IMPACT OF ADS-B LINK CHARACTERISTICS ON THE PERFORMANCES OF IN-TRAIL FOLLOWING AIRCRAFT

Dan IVANESCU*, Eric HOFFMAN, Karim ZEGHAL
EUROCONTROL Experimental Centre, BP 15, 91222 Bretigny, France
Email: {dan.ivanescu, eric.hoffman, karim.zeghal}@eurocontrol.int

ABSTRACT
In the general context of the delegation of some controller tasks to the flight deck, the pilots could be instructed to adjust its aircraft speed so as to maintain a prescribed longitudinal spacing with respect to the aircraft flying ahead. ADS-B (Automatic Dependent Surveillance – Broadcast) technology is one of the potential key enabler to support the implementation of such application. In this paper, the relationship between the ADS-B surveillance data characteristics (information exchanged, update rate, latency, accuracy) and the performance of the in-trail following aircraft application (stability of the in-trail aircraft, expected accuracy of in-trail aircraft time or distance spacing) is investigated based on a mathematical model of the in-trail aircraft.

Keywords: in-trail following aircraft, station-keeping, ADS-B, guidance laws, stability control.

INTRODUCTION
The delegation of spacing tasks from the controller to the flight deck is envisaged as one possible option to increase controller availability, and beyond, to increase safety and/or capacity. For aircraft within an arrival stream, the delegation could consist in tasking the flight crew to perform (manually or automatically) the necessary speed adjustments so as to maintain a given spacing to a lead aircraft. Surveillance information, such as position and velocity of the lead aircraft, is obtained through ADS-B (or TIS-B)[14],[15],[16]. The analysis of the dynamics of in-trail following aircraft can be traced back at least to the in 80’s; in [17], both analytical and experimental aspects were investigated and three spacing criteria were introduced (constant distance, constant time predictor, and constant time delay). To simulate strings of aircraft a mathematical model was used. In a further analysis ([8] and the references therein) two spacing criteria were investigated through pilot-in-the-loop experiments with spacing cues on the cockpit display. In the 90’s, analytical models were used along with pilot-in-the-loop experiments [12],[13]. The impact of top of descent position and of speed reduction on the in-trail following performance was investigated through mathematical models [18]. All these studies, however, assumed perfect surveillance information. An experimental study focussing on closely spaced parallel approaches has been carried out [7]. Although standards are already under development and initial recommendations are proposed [16],[19], the impact of ADS-B characteristics on the performances of the considered application remains a key issue.

The present paper focuses on the in-trail following aircraft application, and will investigate the impact of ADS-B update rate, latency and accuracy on the spacing achieved between aircraft. Although this paper only presents preliminary results, the ultimate goal is to derive ADS-B requirements to meet a set of defined operational requirements in terms of in-trail following performance. A mathematical model comprising aircraft dynamics and pilot behaviours is used to simulate “chains” of aircraft.

The paper is organised as follows: the operational aspects are first considered and the spacing criteria are described. Then, the aircraft model is presented, followed by the guidance law and the ADS-B model. Finally, initial results on the impact on update rate, latency and accuracy are given separately, before concluding.

OPERATIONAL ASPECTS
The operation being simulated here consists of aircraft flying along the same route, and each trailing aircraft has to maintain a given spacing behind its preceding aircraft referred to as the 'lead' aircraft. The aircraft may be in-cruise (i.e. steady altitude) or in evolution (typically in descent).
The desired spacing is computed from the surveillance data (position and speed) from lead aircraft transmitted via ADS-B. Two spacing criteria defined in [17]† are used:

**Constant Distance Criterion (CD):** This criterion is based on the spacing distance between two aircraft. The spacing error is built up out of the difference between the lead aircraft’s position and the trailing aircraft position taking into account the desired spacing:

\[
y_{errorCD} = y_{lead} - y_{trail} - y_{separation} \quad [1.1]
\]

