigation of the windshear phenomenon with special emphasis on forward looking sensors by means of non-real-time off-line simulation. Therefore in a first step the physical and meteorological phenomena have to be modelled in terms of mathematical equations. Since the interaction between aircraft and atmosphere is subject of investigation, both the mathematical model of the aircraft (including subsystems) and the wind model need to be compatible and have to properly consider the effects to be evaluated. The following windshear model was selected from the numerous model approaches for different applications (Fig. 2.5) available from literature which have been broadly reviewed in a GARTEUR FM (AG 05) report [1.3].

The windshear models proposed in this report have been chosen with the understanding that:

- the model must provide realistic wind situations;
- the wavelength of the wind disturbance affecting the aircraft is much larger than its dimensions;
- the aircraft is modelled as a point mass having three degrees of freedom in its symmetrical plane and a one-point aerodynamic model is assumed;
- the application of an earth-fixed stationary wind model is sufficient (time-coordinate can be neglected);
- simple structure and handling and acceptable computation time are to be obtained.

2.2.1 Downburst and microburst

For modelling downburst phenomena the approach of Osegueda and Bowles was chosen [2.3]. It represents a simple analytical downburst developed for real-time and off-line investigations. The model represents an axisymmetric stagnation point flow which is assumed to be time invariant. The flow is incompressible and satisfies the mass continuity equation. The effects of viscosity were parameterized explicitly by using a pair of shaping functions that gave profiles for vertical and radial velocity matching the Terminal Area Simulation System (TASS) [2.4] velocity profiles which are assumed to be close to real-world measurement (Fig. 2.5).

The model provides the radially varying characteristics desired for the horizontal wind where two peaks of equal magnitude and opposite direction are located at a given radius, with a smooth, nearly linear transition between the two (Fig. 2.6a). Beyond the peaks, the velocity should show an exponential decay to zero. The vertical velocity was required to have an extreme along the axis of symmetry, and decays exponentially with increasing radius.

The wind velocities acting in the aircraft's symmetrical plane simply can be calculated from algebraic functions:

- horizontal wind component, \( u_w = \frac{\lambda R^2}{2r} \left[1 - e^{i2\pi r^2} \right] \left(e^{i\phi} - e^{i\phi'}\right) \) \hspace{1cm} (2.1)
- vertical wind component, \( w_w = -\lambda e^{i2\pi r^2} \left[ \varepsilon \left(e^{i\phi'} - 1\right) - z' \left(e^{i\phi'}\right) \right] \) \hspace{1cm} (2.2)

with the scaling factor: \( \lambda = \frac{u_{w_{\text{max}}}}{0.2357 R} \) \hspace{1cm} (2.3)

the actual radial distance to the centre of the Downburst is:

\( r = \sqrt{x^2 + y^2} \) \hspace{1cm} (2.4)

and the vertical coordinate equals the magnitude of altitude \( z = -H \).

The maximum horizontal wind velocity occurs at:

\( r(u_{w_{\text{max}}}) = 1.1212 R \) \hspace{1cm} (2.5)
With the results of TASS it can be assumed that the following applies:

\[ \frac{z_m}{z^*} = 0.22 \]  

\[ \frac{z}{z^*} = 12.5 \text{ with } z^* = H(u_{w_{max}}/2) \]  

The downburst model can be defined by four parameters:

1. a characteristic horizontal dimension (radius of downburst shaft);
2. maximum horizontal wind velocity (\(U_{max}\) or \(u_{w_{max}}\));
3. altitude of maximum outflow (\(z_m\));
4. depth of outflow (\(z\)).

Alternatively, the depth of outflow can be substituted by the specification of the maximum downdraft \(W_{max}\). The wind velocities \(U_{max}\) and \(W_{max}\) then can be calculated exclusively from the actual position of the aircraft relative to the centre of the downburst. This last alternative was chosen in this study.

### 2.2.2 Boundary layer and low-level jet

The chosen model representing both the boundary layer and the low-level jet was developed by Swolinsky [2.5] [2.6] and was selected because it was the only suitable one known to the authors. It was designed together with other engineering models for windshear, frontal windshear, and thunderstorm outflows based on simplified fluid dynamic concepts. The data-base used for the modelling comes from flight test data, airline flight data, and meteorological tower measurements, completed by other information and experimental results.

The shape of the normal boundary layer is based on the use of the power-law:

\[ V_{w1} = V_{wref} \left( \frac{H}{H_{ref}} \right)^n \]  

The low-level jet wind profile then is composed from the superposition of a planar free jet velocity profile and the boundary layer (Fig. 2.7):

\[ V_w(H) = V_{wref} \left( \frac{H}{H_{ref}} \right)^n + V_{wv} \left[ 1 - \tanh^2 \left( C_s \frac{H-H_o}{H_o} \right) \right] \]  

\(C_s\) is a model constant affecting the thickness of the jet layer. Swolinsky arrived at a value of \(C_s = 2.0\) with a standard deviation of \(\sigma_{C_s} \approx 1.0\). For \(V_{wv} = 0\), the low level jet degenerates into the ordinary boundary layer.

The flow direction is calculated from a similar approach (Fig. 2.8):

\[ \chi_w(H) = \chi_{w0} + \arctan \left( \frac{H-H_o}{H_o-H_v} \right) \cdot \tanh \left( \chi_{w0} - \chi_{wv} \right) + \chi_{wl} \cdot \left[ 1 - \tanh^2 \left( C_L \frac{H-H_L}{H_L} \right) \right] \]  

Again \(C_L\) is a model constant. Swolinsky identified a value of \(C_L \approx 2.2\) with a standard deviation of \(\sigma_{C_L} \approx 2.0\) (i.e. very inaccurate).

This semi-empirical model can be adapted to measured wind profiles by means of the model parameters. The good agreement between models and measured wind data is demonstrated in Fig. 2.9.
2.2.3 Turbulence model

Besides the mean flow of the wind higher frequency fluctuations can be observed in the real world atmosphere. Apart from classical approaches to simulate turbulence, there are also innovative proposals available [1.3].

Within this study, which is mainly concerned with windshear phenomenon, turbulence has no effect on the aircraft's flight path and energy situation. Nevertheless, a simplified model (first order Dryden type) has been considered, merely to illustrate the effect of a filtering time-constant for application to the F-factor. The turbulence length scale \( L \) is held constant, independent of height. The standard deviations of the turbulence components used obey the following relation:

\[
\sigma_{\text{v}_w} = 0.1 \, \tilde{v}_{w_0}
\]  
(2.11)

where \( \tilde{v}_{w_0} \) is the wind speed vector.

The complete wind vector is then composed of:

\[
\tilde{v}_w = \tilde{v}_{w_0} + \tilde{v}_{\text{wt}}
\]  
(2.12)

where \( \tilde{v}_{\text{wt}} \) is the turbulence vector.

2.3 Windshear detection system models

2.3.1 Reactive windshear detection systems

Although the problem of detection has been treated in various ways by the avionics and aircraft manufacturers, the basic functional principle of reactive windshear detection systems consists of:

- detection of windshear by using inertial and anemometric measurements,
- generation of warning signals when a certain threshold is exceeded.

Generation of flight guidance command signals will be detailed further in Section 4.3.

The system may incorporate an automatic protection of the flight envelope, especially with regard to angle of attack. The information displayed to the pilot differs from one avionics manufacturer to another. The system may inform the pilot on the available energy for executing a recovery or may indicate the windshear hazards.

Many reactive system concepts are based on the indirect calculation of the hazard index F-factor (Chapter 3). When the derived averaged F-factor exceeds a certain threshold, a windshear warning will be generated.

2.3.2 Forward looking windshear detection systems

Several technologies are under development for forward looking windshear detection (see Appendix A): Doppler radar, IR radiometer, Doppler-lidar. According to recent theoretical and experimental studies executed in the USA, the choice of the sensors will be made as function of their cost, technological maturity and capability to cover the operational needs. Presently, it seems that:

- X-band radar is technologically mature and of moderate cost;
- IR radiometry technology is not yet mature;
- Lidar technology is mature only for the 10.6 \( \mu \)m systems and is of high cost for both the 10.6 \( \mu \)m and 2 \( \mu \)m.
The most promising sensor seems to be the airborne pulsed Doppler weather radar, under the presumption that the problems of ground clutter rejection and detection of "dry" windshear are solved. The advantages of this sensor are:

- existing equipment and well-known technology;
- longer detection range than the lidar;
- angular scanning possible, giving a better space covering;
- detection reliability;
- low installation cost.

The major disadvantage is that this system cannot detect very dry microbursts which the laser can. Fig. 2.10 [2.7] compares the domain of application of airborne radar and lidar. It is noted that the boundary values indicated are not fixed but are a function of many parameters: existence of precipitation particles in the air, emission power, radar frequency bands, etc. The radar domain extends from -60 dBZ to 10 dBZ (or even to -10 dBZ). The lidar domain extends from +25 dBZ to -40 dBZ.

In the framework of AG 05, a simple functional model of an airborne forward looking laser sensor has been defined (Appendix B). The model provides an estimate of the Doppler derived wind speed at various locations ahead of the aircraft. Detailed implementation of this system will be described in Chapter 3.
3. PRINCIPLE OF WINDSHEAR DETECTION AND SENSING ALGORITHMS

3.1 Hazard definition

The key to the design of an airborne windshear detection system is the definition of a hazard criterion. The criterion should exhibit a functional dependence on atmospheric states that can be reliably sensed or derived and that scale with available aircraft performance in such a way that the criterion predicts impending flight path and/or performance deterioration. A certain number of windshear severity factors have been defined in order to quantify the hazard:

- F-factor;
- Energy height error;
- X-factor.

The next sections give a brief description of these factors.

3.1.1 F-factor

The F-factor is defined as follows:

\[ F = \frac{u_w}{g} + \frac{w_w}{V} \]  

(3.1)

where \( u_w \) is the horizontal component of the wind velocity relative to the airplane horizontal flight-path, \( w_w \) is the vertical component of the wind velocity and \( V \) is the aircraft's true airspeed.

This F-factor directly represents the airspeed variation or potential climb angle of an aircraft due to a wind variation as can be expressed by the dynamic equation (valid for small flight-path angle):

\[ \frac{dV}{dt} = g\left[\frac{T-D}{W} - \gamma_k - F \right] \]

(3.2)

where \( T \) is the total thrust, \( D \) the aerodynamic drag, \( V \) the true airspeed, \( W \) the aircraft's weight and \( \gamma_k \) the inertial flight-path angle.

This equation shows directly the effect of windshear on aircraft performance. It also shows the necessary ratio of thrust to weight to maintain constant airspeed and its climb's capacity in the presence of windshear.

From nominal flight \((T-D)/W = \gamma_k\) a constant F-factor provides a variation in airspeed which is proportional to the time interval \( \Delta t \):

\[ \Delta V = -g F \Delta t \]

(3.3)

Eq. (3.3) is used as one of the boundary curves for the determination of threshold values for reactive detection systems, as suggested by Fig. 3.1 [1.6]. In fact, TSO-C117 uses a time interval \( t_s \), which provides a mean-value of \( F \) derived from the time dependent actual value, according to:

\[ F_m(t) = \frac{1}{t_s} \int_{t_s}^{t} F(\tau) \, d\tau \]

(3.4)

Sometimes, it is more convenient to use a parameter which is directly connected to the scale length of windshear rather than a time parameter. This scale length of windshear can be defined by the equation:

\[ L_s = V_k \cdot t_s \]

(3.5)

where \( V_k \) is the inertial speed of the aircraft.
Obviously, there is a strict equivalence between windshear scale length and $t_X$ when one assumes that the aircraft inertial speed is constant. In real windshear encounters, it is well known that the inertial speed is no longer constant, as can be seen from the numerical results of Chapter 5.

The quantitative impact of windshear on aircraft performance, as defined by the F-factor, can also be expressed in terms of variation of aircraft pseudo energy state defined as:

$$H_E = H + \frac{V^2}{2g}$$  \hspace{1cm} (3.6)

where $H$ is aircraft height, and $V$ is airspeed.

It can then be shown that the rate of change of this pseudo specific energy is given by:

$$\dot{H}_E = \left(\frac{T - D}{W} - F\right) V$$  \hspace{1cm} (3.7)

### 3.1.2 Energy height error

From Eq. (3.7), the energy height error due to the horizontal and the vertical windshear is given by an equation which is obtained by decomposing the F-factor terms, using Eq. (3.1):

$$\Delta H_E = - \int_u^t F V \, dt = - \int_u^t \frac{V}{g} \, \dot{u}_w \, dt - \int_u^t w_w \, dt$$  \hspace{1cm} (3.8)

If the airspeed remains constant, the energy height error becomes for constant thrust $T$:

$$\Delta H_E \approx - \int_u^t w_w \, dt - \frac{V_0}{g} \Delta u_w$$  \hspace{1cm} (3.9)

Energy height deviations due to the vertical wind result from the wind magnitude and the time flown through the wind field. This is well known to glider pilots; it simply means that energy gain is maximised by remaining in an updraft area for the longest possible time. Energy height deviations due to a horizontal windshear depend on the change in horizontal windspeed multiplied by the factor $V_0/g$.

### 3.1.3 X-factor

With the F-factor the following points can be noted:

i) the F-factor only takes into account instantaneous local windshear effects on aircraft performance;

ii) it does not take into account the actions from a pilot, for instance to increase thrust to overcome airspeed loss in the presence of windshear;

iii) with pilot action, it seems (Woodfield [3.1]) that the hazard to the aircraft during a windshear encounter, or low-altitude manoeuvres, is better quantified by the loss of altitude than the loss of aircraft energy or airspeed.

All these points, with the use of the F-factor, could be overcome by using the X-factor, as suggested by Woodfield [3.2] and is described briefly hereafter.
The X-factor came about by the following [3.2][3.3]:

i) a parametric study of aircraft response to windshear for several windshear lengths, by taking into account the following assumptions about aircraft behavior:
- constant pitch attitude command,
- maximum thrust command,
- with maximum aircraft acceleration A, thrust response time-constant τ, and pilot time-delay Tp; aircraft response is defined in terms of maximum loss of altitude, called potential height loss, which is reached when the airspeed is recovered to its initial value;

ii) application of this parametric study to a data-base of wind profiles, obtained from 10000 landings of Boeing 747 aircraft of British Airways during a one-year period (period 1981-1982);

iii) suggestion of a severity factor, based on potential height loss, called X-factor [3.2].

**Parametric study**

Fig. 3.2 shows the evolution of different aircraft parameters during a horizontal windshear.

The influence of shear length on height loss $H$ is illustrated in Fig. 3.3 which shows curves of iso-$H$ in terms of shear length, $ΔV$, is the total variation of the horizontal wind velocity. This figure also shows the curves related to the F-factor, which are straight lines, with the assumption of constant inertial speed.

The comparison between iso-$H$ (solid line) and iso-F (dashed line) curves shows the drawbacks to use the F-factor as a hazard criterion for a windshear detection system:

a) For example, for points A in Fig. 3.3, we have, when using $F = 0.1$ as the alerting limit, that at A there will be more alerts generated than when using $H^* = 10$ m, i.e. there is a larger false-alarm rate for windshear with decreasing length. Indeed the loss of altitude is small for a same level of F-factor.

b) For point B, however, when using the same hazard limit of $F = 0.1$, there will be less alerts generated than for $H^* = 10$ m, i.e. there is an underestimation of the hazard for large windshear length. The loss of altitude is greater for the same level of F-factor, which can thus give rise to missed events.

**Analysis of the data-base**

Some results from a data-base of Boeing 747 landings of British Airways are presented in Fig. 3.4 [3.2]. These results are then compared to curves obtained from the parametric study, with characteristics of a B747 in approach/landing configuration (acceleration A of 1.4 m/s², thrust time-constant 2.9 s) and with a 4 s pilot reaction time-delay.

From the comparison, Woodfield obtained the following results:

- the cases of strong windshear encounters related to a potential height loss between the curves of $H^* = 10$ m and $H^* = 20$ m;
- the cases of moderate windshears correspond to a potential height less than 10 m.

These results were used for the proposal of a severity factor associated with potential height loss.
Severity factor

From this parametric study and its application to British Airways B747 statistical data, a severity factor, called X-factor, was defined by the constant values of potential height loss. The following boundaries were suggested:

- the boundary from moderate to strong shear is defined by the potential height loss of $H^* = 10$ m (may alert);
- the boundary from strong to severe shear is defined by the curve $H^* = 20$ m (must alert).

These boundaries are presented as continuous lines in Fig. 3.5. It is also suggested to use similar limits, called X'-factor, which are based upon a simplified contour of these potential height loss curves (see broken lines in Fig. 3.5).

3.1.4 Comparison of severity factors

From a theoretical point of view, it seems that the X-factor, as described above, should be better suitable than the F-factor, or energy-height error, for determination of thresholds for airborne forward looking windshear detection systems. Indeed, contrary to the F-factor (or energy-height error) which provides only information about the intensity of windshear itself, the X-factor takes also into consideration the pilot and the aircraft characteristics and provides a severity factor based upon a predicted trajectory which is assumed to be followed by the aircraft.

