Effect of ADS-B Characteristics on Airborne Conflict Detection and Resolution

Thom Langejan, Emmanuel Sunil, Joost Ellerbroek and Jacco Hoekstra
Control and Simulation, Faculty of Aerospace Engineering
Delft University of Technology, 2628 HS Delft, The Netherlands

***Abstract*—Most Free-Flight concepts rely on self-separation by means of airborne Conflict Detection and Resolution (CD&R) algorithms. A key enabling technology for airborne CD&R is the Automatic Dependent Surveillance-Broadcast (ADS-B) system, which is used for direct state information exchange between aircraft. Similar to other communication systems, ADS-B is affected by a number of limitations which can be broadly classified as system and situation related deficiencies. This research investigates the impact of these limitations on the viability of using ADS-B for airborne CD&R within the Free-Flight context. Here, 'state-based' conflict detection and the modified voltage potential conflict resolution algorithm are used as a case-study. An ADS-B model is developed, and its effect on the aforementioned CD&R method is measured using three fast-time simulation experiments. The experiments studied overall safety with ADS-B, as well as the specific effect of situation related characteristics, i.e., transmission range and interference, on safety. The results indicated that the overall safety with ADS-B was comparable to the case where perfect state information was assumed. Additionally, it was found that increasing ADS-B transmission range also increased signal interference, which in turn lowered safety. This suggests that the degrading effect of ADS-B signal interference should be considered in future airborne CD&R research, particularly for high traffic densities.**

***Index Terms*—ADS-B, Free Flight, Conflict Detection and Resolution (CD&R), Modified Voltage Potential (MVP), Air Traffic Management (ATM), Safety, Self-Separation, BlueSky ATM Simulator**

I. Introduction

The Free-Flight Air Traffic Management (ATM) concept has been proposed as a means of increasing airspace safety, efficiency and capacity by permitting user defined trajectories [1], [2]. Most Free-Flight concepts rely on self-separation using airborne Conflict Detection and Resolution (CD&R) automation. As airborne CD&R requires information sharing between aircraft, a system for inter-aircraft communication is required. In Free-Flight literature, this information sharing is often achieved using the Automatic Dependent Surveillance-Broadcast (ADS-B) system. Aircraft equipped with ADS-B transmitters periodically broadcast their own state information, such as position and velocity, using data obtained from on-board sensors. Aircraft can also receive this information from neighboring traffic, which can in turn be used for detecting and resolving conflicts [3].

Similar to other data-link systems, ADS-B has a number of limitations that affect the quality of the transmitted and received information. These limitations can be broadly classified as system and situation related deficiencies. System related limitations affect the accuracy of the transmitted state information. This is not only affected by the accuracy of on-board sensors, but also by the number of bits available for (digital) data encoding. On the other hand, situation related deficiencies reduce ADS-B message detect and decode probability due to the distance between aircraft and due to signal interference [4]. Previous researchers have modeled these situation related effects, discussed in [4], [5].

Despite these limitations, much of the previous work on airborne CD&R, particularly studies related to the development of novel conflict resolution methods [1], [6], have assumed perfect state information exchange between aircraft. Thus, it is as yet unknown whether the ADS-B system is actually capable of providing usable state information for airborne CD&R purposes. Furthermore, the extent to which the safety of CD&R methods is affected by ADS-B limitations is also unknown.

The research that is presented in this paper represents the initial work done towards understanding the effect of ADS-B on self-separation safety by focusing on one particular airborne CD&R method. Given the plethora of CD&R methods, the frequently used 'state-based' Conflict Detection (CD) method, and the Modified Voltage Potential (MVP) Conflict Resolution (CR) algorithm, have been selected as a case-study. An ADS-B model is developed, and its effect on state-based CD and the MVP CR algorithm are measured using three fast-time simulation experiments. The goal of the first experiment is to determine the overall safety with ADS-B. To this end, an ABS-B system based on Minimum Operational Performance Specifications (MOPS) [7] is compared to one that is based on measured actual performance [8], and to the case where perfect state information is used. The second and third experiments focus on the specific effect of situation related characteristics, i.e., transmission range and interference, on safety.

This paper is organized as follows. An overview of the Automatic Dependent Surveillance-Broadcast (ADS-B) system and its model derivation is described in Section II. Details of the three experiments used to study the safety impact of ADS-B, as well as a description of the Conflict Detection & Resolution (CD&R) method used are presented in Section III. The results are presented and discussed in Section IV. This paper ends with the main conclusions in Section V.

II. ADS-B Model

In this research, the focus is on the airborne ADS-B link between aircraft, enabled by ADS-B IN/OUT. ADS-B transmits specific state information in an omnidirectional manner, called squitter. The following different type of squitter messages exist, with their corresponding transmission rate:

- Airborne positions squitter (2 Hz)
- Surface position squitter (1 Hz)
- Airborne velocity squitter (2 Hz)
- Aircraft identification squitter (0.2 Hz)
- Operational Status (0.4 Hz)
- Target state (0.8 Hz)

The messages are transmitted using Pulse Position Modulation (PPM) on the 1090 MHz carrier frequency. Each message contains 120 bits and is transmitted at 1 Mbps, resulting in a message duration of 120 μs.

