I-BATE: A PRECURSOR TO SPACE-BASED AIR TRAFFIC CONTROL

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ABSTRACT

Air traffic worldwide is becoming more congested due to rapidly increasing flight volumes. ADS-B, Automatic Dependent Surveillance-Broadcast, is a new air traffic management system that is being deployed worldwide. Each aircraft is equipped with both a GPS receiver and a transmitter that broadcasts the aircraft's identifier and state vector (position, altitude, heading, airspeed, etc.) once per second. These signals are received on the ground and used by air traffic controllers to safely route flights. Areas that are not in sight of a ground receiver or traditional radar remain uncontrolled airspace. Ground controllers remain ignorant of the location of aircraft in these areas. The **I**nternational Space University-**B**alloon-borne **A**ir traffic control **T**echnology **E**xperiment (I-BATE) has tracked ADS-B-equipped aircraft from the vantage point offered by a high-altitude balloon during two flights from the Swedish arctic. I-BATE's successful operations has proven that ADS-B transmissions from aircraft within a large coverage area can be received from a high-altitude vantage point. This demonstration paves the way for space-based air traffic monitoring that could create safer skies for air travelers by eliminating unmonitored airspace. This paper presents the I-BATE experiment and the results of both balloon flights.

Key words: Air traffic control; air traffic management; balloon; aviation; airplanes; ADS-B; radar.

1. INTRODUCTION

The I-BATE experiment was carried out by three Masters students at the International Space University (ISU) in Strasbourg, France. I-BATE was run under the oversight of the BEXUS program (**B**alloon **EX**periments for **U**niversity **S**tudents), a joint program between the German Space Agency (DLR) and the Swedish National Space Board (SNSB) in collaboration with the European Space Agency (ESA). I-BATE tracked aircraft by receiving and storing the Automatic Dependent Surveillance-Broadcast (ADS-B) transmissions sent by nearby aircraft. I-BATE flew twice from Esrange Space Center near Kiruna, Sweden, as a payload on a balloon that floated at a 30 km altitude for 3-5 hours to demonstrate the feasibility of high-altitude and space-based air traffic management.

1.1. Background

According to the European Organization for the Safety of Air Navigation, roughly 30 000 commercial aircraft take flight over the European Union every day [1]. This does not include private or military flights. Similarly, in the United States, an average of about 28 000 commercial aircraft took to the skies each day in 2010 [2]. Eurocontrol also forecasts the European flight volume to double in the next ten years [3].

To accommodate the increased flight volume, a new air traffic management system, Automatic Dependent Surveillance-Broadcast (ADS-B), is being deployed. ADS-B mandates that each aircraft must be equipped with a transponder. This transponder broadcasts the plane's GPS position, altitude, heading, airspeed, and flight number, among other messages, once per second. These messages can be read by any receiver in range of the ADS-B-equipped aircraft. Ground receivers listen to these messages for use in traditional air traffic management. Other aircraftt can also receive these messages to give pilots a view of the surrounding air traffic.

Sweden, China, Australia, Europe, and the United States, among others, have either deployed or are in the process of deploying an ADS-B network [4]. Areas that are not in sight of these ADS-B ground stations nor in range of traditional radars, cannot be monitored; the poles and the oceans are prime examples. If an aircraft goes down in an unmonitored area, it may be exceedingly difficult to find, particularly if the emergency location transmitter is damaged or sinks. This was the case of AF447 which crashed off the Atlantic coast of Brazil on 1 June, 2009. Its wreckage was not found for six days [5].

This accident exemplifies why no airspace with commercial aviation traffic should go unmonitored. It is impossible to deploy ADS-B ground stations to cover the entire globe. However, a constellation of space-based ADS-B

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receivers could easily provide global coverage. If such a system were to be deployed, it could inform rescuers of when the aircraft was lost with an accuracy of one second and where it was lost with an accuracy equivalent to that of GPS. This would take the "Search" out of search and rescue.

Space-based ADS-B technology first needs to be demonstrated in an environment comparable to space before a significant financial investment is made in deploying a complete satellite constellation. I-BATE placed a commercial ADS-B receiver provided by Kinetic Avionic Products Ltd. of the UK on board a stratospheric balloon. It demonstrated the feasibility of tracking aircraft from space.