**Constant Time Delay Criterion (CTD):** The CTD criterion is based on time spacing. More precisely, the spacing error is the difference between the elapsed time since the lead aircraft over-flew the current trailing aircraft position, and the desired time spacing:

\[
t_{errorCD} = t - t' \mid y_{lead}(t') = y_{trail}(t) - t_{spacing} \quad [1.2]
\]

which, assuming that the lead aircraft speed is constant, can be approximated as:

\[
t_{errorCTD} = \frac{y_{lead} - y_{trail}}{V_{lead_{true}}} - t_{spacing} \quad [1.3]
\]

The time-based CTD criterion can be rewritten as an equivalent distance-based criterion:

\[
y_{errorCTD} = y_{lead} - y_{trail} - y_{distCTD} \quad [1.4]
\]

where:

\[
y_{distCTD} = V_{lead_{true}} \cdot t_{spacing} \quad [1.5]
\]

The re-formulation of the time-based criterion as a distance-based criterion is used in the design and the implementation of the guidance law controller.

**AIRCRAFT MODEL**

For the purpose of this study, we need to model a realistic behaviour of an aircraft along typical descent profiles, including speed changes and intermediate altitude steps. The aircraft model is divided in two parts:

- The *aircraft dynamics* models the actual physics of the system.
- The *pilot model* is a combined representation of the aircraft auto pilot system and to a certain extent of the pilot actions on it.

For the aircraft dynamics the following general assumptions are made:

- Flat, non-rotating earth.
- Standard atmosphere.
- Fully co-ordinated flight. The sideslip angle \( \beta \) will always be zero and there will not be any side force.

The equations of motion used for the aircraft model are based on the three-dimensional point-mass differential equations, as found in many references [11]. The total set of differential equations results in 7 state variables, \( \{ \gamma \ h \ \phi \ \psi \ x_{east} \ x_{north} \} \), where: \( \gamma \) is the flight path angle, \( V \) the true airspeed, \( h \) vertical distance or altitude, \( \phi \) is the bank angle, \( \psi \) the heading angle, \( x_{east} \) the east position and \( x_{north} \) the north position and \( m \) the aircraft mass. Because the aircraft mass is not considered to be constant, the equations of motion are complemented by an eight equation, describing the loss of mass due to the fuel flow \( (Q) \) of the aircraft. The final set of equations are given hereafter:

\[
\dot{\gamma} = \frac{L + T \cdot \sin \alpha}{m \cdot V} \cdot \cos \phi - \frac{g}{V} \cdot \cos \gamma \quad [1.6]
\]

\[
\dot{V} = \frac{T \cdot \cos \alpha - D}{m} - g \cdot \sin \gamma \quad [1.7]
\]

\[
\dot{h} = V \cdot \sin \gamma \quad [1.8]
\]

\[
\dot{\phi} = p \quad [1.9]
\]

\[
\dot{\psi} = \frac{g \cdot \tan \phi}{V} \quad [1.10]
\]

\[
\dot{x}_{east} = V \cdot \cos \gamma \cdot \cos \psi - V_{wind} \cdot \cos \chi_{wind} \quad [1.11]
\]

\[
\dot{x}_{north} = V \cdot \cos \gamma \cdot \sin \psi - V_{wind} \cdot \sin \chi_{wind} \quad [1.12]
\]

\[
\dot{m} = -Q \quad [1.13]
\]

Here, \( D \) is the drag, \( T \) the engine thrust, \( \alpha \) angle of attack, \( \chi_{wind} \) and \( V_{wind} \) are the wind direction and speed, \( L \) is the lift and \( g \) is gravity. Due to the fact that in the normal flight regime, which is the case considered in this study, \( \alpha \) is relatively small, in [1.7] \( \cos \alpha \) can be approximated to 1. Further, in [1.6], the term \( T \cdot \sin \alpha \) can be considered as negligible in comparison with the lift contribution. This simplifies [1.6] and [1.7] to:

\[
\dot{\gamma} = \frac{L}{m \cdot V} \cdot \cos \phi - \frac{g}{V} \cdot \cos \gamma \quad [1.14]
\]

\[
\dot{V} = \frac{T - D}{m} - g \cdot \sin \gamma \quad [1.15]
\]

The differential equations [1.8] to [1.15] constitute then the basic equations of motion of the aircraft model.