Two main elements can be identified affecting the ADS-B system performance; system and situational related elements. System related elements affect the accuracy of an ADS-B message, while situation related elements mostly affect the probability of proper detection and decoding of an ADS-B message. A schematic overview is shown in Figure 1. Both elements are discussed and modeled in the following subsections.

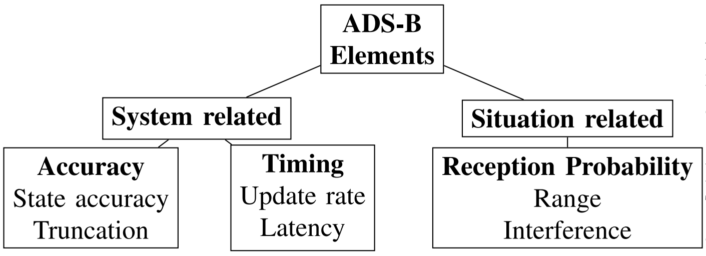


Figure 1. Schematic overview of elements degrading ADS-B performance.

A. System Related ADS-B Elements

The quality of an ADS-B message is affected by truncation, state accuracy and latency.

Truncation:

The position reports contain latitude and longitude locations. The latitude an longitude are both transmitted using 6 significant digits. The offset caused by truncation is the distance between two locations where the 6th digit is changed. The Haversine function, shown in Equation (1), is used to calculate the great-circle distance between two points in meters, expressed in latitude and longitude. In this equation ϕ is latitude (rad), λ is longitude (rad), and R (m) is the earth radius.

$$a = sin(\frac{\Delta\phi}{2}) + cos(\phi_1) \cdot cos(\phi_2) \cdot sin^2(\frac{\Delta\lambda}{2}) \quad (1a)$$

$$c = atan2(\sqrt{a}, \sqrt{1-a}) \quad (1b)$$

$$d = R \cdot c \quad (1c)$$

Using the Haversine function and a position described in longitude and latitude with a six digit significance level results in a accuracy ranging from 9 to 17 m, depending on the location on the earth.

State Accuracy:

In addition to the truncation effect, the accuracy of the on-board measurement sensors affects the location precision. Location is determined using the Global Navigation Surveillance System (GNSS). In [9] it is found that a GPS measurement has an accuracy of $\leq$7.8 meter with a 95% confidence interval.

Latency:

A latency of 20 milliseconds in the ADS-B system is assumed, resulting in an offset of several meters (4.44 meters for an aircraft cruising at 800 km/h). It should be noted different delays are not taken into account in this research.

Based on the truncation, accuracy and latency evaluation, the position accuracy of an ADS-B report is modeled as a standard normal distribution with a standard deviation of 30 meters, selected as a worse case scenario.

B. Situation Related ADS-B Elements

The situation related elements affect the detect and decode probability of an ADS-B report, caused by range and interference. Analytical models for these two aspects are discussed below, based on the research performed in [4], [5].

Range:

The derivation of an analytical model between distance and detect/decode probability is based on the 1090 Extended Squitter (ES) Minimum Operational Performance Specifications (MOPS) [7]. The general approach, described in [5], is followed. This derivation consists of 5 steps.

Step 1: The derivation begins by computing the Free Space Path Loss (FSPL) for the 1090 MHz frequency.

$$FSPL(d) = \frac{4\pi df}{c}^2 \quad (2)$$

In Equation (2) c (speed of light) and f (carrier frequency) are constant. The FSPL per Nautical Mile (NM) is shown in Equation (3).

$$FSPL_{NM}(r) = 95.55 + 20 \cdot log_{10}(r)[\frac{dB}{NM}] \quad (3)$$

Step 2: The second step is to obtain the relation between distance and received power (S_{rec}) for a specific transmit power (S_{trans}), shown in Equation (4).

$$S_{rec} = S_{trans} - FSPL_{1NM} - 20 \cdot log_{10}(r) \quad (4a)$$

$$S_{rec} = S_{rec\_1NM} - 20 \cdot log_{10}(r) \quad (4b)$$

In Equation (4), $(S_{trans} - FSPL_{1NM})$ equals the received power at a distance of 1 Nautical Mile (NM), called S_{rec_1NM}, for a transmitted power of S_{trans}. Rewriting this equation, a relation between distance and received power is obtained, shown in Section II-B.

$$r = 10^{\frac{-(S_{rec} - S_{rec\_1NM})}{20}} \tag{5}$$

Step 3: In this step the detect and decode probability of an ADS-B report (without interference) is modeled as an exponential function of received signal power (S_{rec}) [5]. At the maximum reception distance, r_0, the detect and decode probability is set to zero. The received power at r_0 is defined as S_{rec0} [7]. The variable k is used to scale the curve of the reception probability function, resulting in Equation (6).