Nevertheless, there are some drawbacks linked to the X-factor (or X'-factor):

i) the results described in § 3.13 were limited to analysis of horizontal windshears only;
ii) the boundaries associated with the X-factor were based only on a statistical data-base of one aircraft type (B 747) and it remains to demonstrate the validity of these boundaries to other aircraft types.

Concerning the first item i), Woodfield recently completed the analysis by taking into consideration the vertical wind component [3.3]. A complementary study is necessary in order first to prove the advantage of the X-factor in comparison to other factors (mainly for the reduction of the false-alarm rate) and secondly to provide more reliable boundaries for various kinds of transport aircraft.

3.2 Sensing algorithm for reactive windshear detection systems

3.2.1 Hazard factor $F$

The F-factor, as defined in § 3.1.1, can be used to check against thresholds for the reactive windshear detection systems.

Both components of the F-factors (Eq. (3.1)) can be computed from the actual on-board air data computer information and inertial sensors.

3.2.2 Time averaging filter

The F-factor can be integrated and filtered in order to get the average value, $F_{av}$, in Eq. (3.4).

Guidance strategies will be based on this average $F_{av}$, with some specific values of $t_{av}$ and threshold values are used according to the recommendation of the FAA, given in Fig. 3.1 [1.6].
3.3 Sensing algorithms for forward looking windshear detection systems

3.3.1 Lidar detection system

Hereafter, the study is devoted to the forward looking system based on the Doppler-lidar sensor type, but the results from numerical simulations (see Chap. 5) could be extended without major difficulty to a Doppler-radar system.

A detailed functional description of an airborne laser for windshear detection is given in Appendix B.

A brief summary is provided here for the purpose of this study, which is limited to the motion of the aircraft in the vertical plane only.

Let us recall that a Doppler laser system is based on using the Doppler shift due to a sensed relative speed of particles located in a volume around some point, in front of the aircraft. This volume depends on the pulse length and the width of the laser beam. A controller sets a series of range gates, at which range it processes the sensed signal. At one instant of time, Doppler information becomes available from a minimum laser range \( R_{min} \) to a maximum scanning range \( R_{max} \), as shown in Fig. 3.6. The information as function of range can be processed immediately.

The minimum range at which the laser can operate depends upon the laser pulse width and the time it takes to switch from transmitting to receiving status. The maximum range depends on other system characteristics and is limited by precipitation or presence of the ground.

From the Doppler shift, the laser measures the average speed of air particles at point \( W \) relative to point \( L \), i.e. the component of \( d\vec{R}_L / dt \) along the laser beam. Thus, the following equation can be derived for the Doppler velocity:

\[
V_{Doppler} = \left( \frac{d\vec{R}_L}{dt} \right) \cdot \hat{e}_L = (\vec{V}_w - \vec{V}_L) \cdot \hat{e}_L
\]  

(3.10)

where \( \vec{V}_w \) is the velocity of the particle, \( \vec{V}_L \) is the velocity of the laser source and \( \hat{e}_L \) is the unit vector along the laser beam.

A negative value of \( V_{Doppler} \) means that the relative speed is towards the laser, otherwise it is away from the laser.

By assuming that the laser source is located at the center of mass of the aircraft, and by assuming the motion of aircraft to be in the vertical plane, the measured Doppler speed at a distance \( R_i \) ahead is given by the equation:

\[
V_{Doppler} (R_i) = [u_{w_o} (R_i) - u_{k_o} (R_i)] \cos(\theta + \theta_i) - [w_{w_o} (R_i) - w_{k_o} (R_i)] \sin(\theta + \theta_i)
\]  

(3.11)

where \( \theta_i \) is the angle of the laser beam relative to longitudinal reference axis of the aircraft, \( u_{w_o} \) and \( w_{w_o} \) are the horizontal and the vertical components respectively of wind speed at distance \( R_i \) ahead, \( u_{k_o} \) and \( w_{k_o} \) are the horizontal and the vertical components respectively of the inertial aircraft speed.

By assuming that the velocity of air particles is given by the wind velocity, the laser provides the wind component along the laser beam. Fig. 3.7 shows an example of the wind component along the laser beam for a microburst windfield, as well as the accuracy achieved [2.7].
By pulsing the laser, then at varying distances from close to the aircraft to a maximum range \( R_{\text{max}} \), it is assumed that the Doppler lidar provides instantaneously the following set of measurements:

\[
\left\{ V_{\text{Doppler}}(R_i) \right\} \quad i \in [0,N]
\]  

where for each range bin the range is determined from:

\[
R_i = R_{\text{min}} + i \Delta R, \quad R_{\text{max}} = R_{\text{min}} + N \Delta R \quad \text{and} \quad N = \text{Integer} \left[ \frac{(R_{\text{max}} - R_{\text{min}})}{\Delta R} \right]
\]  

where \( \Delta R \) is the difference between range bins.

A complete model of Doppler lidar measures is quite complex, because it is necessary to take into account the signal-to-noise ratio, and to compute the maximum range limitations due to the precipitation. A model that takes these effects into account is given in Appendix B.

Two other parameters might be taken into account for the lidar model:

i) the laser beam stabilization mode (angle \( \theta \));

ii) the azimuth scanning angle of the laser beam, scanning from either side of the reference longitudinal axis, in order to provide a complete windfield in front of the aircraft.

The purpose of the study is to provide the required minimum range (at worst condition), for a forward looking system.

For the sake of simplification, this study is performed with:

- a simple lidar measurement model, given by Eq. (3.12), maximum range \( R_{\text{c}} \) is a constant parameter;
- only one laser beam stabilization mode has been considered i.e. the beam is stabilized along the inertial flight path angle of the aircraft;
- no scanning in azimuth.

### 3.3.2 Lidar F-factor calculation

By assuming that the laser beam ranges along a horizontal axis, the Doppler lidar measurements from two consecutive range bins at a distance of \( \Delta R \) apart provide the first term of the F-factor of Eq. (3.1), defined as \( F_{\text{laser}} \):

\[
F_{\text{laser}}(R_i, t_j) = F_{\text{n}}(R_i, t_j) = \frac{1}{g} \left( \frac{dV_{w}}{dt} \right) = \frac{1}{g} \frac{dV_{w}}{dx} \frac{dx}{dt} = \frac{1}{g} \frac{\Delta u_w}{\Delta R} \cdot V_k(t_j)
\]  

From Eq. (3.11), one get, with \( \Delta u_w = u_{w0}(R_i) - u_{w0}(R_{i-1}) \):

\[
F_{\text{laser}}(R_i, t_j) = + \frac{1}{g} \left[ \frac{V_{\text{Doppler}}(R_i) - V_{\text{Doppler}}(R_{i-1})}{\Delta R} \right] \cdot V_k(t_j)
\]  

By taking into account, at every time, all the Doppler lidar measurements, from the minimum range \( R_{\text{min}} \) to the maximum range \( R_{\text{max}} \) (Eq. (3.12)), one thus gets the set of \( F_{\text{laser}} \) measurements:

\[
F_{\text{laser}}(R_i, t_j) = + \frac{V_k}{g \Delta R} [V_{\text{Doppler}}(R_i) - V_{\text{Doppler}}(R_{i+1})] \quad i \in [1,N]
\]  

with \( R_i \) given by Eq. (3.13).
On this set of \{F_{\text{laser}}(R_i,t_j)\} measurements, which is available at every discrete time \(t_j\), several methods can be applied for data processing, in order to get one value of the severity factor, which will be used in the criterion for guidance strategies.

Hereafter, several definitions of hazard factors associated with the laser derived F-factor are suggested.

i) \(\overline{F}_{\text{laser}}\) overall mean value from minimum to maximum range

The overall mean of the set of the laser F-factor, given by Eq. (3.16), is calculated by:

\[
\overline{F}_{\text{laser}}(t_j) = \frac{1}{N} \sum_{i=1}^{N} F_{\text{laser}}(R_i,t_j) = \frac{V_K}{g \cdot N \Delta R} \sum_{i=1}^{N} \left( V_{\text{Doppler}}(R_i) - V_{\text{Doppler}}(R_{i+1}) \right)
\]  
(3.17)

It can be easily shown that spatial averaging is strictly equivalent to a time-filtered averaging of the lidar Doppler measurements, in the case where the laser beam is oriented along the flight-path of the aircraft, and a horizontal trajectory is flown with constant ground speed.

With these assumptions, by using the change of variable:

\[
dR = V_K \, dt \quad \text{and} \quad T_L = \frac{R_{\text{max}} - R_{\text{min}}}{V_K}
\]

then Eq. (3.17) becomes (by dropping \(t_j\) for sake of simplification and by taking into account Eq. (3.11)):

\[
\overline{F}_{\text{laser}} \approx \frac{1}{(R_{\text{max}} - R_{\text{min}})} \frac{1}{g} \int_{R_{\text{min}}}^{R_{\text{max}}} \frac{\Delta u_W}{\Delta R} V_K \, dR = \frac{1}{V_K T_L \cdot g} \int_{t_0}^{t_{\infty}} \left( \frac{\Delta u_W}{\Delta R} \right) V_K \cdot V_K \, dt
\]  
(3.18)

or

\[
\overline{F}_{\text{laser}} = \frac{1}{T_L \cdot g} \int_{t_0}^{t_{\infty}} \left( \frac{d u_W}{dt} \right) \, dt = \frac{1}{T_L} \int_{t_0}^{t_{\infty}} F_H(t) \, dt
\]

with: \(t_0 = \frac{R_{\text{min}}}{V_K}\), \(F_H(t) = \frac{1}{g} \left( \frac{d u_W}{dt} \right)\)

This above Eq. (3.18) shows that \(\overline{F}_{\text{laser}}\) can be obtained by time-filtering a severity factor of windshear, with a lead time of about \(T_L\) compared to an equivalent lag \(t_e\), computed for a reactive system (Eq. (3.4)).

ii) \(\overline{F}_{\text{max}}\) time-filtering of the maximum value of the laser Doppler measurements

This \(\overline{F}_{\text{max}}\) is processed in two steps as follows:

- a \((\overline{F}_{\text{laser}})_{\text{max}}\) is defined as:

\[
(\overline{F}_{\text{laser}})_{\text{max}}(t_j) = \max_{i \in [1,N]} \{F_{\text{laser}}(i)\}
\]  
(3.19)

with \(F_{\text{laser}}(i) = F_{\text{laser}}(R_i,t_j)\) for sake of simplification from the whole set of measurements given by the lidar at current time \(t\) (Eq. (3.16)).

- a time-filtering over a time \(t_{\infty}\) is then processed on this measure as follows:

\[
\overline{F}_{\text{max}}(t) = \int_{t_{\infty}}^{t} (\overline{F}_{\text{laser}})_{\text{max}}(\tau) \, d \tau
\]  
(3.20)
This time-filtering for $F_{\text{max}}$ factor provides the following advantage compared to the previous classical mean value (Eq. (3.18)) : the maximum value of $F_{\text{max}}$ implies that the greatest threat to aircraft safety, along the range explored by the laser beam, is taken into account at each moment (while the spatial average value, using the Eq. (3.17) or (3.18) provides some smoothing effect). However, this parameter is filtered in order to cancel noise on the lidar measurements due to turbulence. Fig 3.8 illustrates the results of the different data processings, applied to the $F_{\text{max}}$ values of the Doppler-lidar, according to Eq. (3.17) or (3.18), (3.19) and (3.20).

iii) Other formula

Previous time filtering (Eq. (3.20)) can also be applied to other functions of ($F_{\text{max}}$), instead of using ($F_{\text{max}}$)$_{\text{max}}$ (Eq. (3.19)) such as:

$$\text{Abs}(F_{\text{max}}) = \max_{i \in [1, N]} \{ \text{Abs}(F_{\text{max}}(i)) \}$$

(3.21)

3.3.3 Ideal laser factor $F_{2D}$

In order to quantify also the effect of the vertical component of the wind on the computation of the forward looking severity factor, an exact computation of the severity factor $F$ is provided by assuming that this vertical wind component can be measured.

The "ideal" forward looking laser-Doppler measure, defined by $F_{2D}$, is related to the previous laser F-factor (Eq. (3.14)), by:

$$F_{2D} (i) = F_{\text{max}} (i) + \frac{w_w (i)}{V}$$

(3.22)

with $w_w (i) = w_w (R_i), F_{2D} (i) = F_{2D} (R_i, t_j); i = 1, 2, ..., N$

where $w_w (R_i)$ is the vertical wind component at a distance $R_i$ in front of the aircraft, and the current time $t_j$ is dropped for simplification purpose.

This set (3.22) contains $\{N\}$ measures of a severity factor for an "ideal" Doppler-lidar forward looking sensor.

Similar data-processing can be applied to this set, as was previously done with $F_{\text{max}} (i)$ measurements.

3.3.4 Hazard factor $X$

As quoted previously, the use of a severity factor based on the definition of the F-factor to be used in the thresholds for windshear detection system alerting, could present some drawbacks, viz a higher level of false alarm rate for strong windshears over short lengths and lack of detection for windshears over longer lengths. The use of the X-factor, as suggested by Woodfield [3.2], may be more suitable, since these drawbacks are taken into consideration through the definition of the threat in terms of the predicted height loss.

The Doppler-lidar set of measurements allows for the computation of the horizontal wind variation, $\Delta V_x$, given by:

$$\Delta V_x = \sum_{i=1}^{N} [V_{\text{Doppler}}(i) - V_{\text{Doppler}}(i-1)]$$

(3.23)

which becomes:

$$\Delta V_x = V_{\text{Doppler}}(N) - V_{\text{Doppler}}(0)$$

(3.24)
Let us recall that this measurement must be combined with the windshear length \( L_s \), which equals the lidar range \( (R_n = R_{\text{max}} - R_{\text{min}}) \), in order to test against the potential height loss boundaries, in the \((\Delta V, L_s)\) diagram, such as given by Fig. 3.5.

An application of the X-factor would proceed as follow:

- first a horizontal wind change \( \Delta V \) between two points which are separated by a length \( L_s \) apart along the laser beam is computed;
- secondly, by plotting the obtained value of \( \Delta V \) against the length \( L_s \) in the plane \((\Delta V, L_s)\) of Fig. 3.5, one can then test the location of this point, against the boundaries of \( H^* \) as defined above.

Fig. 3.9 presents the \((L_s, \Delta V)\) curves related to a constant potential height loss for the generic aircraft model, used in this study (see Chapter 2).

The comparison with B747 results, from [3.2] is shown in Fig. 3.10. The guidance strategy will use the same boundary as that suggested by Woodfield [3.2], i.e. the curves related to \( H^* = 10 \text{ m} \) (from moderate to strong) and \( H^* = 20 \text{ m} \) (from strong to severe).

A comparison of different computations for potential height loss is described in more detail in Appendix C.

### 3.3.5 Laser grid size

For the numerical calculation of the F-factor for the laser, it is necessary to define the grid size \( \Delta R \) characterising the numerical accuracy used in the \( F_{\text{laser}} \) calculation of the laser beam (Eq. (3.16)). Several values of this parameter will be considered in the numerical simulations (§ 5.4.3).

### 3.3.6 Laser beam stabilization

The laser beam can be stabilized in various ways. Obviously the direction where the beam is looking will have an effect on the performance of the forward looking windshear detection system.

In the numerical simulations, three stabilization modes will be briefly considered:

1. beam aligned with the inertial flight path angle,
2. beam fixed in the aircraft reference frame,
3. beam inertially stabilized in pitch.
4. FLIGHT CONTROL AND GUIDANCE STRATEGIES

4.1 Generalities

Generally, the control strategy for a normal approach and landing consists of an ILS-tracking (glideslope following), and furthermore the standard flight procedure consists of maintaining a constant approach airspeed (V).

During a typical microburst encounter (Fig. 4.1), the aircraft is successively faced with an increasing headwind, followed by a decreasing headwind accompanied with a downdraft and finally an increasing tailwind. With this scenario, trying to keep a constant airspeed would require a reduction in thrust during the first phase of the downburst, which corresponds to an increase of aircraft pseudo-energy. This action would put the aircraft in too dangerous a situation to overcome the second and third windshear phases, associated with descending vertical wind speeds and an increasing tailwind.

In the past numerous numerical studies have been performed to develop guidance strategies in order to assist airline flight crew to cope with a possible windshear encounter. Aircraft manufacturers have also developed their own guidance strategies, associated with on-board reactive windshear detection systems, which are based on integration of existing airborne sensors (air-data computer and inertial equipment). Some limited studies have also been performed with guidance strategies associated with forward looking sensors [1.7][4.1]. As the choice of a guidance strategy coupled with a windshear detection system can also have an effect on aircraft performance, it is necessary to make a proper choice of this strategy to be associated with the detection logic.

Before the description of the guidance strategies which will be used further on, there is a need to modify the commands of the basic controller for the generic aircraft, in order to be able to perform a complete numerical simulation of the windshear penetrating trajectory.