The aerodynamic forces are based on an aerodynamic model, using an estimate of the aircraft trimmed aircraft polar, with an extension to model the effects of Mach-drag rise. The Mach-drag rise component is

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† The third criterion (Constant Time Predictor), based also on time spacing is not used in the paper due to its poor performance documented in [17].
usually a function of Mach number and lift coefficient. A 2-dimensional look-up table is used to model the aircraft polar.

The thrust is computed from a given thrust over weight ratio for a given aircraft, by multiplying this ratio by a percentage thrust command and the maximum take-off mass of the aircraft type at hand. The thrust over weight ratio is calculated from a two-dimensional look-up table, as function of Mach and pressure altitude. The thrust characteristics used in the model are typical for high by-pass turbofan aircraft. Due to the fact that the thrust is calculated as a dimensionless thrust over weight ratio, the thrust model can be adapted easily to various aircraft types, without significant changes to the trust model. By using a calibration factor (ranging from plus or minus 20%) the model can therefore easily be adapted to any aircraft type.

The autopilot allows the aircraft to follow the reference targets (desired airspeed and altitude). The principle used to design the autopilot is based on the instant update rate, no latency.

Notice that, results presented in these references correspond to a perfect ADS-B, i.e. perfect accuracy, instant update rate, no latency.

GUIDANCE LAW: TUNING AND DESIGN

This guidance law is designed such that it can be used as an outer loop to the basic autopilot. It is expected that for a practical implementation of an in trail following controller in a real aircraft, a similar architecture would be applied.

The guidance law has been designed to provide calibrated air speed (CAS) reference to the basic autopilot.

Based on a classical poles analysis, it can be shown that a second order controller is required in order to guarantee stability of the closed loop spacing controller. In the terminology of control theory, this means that two complex zeros are placed in the left half plane, to attract two potentially unstable poles of the open loop transfer function into the stable area, when the control loop is closed. The basic control law has to be complemented with a proportional plus integral (PI) part in order to prevent steady state errors. To reduce and eliminate the wind-up\(^1\), a saturation link is placed in front of the integral (I) part. This means that the basic control law is of the form (in Laplace domain):

\[
V_{cmd} = \frac{K_p \cdot y_{error(CD,CTD)} + (K_i + s)}{s^2 + 2\zeta_{man} \omega_{man} \cdot s + \omega_{man}^2} \cdot sK_s\]  \[1.16\]

Within this equation, the parameter \(\omega_{man}\) can be interpreted as the manoeuvre bandwidth, and \(\zeta_{man}\) as the manoeuvre damping. The manoeuvre bandwidth should be regarded as the target closed loop bandwidth of the spacing controller. It is good practice to select the bandwidth of spacing error approximately an order lower than the bandwidth of airspeed control (being the first derivative of distance) in order to assure a good control decoupling. The bandwidth of airspeed control of aircraft is in the order of \(.1\) to \(.5\) rad/s, which means that a good value for \(\omega_{man}\) would be around \(.05\) rad/s (for smaller values, the controller time response becomes too large).

The manoeuvre damping \(\zeta_{man}\) is preferably set to an over-damped value of between \(1\) and \(1.5\). A bigger value leads to unstable behaviour. It should be noticed that closed loop damping reaches the value of the manoeuvre damping only when the loop closure gain \(K_c\) approaches infinity. Therefore, to achieve near critical damping of the closed loop system, it is necessary to select an over-damped value of \(\zeta_{man}\) (hence greater than \(1\)).

