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FACULTY OF TRANSPORTATION SCIENCES

Dominika Fonferová

Alternative Navigation Solution for GNSS Backup in Remote Areas

Bachelor Thesis

2020

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

(PROJEKTU, UMĚLECKÉHO DÍLA, UMĚLECKÉHO VÝKONU)

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Zásady pro vypracování

Při zpracování bakalářské práce se řiďte následujícími pokyny:

- Cílem práce je vytvoření modelu alternativního navigačního řešení rozšiřující využití terestriálních konceptů jako zálohy GNSS nad oceánem či odlehlých oblastech bez vybavení pozemní infrastruktury
- Zdroje výpočtu polohové informace při výpadku GNSS a požadavky na navigační výkonnost nad oceány
- Aplikace výměny zpráv mezi letadly jako rozšíření konceptu alternativních navigačních systémů
- Návrh modelu rozšiřující využití terestiálních konceptů
- Ohodnocení modelu pro využití jako alternativní řešení při výpadku GNSS

Rozsah grafických prací: dle pokynů vedoucího bakalářské práce

Rozsah průvodní zprávy: minimálně 35 stran textu (včetně obrázků, grafů a tabulek, které jsou součástí průvodní zprávy)

Seznam odborné literatury: Letecký předpis L10 - O Civilní letecké telekomunikační službě

ICAO Doc 9613 - Performance-based Navigation Manual

ICAO Doc 9924 - Aeronautical Surveillance Manual

Vedoucí bakalářské práce: **Ing. Petr Lukeš**

Ing. Stanislav Pleninger, Ph.D.

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b) v případě odkladu odevzdání práce následující datum odevzdání práce vyplývající z doporučeného časového plánu studia

L. S.

Kraus

doc. Ing. Jakub Kraus, Ph.D.
vedoucí
Ústavu letecké dopravy

doc. Ing. Pavel Hrubeš, Ph.D.
děkan fakulty

Potvrzuji převzetí zadání bakalářské práce.

Fonferová

Dominika Fonferová
jméno a podpis studenta

V Praze dne 28. srpna 2020

Poděkování

Na tomto místě bych ráda poděkovala všem, kteří mi poskytli podklady a odborné rady pro zpracování této práce. Nejvíce bych chtěla poděkovat vedoucímu bakalářské práce Ing. Petru Lukešovi za velkou trpělivost, vstřícnost, cenné rady a za neskutečné množství času investovaného do konzultací. Mé velké poděkování patří také Ing. Tereze Topkové za nasměrování k tématu práce, poskytnuté materiály, přínosný rok strávený pod jejím vedením v Laboratoři ATM a čas strávený konzultacemi, a především za neustálou motivaci. V neposlední řadě patří poděkování mým rodičům a všem blízkým za jejich podporu.

Prohlášení

Předkládám tímto k posouzení a obhajobě bakalářskou práci, zpracovanou na závěr studia na ČVUT v Praze Fakultě dopravní.

Prohlašuji, že jsem předloženou práci vypracovala samostatně a že jsem uvedla veškeré použité informační zdroje v souladu s Metodickým pokynem o etické přípravě vysokoškolských závěrečných prací.

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ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

FAKULTA DOPRAVNÍ

KONCEPT NAVIGAČNÍHO ŘEŠENÍ V ODLEHLÝCH OBLASTECH JAKO ZÁLOHA GNSS

Dominika Fonferová

Bakalářská práce

2020

Abstrakt

Předmětem této bakalářské práce je vytvoření a ohodnocení alternativního navigačního modelu rozšiřující využití terestriálního pokrytí jako záloha GNSS nad oceánem nebo v odlehlých oblastech bez vybavení pozemní infrastruktury. Byly vytvořeny dva modely pro stanovení polohy letadel, založené na výměně signálů mezi okolními letadly. Modely se liší v přístupu k výběru referenčních letadel, což vyúsťuje v rozdílné výsledky z pohledu přesnosti. Oba modely byly vyhodnocené za stejných podmínek aplikováním metody Monte Carlo.

Klíčová slova

Výpadek GNSS, Alternativní navigační prostředky, Navigační model, DME,
RNAV, RNP, APNT, LORAN

CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF TRANSPORTATION SCIENCES

ALTERNATIVE NAVIGATION SOLUTION FOR GNSS BACKUP IN REMOTE AREAS

Dominika Fonferová

Bachelor Thesis

2020

Abstract

The objective of this bachelor thesis is to design and evaluate an alternative navigation model extending the use of the terrestrial coverage as a GNSS backup in the oceanic or remote continental airspace without any ground infrastructure. Two models have been developed for the position determination of aircraft based on the exchange of signals among aircraft in surroundings. The models differ in the approach of the selection of referential aircraft, that derive in different results concerning the accuracy. Both models have been evaluated under the same testing scenario by applying the Monte Carlo simulation method.

Keywords

GNSS Interference, Alternative Navigation Means, Navigation Model, DME,
RNAV, RNP, APNT, LORAN

Table of Contents

Abbreviations

1090 ES	1090 MHz Extended Squitter
2DRMS	Twice the Distance Root Mean Square
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance Broadcast
ADS-C	Automatic Dependent Surveillance Contract
AFI	Africa and Indian Ocean Region (ICAO)
APNT	Alternative Navigation, Positioning and Timing
ATC	Air Traffic Control
ATM	Air Traffic Management
CNS	Communication, Navigation and Surveillance
DME	Distance Measuring Equipment
eLORAN	Enhanced Long Range Navigation
ENU	East North Up
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
INS	Inertial Navigation System
LORAN	Long Range Navigation
NaN	Not a Number
NAT	North Atlantic
NAT HLA	North Atlantic High Level Airspace
NM	Nautical Mile
PSR	Primary Surveillance Radar
RA	Resolution Advisory
RNAV	Area Navigation

RNP	Required Navigation Performance
SATCOM	Satellite Communications
TA	Traffic Advisory
TCAS	Traffic Collision Avoidance System

1 Introduction

The Global Navigation Satellite System (GNSS) is a widely used system, especially in oceanic and remote areas, as there is no ground-based radar coverage. Therefore, the GNSS outage and interference represent a serious threat to the safety of the air traffic. This is the reason why there is a necessity of developing new concepts, to secure a seamless traffic. And that is also the reason of focusing on the Alternative Positioning, Navigation and Timing Systems (APNT) to come up with possible applicable solutions. The currently used navigation systems and methods have been evaluated to ideally come up with a solution based on some of the systems which are already in use.

The GNSS provides positioning and timing information for aircraft and air traffic management systems. It is important for safety and efficiency of flights, for example during reduced visibility conditions. The GNSS is also a main component of important systems, such as communication, navigation and surveillance (CNS) systems, but also flight safety and flight control systems. It is also essential for navigation in oceanic and remote areas. The GNSS is as well important for air traffic management (ATM) and air traffic control (ATC) operations, since aircraft position input from GNSS is necessary for automatic dependent surveillance broadcast (ADS-B). Despite the GNSS benefits, the system is quite vulnerable. As the GNSS signal travels from satellites to receivers on Earth, the received signal is not strong enough and is therefore more susceptible to intended or unintended radio frequency interference. Therefore, APNT systems are crucial in the case of GNSS outage. [1] [2] [3]

The goal of the thesis is to propose an alternative navigation solution extending the terrestrial concepts as the GNSS backup in the oceanic or remote continental airspace without any ground infrastructure (the nonradar area). Another goal is to define the sources for the computing aircraft's position in case of the GNSS failure and apply the requirements for the navigation performance in the oceanic areas and to describe the exchange of information among aircraft in the surroundings beyond the line of sight of the ground stations. The practical part involve d designing a model which extends the usage of terrestrial concepts and later evaluates the proposed model as a possible alternative solution in case of the GNSS outage.

The thesis is divided into two parts, the theoretical and the practical. The theoretical part is focused on the description of requirements in the oceanic and remote areas, the next chapter describes the currently used navigation and surveillance systems. After that, a short chapter deals with the GNSS outage and related accidents. The practical part consists of description of methodology used for model design and evaluation of the model. Based on the methodology, the model is proposed. The model proposal deals with the description of the created models, the necessary criteria used and the simulation itself.

2 Requirements in Remote Areas

The navigation in oceanic and remote continental airspace has specific requirements. Mainly, the airspace s a nonradar area, which means there is no ground-based radar coverage. This area can be considered as “procedural airspace”. Air traffic services are mainly focused on providing procedural control and procedural separation to all flights. Clearances and instructions are issued based on the aircraft equipment authorizations to ensure vertical and horizontal separation. The reliability of aircraft’s reported position is not as high as under the radar control, therefore the distances between aircraft are bigger. [4]

Two currently used navigation applications in oceanic and remote continental airspace, relying mostly on Global Navigation Satellite System (GNSS) are area navigation 10 (RNAV 10) and required navigation performance 4 (RNP 4). [5]

Even though RNAV and RNP have similar characteristics, there is quite a significant difference in terms of the requirements for on-board performance monitoring and alerting. A RNP specification represents a navigation specification including a requirement for on-board navigation performance monitoring and alerting, whereas a RNAV specification represents navigation without these requirements. A RNP system is a RNAV, that fulfils requirements of the RNP specification. [5]

RNP specifies standards of aircraft navigation accuracy, equipment, and flight crew training. The accuracy, integrity, continuity, availability, and functionality evaluate these standards. According to RNP 10, an aircraft must be able to remain within 10 nautical miles (NM) of centerline 95 % of the time and 20 NM of centerline 99.999 % of the time. RNP 4 demands an aircraft to remain within 4 NM of centerline 95 % of the time and within 8 NM 99.999 % of the time. [4]

Performance-Based operations depend on Required Communication Performance, Required Navigation Performance (RNP), and Required Communication Performance. [4]

3 Currently Used Systems in the Remote Areas

3.1 Airborne Collision Avoidance System (ACAS)

Airborne Collision Avoidance System (ACAS) provides advice to the pilot on potential conflicting aircraft, that are equipped with Secondary Surveillance Radar (SSR) transponders (operating in Mode C or Mode S). It is an aircraft system that is based on SSR transponder signals. The operation of the system does not depend on ground-based equipment. It works as a backup collision avoidance service for the air traffic control system. [6][7] The implementation of ACAS is called Traffic collision avoidance system (TCAS). [8] ACAS has antenna diversity – two mounted antennas, one at the top, the other one at the bottom. [9]

ACAS II is mandatory in the Africa and Indian Ocean Region (AFI) and in the North Atlantic (NAT) region for every civil fixed-wing turbine-engine aircraft that has a maximum takeoff mass exceeding 5 700 kg or maximum approved passenger seating configuration of more than 19. [10] [11]

ACAS surveillance electronics, see Figure 1, which is located in the aircraft, periodically interrogates and receives replies from Mode A/C and Mode S transponders on other aircraft in the surroundings. The transponders installed on the interrogated aircraft receive the signals and send back their replies. If it is a Mode C transponder, it replies with its altitude. In the case of Mode S transponder, the reply contains its altitude and unique aircraft address. Based on the replies, ACAS evaluates possible collision threats by computing the range of the intruder with the usage of the time difference between the transmission of the interrogation and the receipt of the reply. In order to determine if the aircraft is a threat; altitude, range and bearing from the reply information are evaluated by the threat detection logic in the ACAS computer. If the intruder represents a possible impending collision then to minimise the risk of the collision, a vertical manoeuvre or vertical manoeuvre restriction is set by the computer threat resolution logic. Every single intruder is evaluated individually, which allows selecting a resolution advisory based on track data. The flight crew is then informed by display advisories to evade the potential collision.

Mode S Transponder is carried on all ACAS-equipped aircraft. Its tasks are to perform the functions of Mode A/C transponders and to provide Mode S air-to-air communications. The Mode S transponder can also communicate with a ground-based Mode S sensor in terms of surveillance and data link purposes. [12] [13]

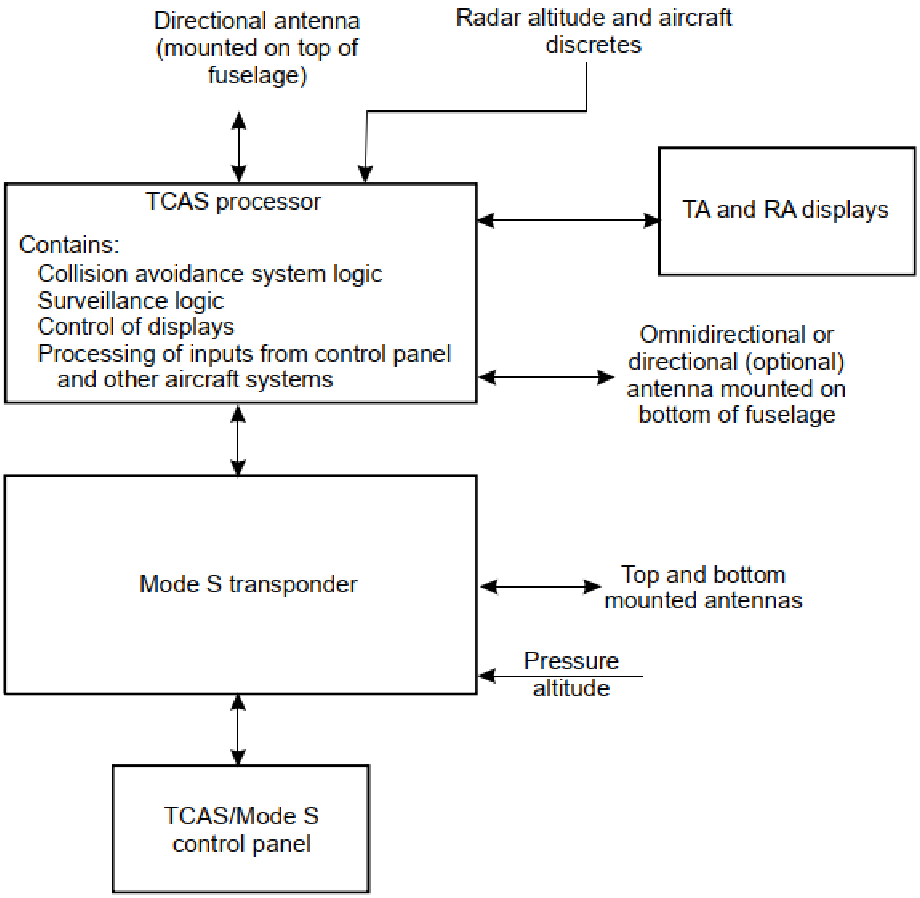


Figure 1. ACAS Components [12]

ACAS can issue two types of advisories (alerts). First one, called traffic advisories (TAs), shows the possible endangering aircraft (potential threats). If the aircraft gets even closer, the second, resolution advisories (RAs), will be displayed indicating vertical manoeuvres or vertical restrictions, which will lead to maintaining or increasing the vertical separation from the threatening aircraft. Warning time of TAs is longer than the one of RAs. It is not necessary for the threatening aircraft to be equipped with ACAS. But in case that the intruding aircraft also has ACAS that can generate resolution advisories, a procedure to ensure that both RAs are compatible is performed using the air-to-air Mode S data link. Aircraft without transponders or with non-operational transponders are not detected by ACAS. [12] [13]

TAs function as a precursor to RAs. RAs recommend actions, such as manoeuvres.