1.2. BEXUS Program

I-BATE is run under the oversight of the BEXUS program. The BEXUS program (`www.rexusbexus.net`) is realized under a bilateral agency agreement between the German Space Agency (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through collaboration with the European Space Agency (ESA). The BEXUS program allows students from universities and higher education colleges across Europe to carry out scientific and technological experiments on stratospheric research balloons. Each year, two balloons are launched, carrying up to 20 experiments designed and built by student teams.

2. EXPERIMENT OVERVIEW

The experiment consists of six primary components: 1) a Gumstix microcomputer, 2) an ERM ADS-B receiver, 3) a power distribution and thermal control unit, 4) an antenna, 5) a battery, and 6) a ground station computer.

The ERM (Embedded Radar Module) receiver was provided to I-BATE by its sponsor, Kinetic Avionics. It is an ADS-B receiver with a reception sensitivity of −94 dBm. It was connected to the microcomputer via a serial connection. The microcomputer was a Gumstix Overo Earth computer-on-module mounted on a Tobi expansion board for input/output. Its Debian linux operating system was installed on a 16 GB microSD card, which also stored received ADS-B messages.

The experiment was powered by a CellTech YT1275F lithium-iron-phosphate battery. It provided 13 V to the power distribution and thermal control board (PDTCU). The custom-designed PDTCU distributed power to the ERM and the microcomputer. It also regulated the temperature of key components via thermal sensors and Kapton foil heaters.

All components were mounted in a metal box that provided both physical protection and electromagnetic shielding. The box was surrounded with polyethylene insulation covered with Velostat to mitigate the risk of electrostatic damage.

Table 1. Link budget for noise-limited range calculation

Parameter	Value	Origin
TX power	250 W	Transponder
TX antenna gain	3 dB	Assumed
Line loss	3 dB	Assumed
Bit rate	1.04 Mb/s	ADS-B spec.
RX antenna gain	5 dB	Known value
RX sensitivity	−94 dBm	Known value
System noise temp.	650 K	Assumed
Received power	−124 dBW	Calculated
Range	691 km	Calculated

The antenna used was a 5 dB gain BS1100WM full-wave dipole antenna. It hung below the balloon gondola from a steel cable with a commanding view of the entire horizon and the area below the balloon.

The experiment connected to the gondola's ELINK telemetry system with a CAT-5 ethernet cable. This provided I-BATE a transparent TCP/IP interface to the experiment. The ground station computer connected to the ground-portion of the ELINK network and was able to receive ADS-B data in real-time. The data was viewed in real-time in both a command-line environment and a software called Obelix, also provided by Kinetic Avionics.

2.1. Predicted range

There are two limiting factors on the range of the experiment: line of sight and noise-limited range. From a balloon altitude of 30 km I-BATE had a line of sight range of 1 000 km to any aircraft flying at 10 km. The noise-limited range was calculated by making a few assumptions about the radio link between ADS-B-equipped aircraft and I-BATE. All calculations and assumptions are listed in Table 1. The noise-limited range was calculated to be 691 km, less than the line of sight range. This means that the experiment should be able to receive every ADS-B signal within 691 km of the balloon.

3. FLIGHTS AND DATA ANALYSIS

When two or more aircraft carry out simultaneous ADS-B transmissions, both transmissions may become corrupted. This effect is termed fruiting and provides a measure of how saturated the ADS-B communications channel is. The major challenge with receiving ADS-B signals from space is the sheer volume of signals that will be within the detectable range. This could cause a high rate of fruiting. I-BATE had hoped to see enough aircraft

Table 2. BEXUS-10 flight details

Date	09 Oct. 2010
Launch time UTC (local)	01:06:12 (03:06:12)
Cut-down time UTC (local)	05:29:39 (07:29:39)
Loss of signal UTC (local)	05:53:24 (07:53:24)
Time to cut-down	4:23:27
Float altitude	25 km
Float distance to loss of signal	217 km
Launch coordinates	67.89 °N, 21.09 °E
Cut-down coordinates	66.96 °N, 25.55 °E

to detect some degree of fruiting. The following discussion focuses on the quantity of signals and relative spacing with the attempt to gauge the likelihood of fruiting and whether it occurred.

I-BATE flew on both BEXUS-10 and BEXUS-11 balloon flights. The launch was from Esrange Space Center in Kiruna, Sweden, just north of the Arctic Circle near $67.9\,°$N $21.1\,°$E. These flights were 9 October, 2010 and 23 November, 2010 respectively. Each flight had its own unique characteristics and are discussed in detail in the following subsections.