With respect to the integral gain \(K_i\) it is evident that this parameter introduces another zero in the control law. It should be avoided to select high values for this gain, because this may introduce overshoot of the controlled variable. The coefficient is increased until it starts affecting the overshoot too much. A good value for \(K_i\) is therefore around \(.1\) rad/s (slightly below the speed control bandwidth). Smaller values for \(K_i\) are not enough to reject steady state errors.

\(^1\) The windup is the phenomenon when the time response overshoot for the large amplitude input step is excessive and persistent. It is typically caused by a large the error integration in the controller.
By selecting the parameters of the control law as described, the closed loop gain $K_p$ can be used to improve performances. A good value for this gain can be between 10 and 50 (see Figure 1).

In order to validate the guidance law design, we used a test scenario with two aircraft. In this scenario the lead aircraft is initialised at FL290, level flight, and airspeed of 272 kts CAS. The trailing aircraft is positioned at equal altitude and airspeed with a 7 Nm spacing distance behind the lead aircraft. At a fixed position both aircraft start a descent to FL100. This scenario has been used for the two spacing criteria, as discussed before.

![Figure 1: Tuning of the proportional gain $K_p$ (CD).](image)

The parameters of the guidance law were selected as follows:

$$K_p=15, \ K_i=0.15 \text{ rad/s}, \ \zeta_{\text{man}}=1.3, \ \omega_{\text{man}}=0.05 \text{ rad/s}$$

![Figure 2: Guidance law errors for the two spacing criteria (blue line CD error, red line CTD error).](image)

Figure 2 shows that the selected parameters result in acceptable behaviour with the 2 spacing criteria.

For the remainder of the paper, the aircraft model used was a Boeing 747-400 for all aircraft.

**ADS-B MODEL**

The surveillance information on each preceding aircraft include at least: position, altitude, and ground speed. This information (called state vector) is transmitted through ADS-B reports. The ADS-B model comprises two blocks: the ADS-B transmitter and the ADS-B receiver. The ADS-B transmitter part is responsible for selecting from the total output vector the surveillance information to be sent. In order to simulate “real” ADS-B transmissions, the following characteristics are modelled:

- **update rate** of reports: sustained rate at which periodic ADS-B report are received. In the sequel except when otherwise noted, we consider a perfect update rate, i.e. the probability of reception is 100%, so each time the report is successfully received.
- **latency** of transmission: delay between the time when the ADS-B report is handled, and the time when position and velocity were measured. This includes not only ADS-B latency, but also additional delays in the processing of the information. We assume that the latency is the same for all information. Furthermore, this latency consists of a mean time delay with a stochastic variation (in order to model jitter). The standard deviation of this stochastic variation gives the amount of jitter in the signal. Latency is modelled by a transport delay block from Simulink toolbox.
- **accuracy** of surveillance information: difference between the state vector transmitted by ADS-B and the true values. It is characterised by a mean (bias) and a variation about the mean defined by the standard deviation sigma (stochastic or gaussian perturbations are modelled). Because the input variables to the ADS-B transmitter in the simulation are directly the state variables, they are not disturbed by any error. Therefore, within the ADS-B transmitter part, the accuracy is modelled through error signals added to the sent items. The trailing aircraft is provided with the received ADS-B state vector, an indication if an update was missing as well as the Navigation Accuracy Category (NACp and NACv). The numerical values for these categories are defined by RTCA, [16] (see Appendix, Table 1).

**MAIN RESULTS**

In this section, we will present the results on the impact of update rate, latency and accuracy of ADS-B on the performance of in-trail following aircraft. Three indicators are used to quantify the performance: the spacing between successive aircraft, the speed variation for each aircraft, and the behaviour of the controls variables (thrust and flight path angle). For
lack of space, in each case considered, we present just the most sensitive ones.

