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A Simulation of Signal Collisions over the North Atlantic for a Spaceborne ADS-B Receiver Using Aloha Protocol

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Abstract

Automatic Dependent Surveillance-Broadcast (ADS-B) is an air traffic surveillance system in which aircraft broadcast GPS position, velocity and status on 1090 MHz at random intervals between 0.4 and 0.6 seconds. ADS-B networks for air traffic monitoring have been implemented worldwide, but ground stations cannot be installed in oceanic regions, leaving these areas uncovered. A solution for tracking aircraft over the ocean is through the monitoring of ADS-B signals by using spaceborne receivers. The Royal Military College of Canada has developed an ADS-B receiver that is scheduled to fly as a technology demonstrator on the Canadian Advanced Nanospace eXperiment-7 (CanX-7) nanosatellite. The payload will collect ADS-B data over the North Atlantic that will be compared to truth data provided by air traffic services. A potential issue for the CanX-7 payload is signal collisions. The extended footprint of the satellite coverage means that a large number of aircraft may be in view at any one time, leading to ADS-B messages that arrive simultaneously at the receiver not being decoded. A simulation of CanX-7 passage over the operations area was carried out to calculate the probability of signal collisions. Using the Aloha Protocol, it was determined that the loss of information as a result of signal collisions is well within the standards of ground based radars used by air traffic system agencies.

Keywords

ADS-B, Satellite, Air Traffic Control, Aloha Protocol

1. Introduction

Automatic Dependent Surveillance-Broadcast (ADS-B) is an air traffic surveillance technology in which aircraft

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transmit identification, GPS position, velocity and status on 1090 MHz. ADS-B is a ground based system that is used to provide surveillance information to Air Traffic System (ATS) agencies where radar coverage is not available, or to improve the performance of the surveillance system in co-operation with radar systems. Canada's ATS provider, NAV CANADA, has implemented ADS-B surveillance in the Hudson Bay corridor and Labrador, while airspace authorities in Europe, the United States and Australia have plans for ADS-B coverage in the future.

The 120-bit ADS-B message has a duration of 120 μs and broadcasts in random intervals between 0.4 and 0.6 seconds to help prevent signal collisions between messages originating from multiple aircraft. The signal is transmitted on a vertically polarized carrier, alternating between top- and bottom-mounted quarter-wave monopole antennas. Transmission power is between 75 and 500 Watts, depending on the aircraft category [1].

A limitation of current ADS-B technology is that ground stations cannot be installed in oceanic regions, leaving these areas uncovered. A constellation of spaceborne ADS-B receivers will allow surveillance of aircraft in areas such as oceanic regions that are not covered by radar. This concept is under development with receivers proposed as secondary payloads on the Iridium Next constellation [2]. The Royal Military College of Canada (RMCC) has conducted ADS-B research since 2009, launching two successful high altitude balloon missions and generating publications in the field [3]-[7]. As a result of this work, RMCC has developed an ADS-B receiver that is scheduled to fly as a technology demonstrator on the Canadian Advanced Nanospace eXperiment-7 (CanX-7) nanosatellite in 2016 [8]. The payload is designed to collect ADS-B data from a low Earth orbit over the North Atlantic, which will subsequently be compared to air traffic information provided by NAV CANADA. The results will be used to verify a signal propagation model designed for the CanX-7 ADS-B mission [6] [7].

A potential issue for the CanX-7 payload is signal collisions. The extended footprint of the satellite payload means that a large number of aircraft may be in view of the receiver at any one time, leading to ADS-B messages that arrive at the receiver simultaneously not being decoded. This paper will calculate the probability of signal collisions in the operational area, determine how many signals can be expected to be lost as a result of signal collisions and compare this result to standard primary surveillance radar used by ATS agencies.

2. Simulation Setup

The simulation assumed a circular orbit at an altitude of 800 km, resulting in a satellite speed of 7.5 km/s and a sensor instantaneous field-of-view of 1360 km radius (see **Figure 1**). Aircraft transmitter power was maximized at 500 W and receiver sensitivity optimized at −103 dBm. Geometries and positions were calculated once per second per aircraft over a 14 minute period centered on the middle of the satellite pass. Only ADS-B transmissions from the upper antenna were considered since reflected signals from the ocean surface are too weak for detection by the CanX-7 ADS-B payload [7]. The four main types of ADS-B messages convey position, velocity, event, and identification information. Multiple messages were transmitted in random intervals as shown in **Table 1**. These intervals are relative to the preceding message, which equates to an average of 6.2 messages per second. Successive messages of each type are transmitted alternately from the top and bottom antennas, so an average of 3.1 messages per second are generated by the top antenna.