4.2 Aircraft controller structure

To maintain flight safety in windshear conditions airspeed and glide path have to be controlled. The control system used for the landing approach consists of an auto-pilot or flight path controller for ILS tracking and an auto-throttle or airspeed controller.

4.2.1 Auto-pilot

In the autopilot the true glide path deviation $\Delta e$, height $H$, vertical acceleration $a_v$, and pitch attitude $\theta$ are processed and the elevator and trim tab are adjusted accordingly (Fig. 4.2).

4.2.2 Auto-throttle

The thrust command is formed by the auto-throttle from airspeed deviation $\Delta V$, longitudinal acceleration $a_x$ and pitch attitude $\theta$ (Fig. 4.3). In order to fulfill the requirement for smoothness of thrust even in turbulence and simultaneously to obtain the quickest possible reaction to an airspeed error, the auto-throttle used does not feed the airspeed rate back until additional filtering has been performed on the longitudinal acceleration $a_x$. For this purpose, the total of low-pass filtered $\dot{V}$ ($T_v = 20$ s) and high-pass filtered $a_x - g \sin \theta$, corresponding approximately to $\dot{V}_k$, is fed back to the throttle levers. However, the closed-loop control circuit works against the necessary flight path acceleration for low frequency wind changes of high amplitude, because $\dot{V}_k$ is set to zero and is delayed too much.
4.2.3 Go-around controller

For the non-real-time simulation a simple go-around controller was designed which feeds back only the pitch angle deviation and pitch rate to the elevator. In the go-around a constant pitch angle \( \theta_{\text{sa}} \) is commanded and an angle of attack protection is included to avoid a stall. The angle of attack protection is realized by a pitch angle protection:

\[
\theta = \alpha + \gamma, \quad \gamma = \frac{\gamma_k - \alpha_w}{\gamma_{\text{prot}}} \\
\alpha_w = \frac{u_{\text{w}}}{\frac{V}{\gamma_k} - \frac{w_{\text{w}}}{V}} \\
\alpha < \alpha_{\text{prot}} \\
\theta < \theta_{\text{prot}} \\
\theta_{\text{prot}} = \alpha_{\text{prot}} + \gamma \\
\theta_{\text{prot}} = \alpha_{\text{prot}} + \theta - \alpha
\]

If the pitch angle becomes greater than the protected pitch angle (or the pitch angle is already greater if a go-around is initiated) then the pitch command is reduced in order to limit the angle of attack (Fig. 4.4 and 4.5).

4.3 Guidance strategy for the reactive windshear detection system

The guidance strategy for the reactive windshear detection system is based upon the computation of the averaged F-factor \( F_{\text{av}} \), and applies the boundary levels as suggested by FAA in TSO-C117 [1.6].

Several alert levels were first defined, according to [1.6] in terms of average severity factors \( F_{\text{av}} \) and corresponding thresholds, as shown in Fig. 4.6. One can distinguish the following levels for time-filtering \( t_s = 5 \text{ s} \):

<table>
<thead>
<tr>
<th>Color</th>
<th>Alert level</th>
<th>( F_{\text{av}} ) factor (( t_s = 5 \text{ s} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>green</td>
<td>1</td>
<td>( F_{\text{av}} \leq 0.04 )</td>
</tr>
<tr>
<td>yellow</td>
<td>2</td>
<td>( 0.04 &lt; F_{\text{av}} \leq 0.1 )</td>
</tr>
<tr>
<td>amber</td>
<td>3</td>
<td>( 0.1 &lt; F_{\text{av}} \leq 0.205 )</td>
</tr>
<tr>
<td>red</td>
<td>4</td>
<td>( F_{\text{av}} &gt; 0.205 )</td>
</tr>
</tbody>
</table>

The guidance strategy for the approach/landing and take-off phases have been based on these alert levels, in the numerical simulations.

4.3.1 Approach/landing

There is a distinction between two aspects:

i) the decision to perform a landing or to initiate a recovery manoeuvre;
ii) the guidance laws to be used for either a continuous landing or a recovery manoeuvre.

The decision to go-around is provided by the upper limit of \( F_{\text{av}} \) severity factor, and corresponds to 0.205 for time-filtering \( t_s = 5 \text{ s} \), and 0.10 for \( t_s = 10 \text{ s} \) as shown in Fig. 4.6.

Penetration approach/landing strategy

The guidance strategy consists of adding a constant speed increment \( \Delta V \) to the final approach speed, the increment depending on the computed \( F_{\text{av}} \), as shown in Fig. 4.6. This speed increment can reach a
maximum value of 20 kts above the reference speed. Thus, if the average of the F-factor \( F_a \) enters the "yellow" zone, an increment of 5 kts will be added to the controlled airspeed. If this factor continues to increase such that it enters into the "amber" zone, another 15 kts will be added to the controlled airspeed, which corresponds to a total speed increase of 20 kts. If this still is not sufficient to cope with the windshear and the "red" zone is entered, the go-around mode will be triggered.

Notice that with the reactive system there is no decision logic to reduce the airspeed when exiting the windshear.

**Go-around strategy**

The go-around guidance has already been described above (§ 4.2.3) and consists of applying full thrust and commanding a constant pitch value (in case of go-around in nominal conditions). When encountering a strong windshear, the go-around controller automatically executes an angle of attack protection by reducing the pitch angle, if necessary.

**Remark on go-around initiation**

Usually the criteria to initiate a go-around, when on a precision approach, have been defined by the Airlines Operation Manual (AOM). Several criteria apply, such as:

- deviation from the glide slope (limited to plus or minus one "dot" - one dot corresponding to an angular deviation of 0.25° around a nominal 3° flight path);
- too high a sink rate (> 5 m/s);
- indicated airspeed lower than 1.1 \( V_s \).

As the purpose of this study consists in evaluating forward looking systems, these conditions are not taken into account for the initiation of the go-around simulation in order to simplify the analysis.

**4.3.2 Take-off**

The guidance strategy during take-off is applied only after lift-off for the reactive system and is quite similar to the go-around strategy, i.e. a constant pitch command, corresponding to a nominal steady flight path angle during the initial climb phase. A reduction in pitch is commanded by the control system in order to prevent aircraft from stalling during a windshear encounter.

Also, another strategy will be evaluated in the numerical simulations. It consists of reducing the pitch angle during the first phase of a windshear encounter (in order to increase the airspeed), then to increase the pitch to a higher value than the nominal value, in order to avoid a loss of altitude during windshear penetration. The decision for this higher pitch is made if the actual vertical speed exceeds a preset vertical inertial speed.

**4.4 Guidance strategy for the forward looking windshear detection system**

Guidance strategies are proposed in this section which can be executed manually or automatically so as to enable the crossing of a windfield with a maximum level of safety, taking into account:

1. available measurements provided by a forward looking sensor of the lidar Doppler type;
2. other measurements from sensors already existing on the aircraft.

As the information coming from a forward looking sensor of the Doppler-lidar type is limited to wind (and shears) along the beam, the associated guidance strategy for an automatic flight must also take into
account other measurements from the existing on-board sensors. For this purpose it is assumed that the aircraft is also equipped with a reactive detection system, i.e. the assumption is made that these aircraft sensors also allow an F-factor to be computed associated with a reactive detection system.

Guidance strategies must take into account the following properties:

i) simplicity of execution;
ii) robustness against windshear fields;
iii) high level of flight safety.

Integrating on-board information coming from a forward looking system and a reactive system is quite complex since one must take into consideration partial information ahead of the aircraft. Moreover this far ahead information about windfields is likely to change depending on the real trajectory of the aircraft.

4.4.1 Approach landing

As previously, there are two aspects:

1) decision strategy for landing or for initiating a recovery manoeuvre;
2) proper guidance law to be provided to the aircraft so as to carry out the decided manoeuvre in the best way.

Decision criteria are suggested below for a forward looking sensor of the Doppler-lidar type in the worst condition, i.e. with reduced range (less than 2000 m). In this condition, due to a small scanning space volume available with this sensor (in reality limited to about +/-10 degrees about nominal beam reference axis) the escape manoeuvre is limited to the vertical plane only. Indeed, with such a sensor the space volume that could be explored would not provide sufficient and accurate enough information on the windfield surrounding the aircraft to allow a safe lateral escape manoeuvre to be considered.

The decision is based upon either the severity factor computed using the F-factor from Doppler lidar measurements, or from the predicted altitude loss, called the X-factor as suggested by Woodfield (see § 3.3).

The F-factors derived from the laser information are tested with the same hazard levels as defined for the reactive system (Fig. 4.6 and 4.7).

The decision to initiate a go-around is provided by the upper limit of the alert level, which corresponds to the boundary of "red alert" in Fig. 4.6 for criteria associated with $F_{\text{Laser}}$, and a predicted altitude loss of 20 m with criteria associated with the X-factor.

As previously, the go-around strategy is performed by a go-around controller and pitch control is thus identical to that of the reactive detection system.

Penetration approach/landing strategy

In case of a windshear penetrating approach (by assuming that threshold levels, associated with windshear detection never enter the "red alert" zone) a more complex airspeed guidance strategy than for the reactive system is suggested. This is described below, for a typical microburst encounter.
Penetration phase

1) Alert level 1 : Normal approach with \( V_e = V_{ref} \);
2) Alert level 2, 3 : Penetrating approach, with speed increments, up to a maximum of 20 kts relative to the reference speed \( V_{ref} \).

End of windshear

The strategy used is defined as :

- a speed reduction back to approach speed depending on the alert level, in the reverse way as during the entering phase ;
- for recovery manoeuvre : constant pitch attitude equal to the nominal pitch attitude without windshear.

The guidance law was used with measurements coming from the reactive detection system. In real life this guidance law should be applied in combination with measurements coming from forward looking sensors in order to be sure that there is no risk of encountering another windshear in front of the aircraft.

Fig. 4.6 and 4.7 sum up the suggested strategies linked to F and X severity factors for the approach/landing phase. Fig. 4.8 shows in the \((\Delta V_e, L_\tau)\) plane a comparison between the alert levels provided by F and X severity factors, as applied to a generic aircraft model.

4.4.2 Take-off

Contrary to the reactive system, a forward looking windshear detection system can be used during the ground-roll phase in order to abort a take-off before decision speed \( V_1 \). Of course during this ground-roll phase, it is necessary to use another scanning process with the laser beam.

The take-off decision and guidance strategy associated with a forward looking sensor are suggested during ground roll and after lift-off as follows (see also [1.7]) :

1) Before lift-off :
   - Before decision speed \( V_1 \) : abort take-off for any windshear alert ;
   - After decision speed \( V_1 \) : carry out take-off and adopt the strategy below.

2) After lift-off (altitude > 50 ft) :
   - Alert level = 1 : normal take-off ;
   - Alert level 2, 3, 4 = pitch attitude guidance law with stall protection.

In fact the take-off strategy is similar to the go-around strategy : it consists of reducing the pitch attitude so as to increase speed- during increasing headwind encounter, then to increase pitch up to a high value so as to prevent an altitude loss.

As this study is more concerned about guidance strategy associated with FLS, only the lift-off phase was performed in the numerical simulations.
4.5 Summary of guidance strategies and definition of control systems

Fig. 4.6 and 4.7 sum up the guidance strategies associated with windshear detection systems during the approach/landing and take-off flight phase as described before.

In the next chapter, the following definitions will be used:

- **reactive system without strategy** or basic AP (automatic-pilot): this configuration is very close to the situation where a reactive system is used by airlines for windshear escape, and it consists of a classical control system for ILS tracking (i.e. auto-pilot) and an auto-throttle maintaining *constant* airspeed; the reactive windshear detection is applied for go-around initiation only;

- **reactive system with strategy**: it consists in using the same system as above, but with a speed increment strategy associated with reactive windshear thresholds as described in § 4.3;

- **forward looking system** with a guidance and control strategy associated with a forward looking sensor as described in § 4.4 and summarized in Fig 4.7.
5. RESULTS OF NUMERICAL SIMULATIONS

5.1 General assumptions

As mentioned previously, the response of an aircraft equipped with an airborne windshear detection system during a windshear encounter can be influenced by a large number of parameters such as:

- type and characteristics of windshear;
- type of windshear detection sensor (reactive or forward looking sensor);
- parameters associated with the windshear detection system (filtering time-constant, type of data-processing, beam stabilization, grid-size for Doppler-lidar type, etc.);
- hazard criteria for windshear detection thresholds;
- guidance strategies.

To achieve the objectives of the study, the numerical simulations were organized as follows:

- simulation results with the reactive windshear detection system are first analysed, and only worst cases of the windshear models are used for more detailed simulations;
- a brief analysis of the influence of several parameters involved with the forward looking system on aircraft performance allows a reduction in the number of parameters which remain to be evaluated in the parametric study;
- finally numerical simulations are then performed with a reduced number of significant parameters.

Table 5.1 presents a summary of the experimental factors used in the numerical simulations.

5.2 Experimental design

Numerical conditions which have been defined for both approach/landing and take-off simulations are given hereafter. The ground-roll during the take-off and flare during the landing were not simulated.

**Approach/landing**

All the trajectories of aircraft response are based upon the following initial conditions:

- horizontal distance $X_0$ from the runway nominal touchdown point, which is chosen as the origin of reference axis = 9 951 m (Fig. 1.2);
- altitude $H_0$ (= 500 m) on the nominal glide path (path angle of - 3°);
- true airspeed $V_0$ = 69.5 m/s.

Other aircraft parameters are given in Table 5.2.

Numerical simulations are ended at nominal final conditions defined by the nominal height of 50 ft (in case of a penetrating approach) or at 600 ft (in case of a go-around), or other conditions which are linked to an abnormal trajectory (crash) or limit of validity of the model in use (maximum angle of attack for penetrating landing).

For the penetrating approach/landing, the following parameters quantify the quality of the end of the approach phase, at final altitude $H_f$ = 15 m:

- $u_k$ = horizontal inertial speed
- $w_k$ = vertical inertial speed
- $\Delta x_r$ = horizontal deviation around runway threshold = ($x_r - \bar{x}$)

$u_k < u_{k_{\text{max}}}$
$w_k < w_{k_{\text{max}}}$
where $x_f$ is the horizontal distance from the origin of the reference axis (at altitude $H_t = 15$ m), $\bar{x}_f$ is the x-coordinate of the runway threshold $\bar{x}_t = -286$ m. Nominal values for these parameters are (Fig. 1.2 and Table 5.2): $u_k = 3$ m/s, $w_k = 3$ m/s, $\Delta x_t = 0$.

Moreover, in order to better analyse different guidance strategies, particularly the speed increment strategy during a windshear penetrating approach, the approach/landing simulations have been performed as follows:

i) penetrating landing with go-around decision inhibited;

ii) aborted landing (i.e. a go-around was triggered) where the go-around initiation is provided by the windshear detection logic only.

**Take-off**

Numerical simulations for take-off are initialized with the aircraft state at a nominal obstacle clearance altitude $H_o = 15$ m at $t_o = 0$. The computations are ended at the final altitude $H_f = 600$ m, or at a final time of $t_f = 40$ s which ever comes first.

The main parameters investigated during take-off are minimum altitude, minimum airspeed and maximum angle of attack respectively during the windshear crossing phase.

**Numerical results**

Table 5.3 summarizes the main simulations which have been performed and which are commented and analysed hereafter.

**5.3 Selection of reference reactive windshear detection system**

The choice of a reference reactive windshear detection system (RWDS) was based upon the simulation of a penetrating approach, with a microburst encounter. The generic aircraft was controlled by the auto-pilot and the auto-throttle as described in Chapter 4, and the microburst model has characteristics as described in § 5.5 (wind 1) and was centered at 3000 m from the runway threshold.

In the presence of a moderate microburst the aircraft successively encountered an increasing headwind, a windshear (decreasing headwind to increasing tailwind), a downdraft and finally a decreasing tailwind (Fig. 5.1). Under the effect of a downburst in such a scenario the aircraft flies above the nominal approach glide path and then below that path; for the airspeed $V$, one can note first a slight increase, then a loss. As the thrust is increased to compensate for the speed loss, $V$ overshoots the nominal speed at the exit of the microburst encounter, which is followed by a maximum reduction of thrust. Landing is then performed with a tailwind, with the ground speed and vertical speed likely to be too high.