The guidance law presented in the previous paragraph has not been designed to compensate for signal imperfections. Nevertheless, this controller has been used without any further provisions, which could be expected to be part of a real design. The response of the controller can therefore be regarded as “worst case” performance. Furthermore, the use of this guidance law without any modifications, can be seen as a good measure to compare the “natural” impact of the ADS-B parameters on the in-trail performances.

**Operational scenario:**

The following scenario is used: a lead aircraft follows its own descent profile and five trailing aircraft adjust speed to maintain the desired spacing to their preceding aircraft. All aircraft start at FL290 and 7Nm/min true airspeed (TAS) (272 kts CAS) and descent to FL100. All aircraft start their descent at the same location (fixed based ToD). The lead aircraft reduces speed from 272 kts to 232 kts (CAS) at FL150. Desired spacing between aircraft are 7Nm (for CD) and 60s (for CTD). At initial time, all aircraft (Boeing 747-400) are at the desired spacing, as well as at the same speed and altitude.

**Reference results:**

The reference results represent in-trail performances with a perfect ADS-B, i.e. perfect accuracy, instant update rate, no latency. The maximum speed variation, compared to the normal profile, is up to 22 kts (for CD) and 3 kts (for CTD) and the maximum spacing error is ~0.03 Nm, i.e 0.4% (for CD) and ~4 sec, i.e. 6% (for CTD). The engine throttle and the flight path angle have smooth behaviours without oscillations.

**Limit test scenario:**

In order to asses the limits (implicitly the robustness) of the in-trail model (and especially for lower update rate values), a very challenging scenario is considered for the lead aircraft: with the auto-flight pilot in altitude hold mode at FL290 and 272 CAS, idle power is applied to achieve the maximum available longitudinal deceleration. At the selected flight level (FL290), a high power level (throttle 57%), is required to maintain steady state conditions. Therefore, the reduction of thrust to idle with result in a significant deceleration. The lead aircraft response settles at a maximum deceleration of around 1.2 kts/s.

**ADS-B UPDATE RATE**

The results are presented in the Figure 3 (solid lines the operational scenario and dashed lines the test scenario, CD and CTD criteria).

**Figure 3:** Impact of ADS-B update rate on in-trail performances: maximum error spacing (%) function of update rate. Solid lines: the operational scenario, dashed lines: the test-limit scenario.

First of all, it appears that for small update rates (up to 5 sec.), the in-trail aircraft is well-conditioned and the spacing error remains small (below 10% for both criteria).

An important degradation is observed starting with an update rate of 6s for CD criterion. On the contrary, using the CTD criterion, the error and speed range function of the update rate have smooth evolutions, almost linear, for update rates up to 12 sec. It should be noticed, that, for small update values (between 0 which stands as ‘perfect accuracy’ and 3 sec.) the CD criterion performs better. This provides a certain robustness of the guidance law, but by the other hand, the tuning of the parameters for a corresponding update rate value may improve performances. As expected, for the limit case when the lead aircraft suddenly decreases speed with the maximum available longitudinal deceleration, the performances are not good (Figure 3, dashed lines). However, for update rates less than 3 seconds, both criteria still lead to acceptable results (below 10% error for CD, and 20% error for CTD) even for this challenging case.

During the operational scenario, the maximum CAS speed variation for the trailing aircraft is presented in Figure 4. Again, the CTD criterion is exhibiting better results: smaller speed variations are required (less than 10 kts CAS for update rates up to 10sec), due to the fact that the trailing aircraft try to duplicate the true airspeed profile of the leader aircraft as function of position. The speed variation is important for CD criterion (~ 40 kts CAS for update rates up to 5 sec).
With regard to third type of indicator, the engine thrust provides oscillations for important update values. The Figure 3 and Figure 4 show also the update rates from which the engine throttle of the trailing aircraft provides maximum peak oscillations of 20% when maintaining spacing. Obviously, a distinction shall be done between a normal variation in the engine throttle (for example when the aircraft is asked to climb or descent), and the non-monotonous oscillations mentioned here.