Aircraft position data was obtained from NAV CANADA for a 24-hour period on 29 April 2012 that described all aircraft transiting through Gander and Shanwick Oceanic Control Areas in the North Atlantic. **Figure 2** illustrates the number of aircraft in these regions as a function of time of day. There is a peak at approximately 0300 UTC representing the eastward flow of aircraft and another peak at 1400 to 1500 UTC representing the westward flow of aircraft.

3. Aloha Protocol

The Aloha protocol is a communication network protocol developed at the University of Hawaii in the 1970s. The first version of the protocol, now called "Pure Aloha", was quite simple in that it transmitted a message when a message was ready without checking whether the channel was busy before transmitting. If it collided with another transmission, indicated by an absence of a receipt message, it resent the data later [10]. ADS-B does not attempt to resend messages so this component of the Aloha protocol was not examined. Two simplifying assumptions have to be made to predict Pure Aloha throughput for ADS-B.

i) All messages have the same length, and any message overlap causes a collision where both messages are

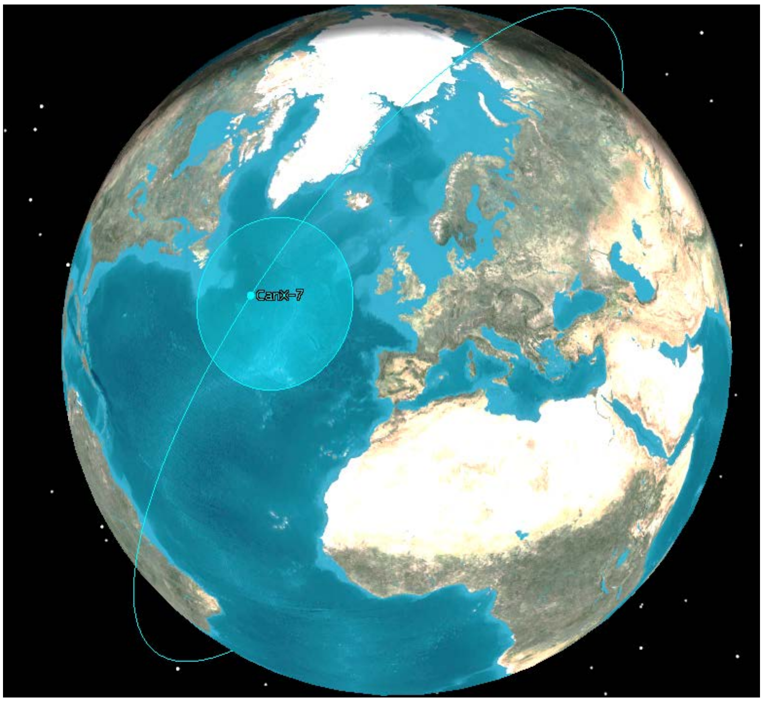

Figure 1. CanX-7 ADS-B receiver reception coverage (circle) with −103 dBm sensitivity at 800 km altitude (AGI STK Software).

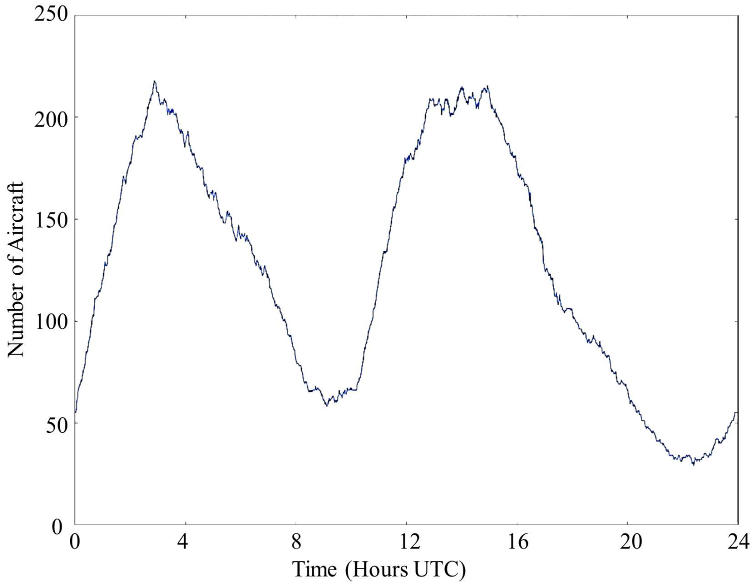

Figure 2. Aircraft traffic in Gander and Shanwick Oceanic Control Areas on 29 April 2012.

discarded.

ii) The length of a message is defined as a frame time T, which is 120 µs for ADS-B messages.

