CZECH TECHNICAL UNIVERSITY IN PRAGUE

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Department of Air Transport

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Analysis of real ACAS surveillance parameters using a model

Master's thesis

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Zásady pro vypracování

Při zpracování diplomové práce se řiďte osnovou uvedenou v následujících bodech:

- Vytvoření softwarového modelu v prostředí MATLAB dle specifikací daných standardy, popisující komunikaci (dotazy/odpovědi) zajišťující přehledovou funkci systému ACAS
- Analýza emitovaných zpráv zachycených na pozemních přijímačích
- Zhodnocení dosažené shody mezi výstupy z modelu a výstupy z analýzy reálného prostředí
- Zmapování reálných parametrů přehledové funkce systému ACAS, které nejsou přesně specifikovány standardy
- Návrh úprav stávajících algoritmů dotazování s ohledem na optimalizaci zatížení RF pásma 1030/1090 MHz a jejich hodnocení za pomoci vytvořeného modelu systému ACAS

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Potvrzuji převzetí zadání diplomové práce.

Bc. Jakub Nosek
jméno a podpis studenta

V Praze dne .... 28. února 2018

Poděkování

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Prohlášení

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Jakub Nosek

CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Transportation Sciences

ANALYSIS OF REAL ACAS SURVEILLANCE PARAMETERS USING A MODEL

Master's thesis

May 2018

Bc. Jakub Nosek

ABSTRACT

The aim of the thesis is to analyze real ACAS surveillance parameters and find out whether the surveillance function of the system works according to technical standards. It uses a MATLAB simulation to simulate real air traffic situations. The output of the simulation is compared with real ADS-B data and further analyzed. Therefore it is focused on selected parameters which can be easily modeled and which contribute to the overall 1030/1090 MHz radio frequency saturation. In the last part of this thesis several amendments to the official ACAS surveillance algorithms, which would help lowering the radio frequency saturation, are suggested.

Keywords:

ACAS, surveillance, hybrid surveillance, ADS-B, simulation

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

Fakulta dopravní

Analýza reálných parametrů systému ACAS s využitím modelu

diplomová práce

Květen 2018

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ABSTRAKT

Cílem této diplomové práce je analýza reálných přehledových parametrů systému ACAS a poukázání na případné odchylky od hodnot uvedených technickými standardy. Z tohoto důvodu byla vytvořena počítačová simulace v prostředí MATLAB, díky níž je možné simulovat reálné situace ve vzdušném prostoru. Výstupy ze simulace jsou porovnány s reálnými ADS-B daty a dále analyzovány. Z tohoto důvodu jsou zvoleny parametry, které je možné modelovat a které přispívají k celkovému zatížení frekvenčního pásma 1030/1090 MHz. V závěru práce je navrženo několik změn přehledových algoritmů za účelem snížení zatížení používaného frekvenčního pásma.

Klíčová slova:

ACAS, sledování, hybridní sledování, ADS-B, simulace

Table of contents

Abbreviations

ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance – Broadcast
AQ	Acquisition
CET	Central European Time
CTU	Czech Technical University
DF	Downlink Format
ES	Extended Squitter
EUROCAE	European Organization for Civil Aviation Equipment
FL	Flight Level
HS	Hybrid Surveillance
ICAO	International Civil Aviation Organization
MLAT	Multilateration
NM	Nautical Miles
RA	Resolution Advisory
RF	Radio Frequency
RTCA	Radio Technical Commission for Aeronautics
TA	Traffic Advisory
TCAS	Traffic Collision Avoidance System
UF	Uplink Format
XPNDR	Transponder

1 Introduction

The volume of air transport has a growing trend over the long term and therefore air traffic density is much higher than it used to be even a few years ago. The airspace becomes extremely dense especially in approach and terminal control areas around big airports and also on the most frequent air routes. Due to this fact there is naturally a higher risk of midair collision. Hence the requirements for the correct and precise functioning of the airborne collision systems are very strict.

The surveillance function of every airborne collision system is responsible for ensuring that positions of all aircraft in vicinity with adequate equipment will be known to the system as well as ensuring that own aircraft's position will be known to all adequately equipped aircraft in vicinity. This requires a kind of communication between all systems, which is done by sending either 56 bites or 112 bites messages on RF 1030/1090 MHz. All interrogations are transmitted on 1030 MHz while replies to these interrogations use 1090 MHz. Since this frequency band is not used solely by airborne collision systems to exchange air-to-air messages but also by secondary ground radars to exchange ground-to-air and air-to-ground messages, it is not only air traffic which is becoming saturated, but also the 1030/1090 MHz frequency band. Seeing that the usage of a new frequency band to lower the saturation of the current one is not at all feasible as it would require an extremely costly adjustment to all systems currently being used, it is necessary to monitor and analyze the RF 1030/1090 MHz saturation and deliver changes, which would help to lower the saturation while keeping the system's safety a priority.

In this Master's thesis I am going to analyze the real parameters of ACAS surveillance function. It is a continuation of my Bachelor's thesis where I have described in detail how the surveillance function of airborne collision systems shall work according to standards and where I have also described the various types of messages used by the system and the information they transmit. In this work I am going to turn this theory into practice and find out whether the real system really works as defined by the standards. I will also try to analyze the real parameters of the system which are not firmly defined by standards but can differ according to the particular manufacturer of the system.

Firstly an aircraft model will be created in Simulink so as it is possible to simulate real air traffic situations. Then an ACAS surveillance function simulation, which will be based on the description provided in my Bachelor's thesis, will be coded in MATLAB and will take aircraft flight data from the Simulink model. The outputs of the simulation will be then compared with real data which were received at ADS-B receivers owned by the Czech Technical University in Prague. The comparison of the outputs will be used for further analysis of the system's real parameters. At the end I will try to suggest some changes based on the results of the analysis which might be beneficial for the process of lowering the saturation of 1030/1090 MHz radio frequency.

2 Airborne Collision Avoidance System

Airborne Collision Avoidance System (ACAS) is an airborne avionic system used to mitigate the risk of midair collision. The system tracks aircraft in vicinity through messages that are transmitted among them. If a risk of collision is detected, ACAS first issues Traffic Advisory (TA) to highlight the intruder on the cockpit screen and provide voice alert. In case that the risk still persists a Resolution Advisory (RA) is issued. This gives the pilots instructions for a proper maneuver to avoid the collision. [4]

In some literature ACAS is sometimes called TCAS (Traffic Alerts and Collision Avoidance System). There is a slight difference between those two terms as ACAS usually refers to a set of standards and recommended practices, while TCAS usually refers to a specific implementation of ACAS in an aircraft. In this document I will not distinguish between these two terms and will always use the term ACAS. [4]

There are currently 3 types of ACAS, but not all of them are in use:

- ACAS I,
- ACAS II and
- ACAS III.

ACAS I does not have the capability of RA so it is not able to provide instructions for the best maneuver to avoid a collision. ACAS II is the type which is currently being used and can provide both TA and RA (vertical only). ACAS III has not been deployed yet. It provides both vertical and horizontal RA. [4]

ACAS II is further divided into several versions. The version being commonly used nowadays is ACAS II version 7.1. Therefore, this document is focused on this version of ACAS. [4]

2.1 Surveillance function

In order to recognize the aircraft's position and issue a possible TA or RA, it is necessary to interrogate all aircraft in vicinity and listen to their replies. To accomplish this, it is not solely ACAS which is used, but also an aircraft transponder (XPNDR). ACAS's role is to interrogate aircraft in vicinity, while aircraft XPNDR is used to reply to these interrogations. These two systems are therefore both necessary to make the tracking functional. ACAS is composed of 3 subsystems: surveillance function, logic unit and antennae. [7]

XPNDR can work in 2 different modes:

- Mode C and
- Mode S.

Messages in Mode C can be transmitted to all aircraft in range while messages in Mode S are selective and thus it is possible to transmit a message to one particular aircraft in a way that no other aircraft will respond to it. For this purpose every Mode S equipped aircraft is assigned a unique 24 bits Mode S address which remains the same throughout the entire aircraft life. Therefore the aircraft can be easily identified. The vast majority of today's commercial aircraft are equipped with Mode S XPNDR. This is the reason why messages transmitted in this mode are the core interest of this work. It is also necessary to mention that all Mode S equipped aircraft must support both Mode S and Mode C messages to ensure that even aircraft not supporting Mode S messages can be tracked. [7]

For the purposes of the ACAS surveillance function simulation, which is going to be made and described later in this document, it is necessary to further divide Mode S equipped aircraft to aircraft which are ACAS hybrid surveillance capable, aircraft which are ADS-B equipped and aircraft which are not equipped with ADS-B and have no ACAS hybrid surveillance capability.

Aircraft with ACAS hybrid surveillance can passively track ADS-B aircraft by listening to the extended squitters which are periodically transmitted at a given transmission rate and by validation of these ES at rates specified in standards. Aircraft with no ACAS hybrid surveillance must track other aircraft actively by interrogating them and listening to their replies. [7]

2.2 Applicable standards and legislation

The requirements for airborne collision avoidance systems are stated in ICAO Annex 10 (volume IV). The technical specifications are defined in RTCA DO-185 and RTCA DO-300 (hybrid surveillance) standards or in relevant European EUROCAE standards.

The mandate in Europe which is valid at the time when this document is being written is as follows.

"The carriage of ACAS II version 7.0 has been mandated in Europe since 1 January 2005 by all civil fixed-wing turbine-engined aircraft having a maximum take-off mass exceeding 5700 kg or a maximum approved passenger seating configuration of more than 19.

Amendments 85 to ICAO Annex 10 (volume IV) published in October 2010 introduced a provision stating that all new ACAS installations after 1 January 2014 shall be compliant with version 7.1 and after 1 January 2017 all ACAS units shall be compliant with version 7.1.

In December 2011, the European Commission published an Implementing Rule mandating the carriage of ACAS II version 7.1 within European Union airspace earlier than the dates stipulated in ICAO Annex 10: from 1 December 2015 by all civil aircraft with a maximum certified take-off mass over 5700 kg or authorized to carry more than 19 passengers, with the exception of unmanned aircraft systems." [4]

3 Simulation

3.1 Aircraft model

Prior to the simulation of ACAS surveillance function, an aircraft model has to be created. It is obvious that for any kind of traffic collision avoidance system simulation at least 2 aircraft are needed to be modeled. In the following paragraphs I am going to describe an aircraft model that I have used for my simulation. This aircraft model can be then copied multiple times depending on the number of aircraft we want to use for the simulation. After copying the aircraft, different initial conditions can be assigned to each of them.

For this kind of simulation it is sufficient to use a simplified aircraft model as the advanced flight properties do not have any significant influence on the ACAS function itself. The only parameters that need to be controlled are initial coordinates, heading, flight path angle, bank angle and velocity. For this reason it is possible to consider the following simplifications:

- The Earth is flat. Taking into account the distances flown by aircraft during the simulation, this is quite true. [16]
- Each aircraft is considered as a single point with its mass. The mass is constant throughout the simulation. [16]
- Neither vertical nor horizontal wind components are being considered.
- Wing lifting mechanism such as flaps, slots etc. is not considered in any phase of flight during the simulation.

The aircraft model can be mathematically described by kinematic and mechanical differential equations.

3.1.1 Kinematic equations

If *x* is considered as East axis and *y* as North axis, it is possible to write:

$$\begin{aligned} \frac{dx}{dt} &= V_p \cdot \cos(\alpha) \cdot \cos(\beta) \\ \frac{dy}{dt} &= V_p \cdot \sin(\alpha) \cdot \cos(\beta) \\ \frac{dz}{dt} &= V_p \cdot \sin(\beta) \end{aligned} \tag{I}$$

Where:

V_p is True Air Speed.

α is Flight Path angle.

β is Heading.

The kinematic equations are based on the charts in figure 1.

If the heading equals 0 (in a straight ahead flight), then it is possible to determine equation (II).

$$\frac{dz}{dx} = \tan(\beta) \qquad \text{(II)}$$

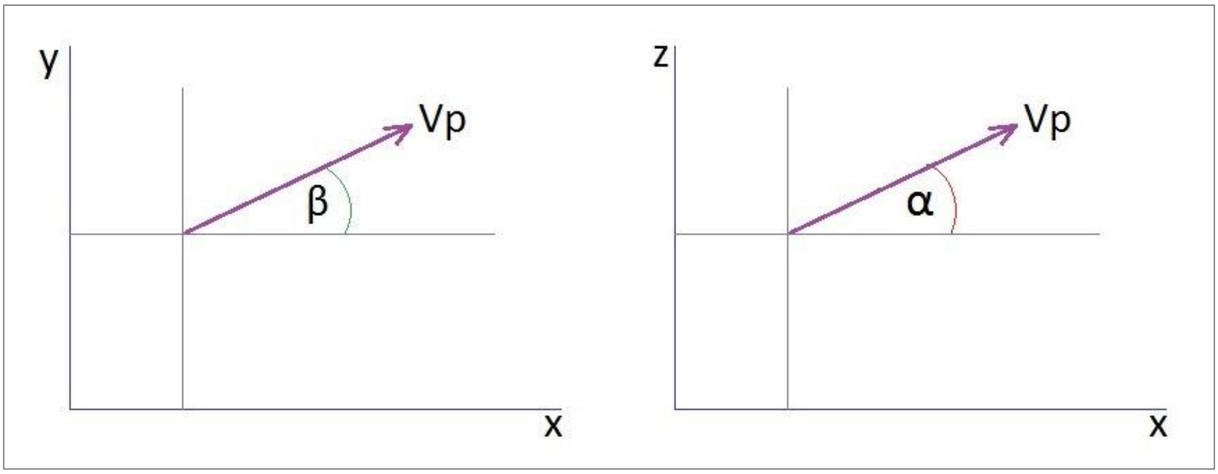

Figure 1 Determination of kinematic equations

3.1.2 Mechanical equations

Taking into account figure 2, it is possible to write:

$$m \cdot \frac{dV_p}{dt} = T - D - m \cdot g \cdot \sin(\beta)$$
$$m \cdot V_p \cdot \frac{d\alpha}{dt} = L - m \cdot g \cdot \cos(\beta) \qquad \text{(III)}$$

Where:

m is the mass of the aircraft and is considered as a constant.

g is the gravitational acceleration considered as 9.81 m/s^2.

T is the thrust of the engines.

D is the total drag of the aircraft.

L is the total lift of the aircraft.

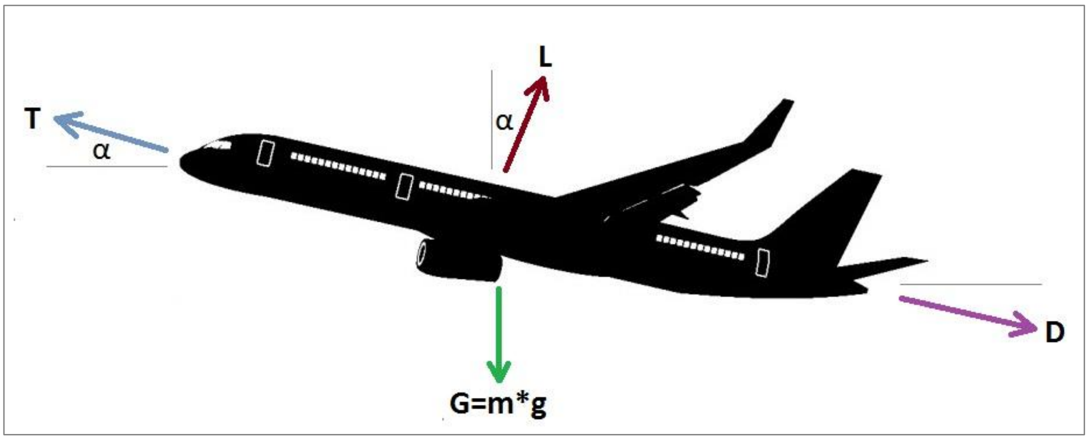

Figure 2 Determination of mechanical equations

If γ is considered to be a bank angle, then the equation (IV) may be determined.

$$V_p \cdot \frac{d\beta}{dt} = g \cdot \tan(\gamma) \qquad \text{(IV)}$$

3.1.3 Final set of equations

Knowing the fact that the horizontal n_x and vertical n_z load factor can be determined according to the equations (V) and (VI), it is possible to derive the final set of equations (VII) which are used to mathematically describe an aircraft flight. [16]

$$n_x = \frac{T - D}{m \cdot g} \qquad \text{(V)}$$

$$n_z = \frac{L}{m \cdot g} \qquad \text{(VI)}$$

$$\left.\begin{aligned}
\frac{dx}{dt} &= V_p \cdot \cos(\alpha) \cdot \cos(\beta) \\
\frac{dy}{dt} &= V_p \cdot \sin(\alpha) \cdot \cos(\beta) \\
\frac{dz}{dt} &= V_p \cdot \sin(\beta) \\
\frac{dV_p}{dt} &= g \cdot (n_x - \sin(\beta)) \\
\frac{d\alpha}{dt} &= g \cdot (n_z - \cos(\beta)) \\
\frac{d\alpha}{dt} &= \frac{g}{V_p} \cdot \tan(\gamma)
\end{aligned}\right\} \qquad \text{(VII)}$$

3.1.4 Software model of aircraft

Since the entire simulation is going to be coded in MATLAB, I decided to create the aircraft model in Simulink which is a block diagram environment. Because of its tight integration with MATLAB environment, it can be easily used to generate aircraft flight data for MATLAB script. Hence the simulation of ACAS surveillance function which is coded in MATLAB will be based (and will take all of the aircraft flight data from it) on Simulink model.

To model an aircraft in Simulink using equations (VII) it is essential to use 7 types of blocks. These blocks are:

- Trigonometric function (the input is an angle and the output is a trigonometric function of this angle),
- Product (multiplication of 2 or more inputs),
- Integrator (integrates its input),
- Constant,
- Add (ads and subtracts 2 or more inputs),
- Out (sends the outputs of the model to another workspace),
- To Workspace (sends the outputs of the model to MATLAB workspace).

If those blocks are connected according to the relations in equations (VII), the model is functional (see figure 3).