$$P(S_{rec}) = 1 - 10^{-k\frac{(S_{rec} - S_{rec0})}{20}}, S_{rec} \geq S_{rec0} \tag{6}$$

Step 4: The distance between transmitter and receiver for a detect and decode probability of zero, as a function of range (instead of received power), can be obtained by substituting Section II-B in Equation (6):

$$P(r) = 1 - \left(r \cdot 10^{-\frac{(S_{rec\_1NM} - S_{rec0})}{20}}\right)^k, r \geq r_0 \tag{7}$$

The received power S_0 results in a zero detect and decode probability with the corresponding distance r_0. Using Section II-B, r_0 is obtained as shown in Equation (8)

$$r_0 = 10^{\frac{-(S_{rec0} - S_{rec\_1NM})}{20}} \tag{8}$$

The inverse of Equation (8) is substituted in Equation (7) to obtain Equation (9).

$$P(r) = 1 - (\frac{r}{r_0})^k, r \geq r_0 \tag{9}$$

Equation (9) is used to determine the no-interference reception probability as a function range, using a fixed transmit power, S_{trans}.

Step 5: For the final step, the value of the scaling variable k is determined. In [7] a minimum triggering level (S_{MTL}) of -90 dBm for Class A3 equipped commercial transport is defined with the following requirements:

1) If link margin ($S_{rec} - S_{MTL}$) = 3dB the minimum reception probability should be ≥ 0.99.
2) If link margin ($S_{rec} - S_{MTL}$) = -3dB the minimum reception probability should be ≥ 0.15.

Substituting these values in Equation (6) results in a scaling factor k of 6.4314. In this model, it should be noted that the maximum reception distance, r_0, is a function of transmit power (S_{trans}) and sensor sensitivity (S_{rec0}).

The following assumptions are made in the detect and decode probability model derived with respect to range:

1) Omni-directional antenna used by transmitting and receiving aircraft.
2) A constant noise level on the 1090 MHz frequency is assumed, based on [7].
3) No multi-path effects.
4) Weather related effects are not taken into account.
5) No shielding by aircraft of ADS-B transmitter/receiver antenna.

Interference

If multiple ADS-B messages are received simultaneously at a receiver, it may not be possible to decode the received messages depending on the degree of overlap. This effect is called interference, and is visualized in Figure 2.

To model the effect of interference on detect and decode probability, the Poisson distribution, shown in Equation (10), has been used. This probability distribution is generally used to calculate the number of events occurring during a specified time interval:

$$P[X = k] = (\lambda t)^k \frac{e^{-\lambda t}}{k!}, \ k = 0, 1, 2, ... \tag{10}$$

In this equation, λ is the expected number of events occurring in unit time, t is the interval length, X is the number of events occurring in interval of length t, and P is the probability of X occurrences in an interval of length t.

The different ADS-B transmission rates, discussed in the previous section for the 6 different ADS-B reports, are considered. Each message has a duration of 120μ seconds and a total update rate of 6.4 Hz is obtained. The effect of the Traffic Collision Avoidance System (TCAS), transmitted on the same frequency is also added. The following assumptions are made:

1) No de-garbling is used. De-garbling can be modeled by selecting a lower message duration.
2) ADS-B message is modeled as 1 message, containing all the state information (instead of several different messages).

λ is calculated by the summation of the message update frequencies (F_{update}), multiplied by the number of aircraft within range (N_{ac}), shown in Equation (11).

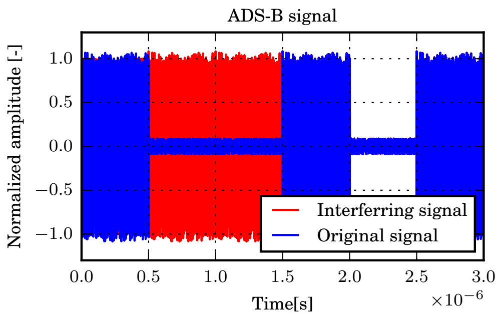


Figure 2. Interference effect; bits from the original signal cannot be decoded anymore due to interference.

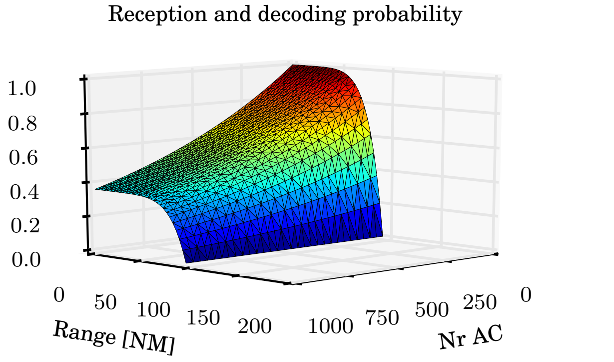


Figure 3. ADS-B detect and decode probability for MOPS specifications, based on number of interferring aircraft and range between aircraft.

$$\lambda = N_{ac} \cdot F_{update} \tag{11}$$

Assume a message is received at t=0. The duration of an ADS-B message τ is $120\mu s$, equal to the time variable in Equation (10).