The offered load is modelled as a Poisson process with a rate G. Equation (1) is the expected number of message transmissions per frame time,

$$G = M_{att} T \,, \tag{1}$$

Table 1. ADS-B message intervals [9].

Message Type	Lower Limit (s)	Upper Limit (s)
ADS-B Position	0.8	1.2
ADS-B Velocity	0.8	1.2
ADS-B Event	0.8	1.2
ADS-B Identification	9.6	10.4

where M_{att} represents messages attempted per second. Equation (2) is the probability that k packets are generated in t frame times,

$$P(k,t)=\frac{(tG)^k}{k!}\mathrm{e}^{-tG}. \quad (2)$$

Examining the assumption that any message overlap causes a collision reveals that a collision occurs if any other message starts within the current frame time or the previous frame time. This means the vulnerability period for a message collision is two frame times. The probability of successful message transmission, $P_{success}$ is then the probability of zero messages attempted in two frame times. Substituting into Equation (2) gives Equation (3),

$$P_{Success}=\frac{(2G)^0}{U!}\mathrm{e}^{-2G}=\mathrm{e}^{-2G}. \quad (3)$$

The throughput rate, S, is therefore the expected number of successful messages per frame time and is given by Equation (4), which is the offered load multiplied by the probability of a successful transmission,

$$S=G\mathrm{e}^{-2G}. \quad (4)$$

Plotting S as a function of G is shown in **Figure 3**.

Converting throughput rate per frame time to received message rate, M_{rx}, in successful messages/s is given by Equation (5),

$$M_{rx}=\frac{S}{T}. \quad (5)$$

The probability of successful message transmission and number of successful messages for varying numbers of aircraft in view assuming 3.1 messages/s per aircraft are shown in **Table 2**. The highest successful ADS-B message rate is predicted to be 1533 messages/s with 1350 aircraft visible to the satellite. This number of aircraft in view may be possible over land, however the maximum number of aircraft observed over the North Atlantic in the NAV CANADA dataset was approximately 220 aircraft. **Figure 4** shows the messages attempted (blue) and received (green) calculated by the model and also the message successes predicted according to the Aloha protocol (black) for a receiver sensitivity of -103 dBm. The values for received and predicted messages exhibit good correlation, thereby providing high confidence in the Aloha Protocol's validity for this scenario. These results demonstrate that the Aloha protocol, which is computationally simpler than running the ADS-B model, is an excellent predictor of signal collisions in the scenario.

4. Signal Latency

Signal collisions imply that the ADS-B signals are not decoded. This is a concern for ATS agencies, so a way to compare the effect of this information loss to the existing radar-based system is required. Signal collisions for the simulation are listed in **Table 3**. A message count of 0 means the signal was not detected as the satellite was out of range of the aircraft, a message count of 1 means there was only one signal received and it was successfully decoded. Message counts of 2 or more indicate that the message was lost due to signal collisions of 2 to 6 messages.

Since a message is either decoded or not, a binomial probability distribution is applicable as shown in Equation (6) [11],

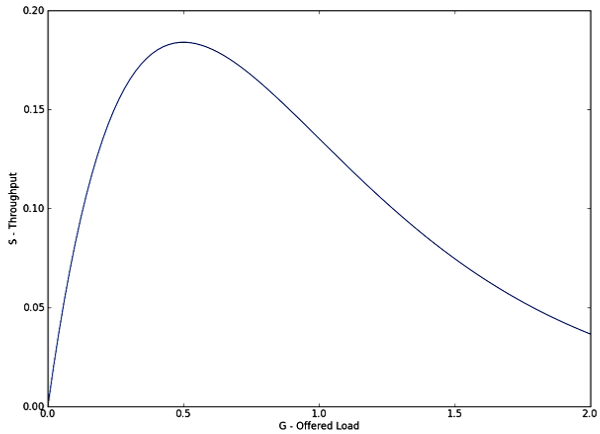

Figure 3. Throughput versus offered load for an Aloha Protocol network.

Table 2. Successful ADS-B messages for different numbers of visible aircraft.

Number of Aircraft	Attempted Messages/s	Probability	Successful Messages/s
50	155	0.9635	149
100	310	0.9283	288
150	465	0.8944	416
200	620	0.8617	534
225	698	0.8459	590
250	775	0.8303	643
300	930	0.8000	744
500	1550	0.6894	1068
1000	3100	0.4752	1473
1500	4650	0.3276	1523
2000	6200	0.2258	1400
2500	7750	0.1557	1206
3000	9300	0.1073	998
3500	10,850	0.0740	803

Table 3. Simulation statistics of ADS-B messages received and the number of signal collisions.