All the parameters are presented in Fig. 5.2, including the F-factor and the energy-height error. This F-factor is computed at each instantaneous time $t$; the average $F_{av}$ factor is computed over a time interval $t_i$. Fig. 5.3 presents various alert levels associated with $t_i$ between 3 and 15 s (see also Fig. 4.6). Averaging the F-factor introduces a delay on the alert value; the longer the time $t_i$, the greater the delay is.
Moreover, the time-filter interval $t_\alpha$ also modifies the alert value as follows:

- with time $t_\alpha = 3\, s$, the maximum alert level achieved is 3, whatever the value of $F_{\alpha\alpha}$, as suggested by TSO-C117 [1.6], and illustrated in Fig. 4.6; that means also there is no go-around decision made with this time interval $t_\alpha$;
- with time $t_\alpha$ between 5 s and 10 s, all alert levels (from 1 to 4) can be reached, and they depend on the value of $F_{\alpha\alpha}$; in the simulation presented in Fig. 5.3, the maximum alert level 4 is reached with time $t_\alpha=7\, s$ and 10 s respectively, but time $t_\alpha = 5\, s$ provides only alert level 3; this means that with $t_\alpha = 5\, s$ no go-around would be initiated in this simulation case;
- with time $t_\alpha = 10\, s$ and 15 s, there is no alert level 3, and alert level 4 is reached when $F_{\alpha\alpha}$ becomes larger than 0.1.

The filtering effect is small with respect to the change of critical value of $F$ which determines the boundary for the red alert zone provided by TSO [1.6].

In the presence of turbulence it is necessary to filter the F-factor as suggested by the FAA in order to avoid a higher level of false alarms. Fig. 5.4 presents the results obtained with computations similar to those shown in Fig. 5.2 and 5.3, but with the turbulence taken into account in the windshear model. In the presence of turbulence, the necessity can be seen to adopt a large enough time-filter interval $t_\alpha$ in order to avoid high levels of false alarms. With time $t_\alpha = 3\, s$, several changes of alert level are observed when entering the shear, as shown in Fig. 5.4. These changes disappear, with time $t_\alpha$ larger than 5 s, at least with the simulated wind profile which was considered.

In the following the reactive system is simulated with a time-filtering $t_\alpha = 5\, s$, which seems to be the best compromise between the delay of the alert time and the reduction of the false-alarm rate due to turbulence.

**5.4 Selection of nominal forward looking windshear detection system**

This analysis was performed for the approach segment along the ILS with a microburst encounter, in a similar way as in the previous paragraph. Two windfields were used for this purpose (wind 1 and wind 2 as described in § 5.5).

Along the aircraft flight path, various characteristic parameters associated with the FLS, as shown in Table (5.1), were computed:

- Fig. 5.5 shows the aircraft parameters, the severity factors related to the reactive windshear detection system and some parameters related to the FLS ($F_{\text{laser}}$ measurements and angle of laser beam to x-reference axis);
- Fig. 5.6 and 5.7 show various processing techniques associated with $F_{\text{laser}}$ measurements, computation of wind change according to the X-factor, and the corresponding alert levels;
- Fig. 5.8 and 5.9 show, for different aircraft position along its flight path (presented in terms of time to the instant where the aircraft reaches its nominal final altitude of 15 m), the volume of the space scanned by the laser beam; Fig. 5.8 is related to a laser beam stabilized along the aircraft inertial path, and Fig. 5.9 is related to a laser beam fixed along an aircraft reference axis; these figures also show the results of $F_{\text{laser}}$ obtained by spatial averaging;
- Fig. 5.10 shows the influence of the laser beam stabilization mode on the $F_{\text{laser}}$ measurements, with a range defined as $R_{\text{min}} = 350\, m$ and $R_{\text{max}} = 2100\, m$, and a grid size $= 350\, m$;
- Fig. 5.11 shows the effect of FLS range and grid size on the $F_{\text{laser}}$ measures;
- Fig. 5.12 shows the effect of FLS range on the measure of wind change, by using X-factor computation.

All these effects are analysed in more detail hereafter.
5.4.1 Choice of data processing with $F_{\text{laser}}$ measurements

Two methods of computing the F-factor associated with laser measurements have previously been described:

1. Spatial averaging between the two ranges $R_{\text{min}}$ and $R_{\text{max}}$; the values obtained are defined by $\overline{F}_{\text{laser}}$ given by Eq. (3.17) (§ 3.3.2);
2. Time averaging over interval $t_c$ of several data processing techniques associated with Doppler lidar measurements, as described in § 3.3.2.

1) Spatial averaging

Fig. 5.8 shows in detail the variations in $F_{\text{laser}}$ factors due to the data-processing applied during the various phases of the microburst crossing. The characteristics chosen in this example are: range 350-2100 m, grid-size 300 m, stabilization along the inertial flight path. The time interval $(t-t_0)$ is counted from the final instant $t_c$ where the aircraft reaches the final altitude of 15 m.

In the area where the headwind increases (-110 s, -90 s), the $F_{\text{laser}}$ factor is negative all along the beam. When the beam penetrates the windshear area (70 s) $F_{\text{laser}}$ changes sign. At the centre of the microburst $F_{\text{laser}}$ reaches the maximum positive value (50 s). At the end of the windshear, when the tailwind decreases, $F_{\text{laser}}$ changes sign again and becomes negative (30 s).

Since the spatial averaging ($F_{\text{laser}}$) lowers the value of the F-factor it will not be used in the following.

2) Time averaging

Fig. 5.6 provides several data-processing techniques applied to $\{F_{\text{laser}}(i)\}$ measurements before time-filtering:

\[ \text{a) } \text{Abs} \ (F_{\text{laser}}) = \max_{i=1,N} |F_{\text{laser}}(i)| \]
\[ \text{b) } F_{\text{max}} = \max_{i=1,N} F_{\text{laser}}(i) \]
\[ \text{c) } F_{\text{min}} = \min_{i=1,N} F_{\text{laser}}(i) \]

The maximum of the absolute value of $F_{\text{laser}}$, presented in Fig. 5.6a (dashed line), shows two parts: one increasing part which is due to the microburst crossing, and one decreasing part which is due to the earth's boundary layer. This data processing technique does not enable the dangerous area to be distinguished from the area where the aircraft increases its energy (increasing headwind, or decreasing tailwind). By comparing it to the F-factor of a reactive system (Fig. 5.6), it can then be noted:

- the severity factor based on the $F_{\text{laser}}$ is less than the F-factor from the reactive system within the microburst; such a difference is due to the absence of the vertical wind component in the $F_{\text{laser}}$ measurements;
- when the system ranges close to the ground the $F_{\text{laser}}$ factor the level becomes larger with a large variation in amplitude. This is due both to large variations in flight path and to the earth boundary layer at the end of the approach phase;
- the laser system provides an earlier alert.

In order to separate positive from negative effects we will in what follows only retain the maximum positive value of $F_{\text{laser}}(i)$ which characterizes the danger (within the microburst) (Fig. 5.6 "Max $F_{\text{laser}}$.")
One can also see in Fig. 5.6e the instantaneous value of \( \text{Max } F_{\text{laser}} \) and its time average value: \( \text{Max } F_{\text{laser}} \times 5 \text{ s} \) with a time-constant equal to 5 s. Later this time average will be used for the determination of a guidance strategy and will be noted by the symbol \( F_{\text{opt}} \) for the sake of simplification.

Fig. 5.7 shows similar data processing applied to \( F_{\text{laser}} \) measurements, but related to the more severe microburst wind profile. This figure also shows various data processing techniques applied to ideal laser measurements (\( F_{\text{sat}} \) symbol). In this case the laser measurements provide almost the same values as \( F_{\text{opt}} \), given by a reactive windshear detection system, but with an alert time equal to the ratio of the maximum range of FLS to the aircraft velocity.

### 5.4.2 Stabilization modes

Three stabilization modes were considered (beam stabilized along inertial flight path, inertially stabilized in pitch and fixed in the aircraft reference frame).

Fig. 5.8 presents simulation results performed with a laser beam stabilized along the inertial flight, and Fig. 5.9 with the laser stabilized at a fixed angle in the aircraft reference axis. Fig. 5.10 shows the differences between both stabilization modes ("\( \theta \) laser" parameter) in flight path as well as in the forward looking factor. Except for the constant angle in the aircraft axis the other two modes provided identical \( F_{\text{laser}} \) measurements during the microburst crossing.

Differences between these two modes appear when the laser beam ranges through the earth's boundary layer. Because of the small differences between these two modes the alignment along the flight path angle was preferred because it more closely follows the future flight path.

### 5.4.3 Grid size

As is shown in Fig. 5.11 the several along beam discrete grid size values (between 150 and 350 m) did not significantly affect the amplitude of \( F_{\text{laser}} \) outside the boundary layer. Therefore it was decided to use a grid size value of about 150 m.

### 5.4.4 X-factor computation

Fig. 5.12 shows the application of the X-factor obtained for \( \Delta V_S \) with windshear length \( L_S \) along a penetrating approach trajectory with various look-ahead distances. For each aircraft discrete position \( (x(t)) \) along the flight path, \( \Delta V_S \) was computed according to the relation (Eq. (3.24) in Chap. 3), by assuming an horizontal flight path:

\[
\Delta V_S = u W (x(t)+R_{\text{max}}) - u W (x(t)+R_{\text{min}})
\]

where \( R_{\text{max}} \) and \( R_{\text{min}} \) are respectively the maximum and the minimum range of the Doppler-lidar system.

Fig. 5.12 shows the results obtained with the following numerical values: \( R_{\text{min}} = 0 \); \( R_{\text{max}} = 700 \text{ m}, 1400 \text{ m}, 2100 \text{ m}, ... \)

### 5.4.5 Nominal forward looking windshear detection system

In what follows, simulations were performed with a nominal forward looking detection system having the following characteristics:

- the use of the severity factor \( F_{\text{laser}} \) as described in Eq. (3.20),
- laser beam stabilized along the inertial flight path angle,
- a look-ahead distance of 1400 m, which corresponds to an alert time of about 20 s.
5.5 Selection of worst case wind field

In order to determine the wind field model to be used in further simulations, approaches/landing have been simulated with the following wind profiles (see description in § 2.2):

1) Downburst:

- Three windshear profiles were used which correspond respectively to a moderate (wind 1), a severe (wind 2) and an extreme (wind 3) microburst:

<table>
<thead>
<tr>
<th>wind 1</th>
<th>wind 2</th>
<th>wind 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{max}} = u_{w_{\text{max}}} = 12 \text{ m/s}$</td>
<td>$U_{\text{max}} = u_{w_{\text{max}}} = 20 \text{ m/s}$</td>
<td>$U_{\text{max}} = u_{w_{\text{max}}} = 28 \text{ m/s}$</td>
</tr>
<tr>
<td>$W_{\text{max}} = w_{w_{\text{max}}} = 9 \text{ m/s}$</td>
<td>$W_{\text{max}} = w_{w_{\text{max}}} = 13 \text{ m/s}$</td>
<td>$W_{\text{max}} = w_{w_{\text{max}}} = 13 \text{ m/s}$</td>
</tr>
<tr>
<td>$R = 892 \text{ m}$</td>
<td>$R = 892 \text{ m}$</td>
<td>$R = 713 \text{ m}$</td>
</tr>
<tr>
<td>$z_{m} = 40 \text{ m}$</td>
<td>$z_{m} = 40 \text{ m}$</td>
<td>$z_{m} = 40 \text{ m}$</td>
</tr>
</tbody>
</table>

The distance from the core of the microburst to the touch-down point is a parameter which is taken into account in the numerical simulations.

2) Low-level jet: the worst case of this windfield which has been encountered corresponds to the following characteristics [2.6]:

- Reference height $H_{\text{ref}} = 300.0 \text{ m}$ ; reference windspeed $V_{w_{\text{ref}}} = 16 \text{ m/s}$ ;
- Jet height $H_{J} = 120 \text{ m}$ ; jet velocity $V_{w_{J}} = 13 \text{ m/s}$ ; exponent $m = 0.6$.

The following three configurations were used (see definition in § 4.5 and above § 5.3 and § 5.4):

- Basic automatic pilot AP ;
- Reactive system with speed increment strategy ;
- Nominal forward looking system.

The simulations with the low-level jet model are shown in Fig. 5.13-5.15. Those with the downburst models are shown in Fig. 5.24 to 5.26.

Fig. 5.13-5.15 show that the worst low-level jet wind field does not represent a danger to the aircraft safety. Fig. 5.13 shows that a classical auto-pilot (with classical auto-throttle) can provide ILS tracking during approach/landing with enough safety, except for a slight overshoot of one "dot" glide slope deviation at a height of about 25 m, a few seconds before flare initiation. Results with the windshear detection system are very similar to those shown in Fig. 5.13-5.15.

The moderate microburst (wind 1) provides similar results to the low-level jet on the influence of the windshear detection system on aircraft performance (Fig. 5.2 or 5.5).

Only the extreme downburst (wind 2) can demonstrate the interest of the forward looking windshear detection system to improve aircraft safety, as can be seen in Fig. 5.24 to 5.26. The severe downburst (wind 2) did not provide a critical enough situation for the purpose of this study.

Further simulations were performed with this extreme downburst model (wind 3).
5.6 Penetration landing in the presence of a microburst

The simulations dealt with in this paragraph are performed without using the go-around strategy so as to assess the effect of a speed increase in comparison to a constant reference speed.

5.6.1 Comparison between reactive and forward looking systems

Fig. 5.16-5.18 present the response of a generic aircraft model during a penetrating landing, with a microburst centered at 4000 m from the runway threshold. With the reactive system the aircraft stalled about half way down the approach. It was found that increasing the approach speed early enough which was obtained with the nominal FLS improved the stall margin and the aircraft could reach the runway threshold in good landing conditions.

5.6.2 Effect of look-ahead distance

During the approach along the glide path with the AP on, a forward looking system provides a timely alert such that the approach speed can be increased which allows the microburst to be traversed. Fig. 5.19 shows the results of an approach simulation using a forward looking system with a 2100 m range (and the $F_{\text{per}}$ factor) across a severe microburst. The trajectory is strongly altered and the limits of ±1 dot are exceeded, as well as the limit $V/V_S = 1.1$. At the center of the microburst the thrust is at its maximum value while it is completely reduced in the tailwind leg. Overshooting the glide path imposes a high descent rate (up to 10 m/s) in order to recapture the nominal trajectory; this manoeuvre is especially dangerous when the aircraft is close to the ground.

Fig. 5.20 shows the trajectory and flight parameters as a function of forward looking distance, for the same microburst. The conditions found at $H_I = 15$ m are presented in the table below:

<table>
<thead>
<tr>
<th>Look-ahead distance</th>
<th>$\Delta x_I$</th>
<th>$w_{so}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 m</td>
<td>- 148 m</td>
<td>+ 5.4 m/s</td>
</tr>
<tr>
<td>1400 m</td>
<td>- 23 m</td>
<td>+ 3.7 m/s</td>
</tr>
<tr>
<td>2100 m</td>
<td>- 12 m</td>
<td>+ 3.5 m/s</td>
</tr>
</tbody>
</table>

The final conditions for the short range (700 m) are not acceptable, as shown in the table. For longer range (1400 m and 2100 m), the aircraft reached the altitude of 15 m with good conditions, both with respect to position along the runway as well as for vertical speed, and could safely perform the flare and landing.

5.6.3 Effect of location of microburst

For a given microburst windfield the position along the approach flight path relative to the touch-down point has a large influence on the safety of the aircraft flight.
The table below indicates the results of a simulation performed with a forward looking system (1400 m range and speed strategy based on $F_{\text{min}}$) with the microburst windfield being located at different distances along the approach flight path.

<table>
<thead>
<tr>
<th>Distance of microburst/runway from threshold</th>
<th>- 5000 m</th>
<th>- 4000 m</th>
<th>- 3625 m</th>
<th>- 3250 m</th>
<th>- 2500 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude where first red alert occurs</td>
<td>380 m</td>
<td>300 m</td>
<td>290 m</td>
<td>260 m</td>
<td>240 m</td>
</tr>
<tr>
<td>Final conditions ($H_r = 15$ m)</td>
<td>landing</td>
<td>landing</td>
<td>landing</td>
<td>too high</td>
<td>overshoot</td>
</tr>
<tr>
<td></td>
<td>possible</td>
<td>possible</td>
<td>possible</td>
<td>sink rate</td>
<td>&quot;glide&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$w_{ks} = 3.9$ m/s</td>
<td>$w_{ks} = 7.48$ m/s</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>5.21</td>
<td>5.21</td>
<td>5.21</td>
<td></td>
<td>5.21</td>
</tr>
</tbody>
</table>

One can see that the aircraft's behavior is all the more critical the closer the microburst is located to the runway threshold.

### 5.6.4 Comparison between forward looking hazard factors

Penetrating approaches/landing in the presence of a severe microburst with a forward looking system is difficult whatever the type of hazard criterion applied. Using the X-factor (Fig. 5.22), or the ideal $F_{\text{in}}$ factor (Fig. 5.23) produced results similar to those of the $F_{\text{int}}$ factor (Fig. 5.21). The maximum angle of attack which was reached along the approach trajectory increased and was strongly related to the intensity of the horizontal windshear.

These results show that the severity level of the microburst was too severe, so that the behavior of the aircraft became independent of the severity factor under consideration.

### 5.7 Aborted landing

#### 5.7.1 Comparison between reactive and forward looking systems

Guidance strategies coupled to a forward looking detection system with go-around logic were evaluated in a strong microburst windfield located at 5000 m and then at 2500 m from the runway threshold, i.e. with the same conditions simulated as in the previous case of a penetrating landing.