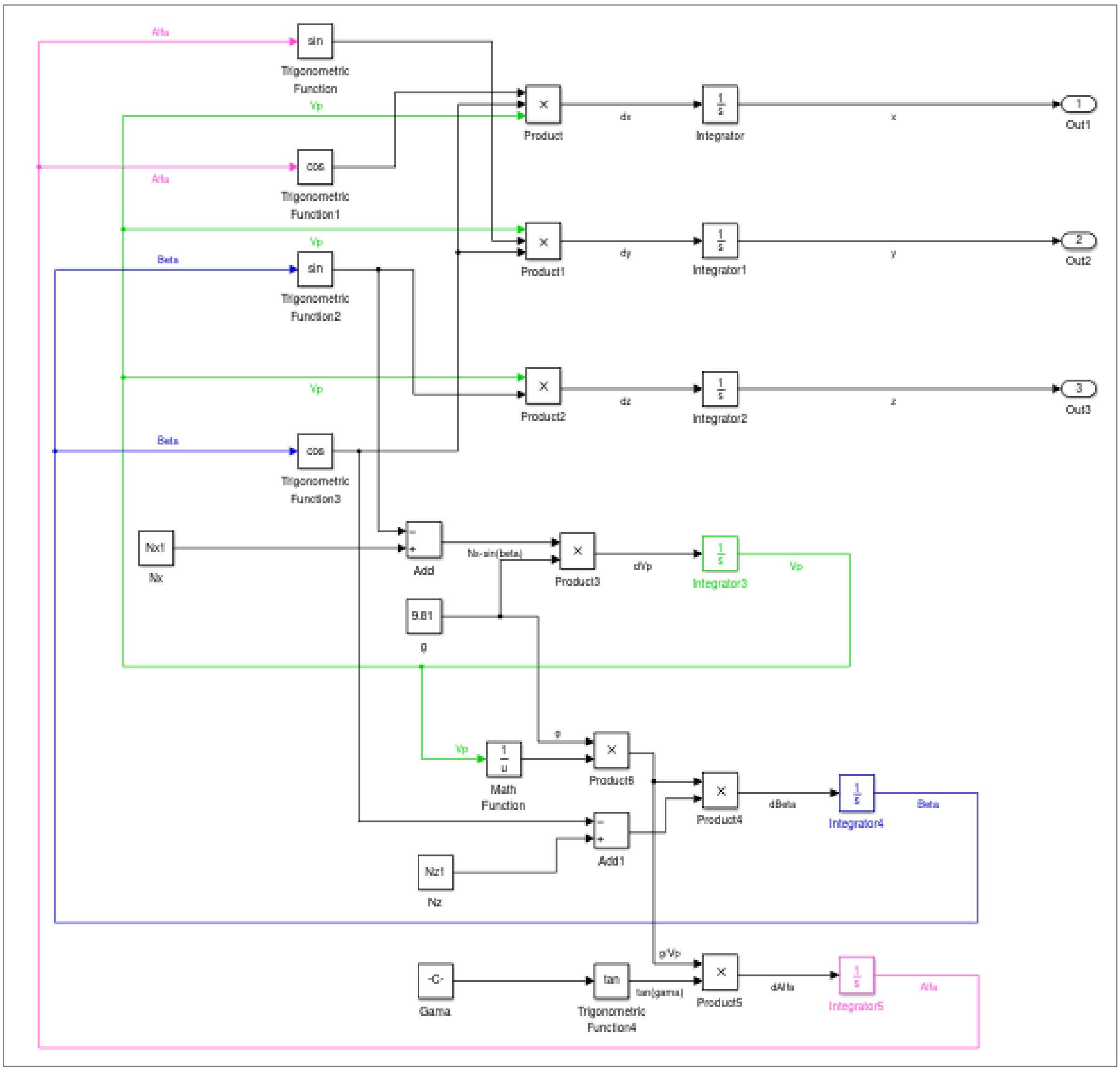

Figure 3 Aircraft model in Simulink

3.2 Simulation of ACAS surveillance function

As it was already said before, the ACAS surveillance function is simulated in MATLAB software and uses aircraft flight data which are generated in Simulink aircraft model. The simulation itself consists of a set of several functions and two scripts which are going to be described in this chapter.

3.2.1 Scripts

3.2.1.1 initial_conditions

As is apparent from its name, this script is used for entering the initial conditions of all the aircraft that are going to be modeled. The set of initial conditions for each aircraft is as follows:

- *ix* – x-coordinate of the aircraft's initial position.
- *iy* – y-coordinate of the aircraft's initial position.
- *iz* – z-coordinate of the aircraft's initial position (initial altitude).
- *Vp* – initial value of True Air Speed in knots.
- *Beta* – heading (see chapter 3.1.1).
- *Alfa* – flight path angle (see chapter 3.1.1).
- *Gama* – bank angle (see chapter 3.1.1).
- *Nz* – vertical load factor.
- *Nx* – horizontal load factor.
- *TCAS* – indicates whether ACAS is switched on (1) or switched off (2).
- *AQ* – indicates whether the aircraft is equipped with transponder working in mode S and whether the ACAS is without hybrid surveillance capability (1) or not (2). If the aircraft is equipped with Mode S transponder and with ACAS hybrid surveillance capability, then both *AQ* and *HS* shall indicate (1). All possible combinations of equipage initial conditions are stated in table 1.
- *HS* – indicates whether the aircraft is equipped with Mode S transponder and ACAS with hybrid surveillance capability (1) or not (2).
- *ADSB* – if this initial condition is set to (1), it indicates that the aircraft is equipped with ADS-B (mode S transponder with extended squitter capability). Hence if *ADSB* indicates one (1), then *AQ* shall also indicate one (1).

- *ModeC* – indicates whether the aircraft is equipped with only Mode C transponder (1) or not (2). In most of the cases, this initial condition should indicate (2).

Each of these initial conditions in the script has its index according to the aircraft this particular initial condition belongs to (for example *ix1* means it is an initial x-coordinate of the first aircraft, *Gama5* means it is a bank angle of the fifth aircraft etc.). If the aircraft's ACAS is switched on it must also be equipped with a transponder of any of the described types.

Table 1 All possible equipment combinations

Scenario	**Description**
TCAS=1, *AQ*=1, *HS*=2, *ADSB*=2, *ModeC*=2	The aircraft is equipped with mode S transponder but has neither ADS-B nor hybrid surveillance capability.
TCAS=1, *AQ*=1, *HS*=2, *ADSB*=1, *ModeC*=2	The aircraft is equipped with mode S transponder, has ADS-B, but no hybrid surveillance capability.
TCAS=1, *AQ*=2, *HS*=1, *ADSB*=2, *ModeC*=2	The aircraft is equipped with mode S transponder and is both ADS-B and hybrid surveillance capable.
TCAS=1, *AQ*=2, *HS*=2, *ADSB*=2, *ModeC*=1	The aircraft is equipped with only mode C transponder.
TCAS=2, *AQ*=2, *HS*=2, *ADSB*=2, *ModeC*=2	The aircraft does not have a transponder nor ACAS.

Except the initial conditions, this script also contains the unit conversions and general settings of the simulation:

- *time_step*,
- *whisper_shout_rate*,
- *acas_range*,
- *nominal_surveillance*.

It is recommended not to change the unit conversions and time step value (time step value has no direct impact on the simulation). However, if it is for any reason changed, the value of time step must also be changed in Simulink aircraft model.

The default value of whisper shout rate is 6. This represents the minimum number of whisper shout messages in one sequence according to the RTCA standard. If a higher number of messages in one sequence is expected, then this value can be easily changed here. [1]

ACAS range initial condition allows us to define the range at which the system will be functional. Hence if the range between any two of the modeled aircraft is higher than the value of acas_range, the ACAS surveillance function simulation will not count any messages.

Nominal surveillance defines the transmission rate of DF0 messages. The default value is 5 seconds. According to the RTCA standard, the aircraft shall interrogate each other at least once per 5 seconds, therefore the value shall never be greater than 5. [1]

After all the initial conditions are defined, the script can be run. This will store the initial values in the workspace variables and make these variables accessible by Simulink. The aircraft model which is made in Simulink can now be open. After setting the time of simulation (in seconds), the Simulink model can be run. This will store new array variables in the workspace. These new variables (matrices) represent the sample values of flight properties such as coordinates, bank angle, heading etc. throughout the entire flight during the simulation time. It is obvious that the number of sample values depends on the simulation time and time step. The longer simulation time the more sample values but the higher time step, the less sample values we get.

3.2.1.2 main_file

This script launches all the functions which are used to do the necessary calculations needed to determine the number and type of messages transmitted among all the modeled aircraft. It is important not to change any part of the code in this script. Few minutes (in some cases it may take 5-10 minutes depending on the complexity of the situation which is being simulated) after running this script, the following graphs will appear in separate windows:

- aircraft's flight overview in 2-D,
- aircraft's flight overview in 3-D,
- bar chart showing the number of all transmitted messages (DF11, DF17, DF0, DF16, UF0/UF16 and Mode C Only All Call),
- bar chart showing the number of all transmitted messages in detail.

Running the script will also store new workspace variables which, in fact, define the number of all transmitted messages. It is possible to call these variables in MATLAB command window and thus see the exact number of transmitted messages of a specific message type. These variables are as follows:

- *DF11* (all Acquisition Squitter messages transmitted by all the modeled aircraft which are equipped with Mode S transponder),
- *DF17* (all extended squitter messages transmitted by all the modeled aircraft which are equipped with Mode S transponder and ADS-B),
- *ModeC_Only_All_Call* (all Mode C messages transmitted by all the modeled aircraft),
- *sumES_APS* (all transmitted Airborne Position Squitter messages),
- *sumES_AVS* (all transmitted Airborne Velocity Squitter messages),
- *sumES_AIS* (all transmitted Aircraft Identification Squitter messages),
- *DF0* (all transmitted DF0 messages),
- *UF0* (all transmitted UF0/UF16 messages),
- *DF16* (all transmitted DF16 messages),
- *UF16_count* (all transmitted UF16 messages which are used to count the number of aircraft in vicinity if the aircraft is flying below FL180). [7]

3.2.2 Functions

Functions are used to make the necessary calculations needed to determine the number of transmissions among all the modeled aircraft and are launched by running the *main_file* script. It is very important that all the functions are stored in the same folder as *main_file* script which is used to call them.

3.2.2.1 range_calculation

As is apparent from the function name, this function calculates ranges at each time step among all the modeled aircraft. The function is divided into 6 sections. The 1st section is used to calculate ranges among all modeled aircraft no matter what their equipment is like, the 2nd section calculates ranges among all mode S (AQ) equipped aircraft, 3rd section calculates ranges among all mode S (HS) equipped aircraft, the 4th section calculates ranges among all mode S equipped aircraft, the 5th section calculates ranges among all aircraft which are only Mode C equipped and finally the last section is used to calculate ranges among all mode S equipped aircraft with no ACAS hybrid surveillance. These ranges are used as inputs in the other functions.

The function also controls whether a particular aircraft is located within ACAS range detection of other aircraft. This ACAS range is defined in the initial conditions script as described earlier in this chapter. Hence if the range between any 2 modeled aircraft is higher than *acas_range*, then those aircraft will not interrogate each other and thus no messages will be counted.

3.2.2.2 modeS_AQ

This function calculates the number of messages that are transmitted by mode S equipped aircraft. Hence it counts the number of DF11 (acquisition squitter), UF0/UF16 (short/long ACAS interrogation), DF0 (short ACAS reply to UF0) and DF16 (long ACAS reply to UF16) messages, eventually DF17 messages if the particular aircraft is equipped with ADS-B. The interrogation rates are set in accordance with the RTCA standards and are shown in tables below (table 2, table 3 and table 4). [1]

Table 2 DF11 transmission rate

Message type	**Period [s]**
DF11 (acquisition squitter)	1

Table 3 UF0/UF16 interrogation rates

Message type	**Period [s]**	**Condition**
UF0	No interrogation	One of the aircraft is on the ground and the other is more than 2000 ft. above ground level.
UF0	10	The aircraft's altitude separation is equal to or higher than 10000 ft.
UF16	1	In case of active TA or RA.
UF0	5	The aircraft which is being interrogated is below FL180.
UF0	<=5	In all other cases. Since the RTCA standard does not specify a particular value but only mandates that the aircraft shall be interrogated at least every 5 seconds, this value can be set according to a particular situation in initial conditions script.

Table 4 DF17 transmission rates

Type of ES message	**Period [s]**
Aircraft Identification Squitter	5
Airborne Position Squitter	0.5
Airborne Velocity Squitter	0.5

In addition to the interrogation rates described in table 3, the aircraft is interrogated at a rate of once per second if equation (VIII) is met. Since such a situation is not common in reality, this condition was not added into this function.

$$TAU = -\frac{r - \frac{SMOD^2}{r}}{\min(-6kt, rdot)} \qquad \text{(VIII)}$$

Where:

r is the tracked angle.

rdot is the estimated relative range rate.

SMOD is a surveillance distance modifier which for this purpose shall be equivalent to 3 NM. [1]

For the purposes of this simulation it is considered that for every interrogation (uplink format message) the aircraft always receives a reply (downlink format message). Therefore the number of uplink format messages is always equal to the number of downlink format messages.

I had described in detail how the aircraft interrogate each other according to different situations in my Bachelor's thesis.

3.2.2.3 modeS_ES

The modeS_ES function is used to determine the number of extended squitter messages (DF17) as well as the messages which are sent to validate information contained in ES (UF0/UF16 and DF16).

For the simplification of this simulation it is considered that if the aircraft's ACAS has hybrid surveillance capability, then it is also equipped with ADS-B and thus the transponder is capable to send extended squitter messages. In reality, this is true in most of the cases.

The function deals with 3 types of extended squitter messages, which are shown together with the interrogation rates in table 4.

Since the simulation only deals with airborne aircraft, Surface Position Squitter is not counted.

Information contained in DF17 messages are validated by sending either UF0 or UF16 validation messages. As it is not easy to determine whether the validation message will be in short (UF0) or long (UF16) format, this simulation does not distinguish them and count them together as UF0/UF16 in the outputs.

Reply to the validation message is always in a long format (DF16). This is because there is an RL field in the validation message which always equals 1 no matter if a short or long surveillance message was transmitted. This means that the long message is required as a reply. [7]

The interrogation rate of UF16/DF16 messages, intended to validate the information contained in the ES, depends on the range between the aircraft.

If equation (IX) is met, the interrogation rate is 1 second and the aircraft is considered as a NEAR THREAT. The interrogation rate is 10 seconds if equation (X) is met. The aircraft is then considered as a THREAT. If none of those equations is met, then the interrogation rate is 60 seconds. [13]

$$|a| \leq 10000\,ft \wedge \left\{ \left(|a| \leq 3000\,ft \vee \frac{|a - 3000\,ft|}{|\dot{a}|} \leq 60s \right) \vee \left(r \leq 3NM \vee \frac{r - 3NM}{|\dot{r}|} \leq 60s \right) \right\} \qquad \text{(IX)}$$

$$|a| \leq 10000\,ft \wedge \left\{ \left(|a| \leq 3000\,ft \vee \frac{|a - 3000\,ft|}{|\dot{a}|} \leq 60s \right) \wedge \left(r \leq 3NM \vee \frac{r - 3NM}{|\dot{r}|} \leq 60s \right) \right\} \qquad \text{(X)}$$

Where:

a is intruder altitude separation in feet.

$\dot{a}$ is altitude rate in feet/second.

r is intruder slant range in NM.

$\dot{r}$ is range rate in NM/second.

3.2.2.4 modeS_ADSBHS

This function is called in case there are 2 or more aircraft being simulated, where some of those aircraft are HS capable and some are not (they have only ADS-B). In such a scenario, the HS capable aircraft will validate the position data contained in ES by UF0/UF16 validation messages. Aircraft with no HS capability will interrogate other aircraft with UF0 nominal surveillance.

3.2.2.5 modeC

This is the last transponder mode which has not been covered in the simulation yet. If the aircraft's transponder does not work in Mode S, it has to interrogate all other aircraft in vicinity with Mode C Only All Call format messages which are sent once per second. In reality, these messages are transmitted by all aircraft no matter the transponder mode, as every aircraft must ensure it will get replies from aircraft only equipped with a Mode C transponder. This function performs calculations to get the number of those messages throughout the entire time of simulation. [1]

3.2.2.6 other_messages

If a mode S equipped aircraft is flying below FL180, it sends UF16 messages at least once every 10 seconds in order to count the number of aircraft in vicinity. This function calculates the number of these messages which are sent throughout the entire time of simulation. [1] [7]

3.2.2.7 Number_of_messages

In this function all the messages are summed up. Hence, it allows us to call a specific message type and get the total count of transmitted messages of this type.

3.2.2.8 aircraft_plot

This provides the 2-D and 3-D plots showing the flight paths of all the modeled aircraft. The 2-D plot is divided into 2 subplots. The first one shows the flights in x-y coordinates, the other one shows the same flights in x-z coordinates.

3.2.2.9 messages_plot

2 plots appear by calling this function. The first plot is a bar chart showing the number of all transmitted messages (UF0/UF16, DF0, DF16, DF11, DF17, Mode C Only All Call) during the entire simulation time, the other plot shows in detail the number of transmitted DF0, DF17 and DF16 messages.

4 Data analysis

In this chapter I am going to analyze real ACAS surveillance parameters. The analysis will be done by comparing real data (messages) which had been received by our ADS-B receivers to the output of the MATLAB simulation. Since the MATLAB simulation is based on published standards, using this approach it should be possible to find out whether the real data are in compliance with the standardized simulation output or not and determine possible differences.

4.1 Real data

The real data are taken from ADS-B receivers owned by the Czech Technical University. These receivers are made in a way so they can only be used to receive messages in downlink format and therefore the message types which can be utilized for this analysis are: DF11, DF17, DF0 and DF16.

The configuration of CTU receivers consists of 4 ADS-B receiver units which are located in and near Prague. Their exact location and technical properties will be discussed later in this chapter.

The configuration of 4 ADS-B receivers allows us to receive high amount of messages transmitted by aircraft within range and thus make a precise analysis. Moreover, it allows us to use the configuration as a MLAT system for surveillance purposes. As it is very likely that we receive the same message (with the same data) at more than 1 receiver at a time, it is necessary to filter this duplicate data. For this purpose I have used a MATLAB program made by another student who had been working on the same project. This program helps to get rid of the duplicate data and it can also make a fusion of data from different ADS-B receivers so that there is only one file to deal with. [6]

This real data will be used in the next chapter for further analysis and comparison with the output obtained in the simulation.