Message Count	Number of Messages	Comment
0	119,519	Message not received
1	398,694	Message received
2	54,922	2 Collisions—Messages not received
3	3861	3 Collisions—Messages not received
4	189	4 Collisions—Messages not received
5	14	5 Collisions—Messages not received
6	0	Maximum signal collision = 5

$$P_B\left(x,n,p\right)=\frac{n!}{x!\left(n-x\right)!}p^x\left(1-p\right)^{n-x}, \tag{6}$$

where x is the number of unsuccessful events, n is the number of attempts, p is the probability of an unsuccessful event and $1 - p$ is the probability of a successful event. As position message transmission intervals average to once per second, the probability of all unsuccessful transmissions in the time interval (the case where $x = n$) simplifies Equation (6) to Equation (7),

$$P_B\left(x,|\,n,p\right)=p^x. \tag{7}$$

Table 4 illustrates the probability that no position messages were successfully received from an individual aircraft for different time intervals in the simulation. Equation (7) assumes that all unsuccessful messages are

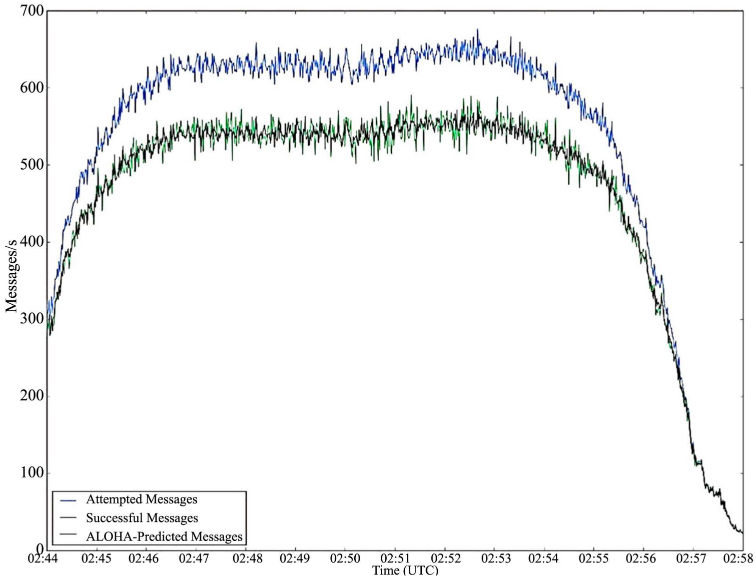

Figure 4. Attempted, received and ALOHA-Predicted ADS-B Messages for receiver sensitivity of −103 dBm.

Table 4. Probability of consecutive unsuccessful message reception due to signal collisions.

Time (s)	Probability	Events per Million
1	0.15	150,000
2	0.0225	22,500
3	0.003375	3375
4	0.00050625	506.25
5	7.59375E−005	75.9375
6	1.13906E−005	11.390625
7	1.70859E−006	1.70859375
8	2.56289E−007	0.256289062
9	3.84433E−008	0.038443359
10	5.7665E−009	0.005766503
15	4.3789E−013	4.3789E−007
36	2.1841E−030	2.1841E−024

lost due to signal collisions and does not take into account messages that are lost due to nulls in antenna radiation patterns. The column 'Events per Million' is included for comparison as the permitted failure rate in a Six Sigma process is 3.4 events per million before corrective action is required [12]. In ATS operations, three consecutive failures of an aircraft to respond to secondary surveillance radar interrogations are required before the controller is notified to take corrective action. This corresponds to 15 seconds of missed contact in a Terminal Control Area (TCA) or 36 seconds outside a TCA. **Table 4** shows that the likelihood of an ADS-B position message not being received by a satellite within the parameters of the scenario within the 15 and 36 second periods permitted under radar control is extremely remote.

5. Other 1090 MHz Signals

Other aircraft systems transmitting in the 1090 MHz band include Modes A, C and S transponders, Traffic Collision Avoidance System (TCAS). Since the operation area for the CanX-7 ADS-B receiver is over the centre of the North Atlantic, the aircraft are out of range of secondary surveillance radars and transponders normally do not transmit. The exception to this is TCAS, which is designed to increase cockpit awareness of nearby aircraft and suggest avoidance maneuvers if required. This is achieved by passively monitoring ADS-B messages or other aircraft transponder transmissions. If required, TCAS can actively interrogate aircraft that appear to be a collision threat. To aid monitoring, all TCAS-equipped aircraft must broadcast a Mode S "All Call" reply message every 0.8 s to 1.2 s [9]. Additional TCAS messages can be transmitted, but their rate is highly dependent on the relative geometry between aircraft when in close proximity. As these instances are rare over the expanse of oceanic areas, their contributions are minimal and not included in this analysis.