To obtain the probability no other messages are received in this time interval the variable X in Equation (10) is set equal to 0, resulting in Equation (12).

$$P[X = 0] = (\lambda t)^0 \frac{e^{-\lambda t}}{0!} \tag{12a}$$

$$P[X = 0] = e^{-N_{ac}(\cdot F_{ADS-B} \cdot \tau_{ADS-B} + F_{TCAS} \cdot \tau_{TCAS})} \tag{12b}$$

C. Situation Related ADS-B Model

The detect and decode probabilities described in Section II-B can be combined. The corresponding detect and decode probability is shown in Equation (13). The probability $P_{T(i,j)}$ resembles the combined detect and decode probability of aircraft i receiving an ADS-B message from aircraft j, depending on range and interference. $P_{R(i,j)}$ is the detect and decode probability of aircraft i with respect to aircraft j due to range between the two aircraft. $P_{I(i,j)}(N_{acscaled})$ is the probability due to interference. The number of aircraft ($N_{acscaled}$) are scaled according to the distance of aircraft j at aircraft i. The model is shown in Figure 3.

$$\overbrace{P_{T(i,j)}(r, N_{acscaled})}^{\text{Total probability}} = \overbrace{P_{R(i,j)}(r)}^{\text{Range}} \cdot \overbrace{P_{I(i,j)}(N_{acscaled})}^{\text{Scaled Interference}} \tag{13}$$

III. Experiment Design

In this section the design of three separate fast-time simulation experiments are described. The goal of the first experiment is to assess the overall safety of the ADS-B system. The aim of the second experiment is to study the effect of ADS-B range. The goal of the third experiment is to differentiate between the contribution of the range effect and the interference effect in the ADS-B model. Since experiment has a different goal, the independent variables for each experiment are different. But, the scenario settings, Conflict Detection (CD) and Conflict Resolution (CR) method, and dependent variables are similar between the experiments.

A. Simulation Environment

BlueSky, an open-source Python based Air Traffic Control (ATC) simulator developed at the Delft University of Technology, is used as simulation environment. Many useful features are already available in the simulator, such as CD and CR in the Airborne Separation Assurance System (ASAS) module. DataLog options, way-point routing and aircraft performance limitations (accelerations, bank angles etc.) are also implemented. The open-source characters enables easy implementation of new modules, such as an ADS-B model, in the simulator. For this research, the simulation update rate was set to 10 Hz. Further information regarding the simulator can be found in [10].

B. Conflict Detection

In the context of CD&R it is important to distinguish between intrusions and conflicts. An intrusion, also known as Loss Of Separation (LOS), occurs when the following minimum separation requirements are violated [11]:

- 5 Nautical miles in the horizontal plane
- 1000 feet in the vertical plane

On the other hand, a conflict is a predicted intrusion within a certain look-ahead time; a five minute look-ahead time used in this work [11]. To detect conflicts, the simple state-based CD method is used. Here, linear extrapolation of aircraft state vectors over the look-ahead time is used to detect conflicting trajectories.

C. Conflict Resolution - MVP

The Modified Voltage Potential (MVP) conflict resolution method is based on modeling aircraft as similarly charged particles that repel each other as described in [12], [1]. The determination of the MVP-based resolution vector is shown in more detail in Figure 4:

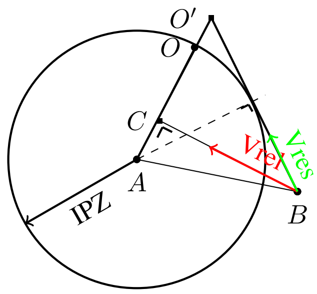


Figure 4. MVP-based conflict resolution for aircraft A and B in the horizontal plane. The relative velocity vector (V_{rel}) and the MVP-based resolution vector (V_{res}) are displayed.

The relative velocity vector with respect to a conflicting aircraft (A) is calculated (V_{rel}). This relative velocity vector results in a loss of separation without any intervention. Using this relative velocity and distance between the two aircraft, the Closest Point of Approach (CPA), point C, can be determined. Subsequently the closest distance out of the Intruder Protected Zone (IPZ), point O, is determined. The corresponding resolution vector CO still results in a LOS. Therefore Equation (14) can be used to find the final displacement (V_{res}):

$$\frac{|CO'|}{|CO|} = \frac{1}{|cos(arcsin(\frac{R}{AB}) - arcsin(\frac{AC}{AB})|} \tag{14}$$

Using the distance vector CO', the resolution velocity vector is calculated using Equation (15) [6]. In this equation, t_C is the time required for aircraft B to reach point C when traveling with its pre-resolution velocity.