Figures 5.24 to 5.26 display the results obtained with the following guidance strategies ($\S$ 4.4.5) :

1) Reactive system without speed increment strategy (basic AP with go-around initiated by the reactive system);
2) Reactive system with speed increment strategy;
3) Nominal forward looking system.

The following can be noted :

- increasing the speed before actually entering the shear may increase the survivability of the aircraft;
- the earlier the speed is increased, the better the energy state of the aircraft will be, which shows the importance of a forward looking system (Fig. 5.25);
- the advantage of a forward looking system compared to a reactive system is that the go-around can be initiated early enough to enhance the aircraft's flight safety (Fig. 5.24 to 5.26).
5.7.2 Effect of the look-ahead distance and the location of the microburst

The results of the simulations are shown in Fig. 5.24-5.26, 5.31 and 5.32. These are quite similar to the results for penetrating landing.

One can see that in a critical windshear encounter the suggested guidance strategy with a forward looking sensor, allowing a 20 s alert time (1400 m range) increases aircraft safety when crossing. The trajectory of the aircraft - illustrated in Fig. 5.24-5.26 - remains above the nominal descent flight path (represented by the broken line).

With a look-ahead distance of a shorter range (700 m) the results (Fig. 5.31, 5.32) are similar to those obtained with a reactive system, and are therefore not safe enough for the conditions of simulation presented here.

5.7.3 Comparison of forward looking severity measures

It should be recalled that the $F_{2D}$ factor is a theoretical factor computed by using the horizontal and vertical wind components along the laser beam. The amplitude of $F_{2D}$ is then similar to the F-factor obtained with a reactive sensor. In Fig. 5.27, 5.28 and 5.30 go-around trajectories for three different locations of the same microburst windfield are shown with guidances strategies corresponding to the $F_{laser}$, the $F_{2D}$ and the X-factor (1400 m range).

The look-ahead measure of the exact severity of the phenomenon (provided by $F_{2D}$) allows the go-around procedure to be initiated earlier than with the $F_{laser}$ or the X factor. Such a go-around may then be performed under satisfactory safety conditions. Indeed the $V/V_S$ ratio remains above 1.1 and the maximum angle of attack stays below 15°.

Go-around trajectories in relation with $F_{laser}$ and X factors led to similar minimum conditions. In both cases the minimum $V/V_S$ ratio was quite the same as above. In the most severe case (Fig. 5.30) a drop below 1.1 could be noted.

5.8 Take-off

During take-off, after the lift-off phase, the most interesting cases are those where extreme microbursts are encountered far enough from the runway. Indeed, a take-off should already be aborted in cases where these microbursts are detected to be near the runway, e.g. by airport equipment or on-board forward looking windshear detection systems.

5.8.1 Comparison between various flight systems

Figures 5.34 to 5.37 present the response of the generic aircraft during take-off, after clearing an obstacle height of 15 m, with the following flight control systems:

- basic control system (i.e. with constant pitch);
- reactive system with pitch guidance strategy, as described in § 4.4.3 (Fig. 4.7);
- nominal forward looking system with guidance strategy described above (§ 4.4 and Fig. 4.8).

These results lead to the following comments:

- the guidance strategy associated with a windshear detection system (reactive or forward looking system) does not provide better results than those obtained with a constant pitch attitude command (with angle of attack protection system);
- the forward looking system does not provide better results, in these cases, than the reactive system does, as can be seen in Fig. 5.35 to 5.38; the results show that, when encountering extreme windshear, the behavior of the aircraft relies more on its performance than on the applied guidance strategy and windshear detection systems.
5.8.2 Effect of downburst location and look-ahead distance

As mentioned already before the aircraft response exhibits a low sensitivity to changes in forward looking system characteristics, or in the location of the microburst, as shown in Fig. 5.36-5.38.

The results also remain unchanged when hazard factors used are replaced by the ideal $F_{2D}$.

5.9 Summary of results

It should be noted that other numerical simulations than those presented above were also performed in order to evaluate some parameters of the guidance strategies which were associated with the windshear detection systems.

Penetrating landing

In case of an actual situation of an extreme microburst, the aircraft would initiate a go-around manoeuvre. This go-around strategy was inhibited, however, in the numerical simulations in order to evaluate the effect of speed strategy coupled to a windshear detection system.

This speed strategy was evaluated under the following conditions:

i) a speed increment of up to a maximum of 20 kts above the reference approach speed when entering the microburst, in terms of severity factors, for both reactive and forward looking systems;

ii) a speed reduction, back to reference approach speed, at the exit of the microburst, used with a forward looking system, in combination with a reactive system. All the numerical simulations presented above, adopted this speed decrement strategy.

Concerning point i), Fig. 5.39 shows the following characteristic parameters along the approach trajectory: maximum angle of attack reached, the minimum and maximum value respectively of the airspeed, presented by the ratio $V/V_{\text{r}}$ and the maximum value of $F$-factor and $F_{\text{lidar}}$.

These results are plotted versus the position of the microburst from the runway threshold, and for various windshear detection systems parameters. They confirm the following issues:

- in the presence of a severe/extreme microburst, increasing the approach speed early enough (with a forward looking detection system) allows aircraft stall to be avoided;

- with the same windfield model, the location of the microburst along the approach trajectory changes the windshear parameters on the aircraft: the maximum $F$-factor sensed by the reactive system is independent of the downburst position and equal to 0.45. Values of the Doppler-lidar ($F_{\text{lidar}}$) show that the radial windshear (which is sensed by the FLS) is more important when the microburst is located closer to runway threshold.

Concerning point ii), Fig. 5.40 presents results of airspeed and inertial speed at final altitude of $H_f = 15$ m with a nominal forward looking system (look ahead distance of 1400 m), with and without using the speed decrement strategy respectively at the end of the windshear. The following comments can be made:

- without airspeed reduction, the aircraft reaches the altitude of 15 m with an excessive horizontal ground speed, and a vertical speed which exceeds the maximum allowable limit for landing, in case the microburst is located 4000 m from the runway threshold;

- with airspeed reduction, all final conditions on airspeed and on inertial speed components remain below the acceptable limits for a normal landing condition.
Aborted landing

Go around initiation

Figures 5.41 and 5.42 respectively show the aircraft altitude, severity factor and aircraft parameters at the instant where the go-around was initiated, with different windshear detection systems. For a microburst located at 2.5 km or 4.0 km from the runway threshold, the go-around was initiated by the windshear detection algorithm (Fig. 5.41d and 5.41e). Go-around initiation occurred earlier for the FLS than for the reactive system, and depended strongly on the forward looking distance of the Doppler-lidar.

For a microburst located at 5.0 km from the runway threshold, go-around initiation occurred earlier with the reactive system than with the forward looking systems. For this case, the go-around was initiated by other parameters than by the forward looking hazard factor (Fig. 5.41c).

Aircraft parameters

For several windshear detection systems Fig. 5.43 sums up the characteristic parameters of the aircraft along the recovery trajectory: minimum altitude reached, maximum sink rate, maximum angle of attack, maximum pitch angle, the maximum F-factor and $F_{\text{laser}}$ from the windshear detection systems.

These results illustrate the following outcomes:

- since forward looking systems provide earlier go-around initiation than reactive systems, they allow an increased survivability of the aircraft during crossing the windshear. A large look-ahead distance allows the microburst to be penetrated with increased safety: the minimum altitude is higher and the maximum angle of attack or pitch angle is lower than with a short look ahead distance;
- for a reactive system, the adoption of a speed increment strategy may improve survivability, as can be seen in case of a microburst located at 4 km from the runway threshold.

Comparison between $F_{\text{laser}}$ and $F_{2D}$

Fig. 5.44 shows a comparison of results obtained with $F_{\text{laser}}$ and $F_{2D}$. These results illustrate the underestimation of windshear severity by a forward looking system which only senses the radial component of windshear (i.e. $F_{\text{laser}}$), the consequence of which consists of a delay in the detection of the windshear severity. The time delay is in order of 20 s (XdB = 5 km) 10 s (XdB = 4 km) 4 s (XdB = 2,5 km).

This delay is strongly dependent on the parameters which are involved in the simulations (wind profile, severity factor, logic decision, laser-beam stabilization, etc.).
6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Model aspects
Models of a reactive and a forward looking windshear detection system (the latter of the laser type) were developed and successfully applied for the purpose of numerical simulation. A linear aerodynamic model of a generic twin-engined heavy transport aircraft was used in the simulations. The conclusions are only valid within the limitations of the models used.

6.1.2 Numerical simulations
A. APPROACH AND LANDING

The numerical results have shown that:

Reactive system

A reactive system's functioning is sensitive to the filter time applied to the F-factor averaging process. There is a compromise between early detection and turbulence rejection. The averaging process affects flight safety in a negative sense.

A speed increment based on the information from a reactive windshear detection system, allows an increase in aircraft safety, but not enough to help the aircraft to get out of danger when encountering a severe or extreme microburst.

Since a reactive system only senses the windshear once the aircraft is in the shear already, the starting position of the aircraft, if compared to a go-around (or recovery) initiated on a forward look alert, is less favorable and therefore the performance degradation to occur will be larger.

Laser System

Comparable results for the various F-factor definitions for the forward looking windshear detection system were obtained, in terms of aircraft performance. Since the laser system does not measure or derive the vertical component of the windshear, it underestimates the real windshear danger.

Results prove that an early detection and go-around initiation can lead to a safe way out (escape) of the windshear, whereas a recovery, initiated after a reactive system alert occurred, sometimes lead to a crash.

Results indicate that the earlier the windshear is detected the better. A minimum detection range of 2100 m, or equivalently a lead time of 30 s leads to the best flight safety. For a lead time of 10 seconds, the results of the laser system can be compared to those of a reactive system. Therefore a minimum lead time of 20 s is an absolute minimum to improve flight safety for a fully automated windshear detection system coupled to a guidance strategy.

An early increase in flight speed, in order to increase the energy level of the aircraft before entering the shear, improves flight safety.

The combined use of a reactive and a forward looking windshear detection system seems to be the most promising concept. Indeed, this allows a speed decrement strategy to be used at the exit of microburst,
with enough safety. Furthermore, the reactive system provides a redundancy in the windshear detection. This could allow for a safer penetrating approach and landing under windshear conditions.

B. TAKE-OFF

Reactive system
Compared to an aircraft flying into a downburst without a pitch strategy, a small improvement in flight safety could be observed, if the pitch strategy is used to prevent further speed loss by pitching down.

Laser system
The main advantage of a forward looking system derives from its capability to provide early information to the pilot during the ground roll phase, in order to abort the take-off before reaching decision speed $V_1$.

After lift-off an early pitch down, as the result of a laser windshear alert, in order to gain speed before entering the shear, the limited simulation results showed an improvement of flight safety. However it may be in conflict with the pilot's operational procedure for maneuvering at low altitude.

6.1.3 Sensing algorithms for forward looking systems
This study took into consideration a forward looking system, based upon a Doppler-lidar sensor, which measures the Doppler derived air velocities along the laser beam. Some characteristic parameters of the Doppler-lidar were evaluated in numerical simulations such as: laser beam stabilization modes, various data processing associated with the whole set of Doppler-lidar measurements, which could be obtained at each instant, by focusing the laser beam at various distances in front of the aircraft or by using a pulsar laser.

The outcomes of this parametric study are:

- among the three stabilization modes which were considered (i.e. the beam stabilized along the inertial flight path, along an inertial pitch angle, or fixed in the aircraft reference frame) the differences between the stabilization along the flight path vector or an inertial pitch angle were small, and revealed to be more suitable than the body-fixed mode for an appropriate early windshear detection;
- the grid-size had no effect, as expected, on the measures of $F_{\text{laser}}$ outside of the atmospheric boundary-layer, because turbulence was not considered;
- several data-processing techniques were applied to the $F_{\text{laser}}$ informations derived from the Doppler-lidar, such as spatial averaging, time-filtering over maximum laser measures, etc. From the data-processing techniques which were evaluated, the time filtering over maximum laser measures provided the best result in terms of timely detection of windshear severity.

Two hazard factors, associated with the laser measurements were developed and evaluated in the numerical simulations. The first one used the Doppler-lidar measurements to compute the hazard factor, called $F_{\text{laser}}$-factor, which is equivalent to the reactive F factor used by the FAA regulation organization. The second one used another hazard factor, called X-factor, which was suggested by Woodfield [3.1]. The X-factor should be more suitable than the F-factor, and should lower the false alarm rate which was encountered with the F-factor [6.1]. Nevertheless, the limited number of numerical simulations which were performed, associated with a large number of parameters involved, did not yet allow a clear conclusion to be formulated on the assumed advantage of the X-factor, when compared to the F-factor.
6.2 Recommendations

The conclusions are valid for the investigated aircraft type and windshear models only. To be able to generalize the conclusions any further, it is recommended to perform simulations with different classes of aircraft (types) and windshear models. Although a limited investigation has been performed towards the issue, any follow-on study should include turbulence effects.

It is recommended to perform additional numerical simulations, in order to better quantify the usefulness of the so-called X-factor, in terms of a reduction of false alarm rate compared to the wellknown F-factor. Different filtering techniques should also be investigated.

Moreover, in order to improve the various hazard detection algorithms, it is proposed to take into account an estimation of the vertical wind component.

Finally, it is recommended to include the information of a forward looking windshear detection system in an autopilot, autothrottle and/or flight-director system. Logic needs to be designed and evaluated. Special attention should be given to the integration of the information of the forward looking and reactive system in an optimal way. Various aspects of man-machine interface issues need to be evaluated through manned simulations (displays, icons, etc.). In particular the adoption of a speed increment procedure coupled to the reactive/predictive windshear detection should be evaluated for pilot's acceptance.
7. REFERENCES


[1.5] Rouwhorst W.F.J.A., Haverdings H., Huynh H.T., Descatoire F., König R., Hahn K.-U., Experimental design and test plan for a piloted investigation of a flight director go-around mode, a reactive windshear detection system, a forward looking windshear detection system and a windshear display, on the NLR research flight simulator, GARTEUR TP-093, (1995)


# TABLES

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Landing Configuration</th>
<th>Take-off Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>m</td>
<td>120000 kg</td>
<td>137000 kg</td>
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<tr>
<td>Inertia</td>
<td>$I_{yy}$</td>
<td>9.72E+6 kg m²</td>
<td>11.097E+6 kg m²</td>
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<tr>
<td>Wing Area</td>
<td>S</td>
<td>260 m²</td>
<td>260 m²</td>
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<td>Wing Aspect Ratio</td>
<td>$\Lambda$</td>
<td>7.7332</td>
<td>7.7332</td>
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<tr>
<td>Mean Chord</td>
<td>$\overline{c}$</td>
<td>6.608 m</td>
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Table 2.1. : Aircraft parameters

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<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
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<th>Take-off Configuration</th>
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<tbody>
<tr>
<td>Drag Bias</td>
<td>$C_{D0}$</td>
<td>0.0885</td>
<td>0.0326</td>
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<td>Oswald Factor</td>
<td>$e$</td>
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<tr>
<td>Lift Derivative of Angle of Attack</td>
<td>$C_{L_a}$</td>
<td>5.6</td>
<td>5.39</td>
</tr>
<tr>
<td>Lift Derivative of Elevator Deflection</td>
<td>$C_{L_{be}}$</td>
<td>0.436</td>
<td>0.436</td>
</tr>
<tr>
<td>Lift Derivative of Trim Deflection</td>
<td>$C_{L_{bd}}$</td>
<td>0.77</td>
<td>0.77</td>
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<tr>
<td>Lift Derivative of Pitch Rate</td>
<td>$C_{L_{lq}}$</td>
<td>3.92</td>
<td>3.05</td>
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<td>Pitch Bias</td>
<td>$C_{m0}$</td>
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<td>Pitch Derivative of Angle of Attack</td>
<td>$C_{m_a}$</td>
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</table>

Table 2.2. : Aerodynamic bias and derivatives
a)  **Approach and Landing**

Landing Configuration: Slats 25° / Flaps 25°

Gear down

\[ V_{\text{Still}} = 51.5 \text{ m/s} \]
\[ V = 1.3 \times V_{\text{Still}} + 5 \text{ kt} = 69.5 \text{ m/s} \]
\[ V_{\min} = 1.06 \times V_{\text{Still}} = 54.5 \text{ m/s} \text{ (Safety Speed } \rightarrow \alpha_{\text{Still}} \text{ Protection)} \]
\[ V_{\text{max1}} = 87.5 \text{ m/s} \text{ (Safety Speed } \rightarrow \text{ Landing)} \]
\[ V_{\text{max2}} = 90 \text{ m/s} \text{ (Safety Speed } \rightarrow \text{ Flaps Structural Limitation)} \]
\[ \alpha_{\text{Still}} = 19.2° \]
\[ \alpha_{\text{Protect}} = 16.4° \]

b)  **Go-Around**

Landing Configuration: Slats 25° / Flaps 25° (no configuration change)