There are three generations of ACAS: ACAS I, ACAS II and ACAS III. ACAS I does not provide RAs. Resolution advisories of ACAS II do not show horizontal escape manoeuvres. [12]

3.2 Automatic Dependent Surveillance (ADS)

Automatic dependant surveillance (ADS) is a system which allows aircraft to automatically transmit and/or receive data through a data connection. [14] Two versions of ADS are currently in use, ADS Contract (ADS-C) and ADS Broadcast (ADS-B). GNSS provides position information, that is used by ADS-B and ADS-C. [15]

3.2.1 Automatic Dependent Surveillance – Contract (ADS-C)

Automatic dependant surveillance Contract (ADS-C) is a point-to-point transmission. Aircraft transmits data based on defined plan or contract. ADS-C is used in remote or oceanic areas using Satellite Communications (SATCOM), where an installation of radar or ADS-B ground station is not an option. ATC receives GNSS position reports from ADS-C via satellite at significant points or time intervals specified in a contract. Usage of ADS-C has allowed to reduce separation standards in some oceanic and non-radar areas. [9] [14] [16]

ADS-C position reports are composed from the data blocks listed below. The only mandatory block is the “Basic ADS-C”. [15]

- Aircraft Identification
- Basic ADS-C
  - Latitude
  - Longitude
  - Altitude
  - Time
  - Figure of Merit
- Ground Vector
  - Track
  - Ground Speed
  - Rate of Climb or Descent
- Air Vector
  - Heading
  - Mach or Indicated Airspeed (IAS)
  - Rate of Climb or Descent
- Projected Profile
  - Next Waypoint
  - Estimated Altitude at Next Waypoint
  - Estimated Time at Next Waypoint
  - (next + 1) Waypoint
  - Estimated Altitude at (next + 1) Waypoint

        - Estimated Time at (next + 1) Waypoint
- Meteorological Information
    - Meteorological Information
    - Wind Speed
    - Wind Direction
    - Wind Quality Flag (if available)
    - Temperature
    - Turbulence (if available)
    - Humidity (if available)
- Short-term Intent
    - Latitude at Projected Intent Point
    - Longitude at Projected Intent Point
    - Altitude at Projected Intent Point
    - Time of Projection

3.2.2 Automatic Dependent Surveillance – Broadcast (ADS-B)

Automatic dependent surveillance Broadcast (ADS-B) transmits data automatically within a specific range. ADS-B depends on GNSS position, velocity and other on-board data broadcasted by aircraft. Everything that is located within the range can receive the transmitted data. ADS-B can be used instead of a radar in certain low traffic density areas. ADS-B ground stations are not as pricey as radars. Aircraft ADS-B data are received and processed by the ground stations and used on controller situation displays. ADS-B has been implemented in several areas without radar coverage, which has allowed to reduce aircraft separation and therefore increasing the capacity of airspace. ADS-B uses antenna diversity, that means two mounted antennas, one at the top, the other one at the bottom. Its purpose is an improvement of the transmission and reception capabilities. [9] [14] [16]

ADS-B has two functions, ADS-B OUT and ADS-B IN. ADS-B OUT is a function which periodically transmits its horizontal and vertical position and also another information taken from on-board systems. Those messages are received by ADS-B IN, which process them and display them to the crew. It is possible for an aircraft to be equipped only with ADS-B OUT without ADS-B IN. [14] [16]

There are currently three ADS-B transmission technologies: 1090 Extended Squitter (1090 ES), Very High Frequency (VHF) Data Link – Mode 4 (VDL-Mode 4) and Universal Access Transceiver (UAT). The VDL-Mode 4 and UAT will not be further mentioned, since the 1090 ES is the most globally developed one in terms of operations. [14]

1090 ES is a spontaneous periodic transmission. It transmits 1090 MHz 112-bit Mode signal format. It contains 56 bits of additional information. [9]

3.3 Long Range Navigation (LORAN)

The Long-Range Navigation (LORAN) system is a terrestrial, low frequency hyperbolic radio navigation system. LORAN has various forms, LORAN-A, LORAN-C, eLORAN. This subchapter will cover LORAN-C and eLORAN. [17] [18] [19]

Signal's long range and easy integration of barometric altimeter for vertical navigation are considered as some of the LORAN's advantages. [18]

3.3.1 Enhanced LORAN (eLORAN)

An enhanced Long-Range Navigation (eLORAN) system is considered as an Alternative Navigation, Positioning and Timing (APNT) solution. This system is based on the LORAN-C technology. It is a suitable solution for areas where GNSS is denied. Thanks to its low frequency and high power it is considered as a cost-effective backup system for GNSS outage. It fulfils RNP 0.3 requirements in terms of accuracy, integrity, and availability for aviation traffic (en-route and also non-precision approach). Unlike the GNSS, the maintenance cost of LORAN infrastructure is significantly cheaper. [18]

3.4 Global Navigation Satellite System (GNSS)

The Global Navigation Satellite System (GNSS) is a generic term used by ICAO to define any global position, speed, and time determination system, that is composed by one or more main satellite constellations. These could be GPS and the global navigation satellite system (GLONASS), aircraft receivers and several integrity monitoring systems, including aircraft-based augmentation systems (ABAS), satellite-based augmentation systems (SBAS), such as the wide area augmentation systems (WAAS), and ground-based augmentation systems (GBAS), such as the local area augmentation system (LAAS).

The basic architectural scheme of the GNSS includes the space segment (constellation of satellites), the user segment and the control/ground segment, as represented in Figure 2Figure.

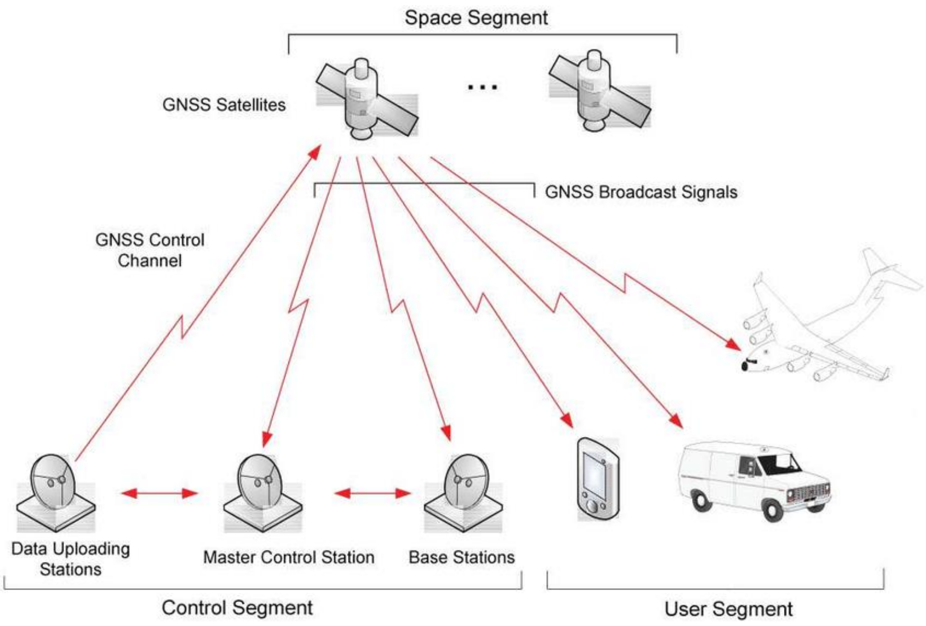


Figure 2. Basic Architectural Scheme for GNSS [**Chyba! Nenalezen zdroj odkazů.**]

The Global Positioning System (GPS), see Figure 3, is the satellite navigation system operated by the United States. The GPS works based on the principle of passive triangulation (Figure 4) and it performs precise range measurements to determine position, velocity, and time anywhere in the world. For the GPS, the space segment is composed by at least 24 satellites in 6 orbital planes, while the control segment consists of 5 monitor stations, 3 ground antennas, and a master control station. The user segment includes antennas and receivers that provide the required information to the user: positioning, velocity, and precise timing. [21]

Because of the low power of received GNSS signal, it makes the system vulnerable to jamming. Even though GNSS outage is quite rare, it represents a major threat for the air traffic, therefore it impacts the aerospace industry. [18]

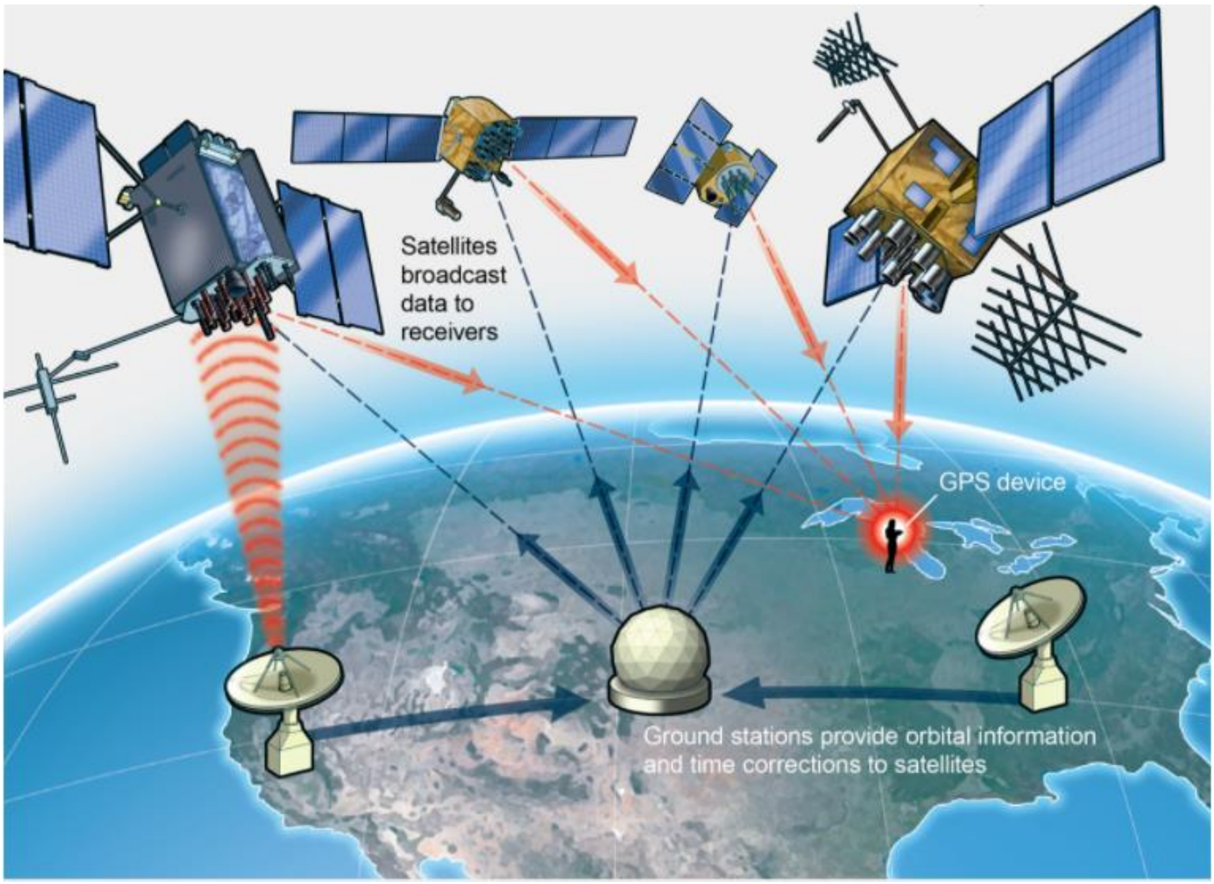
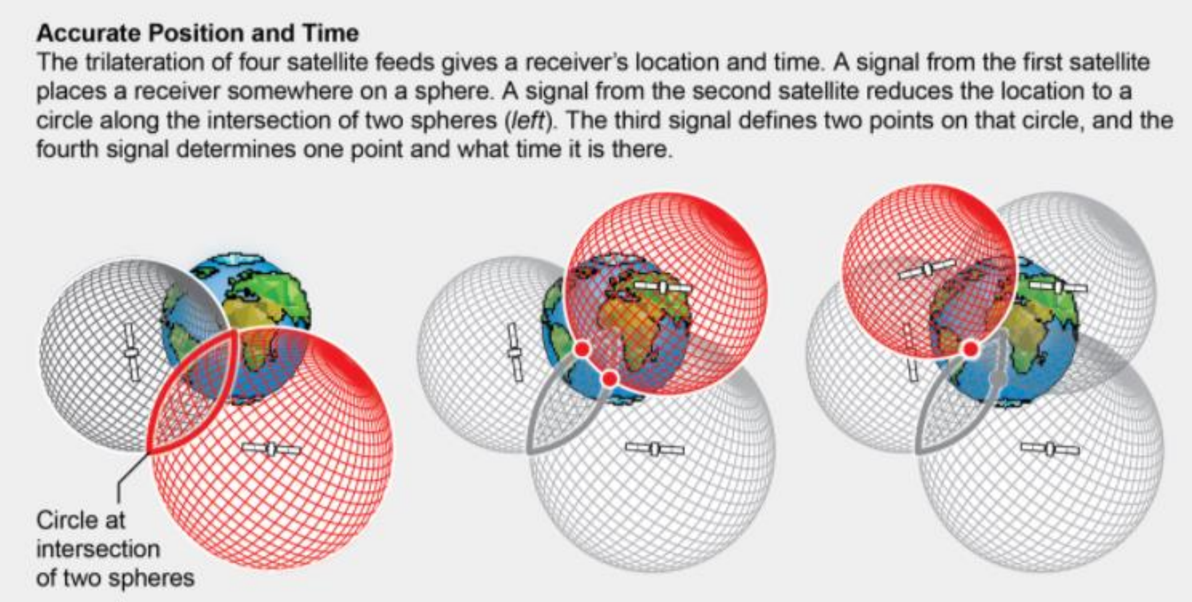


Figure 3 GPS [22]



Accurate Position and Time

The trilateration of four satellite feeds gives a receiver's location and time. A signal from the first satellite places a receiver somewhere on a sphere. A signal from the second satellite reduces the location to a circle along the intersection of two spheres (*left*). The third signal defines two points on that circle, and the fourth signal determines one point and what time it is there.