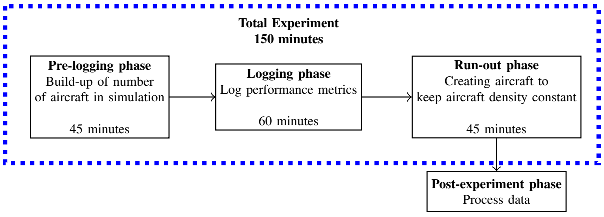
$$\boldsymbol{V_{MVP}} = \frac{\boldsymbol{CO'}}{t_C} + \boldsymbol{V_{current}} \tag{15}$$

After a successful conflict resolution, aircraft are required to follow the heading back to their original destination, i.e., aircraft do not recover their original track but fly the heading that leads them directly to their destination. Other aircraft states, such as altitude and velocity, are also restored.

D. Traffic Scenarios

A common set of traffic scenarios were created for all three experiments. The testing region is discussed first, followed by the traffic demand.

Testing Region: A cylindrical region is used, consisting of an initialization volume and test volume. Aircraft are only logged while they are within the experiment area and deleted when leaving the experiment area. To maintain a constant air traffic density the experiment is divided in three phases.



Traffic demand: A scenario generator is constructed to create similar air traffic scenarios (with different random number seeds). Aircraft are created on the edge of the initialization boundary at one of the 40 discrete points. Aircraft are created on three different flight levels and will randomly climb or descend to a different flight level or continue cruising at the current flight level. This results in conflicting aircraft from all possible directions. Three traffic densities are defined with their corresponding steady state number of aircraft, named Low (50), Medium (75) and High (100).

E. Independent Variables - Experiment I

The goal of this experiment is to assess the overall safety of the MVP method using ADS-B based state information. An overview of the independent variables is shown in Table I. Three ADS-B models are used; one based on the MOPS specifications (MOPS), one on measurements (Realistic) and one without ADS-B for perfect state information (Perfect).

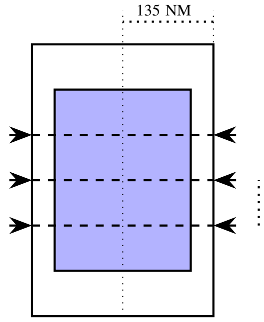


Figure 5. Three flight levels

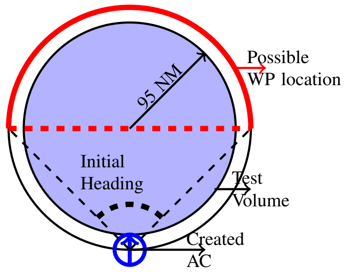


Figure 6. Initialization of AC with 45° heading caption.

TABLE I
INDEPENDENT VARIABLES. EXPERIMENT - I

AC density	Low	Medium	High
ADS-B	MOPS	Realistic	Perfect

The ADS-B performance described in the previous section is based on the MOPS specifications. However, from measurements it is obtained that the ADS-B system has a larger range than the MOPS specifications [8]. Also the interference effect can be reduced using de-garbling. This can be modeled by reducing the specific message length in the Poisson distribution. Therefore two ADS-B models are assessed, one based on MOPS specifications and one on measurements. The parameters to determine the two ADS-B models are shown in Table II.

TABLE II
PARAMETERS DESCRIBING ADS-B DETECT AND DECODE PROBABILITY, BASED ON MOPS [7] AND MEASUREMENTS[8].

	ADS-B Assumptions Type	
	MOPS [7]	Realistic
$R_0[km]$	176	370
$R_0[NM]$	95	200
S_{trans} [dBm]	51	57
S_{trans} [W]	125	500 [8]
τ ADS-B μs	120	60
τ TCAS μs	64	32
State accuracy (Table III)	MOPS	Realistic

The resulting range and interference detect and decode probability curves are shown in Figure 8 and Figure 7.

The different system related inaccuracies used in the MOPS and realistic model are shown in Table III.

Five repetitions were performed for each independent variable combination, using a different traffic scenario for each repetition. This resulted in 45 separate runs for Experiment I (3 ADS-B settings x 3 traffic densities x 5 repetitions).

F. Independent Variables - Experiment II

The goal of the second experiment is to study the effect of changing the maximum reception distance. From Section II

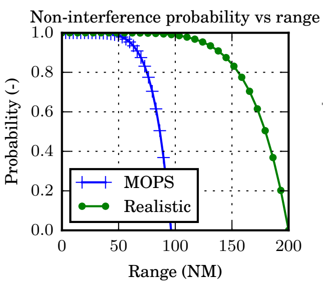


Figure 7. MOPS and Realistic. Range.

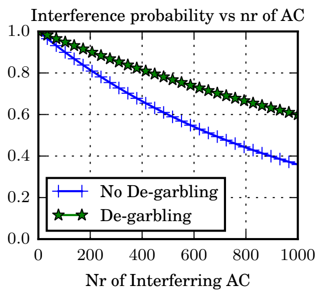


Figure 8. MOPS and Realistic. Interference.