Gear down

Go-Around has to be initiated if

\[ V \leq 1.1 \times V_{\text{Still}} = 56.7 \text{ m/s} \]
\[ \text{or } |\Delta \varepsilon| \geq 0.25° (=1 \text{dot}) \]
\[ \text{or } H \leq 5 \text{ m/s} \]

Go-Around Attitude

\[ \theta_{\text{GA}} = 17.3° \]

c)  **Take-off**

Take-off Configuration: Slats 20° / Flaps 8°

Gear up

\[ V_{\text{Still}} = 58 \text{ m/s} \]
\[ V_s = 1.32 \times V_{\text{Still}} = 76.6 \text{ m/s} \]
\[ V = V_s + 10 \text{ kt} = 81.7 \text{ m/s} \]
\[ V_{\min} = 1.06 \times V_{\text{Still}} = 61.5 \text{ m/s} \text{ (Safety Speed, } \alpha_{\text{Still}} \text{ Protection)} \]

Table 2.3: Configurations and speed settings
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<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
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<tr>
<td>Effective Thrust Inclination Angle</td>
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<td>Engine Model Time Constant for Acceleration</td>
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<td>Engine Model Time Constant for Deceleration</td>
<td>$T_{pd}$</td>
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<td>Maximum Thrust Rate for Acceleration</td>
<td>$\dot{\delta}<em>{T</em>{max}}$</td>
<td>30 %/s</td>
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<td>Maximum Thrust Rate for Deceleration</td>
<td>$\dot{\delta}<em>{T</em>{max}}$</td>
<td>-23 %/s</td>
</tr>
<tr>
<td>Minimum Thrust (Percent of Maximum Thrust)</td>
<td>$\delta_{T_{min}}$</td>
<td>6.0 %</td>
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<tr>
<td>Thrust at Transition from Phase I to Phase II</td>
<td>$\delta_{T1}$</td>
<td>30.175 %</td>
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<tr>
<td>Thrust at Transition from Phase II to Phase III</td>
<td>$\delta_{T2}$</td>
<td>71.5 %</td>
</tr>
<tr>
<td>Gradient Phase I</td>
<td>$1/T_1$</td>
<td>1/0.95</td>
</tr>
<tr>
<td>Gradient Phase III</td>
<td>$1/T_2$</td>
<td>1/0.95</td>
</tr>
</tbody>
</table>

Table 2.4 - Thrust parameters
<table>
<thead>
<tr>
<th>Experimental Factor</th>
<th>Levels</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| Windshear detection sensors   | reactive system laser : 350 - 2100 m  
laser : 350 - 1400 m  
laser : 350 - 700 m |                                   |
| Hazard criteria               | F-factor  
X-factor                                                   | not with reactive system          |
| Type of operation             | Approach  
Take-off                                                     |                                   |
| Turbulence                    | None  
Dryden spectrum                                              | reference                         |
| Filter time interval $T_x$    | (2 s)  
5 s  
10 s                                                        | only for F-factor                 |
| Laser beam stabilization      | pitch-stabilized flight path vector  
fixed in frame                                               | only for laser                    |
| Grid size $\Delta R$          | 140 m  
350 m  
210 m                                                      | only for laser and F-factor       |
| Type of windshear             | Downburst  
Low-Level-Jet  
none                                                          | worst case                        |

Table 5.1 - Summary of experimental design

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Landing Configuration</th>
<th>Take-off Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>$H$</td>
<td>500 m</td>
<td>10.7 m</td>
</tr>
<tr>
<td>Air Density (const. during simulation)</td>
<td>$\rho$</td>
<td>1.225 kg/m$^3$</td>
<td>1.225 kg/m$^3$</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>$C_d$</td>
<td>0.205</td>
<td>0.015</td>
</tr>
<tr>
<td>Lift Coefficient</td>
<td>$C_l$</td>
<td>1.51</td>
<td>1.18</td>
</tr>
<tr>
<td>Pitch Moment Coefficient</td>
<td>$C_m$</td>
<td>-0.05</td>
<td>-0.135</td>
</tr>
<tr>
<td>Angle of Attack</td>
<td>$\alpha$</td>
<td>6.67°</td>
<td>9.25°</td>
</tr>
<tr>
<td>Thrust</td>
<td>$T$</td>
<td>96.61 kN</td>
<td>360.4 kN</td>
</tr>
<tr>
<td>Trim Angle</td>
<td>$\delta_e$</td>
<td>-7.54°</td>
<td>-3.02°</td>
</tr>
<tr>
<td>Flight Path Angle</td>
<td>$\gamma$</td>
<td>-3°</td>
<td>-</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Flight phase</th>
<th>Penetrating landing</th>
<th>Abort landing</th>
<th>Take-off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windfield</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-level jet</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Microburst</td>
<td>Wind 1 (see § 5.5)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Wind 2 (see § 5.5)</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Wind 3 (see § 5.5)</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Location</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Turbulence</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic automatic pilot (with auto-throttle)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Reactive system</td>
<td>without speed increment strategy</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>with speed increment strategy</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Forward looking system</td>
<td>Nominal</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Stabilization mode</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time filtering</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hazard criterion</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Look-ahead distance</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Vertical component measurement $F_{2D}$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Figures</td>
<td>5.13 5.14 5.2 5.3 5.4</td>
<td>5.5 5.6</td>
<td>5.7 to 5.12</td>
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Reactive systems

![Diagram of reactive systems]

Predictive systems

![Diagram of predictive systems]

Figure 1.1 - General synoptic of the simulation
Landing Approach Geometry

\[ \vec{V}_x = \vec{V} + \vec{V}_w \]

\[ \theta = \alpha + \gamma_k - \alpha_w \]

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**Figure 2.6 - Microburst model [2.3]**

a) wind profiles in vertical plane (analytical model)

b) wind profiles in radial plane (analytical model)
\[ V_{W}(H) = V_{W_{\text{ref}}} \left( \frac{H}{H_{\text{ref}}} \right)^m + V_{W_{s}} \left( 1 - \tanh \left( C_s \frac{H - H_s}{H_s} \right) \right) \]

Figure 2.7 - Composition of the speed profile [2.5]
\[ x_W(H) = x_W^0 + \arctan\left(\frac{H - H^0}{H_G - H^0} \tan(x_W^G - x_W^0)\right) + \\
+ x_W^L \left(1 - \tanh^2\left(C_L \frac{H - H_L}{H_L}\right)\right) \]

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Simplified Potential Height Change contours $V = 75 \text{m/s}$

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Lidar located 2000 m from the microburst center at 100 m altitude. The dashed line shows the signal-to-noise ratio for a Doppler-lidar of 2 μm. The continuous line shows the mean wind velocity for each range gate, standard deviation is also indicated.

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\[
V = 70 \text{m/s}
\]

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\[ K_e = f(\theta) \]

\[ \theta \text{ [deg]} \]

\[ H \text{ [m]} \]

\[ \Delta \varepsilon \text{ [\mu A]} \]

\[ a_{2f} + g \cos \theta \]

\[ H \geq 30.5 \text{ m}: \quad K_e = 0.029 + 0.000365 H \]

\[ H < 30.5 \text{ m}: \quad K_e = -0.040 + 0.002620 H \]

\[ 0 \leq K_e \leq 0.14 \]
Block Diagram of the Autothrottle
Figure 4.4 - Block diagram of the Go-around Controller

Block Diagram of the Go-Around-Controller
Figure 4.5 - Generic aircraft. Go-around in presence of horizontal windshear
4.6a) Definition of alert levels in terms of $F$-factor [1.6]

![Graph showing shear intensity curve with alert values]

4.6b) Definition of alert levels in terms of predicted height loss according to the $X$-factor [3.2]

![Graph showing shear length vs. level with levels 1 to 4]

Figure 4.6 - Definition of alert levels
### Guidance strategies associated with hazard criteria

<table>
<thead>
<tr>
<th>Alert level</th>
<th>Reactive system $F_m$ (cf Fig. 4.5)</th>
<th>Forward looking system</th>
<th>Approach landing</th>
<th>Guidance strategy</th>
<th>Take-off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color [1]</td>
<td>Value</td>
<td>$t_c = 5 \text{ s}$</td>
<td>$t_c = 10 \text{ s}$</td>
<td>Severity factor $F_{m,x}$</td>
<td>X-factor (Fig. 3.9) landing only</td>
</tr>
<tr>
<td>Green</td>
<td>1</td>
<td>$F_m \leq 0.04$</td>
<td>$F_{m,x} \leq 0.04$</td>
<td>$H^* \leq 10 \text{ m}$</td>
<td>normal approach</td>
</tr>
<tr>
<td>Yellow</td>
<td>2</td>
<td>$0.04 &lt; F_m \leq 0.1$</td>
<td>$0.04 &lt; F_{m,x} \leq 0.1$</td>
<td>$10 \text{ m} &lt; H^* \leq 15 \text{ m}$</td>
<td>Penetrating approach with speed increment</td>
</tr>
<tr>
<td>Amber</td>
<td>3</td>
<td>$0.1 &lt; F_m \leq 0.205$</td>
<td>$0.1 &lt; F_{m,x} \leq 0.205$</td>
<td>$15 \text{ m} &lt; H^* \leq 20 \text{ m}$</td>
<td>aborted landing</td>
</tr>
<tr>
<td>Red</td>
<td>4</td>
<td>$F_m &gt; 0.205$</td>
<td>$F_{m,x} &gt; 0.205$</td>
<td>$H^* &gt; 20 \text{ m}$</td>
<td>Penetrating approach (cf. take-off for go-around)</td>
</tr>
</tbody>
</table>

### End of windshear

| Yellow       | 2                                 | $0.04 < F_m \leq 0.1$ | $0.04 < F_{m,x} \leq 0.1$ | $10 \text{ m} < H^* \leq 15 \text{ m}$ | If $ALF > 1$ : no modification of strategy $\forall ALR$ (1) | $\theta = \theta_{(3)}$ as soon as $W_c \geq W_{\text{lim}}$ |
| Green        | 1                                 | $F_m \leq 0.04$        | $H^* \leq 10 \text{ m}$ | If $ALF = 1$ : reduction of $V$ only if $ALR \leq 2$ | $ALR = 2 \Rightarrow V_c = V_{ref} + \Delta V_1$ | $ALR = 1 \Rightarrow V_c = V_{ref}$ |

1. $ALF = $ Alert Level Forward look system ; $ALR = $ Alert Level Reactive system
2. $\theta_i$ = smaller \{ than $\bar{\theta}$ \} (relative to nominal climbing flight path)
3. $\theta_2$ = greater
Horizontal windshear

$\Delta V_s \text{ (m/s)}$

Forward-looking system range

Length of windshear

Forward looking

- Level 3
- Level 1
- Level 2
- Level 4

$F = 0.04$

$H^* = 10 \text{ m}$

$H^* = 20 \text{ m}$

$\Delta t = 5 \text{ s}$

$F = 0.21$

$F = 0.1$

$V = 70 \text{ m/s}$

$A_T = 2.28 \text{ m/s}^2$ (aircraft acceleration)

$AT_s = 11 \text{ m/s}$ ($T_s = \text{ pilot delay} = 4.8s$)

$A_\tau = 11 \text{ m/s}$ ($\tau = \text{ engine time response} = 4.8s$)

$\alpha/C_L = 3.7$

Alert level according to Fig. (4.6) and (4.7)

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b) Alert value level (see Fig. 4.7)

Legend:
- --- instantaneous F-factor
- --- $F_{av}$ average F-factor, with different time-filter $t_a$

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Figure 5.7 - Comparison between several hazard criteria associated with F (severe microburst 2)
a) Aircraft position (•) and space volume sensed by laser beam (→)

$t_1 = -110s$

$t_2 = -90s$

$t_3 = -70s$

$t_4 = -50s$

$t_5 = -30s$

$t_6 = -10s$

b) $F_{laser}$ measurements

Legend:
- $t_i =$ time counted from the instant 0 where the aircraft reaches the runway threshold
- $F_{laser}$ measures along lidar beam
- $F_{laser}$ spatial averaging (Eq. (3.17))

Figure 5.8 - Aircraft position and laser beam along inertial flight path.
a) Aircraft position and space volume sensed by laser beam

Legend:
- \( t_i \) = time counted from the instant 0 where the aircraft reaches the runway threshold
- \( \{F_{\text{laser}}(i)\} \) measures along lidar beam
- \( F_{\text{laser}} \) spatial averaging (Eq. (3.17))

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Alpha max on penetrating landing

V/Vs minimum on penetrating landing

V/Vs maximum on penetrating landing

F and F laser factor on penetrating landing

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Figure 5.44 - Aborted landing - Aircraft characteristic parameters with FLS using $F_{\text{las}}$ and $F_{2D}$ measures
A.1 DESCRIPTION OF AIRBORNE FORWARD-LOOKING SENSORS FOR WINDSHEAR DETECTION

A.1.1 Lidars

The principle of operation of a Light Detection And Ranging system (LIDAR) is based on the back scattering of laser light from air particles. The Doppler shift in the back-scattered light is measured. The range is determined from pulsed Doppler transmissions.

In 1990, Lockheed announced to build a coherent Laser radar Airborne Shear Sensor (CLASS) in a 3-phase program, sponsored by NASA/FAA, worth 4 Million dollars (Flight, 1990). To decide which type of lidar could best be build, two lidars were investigated in simulations by NASA (Bowles, 1990) : the solid-state Ho:YAG at a wave length of 2.1 μm, and the CO₂ transmitting at 10.6 μm. Both can give the pilot information on the line-of-sight component of a windshear threat from his present position to a region extending 2-4 km in front of the aircraft. Both lidars performed well. The useful range of a lidar is seriously degraded, however, by precipitation. The attenuation can be as much as 9 dB/km per inch of rain per hour. A simplified form of the lidar equation used for the above calculation is shown below:

\[
\frac{S}{N} = \frac{\pi E D^2 \beta \eta K(R)}{8 R^2 B h}
\]  

(A.1)

The meaning of the various parameters in this equation is given in Appendix B.

At that time the Ho:YAG was much less mature and not ready for production, although it had much better performance than the CO₂ laser due to its several dB/km lower attenuation in rain. Representative results are given by Huffaker and Russell (1989). Based on these results, a coherent Q-switched CO₂ laser at 10.6 μm was designed and developed by the Lockheed Missiles and Space Company for flight evaluation in early 1992. Bowles (1990) gives further information about the characteristics of this laser. In 1991 and 1992 two periods of flight testing took actually place, see Finneran (1995). Results obtained with the lidar showed good correlation with in-situ obtained results, see Robinson (1993).

In 1988, Bowles and Russell stated that a 5 mJ, radio-frequency pumped waveguide CO₂ laser represented the state-of-the-art of that moment for compact, reliable, Class I eye-safe CO₂ lasers. However, even 8 mJ was achieved. Without special design, the optical package, including laser transmitter, local oscillator, detector and beam scanner, has a volume of approx. 3 cubic feet (Bowles and Frost, 1987). Design optimization will lead to lower weight and volume. Furthermore, simulation studies were executed to investigate techniques to measure both the radial (line-of-sight) and vertical winds, e.g. by using scanning techniques to allow the spatial extent of the windshear threat. See Vicroy (1994).

Since the 2 μm laser technology offers better (commercial) potential than the CO₂ laser technology, it is still being improved to become mature. Furthermore applications in the field of wake vortex detection are foreseen.
A.1.2 Infrared

Radiometers measure emission from the 14 μm band of atmospheric CO₂. A change in temperature measure is determined by comparing the emission at a certain distance ahead (2 to 3 km) with that in the neighborhood of the aircraft. Simple relationships between windspeed and temperature are greatly needed for their successful application.

An empirical relationship has been developed by NASA (Bowles, 1990):

\[ U_{\text{max}}(t) = 2.5 \Delta T_{\text{min}}(t) + C \quad (A.2) \]

where \( U_{\text{max}} \) is the maximum peak outflow (m/s), and \( \Delta T_{\text{min}} \) is the minimum temperature change (i.e. max. temperature drop) that occurs through the downburst. C is the translational speed of the downburst (= 0 when stationary). The peak change across the downburst is then:

\[ \Delta U_{\text{max}} = -5 \Delta T_{\text{min}} \quad (A.3) \]

Application of this formula (and a similar one by Faw bush and Miller, 1954) during events other than a downburst is not yet known. The question of nuisance alerts has also not been addressed (Bowles, 1990).

Two firms were developing an infrared predictive warning system, viz. Turbulence Prediction Systems and Delco Electronic Corp. (Aviation Week, 1989a and 1989b, Adamson, 1988). The device of Delco scanned around in azimuth to detect regions of lower temperature, which are translated into a warning signal once a certain threshold is exceeded. A prototype infrared radiometer has been flight-tested on a Cessna T207 by Colorado State University (CSU) (Aviation Week, 1990). There is a strong need, however, to characterize microburst physics better before commercial systems can be developed, since no reliable correlation could be established between outside temperature drops measured and windshear. Therefore the activities in the field of infrared windshear detection stopped. Previous work in the area of remote sensing using infrared has been done by Kuhn (1979) and others (Huhn et al, 1978, 1983 and 1984).