3.1. BEXUS-10

Safely launching a 75 m flight train with a 12 000 m^3 balloon necessitates calm winds. The BEXUS-10 launch occurred at 03:06 local time on 09 October, 2010. This was the only time during the launch campaign week when the winds were calm enough to safely allow a launch. The early morning launch was unfavorable to I-BATE as, naturally, few aircraft are operating at this time of day.

For the BEXUS-10 flight, the winds at the 25 km float altitude were slow. They carried the balloon east into Finland as seen in Figure 1. The slow winds allowed a longer time aloft before the balloon left radio range. The cut-down command was sent at 07:29 local time. Signal was lost at 07:53 local time equating to a flight time of 4:23. The long flight time allowed I-BATE to track departing early morning flights. As seen in the map in Figure 1, I-BATE was fortunate enough to fly close to the Finish city of Oulu, which is home to the second busiest airport in Finland [6]. Its close proximity provided a favorable target-rich environment. Specific details for the flight can be seen in Table 2.

At the average float altitude of 24.5 km, I-BATE had a line of sight range of 915 km to aircraft at an altitude of 10 km. This means that the experiment remained limited in detection range by the signal strength rather than its line of sight as described earlier.

A total of 8,178 unique ADS-B signals were detected, originating from 24 aircraft. A maximum of five signals from unique aircraft were detected in a single second with no corruption. Note that these are signals from different aircraft, not unique signals from the same aircraft.

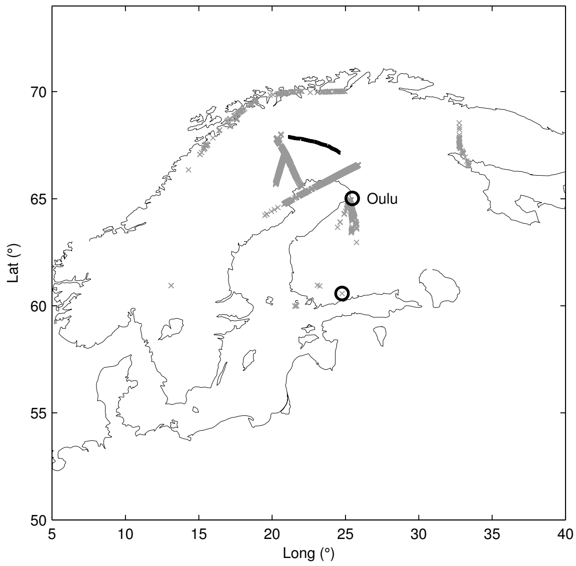

Figure 1. Map of the BEXUS-10 flight. The track of the balloon flight is indicated with a black line. ADS-B position messages are shown in gray x's. Note the aircraft beyond line of sight from the balloon at $60.6\,°$*N,* $24.8\,°$*E, indicated with a black circle.*

Table 3. BEXUS-10 detected signals

Number of ADS-B messages received	8 178 messages
Total number of unique aircraft tracked	24 flights
Maximum number of unique aircraft tracked during a one-second interval	5 flights
Number of instances of tracking five aircraft during a one-second interval	25 instances
Minimum spacing between two signals from different aircraft	$262.02\,\mu$s
Number of instances spacing between messages from different aircraft less than 1 ms	12 instances

Detecting five aircraft within one second occurred on 25 different occasions. The minimum spacing between two signals from different aircraft was $262.02\,\mu$s. The details can be seen in Table 3.

No fruiting was detected over the duration of the BEXUS-10 flight. Knowing each signal takes about $108\,\mu$s to transmit (112 bits at 1.04 Mb/s), the two signals that were separated by $262\,\mu$s were rather close to interfering with one another.

Figure 2 shows a histogram of ADS-B signals detected during BEXUS-10 with 30 min bins displayed in UTC. Note that local time is UTC+2hr. 79% of all ADS-B signals were detected after 07:00 local time, which corresponds to 8.5% of the time the balloon was aloft. No stored data was recovered after cut-down.