TABLE III
SYSTEM RELATED INACCURACIES

System related inaccuracies			
		Cases	
Parameters	Distribution	Realistic	MOPS
Position [m]	Normal	$\mu = 0, \sigma = 30$	$\mu = 0, \sigma = 50$
Velocity $\frac{m}{s}$	Normal	-	$\mu = 0, \sigma = 10$
Heading [°]	Normal	-	$\mu = 0, \sigma = 3$

it can be obtained that an increase in range results in a stronger interference effect. Therefore different ADS-B ranges are assessed and compared. The same traffic densities are used. The range of these ADS-B models, based on the MOPS model, are shown in Table IV. The maximum reception range can be modified by adapting the transmit power.

TABLE IV
INDEPENDENT VARIABLES EXPERIMENT II (RANGE ANALYSIS).

MOPS fraction	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1	2
ADS-B Range [NM]	12	24	48	96	192
AC density	Low	Medium	High	-	-

The corresponding reception probability curves (defined as fractions of the MOPS range) are shown in Figure 9.

Once again, five repetitions were performed. This resulted in 75 separate runs for Experiment II (5 range settings x 3 traffic densities x 5 repetitions).

G. Independent Variables - Experiment III

An experiment is performed to asses the individual contribution of the two situation related properties; range and interference. Three traffic densities are assessed. An overview of the independent variables is shown in Table V.

TABLE V
INDEPENDENT VARIABLES. EXPERIMENT - III

AC density	Low	Medium	High
ADS-B	MOPS	MOPS interference	MOPS range

The following ADS-B settings are used as independent variables:

1) **ADS-B MOPS settings**, interference and range effect.
2) **MOPS based range effect only**.
3) **MOPS based interference effect only**.

For this experiment, five repetitions were also performed. This resulted in 45 separate runs for Experiment III (3 ADS-B models x 3 traffic densities x 5 repetitions).

H. Dependent variables

The conflicts detected, based on ADS-B state information are being logged. Additionally the conflicts detected when perfect state information would be available are logged. From these two metrics the false alerts (false positives) and missed conflicts (false negatives) can be obtained. Besides conflicts detected, the intrusions are logged.

Data representation: Each observed dependent variable is shown in a figure. The different traffic densities are shown on the x-axis, and the dependent variable on the y-axis. The legend indicates the ADS-B model. The 95% confidence interval is shown with the error bar for the 5 repetitions of each experiment setting.

IV. RESULTS AND DISCUSSION

In this section the results of the three different experiments are presented and discussed.

A. Results Experiment - I

The goal of this experiment is to identify the overall effect on safety when ADS-B is used for inter-aircraft information sharing. An overview of the type of detected conflicts is shown in Table VI.

TABLE VI
TYPE OF CONFLICTS DETECTED AS PERCENTAGE OF TOTAL CONFLICTS FOR THE MOPS AND PERFECT ADS-B SETTINGS.

ADS-B model	Conflict type	Traffic density			Cumulative
		Low	Medium	High	
MOPS	Real Conflict	92	88	89	89
	False Positive	8	12	11	11
	False Negative	5	4	5	5
Realistic	Real Conflict	95	94	94	94
	False Positive	5	6	6	6
	False Negative	3	3	4	4

It can be observed that the percentage of false positive conflicts increases with traffic density. The percentage of false alerts is larger for the MOPS based ADS-B model than the Realistic ADS-B model. The detected number of conflicts per

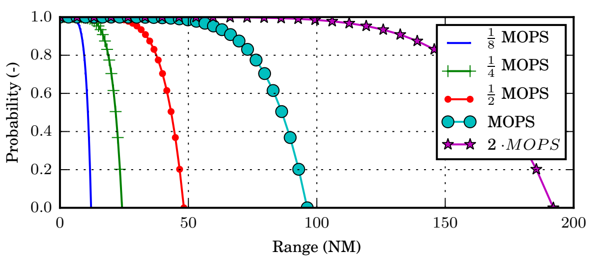


Figure 9. MOPS based reception models defined as fraction of MOPS range. Non-interference probability vs range.

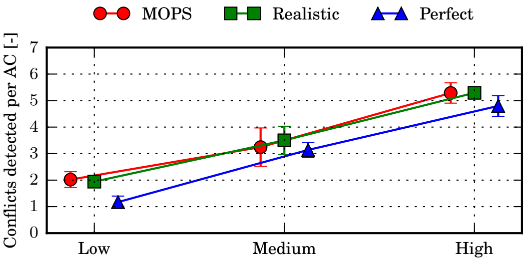


Figure 10. Number of detected conflicts per aircraft.Experiment - I.