**ADS-B Update rate with probability of reception**

The results presented here were obtained when the ADS-B receiver is assumed to be receiving all reports with a 100% probability. We now investigate the in-trail performances when reception errors occurs, this resulting in a failure to update the received ADS-B state vector (probability of reception < 100%). The results show (Figure 5) that the impact of stochastic or gaussian perturbations is most visible on the behaviour of the control parameters (engine throttle).

*Figure 4: Impact of ADS-B update rate on in-trail performances: Maximum CAS speed variation (kts) function of update rate. The operational scenario.***

A monte-carlo type approach has been used to identify the appropriate engine throttle level. Clearly, CTD criterion exhibits better performances with better resilience to lost messages.

**ADS-B LATENCY**

In order to compensate for latency, a Report Time Error is foreseen to be transmitted in ADS-B reports. It corresponds in this study to the delay between the time when the ADS-B report is sent, and the time when position and velocity were measured. The report time error is defined by RTCA as the difference between the time used by the last measurement to update the ADS-B report, and the value in the time field of the ADS-B report. Two cases are considered:

A. *The report time error is zero*, meaning that it is undefined or not filled when sending the ADS-B report. In this case, the delay cannot be compensated. The results are shown in Figure 6 and Figure 7 (solid lines for constant latency, dashed lines for latency with jitter). The jitter is computed like a stochastic variation where the bias is the constant latency (tLat ) and a standard deviation (σ). For each bias, we consider the maximum admissible important jitter. Again, CTD provides better performance. Using CD important degradation starts even for very small latency (about 2 sec.). Two important aspects should be noticed:

- the ADS-B latency induces a permanent steady spacing error. Due to the delayed position of lead aircraft, the trailing aircraft thinks that he is closer than he in fact is. Therefore the trailing aircraft starts to decelerate initially, such that the perceived spacing is controlled to 7 nm. It could be noticed that this permanent error can be expressed analytically as tLat * lead aircraft ground speed. For 5s of latency this gives an error equals to: 5s * 268 kts ÷ 700 m ÷ 0.4 Nm ( 6% ) for the CD and an error equals to 5s ( 8% ) for CTD.

*Figure 5: Engine throttle oscillations (%) function of probability of reception of ADS-B.*

As long as the required controls stay within feasible bounds the spacing error is maintained below 10%.

But when these engine throttle oscillations exceed 100%, the auto-pilot is saturated and the spacing cannot be maintained. For this reason, we chose to show here the engine throttle oscillations function of probability of reception for various update rates (Figure 5).

For lack of time, the validation uses 10 tests, with random values from the intervals defined by the standard deviations.

**The maximum admissible jitter is computed as follows: the delay block in Simulink is initialised with the latency bias. Since such block cannot accept negative values, we can assure that, for any bias the resulting minimum latency is still positive. Within a 99 percent confidence level the minimum value is tLat - 3σ, which must be greater than zero. For a given latency the considered jitter will be equal to σ = tLat/3.***
In the presence of jitter, the level of performance decreases (see Figure 6 and Figure 7, the dashed lines). However, for latency up to 4 seconds, both criteria still work within an acceptable level of performances (~10% maximum error, 20 kts CAS speed variation for CTD and ~35 kts CAS for CD). It should be mentioned that, however, we considered here the maximum possible stochastic deviation. For a real system, the jitter can be expected to be smaller.

**Figure 6**: Impact of ADS-B latency on in-trail performances. Maximum error spacing (%) function of latency. Solid lines: constant latency, dashed lines: jitter.

**Figure 7**: Impact of ADS-B latency on in-trail performances. Maximum CAS speed variation (kts) function of latency. Solid lines: constant latency, dashed lines: jitter.

**B. The report time error equal to latency.** In this case, the constant latency can be compensate and furthermore a zero latency can be used. To do this, the guidance law can be modified: the error could contain a parameter to correct for a constant latency. This will be dealt with in further work.