Figure 4 GPS Trilateration [22]

3.5 Distance Measuring Equipment (DME)

The Distance Measuring Equipment (DME) is a secondary radar system that determines the distance (slant range) between an aircraft and a ground station. The DME consists of the aircraft avionics (on-board DME interrogators) and the ground facilities (ground transponders). The distance is calculated as the elapsed time from the aircraft radio interrogation to the receipt of the ground system reply, then it is corrected by the reply delay error and after that it converts the time to the distance. This DME air-ground-air process begins with the aircraft avionics transmitting interrogation pulse-pair signals in space, the ground transponder with corresponding radio frequency receiving the signal, then it continues with the transponder decoding valid interrogations and sending a copy of the signal after a fixed delay. DME interrogator is receiving the reply, decoding it, determining the time of the signal journey, and determining the slant range distance using a math equation. The equation is equal to a half of difference between time of the radio signal broadcast and the fixed delay in the DME ground station (50 μs for channel X) multiplied by the speed of the electromagnetic waves propagation (3×10^8 m/s). The DME uses radio L-band between 960 and 1215 MHz divided into 252 channels with 1 MHz spacing. There are two different kinds of the DME, DME narrowband (DME/N) and DME precision (DME/P**).** [19][23][24][25]

3.6 Performance-based navigation (PBN)

The Performance Based Navigation (PBN) includes the navigation specifications in terms of the accuracy, integrity, availability, continuity, and functionality needed for the operation of the aircraft in a particular airspace concept. It is considered as a shift from sensor-based to performance-based navigation. [26]

The main advantages of the PBN over the sensor-specific method with respect to the airspace developing are that with the PBN systems, the need to maintain sensor-specific routes and procedures is reduced, including its operational cost. Also, the PBN systems permit a more efficient use of the airspace, that is reflected in fuel efficiency and noise abatement. [26]

For the operation of the PBN, it is required to have an appropriate navigation specification and the navigation aid infrastructure, including both ground- and space-based, allowing the system to operate. [26]

There are two different types of PBN: The Area Navigation (RNAV) and the Required Navigation Performance (RNP). The main difference between them is the requirement of on-board performance monitoring and alerting, that is included only in the RNP system. [26]

3.7 Area Navigation (RNAV)

The Area Navigation (RNAV) is a method of navigation that allows aircraft operation according to any desired flight path, while staying inside the area covered by the station-referenced navigation aids or the limit capacity of its self-contained aids, or a combination of these. This characteristic of RNAV removes the restriction of conventional routes, where the aircraft overfly referenced navigation aids, see Figure 5, giving to RNAV an advantage of operational flexibility and efficiency. [26]

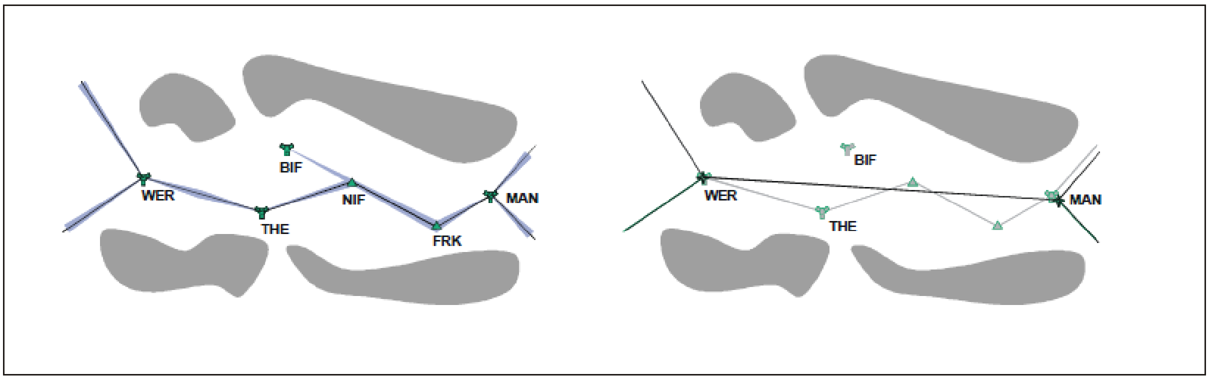


Figure 5. RNAV [26]

The functions that RNAV fulfil are navigation, flight plan management, guidance and control, and display and system control. For the navigation function the computed data includes the aircraft position, velocity, track angle, vertical flight path angle, drift angle, magnetic variation, barometric-corrected altitude, and wind direction and magnitude. This data is obtained through the multisensory RNAV systems, that include a variety of navigation sensors (GNSS, DME, VOR and IRS). Once the position is computed by these sensors, the system will typically consider the most accurate positioning sensor available for its calculations. [26]

As an example of RNAV system there is the RNAV 10, which was developed for operating in oceanic and remote areas and does not require ground-based navaid infrastructure or assessment. This system supports a distance-based separation minimum of 50 NM lateral and 50 NM longitudinal in oceanic or remote area airspace. [26]

3.8 Required Navigation Performance (RNP)

The Required Navigation Performance (RNP) corresponds to the RNAV system, with the difference that it supports the on-board performance monitoring and alerting capabilities, provided as a display and indication of both the required and the estimated navigation system performance. When the ANP (Actual Navigation Performance) exceeds the RNP, a caution alert is initiated by the FMC and it means that the performance of an FMC position update sensor has deteriorated, and the navigation system accuracy can no longer ensure containment. [26]

For oceanic and remote continental airspace, the air traffic services providers provide RNP 10 (also known as RNAV 10) and RNP 4 based separation minima. The ATS providers determine the minimum separation between adjacent aircraft based on the authorized capability of each aircraft operator indicated in the flight plan. For the systems mentioned previously:

- ✓ RNP 10 has as a requirement that the aircraft remains within 10 nautical miles (NM) of center line 95% of the time, and within 20 NM 99.999% of the time.
- ✓ RNP 4 has as a requirement that the aircraft remains within 4 NM of center line 95% of the time, and within 8 NM 99.999% of the time. [10]

Figure 6 shows the improvements regarding the use of available airspace passing from the conventional systems to RNAV and RNP, obtaining a narrower area covered by the path of the aircraft.

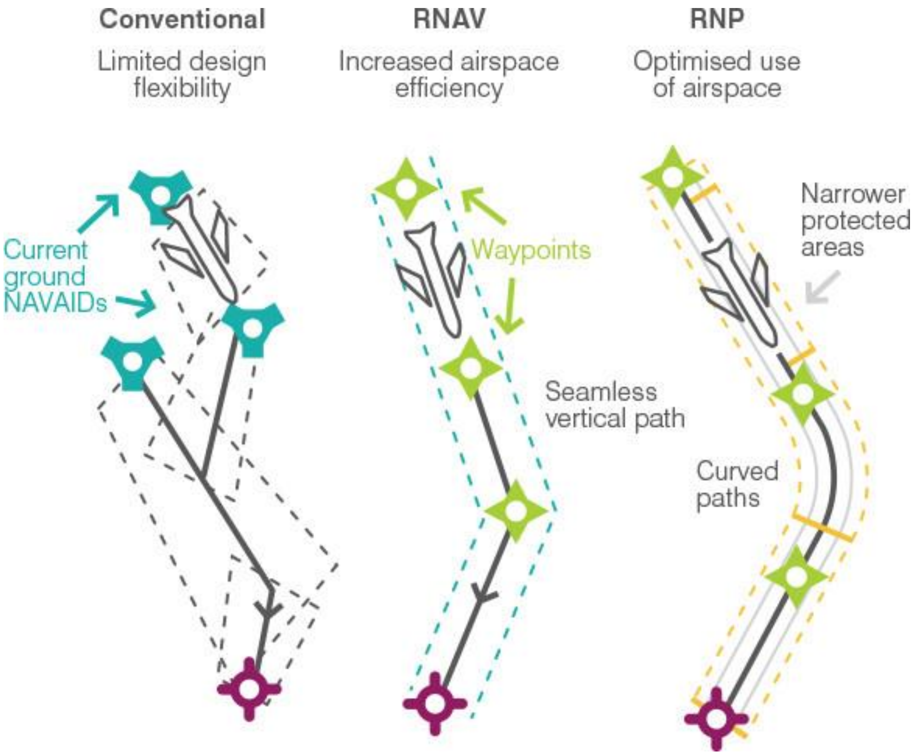


Figure 6. RNAV vs RNP [27]

3.9 Secondary Surveillance Radar (Mode S)

Secondary surveillance radar is a system of surveillance radars. [7] Although this subchapter is mainly about SSR, Primary surveillance radar (PSR) is also mentioned as it is being compared with SSR.

PSR is a type of independent non-cooperative surveillance radar system that works with reflected radio signal (passive echoes). It transmits pulses and after it receives reflections, it detects and processes them. Ground station of PSR usually contains a transmitter, receiver, and rotating antenna. PSR is able to determine aircraft's position as long as the aircraft is constructed from a reflective material (onboard equipment is not necessary). Apart from the aircraft, it can also detect objects intruding in a protected area. Another PSR's capability is to detect meteorological conditions. PSR determines slant range of the aircraft by computing the time between transmission of the signals and the reception of the reflection. Impulses are not reflected only by the aircraft but also by other fixed objects, such as mountains or buildings. This is one of the issues of PSR, since reflections obtained not only from aimed targets lead to cluttering. So far, ICAO has not standardized PSR. [15] [28] [9]

SSR provides much more information than primary surveillance radar (PSR). It provides altitude, an identification code, any technical problems on board such as loss of radiocontact (PSR provides only direction, height, distance of targets). [28]

SSR has several modes, Mode A/C, Mode A, Mode C, Mode S.

SSR uses two antennas, so called “Antenna diversity”, one mounted at the top and the other one at the bottom of the aircraft. [9]

4 Cases of Interferences to GNSS

More than 12 0000 miles distance between satellites and receivers placed on the Earth, weaken the GPS signals when reaching the Earth and therefore they are more likely to be jammed or spoofed. [22]

Here are some most recent incidents caused by GNSS interference.

In April 2014, GLONASS was shut down for over 11 hours. It was caused by uploading “bad ephemerides”. Another failure occurred only two weeks later. [29]

On 5 August 2016, Cathay Pacific Flight 905 flying from Hong Kong to Manila experienced loss of GPS guidance for the final 8 NM. The crew was instructed by controllers to land the aircraft, relying solely on their own vision. The flight landed safely. [22]

In July and August 2016, ICAO received over 50 reports of GPS interference at the Manila airport. For several landing aircraft, it meant another landing attempt. [22]

In June 2019, a passenger aircraft nearly crashed into a mountain after a sudden loss of GPS guidance. [22] [30]

5 Methodology

Two different scripts named “Model_v5_3A.m”, “Model_v5_4A.m” and one function named “position.m” (further referred to as M3A, M4A and Position function, respectively) have been created using the MATLAB environment and its “Mapping Toolbox” and “Aerospace Toolbox”. The following subchapters describe both M3A and M4A models. Whenever the scripts differ, the difference is mentioned and described.

5.1 Methods

Monte Carlo simulation has been chosen to determine the reliability of the proposed model. The principle of Monte Carlo technique is repeating the simulation many times (in the case of this model it is 10 000 times) to obtain a large number of results. One of the methods used by Monte Carlo methods is the Law of Large Numbers. [31] The law states that the more results, the higher the probability for the average to be closer to the “true” value. [32]

The computation of the aircraft’s location is based on equations used for GPS. It is described in the chapter 6.5.

After the simulation is concluded, the outliers (extreme values) are removed using MATLAB’s function called “rmoutliers” which removes all the values that are more than three scaled median absolute deviations (MAD). [33]

The final step is to calculate twice the distance root mean square (2DRMS) of horizontal errors for each estimated aircraft, including the aircraft from the first group. 2DRMS is one of the ways how to measure position accuracy in horizontal dimension. [34] 2DRMS corresponds to twice the square root of the sum of squares of the lengths of the semimajor and semiminor axes of the error ellipse. The true horizontal values are, with a certain probability (95.4 - 98.2 %), contained in a circle of radius 2DRMS. [35]

5.2 Procedures

The process starts by entering and specifying the input values. After that, the first step is to transform the variables into units necessary for future computing. Therefore, the heights are transformed from orthometric to ellipsoidal and coordinates from geodetic to ENU. In the next step, the real position of the aircraft is plotted (in the case of M3A only the selected aircraft are plotted). They are used as referential points for the positions computed later in the process. In the next step, it is necessary to compute distances between the aircraft in layer “x” and layer “x+1”. These results are then divided by the speed of light. The reason for these two steps is to simulate the real-life communication between the aircraft, where one aircraft interrogates the aircraft in the surroundings and based on the time between the interrogation, and the reception of the reply calculates the distance. After that, the variables for storing the results of the simulation are created; later on, they are plotted in the already existing graph. The last step before starting the simulation itself is to save into a variable the tolerance of Mode S.

The simulation has three sections, one section per each “unknown” layer. The first one, determining positions of all the aircraft in the first unknown layer the second one computing the aircraft from the second unknown layer and the third one for the third unknown layer. Apart from the specific indices in each layer, the process to find the positions is the same and it is based on the GPS computation. Problematic results of the computation are identified, separated from the others, and later evaluated. After the whole simulation part is over, results that are significantly different (extreme values) are removed. 2DRMS is calculated using the corrected values. In the end, the positions and the 2DRMS are plotted.

5.3 Criteria

For the purpose of the model, the following is considered:

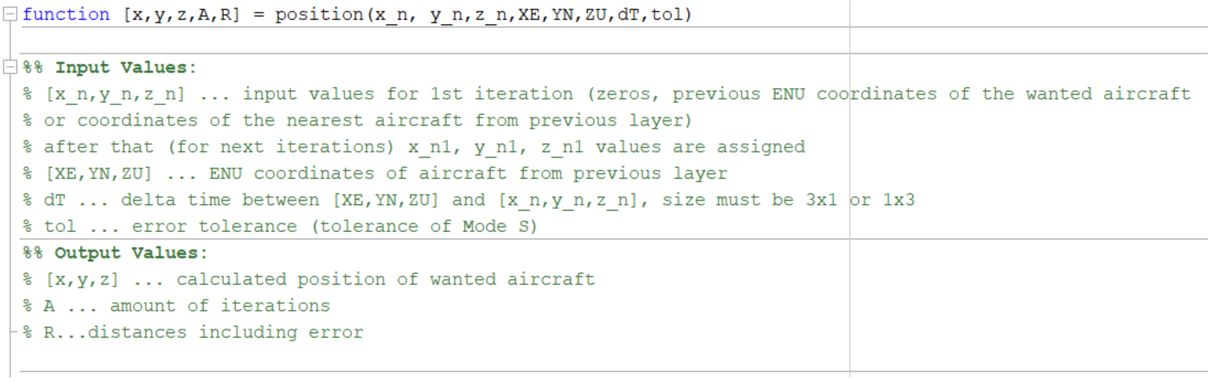
- ✓ Aircraft are still in time. The inaccuracy caused by aircraft movement is considered negligible.
- ✓ The input values are taken from external source (for instance “Flight Radar 24” [36]) and entered manually. The input values are:
  - Reference Point A0: Altitude [feet], Latitude [degrees], Longitude [degrees]
  - Positions of aircraft for 4 layers (3 to 4 aircraft per layer), units are same as for reference point A0
  - Choice of 3 reference aircraft from each layer (applicable only for model M3A)
  - Accuracy for results (optional) [nautical miles] - if applied corresponding lines in section “Assigning Values to Variables” shall be uncommented
  - Aircraft Position Error [meters]
  - Amount of Simulations.
- ✓ All the aircraft in the first layer already know their position

5.4 Position Function

For the purpose of this model a MATLAB function ‘position.m’ has been created for calculating aircraft’s position coordinates.

There are eight input values and five output values for the function, see Figure 7. The first three input values are ENU coordinates [x_n, y_n, z_n] that are used for the first iteration and for every other iteration are assigned [x_n1, y_n1, z_n1] variables. [x_n1, y_n1, z_n1] represent $x_{n+1}, y_{n+1}, z_{n+1}$ values. The next inputs [XE, YN, ZU] are three one-by-three matrices containing three reference aircraft each. Reference aircraft are used for calculating the position of the aircraft with unknown coordinates. The one-by-three vector ‘dT’ stands for the time difference (in seconds) between the wanted aircraft and the three reference aircraft. The last input variable is ‘tol’, tolerance of Mode S in seconds.

The output values consist of aircraft’s calculated ENU coordinates, variable ‘A’ which stores the number of iterations performed and three-by-one variable ‘R’ containing distances in meters (including the error of Mode S) between the calculated aircraft and the reference aircraft.