The location of all four ADS-B receivers is shown in figure 4.

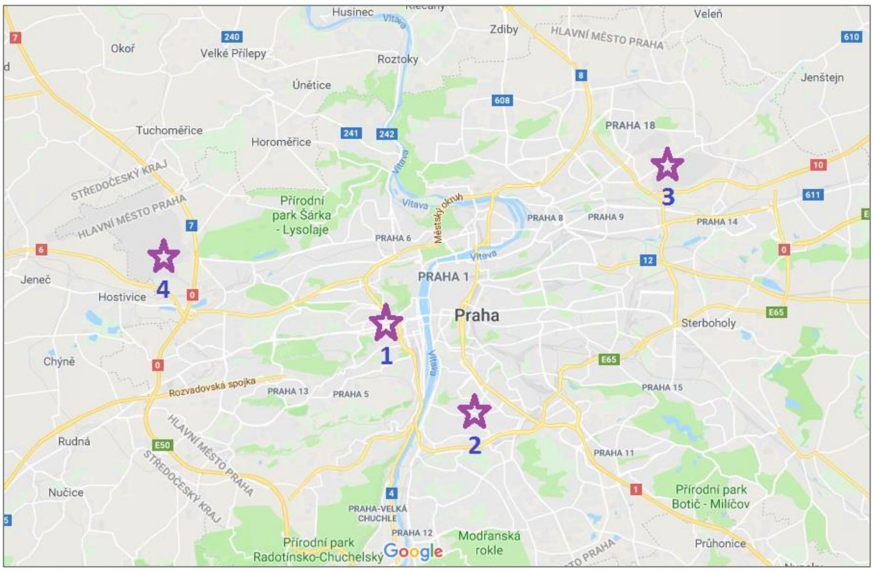

Figure 4 Location of ADS-B receivers

4.1.1 Strahov receiver

The Strahov receiver is located on the roof of the Block 11 building of the Strahov dormitory complex. Since Strahov is on top of the Petřín hill, the receiver has a large range of message reception (as shown in figure 5) and thus can receive messages from faraway aircraft. Different colors in the picture are used to show the difference in range of receiver reception in different altitudes (light green: 0-9999 ft, green: 10000-19999 ft, magenta: 20000-29999 ft, red: 30000 ft and above). Detailed information about this receiver are stated in table 5. [6]

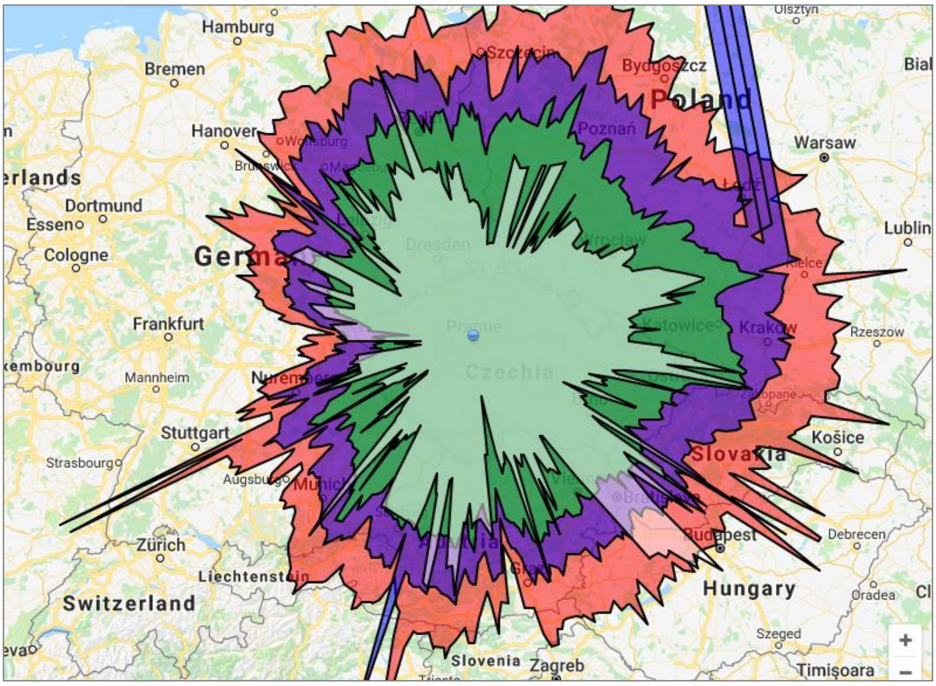

Figure 5 Strahov receiver range

Table 5 Strahov receiver information

Receiver number (figure 4)	1
Receiver name	Strahov receiver
Latitude	50.080512805
Longitude	14.395710655
Altitude	338.33

4.1.2 Pankrác receiver

The receiver is located on top of a skyscraper in the Pankrác district. As shown in figure 6 it is only able to receive messages coming from the west. Detailed information about this receiver are stated in table 6.

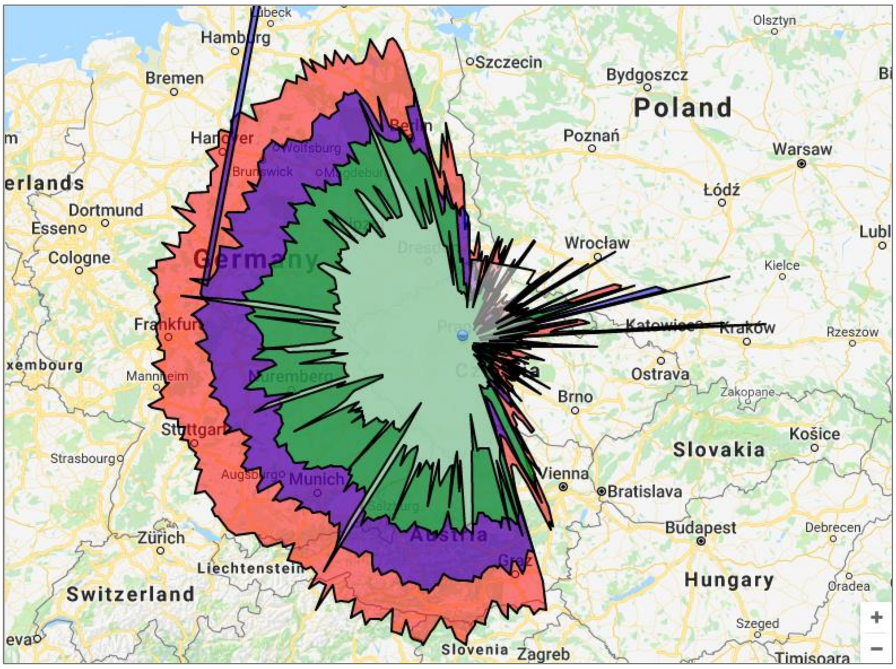

Figure 6 Pankrác receiver range

Table 6 Pankrác receiver information

Receiver number (figure 4)	2
Receiver name	Pankrác receiver
Latitude	50.050384622
Longitude	14.436212947
Altitude	377.21

4.1.3 Letňany Airport receiver

This receiver is located at Letňany Airport and there are no obstacles in the vicinity. For this reason it is appropriate to use it to receive messages from long range aircraft (figure 7). Table 7 provides detailed information about this receiver.

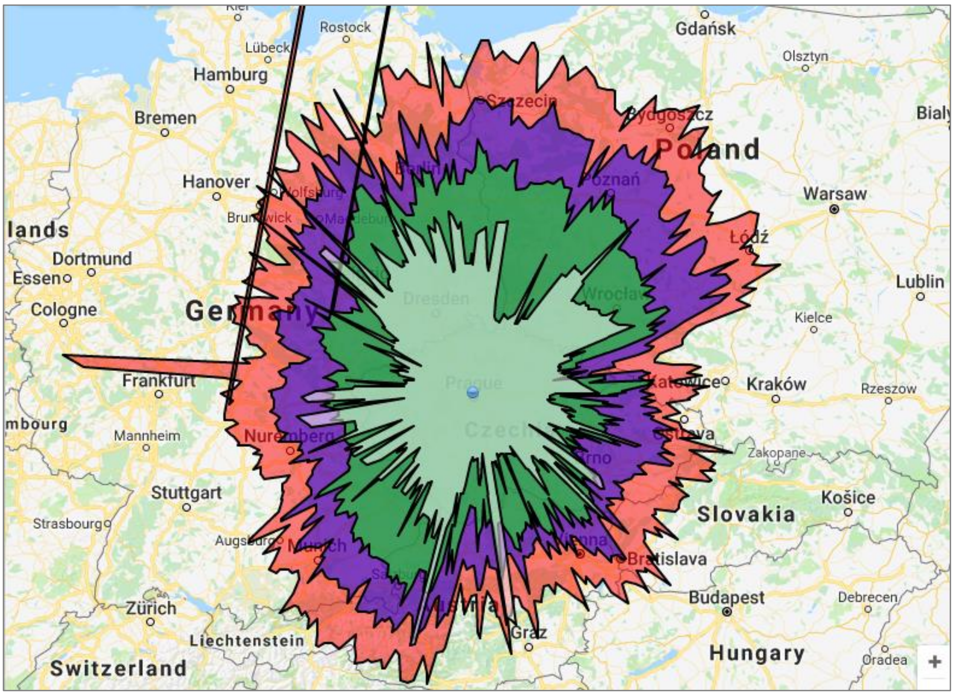

Figure 7 Letňany Airport receiver range

Table 7 Letňany Airport receiver information

Receiver number (figure 4)	3
Receiver name	Letňany Airport receiver
Latitude	50.129189
Longitude	14.525771
Altitude	285.0

4.1.4 Prague Airport receiver

This is our newest receiver. It is located at the top of the APC building of Prague Airport. Its former location was our faculty building but it had been shielded from one side and therefore had to be moved to another place. Information about this receiver can be found in table 8.

Table 8 Prague Airport receiver information

Receiver number (figure 4)	4
Receiver name	LKPR receiver
Latitude	50.106222
Longitude	14.273418
Altitude	208.62

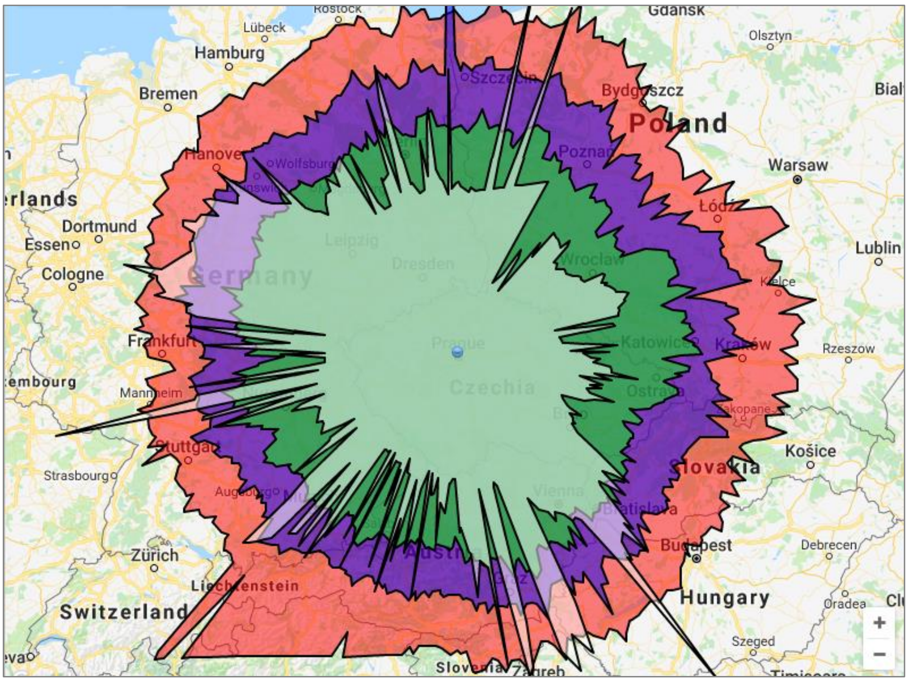

Figure 8 Prague Airport receiver range

4.2 Comparison of simulation output with real data

In this chapter I am going to compare the simulation output with real data received by our ADS-B receivers and then evaluate whether the real system works as described by standards. The comparison will be done on real air traffic situations. The information about each aircraft in a situation will be taken from the internet application www.planefinder.net which shows live air traffic as well as past air traffic with all the needed information (time, mode-S address, altitude, velocity etc.) and thus is a perfect tool to find a convenient aircraft arrangement which can be easily simulated and analyzed.

4.2.1 Situation 1

4.2.1.1 Description and initial conditions

In this situation there are 3 aircraft with different equipment (table 9) and thus different messages are transmitted. All aircraft in this situation have hybrid surveillance capability (no DF0 messages were received but only DF16 messages). This means that the aircraft will use DF16 messages as a reply to the UF0/UF16 position validation messages. Apparently, all aircraft are also equipped with ADS-B. The simulation information are stated in table 10.

Table 9 Situation 1: aircraft information

	Aircraft 1	**Aircraft 2**	**Aircraft 3**
Type of aircraft	B737-82R	A321-211(SL)	B737-86N
Age of aircraft	7 years	8 months	18 years
Company (airline)	Pegasus Airlines	Aeroflot Russian A.	Pegasus Airlines
Mode-S address	4B85B0	42434D	4B8432
Altitude	35000 ft	34975 ft	37000 ft
Velocity	516 kts	491 kts	517 kts
X-coordinate	0	28	6.5
Y-coordinate	0	-15.5	-27
Bearing	328°	30°	333°
Transponder capability	ES capable	ES capable	ES capable
Hybrid s. capability	HS capable	HS capable	HS capable

Table 10 Situation 1: simulation information

Date and time	09.03.2018 01:30 CET
Number of aircraft	3
Time duration of simulation	3 minutes
ACAS range	40 NM
Nominal surveillance rate	5 seconds
Whisper-shout sequence	6

The situation at 01:30 CET when the simulation starts as shown on www.planefinder.net is depicted in figure 9 and the same situation at the end of simulation (at 01:33 CET) as shown on www.planefinder.net is depicted in figure 10.

Figure 9 Situation 1: initial aircraft position

Figure 10 Situation 1: final aircraft position

The aircraft's initial conditions (altitude, velocity, position, equipment etc.) have been inserted to the aircraft model. The output is shown in figure 11. The aircraft flight paths in this figure correspond to the real situation shown in figure 9 and figure 10, so the simulation used to count the transmitted messages can be now run.

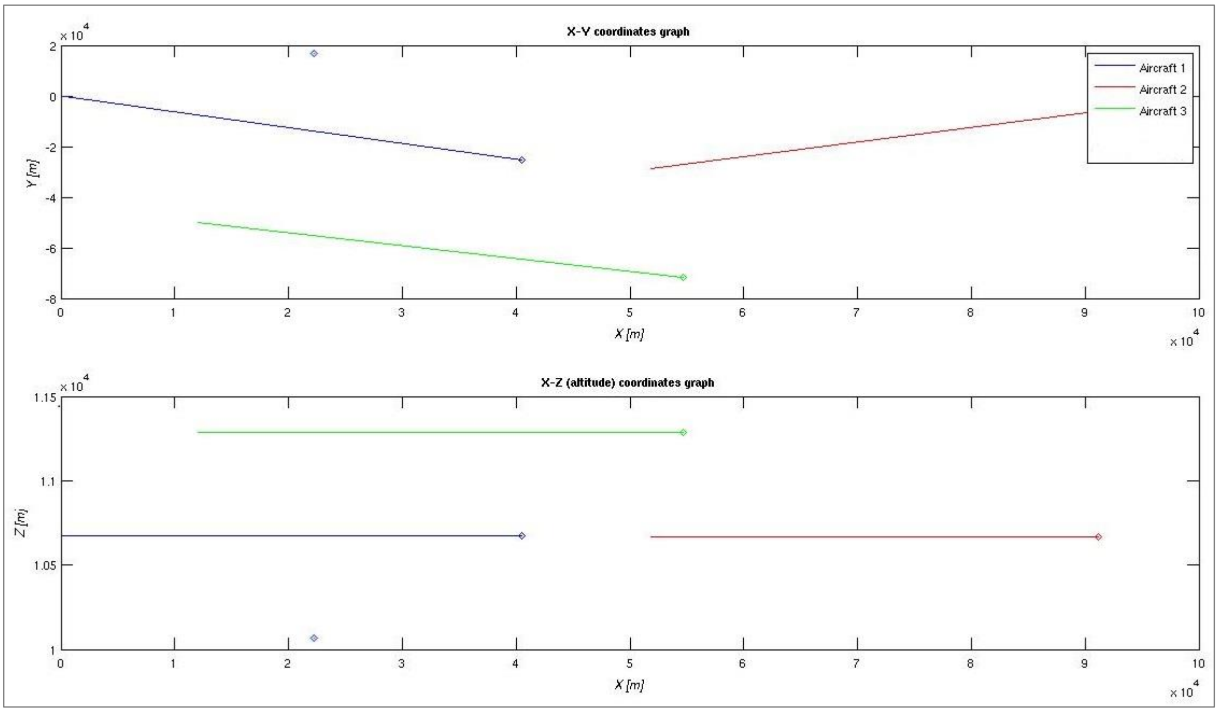

Figure 11 Situation 1: simulated aircraft position

4.2.1.2 Simulation outputs

Number of all transmitted messages according to the simulation (which is made based on standards) distinguished by type is shown in figure 12. As all aircraft in this situation have hybrid surveillance capability and are equipped with ADS-B, no DF0 messages were transmitted.

Number of all transmitted DF17 messages is depicted in figure 13. All DF16 messages were transmitted at a rate of once per 10 seconds.