Figure 3 displays a histogram representing the number of ADS-B position signals received by I-BATE at various ranges. This histogram does not include every ADS-B signal received, as identification and velocity messages

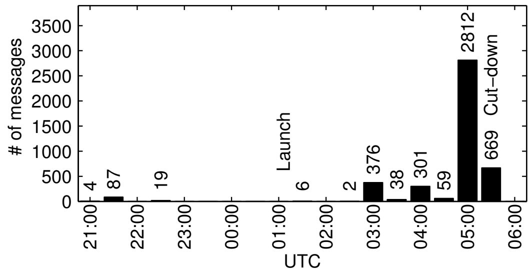

Figure 2. Histogram of the received time of ADS-B messages for the BEXUS-10 flight

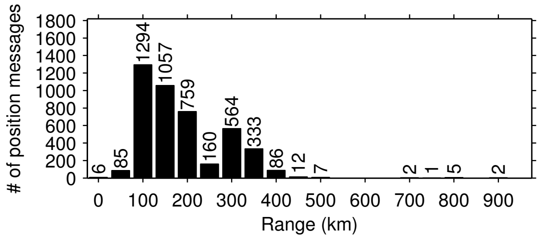

Figure 3. Histogram of the range of position messages received for the BEXUS-10 flight

do not include position data and therefore cannot be used to calculate range.

I-BATE received the majority of position messages in the 100 km to 150 km range, comprising over 29% of the total ADS-B position messages received during the BEXUS-10 flight. In the 150 km to 200 km range, I-BATE received 17% of all position messages. Almost 56% of all position messages received during BEXUS-10 were within 200 km and 90% of the signals received were within 350 km of the balloon. The flights tracked were not evenly distributed. This is not believed to be because of the receiver sensitivity, but rather because of the high number of ADS-B-equipped aircraft operating via Oulu airport.

The 10 ADS-B position messages that were received at or beyond 700 km are rather interesting. The signals were received in clusters of a few messages grouped together. The range at which these messages were received was beyond the theoretical noise-limited detection range. Furthermore, one signal was received from over the horizon. The data point is circled in gray in Figure 1.

It is important to note that the team downlinked all stored logs immediately before cut-down. No data was recovered from stored memory after landing. It is believed that the experiment continued to operate after landing.

The team noticed a concerning memory leak during the flight. The leak was such a concern that the team rebooted the experiment twice during the flight. Once at 02:43:45 UTC and again at 04:37:11 UTC. This leak was not experienced during testing with real aircraft signals or with a signal generator. This will be discussed in the BEXUS-11 section.

Table 4. BEXUS-11 flight details

Date	23 Nov. 2010
Launch time UTC (local)	08:18:44 (09:18:44)
Cut-down time UTC (local)	11:40:00 (12:40:00)
Loss of signal UTC (local)	11:49:28 (12:49:28)
Time to cut-down	03:21:16
Float altitude	33 km
Float distance to loss of signal	441 km
Launch coordinates	67.53 °N, 21.05 °E
Landing coordinates	64.7775 °N, 27.2236 °E

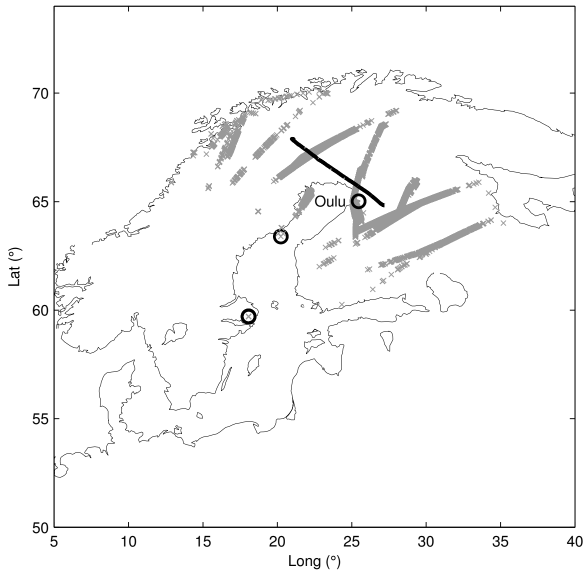

Figure 4. Map of the BEXUS-11 flight. The track of the balloon flight is indicated with a black line. ADS-B position messages are shown in gray x's. Note the aircraft beyond line of sight from the balloon at 50.7 °*N,* 18.1 °*E and at* 63.4 °*N,* 20.2 °*E, indicated with black circles.*

3.2. BEXUS-11

The details of the BEXUS-11 flight are given in Table 4. The BEXUS-11 launch occurred at 09:18:44 local time on 23 November, 2010. The daytime fight was more conducive to detecting air traffic as there are many more aircraft in flight during daylight hours. BEXUS-11 also flew 8 km higher than BEXUS-10 although this did not affect the detection of aircraft. The BEXUS-11 flight was about 30% shorter due to faster winds at the float altitude compared to BEXUS-10. Despite the shorter float time, BEXUS-11 flew 441 km, almost twice the distance of BEXUS-10.