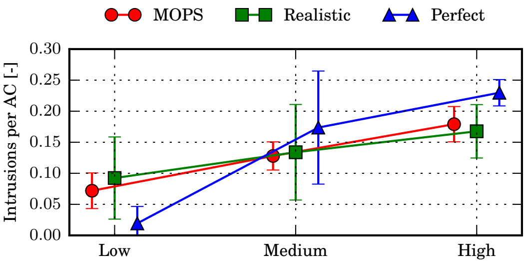


Figure 11. Number of intrusions per aircraft.Experiment - I.

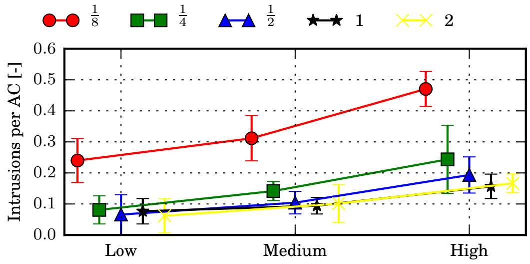


Figure 13. Number of intrusions per aircraft.Experiment - II.

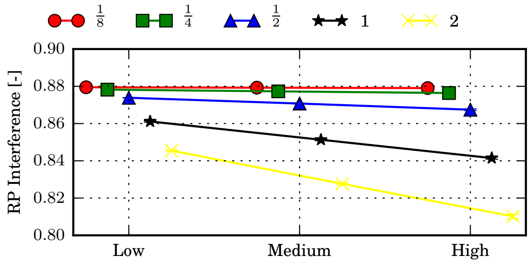


Figure 14. Mean interference reception probability.Experiment - II.

aircraft are shown in Figure 10. It is shown that more conflicts are detected for the ADS-B based state information cases.

The number of intrusions[6] per aircraft is shown in Figure 11. The number of intrusions when perfect state information is used is larger than the case where the ADS-B model is used for the medium and high traffic density situation. However, no significant differences are observed.

B. Results Experiment - II

In addition to the simulations, described in Section IV-A, a range analysis is performed. The goal of this analysis is to assess the effect of an increase in range, which also results in an increasing interference effect. The legend indicates the ADS-B model as fraction of the MOPS range. The number of detected conflicts [6] for each model are shown in Figure 12. The models with $\frac{1}{8}^{th}$ and $\frac{1}{4}^{th}$ of the MOPS range show a smaller amount of detected conflicts.

Figure 13 shows the number of intrusions. Large differences start to occur between $\frac{1}{8}^{th}$ and $\frac{1}{4}^{th}$ of the range of the MOPS performance (12 NM and 24 NM). At 25% of the MOPS range, the number of intrusions show about a 50% increase,

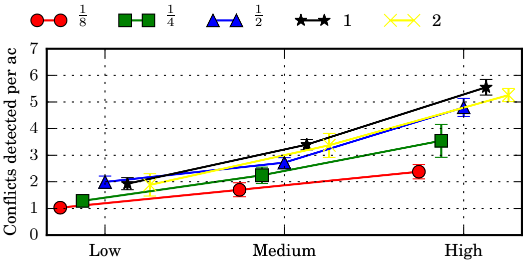


Figure 12. Number of detected conflicts per aircraft.Experiment - II.

while at 12.5% of the MOPS range the number of intrusions increases with 250% for the highest traffic density.

From the number of intrusions it is found that the performance difference for the single MOPS model, with a range of 96 NM ("1") is slightly better than the model with double the MOPS model, with a range of 190 NM ("2") regarding number of intrusions. With the 5 minutes look-ahead time, for both ADS-B models, the range dependent detect and decode probabilities are in the linear region, close to 1. However, the effect of interference increases. This is clearly shown in Figure 14; where the decreased detect and decode probability caused by interference is shown. The increased range results in a decrease of detect and decode probability due to additional interference. Therefore it can be concluded that the interference effect should be taken into account in extremely high traffic density situations.

C. Results Experiment - III

The goal of this final experiment is to differentiate between the two main situation related effects; interference and range. The number of detected conflicts are shown in Figure 15. It is obtained that the number of detected conflicts for the range-only model is slightly lower than for the other two.

The number of intrusions while using the interference-only model is higher than the range-only model, especially at the higher traffic densities. The interference effect has a more negative impact than the range effect, especially at the High traffic density.

D. Discussion

From the first experiment it can be concluded that the effect of ADS-B based state information is small for the MVP method for the assessed traffic densities, compared

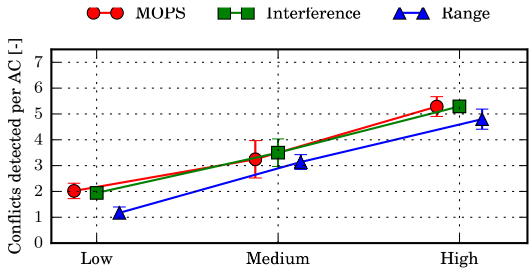


Figure 15. Number of detected conflicts per aircraft.Experiment - III.