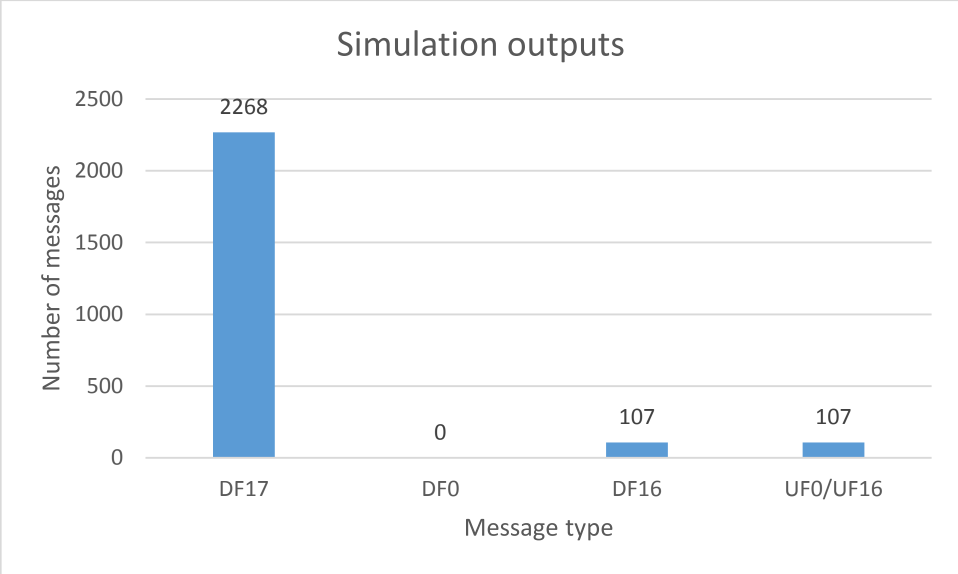

Figure 12 Situation 1: simulation outputs

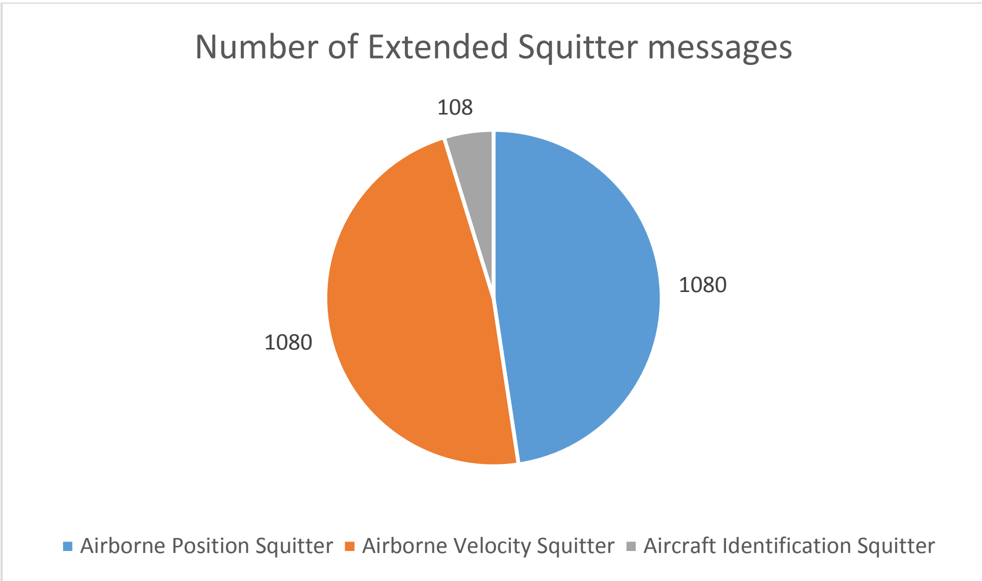

Figure 13 Situation 1: number of DF17 messages

4.2.1.3 Real data analysis

The analysis of DF16 messages that were received by the ADS-B receivers is presented in table 11. At the top, there is a mode S address of an aircraft which sent the messages listed below. Message pairs relating to each other have the same color (this was determined from the sequence pattern). As we can see, the reply rate of all messages is 10 seconds which corresponds with the simulation output. According to the table, there are 8 messages that were not received at any of our receivers and so they are missing from the message sequence. Since it is clear that these messages must have been transmitted and they were just not received by our receivers, they will be manually added to the final number. Messages which were transmitted out of the sequence pattern have no background in the table. Two of them (at times 5419.675 and 5508.629) are probably just duplicates of previous messages and therefore they will not be counted. The message at 5483.676 was transmitted out of the sequence pattern, but because it cannot be a duplicate, it will be counted.

Table 11 Situation 1: real data

42434D			4B85B0			4B8432		
Time	Receiver	Message	Time	Receiver	Message	Time	Receiver	Message
5408,406	1	16	5520,409	1	16	5446,364	1	16
5409,626	1	16	5528,413	1	16	5450,626	4	16
5418,406	1	16	5530,409	1	16	5456,364	1	16
5419,626	1	16	5538,364	1	16	5460,626	4	16
5419,675	1	16	5540,459	1	16	5466,414	1	16
5428,407	1	16	5548,367	1	16	5470,626	1	16
5429,626	1	16	5550,409	1	16	5476,364	1	16
5438,457	1	16	5558,364	4	16	5480,626	1	16
5439,675	1	16	5560,411	1	16	5487,414	1	16
5448,407	1	16	5568,363	1	16	5490,626	1	16
5449,626	1	16	5570,409	1	16	5497,364	1	16
5458,407	1	16	5578,364	4	16	5500,626	1	16
5459,626	1	16	5580,41	1	16	5507,414	1	16
5468,41	1	16	5588,363	4	16	5510,626	1	16
5469,679	1	16	5590,41	1	16	5517,364	1	16
5478,408	1	16	5598,363	1	16	5520,626	1	16
5483,676	1	16	5600,41	1	16	5527,364	1	16
5488,408	1	16	5608,363	1	16	5530,626	1	16
5488,626	1	16	5610,41	1	16	5537,367	1	16
5498,408	1	16	5618,363	1	16	5540,626	1	16
5498,626	1	16	5620,41	1	16	5547,364	1	16
5508,408	1	16	5628,365	1	16	5550,676	1	16
5508,626	1	16	5630,411	1	16	5560,626	1	16
5508,629	1	16	5638,363	1	16	5567,364	1	16
5518,409	4	16	5640,411	1	16	5570,627	1	16
5518,626	1	16	5648,363	4	16	5577,364	1	16
5528,409	1	16	5650,411	1	16	5580,627	1	16
5528,629	1	16	5658,363	1	16	5587,413	1	16
5538,626	1	16	5668,364	1	16	5590,627	1	16
5543,412	1	16	5670,412	1	16	5597,413	1	16
5548,626	1	16	5678,364	1	16	5600,627	1	16
5553,459	1	16	5688,363	4	16	5607,364	1	16
5558,627	1	16	5698,413	4	16	5610,629	1	16
5563,409	1	16						
5578,627	1	16						

4.2.1.4 Comparison of simulation output with real data

The comparison of simulation output with real data for this situation is shown in figure 14. Since the number of DF17 messages is firmly stated in the standards and shall not change according to the aircraft's mutual positions, it can be used to determine the percentage of received messages. In this case it is 93 %. Therefore, approximately 7 % of messages were not received by our receivers. That is why we did not receive 107 DF16 messages which should have been received according to the standards. The probable cause of the loss of the messages is that only 2 out of 4 receivers were operational at the time.

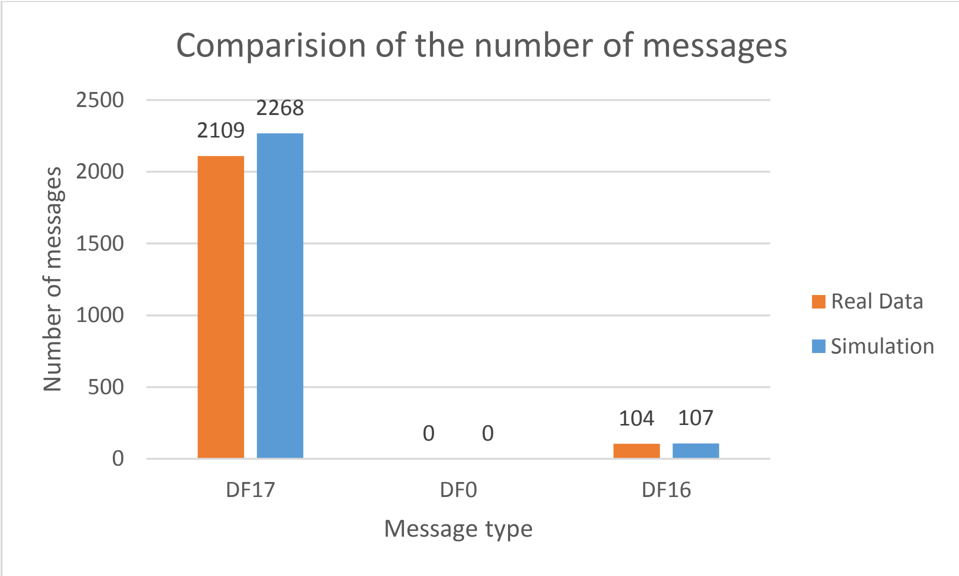

Figure 14 Situation 1: comparison of simulation outputs with real data

4.2.2 Situation 2

4.2.2.1 Description and initial conditions

Unlike in situation 1 there are only 2 aircraft in this situation and only one of them has hybrid surveillance capability (DF0 as well as DF16 messages were received). Both aircraft are equipped with ADS-B (table 12). This means that the aircraft without hybrid surveillance capability will interrogate the other aircraft with UF0 messages and will receive DF0 replies. The aircraft with hybrid surveillance capability will interrogate with UF0/UF16 messages and will receive DF16 replies. The simulation information are stated in table 13.

Table 12 Situation 2: aircraft information

	Aircraft 1	**Aircraft 2**
Type of aircraft	A321-211(SL)	A321-232(SL)
Age of aircraft	2 years	3 years
Company (airline)	Aeroflot Russian Airlines	Wizz Air
Mode-S address	424304	471F87
Altitude	32000 ft	39000 ft
Velocity	493 kts	489 kts
X-coordinate	0	12
Y-coordinate	0	-21
Bearing	37°	22°
Transponder capability	ES capable	ES capable
Hybrid s. capability	HS not capable	HS capable

Table 13 Situation 2: simulation information

Date and time	31.03.2018 00:40 CET
Number of aircraft	2
Time duration of simulation	3 minutes
ACAS range	31 NM
Nominal surveillance rate	5 seconds
Whisper-shout sequence	6

The situation at 00:40 CET, when the simulation starts as shown on www.planefinder.net, is depicted in figure 15 and the same situation at the end of simulation (at 00:43 CET) as shown on www.planefinder.net is depicted in figure 16.

Figure 15 Situation 2: initial aircraft position

Figure 16 Situation 2: final aircraft position

The aircraft's initial conditions (altitude, velocity, position, equipment etc.) have been inserted to the aircraft model. The output is shown in figure 17. The aircraft flight paths in this figure correspond to the real situation shown in figure 15 and figure 16, so the simulation used to count the transmitted messages can be run.

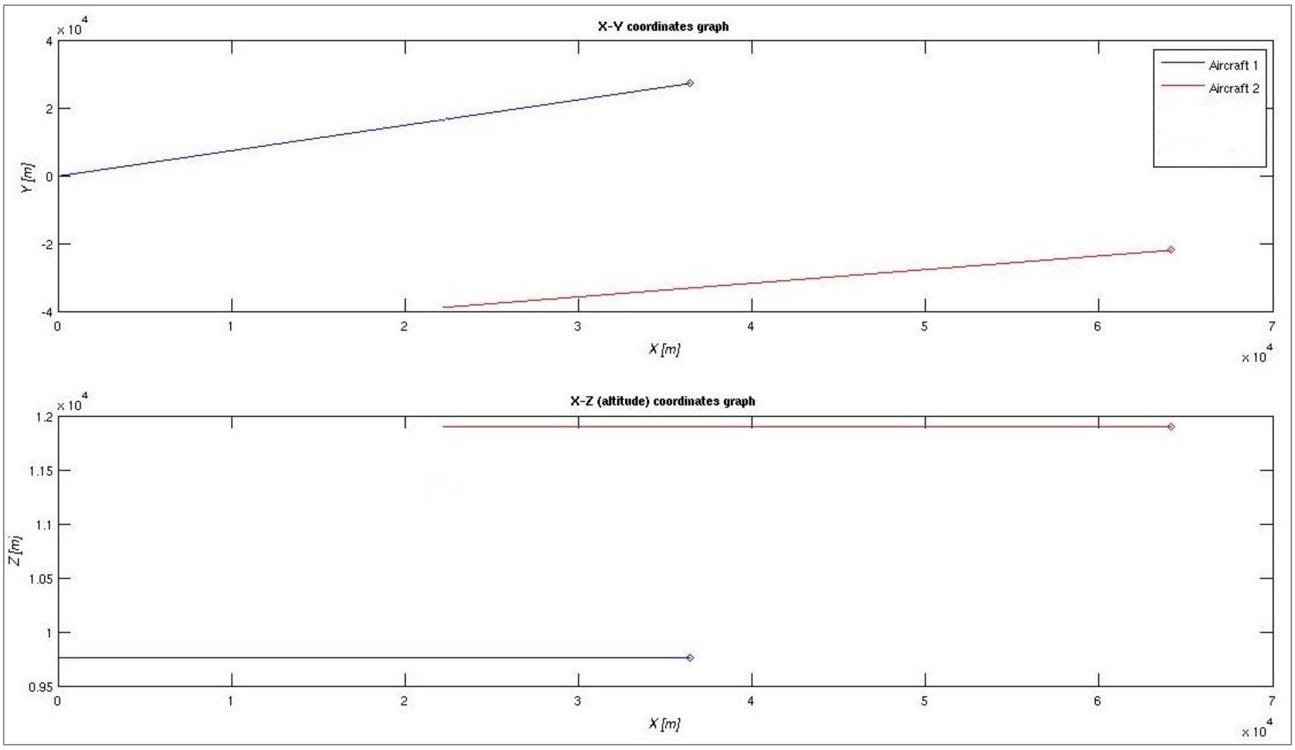

Figure 17 Situation 2: simulated aircraft position

4.2.2.2 Simulation outputs

Number of all transmitted messages according to the simulation (which is made based on standards) distinguished by their types is shown in figure 18. Only one aircraft in this situation has hybrid surveillance capability and therefore there are both DF0 and DF16 messages transmitted in this situation.

The number of all DF17 messages which were transmitted is shown in figure 19. All DF0 messages should be transmitted at a nominal rate of once per 5 seconds, and all DF16 messages once every 60 seconds.

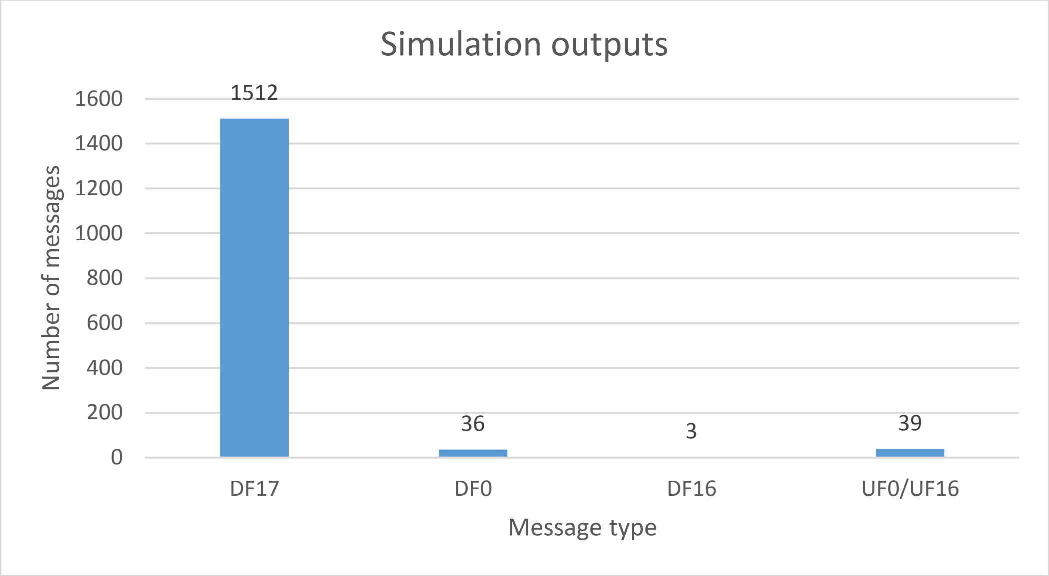

Figure 18 Situation 2: simulation outputs

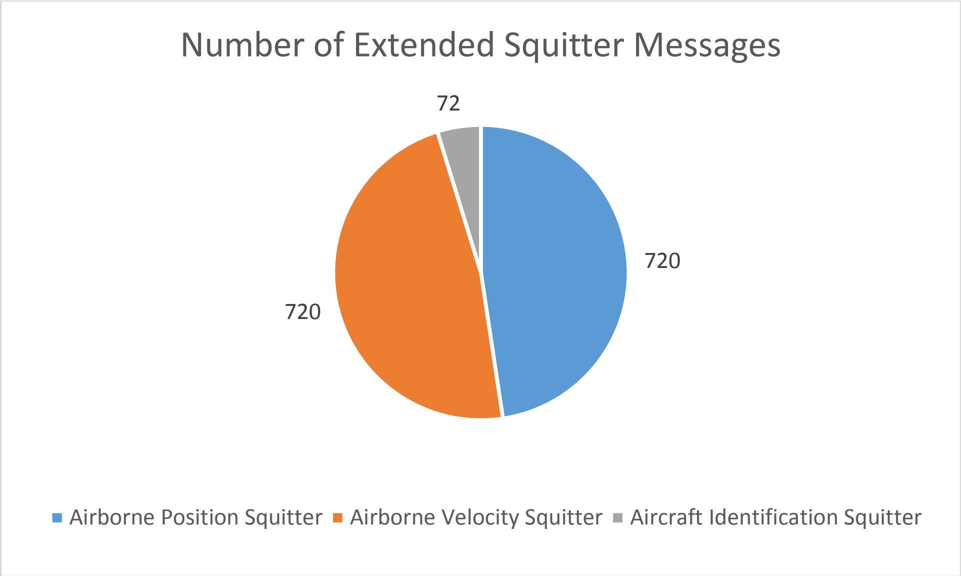

Figure 19 Situation 2: number of DF17 messages

4.2.2.3 Real data analysis

All received DF0 and DF16 messages from both aircraft are listed in table 14. As we can see, the reply rates correspond to the simulation outputs.