A.1.3 Airborne Doppler radar

A preliminary trade off and assessment study was conducted by NASA to evaluate the performance of airborne Doppler radar sensors to detect hazardous microburst windshear during aircraft landing (Bowles, 1990, Bracalente et al, 1990). The program included excellent models of microburst windfields (the so-called TASS model), realistic clutter maps of airports, and accurate models of Doppler radar operation and signal processing. Doppler returns are processed ultimately into equivalent F-factor values (or hazard index), which can then be displayed. The Doppler radar in fact can only detect the horizontal component contained in this F-factor.

Ground clutter is a great problem. By choosing an optimal frequency band, limiting the range of data-processing and employing proper antenna tilt control, the CSR (Clutter-to-Signal Ratio) levels could be kept below 40 dB, which is well within the dynamic range capabilities of present-day Doppler radar receiver design technology. In order to be able to detect both "wet" and "dry" types of windshear, the problem of "low" (less than 35 dBZ) reflectivity had to be solved, since a radar needs reflectivity to work on/ Special signal processing features and the choice of the X-band brought 0 dBZ levels within reach.

From the total set of airborne forward-looking windshear sensors investigated by NASA, the Doppler radar sensor turned out to be best and its development continued. Ultimately this resulted in the technology required to establish commercial forward-looking windshear detection system products. Currently three Doppler radar systems have been fully certified and are available on the aviation

A.2 REFERENCES

14. Kuhn, P.M., 1979: "Detection of CAT and low altitude windshear by on-board aircraft IR sensors—an update".
B.1 INTRODUCTION

In the framework of the Action Group FM (AG 05) of GARTEUR, an online simulation will be performed of an aircraft, flying through windshear, where an airborne windshear warning system will provide a warning in case a certain safety criterion is exceeded. The airborne sensor principle is based on forward-looking measurements of the air ahead of the aircraft, using a pulsed laser.

In this report some kinematical relationships will be given, that will relate wind velocities and aircraft velocity, based on the Doppler line-of-sight measurement, using a pulsed laser.

B.2 Functional description

B.2.1 General layout and reference frames

For a situational layout the reader be referred to Figure B.1, where a diagram is given of the velocity vectors and position vectors involved. Of particular interest are a number of reference frames, in which all the quantities are referenced. These reference frames are:

a) the body reference, or B-frame. The origin is located at the aircraft center of gravity (G). The X-axis is oriented along the longitudinal axis of the aircraft, the Y-axis is to the right, and the Z-axis is pointing downward, and is perpendicular to the X-Y plane. The origin of the B-frame moves with velocity vector $\vec{V}_b$ relative to the earth, and rotates with an angular velocity vector $\vec{\omega}$. The orientation of the B-frame relative to the earth is through Euler angles $\alpha$, $\beta$, and $\gamma$.

b) The laser reference or L-frame. The origin is located at the laser beam transmitter point, at position $(x_L, y_L, z_L)$ in the B-frame. The orientation of the X-axis of the L-frame is along the laser beam, which is rotated to the right of the X-axis of the B-frame through an angle $\theta_L$, and tilted upwards with respect to the X-Y-plane of the B-frame over an angle $\phi_L$, see Figure B.2. These angles may be functions of time, if necessary (i.e. variable sweep and tilt when scanning the laser).

c) The earth-fixed, or E-frame. The origin is located at an arbitrary point, and is oriented such that the X-axis points north, the Y-axis points eastward, and the Z-axis points downward (i.e. into the earth).

Quantities which are expressed in units, referenced to a particular reference frame, have a lower-case superscript, corresponding to the particular reference frame involved. For example, the angular rotation vector $\vec{\omega}$, which has as components $p$, $q$ and $r$ when expressed in the B-frame, is written using the lower-case 'b' as follows: $\vec{\omega}^b = \hat{i}^b p + \hat{j}^b q + \hat{k}^b r$.

B.2.2 Transformations

Between the various reference frames there exist transformation matrices, which transform vectors from one reference frame to another. To denote the transformation from reference frame A to reference frame B, for example, the particular transfer matrix is indicated using as subscripts the lower-case letters 'ba', corresponding to the reference frames used. For example, the transformation
matrix between the L-frame and the B-frame is \([T_{bl}]\). The transformation matrix from the L-frame to the E-frame, for example, can be obtained by successive multiplication of the transformation matrices \([T_{eb}]\) and \([T_{bl}]\) as follows: \([T_{el}] = [T_{eb}][T_{bl}]\).

One can derive for the matrix \([T_{bl}]\):

\[
[T_{bl}] = \begin{bmatrix}
\cos \theta_L \cos \psi_L & -\sin \psi_L & \sin \theta_L \cos \psi_L \\
\cos \theta_L \sin \psi_L & \cos \psi_L & \sin \theta_L \sin \psi_L \\
-\sin \theta_L & 0 & \cos \theta_L
\end{bmatrix}
\]  

(B.1)

The matrix \([T_{eb}]\) is the standard Euler transformation matrix. Without derivation it is given as follows:

\[
[T_{eb}] = \begin{bmatrix}
\cos \theta \cos \psi & \sin \theta \sin \psi \cos \phi - \cos \theta \sin \psi \sin \phi & \sin \theta \cos \psi \cos \phi + \sin \theta \sin \psi \sin \phi \\
\cos \theta \sin \psi & \sin \theta \sin \psi \sin \phi + \cos \theta \cos \psi \sin \phi & \sin \theta \cos \psi \cos \phi - \sin \theta \sin \psi \sin \phi \\
-\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi
\end{bmatrix}
\]  

(B.2)

**B.2.3 Laser beam pointing**

What the laser measures, is the Doppler shift due to a sensed windspeed component along the laser beam at the scanned location point \(W\), or rather, volume \(Vol\). Through pulsing the laser the system derives distance information. The controller sets a series of range gates, at which range it processes the sensed signal. So, with one flash of the laser, i.e. at one instant of time, Doppler information becomes available from the minimum to the maximum scanning range. This information as function of range can be processed immediately, depending on the scanning strategy used.

From Figure B.1 the following equation for the position vectors can then be derived:

\[
\vec{p}_L = \vec{p} + \vec{p}_L
\]  

(B.3)

and

\[
\vec{p}_W = \vec{p}_k + \vec{R}_L
\]  

(B.4)

When defining the unit vector along the X-axis of the L-frame as \(\vec{e}_L\), one can write the vector \(\vec{R}_L\) as:

\[
\vec{R}_L = R_L \vec{e}_L
\]  

(B.5)

where \(R_L\) a scalar quantity, equals the length of vector \(\vec{R}_L\).

When expressing in proper reference frames, one can write for the position vector in Eq.(B.3):

\[
\vec{p}_W^* = \vec{p}^* + [T_{el}]\vec{p}_L + R_L[T_{el}][\vec{e}_L]
\]  

(B.6)

For the velocity vectors the following hold:

\[
\vec{V}_e = \frac{d\vec{p}}{dt}
\]

\[
\vec{V}_L = \vec{V}_e + \vec{p}_L / dt
\]

\[
= \vec{V}_e + \vec{p}_L / \partial t + (\vec{\omega} \times \vec{p}_L)
\]  

(B.7)

In the body reference frame B, however, we have : \(\vec{p}_L / \partial t = 0\).
B.2.4 Sensing

The pulsed laser receives Doppler information continuously from minimum to maximum range. However, the Doppler returns are processed for a series of range gates, from some minimum distance to some specified maximum range ahead of the aircraft. Normally for each range gate an averaging of laser pulse information also is performed, i.e. a series of laser pulses are used, in order to eliminate spurious signals and noise. At some specific point ahead, e.g. at point W at range RL, from the laser along the beam (i.e. along the X-axis in the L-frame), the laser in fact senses a volume 'Vol', which extends from RL to RL + ΔRL, and with a beam angle δ, as given in figure D.3. What the laser thus measures is the average wind vector component along the laser beam within this volume. It is assumed that the averaging in this volume is an averaging along a line, since the laser beam is very narrow. The pulse length of the laser is assumed to be 140 m, which equates to a pulse length J of 0.447 μs. Eleven points (i.e. 10 intervals of 14 m) are taken within this length to calculate the average Doppler-wind.

The minimum range at which the laser can measure depends upon the laser pulse width and the time it takes to switch from transmitting to receiving status, and is at least equal to ΔRL. The maximum range is set by the system, but may be limited by precipitation.

For the derivation of the sensed Doppler velocity of the wind vector at point W, it should be realised that from the Doppler shift the laser measures the average air particle velocity at point W relative to point L, i.e. the component of d Ri/dt along the laser beam. This component can be found by taking the dot-product of the two vectors. Therefore the following equation can be derived for the Doppler-derived velocity:

\[
V_{\text{doppler}} = \left( \frac{d\vec{R}_L}{dt} \right) \cdot \vec{e}_L = \left( \frac{d\vec{w}_W}{dt} - \frac{d\vec{p}_L}{dt} \right) \cdot \vec{e}_L = \vec{V}_{w,a} - \vec{V}_L \cdot \vec{e}_L
\]  

(B.8)

where the average wind velocity vector

\[
\vec{V}_{w,a} = \frac{1}{11} \sum_{j=1}^{11} \vec{V}_{w,j}
\]

(B.9)

This holds true for any reference frame (E-, B- or L-frame). A negative value of \(V_{\text{Doppler}}\) means that the relative speed is towards the laser, otherwise it is away from the laser.

Using Eq.(B.7) the following can be derived:

\[
V_{\text{Doppler}} = \left( \vec{V}_{w,a} - \vec{V}_L \right) \cdot \vec{e}_L = \left( \vec{\omega}^b x \vec{p}_L \right) \cdot \vec{e}_L
\]

(B.10)

When using the proper reference frames (e.g. \(\vec{\omega}^b = i^b p + j^b q + k^b r\), etc.) then Eq.(B.8) can be rewritten, using the transformation matrices, as :

\[
V_{\text{Doppler}} = \left( \vec{V}_{w,a}^e - \vec{V}_L^e \right) \cdot \left( [T_e] \vec{e}_L \right) = \left( \vec{\omega}^b x [T_L^e] \vec{e}^*_L \right)
\]

(B.11a)
where
\[
\begin{align*}
\bar{\epsilon}_L &= \bar{\epsilon}_L^1 \\
\bar{\omega}_b &= \bar{\omega}_b^1 p + \bar{\omega}_b^2 q + \bar{\omega}_b^3 r \\
\bar{p}_L^1 &= \bar{p}_L^2 x_L + \bar{p}_L^3 y_L + \bar{p}_L^4 z_L \\
\bar{V}_k^1 &= \bar{V}_k^2 x_w + \bar{V}_k^3 y_w + \bar{V}_k^4 z_w \\
\bar{V}_{w,h}^1 &= \bar{V}_{w,h}^2 u_w + \bar{V}_{w,h}^3 v_w + \bar{V}_{w,h}^4 w_w
\end{align*}
\]
(B.11b)

B.2.5 The lidar equation

A simplified form of the lidar equation signal-to-noise ratio S/N is used. The equation is used to determine the maximum signal detection range, when receiving reflected signals, which have been attenuated by precipitation for instance.

When the threshold of S/N drops to below, say, 3 dB, then it is assumed that no valid signal has been received at that range. The equation is:

\[
S = \frac{\pi E D^2 \beta \eta K(R_L)}{8 R_L^2 B h}
\]
(B.12)

where the system bandwidth \( B = 1/\tau \) (Hz).

The values for attenuation by rain are taken from data obtained by Chu and Hogg (Ref. 1). Their best-fit regression line has been adopted to the maximum signal detection range, when receiving reflected signals, which have been attenuated by precipitation for instance. The equation is:

\[
K_{\text{rain}}(\lambda = 2.0913 \, \mu m) = 0.171 RF + 2.926 \, [\text{dB/km}] \quad \text{(B.13a)}
\]
\[
K_{\text{rain}}(\lambda = 10.391 \, \mu m) = 0.217 RF + 3.724 \, [\text{dB/km}] \quad \text{(B.13b)}
\]

where RF is rainfall rate in mm/hr, and \( K_{\text{rain}} \) is the one-way attenuation. Although the data measurements were valid for rainfall rates between 10 and 60 mm/hr, extrapolation of the results of Chu and Hogg give conservative results, and are in agreement with measurements by Rensch and Long (Ref. 3) and Chimeles (Ref. 4). Attenuation by clouds, fog, snow and hail is not included in this simulation.

The total extinction coefficient correction factor \( K(R) \), as used in the lidar equation, is twice the integral over range of the attenuation \( K_{\text{rain}} \, \text{dB/km} \), because the reflected signal travels back the same path as the outgoing signal.

Hence:

\[
K_{\text{db}}(R) = 2 \int_{0}^{R} K_{\text{rain}}(RF(x,y,z)) dx
dR = 2 \int_{0}^{R} RF(x,y,z) dx + 2bR
\]
(B.14)

Here \( a = .171 \) or .217 and \( b = 2.926 \) or 3.724 (see Eq.(D.11)). The value of \( K_{\text{db}} \) is transformed to normal units as follows:

\[
K = 10^{K_{\text{db}}/10}
\]
(B.15)
The integral $I_{rf}$ in Eq. (B.14) is calculated using e.g. Euler's rule, for each distance $R_i$ (from $R_{\text{min}}$ to $R_{\text{max}}$), and can be put in the following recursive formula, where index $i$ denotes range:

$$I_{rf}(i) = I_{rf}(i-1) + \frac{AR}{2} \left[ RF(i) + RF(i-1) \right], \quad i = 2, 3, \ldots, i_{\text{max}} \quad (B.16)$$

with initial conditions: $I_{rf}(1) = 0$.

With this equation one can write for $K_{dB}$:

$$K_{dB}(R_i) = 2[a_{1rf}(i) + b_{1rf}]/1000, \quad i = 1, 2, \ldots, i_{\text{max}} \quad (B.17)$$

where $i_{\text{max}} = (R_{\text{max}} - R_{\text{min}})/R_i + 1$. The factor 1000 comes from converting km to m.

**B.3 Signal processing**

**B.3.1 Process noise**

In Ref 5 Bowles gives an indication of the noise in the Doppler-derived estimate of the windspeed for two types of lasers, viz. the CO$_2$ and the Yt:HAG solid-state laser. This noise is added to the scalar value of $V_{\text{Doppler}}$, obtained from Eq. (B.10), to derive an estimate $\hat{V}_D$ as follows:

$$\hat{V}_D = V_{\text{Doppler}} + \nu_V \quad (B.18)$$

Here $\nu_V$ is a random white-noise process with a Gaussian probability distribution, with a zero mean and standard deviation $F_V$. The specifications of $F_V$ as function of range is taken from Fig. 8 in Ref. 8, and is given for the two types of laser in Table 1.

In real time application, the estimate $\hat{V}_D$ is generated using a random number generator with a Gaussian probability density distribution to generate $\nu_V$.

**B.3.2 Wind estimation**

The unit vector along the laser beam and the attenuated Doppler velocity vector are used to derive an estimate of the wind vector. The approximation is made that the wind component along the laser beam is all that is needed to estimate the wind vector, unless a more sophisticated algorithm has been designed. Aircraft inertial speed is added to the Doppler-derived velocity to get an estimate of the wind vector:

$$\hat{V}_{\text{wind}} = \hat{V}_D \bar{e}_L + \bar{V}_L$$

$$= \hat{V}_D \bar{e}_L + \bar{V}_k + (\bar{\omega} \times \bar{\rho}_L) \quad (B.19)$$

Putting this equation in the proper form, using transformation matrices, yields the following:

$$\hat{V}_{\text{wind}}^* = \hat{V}_D [T_d] \bar{e}_L + \bar{V}_k^* + [T_d](\bar{\omega}^* \times \bar{\rho}_L) \quad (B.20)$$
B.3.3 Windshear warning algorithm

The windshear warning algorithm can be based on a number of factors, which is one of the areas for research. For example, one may take the F-factor as the basis for the windshear alert criterion, or e.g. the X-factor, derived by Woodfield (Ref.8). Other types of severity factors will be investigated later. One of them will be the energy change of the aircraft.

B.3.3.1 Based on the X-factor

The F-factor is based on the deficit, or surplus, of specific excess power an aircraft may have available to counteract an airspeed change. The algorithm for the F-factor is typically:

\[
F(i) = \frac{V_x}{g\Delta R} [u_{w}(i) - u_{w}(i-1)] + \frac{w_{w}(i)}{V}, \quad i = 1, \ldots, N
\]  
(B.21)

The windspeed components are referenced in the wind axis system. Backward differences are used for the headwind component \(u_{w}\), but central differences may be used if deemed necessary. For \(i=1\) the initial conditions are \(u_{w}(0) = u_{w}(1)\) and \(F(1) = 0\).