It should be noticed that the controls are less affected than in the update rate analysis. For this reason, the engines behaviour (which provide smooth characteristics) are not presented here.

**ADS-B accuracy**

To study the impact of the ADS-B accuracy, we modelled the uncertainties (gaussian noise) for the position and speed information. The ADS-B accuracy values used in the paper are in terms of a standard variation from an assumed zero mean error, defined as follows:

- Standard deviation of horizontal position accuracy ($\sigma_{hp}$)
- Standard deviation of horizontal velocity accuracy ($\sigma_{hv}$)

The RTCA Navigation Accuracy Categories (NAC) defined in Appendix (see Appendix, Table 1), provide the 95% accuracy bounds on horizontal and vertical position. Since we assume no uncertainty on the vertical position, a navigation accuracy category for position is defined as the radius of a circle, centred on the reported position, such that the probability of the actual position being outside the circle is 0.05. Assuming zero mean error, and 95% probability, this categories are given in terms of $2\sigma_{hp}$ (for example, NAC$_{p}$ = 9 means an accuracy bound less than 30m, i.e. $2\sigma_{hp} < 30$). A similar approach is used for the horizontal velocity categories.

The CD criterion uses only the lead aircraft position so only the position accuracy will affect its performance. The CTD uses both position and speed, so in this case, the performances are dependent on both terms accuracy.

Again, the analysis shows that the most sensitive parameter is the engine throttle. The error spacing is maintained at low value, less than 8%, by manoeuvring the thrust. As consequence, low accuracy, implies big throttle oscillations. As long as the throttle oscillations are under 100%, the spacing is maintained with no significant errors (compared against the reference results, i.e. below 3% spacing error for CD and 8% for CTD). When the oscillation in thrust exceeds 100%, the guidance law cannot maintain anymore the spacing. Figure 8 shows these results. Again, a monte-carlo type approach has been used to validate the performance and to identify the corresponding accuracy level. In solid line, we represent the engine throttle as a function of standard deviation of horizontal accuracy when the distance criterion is used. The standard values corresponding to each NAC$_{p}$ are identified on the figure by vertical red lines.
The present paper presented an initial evaluation of the impact of ADS-B characteristics on the performance of in-trail following aircraft through the use of a mathematical model. Two spacing criteria (time and distance) were used, and three characteristics of ADS-B were investigated: update rate, latency and accuracy. The performance indicators consisted in spacing achieved between aircraft, the speed variation and the engine throttle behaviour.

For the two spacing criteria, the proposed guidance law is capable of maintaining spacing in nominal cases. Of the three type of “disturbances” considered, update rate appears to be the one having the most severe impact on the in-trail following performances. CTD appears to be more robust that CD to update rate, latency and position accuracy characteristics. However, due to the way the spacing is computed, it is severely impacted by speed accuracy characteristics.

The results obtained here are anticipated to be quite conservative as the guidance law used is quite basic and neither optimisation nor compensation for signal imperfection having been used. Future work will look at some simple compensate mechanisms as well as at more elaborate ADS-B characteristics models.

REFERENCES


Appendix

Table 1: Navigation Accuracy Categories - Position and Velocity ([16])

<table>
<thead>
<tr>
<th>NAC position</th>
<th>Horiz. Error (95%)</th>
<th>NAC velocity</th>
<th>Horiz. Velocity Error (95%)</th>
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<td>0</td>
<td>Unknown</td>
<td>0</td>
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<tr>
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<td>1</td>
<td>&lt; 10 m/s</td>
</tr>
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<td>2</td>
<td>&lt; 5 nm</td>
<td>2</td>
<td>&lt; 3 m/s</td>
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<td>&lt; 1 nm</td>
<td>3</td>
<td>&lt; 1 m/s</td>
</tr>
<tr>
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<td>&lt; 0.5 nm</td>
<td>4</td>
<td>&lt; 0.3 m/s</td>
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<tr>
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<td>&lt; 0.75 nm</td>
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