Table 14 Situation 2: real data

424304			471F87		
Time	Receiver	Message	Time	Receiver	Message
2439,823	1	16	2406,341	2	0
2499,823	1	16	2411,311	1	0
2559,823	1	16	2416,271	2	0
			2421,171	1	0
			2426,221	1	0
			2431,311	1	0
			2436,361	1	0
			2441,331	1	0
			2446,311	4	0
			2451,201	4	0
			2456,181	2	0
			2461,181	4	0
			2466,232	4	0
			2471,262	4	0
			2476,312	1	0
			2481,212	4	0
			2486,332	4	0
			2491,202	1	0
			2496,182	4	0
			2501,182	4	0
			2506,252	4	0
			2511,312	4	0
			2516,252	4	0
			2521,232	4	0
			2526,182	1	0
			2531,342	1	0
			2536,263	4	0
			2541,243	4	0
			2546,293	4	0
			2551,173	4	0
			2556,233	4	0
			2561,273	4	0
			2566,173	4	0
			2571,263	4	0
			2576,183	1	0
			2581,283	1	0

4.2.2.4 Comparison of simulation output with real data

The comparison of simulation output with real data is presented in figure 20. The DF0 and DF16 messages are equal, which means that the surveillance works perfectly according to the standards. The nominal interrogation rate of DF0 messages is not firmly defined in standards, however the period shall not be higher than 5 seconds. In this case it is evident that the ACAS surveillance algorithm is programmed to interrogate every 5 seconds.

As much as DF0 and DF16 messages are equal, DF17 messages are not. In this situation it is a different inequality from the previous one, as the number of real transmitted messages is higher than the simulated ones. The ES messages which shall be transmitted in regular time intervals when the aircraft is airborne are Aircraft Identification Squitter, Airborne Position Squitter and Airborne Velocity Squitter. The transmission time intervals of these ES messages, defined in standards, are provided in one of the previous chapters.

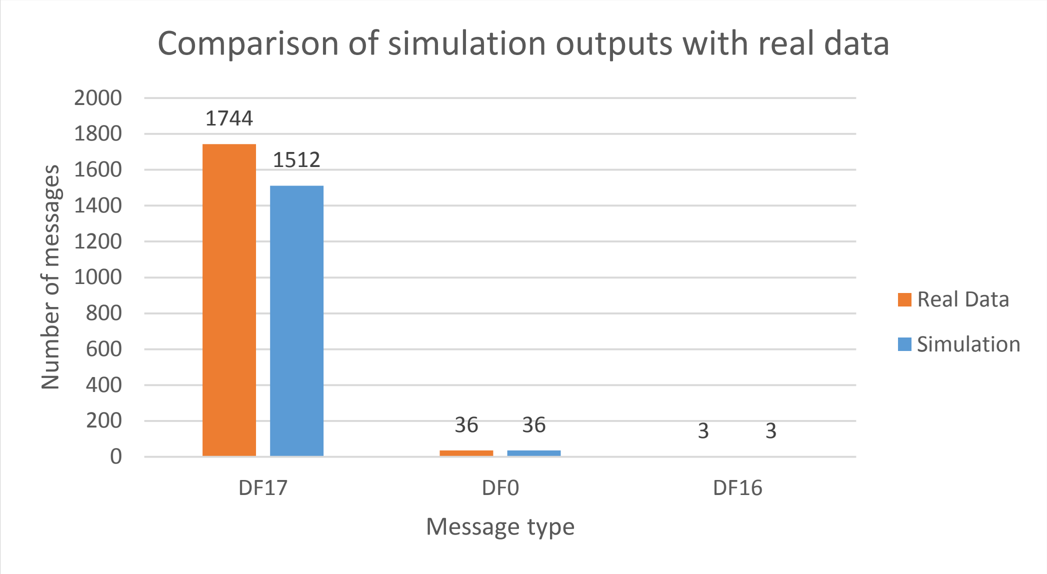

Figure 20 Situation 2: comparison of simulation outputs with real data

These 3 squitters are the ones that must always be transmitted, but there are other types of extended squitters which may be transmitted either at some special occasions (such as Event Driven Squitter) or when the aircraft transmits additional information extracted from particular BDS register. Since in this case the difference is somewhere around 230 messages and thus they all cannot be duplicates, there must be other ES messages transmitted along with the 3 typical squitters. Hence I have done a deeper analysis of received DF17 messages in order to find those extra squitters.

The type of DF17 messages is provided in the first 5 bits of byte 5 of the message in binary code. Since the length of a DF17 message is 112 bits (14 bytes), this information is placed in bits 33 to 37. These 5 bits are called Type Code. [2]

According to DF17 messages analysis, there are 6 types of ES being transmitted by one of the aircraft (Aircraft 1) in this situation. The other aircraft transmits the 3 conventional types of DF17 as simulated and defined by standards. That means that the first aircraft transmits 3 additional types of the DF17 message. All 6 types in binary code are illustrated in figure 21 (the 5 bites that represent Type Code are highlighted).

```
10001101010000100100001100000100 01011 000101001011000000011101100010101110010000011111101101110101001010000010001
10001101010000100100001100000100 10011 001000010011000010100100110010100000000001001000001000101101110010111010110 0
10001101010000100100001100000100 00100 011000001000110001100110010110101110001110011100000111011000110111110111101
10001101010000100100001100000100 11101 010001111101001100001100000000000010011110000000100000000111110001110000000111
10001101010000100100001100000100 11111 000001000110000000000000100000000001001001101110001011000011111010111100 10
10001101010000100100001100000100 11100 001000000110001101010000000000000000000000000000001100000011010000000000100
```

Figure 21 Situation 2: binary codes of DF17 messages

These 5 highlighted binary codes are converted to decimal format as shown below:

- 01011 = 11 which represents Airborne Position Message,

- 10011 = 19 which represents Airborne Velocity Message,
- 00100 = 4 which represents Aircraft Identification and Type Message,
- 11101 = 29 which represents Target State and Status Message,
- 11111 = 31 which represents Aircraft Operational Status Message.
- 11100 = 28 which represents Aircraft Status Message

Hence the 3 additional DF17 types are Target State and Status Message, Aircraft Operational Status Message and Aircraft Status Message. The period at which they are transmitted according to standards is provided in table 15. [5]

Table 15 Situation 2: transmission rates of 3 additional DF17 messages

<table>
<tr><th>Type of ES message</th><th>Period [s]</th></tr>
<tr><td>Target State and Status Message</td><td>1.2 – 1.3</td></tr>
<tr><td rowspan="2">Aircraft Operational Status Message</td><td>0.7 – 0.9 (when there is no Target State and Status Message transmitted)</td></tr>
<tr><td>2.4 – 2.6 (when Target State and Status Message is also transmitted)</td></tr>
<tr><td>Aircraft Status Message</td><td>1</td></tr>
</table>

Target State and Status Message

This message is used to identify whether the aircraft vertical data are available or not, the aircraft's capabilities for providing altitude data, aircraft's intended altitude and heading, whether the aircraft horizontal data are available and other information. [5]

Aircraft Operational Status Message

This message is used to report the operational capability of the aircraft such as for whether the TCAS is installed and operational or whether the RA or IDENT switch is active etc. [5]

Aircraft Status Message

This message is used to provide additional information on aircraft status such as emergency status, minimum fuel etc. If its subtype code equals 0, then there is no additional aircraft status information being delivered. [5]

According to RTCA DO-260 technical standard, there are 3 versions of ADS-B - ICAO version 0, ICAO version 1 and ICAO version 2. ICAO version 0 was the first ADS-B specification defined in 2000. The other versions were defined in 2003 and 2009 respectively. The information about a particular version is encoded in Aircraft Operational Status Message and therefore every aircraft knows the version of ADS-B by receiving this type of DF17 message. However, Aircraft Operational Status Message is only transmitted by ADS-B ICAO version 1 and 2 capable aircraft. From this reason, if an aircraft does not receive any Aircraft Operational Status Message, it automatically supposes the intruder aircraft is equipped with ADS-B ICAO version 0. If it does receive Aircraft Operational Status Message, the information about whether the intruder's ADS-B is ICAO version 1 or ICAO version 2 capable is placed in 41-43 ME bits. Taking into account this information and RTCA DO-260 document, it is apparent that those 3 additional DF17 messages (Target State and Status Message, Aircraft Operational Status Message and Aircraft Status Message) are always transmitted by ADS-B ICAO version 1 or 2 capable aircraft. If an aircraft is equipped with the oldest ADS-B ICAO version 0, it only transmits the 3 conventional DF17 messages (Airborne Position Squitter, Airborne Velocity Squitter and Aircraft Identification Squitter). [2] [14]

If these 3 types of Extended Squitter messages are added to the simulation outputs, the comparison of DF17 messages is changed as shown in figure 23. The number of different DF17 messages is depicted in figure 22.

It is apparent that the number of messages is now almost equal. There is just a slight difference which shows us that we received almost 91.5 % of all transmitted messages in this air traffic situation.

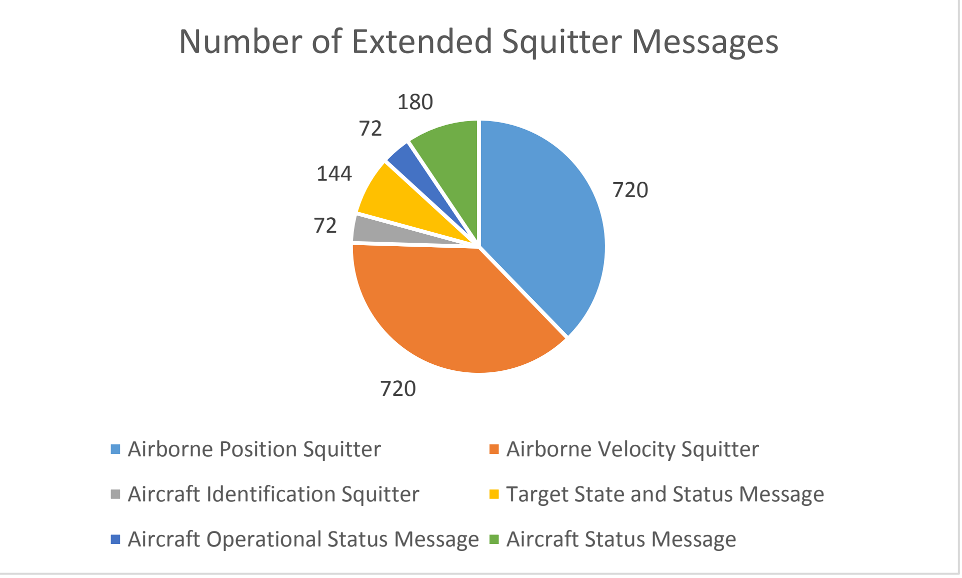

Figure 22 Situation 2: number of all transmitted DF17 messages

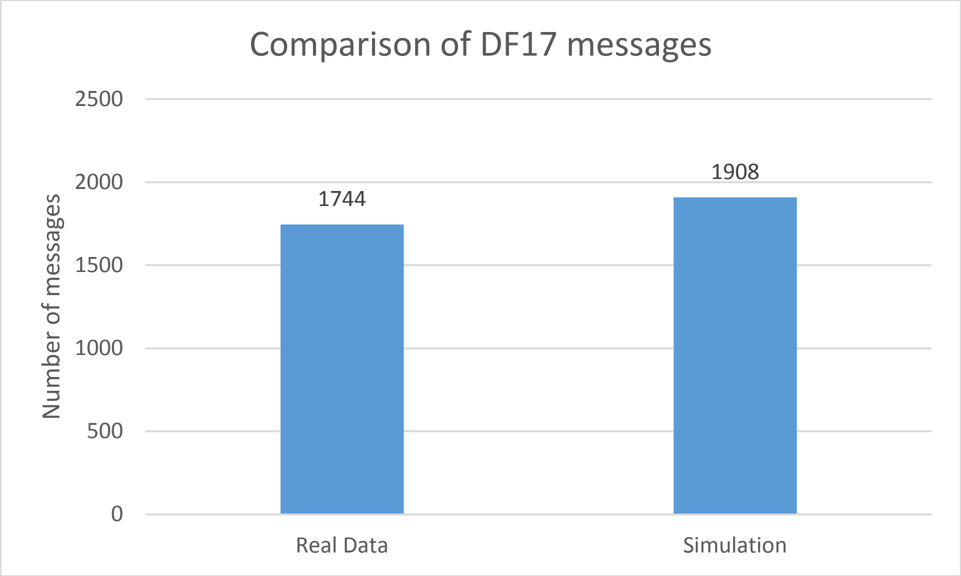

Figure 23 Situation 2: comparison of DF17 messages

4.2.3 Situation 3

4.2.3.1 Description and initial conditions

There are again 2 aircraft in this situation, both ADS-B equipped (table 16). Only one aircraft is ACAS hybrid surveillance capable. Therefore, the aircraft that is not ACAS hybrid surveillance capable will transmit DF16 messages as replies to the hybrid surveillance validation interrogations. The other aircraft will transmit DF0 messages as replies to nominal UF16 interrogations. The simulation information are stated in table 17.

Table 16 Situation 3: aircraft information

	Aircraft 1	**Aircraft 2**
Type of aircraft	A320-232	B777-FS2
Age of aircraft	9 years	4 years
Company (airline)	Wizz Air	Federal Express
Mode-S address	471EA5	AC5868
Altitude	37000 ft	29000 ft
Velocity	462 kts	509 kts
X-coordinate	0	28
Y-coordinate	0	-13.5
Bearing	3°	14°
Transponder capability	ES capable	ES capable
Hybrid s. capability	HS capable	HS not capable

Table 17 Situation 3: simulation information

Date and time	18.03.2018 00:40 CET
Number of aircraft	2
Time duration of simulation	5 minutes
ACAS range	32 NM
Nominal surveillance rate	5 seconds
Whisper-shout sequence	6

The situation at 00:40 CET, when the simulation starts as shown on www.planefinder.net, is depicted in figure 24, and the same situation at the end of simulation time (at 00:45 CET) as shown on www.planefinder.net is depicted in figure 25.

Figure 24 Situation 3: initial aircraft position

Figure 25 Situation 3: final aircraft position

The aircraft's initial conditions (altitude, velocity, position, equipment etc.) have been inserted to the aircraft model. The output is shown in figure 26. The aircraft flight paths in this figure correspond to the real situation shown in figure 24 and figure 25, so the simulation used to count the transmitted messages can be run.

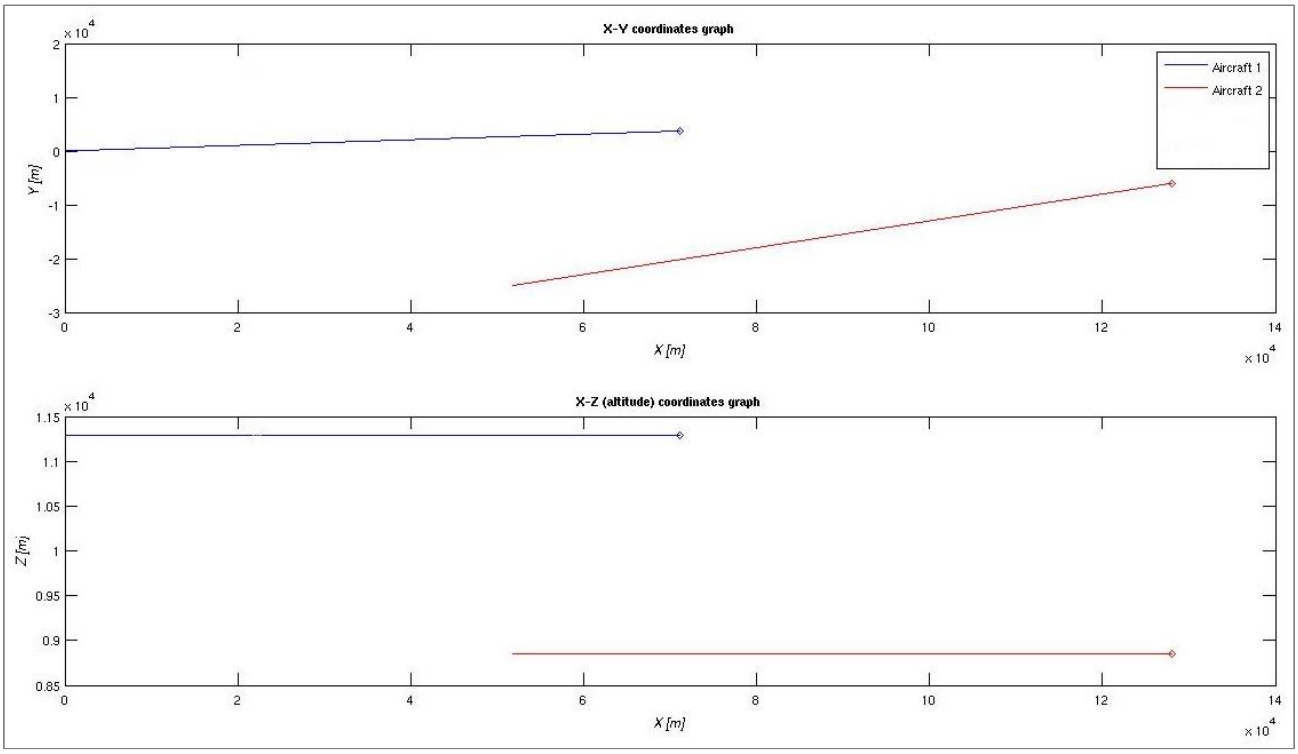

Figure 26 Situation 3: simulated aircraft position

4.2.3.2 Simulation outputs

Number of all transmitted messages according to the simulation (which is made based on standards) distinguished by their type is shown in figure 27. As already mentioned, only one aircraft in this situation has hybrid surveillance capability and therefore both DF0 and DF16 messages were transmitted in this situation.