The above algorithm can also be put in a recursive form, as done by Bowles and Targ (Ref.5), but that is only required when processing the F-factor algorithm synchronously in the time domain. In that case the values for the F-factor are built up as time goes on during simulation.

Targ et al (Ref.6) derived a formula for the F-factor, which is based on the Doppler-derived radial velocity along the laser beam \(V_r\) (i.e. \(V_r = V_k \cdot V_{Doppler}\)). Although he uses a vertical wind \(V_z\) in the equation, it is later stated that the laser cannot detect the vertical component of the wind (yet). Hence a typical "laser F-factor" \(F_{laser}\) that can be used, is as follows:

\[
F_{laser}(i) = -\frac{V_x}{g\Delta R} [V_{Doppler}(R_{Li}) - V_{Doppler}(R_{Li} - \Delta R)]
\]  
(B.22)

A minus sign was added because of different sign conventions for the Doppler speed and the F-factor itself (i.e. a negative value of \(F\) also means a performance loss). Furthermore Targ et al (Ref.6) used a central differencing algorithm on the radial velocity, i.e. the F-factor is evaluated at \(R + \Delta R/2\), but this term \(\Delta R/2\) has been ignored in Eq.(B.21).

The headwind and vertical wind components in the F-factor are derived using Eq.(B.20) through the process given in Eq.(B.23):

\[
\begin{align*}
\tilde{V}^b &= \tilde{i}^b (V \cos \alpha) + \tilde{k}^b (V \sin \alpha); \\
\tilde{V}^{e} &= [T_{ab}] \tilde{V}^{b}; \\
u_{w} &= (\tilde{V}_{w_{\text{eq}}} \cdot \tilde{V}^{e}) / \sqrt{\tilde{V}^{e} \cdot \tilde{V}^{e}}; \\
w_{w} &= \tilde{V}_{w_{\text{eq}}} (3)
\end{align*}
\]  
(B.23)

In Eq.(B.23) the projection of the wind vector onto the airspeed vector (at zero sideslip angle) is the horizontal windspeed component \(u_{w}\) (using the vector dot-product).

If \(F(i) < -0.1\) or \(-0.12\) then an alert will be given. The factor has been defined such that a negative value of \(F\) also has a negative interpretation, i.e. a performance loss.
B.3.3.1.1 Filtering the F-factor

Care should be taken to properly filter the F-factor value $F(i)$ as function either of time $t_i$ or of range index $i$ (i.e. range $R_L[i:i+\Delta R]$), in order to avoid nuisance alerts due to turbulence entering through the wind components $u_{W,k}$ and $w_{W,k}$. According to TSO-C117 (Ref.9), which applies to reactive systems, an average F-factor $F_{av}$ is to be calculated as function of "filter time" $t_x$, which may be chosen. The level of $F_{av}$ which triggers the alert depends on the choice of $t_x$.

The average F-factor is defined in TSO-C117 as:

$$F_w(t_x) = \frac{1}{t_x} \int_{t_x}^{t_f} F(\tau) d\tau \quad (B.24)$$

where it is understood that the reactive system starts operating in a windshear environment at time $t=0$, after which time, at time $t_x$, the system may give an alert if $F_{av}$ exceeds certain thresholds.

For the simulation in question, a "running integrator" filter is designed which integrates over the time interval $t_x$, from the previous time $t-t_x$ to the present time $t$, the "past" values of $F(\tau)$ in order to compute the present average F-factor $F_{av}(t)$ as follows:

$$F_w(t) = \frac{1}{t_x} \int_{t_x}^{t} F(\tau) d\tau \quad (B.25)$$

Putting Eq.(B.25) in differential form, with $t_x$ a constant, one can calculate:

$$\frac{dF_w(t)}{dt} = \frac{1}{t_x} [F(t) - F(t-t_x)] \quad (B.26)$$

and then use $dF_{av}(t)/dt$ in a recursive form using some numerical integration algorithm to compute $F_{av}(t_i)$, e.g. as follows:

$$F_w(t_i) = F_w(t_{i-1}) + \frac{dF_w(t_{i-1})}{dt} \Delta t \quad (B.27)$$

When synchronizing $t_x$ and $\Delta t$ such that $t_x = k \cdot \Delta t$, then one can write:

$$F_w(i) = F_w(i-1) + \frac{1}{k} [F(i-1) - F(i-k-1)] \quad (B.28)$$

This is a recursive expression for $F_{av}(i)$, and is to be evaluated at each time step $i$.

For a forward-looking, scanning laser, the values for $F_{av}$ can be predicted along the flight path of the aircraft by scanning along distance. With each flash of the laser all the information is available to compute the required values of $F$ and $F_{av}$ as function of range from the aircraft. The filtering algorithm given previously is converted into the space domain using the following relationship:

$$dr = V_s(t) . dt \Rightarrow r_s = V_s(t) . t_x \quad (B.29)$$

so that Eq.(B.25) is now rewritten for the scanning laser F-values as:

$$F_w(R_{L,i}) = \frac{1}{t_x} \int_{R_{L,i}-t_x}^{R_{L,i}} F(x) dx \quad (B.30)$$

where $r_x$ is given by Eq.(B.29). A choice of value for $t_x$ simultaneously fixes the value of $r_x$, given the inertial speed. The alert boundaries in TSO-C117 for specific values of $t_x$ can now be interpreted as boundaries for specific values of $r_x$, given Eq.(B.29).
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The expression for $F_{AV}(R_{li})$ can also be cast in a recursive form, using an approach similar to that of Eq.(B.supprimJce), by calculating the derivative of Eq.(B.30) with respect to range as:

$$\frac{dF_w(R_{li})}{dr} = \frac{1}{r_x}[F(R_{li}) - F(r_x)]$$  \hspace{1cm} (B.31)

and then to use this expression in a recursive form in some integration algorithm to compute $F_{AV}(R_{li})$, e.g. as follows:

$$F_w(R_{li}) = F_w(R_{li+1}) + \frac{dF_w(R_{li+1})}{dr}.\Delta R$$  \hspace{1cm} (B.32)

With the sampling interval $\Delta R$ defined such that $r_x$ is an integer multiple of $\Delta R$, say $r_x = k. \Delta R$, one can then write for $F_{AV}(R_{li})$:

$$F_w(i) = F_w(i-1) + \frac{1}{k}[F(i-1)-F(i-k-1)]$$  \hspace{1cm} (B.33)

where by definition $k=r_x/\Delta R$. The expression above is also a recursive expression for $F_{AV}$ (it is the same as Eq.(D.24b), but now it can be evaluated at one time moment for all values of $i$. Here the index $i$ goes from $i=1$ to $i_{max}=(R_{max}-R_{min})/\Delta R + 1$, where $i$ stands for range:

$$R(i) = R_{min} + (i-1)*R, \text{ up to } R(i_{max})=R_{max}.$$  \hspace{1cm} (B.34)

B.3.4 Laser beam scanning

The laser beam is not fixed rigidly in the fuselage, but may be scanning in a certain pattern. For the simulation only 2 stabilization modes are provided, as described next.

B.3.4.1 Stabilization modes

The following stabilization modes are provided:

Stab.1: 'FLTP'. The laser beam is aligned with the momentary inertial flight path angle $\gamma$. In this way the laser is always looking at where the aircraft is going. The laser azimuth angle $\psi_L$ is set at zero.

The inertial flight path angle is obtained from the flight management system, or else from the inertial altitude rate $dh/dt$ and inertial, or groundspeed $V_k$ as follows:

$$\gamma = \sin^{-1}\left(\frac{dh/dt}{V_k}\right)$$  \hspace{1cm} (B.35)

Stab.2: 'PITCH'. The laser beam is stabilized in pitch. The laser pitch angle with respect to the horizon, $\psi_L = \psi_L \cos \phi + \theta$ is maintained throughout. The reference pitch angle may be set by the pilot.
B.4 REFERENCES


B.5 LIST OF SYMBOLS

A  Aircraft inertial acceleration, used in X-factor (m/s²)
a  lift curve slope (l/rad)
B  laser system bandwidth (Hz)
cₖ  lift coefficient at t = 0
D  laser telescope diameter (m)
E  laser pulse energy (J)
ℓ  unit vector in L-frame
F, F激光  F-factors
g  gravitational constant (m/s²)
H  potential height loss (when < 0) at A=1.0 m/s²
H₁  Potential Height loss criterion of either -10 or -20 m
h  Planck's constant (J·0K)
I₁  integral, Eq.(D.12), (D.13)
i  time or spatial (range) index
K  (Round-trip) extinction correction factor
Kₙₐᵣₙ  one-way attenuation factor
LS  windshear duration distance (m)
p  aircraft roll rate (rad/s)
̂p  position vector
q  aircraft pitch rate (rad/s)
RF  rainfall rate (mm/h)
Rₘᵦᵣₙ, Rₘₐₓ  minimum and maximum range of laser scan
Rₗ  Range at which the laser beam scans (m)
Rₗ  (laser) ranging vector between point L and W
r  aircraft yaw rate (rad/s)
S/N  signal-to-noise ratio of laser system signal
Tₐ  transformation matrix between the B-frame and the L-frame
Tₑ  transformation matrix between the E-frame and the B-frame
Tel  transformation matrix between the E-frame and the L-frame
\( T_S \) duration of shear (s)
\( T_0 \) time when \( \Delta V = 0 \) for \( t > 0 \)
\( u_W \) along-track wind component (m/s)
\( V \) airspeed (m/s)
\( \vec{V}_k \) velocity vector (inertial) of the aircraft
\( V_k \) aircraft inertial speed (length of speed vector) (m/s)
\( \hat{V}_D \) noisy estimate of Doppler-derived velocity (m/s)
\( V_{Doppler} \) Doppler-derived velocity (m/s)
\( \vec{V}_L \) velocity vector of point L
\( V_t \) airspeed (= initial groundspeed) at time \( t \) (m/s)
\( V_{vol} \) scanned volume at point W (m\(^3\))
\( \vec{V}_w \) wind vector at scanned location(s)
\( \vec{V}_{wa} \) average wind vector within pulse volume at scanned location
\( W_W \) vertical wind component (m/s)
\( W/S \) wing loading (N/m\(^2\))
\( X \) X-factor value
\( $ \) backscatter cross-section of laser
\( \Delta R \) range grid or range bin interval along the laser beam (m)
\( \Delta R_L \) laser pulse length (m)
\( \Delta V \) airspeed change at time \( t \) (m/s)
\( \Delta V_s \) change of headwind over shear length \( L_s \) (or over \( T_S \) seconds)
\( \delta \) laser beam width angle (rad)
\( \eta \) detection and mixing efficiency
\( \Theta \) aircraft pitch angle (Euler angle) (rad)
\( \Theta_L \) laser beam tilt angle relative to the longitudinal axis (rad)
\( \Theta_L^c \) laser beam pitch angle relative to earth (rad)
\( \lambda \) laser wave length (m)
\( \rho_0 \) air density at standard sea level conditions (kg/m\(^3\))
\( \sigma \) relative air density
\( \hat{\rho}_L \) position vector of point L
\( \tau \) laser pulse duration (s)
\( \phi \) aircraft bank angle (Euler angle) (rad)
\( \psi \) aircraft heading (Euler angle) (rad)
\( \psi_L \) laser beam azimuth angle relative to the longitudinal axis (rad)
\( \omega \) angular velocity azimuth angle of the aircraft

**Subscripts**
- \( E \) earth-fixed reference point
- \( L \) Laser
- \( W \) point at which the wind vector is observed

**Superscripts**
- \( b \) body-fixed reference
- \( e \) Earth-fixed reference
- \( l \) Laser-fixed reference
TABLE 1. Velocity error $\sigma(V)$, m/s

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<th>Range km</th>
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<tr>
<td>9</td>
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Fig. B.1 - General Layout
Fig. B.2 - Laser reference or L-Frame

Fig. B.3 - Laser beam geometry and scanning volume
APPENDIX C

ANALYSIS OF X-FACTOR

Within the scope of this GARTEUR study, it was not possible to analyse all the characteristic parameters of forward-looking windshear detection systems which could influence the aircraft performance during a windshear encounter. In particular, the decision for choosing to continue approach and landing or make a recovery manoeuvre relies upon a severity criterion and the numerical values which are associated with.

After an analysis of several criteria associated with severity of windshears, it was found that the criterion, defined as the X-factor (see § 3), seemed to be more promising than the F-factor criterion defined by NASA and adopted by the FAA for regulation purposes.

The main reasons are:

- X-factor relies on a predicted aircraft height loss (called potential height loss H*), by taking into account both the aircraft and the pilot characteristics parameters (aircraft acceleration, thrust time constant, pilot reaction time), whereas the F-factor doesn’t;
- Use of potential height loss as boundaries for guidance strategy decision would reduce the level of false alarm rate in comparison with the use of boundaries based on the F-factor. Indeed, the F-factor is equivalent to an acceleration measure and thus is more sensitive to turbulence effects (even if filtered values are actually applied) than potential height loss which is obtained from the F-factor by a double time integration.

Nevertheless, several studies remain to be conducted with X-factor, in order to solve some drawbacks, which are:

- level of validity of calculation of potential height loss, when compared to actual aircraft and windfield models;
- sensitivity of potential height loss to aircraft and pilot parameters such as pilot reaction time, assumption of constant pitch guidance strategy during windshear penetration;
- influence of vertical wind component;
- numerical value of boundaries of potential height loss, etc.

Some calculations were performed in order to compare the computed potential height loss with the actual height obtained by numerical simulations, using the generic aircraft model developed in this GARTEUR study.

Let us recall the methods which are used to compute this potential height loss:

i) Woodfield formulae;
ii) numerical simulation;
iii) other approximations.

I) Woodfield formulae:

The following assumptions were used:

- only a horizontal windshear was considered, with a constant wind gradient, as shown in Fig. 3.2;
- during windshear crossing, the aircraft maintains a constant pitch attitude command;
- a first order thrust model was assumed, with thrust-time constant \( \tau \), a pilot reaction time \( T_a \) was also introduced.
With these assumptions the following airspeed variation was obtained:

\[
0 \leq \frac{t}{T_s} \leq \frac{T_s}{T_i}, \quad \frac{\Delta V}{V} = -\frac{\Delta V_i}{V} \left( \frac{t}{T_i} \right)
\]

\[
\frac{T_s}{T_i} < \frac{t}{T_i} \leq 1, \quad \frac{\Delta V}{V} = -\frac{\Delta V_i}{V} \left( \frac{t}{T_i} \right) + \frac{AT_s}{V} \left[ \frac{t}{T_i} - \frac{T_s}{T_i} \right] + \frac{AT}{V} \left( e^{-\frac{T_s}{T_i} \left( \frac{t}{T_i} - \frac{T_s}{T_i} \right)} - 1 \right)
\]

\[
\frac{t}{T_i} > 1, \quad \frac{\Delta V}{V} = -\frac{\Delta V_i}{V} + \frac{AT_s}{V} \left[ \frac{t}{T_i} - \frac{T_s}{T_i} \right] + \frac{AT}{V} \left( e^{-\frac{T_s}{T_i} \left( \frac{t}{T_i} - \frac{T_s}{T_i} \right)} - 1 \right)
\]

The potential height error was then computed by:

\[
H^* = \Delta H = V \cdot \frac{C_{L}}{a} \int_{t}^{T_s} \frac{2 + \frac{\Delta V}{V}}{\left[ 1 + \frac{\Delta V}{V} \right]^2} \, dt
\]

where \( a \) is the aircraft lift gradient, \( C_L \) the lift coefficient.

Fig. C.1 illustrates the difference between the non linear simulation and the Woodfield approximation for constant windshear due to an increasing tailwind. The difference stems from the fact potential height is computed by using the ratio \( \Delta V/V_0 \) from the numerical simulation for the integration, instead of using the actual value \( \Delta V/V \).

Curves of constant potential height loss of \( H^* = 10 \) m are drawn in the plane of wind change (\( \Delta uW \)), in terms of shear length \( L_g \) with the following conditions (see Fig. C2, C3 and C4):

- windshear due to a decreasing headwind or to an increasing tailwind respectively;
- several pilot reaction times: 1.2 s and 4.8 s.

It can be noticed that potential height losses are strongly dependent on windshear type (headwind or tailwind) and also on pilot reaction time. Computed height loss always overestimates the actual value.

The effect of the quality of constant pitch guidance during windshear crossing was also evaluated, as can be seen in Fig. C.5.

All these results show the difficulty to choose the appropriate parameters to be used for a severity criterion, according to the X-factor.
Fig. C1 - Airspeed error and potential height error due to increasing tailwind maintaining pitch attitude
Fig. C2 - Effect of windshear gradient type and pilot reaction time on potential height loss
Fig. C3 - Effect of windshear gradient type and pilot reaction time on potential height loss (cont'd)
Fig. C4 - Effect of windshear gradient type and pilot reaction time on potential height loss (cont'd and end)
Fig. C5 - The influence of the quality of pitch guidance to the potential height error (complete simulation and "Woodfield" approximation using speed error from simulation)
APPENDIX D

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