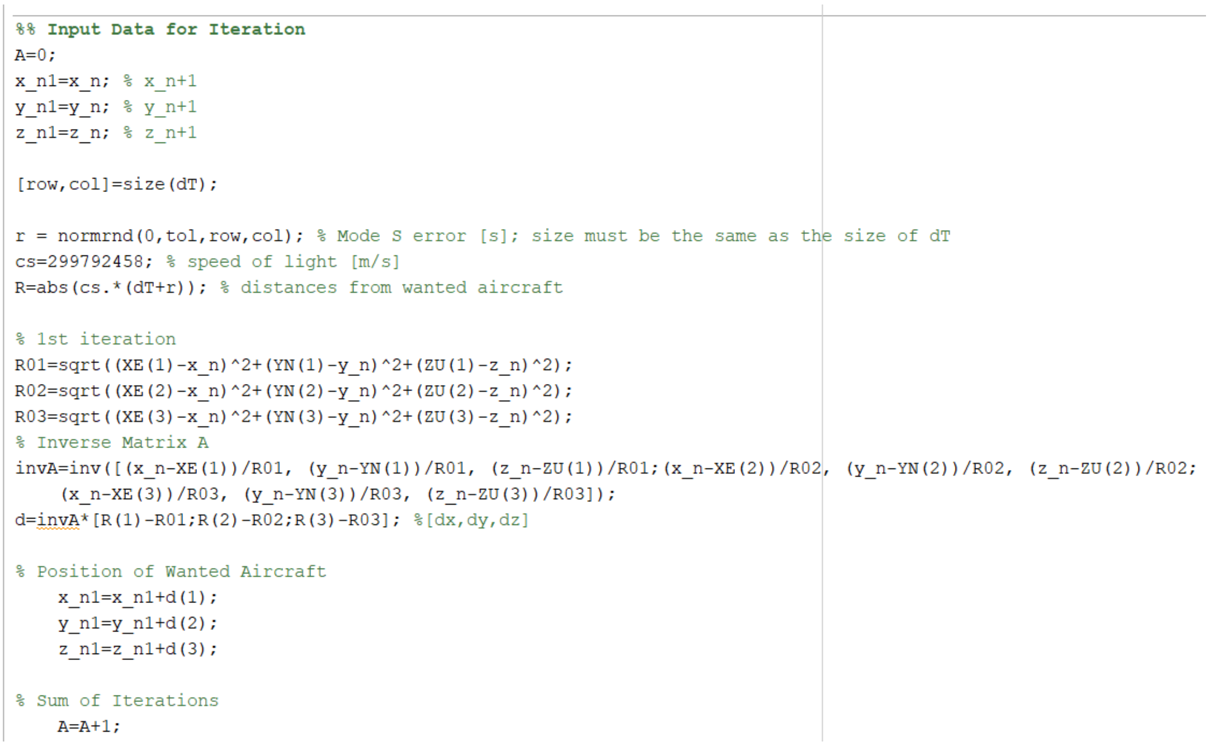


```
function [x,y,z,A,R] = position(x_n, y_n,z_n,XE,YN,ZU,dT,tol)

%% Input Values:
% [x_n,y_n,z_n] ... input values for 1st iteration (zeros, previous ENU coordinates of the wanted aircraft
% or coordinates of the nearest aircraft from previous layer)
% after that (for next iterations) x_n1, y_n1, z_n1 values are assigned
% [XE,YN,ZU] ... ENU coordinates of aircraft from previous layer
% dT ... delta time between [XE,YN,ZU] and [x_n,y_n,z_n], size must be 3x1 or 1x3
% tol ... error tolerance (tolerance of Mode S)
%% Output Values:
% [x,y,z] ... calculated position of wanted aircraft
% A ... amount of iterations
% R...distances including error
```

Figure 7. Position Function (Input and Output Values Description)

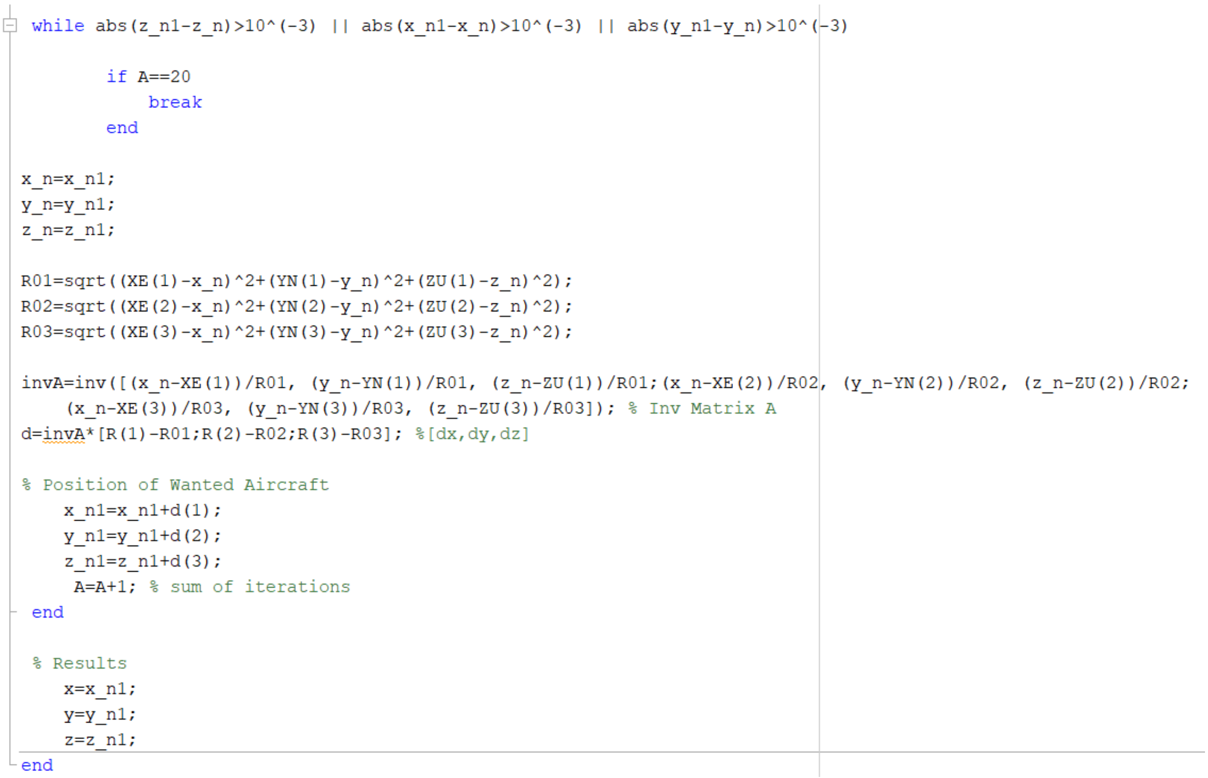
Before the start of the iteration, couple more variables are defined, see Figure 8 and Figure 9. The Variable ‘A’ is set to zero, variables [x_n1, y_n1, z_n1] are assigned [x_n, y_n, z_n] values and the size of time difference (‘dT’) is found and saved. After that, the standard normal distribution (with mean 0 and standard normal deviation (sigma) equal to the tolerance of Mode S (equal to $0.25 \cdot 10^{-6}$ seconds) generates errors according to the size of the time difference variable. After that, the time distance vector is corrected by the generated errors and then multiplied by the speed of light to get the distance in meters between the wanted aircraft and the three reference aircraft.

The first iteration begins as it is described in the next subchapter.



```
%% Input Data for Iteration
A=0;
x_n1=x_n; % x_n+1
y_n1=y_n; % y_n+1
z_n1=z_n; % z_n+1

[row,col]=size(dT);

r = normrnd(0,tol,row,col); % Mode S error [s]; size must be the same as the size of dT
cs=299792458; % speed of light [m/s]
R=abs(cs.*(dT+r)); % distances from wanted aircraft

% 1st iteration
R01=sqrt((XE(1)-x_n)^2+(YN(1)-y_n)^2+(ZU(1)-z_n)^2);
R02=sqrt((XE(2)-x_n)^2+(YN(2)-y_n)^2+(ZU(2)-z_n)^2);
R03=sqrt((XE(3)-x_n)^2+(YN(3)-y_n)^2+(ZU(3)-z_n)^2);
% Inverse Matrix A
invA=inv([(x_n-XE(1))/R01, (y_n-YN(1))/R01, (z_n-ZU(1))/R01;(x_n-XE(2))/R02, (y_n-YN(2))/R02, (z_n-ZU(2))/R02;
    (x_n-XE(3))/R03, (y_n-YN(3))/R03, (z_n-ZU(3))/R03]);
d=invA*[R(1)-R01;R(2)-R02;R(3)-R03]; %[dx,dy,dz]

% Position of Wanted Aircraft
    x_n1=x_n1+d(1);
    y_n1=y_n1+d(2);
    z_n1=z_n1+d(3);

% Sum of Iterations
    A=A+1;
```

Figure 1. Position Function (First part)



```
 while abs(z_n1-z_n)>10^(-3) || abs(x_n1-x_n)>10^(-3) || abs(y_n1-y_n)>10^(-3)

        if A==20
            break
        end

x_n=x_n1;
y_n=y_n1;
z_n=z_n1;

R01=sqrt((XE(1)-x_n)^2+(YN(1)-y_n)^2+(ZU(1)-z_n)^2);
R02=sqrt((XE(2)-x_n)^2+(YN(2)-y_n)^2+(ZU(2)-z_n)^2);
R03=sqrt((XE(3)-x_n)^2+(YN(3)-y_n)^2+(ZU(3)-z_n)^2);

invA=inv([(x_n-XE(1))/R01, (y_n-YN(1))/R01, (z_n-ZU(1))/R01;(x_n-XE(2))/R02, (y_n-YN(2))/R02, (z_n-ZU(2))/R02;
    (x_n-XE(3))/R03, (y_n-YN(3))/R03, (z_n-ZU(3))/R03]); % Inv Matrix A
d=invA*[R(1)-R01;R(2)-R02;R(3)-R03]; %[dx,dy,dz]

% Position of Wanted Aircraft
    x_n1=x_n1+d(1);
    y_n1=y_n1+d(2);
    z_n1=z_n1+d(3);
     A=A+1; % sum of iterations
 end

 % Results
    x=x_n1;
    y=y_n1;
    z=z_n1;
end
```

Figure 2. Position Function (Second part)

5.5 Computing Position

The following computation is used to determine the position of aircraft. Firstly, the true range is calculated as an equation (5.1)

$$R = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{5.1}$$

, where [x_i, y_i, z_i] are the known coordinates of aircraft from the previous group, and [x, y, z] are coordinates of aircraft with unknown coordinates.

Using Taylor's series, the equation (5.2) can be expanded as

$$R_i = R_i(x_n, y_n, z_n) + \frac{x_n - x_i}{R_i(x_n, y_n, z_n)}\Delta x + \frac{y_n - y_i}{R_i(x_n, y_n, z_n)}\Delta y + \frac{z_n - z_i}{R_i(x_n, y_n, z_n)}\Delta z \tag{5.2}$$

Where $\Delta x = x - x_n$; $\Delta y = y - y_n$; $\Delta z = z - z_n$. [x_n, y_n, z_n] represent initial coordinates of searched aircraft (assumed as coordinates of the nearest aircraft from the previous row or the last known coordinates of the searched aircraft). Taylors expansion can be ignored after linear expressions.

We can rewrite equation (5.2) for three aircraft in a form of a matrix

$$\begin{bmatrix} R_1 - R_1(x_n, y_n, z_n) \\ R_2 - R_2(x_n, y_n, z_n) \\ R_3 - R_3(x_n, y_n, z_n) \end{bmatrix} = \begin{bmatrix} \frac{x_n - x_1}{R_1(x_n, y_n, z_n)} & \frac{y_n - y_1}{R_1(x_n, y_n, z_n)} & \frac{z_n - z_1}{R_1(x_n, y_n, z_n)} \\ \frac{x_n - x_2}{R_2(x_n, y_n, z_n)} & \frac{y_n - y_2}{R_2(x_n, y_n, z_n)} & \frac{z_n - z_2}{R_2(x_n, y_n, z_n)} \\ \frac{x_n - x_3}{R_3(x_n, y_n, z_n)} & \frac{y_n - y_3}{R_3(x_n, y_n, z_n)} & \frac{z_n - z_3}{R_3(x_n, y_n, z_n)} \end{bmatrix} \times \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \tag{5.3}$$

where R_1, R_2, R_3 represent distances between aircraft from the previous layer and the layer where is the aircraft, that needs to be located A1, including Mode S error. We can substitute the 3x3 matrix = M.

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = M^{-1} \begin{bmatrix} R_1 - R_1(x_n, y_n, z_n) \\ R_2 - R_2(x_n, y_n, z_n) \\ R_3 - R_3(x_n, y_n, z_n) \end{bmatrix} \tag{5.4}$$

The last step to obtain x,y,z coordinates is the Iterative method.

$$n = 1,2,3 \dots k \tag{5.5}$$

$$x_n = x_{n-1} + \Delta x_n \tag{5.6}$$

$$y_n = y_{n-1} + \Delta y_n \tag{5.7}$$

$$z_n = z_{n-1} + \Delta z_n \tag{5.8}$$

The average amount of iterations (only considering when the final x,y,z are close to the real position of the searched aircraft) based on the initial simulations k was set as 20. A large number of iterations can indicate not intersecting spheres or the initial coordinates [x_n, y_n, z_n] being set too far from the position of searched aircraft.

Example: After the coordinates of A21 are successfully found, the same process begins again but this time trying to determine the position of A22, then A23 and A24. Then group A1 is replaced by A2 and A2 by A3 and after that, the last one remains, the reference group is A3 and the unknown coordinates are in A4.

All the processes written above happens within one simulation.

6 Model Proposal

There are five layers of the aircraft from A0 to A4 (see Figure 10). The first group contains only one aircraft (A0) and the other four contain four aircrafts each.

Figure 103. Real traffic situation [36]

Two different alternative navigation models were created and analysed. The difference between the models is the selection of the target aircraft's initial position for the first iteration. For the first model (Model_v5_3A), the previous position of the wanted aircraft is necessary, whereas the second model (Model_v5_4A) does not require it. Model v5_3A uses the last known position of the wanted aircraft, which is a position known before the GNSS failure and only 3 aircraft are necessary in the previous layer. In the Model v5_4A the wanted aircraft does not need to know its position at all. Also, this model requires four aircraft in each layer.

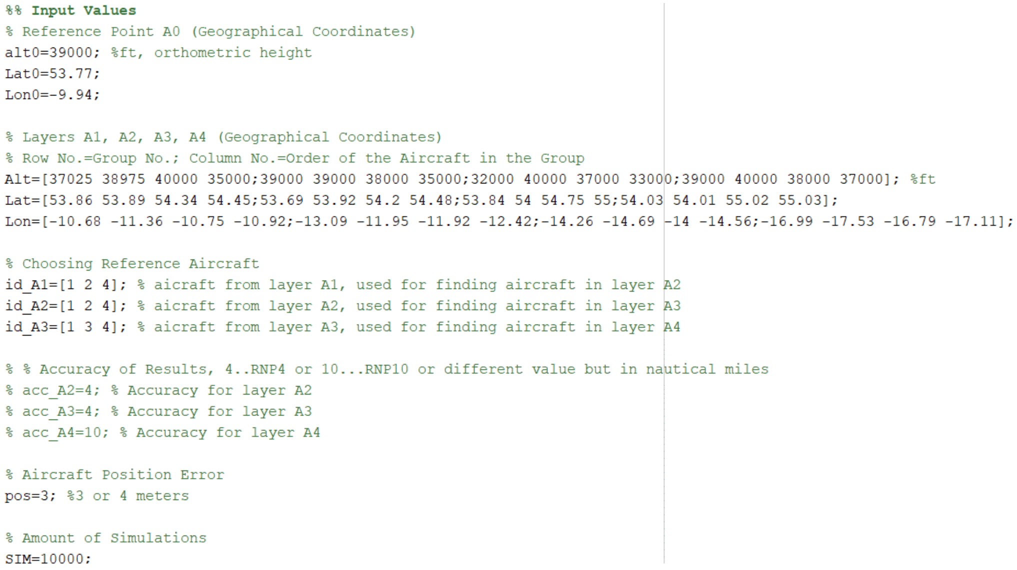
6.1 Model v5_3A

The script called Model v5_3A consists of the following sections: Input Values, Coordinates Transformation, Plotting Real Traffic Situation, Variables, Simulation, Processing Results, Plotting Results.