A map of the BEXUS-11 flight is shown in Figure 4. The balloon position is plotted from Esrange-provided GPS data. Once again, the balloon flew nearby Oulu, providing many targets originating from the nearby airport.

A significantly higher number of ADS-B transmissions were received during the BEXUS-11 flight as compared to the BEXUS-10 flight, in spite of the shorter flight time.

Table 5. BEXUS-11 detected signals

Number of ADS-B messages received	38 176 messages
Total number of unique aircraft tracked	77 flights
Maximum number of unique aircraft tracked during a one-second interval	12 aircraft
Number of instances of tracking twelve aircraft during a one-second interval	7 instances
Minimum spacing between two signals from different aircraft	240 ns
Number of instances spacing between messages from different aircraft less than 1 ms	650 instances

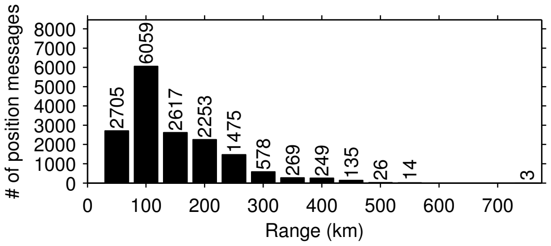

Figure 5. Histogram of the range of all received ADS-B position messages for the BEXUS-11 flight

Various details about the messages received are listed in Table 5. A total of 38 176 unique ADS-B messages were received with only a single corrupt message. This is primarily due to the fact that a significantly higher number of individual aircraft were tracked during the BEXUS-11 flight. A total of 77 unique aircraft were tracked.

It is worth noting that there were 7 separate instances of 12 unique aircraft being tracked within a single second. This is a significantly higher number of simultaneous broadcasts than what was seen during the BEXUS-10 flight.

The minimum spacing between two messages from different aircraft was 240 ns. Assuming each aircraft is transmitting according to the ADS-B specification at 1.04 Mb/s, each message should take 108 μs to transmit. This brief spacing between messages is theoretically impossible. This leads to the assumption that one or more of the transmitting aircraft may have provided an inaccurate timestamp. Such an error could feasibly be caused by an inaccurate real-time clock on the aircraft or a delay in the aircraft's ADS-B transmission system.

What is also interesting about the BEXUS-11 flight compared to the BEXUS-10 flight is the difference in range. Figure 5 shows a histogram of range of aircraft detected. This plot only represents the subset of ADS-B messages that pertain to position and do not sum to the total number of ADS-B messages received.

Each column in the histogram represents the number of messages received in a given 50 km range bin. The most data, 6 059 messages, were received between 100 km and 150 km. The number of messages received tapers off as range increases. This is most likely due to the high flight volume from the heavily travelled airport in close proximity to the balloon track.

Only three ADS-B position messages were received from beyond the theoretical noise-limited range, compared to ten received during BEXUS-10. These three messages all originate from the same aircraft between 12:41:53 and 12:42:22 UTC. Four other non-position ADS-B messages were also broadcasted from the same aircraft during the same time window. These seven messages were broadcasted from an aircraft altitude that increased from 1 440 m to 1 950 m. The line of sight range from the aircraft to the balloon's 331 m-elevation landing site in Finland was 223 km, well short of the actual 740 km range that was detected. Eight other ADS-B messages were received from a different aircraft that was beyond line of sight from the balloon. These messages were received between 12:51:22 and 12:55:23 UTC from an altitude around 2 460 m. The line of sight range was 242 km, short of the actual range of 375 km. Both of these beyond line of sight data points are indicated with gray circles in Figure 4. The fact that the aircraft detected were not in the line-of-sight of the gondola is an interesting phenomenon. There must be some variety of signal bending or bouncing to allow the aircraft to be detected.

The massive increase in flight volume seen in BEXUS-11 compared to BEXUS-10 is almost certainly due to the time of day of the flight. This is best seen in the histogram displayed in Figure 6. This has been produced by binning all ADS-B messages saved to disk as a function of 30 min UTC increments. Launch and cut-down are both indicated.