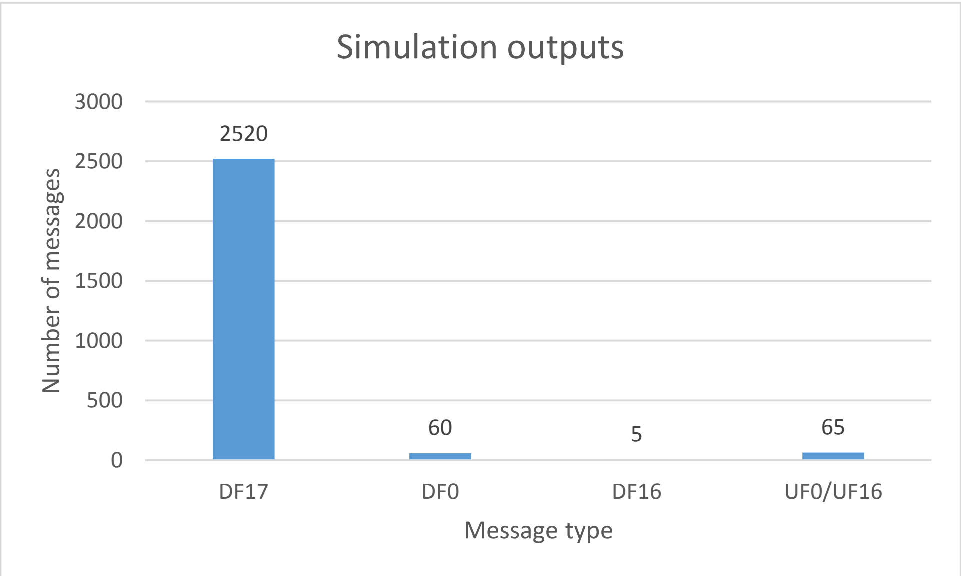

Figure 27 Situation 3: simulation outputs

The number of all DF17 messages which were transmitted is shown in figure 28. All DF0 messages should be transmitted at nominal rate, and all DF16 messages once every 60 seconds, so these surveillance rates are the same as in the previous situation.

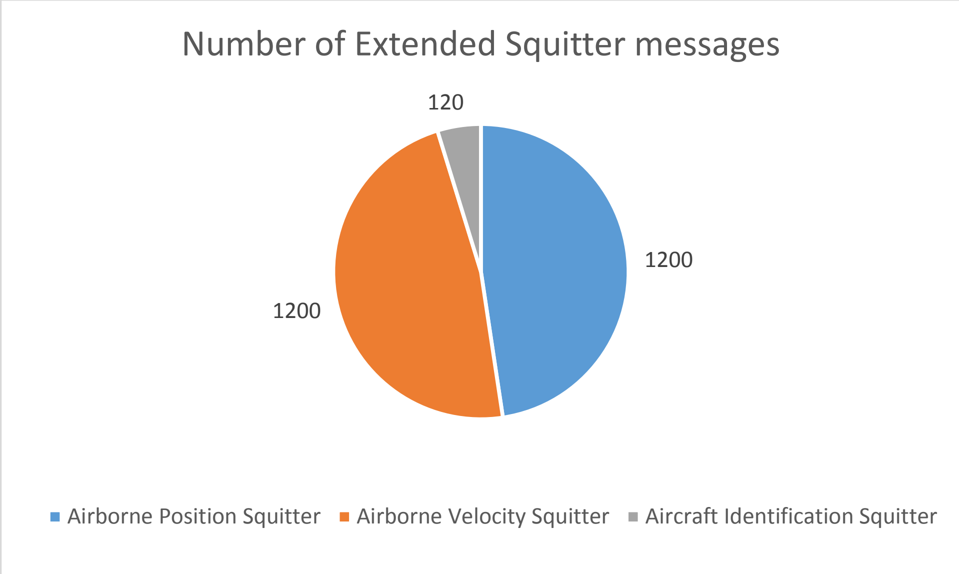

Figure 28 Situation 3: number of DF17 messages

4.2.3.3 Real data analysis

All received DF0 and DF16 messages from both aircraft are listed in table 18. Newly in this situation, there are messages in the table, which are written in red. These messages were, after an analysis of their binary codes, identified as replies to acquisition interrogations. Acquisition interrogations are DF0 interrogations with AQ field equal to 1 and are transmitted to acquire a range of lately identified aircraft. The replies to these acquisition interrogations are identified by analysis of their RI field as shown in figure 29. If the first bit of this field (14^{th} bit of the message) equals 1, it means this is a reply to acquisition interrogation. Hence, there must have been another aircraft in the situation which was not, for some reason, visible on www.planefinder.net and which suddenly got in the detection range of the 2 analyzed aircraft. In some cases these RI=1 replies are followed by one or more RI=0 messages. This will be further analyzed at the end of this chapter. [1]

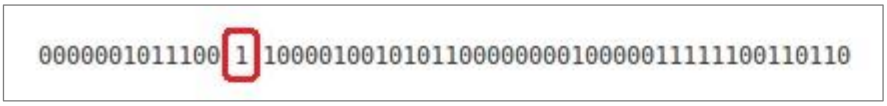

Figure 29 Situation 3: binary code of DF0 acquisition reply message

Table 18 Situation 3: real data

AC5868			471EA5		
Time	Receiver	Message	Time	Receiver	Message
2447,4664	1	16	2419,1832	4	0
2507,4663	1	16	2424,2534	4	0
2567,4661	1	16	2429,2035	4	0
2618,433	4	0	2434,2537	4	0
2627,466	1	16	2439,1938	4	0
2650,45	4	0	2444,114	4	0
2685,4758	4	0	2449,0941	4	0
2687,4657	4	16	2454,2443	4	0
2696,4154	1	0	2459,1545	1	0
			2464,2446	1	0
			2469,2448	1	0
			2474,2049	1	0
			2484,2253	1	0
			2489,2354	1	0
			2499,1657	4	0
			2504,1559	1	0
			2509,2661	4	0
			2514,1562	4	0
			2524,2766	4	0
			2529,1867	4	0
			2534,1769	4	0
			2539,147	4	0
			2544,1972	4	0
			2549,2373	4	0
			2554,1175	4	0
			2559,2577	1	0
			2564,1678	1	0
			2569,218	4	0
			2574,1181	4	0
			2579,2183	4	0
			2584,2485	4	0
			2589,2086	4	0
			2594,2488	1	0
			2599,169	4	0
			2604,1591	1	0
			2609,1993	4	0
			2614,0994	1	0
			2619,2696	1	0
			2621,4592	1	0
			2624,4584	1	0
			2628,1342	1	0
			2628,182	1	0
			2629,1799	1	0
			2634,2001	4	0
			2636,4332	4	0
			2638,1822	1	0
			2638,2322	1	0
			2639,2077	4	0
			2640,1323	1	0
			2640,1821	1	0
			2640,4193	4	0
			2642,1321	1	0
			2643,7685	1	0
			2644,1779	4	0
			2649,1106	4	0
			2651,4234	1	0
			2654,2307	4	0
			2655,428	4	0
			2659,2409	4	0
			2661,1822	1	0
			2664,141	4	0
			2669,1712	4	0
			2673,4287	4	0
			2679,2115	4	0
			2682,4656	1	0
			2684,1817	1	0
			2689,2519	1	0
			2691,1324	1	0
			2692,769	1	0
			2693,1324	1	0
			2695,152	4	0
			2696,4277	4	0
			2700,1322	4	0

4.2.3.4 Comparison of simulation output with real data

The comparison of simulation outputs with real data is shown in figure 30. Since only 2 receivers were operational at the time, taking into account the number of DF17 messages, only approximately 81 % of messages were received. DF0 replies to acquisition interrogations are not counted in the figure.

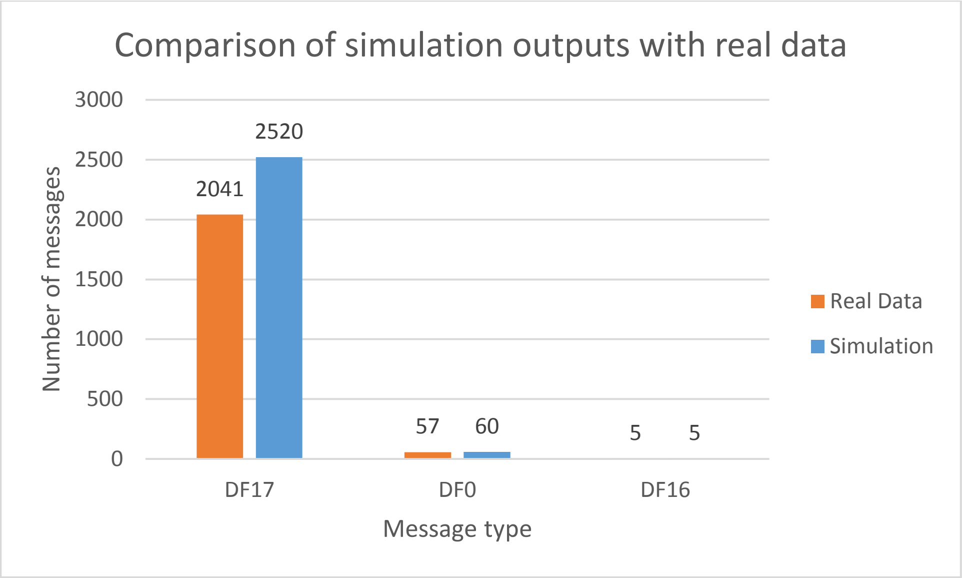

Figure 30 Situation 3: comparison of simulation outputs with real data

4.2.4 Situation 4

4.2.4.1 Description and initial conditions

2 aircraft in this situation have the same equipment as the aircraft in situation 2 and 3 (table 20). Hence the surveillance between them will be done as described in previous 2 situations. The simulation information are stated in table 19.

Table 19 Situation 4: simulation information

Date and time	24.03.2018 03:46 CET
Number of aircraft	2
Time duration of simulation	3 minutes
ACAS range	31 NM
Nominal surveillance rate	5 seconds
Whisper-shout sequence	6

Table 20 Situation 4: aircraft information

	Aircraft 1	Aircraft 2
Type of aircraft	B747-406M	A350-941
Age of aircraft	16 years	2 months
Company (airline)	KLM Royal Dutch Airline	Malaysia Airlines
Mode-S address	484175	75044B
Altitude	36000 ft	40000 ft
Velocity	496 kts	489 kts
X-coordinate	0	26
Y-coordinate	0	16
Bearing	145°	159°
Transponder capability	ES capable	ES capable
Hybrid s. capability	HS not capable	HS capable

The situation at 03:46 CET when the simulation starts as shown on www.planefinder.net is depicted in figure 31 and the same situation at the end of simulation (at 03:49 CET) as shown on www.planefinder.net is depicted in figure 32.

Figure 31 Situation 4: initial aircraft position

Figure 32 Situation 4: final aircraft position

The aircraft's initial conditions (altitude, velocity, position, equipment etc.) have been inserted to the aircraft model. The output is shown in figure 33. The aircraft flight paths in this figure correspond to the real situation shown in figure 31 and figure 32, so the simulation used to count the transmitted messages can be run.

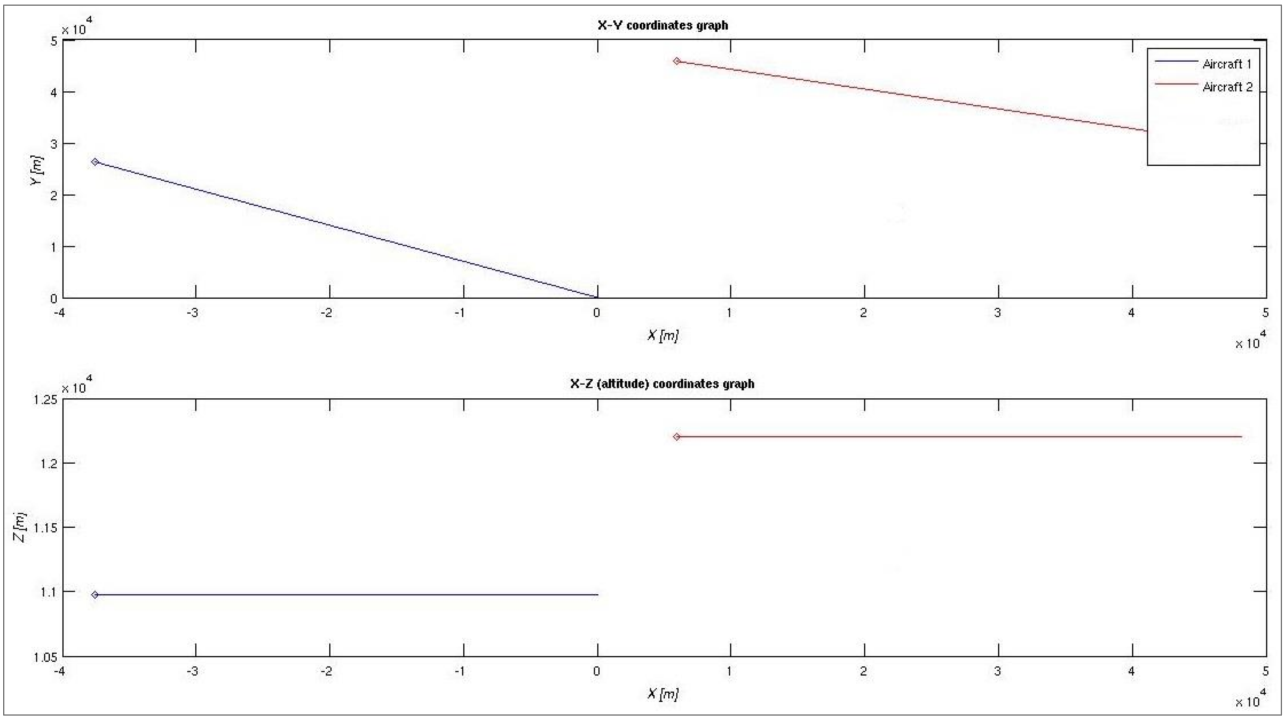

Figure 33 Situation 4: simulated aircraft position

4.2.4.2 Simulation outputs

Number of all transmitted messages according to the simulation (which is made based on standards) distinguished by type is shown in figure 34. As well as in the previous 2 situations, only one aircraft in this situation has hybrid surveillance capability and therefore both DF0 and DF16 messages are transmitted.

The number of all DF17 messages which were transmitted is shown in figure 35. All DF0 messages should be transmitted at a nominal rate of once per 5 seconds and all DF16 messages once every 10 seconds.

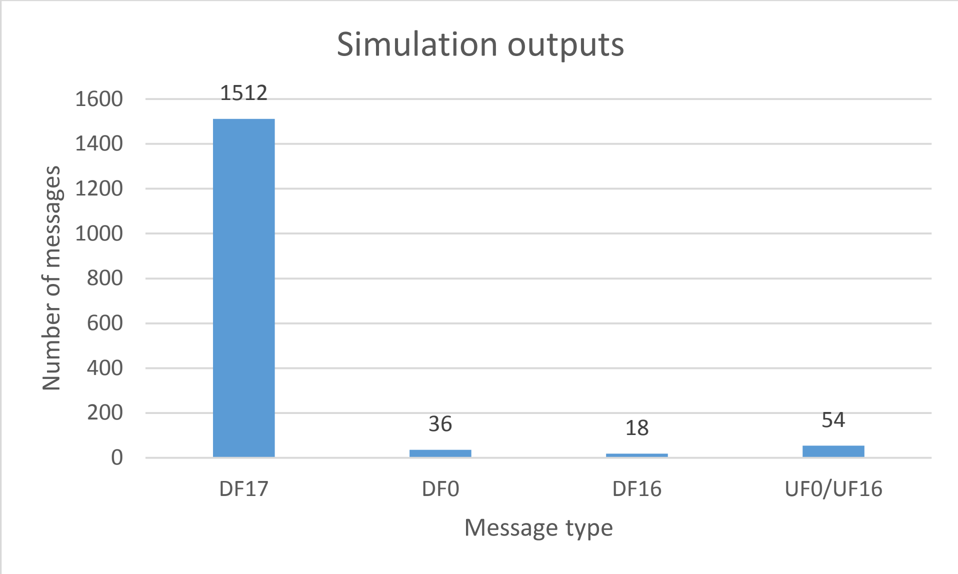

Figure 34 Situation 4: simulation outputs

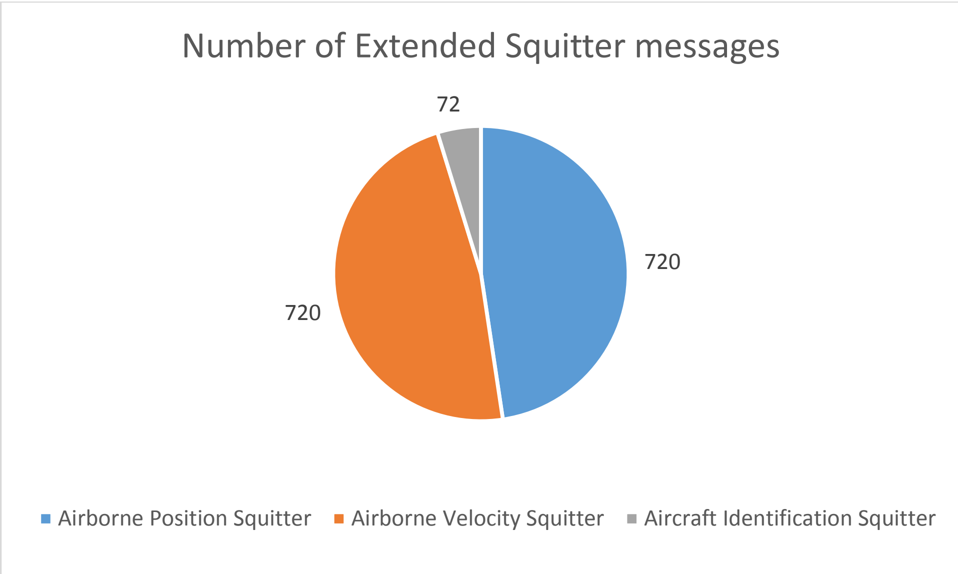

Figure 35 Situation 4: number of DF17 messages

4.2.4.3 Real data analysis

All received DF0 and DF16 messages from both aircraft are listed in table 21. Since Aircraft 1 (484175) has no hybrid surveillance capability, only DF0 messages were received from Aircraft 2 (75044B). All these DF0 messages were transmitted at nominal rate which, in this case, is again 5 seconds. One message is missing from the sequence (it was not received at any of our receivers although it must have been transmitted) and thus it will be manually added to the final number of transmitted messages.

There are 6 messages with no background color in the table that were received from both aircraft. These messages do not belong to any sequence pattern and they are not replies to acquisition interrogations according to their RI field. Therefore it is hard to determine why they were transmitted. However since they were received, they will be added to the final number of transmitted DF0 messages.

Transmission rate of DF16 validation messages received from Aircraft 1 is 10 seconds, which is exactly the same rate as described in standards.