The Input Values

This section, see Figure 11, contains all the data which is necessary for the simulation. It starts with entering coordinates of the refence point, which for the purpose of this model is the aircraft A0, but in general it can be any other convenient point. The A0 should be chosen wisely as it is later used to determine the centre of the new coordinate system. "This coordinate system is best used for smaller area extents, where the curvature of the earth is not a concern (less than 4 km)". [37] Then, Altitude, Latitude and Longitude of sixteen aircraft are entered. Each row represents one layer, each column represents aircraft's position within the layer, e.g. an element in the third row and the second column represents the aircraft A32 (the aircraft from the third layer).

The next three variables store indices of the aircraft, which are later used during the simulation, that means the three aircraft from the layer A1 are chosen for determining positions of the aircraft in layer A2, the aircraft from the layer A2 to determine the layer A3 and the aircraft from the layer A3 to determine the layer A4. The criteria for choosing these three aircraft is their layout in the area, the better the geometry of the aircraft is, the more accurate the results are. Figure 12 and Figure 13 illustrate good and poor geometry of GPS satellites respectively, the principle is the same also for our model. It is possible to set up the accuracy of the results, even though this option stays in the current model for possible usage, it is commented as the extreme values are treated at the end. Last two variables to set up in this section are aircraft position error and the desired amount of simulations.



```
%% Input Values
% Reference Point A0 (Geographical Coordinates)
alt0=39000; %ft, orthometric height
Lat0=53.77;
Lon0=-9.94;

% Layers A1, A2, A3, A4 (Geographical Coordinates)
% Row No.=Group No.; Column No.=Order of the Aircraft in the Group
Alt=[37025 38975 40000 35000;39000 39000 38000 35000;32000 40000 37000 33000;39000 40000 38000 37000]; %ft
Lat=[53.86 53.89 54.34 54.45;53.69 53.92 54.2 54.48;53.84 54 54.75 55;54.03 54.01 55.02 55.03];
Lon=[-10.68 -11.36 -10.75 -10.92;-13.09 -11.95 -11.92 -12.42;-14.26 -14.69 -14 -14.56;-16.99 -17.53 -16.79 -17.11];

% Choosing Reference Aircraft
id_A1=[1 2 4]; % aicraft from layer A1, used for finding aircraft in layer A2
id_A2=[1 2 4]; % aicraft from layer A2, used for finding aircraft in layer A3
id_A3=[1 3 4]; % aicraft from layer A3, used for finding aircraft in layer A4

% % Accuracy of Results, 4..RNP4 or 10...RNP10 or different value but in nautical miles
% acc_A2=4; % Accuracy for layer A2
% acc_A3=4; % Accuracy for layer A3
% acc_A4=10; % Accuracy for layer A4

% Aircraft Position Error
pos=3; %3 or 4 meters

% Amount of Simulations
SIM=10000;
```

Figure 11. Input Values

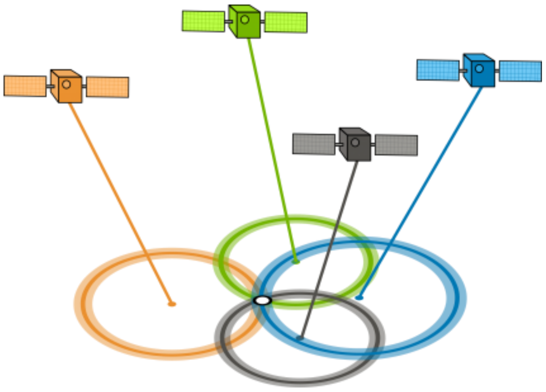


Figure 124. Good Geometry [38]

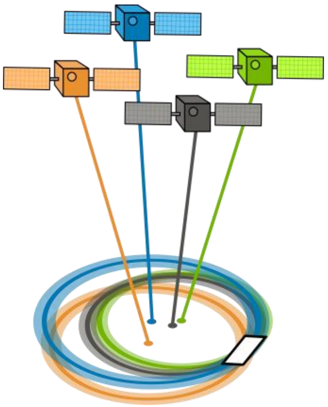
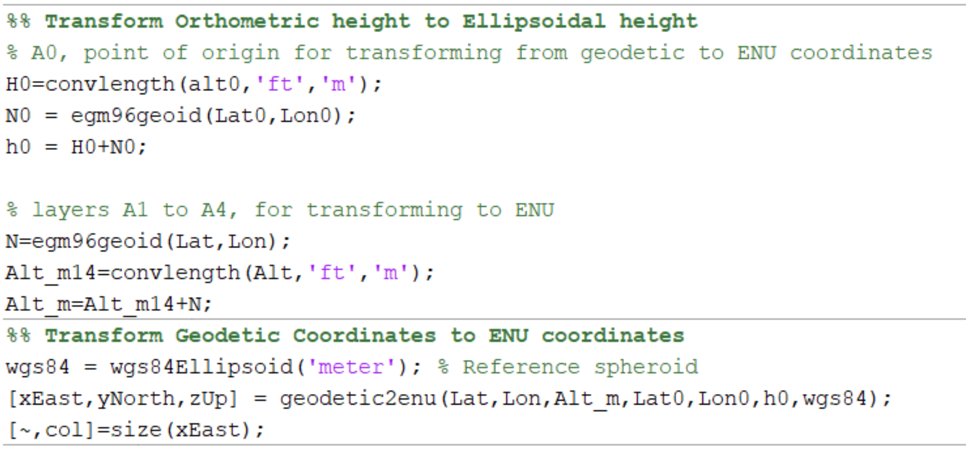


Figure 13. Poor Geometry [38]

Coordinates Transformation

This section, see Figure 14, is focused on transformation from geodetic to the East North Up (ENU) coordinate system. Firstly, it is important to transform all the entered altitudes from the orthometric (geoid) height to the ellipsoidal height. The MATLAB’s built-in function called “egm96geoid” is used for this purpose. After the reference spheroid is specified, the aircraft’s geodetic coordinates are transformed to the ENU coordinate system. At the end, the size of the variable xEast is stored, so it can be used for the loops later in the script.

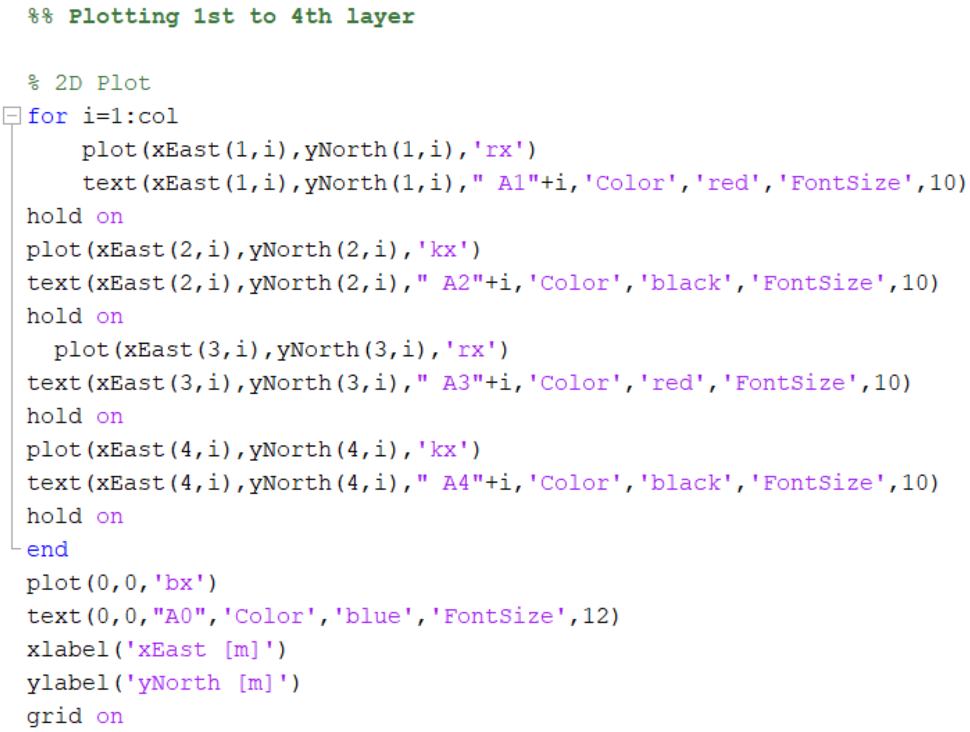


```
%% Transform Orthometric height to Ellipsoidal height
% A0, point of origin for transforming from geodetic to ENU coordinates
H0=convlength(alt0,'ft','m');
N0 = egm96geoid(Lat0,Lon0);
h0 = H0+N0;

% layers A1 to A4, for transforming to ENU
N=egm96geoid(Lat,Lon);
Alt_m14=convlength(Alt,'ft','m');
Alt_m=Alt_m14+N;
%% Transform Geodetic Coordinates to ENU coordinates
wgs84 = wgs84Ellipsoid('meter'); % Reference spheroid
[xEast,yNorth,zUp] = geodetic2enu(Lat,Lon,Alt_m,Lat0,Lon0,h0,wgs84);
[~,col]=size(xEast);
```

Figure 14. Transforming Coordinates

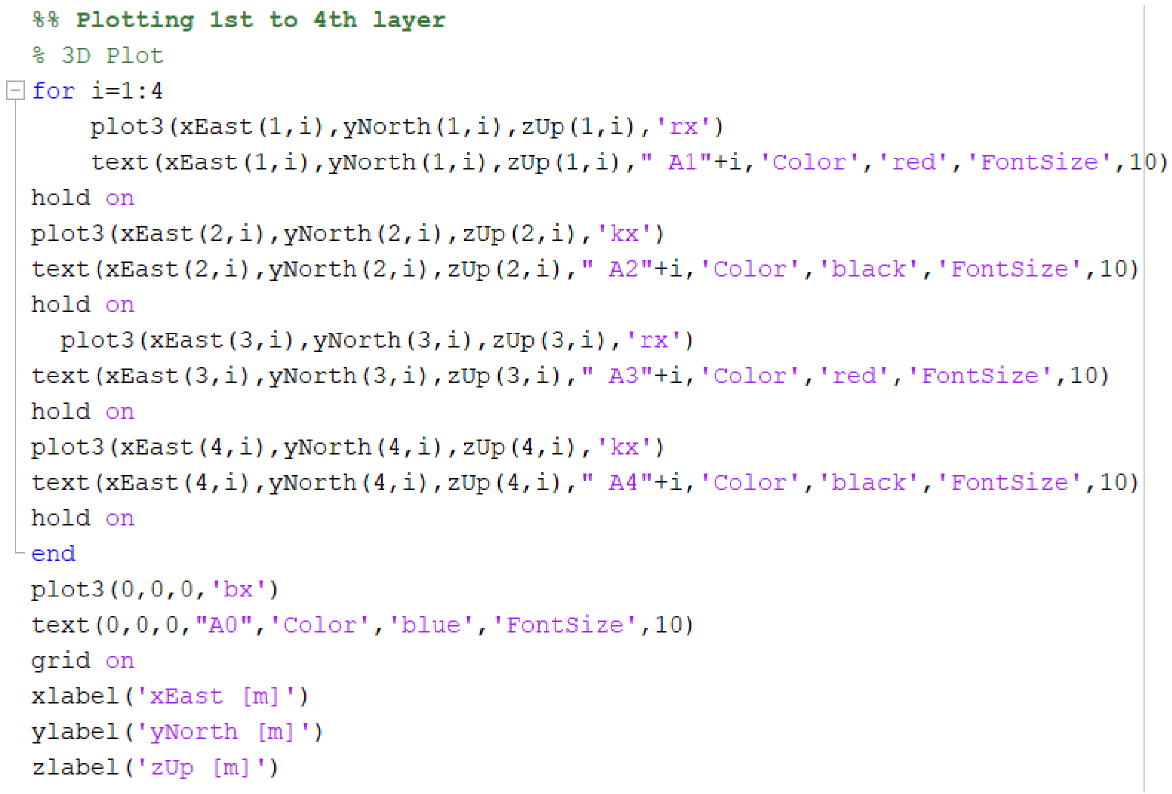
Plotting Real Traffic Situation

In the Plotting Real Traffic Situation part, see Figure 15 and Figure 16, all four layers of the aircraft (A1 – A4) including the point of origin (A0) are plotted in the 2D ENU coordinate system, see Graph 1 and Graph 2. Since the focus of this model is on the horizontal accuracy, the 2D graph displaying the horizontal situation is enough, see **Chyba! Nenalezen zdroj odkazů.**, however, it is possible to uncomment the 3D plotting segment, that is mainly for getting an idea how the aircraft are deployed in the space, see **Chyba! Nenalezen zdroj odkazů.**.



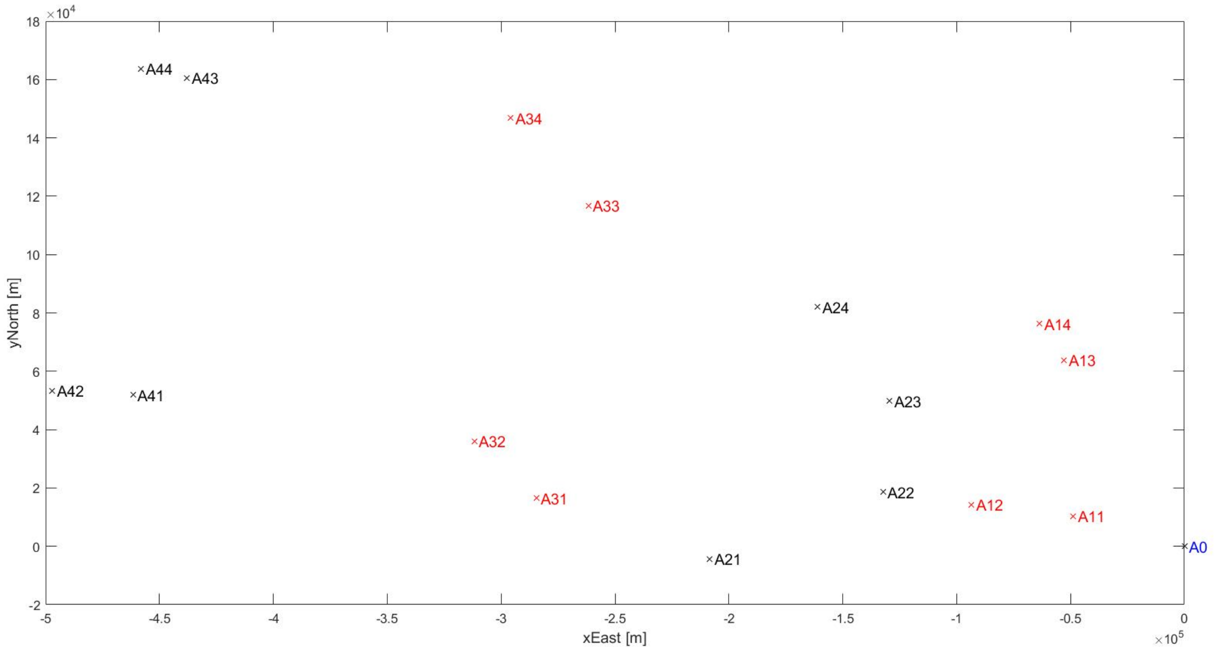
```
%% Plotting 1st to 4th layer

% 2D Plot
for i=1:col
    plot(xEast(1,i),yNorth(1,i),'rx')
    text(xEast(1,i),yNorth(1,i)," A1"+i,'Color','red','FontSize',10)
hold on
plot(xEast(2,i),yNorth(2,i),'kx')
text(xEast(2,i),yNorth(2,i)," A2"+i,'Color','black','FontSize',10)
hold on
  plot(xEast(3,i),yNorth(3,i),'rx')
text(xEast(3,i),yNorth(3,i)," A3"+i,'Color','red','FontSize',10)
hold on
plot(xEast(4,i),yNorth(4,i),'kx')
text(xEast(4,i),yNorth(4,i)," A4"+i,'Color','black','FontSize',10)
hold on
end
plot(0,0,'bx')
text(0,0,"A0",'Color','blue','FontSize',12)
xlabel('xEast [m]')
ylabel('yNorth [m]')
grid on
```