The flight software logs indicate a memory leak at 08:30 UTC, just after launch. This was similar to the leak during BEXUS-10. Little data was saved to disk, even though the balloon launched at 08:18:44 UTC (09:18:44 local time) when air traffic should have been high. This memory leak continued until 09:31:10 UTC when the Gumstix was rebooted via ground command. After the reboot, the rate of data collection skyrocketed. The current understanding is the memory leak prevented data from being saved to disk. The reboot allowed the system to recover and continue operating. The memory leak reoccurred soon after landing at 13:08:53 UTC and caused a watchdog timer expiration and reboot at 20:28:28 UTC.

The leading hypothesis of the data distribution in Figure 6 is that memory leaks caused large amounts of data to be lost. The only portion of Figure 6 that may be valid is between 09:30 UTC and 13:00 UTC. Outside of that time range, the flight software was showing symptoms of data loss. It is also interesting to note that a significant amount of data was collected after the 11:40:00 UTC cut-down. It is unknown how long the balloon took to drift from that altitude to the surface. Making the unrealistic assumption that it took an hour to reach the ground from the last data point, 8,659 messages were received after landing. This corresponds to 23% of all ADS-B messages received during this balloon flight. Note that the X-axis is in UTC. Local time is UTC+1.

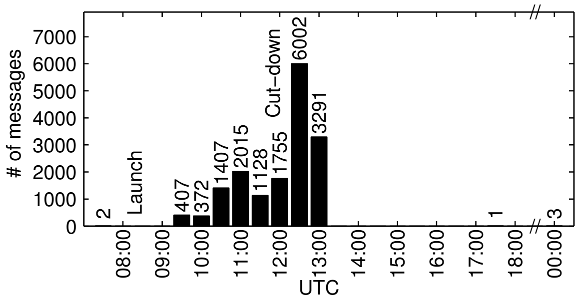

Figure 6. Histogram of the received time of all ADS-B messages for the BEXUS-11 flight

4. CONCLUSION

The interesting observation from this experiment were the ADS-B messages received both beyond the theoretical noise-limited range and from over the horizon. Since 1 090 MHz is well above the plasma frequency of the ionosphere, this cannot be explained by ionospheric bounce. Rather, it is believed that the beyond-line-of-sight signal is due to atmospheric refraction. Future tools using ADS-B messages will have to be robust to anomalous data points such as these. Furthermore, future space assets designed to receive ADS-B signals will have to recognize that such atmospheric phenomena may prevent some transmissions from being received in space. The refraction of ADS-B signals is only believed to be sporadic since I-BATE only sporadically detected a few messages at these long ranges.

The flight volumes experienced during both flights were less than those that would be observed near a major airport like London's Heathrow or Paris' Charles de Gaulle. Future experiments or demonstrations should focus on heavily travelled areas to better replicate the volumes that are expected to be seen from a space-based receiving platform.

The I-BATE experiment has been an interesting investigation of certain technical aspects critical to implementing next generation air traffic management system. The successful completion of the experiment has validated that the ERM receiver is capable of operating at the low-temperatures and near-vacuum pressures that are characteristic of the stratosphere. I-BATE has proven that it is possible to track aircraft in real-time from the commanding vantage point that is offered by a stratospheric balloon. It is therefore proposed that I-BATE has increased the technology readiness level (TRL) of space-based ADS-B reception to 6.

More information can be found at `http://i-bate.isunet.edu/`.

ACKNOWLEDGMENTS

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REFERENCES

[1] Eurocontrol. *Eurocontrol Annual Report - 2009*. Eurocontrol, July 2010.

[2] Research and Innovative Technology Administration Bureau of Transportation Statistics. Data elements. `http://www.transtats.bts.gov/Data_Elements.aspx?Data=2`, 2011.

[3] Eurocontrol Central Flow Management Unit. Executive summary 2006. Technical report, Eurocontrol, 2006.

[4] Eurocontrol. Information from ANC/11 related to ADS-B, ASAS and ACAS. `http://www.eurocontrol.int/care-asas/gallery/content/public/docs/CA-04-064(1.0).pdf`, May 2004.

[5] Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile. Interim report on the accident on 1st June 2009. Technical report, BEA, December 17, 2007.

[6] Irmeli Paavola. Journeys and landscapes 2009 Finavia's annual report. `http://www.finavia.fi/files/finavia2/vuosikertomukset_pdf/FINAVIA_vsk_GB_LR.pdf`, March 2010.