The "All Call" reply (DF11) message was not included in the previous scenario as the duration of the message is 64 µs instead of 120 µs for the ADS-B messages. This would have invalidated the applicability of using the Aloha protocol as the protocol assumes all messages have the same length. **Table 5** shows the message transmission intervals for a scenario including ADS-B and TCAS. To assess if a modification to the Aloha protocol could successfully predict message success rate with variable-length messages, an average message length of 106.34 µs was used. This is smaller than the 120 µs average message length used in the first scenario, but is offset by the greater number of messages transmitted per second. The probability of successful message transmission and number of successful messages for varying numbers of aircraft in view are shown in **Table 6**. **Figure 5** shows

Table 5. ADS-B and TCAS message intervals [9].

Message Type	Lower Limit (s)	Upper Limit (s)
ADS-B Position	0.8	1.2
ADS-B Velocity	0.8	1.2
ADS-B Event	0.8	1.2
ADS-B Identification	9.6	10.4
TCAS	0.8	1.2

Table 6. Successful ADS-B and TCAS messages for different numbers of visible aircraft.

Aircraft	Attempted Messages/s	Probability
50	205	0.9573
100	410	0.9165
150	615	0.8774
200	820	0.8400
225	923	0.8218
250	1025	0.8041
300	1230	0.7698

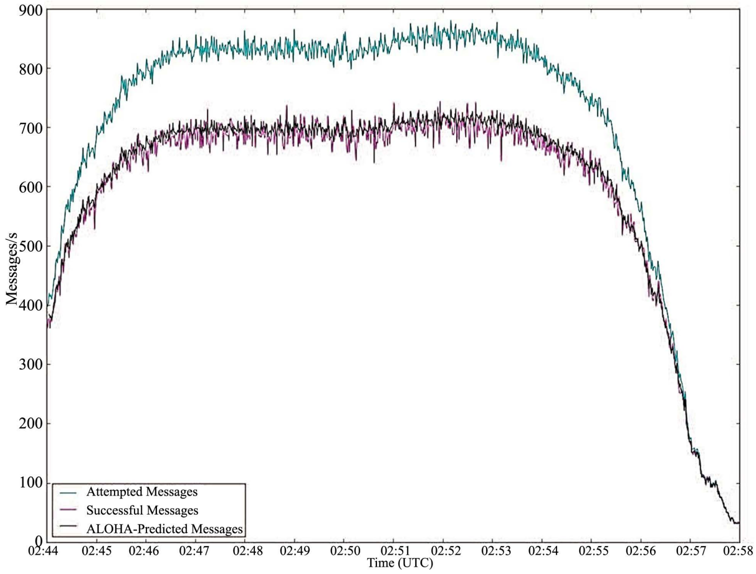

Figure 5. Attempted, received and Aloha-predicted ADS-B and TCAS messages for receiver sensitivity of −103 dBm.

the messages attempted (cyan) and received (magenta) calculated by the model and also the message successes predicted according to the Aloha protocol (black) for a receiver sensitivity of -103 dBm. The received and predicted values exhibit good correlation, thereby confirming modification to the Aloha protocol calculations by incorporating an average message length is valid. Examining each aircraft's data in this scenario revealed that no aircraft went longer than 3.7 s between successful receptions, which is well within range of the 15 second TCA radar standard.

6. Conclusions

The advent of spaceborne ADS-B will usher in an era in which aircraft can be tracked in oceanic areas that are currently not under surveillance. The CanX-7 nanosatellite will host an RMCC payload that will monitor aircraft ADS-B positions over the North Atlantic. This technology demonstrator will allow the verification of an ADS-B signal transmission model that could potentially aid the development of an operational constellation.

A potential issue for the CanX-7 ADS-B receiver is signal collisions. A large number of aircraft may be in view at any one time as a result of the sensor's large footprint. This could lead to ADS-B messages arriving at the receiver not being decoded. The Aloha protocol is a computationally simple method of determining signal collisions and alleviating the necessity of running the full ADS-B model to determine missed messages. Simulations based on actual aircraft data in the CanX-7 operations area demonstrate that signal collisions will not have an adverse effect on the system's ability to track aircraft. Even when TCAS transmissions are added to the simulation, the longest observed time period that an aircraft went unobserved is 3.7 seconds, which is well within the 15-second missed contact radar standards of TCAs. In the case of ADS-B transmissions over the North Atlantic, the probability of going 15 seconds without observing a specific aircraft transmission is 4.3789×10^{-13}.

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