Figure 15. Plotting all layer in 2D

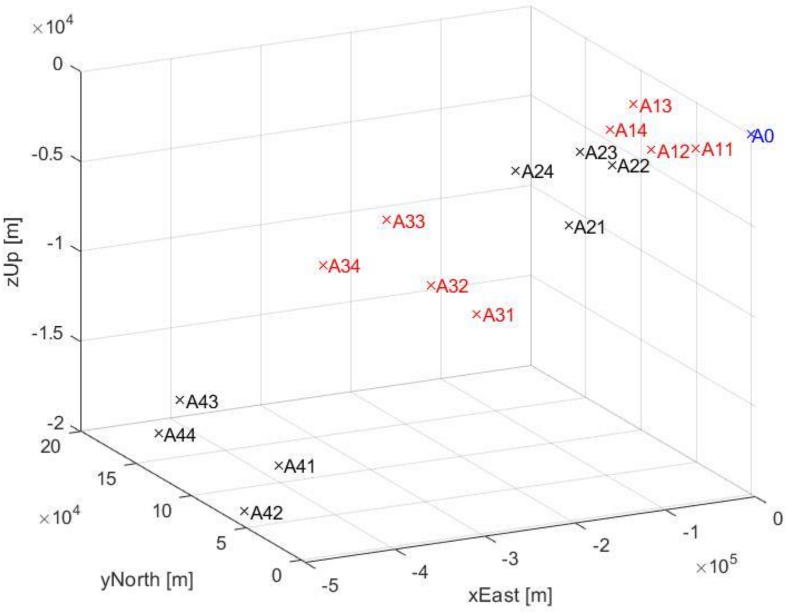


```
%% Plotting 1st to 4th layer
% 3D Plot
for i=1:4
    plot3(xEast(1,i),yNorth(1,i),zUp(1,i),'rx')
    text(xEast(1,i),yNorth(1,i),zUp(1,i)," A1"+i,'Color','red','FontSize',10)
hold on
plot3(xEast(2,i),yNorth(2,i),zUp(2,i),'kx')
text(xEast(2,i),yNorth(2,i),zUp(2,i)," A2"+i,'Color','black','FontSize',10)
hold on
  plot3(xEast(3,i),yNorth(3,i),zUp(3,i),'rx')
text(xEast(3,i),yNorth(3,i),zUp(3,i)," A3"+i,'Color','red','FontSize',10)
hold on
plot3(xEast(4,i),yNorth(4,i),zUp(4,i),'kx')
text(xEast(4,i),yNorth(4,i),zUp(4,i)," A4"+i,'Color','black','FontSize',10)
hold on
end
plot3(0,0,0,'bx')
text(0,0,0,"A0",'Color','blue','FontSize',10)
grid on
xlabel('xEast [m]')
ylabel('yNorth [m]')
zlabel('zUp [m]')
```

Figure 16. Plotting all layers in 3D



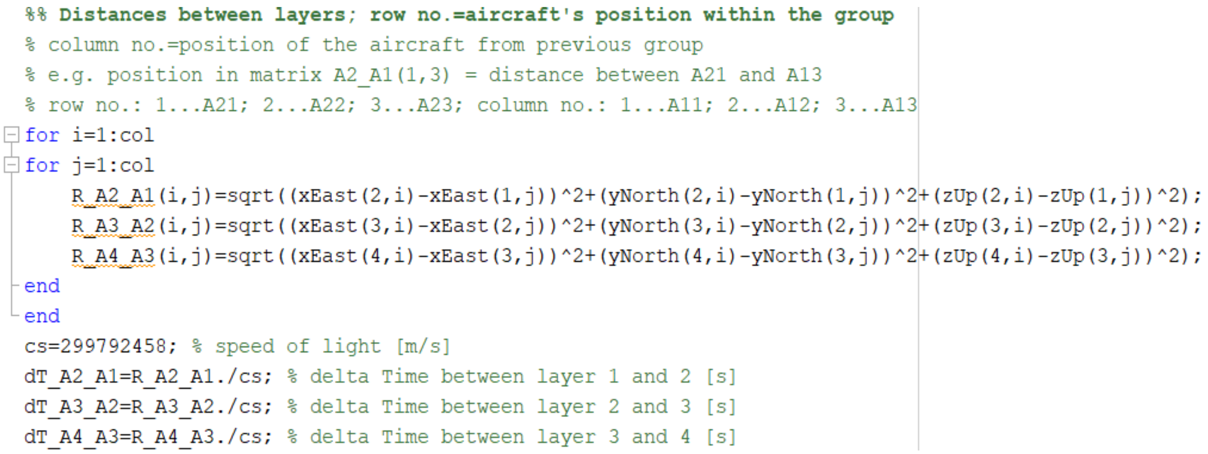
Graph 1. Deployment of Aircraft in 2D - ENU Coordinate System



Graph 2. Deployment of Aircraft in 3D - ENU Coordinate System

Variables

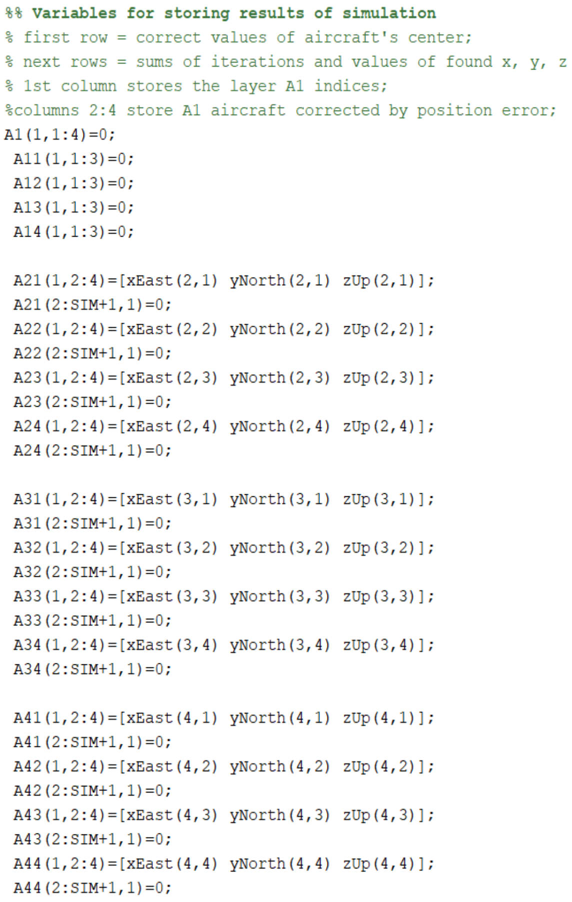
The distances between the layers A2 – A1, A3 – A2 and A4 – A3 are calculated in the Variables segment, see Figure 17. Firstly, the distances are calculated in a loop, where the maximum number of loops is defined by the number of columns in matrix xEast, defined in the Coordinates Transformation. The row number specifies the aircraft's position within the layer; the column number specifies the aircraft's position within the previous layer. For example, an element with position 23 in matrix R_A3_A2, means the distance between-aircraft A32 and aircraft A13. After that, these three variables storing the distances between the layers are divided by the speed of light and saved as the time distance between the layers.



```
%% Distances between layers; row no.=aircraft's position within the group
% column no.=position of the aircraft from previous group
% e.g. position in matrix A2_A1(1,3) = distance between A21 and A13
% row no.: 1...A21; 2...A22; 3...A23; column no.: 1...A11; 2...A12; 3...A13
for i=1:col
for j=1:col
    R_A2_A1(i,j)=sqrt((xEast(2,i)-xEast(1,j))^2+(yNorth(2,i)-yNorth(1,j))^2+(zUp(2,i)-zUp(1,j))^2);
    R_A3_A2(i,j)=sqrt((xEast(3,i)-xEast(2,j))^2+(yNorth(3,i)-yNorth(2,j))^2+(zUp(3,i)-zUp(2,j))^2);
    R_A4_A3(i,j)=sqrt((xEast(4,i)-xEast(3,j))^2+(yNorth(4,i)-yNorth(3,j))^2+(zUp(4,i)-zUp(3,j))^2);
end
end
cs=299792458; % speed of light [m/s]
dT_A2_A1=R_A2_A1./cs; % delta Time between layer 1 and 2 [s]
dT_A3_A2=R_A3_A2./cs; % delta Time between layer 2 and 3 [s]
dT_A4_A3=R_A4_A3./cs; % delta Time between layer 3 and 4 [s]
```

Figure 17. Distance between layers

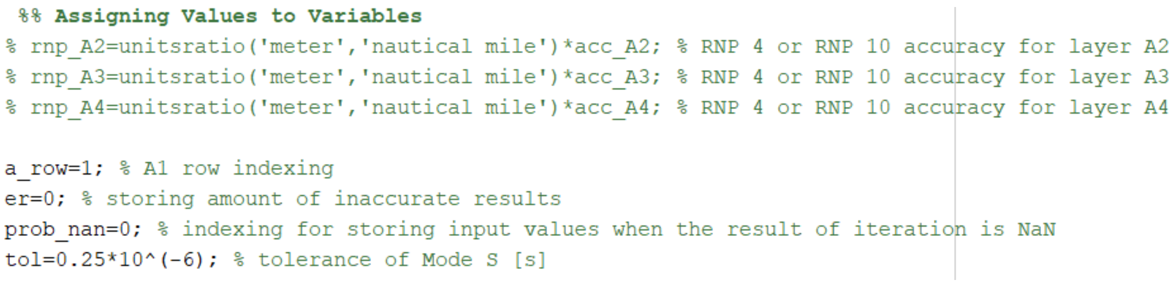
After that, the variables for saving the results of simulations are created, see Figure 18. The first line stores the correct position (without any errors) of a specific aircraft. All the following lines store the number of iterations (first column), x, y, and z in the second, third, and fourth columns, respectively.



```
%% Variables for storing results of simulation
% first row = correct values of aircraft's center;
% next rows = sums of iterations and values of found x, y, z
% 1st column stores the layer A1 indices;
%columns 2:4 store A1 aircraft corrected by position error;
A1(1,1:4)=0;
 A11(1,1:3)=0;
 A12(1,1:3)=0;
 A13(1,1:3)=0;
 A14(1,1:3)=0;

 A21(1,2:4)=[xEast(2,1) yNorth(2,1) zUp(2,1)];
 A21(2:SIM+1,1)=0;
 A22(1,2:4)=[xEast(2,2) yNorth(2,2) zUp(2,2)];
 A22(2:SIM+1,1)=0;
 A23(1,2:4)=[xEast(2,3) yNorth(2,3) zUp(2,3)];
 A23(2:SIM+1,1)=0;
 A24(1,2:4)=[xEast(2,4) yNorth(2,4) zUp(2,4)];
 A24(2:SIM+1,1)=0;

 A31(1,2:4)=[xEast(3,1) yNorth(3,1) zUp(3,1)];
 A31(2:SIM+1,1)=0;
 A32(1,2:4)=[xEast(3,2) yNorth(3,2) zUp(3,2)];
 A32(2:SIM+1,1)=0;
 A33(1,2:4)=[xEast(3,3) yNorth(3,3) zUp(3,3)];
 A33(2:SIM+1,1)=0;
 A34(1,2:4)=[xEast(3,4) yNorth(3,4) zUp(3,4)];
 A34(2:SIM+1,1)=0;

 A41(1,2:4)=[xEast(4,1) yNorth(4,1) zUp(4,1)];
 A41(2:SIM+1,1)=0;
 A42(1,2:4)=[xEast(4,2) yNorth(4,2) zUp(4,2)];
 A42(2:SIM+1,1)=0;
 A43(1,2:4)=[xEast(4,3) yNorth(4,3) zUp(4,3)];
 A43(2:SIM+1,1)=0;
 A44(1,2:4)=[xEast(4,4) yNorth(4,4) zUp(4,4)];
 A44(2:SIM+1,1)=0;
```

Figure 18. Variables for Sorting Results of Simulation

The last part of the Variable section is to assign values to variables, see Figure 19. RNP accuracy lines are commented and are not being considered for the current model. Nevertheless, this section is kept in case of defining the accuracy of the results at the beginning, in the section of The Input Values. The last three variables are set up. The variable “er” saves the number of inaccurate results. The variable “prob_nan” is an index that changes with every new NaN (not a number) value. It is used during the simulations as a changing row index, that stores the NaN results of the iterations. The variable “tol” is a tolerance of the Mode S, and it is later used during the iteration process.



```
 %% Assigning Values to Variables
% rnp_A2=unitsratio('meter','nautical mile')*acc_A2; % RNP 4 or RNP 10 accuracy for layer A2
% rnp_A3=unitsratio('meter','nautical mile')*acc_A3; % RNP 4 or RNP 10 accuracy for layer A3
% rnp_A4=unitsratio('meter','nautical mile')*acc_A4; % RNP 4 or RNP 10 accuracy for layer A4

a_row=1; % A1 row indexing
er=0; % storing amount of inaccurate results
prob_nan=0; % indexing for storing input values when the result of iteration is NaN
tol=0.25*10^(-6); % tolerance of Mode S [s]
```

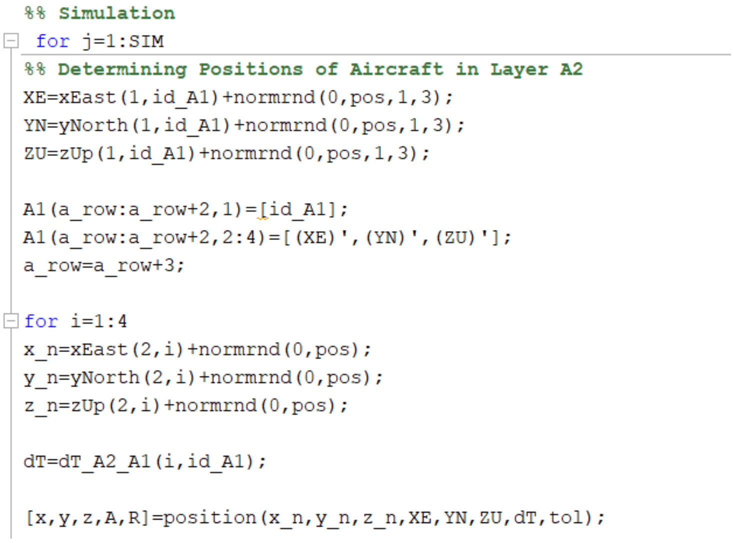
Figure 19. Assigning Values to Variables

Simulation

The simulation has three subsections each for determining the positions of one of the layers A2, A3 and A4. It starts with determining the positions of the aircraft in layer A2, see Figure 20. In the beginning, XE, YN and ZU are defined. Each of them is assigned three aircraft from layer A1, which were specified in the Input Values. XE, YN and YU are assigned the East, North, and Up coordinates, respectively. An error is generated from a standard normal distribution with mean 0 and standard normal deviation (sigma) equal to position error (which is specified in the Input Values). For each of the XE, YN and ZU variables, three different errors are generated and are added to each aircraft's position. These variables stay the same for the whole A2 layer.