Table 21 Situation 4: real data

75044B			484175		
Time	Receiver	Message	Time	Receiver	Message
13561,65	4	0	13566,27	4	16
13566,7	4	0	13576,32	1	16
13571,63	4	0	13586,27	4	16
13576,58	4	0	13596,27	1	16
13581,58	4	0	13599,15	4	0
13586,6	4	0	13606,27	1	16
13588,58	4	0	13616,27	4	16
13591,69	4	0	13626,32	1	16
13595,53	4	0	13636,27	1	16
13596,65	4	0	13646,32	1	16
13601,54	4	0	13649,21	1	0
13602,15	4	0	13656,27	1	16
13606,54	1	0	13666,27	1	16
13611,71	1	0	13676,27	1	16
13616,75	1	0	13686,32	4	16
13621,57	4	0	13696,27	4	16
13626,66	4	0	13706,37	4	16
13631,58	4	0	13716,27	1	16
13636,63	1	0	13726,27	1	16
13641,62	1	0	13736,32	1	16
13646,69	1	0			
13649,2	4	0			
13651,65	4	0			
13656,55	1	0			
13661,53	1	0			
13666,63	1	0			
13671,71	1	0			
13676,6	1	0			
13681,55	1	0			
13691,7	1	0			
13696,62	4	0			
13701,58	1	0			
13706,71	4	0			
13711,56	4	0			
13716,69	4	0			
13721,7	4	0			
13726,66	4	0			
13731,64	4	0			
13736,63	1	0			

4.2.4.4 Comparison of simulation output with real data

The comparison of simulation outputs with real data is presented in figure 36. As we can see, the count of DF16 messages is equal. The number of DF0 messages is higher than it should be according to the standards. This is caused by the DF0 messages which were received out of the sequence pattern as described in one of the previous paragraphs. If those messages would not have been received, the number of DF0 would be the same.

The number of received DF17 messages is much higher than it should be according to the simulation output. Hence a further analysis of these messages to explain this inequality must have been done. As well as in situation 2 I have analyzed the binary codes of the received messages and found out that there are the same 3 additional types of extended squitter messages on top of the 3 types which must be transmitted in every situation. These 3 additional types of messages were transmitted only by Aircraft 2 and they are:

- Target State and Status Message,
- Aircraft Operational Status Message and
- Aircraft Status Message.

These types of DF17 messages were already described in situation 2 so as well as in this situation we can suppose the aircraft is equipped with ADS-B ICAO version 1 or 2.

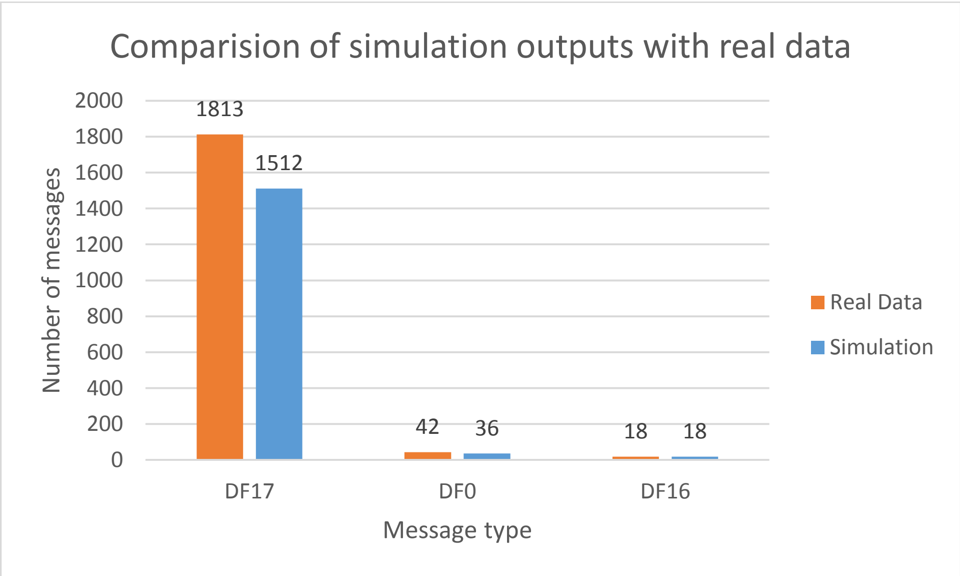

Figure 36 Situation 4: comparison of simulation outputs with real data

The number of simulated Extended Squitter messages after adding the Target State and Status Message, Aircraft Operational Status Message and Aircraft Status Message are shown in figure 37.

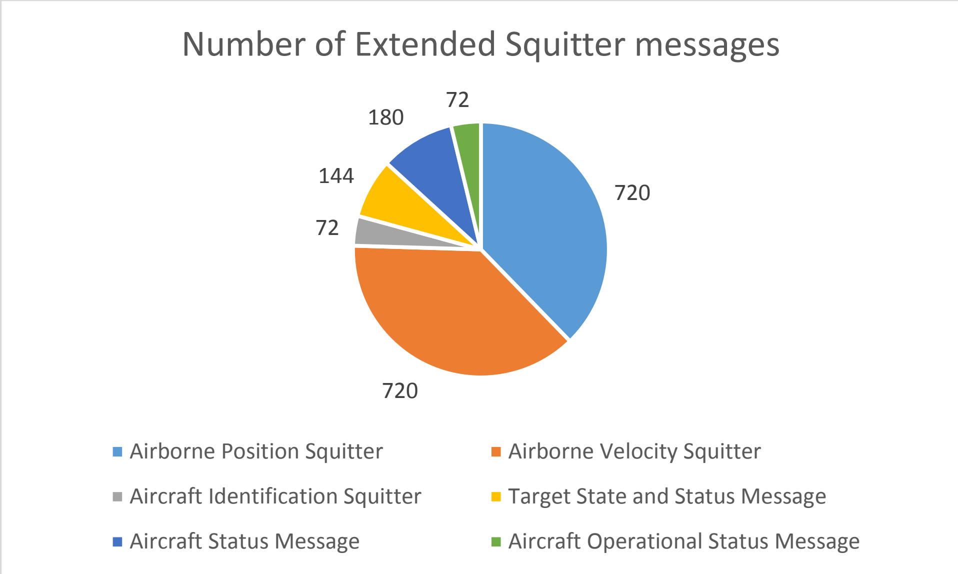

Figure 37 Situation 4: number of all DF17 messages

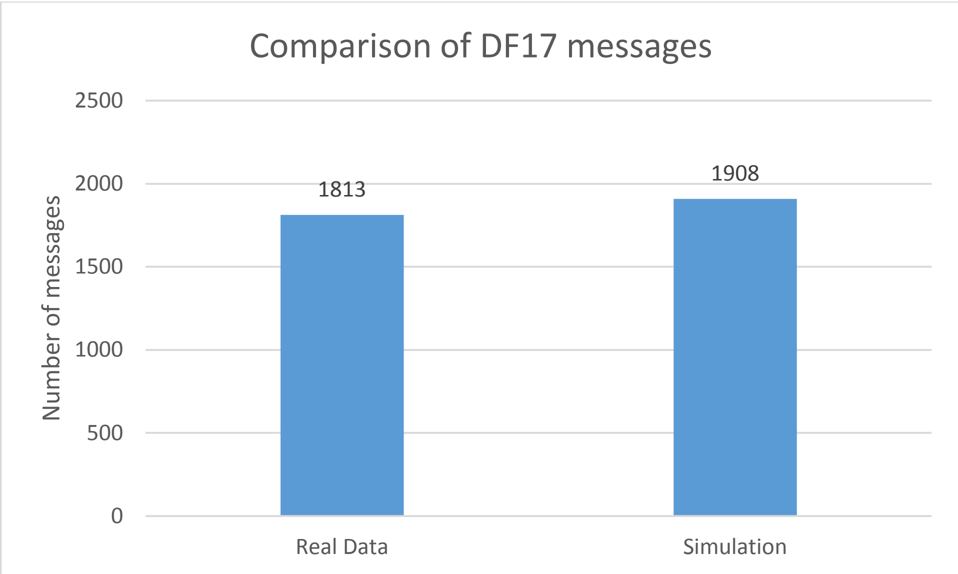

Figure 38 Situation 4: comparison of DF17 messages

From figure 38 it is apparent that we received more than 95 % of all transmitted messages.

4.3 Results

4.3.1 ACAS surveillance range

Technical documentation describes the Maximum ACAS surveillance range as follows:

"TCAS II can simultaneously track up to 30 aircraft, within a nominal range of 14 NM for Mode A/C targets and 30 NM for Mode S targets. In implementations that allow for the use of the Mode S extended squitter, the nominal surveillance range may be increased beyond the nominal 14 NM. However, this information is not used for collision avoidance purposes." [1]

In all situations that had been analyzed, the ACAS surveillance range was higher than 30 NM. In situation 1, the range was even 40 NM and it is possible that it would have been even more than 40 NM if the simulation time had been longer. For this reason I have decided to analyze this parameter on another situation so I can confirm the maximum ACAS surveillance range in low density air traffic is much higher than stated in standards.

The situation is shown in figure 39.

Figure 39 Aircraft situation used for ACAS range determination

The situation starts on the 1st of April at 01:22 CET. I have analyzed the real messages which were received from the aircraft circled in blue and found out that the first replies to interrogations from the aircraft circled in red were sent after 134 seconds (at 01:24:14). The first transmitted replies are shown in table 22. After analyzing the binary codes of the messages, I have identified that the first 3 messages were replies to acquisition transmissions and thereafter the nominal surveillance at a rate of once per 5 seconds started.

Table 22 Real data for ACAS range determination

505C6A		
Time	Receiver	Message
5055,77	1	0
5057,73	1	0
5067,7	1	0
5069,64	1	0
5070,71	1	0
5075,65	1	0
5080,75	1	0
5085,62	1	0
5090,63	1	0

I have used the MATLAB simulation to find out the range between these 2 aircraft at time 01:24:14 when the transmission starts. The aircraft flight paths are shown in figure 40. The simulation time was 134 seconds and thus the aircraft position at the end of simulation is the position when the interrogation starts. According to the simulation, this is almost 65 NM. Therefore I can confirm the ACAS surveillance range in low air traffic density is much higher than it is defined in standards.

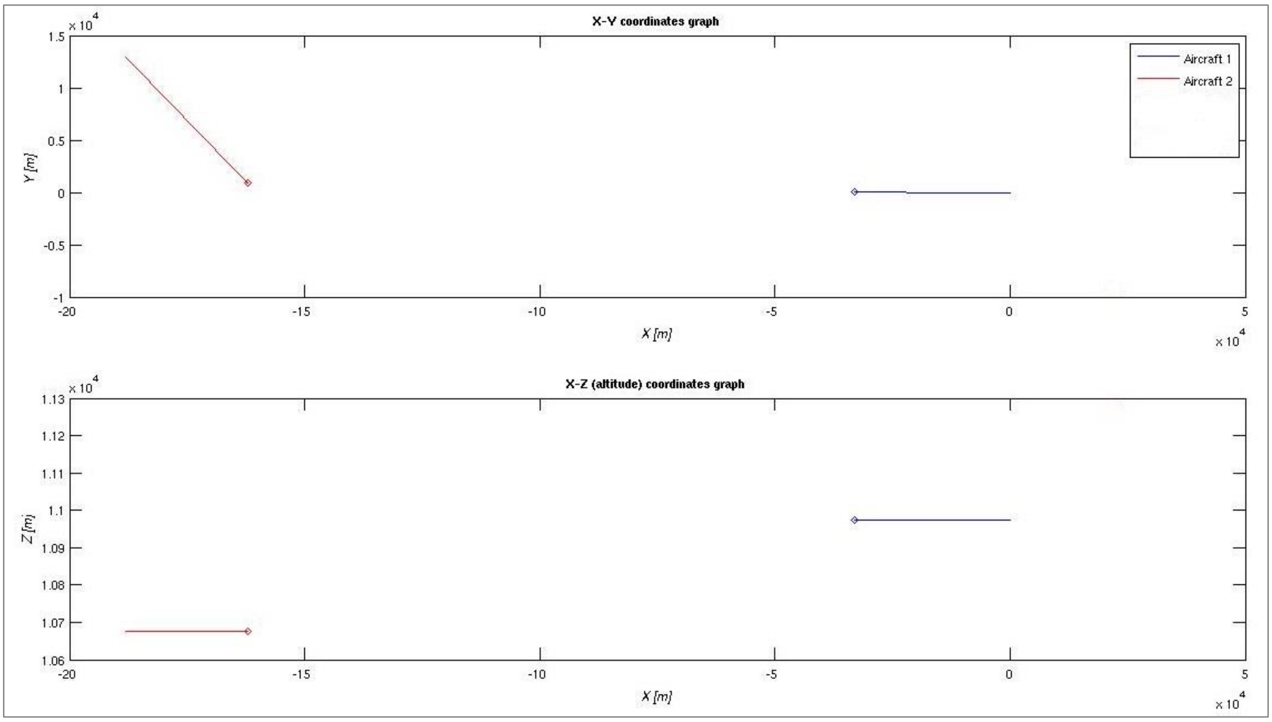

Figure 40 Simulated aircraft flight paths for ACAS range determination

4.3.2 ACAS nominal surveillance rate

If the aircraft (both own and intruder aircraft) are above FL180 and the value of TAU is higher than 60 seconds, the nominal surveillance rate shall be at least 5 seconds.

“All intruders shall be interrogated at least once every five surveillance update intervals. An intruder with a TAU value of equal to or less than 60 seconds shall be interrogated at the nominal surveillance update rate of once every surveillance update interval. An intruder with a TAU value greater than 60 seconds shall be interrogated at a rate of no more than once every five surveillance update intervals if:

a. the tracked barometric altitude of own aircraft is less than 18,000 ft, and

b. the tracked altitude of the intruder aircraft is less than 18,000 ft.” [1]

Therefore, in standards the surveillance rate in this kind of situation is not firmly defined and the decision is left on the manufacturer. In all analyzed situations, there were 4 aircraft which met the criteria of at least once per 5 seconds interrogation rate. All of these aircraft interrogated exactly at the 5 second rate and hence I am able to say that the nominal rate chosen by manufacturers in most of the cases is **5 seconds**.

4.3.3 DF17 messages

If an aircraft is equipped with ADS-B, it shall regularly transmit 3 types of DF17 (extended squitter) messages. These are Aircraft Identification Squitter Message, Airborne Velocity Squitter Message and Airborne Position Squitter Message. In the analyzed situations, there were 9 ADS-B equipped aircraft in total from which the extended squitter messages were received. However, there were another 3 types of DF17 messages which were received from 2 out of the 9 aircraft. These messages were Target State and Status Message, Aircraft Operational Status Message and Aircraft Status Message. The transmission rates and other information about these messages were described in the previous paragraphs. After a deeper analysis which had been done, I found out there are 3 versions of ADS-B. If an aircraft is equipped with ADS-B ICAO version 1 or 2, then it regularly transmits 6 types of DF17 messages. Only aircraft which are equipped with ADS-B ICAO version 0 transmit 3 types of DF17 messages. Taking into account this information I am able to say that 78 % of all analyzed aircraft in this work were ADS-B ICAO version 0 equipped, which is the oldest version from 2000 and only 22 % of all aircraft were either ADS-B ICAO version 1 or ADS-B ICAO version 2 equipped. Those results are based on a very small sample of data (only 9 aircraft) however it pretty well corresponds to the analysis which had been done by another CTU student in his Master's thesis that was focused on ADS-B. He had analyzed more than 8500 aircraft and found out that 76 % of all aircraft were ADS-B ICAO version 0 equipped. [14]

4.3.4 UF0/DF0 acquisition messages

There were 2 situations in the analysis where the acquisition messages had been transmitted. These were situation 3 and then the situation which was used in this chapter to determine the maximum ACAS surveillance range.

"The total number of acquisition interrogations addressed to a single target shall not exceed three within a single surveillance update cycle and a total of nine within the first six surveillance update cycles."

"If additional attempts are made to acquire the target, they shall conform to the pattern described in the requirement above for the first attempt except that:

a. On the second and third attempt, only one interrogation is made during each single surveillance update interval; and in the absence of valid replies, six interrogations are transmitted during the first six surveillance update intervals.

b. Any further attempts consist of a single interrogation during the entire six surveillance update intervals." [1]

Referring to the example in the situation used to determine the ACAS surveillance range (table 18), we can see that 3 acquisition replies were sent. The first 2 messages were transmitted in the same surveillance update interval, while the last one in a different one. In the table there is one message which is not the acquisition reply nor a message from the surveillance rate pattern. The presence of this message can be probably explained as follows.

"Following successful receipt of a valid acquisition reply from an airborne aircraft, one or more additional interrogations shall be transmitted to the target in order to confirm the reliability of the altitude data and the altitude quantization bit and to determine whether to establish track." [1]

The example in situation 3 is not that clear. There is quite a lot of acquisition reply messages in table 14. This was probably caused by an aircraft flying at the boundary of the ACAS surveillance range of the 2 aircraft being analyzed. Anyway, all the acquisition messages as well as the additional interrogations conform to the citation above and thus it is possible to say that the transmission of DF0 acquisition messages in these 2 examples is in conformity with the standards.

4.3.5 Aircraft equipment

If we take only the 4 situations described in the previous chapter into account, 9 aircraft were analyzed. The age of these aircraft ranges between 2 months and 18 years. It is still not mandatory for aircraft operators in Europe to have their aircraft equipped with ADS-B, however this will become mandatory in 2020.

"5. Operators shall ensure that by 7 June 2020 at the latest:

(b) aircraft with a maximum certified take-off mass exceeding 5 700 kg or having a maximum cruising true airspeed capability greater than 250 knots, operating flights referred to in Article 2(2), are equipped with secondary surveillance radar transponders having, in addition to the capabilities set out in Part A of Annex II, the capabilities set out in Part B of that Annex;" [9] [10]

In spite of this fact, all of these aircraft (100 %) were ADS-B equipped.

6 of the analyzed aircraft were hybrid surveillance capable (66.7 %). According to all the concerned aircraft, the ACAS hybrid surveillance capability does not depend on the age of aircraft. Hence it cannot be said that most of the newly manufactured aircraft are ACAS hybrid surveillance capable. Anyway, nowadays it is not at all mandatory for commercial aircraft to have ACAS hybrid surveillance capability.