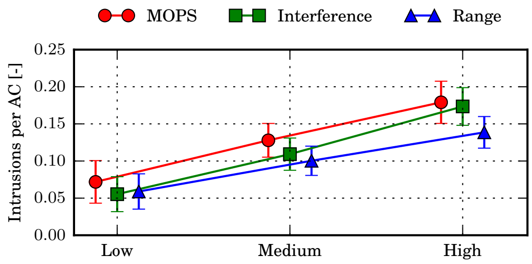


Figure 16. Number of intrusions per aircraft.Experiment - III.

to using perfect state information. This is partly due to the look-ahead time of 5 minutes, resulting in a detect and decode probability close to one. Also the position accuracy is high with respect to the dimensions of the IPZ. However, the interference effect should be taken into account. A larger transmit power increases the number of aircraft within range causing interference. Additionally, the impact of each aircraft increases, due to the higher transmitted power level. Also in the sensitivity analysis (Experiment - III) the effect of interference became larger at higher traffic densities. The detect and decode probability decreases with increasing number of aircraft according to the Poisson distribution. Additionally an increase in maximum reception range (i.e. transmit power) decreases the interference probability even further. Since significant ATM research efforts are devoted towards increasing airspace capacity, it is necessary to consider the impact of ADS-B signal interference when these higher densities are realized.

V. Conclusion

In this paper, an ADS-B model based on system and situation related characteristics was presented. The effect of these characteristics on airborne Conflict Detection and Resolution (CD&R) was studied using fast-time simulation experiments. Here, state-based conflict detection and the Modified Voltage Potential (MVP) conflict resolution algorithm was used as a case-study. For the studied conditions, the following conclusions can be drawn:

- The difference in safety between using ADS-B based state information and perfect state information was small.
- The range analysis showed that the combination of state-based conflict detection and MVP is a very robust CD&R method, even when the maximum range was artificially reduced to $\frac{1}{4}^{th}$ of the ADS-B minimum ADS-B specifications.
- An increase in maximum reception range (by increasing transmission power) decreases the total detect and decode probability. This is because increasing range also increases signal interference as additional aircraft are detected.
- The interference effect becomes more dominant than the range effect for higher traffic densities.
- The ADS-B system should not be considered as a direct limiting factor for self-separation or Free Flight. However, the interference effect at high traffic densities should be taken into account. The use of a single carrier frequency, increase in transmit power and high traffic density increase the interference effect.
- Future research will investigate the effect of ADS-B characteristics on additional CD&R methods and for higher densities.

References

[1] M. S. Eby, “A Self-Organizational Approach for resolving Air Traffic Conflicts,” *The Lincoln Laboratory Journal*, vol. 7, no. 2, pp. 239–253, 1994.
[2] K. Bilimoria, K. Sheth, H. Lee, and S. Grabbe, “Performance evaluation of airborne separation assurance for free flight,” in *18th Applied Aerodynamics Conference*. AIAA, 2000.
[3] M. Eby and I. Kelly, W.E., “Free flight separation assurance using distributed algorithms,” *1999 IEEE Aerospace Conference. Proceedings (Cat. No.99TH8403)*, vol. 2, 1999.
[4] R. Barhydt, M. T. Palmer, and N. Langley, “Ads-b within a multi-aircraft simulation for distributed air-ground traffic management,” *AIAA Digital Avionics Systems Conference*, 2004.
[5] W. Chung and R. Staab, “A 1090 Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B) Reception Model for Air-Traffic-Management Simulations,” *AIAA 2006-6614, Modeling and Simulation Technologies Conference and Exhibit*, no. August, pp. 1–11, 2006.
[6] J. Maas, E. Sunil, J. Ellerbroek, and J. Hoekstra, “The effect of swarming on a voltage potential-based conflict resolution algorithm,” *ICRAT*, 2016.
[7] RTCA Special Committee 186, “Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B),” *RTCA/Do-242a*, 2002.
[8] B. S. Y. D. Ali, W. Schuster, W. Ochieng, A. Majumdar, and T. K. Chiew, “Framework for ADS-B Performance Assessment : the London TMA Case Study,” *AIAA*, pp. 39–52, 2013.
[9] Global positioning system standard positioning service performance standard (2008). [Online]. Available: http://www.gps.gov/technical/ps/2008-SPS-performance-standard.pdf
[10] J. M. Hoekstra and J. Ellerbroek, “BlueSky ATC Simulator Project : an Open Data and Open Source Approach,” *ICRAT 2016*.
[11] E. Sunil, J. Ellerbroek, and J. Hoekstra, “Analysis of airspace structure and capacity for decentralized separation using fast-time simulations,” *Journal of Guidance Control and Dynamics*, 2016.
[12] J. Hoekstra, R. van Gent, and R. Ruigrok, “Designing for safety: the free flight air traffic management concept,” *Reliability Engineering & System Safety 75*, pp. 215–232, 2002.