After that, a loop with four repetitions starts. Each repetition represents one aircraft from layer A2 with the unknown position. Variables x_n, y_n and z_n are assigned East, North, and Up coordinates, respectively, corrected for the position error. These corrected coordinates represent aircraft's last known position. The last variable that is necessary for the position function is delta time (dT). For each loop, one row (according to the index i) from the time distance matrix is saved to the delta time variable. Which columns from the time distance matrix are chosen depends on the specified aircraft (id_A1). E.g. to determine the position of aircraft A21, the second row of the time distance matrix is assigned.

In the next step, the position function is called. The outcomes are coordinates [x,y,z], amount of performed simulations A and R is a one by three vector containing distances (in meters; corrected for the Mode S error) between the three chosen layer A1 aircraft and the wanted aircraft.



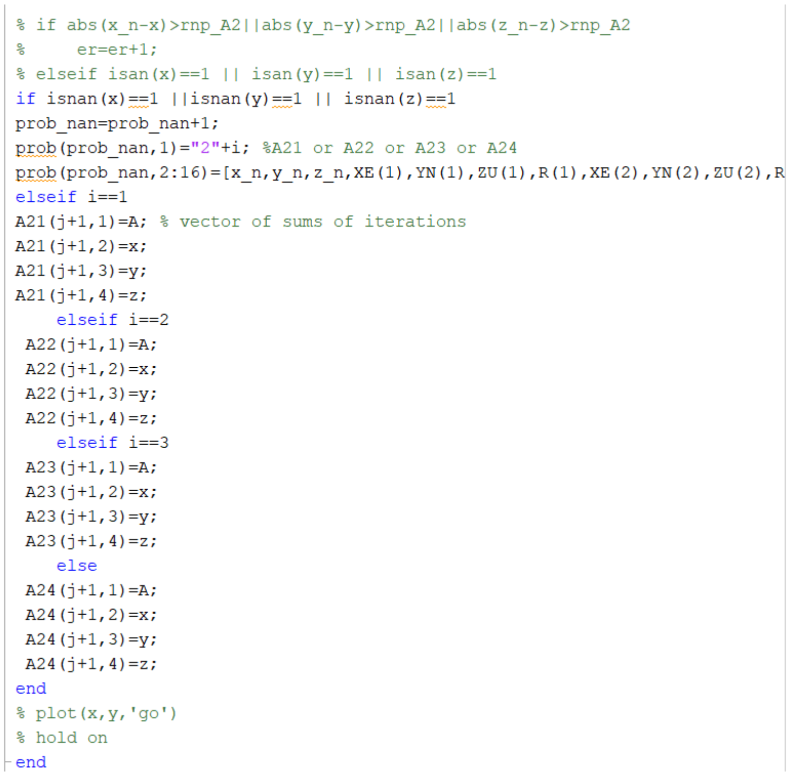
```
%% Simulation
 for j=1:SIM
%% Determining Positions of Aircraft in Layer A2
XE=xEast(1,id_A1)+normrnd(0,pos,1,3);
YN=yNorth(1,id_A1)+normrnd(0,pos,1,3);
ZU=zUp(1,id_A1)+normrnd(0,pos,1,3);

A1(a_row:a_row+2,1)=[id_A1];
A1(a_row:a_row+2,2:4)=[(XE)',(YN)',(ZU)'];
a_row=a_row+3;

for i=1:4
x_n=xEast(2,i)+normrnd(0,pos);
y_n=yNorth(2,i)+normrnd(0,pos);
z_n=zUp(2,i)+normrnd(0,pos);

dT=dT_A2_A1(i,id_A1);

[x,y,z,A,R]=position(x_n,y_n,z_n,XE,YN,ZU,dT,tol);
```

Figure 20. Simulation (Beginning)

After executing the position function, results are filtered, see Figure 21. The first ‘if’ condition compares the difference between resulting coordinates and the original coordinates with the RNP limit, which was set at the beginning of the script. If the difference between the coordinates exceeds the RNP limit, the values are not saved, and the “er” value rises by one. However, this section is commented as another approach on how to treat the outliers was selected. Nevertheless, it is kept in the code as it allows to immediately filter the calculated coordinates which are exceeding the manually defined limits.

The first enabled condition searches for NaN values. If at least one of the conditions is met, the variable ‘prob_nan’ increases by one. It is used as a row index for the variable ‘prob’. This variable stores aircraft’s indices (e.g. A23), the coordinates [x_n, y_n, z_n], which were used as the aircraft’s estimated position for the first iteration, the coordinates [XE, YN, ZU] of the three aircraft used for calculations and their distance (corrected by the Mode S error) from the aircraft with the unknown position.

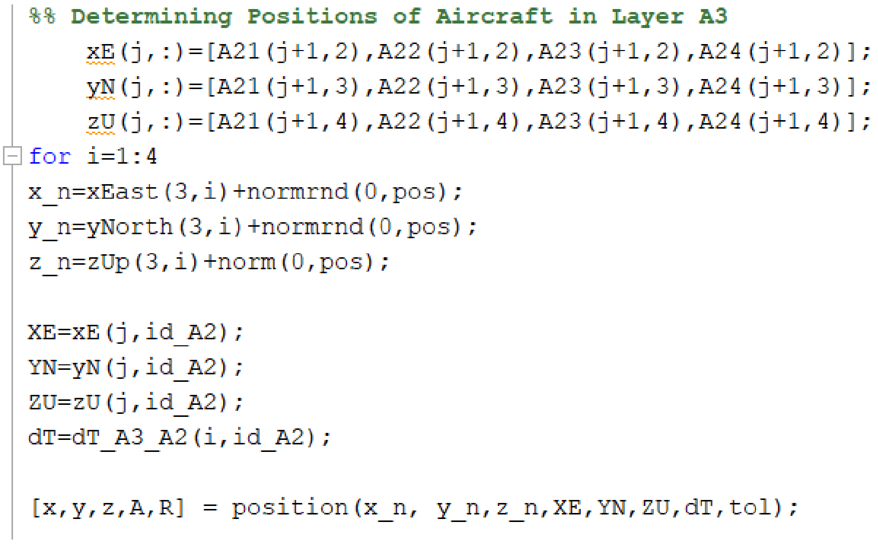
If the there are no NaN values, the number of performed iterations and the calculated coordinates [x, y, z] are assigned to A21, A22, A23 or A24 variable according to the value of index ‘i’. After the loop is over, it is possible to plot the new results. Since the results are being filtered at the end of the script, this option is commented.



```
% if abs(x_n-x)>rnp_A2||abs(y_n-y)>rnp_A2||abs(z_n-z)>rnp_A2
%     er=er+1;
% elseif isan(x)==1 || isan(y)==1 || isan(z)==1
if isnan(x)==1 ||isnan(y)==1 || isnan(z)==1
prob_nan=prob_nan+1;
prob(prob_nan,1)="2"+i; %A21 or A22 or A23 or A24
prob(prob_nan,2:16)=[x_n,y_n,z_n,XE(1),YN(1),ZU(1),R(1),XE(2),YN(2),ZU(2),R(2),XE(3),YN(3),ZU(3),R(3)];
elseif i==1
A21(j+1,1)=A; % vector of sums of iterations
A21(j+1,2)=x;
A21(j+1,3)=y;
A21(j+1,4)=z;
    elseif i==2
 A22(j+1,1)=A;
 A22(j+1,2)=x;
 A22(j+1,3)=y;
 A22(j+1,4)=z;
    elseif i==3
 A23(j+1,1)=A;
 A23(j+1,2)=x;
 A23(j+1,3)=y;
 A23(j+1,4)=z;
    else
 A24(j+1,1)=A;
 A24(j+1,2)=x;
 A24(j+1,3)=y;
 A24(j+1,4)=z;
end
% plot(x,y,'go')
% hold on
end
```

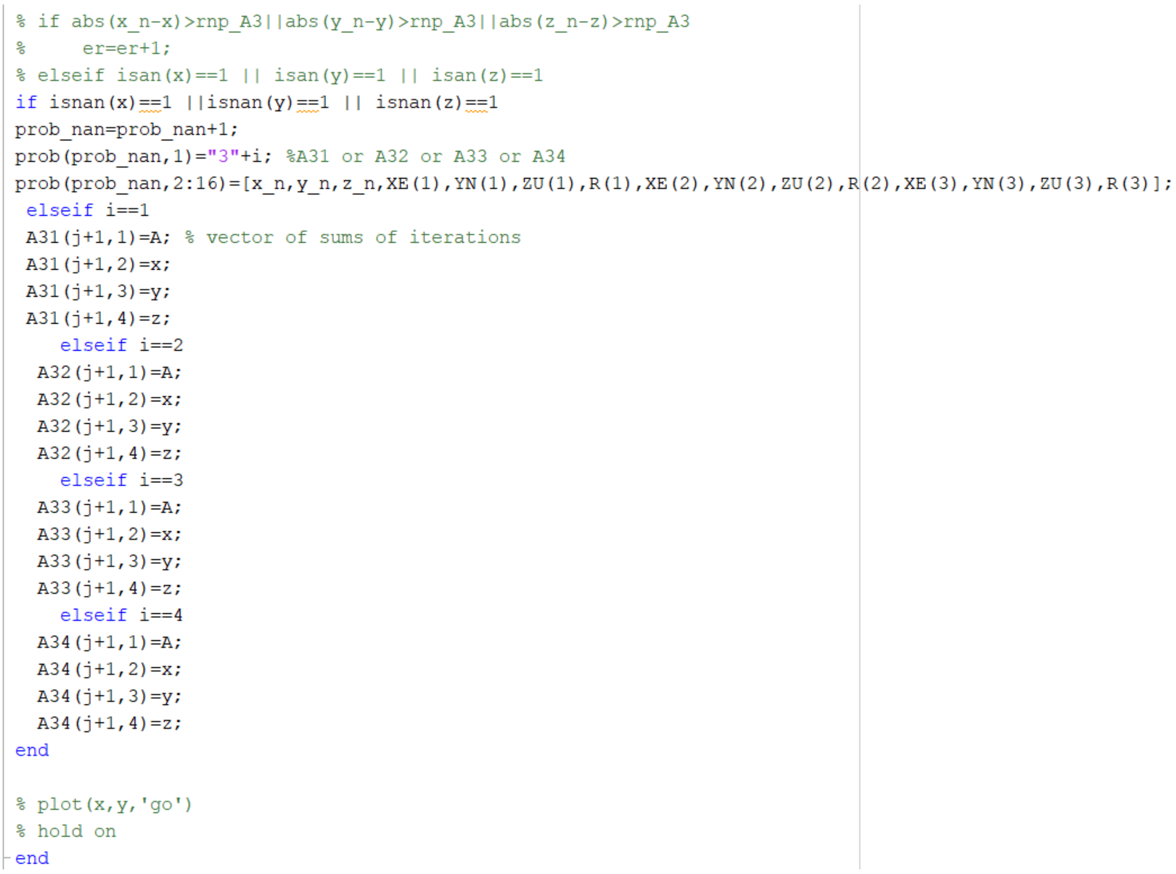
Figure 21. Simulation (Layer A2)

The calculation of layer A3 begins with saving the calculated positions of layer A2 into variables ‘xE’, ‘yN’ and ‘zU’, see Figure 22 and Figure 23. The rest of the A3 part is the same as for determining the A2 layer. The difference is in indexing which is appropriate for determining layer A3, using defined aircraft for layer A3 (so instead of ‘id_A1’, there is ‘id_A2’), using time distance between layer A3 and A2 (‘dT_A3_A2’) and assigning the results into variables A31, A32, A33 and A34.



```
%% Determining Positions of Aircraft in Layer A3
    xE(j,:)=[A21(j+1,2),A22(j+1,2),A23(j+1,2),A24(j+1,2)];
    yN(j,:)=[A21(j+1,3),A22(j+1,3),A23(j+1,3),A24(j+1,3)];
    zU(j,:)=[A21(j+1,4),A22(j+1,4),A23(j+1,4),A24(j+1,4)];
for i=1:4
x_n=xEast(3,i)+normrnd(0,pos);
y_n=yNorth(3,i)+normrnd(0,pos);
z_n=zUp(3,i)+norm(0,pos);

XE=xE(j,id_A2);
YN=yN(j,id_A2);
ZU=zU(j,id_A2);
dT=dT_A3_A2(i,id_A2);

[x,y,z,A,R] = position(x_n, y_n,z_n,XE,YN,ZU,dT,tol);
```

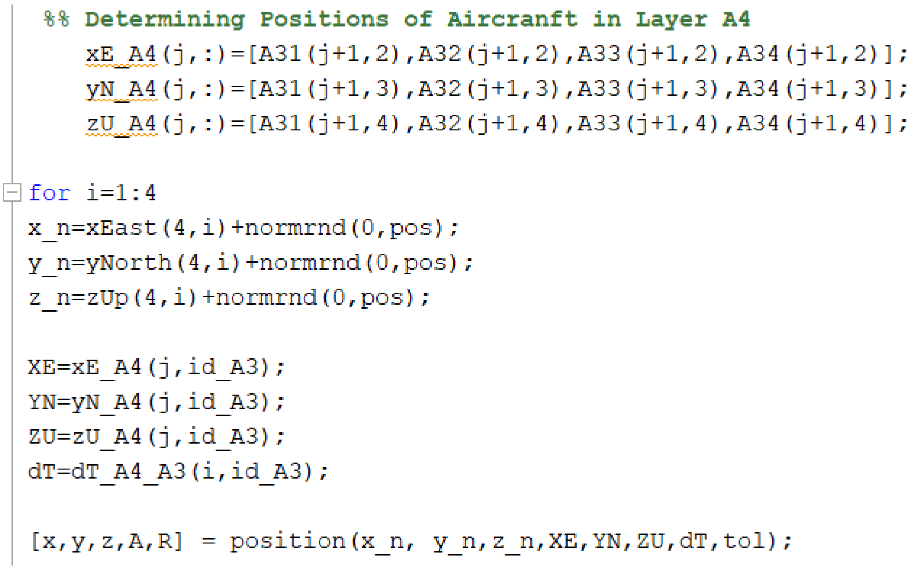
Figure 22. Simulation (Layer A3, part 1)



```
% if abs(x_n-x)>rnp_A3||abs(y_n-y)>rnp_A3||abs(z_n-z)>rnp_A3
%     er=er+1;
% elseif isan(x)==1 || isan(y)==1 || isan(z)==1
if isnan(x)==1 ||isnan(y)==1 || isnan(z)==1
prob_nan=prob_nan+1;
prob(prob_nan,1)="3"+i; %A31 or A32 or A33 or A34
prob(prob_nan,2:16)=[x_n,y_n,z_n,XE(1),YN(1),ZU(1),R(1),XE(2),YN(2),ZU(2),R(2),XE(3),YN(3),ZU(3),R(3)];
 elseif i==1
 A31(j+1,1)=A; % vector of sums of iterations
 A31(j+1,2)=x;
 A31(j+1,3)=y;
 A31(j+1,4)=z;
    elseif i==2
  A32(j+1,1)=A;
  A32(j+1,2)=x;
  A32(j+1,3)=y;
  A32(j+1,4)=z;
    elseif i==3
  A33(j+1,1)=A;
  A33(j+1,2)=x;
  A33(j+1,3)=y;
  A33(j+1,4)=z;
    elseif i==4
  A34(j+1,1)=A;
  A34(j+1,2)=x;
  A34(j+1,3)=y;
  A34(j+1,4)=z;
end

% plot(x,y,'go')
% hold on
end
```