“Hybrid surveillance is a method that decreases the number of Mode S surveillance interrogations made by an aircraft's TCAS II unit. This feature, new to TCAS II version 7.1, may be included as optional functionality in TCAS II units.” [4]

5 Proposal of amendments to the official ACAS surveillance algorithms

In this chapter I would like to propose amendments to the official ACAS surveillance algorithms. The objective of the amendments is to lower the 1030/1090 MHz radio frequency saturation. The safety aspects of these amendments will be taken into account but it is not the scope of this work to prove them using a model or any other kind of sophisticated approach. Therefore the results of this chapter should be considered only as a guidance of how the surveillance algorithms could be amended in order to lower the frequency saturation. A further and deeper study of all the aspects would have to be done to confirm that these amendments could be safely deployed into the real systems.

The amendments will be based on the analysis which was done in previous chapters. It is necessary to say that the real surveillance algorithms were invented by experts in this field and they also have been tested many times before they were deployed. For this reason it is not easy to suggest changes which would enhance the system's functionality.

I would like to introduce one major amendment that I think would be beneficial for lowering the frequency saturation. As mentioned earlier in this document, the surveillance rate of UF0/UF16 hybrid surveillance validation messages depends on equations (VIII) and (IX). Referring to these equations, the surveillance rate can be either once per second, once per 10 seconds or once per 60 seconds. On the other hand, if the aircraft are not equipped with hybrid surveillance capable ACAS, the surveillance rate is either once per second, once per 5 seconds or once per 10 seconds, depending on the conditions described in previous chapters. It is evident that the surveillance rates in these 2 types of interrogation (once per second) are identical when the aircraft are close enough, so there is a higher risk of collision. However, if the aircraft are more distant so there is no immediate risk of collision, and this happens in most of the cases, the surveillance rates are quite different. In case of hybrid surveillance, there is less interrogation. This is understandable since the aircraft get the position information regularly in the extended squitter messages. Nevertheless, I believe that the surveillance rates could be set to interrogate less frequently also in case of aircraft which are not hybrid surveillance capable. I would propose to set the interrogation rates according to equations (XI), (XII) and (XIII).

$$|a| \leq 10000\,ft \wedge \left\{ \left(|a| \leq 3000\,ft \vee \frac{|a - 3000\,ft|}{|\dot{a}|} \geq 80s \right) \vee \left(r \leq 3NM \vee \frac{r - 3NM}{|\dot{r}|} \geq 80s \right) \right\} \quad \text{(XI)}$$

$$|a| \leq 10000\,ft \wedge \left\{ \left(|a| \leq 3000\,ft \vee \frac{|a - 3000\,ft|}{|\dot{a}|} < 80s \right) \vee \left(r \leq 3NM \vee \frac{r - 3NM}{|\dot{r}|} < 80s \right) \right\} \quad \text{(XII)}$$

$$|a| \leq 10000\,ft \wedge \left\{ \left(|a| \leq 3000\,ft \vee \frac{|a - 3000\,ft|}{|\dot{a}|} \leq 60s \right) \wedge \left(r \leq 3NM \vee \frac{r - 3NM}{|\dot{r}|} \leq 60s \right) \right\} \quad \text{(XIII)}$$

Where:

a is intruder altitude separation in feet.

ȧ is altitude rate in feet/second.

r is intruder slant range in NM.

ṙ is range rate in NM/second.

If equation (XI) is met, that means that both equations in the brackets are higher than 80 seconds, the surveillance rate is once in 10 seconds. Since the aircraft would be far enough from each other in this case, this surveillance seems to be sufficient and safe even without position information received in extended squitter messages.

If equation (XII) is met, the surveillance rate is once in 5 seconds. Finally, if the last equation (XIII) is met, the surveillance rate is once per second.

Another change would be if the aircraft altitude separation was higher than 10000 feet. In such a case, I would propose to set the surveillance rate to once per 15 seconds, compared to once in 10 seconds as it is set in systems which are nowadays deployed.

The consequences of these amendments will be now analyzed and compared in an example.

5.1 Example

I will use the MATLAB simulation to simulate a fictional air traffic situation. The same situation will be simulated with the standardized ACAS surveillance algorithms as well as with the amended algorithms described in this chapter. The results will be compared so the effect of the amendments on the frequency saturation can be discussed.

The air traffic situation consists of 5 aircraft. Their initial conditions and equipment are stated in table 23. The duration of the simulation is 180 seconds, the ACAS surveillance range was set to 40 NM and the nominal surveillance for simulation using standardized algorithms is 5 seconds. The situation (aircraft flights) is illustrated in figure 41.

Table 23 Aircraft initial conditions

Initial conditions	Aircraft 1	Aircraft 2	Aircraft 3	Aircraft 4	Aircraft 5
x-coordinate	0	25	-27	8	5
y-coordinate	0	0	-10	12	10
Altitude [ft.]	41000	36000	37000	31000	20000
Velocity [kt.]	480	450	389	415	376
Heading	0	180	10	17	197
ADS-B	•	•	•	•	•
HS		•		•	

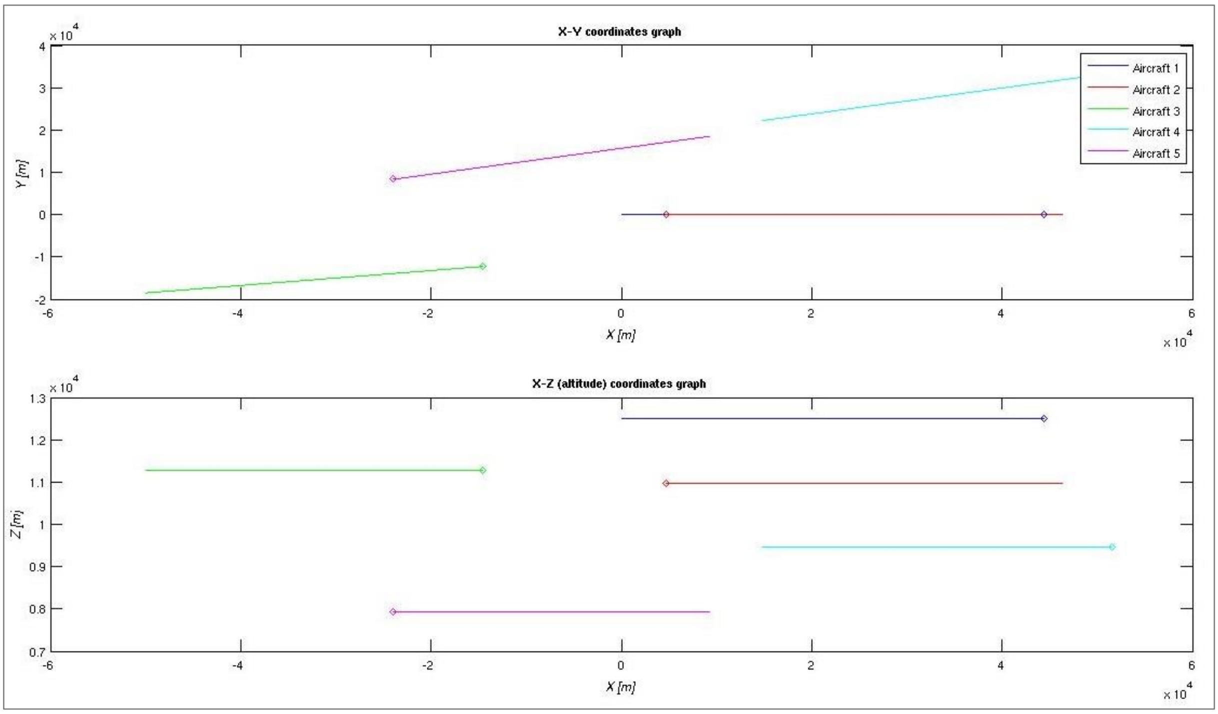

Figure 41 Situation overview

The results are presented in figure 42. Since hybrid surveillance algorithms were not amended, only the number of transmitted DF0 messages is different. As apparent, if the system works according to the amended ACAS surveillance algorithms, the number of transmitted DF0 messages is lower. In case of this fictional air traffic situation the number of DF0 messages is lowered by 45 % which fundamentally relieves the 1030/1090 MHz radio frequency saturation.

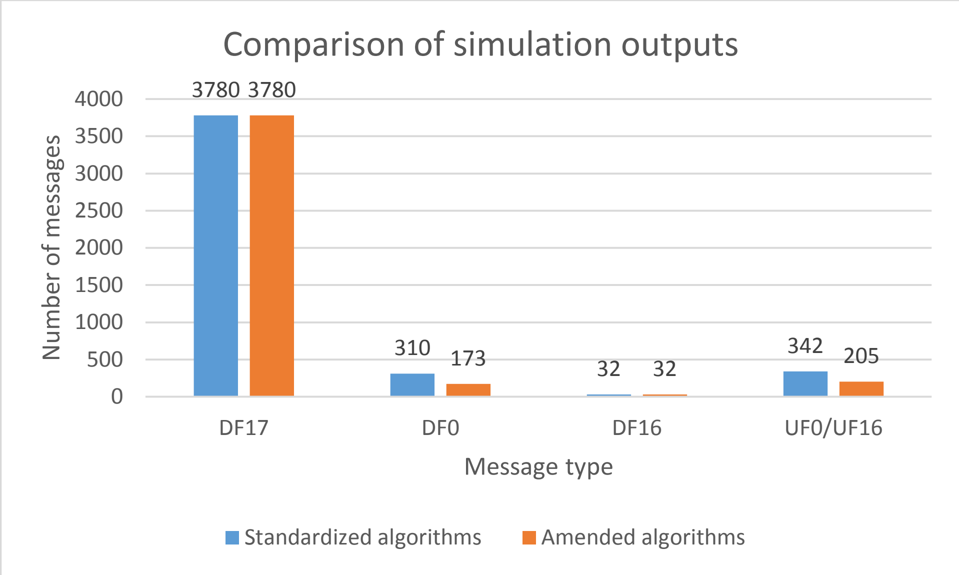

Figure 42 Comparison of simulation outputs

6 Conclusion

The volume of air traffic is constantly rising and this trend is not forecast to change in the nearest future if there are no unexpected circumstances. Hence it is important that the communication, navigation and surveillance systems maintain their functionality at the highest safety level and with the highest reliability also in dense areas.

The surveillance infrastructure in aviation mostly uses only one common radio frequency band, which is RF 1030/1090 MHz and thus the vast majority of transmissions for surveillance purposes are sent via this frequency. Since air traffic in some areas is becoming extremely dense, it may happen that this RF gets oversaturated. As a result of this saturation the air traffic controllers could simply lose the aircraft on the radar screen which could lead to an accident.

The transmissions which are sent via RF 1030/1090 MHz can be divided as ground-to-air transmissions, air-to-ground transmissions and air-to-air transmissions. The topic of this work was airborne collision avoidance system, which uses air-to-air messages to interrogate other aircraft in order to avoid a possible collision.

The aim of this Master's thesis was to analyze real ACAS surveillance parameters in order to find out whether the real system works according to the technical standards and how much the ACAS air-to-air messages contribute to the overall radio frequency saturation. The transmission rates of these messages are standardized and made in a way that the system has the position data of all aircraft in vicinity long before a possible collision is detected. However, not all transmission rates and other surveillance parameters are firmly defined in the standards and thus it is left to the system's manufacturer to set up those parameters. In this work I created a MATLAB/Simulink simulation of the ACAS surveillance function using surveillance parameters based on the standards. Next, I analyzed real ACAS messages that have been received by ADS-B receivers owned by the Czech Technical University in Prague. This simulation allowed me to simulate real air traffic situations and therefore I could compare the simulation outputs with real messages received by the ADS-B receivers. Using the compared data I was able to discuss whether the real surveillance function really works according to the standards, and point out some probable differences, if any. I could also analyze the parameters not firmly defined in standards. In this work I described 4 air traffic situations in detail, but the analysis was based on more situations. However, the length constraints of this thesis did not allow for them to be commented.

The simulation part consists of an aircraft model created in Simulink, and the ACAS surveillance function programmed in MATLAB. The aircraft model sends its position data to the surveillance function, where this data is used to define ranges among all the modeled aircraft and also to define surveillance rates. The outputs of the simulation are plots showing the number of different transmitted messages during the entire simulation.

Having applied the approach described in the previous paragraphs I was able to analyze some of the ACAS surveillance parameters and finally present the results. Those parameters were ACAS surveillance range, nominal surveillance rate, transmission rates of UF0/DF0 acquisition messages, types of transmitted DF17 messages and I also tried to find out whether there is a relation between the aircraft age and its equipment used for air-to-air interrogations. While some of the results were quite surprising, such as ACAS surveillance range which was found to be much higher than the one defined in standards or different ICAO versions of ADS-B and its corresponding DF17 messages which were transmitted, some of the parameters just confirmed my expectations, such as the nominal surveillance rate, which was found to be 5 seconds even if the standard does not firmly define it.

In the last part of this Master’s thesis I tried to suggest some amendments to the official ACAS surveillance algorithms which could be potentially beneficial for lowering the 1030/1090 MHz radio frequency saturation. I also added those changes into the MATLAB code so I could compare the number of transmitted messages to the current surveillance algorithms. The results were then presented in the form of a graph.

Regardless of how much I tried to make the aircraft model and the surveillance function simulation realistic, it was necessary to apply a couple of simplifications. In case of the aircraft model the applied simplifications are not crucial for the functioning of the ACAS surveillance algorithms. The simplifications to the surveillance function simulation must be taken into account when simulating a complex air traffic situation, as there are two parameters which are not included and this could influence the results. The simulation does not include traffic and resolution advisories and it does not have a script for situations when the aircraft are too close to each other, in which case the surveillance rate must change to once per second. Nonetheless, when working on this thesis and analyzing the real data, I did not encounter any situation which would require the simulation to have these scripts. Anyway, in some other situations this could be required.

This work brings forward some important ACAS surveillance parameters which should be deeply analyzed and possibly amended in order to maintain the RF 1030/1090 MHz unsaturated and safe for its usage in the future. It is based on the theoretical description already done in my Bachelor’s thesis, and I believe that also this thesis can be used as a basis for further works. Especially the parameters such as ACAS surveillance range and UF0/DF0 acquisition messages would require further analysis in more situations. There was not enough space in this work to analyze all those parameters in a sufficient number of air traffic situations, as each of the parameters would require to be studied in a single work.

I also believe that the MATLAB simulation can be used by other students working on this project in the future, e.g. for analyzing purposes of the parameters stated in the previous paragraph. It is possible to use the aircraft Simulink model separately for other purposes and thus it can serve as a basis for different aviation simulations.

7 References

[1] RTCA/DO-185A: SC-147. *Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II)*. [PDF]. 2007. RTCA, Inc.

[2] RTCA/DO-260B. *Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Services – Broadcast (TIS-B)*. [PDF]. 2009. RTCA, Inc.

[3] MINISTRY OF TRANSPORT OF THE CZECH REPUBLIC. *Předpis L10 – O civilní letecké telekomunikační službě, svazek IV – Přehledový radar a protisrážkový systém, svazek IV.* [ONLINE]. 2016. [2018-01-29]. Available from: https://lis.rlp.cz/predpisy/predpisy/index.htm

[4] EUROCONTROL. *ACAS Guide - Airborne Collision Avoidance*. [PDF]. 2017.

[5] ORLANDO, Vincent. *Proposed Revisions to Appendix A for 1090 TIS-B and ADS-B MASPS Changes*. [PDF]. 2002.

[6] VOJTĚCH, Vít. *Monitorování vysílání palubních SSR odpovídačů v reálném prostředí*. Praha, 2017. Master's thesis. Czech Technical University in Prague.

[7] NOSEK, Jakub. *Modelování množství přenosů generovaných systémem ACAS v reálném prostředí*. Praha, 2016. Bachelor's thesis. Czech Technical University in Prague.

[8] MATHWORKS. *MATLAB for Deep Learning*. [ONLINE]. [2017-11-19]. Available from: https://www.mathworks.com

[9] EUR-Lex. *Commission Implementing Regulation (EU) No 1207/2011 of 22 November 2011 laying down requirements for the performance and the interoperability of surveillance for the single European sky*. [ONLINE]. 2011. [2018-03-29]. Available from: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32011R1207

[10] EUR-Lex. *Commission Implementing Regulation (EU) 2017/386 of 6 March 2017 amending Implementing Regulation (EU) No 1207/2011 laying down requirements for the performance and the interoperability of surveillance for the single European sky*. [ONLINE]. 2017. [2018-03-19]. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.059.01.0034.01.ENG&toc=OJ:L:2017:059:TOC

[11] PLANEFINDER.NET. [ONLINE]. 2018. Available from: https://planefinder.net

[12] ICAO. *Doc 9871, Technical Provisions for Mode S Services and Extended Squitter, Advanced edition (unedited).* [PDF]. ND.

[13] PLENINGER, Stanislav. *Acas_2.7_153: Palubní protisrážkový systém ACAS*. 2013. Study material for CNS systems students. Czech Technical University in Prague, Faculty of Transportation Sciences.

[14] TÉSI, Simon. *Analýza indikátorov kvality v ADS-B správach*. Praha, 2016. Master's thesis. Czech Technical University in Prague.

[15] JUNZI, Sun. *The 1090 MHz Riddle (An open-access book about decoding Mode-S and ADS-B data)*. [ONLINE]. ND. [2018-04-04]. Available from: http://mode-s.org/

[16] ARRIVE Pierre, NOSEK Jakub, KALFON Vincent. *Analysis and modelling of TCAS*. Toulouse, 2016. Project report. Ecole Nationale de l'Aviation Civile. Project tutor: MIQUEL Thierry.

8 List of figures

9 List of tables

10 Attachments

All attachments are provided on attached CD. This CD includes the following files:

ACAS_simulation.zip

- Simulink aircraft model AC_model_simulink.slx
- Script initial_conditions.m
- Script main_file.m
- Function range_calculation.m
- Function modeS_AQ.m
- Function modeS_ES.m
- Function modeS_ADSBHS.m
- Function ModeC.m
- Function other_messages.m
- Function Number_of_messages.m
- Function aircraft_plot.m
- Function messages_plot.m

ACAS_simulation_AMENDED.zip

- Simulink aircraft model AC_model_simulink.slx
- Script initial_conditions.m
- Script main_file.m
- Function range_calculation.m
- Function modeS_AQ.m
- Function modeS_ES.m
- Function modeS_ADSBHS.m
- Function ModeC.m
- Function other_messages.m

- Function Number_of_messages.m
- Function aircraft_plot.m
- Function messages_plot.m