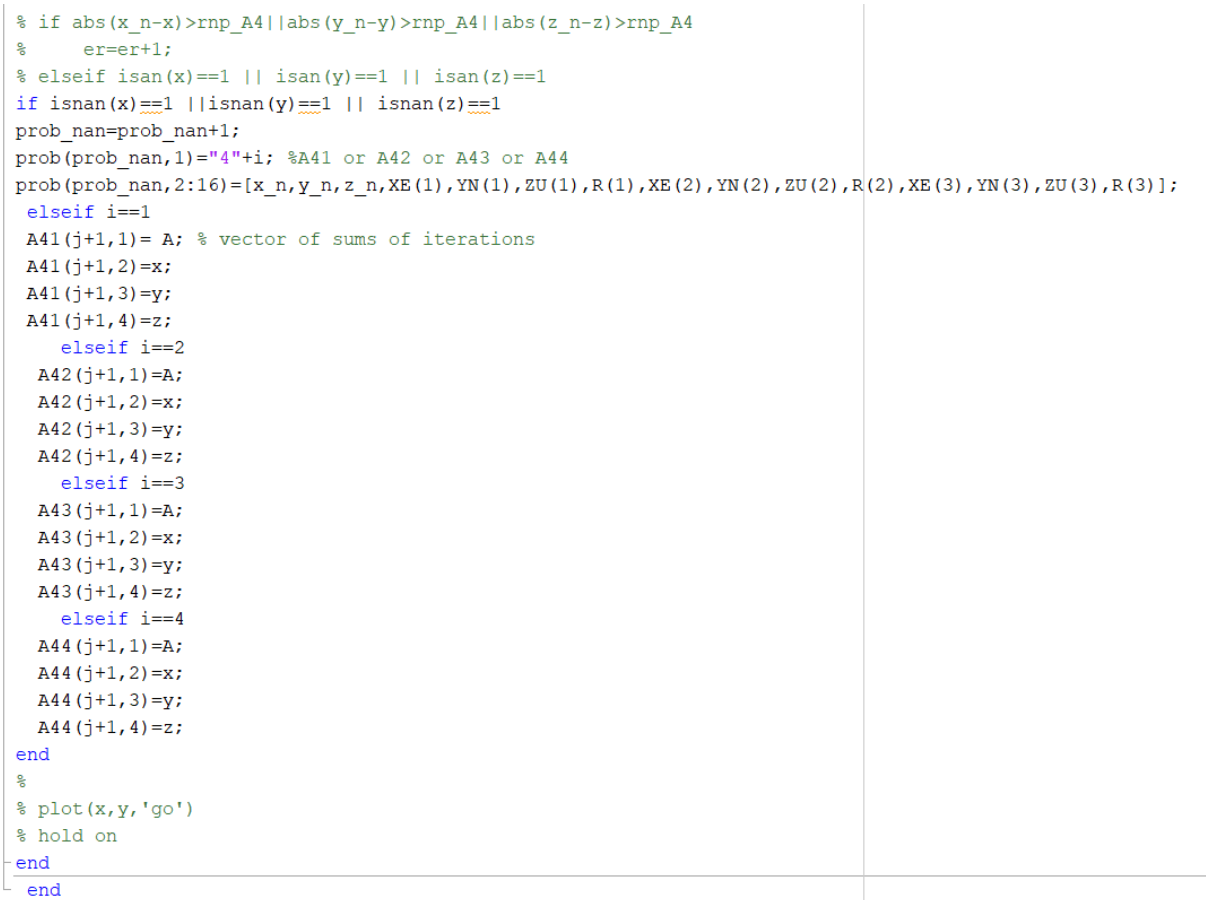
Figure 23. Simulation (Layer A3, part 2)

The last section of the Simulation part is determining layer A4, see Figure 24. It is the same as for layer A3, but with indexing appropriate for determining layer A4, using defined aircraft for layer A4 (so instead of ‘id_A2’, there is ‘id_A3’), using time distance between layer A4 and A3 (‘dT_A4_A3’) and assigning the results into variables A41, A42, A43 and A44.



```
 %% Determining Positions of Aircranft in Layer A4
    xE_A4(j,:)=[A31(j+1,2),A32(j+1,2),A33(j+1,2),A34(j+1,2)];
    yN_A4(j,:)=[A31(j+1,3),A32(j+1,3),A33(j+1,3),A34(j+1,3)];
    zU_A4(j,:)=[A31(j+1,4),A32(j+1,4),A33(j+1,4),A34(j+1,4)];

for i=1:4
x_n=xEast(4,i)+normrnd(0,pos);
y_n=yNorth(4,i)+normrnd(0,pos);
z_n=zUp(4,i)+normrnd(0,pos);

XE=xE_A4(j,id_A3);
YN=yN_A4(j,id_A3);
ZU=zU_A4(j,id_A3);
dT=dT_A4_A3(i,id_A3);

[x,y,z,A,R] = position(x_n, y_n,z_n,XE,YN,ZU,dT,tol);
```

Figure 24. Simulation (Layer A4, part 1)

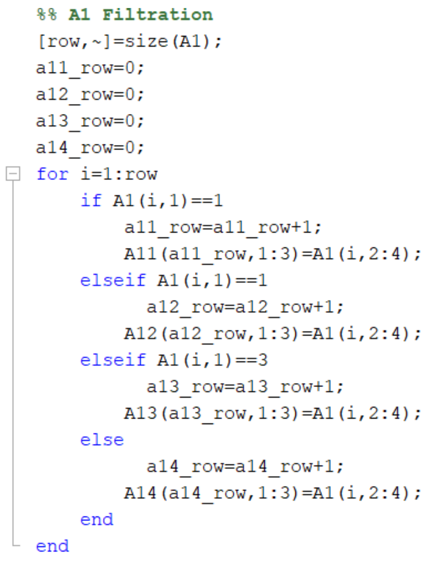


```
% if abs(x_n-x)>rnp_A4||abs(y_n-y)>rnp_A4||abs(z_n-z)>rnp_A4
%     er=er+1;
% elseif isan(x)==1 || isan(y)==1 || isan(z)==1
if isnan(x)==1 ||isnan(y)==1 || isnan(z)==1
prob_nan=prob_nan+1;
prob(prob_nan,1)="4"+i; %A41 or A42 or A43 or A44
prob(prob_nan,2:16)=[x_n,y_n,z_n,XE(1),YN(1),ZU(1),R(1),XE(2),YN(2),ZU(2),R(2),XE(3),YN(3),ZU(3),R(3)];
 elseif i==1
 A41(j+1,1)= A; % vector of sums of iterations
 A41(j+1,2)=x;
 A41(j+1,3)=y;
 A41(j+1,4)=z;
    elseif i==2
  A42(j+1,1)=A;
  A42(j+1,2)=x;
  A42(j+1,3)=y;
  A42(j+1,4)=z;
    elseif i==3
  A43(j+1,1)=A;
  A43(j+1,2)=x;
  A43(j+1,3)=y;
  A43(j+1,4)=z;
    elseif i==4
  A44(j+1,1)=A;
  A44(j+1,2)=x;
  A44(j+1,3)=y;
  A44(j+1,4)=z;
end
%
% plot(x,y,'go')
% hold on
end
 end
```

Figure 25. Simulation (Layer A4, part 2)

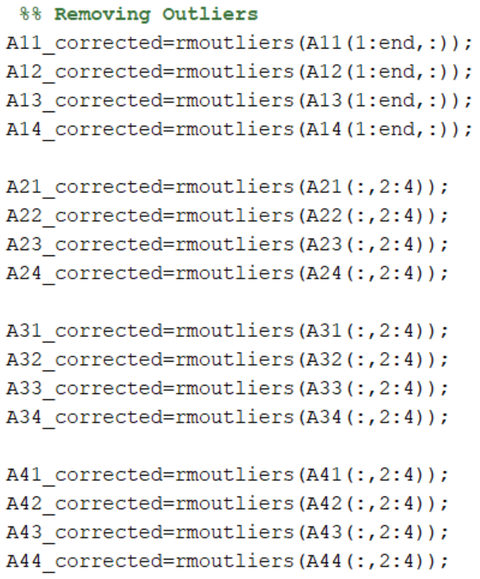
Processing Results

For the purpose of further statistical computation, the selected aircraft from the first layer are saved into variables and sorted, see Figure 26. After the simulation is over, the obtained positions are filtered using MATLAB’s function for removing outliers called ‘rmoutliers’, see Figure 27. The filtered data are used to find the standard deviation using another built-in function called ‘std’. The standard deviation is necessary for calculating the 2DRMS, which determines the position error, see Figure 28.



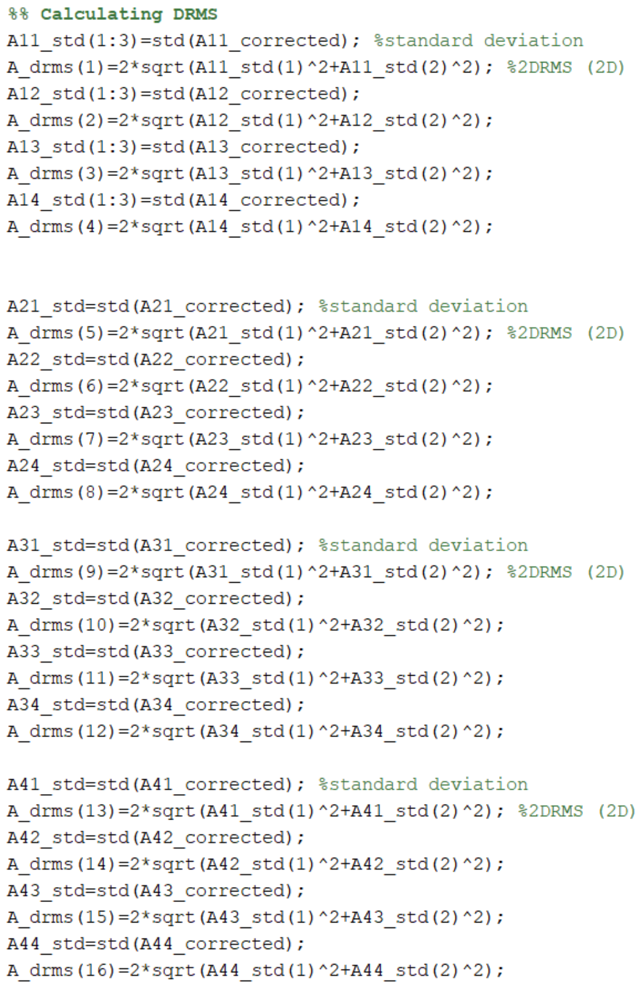
```
%% A1 Filtration
[row,~]=size(A1);
a11_row=0;
a12_row=0;
a13_row=0;
a14_row=0;
for i=1:row
    if A1(i,1)==1
        a11_row=a11_row+1;
        A11(a11_row,1:3)=A1(i,2:4);
    elseif A1(i,1)==1
          a12_row=a12_row+1;
        A12(a12_row,1:3)=A1(i,2:4);
    elseif A1(i,1)==3
          a13_row=a13_row+1;
        A13(a13_row,1:3)=A1(i,2:4);
    else
          a14_row=a14_row+1;
        A14(a14_row,1:3)=A1(i,2:4);
    end
end
```

Figure 26. Removing Outliers



```
 %% Removing Outliers
A11_corrected=rmoutliers(A11(1:end,:));
A12_corrected=rmoutliers(A12(1:end,:));
A13_corrected=rmoutliers(A13(1:end,:));
A14_corrected=rmoutliers(A14(1:end,:));

A21_corrected=rmoutliers(A21(:,2:4));
A22_corrected=rmoutliers(A22(:,2:4));
A23_corrected=rmoutliers(A23(:,2:4));
A24_corrected=rmoutliers(A24(:,2:4));

A31_corrected=rmoutliers(A31(:,2:4));
A32_corrected=rmoutliers(A32(:,2:4));
A33_corrected=rmoutliers(A33(:,2:4));
A34_corrected=rmoutliers(A34(:,2:4));

A41_corrected=rmoutliers(A41(:,2:4));
A42_corrected=rmoutliers(A42(:,2:4));
A43_corrected=rmoutliers(A43(:,2:4));
A44_corrected=rmoutliers(A44(:,2:4));
```

Figure 27. Removing Outliers

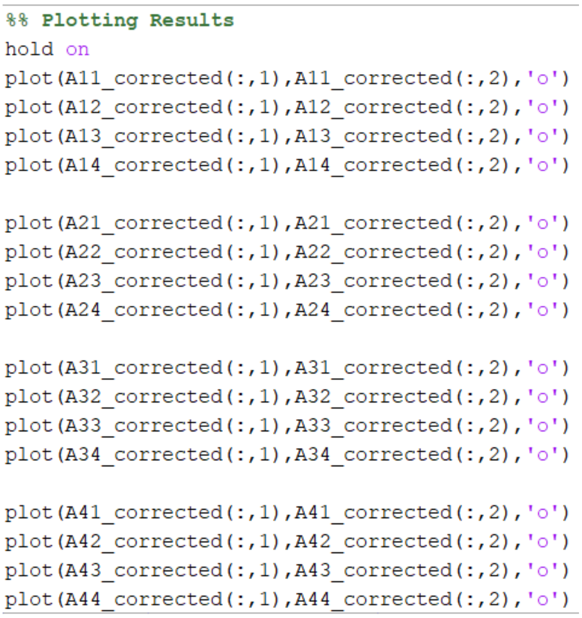


```
%% Calculating DRMS
A11_std(1:3)=std(A11_corrected); %standard deviation
A_drms(1)=2*sqrt(A11_std(1)^2+A11_std(2)^2); %2DRMS (2D)
A12_std(1:3)=std(A12_corrected);
A_drms(2)=2*sqrt(A12_std(1)^2+A12_std(2)^2);
A13_std(1:3)=std(A13_corrected);
A_drms(3)=2*sqrt(A13_std(1)^2+A13_std(2)^2);
A14_std(1:3)=std(A14_corrected);
A_drms(4)=2*sqrt(A14_std(1)^2+A14_std(2)^2);


A21_std=std(A21_corrected); %standard deviation
A_drms(5)=2*sqrt(A21_std(1)^2+A21_std(2)^2); %2DRMS (2D)
A22_std=std(A22_corrected);
A_drms(6)=2*sqrt(A22_std(1)^2+A22_std(2)^2);
A23_std=std(A23_corrected);
A_drms(7)=2*sqrt(A23_std(1)^2+A23_std(2)^2);
A24_std=std(A24_corrected);
A_drms(8)=2*sqrt(A24_std(1)^2+A24_std(2)^2);

A31_std=std(A31_corrected); %standard deviation
A_drms(9)=2*sqrt(A31_std(1)^2+A31_std(2)^2); %2DRMS (2D)
A32_std=std(A32_corrected);
A_drms(10)=2*sqrt(A32_std(1)^2+A32_std(2)^2);
A33_std=std(A33_corrected);
A_drms(11)=2*sqrt(A33_std(1)^2+A33_std(2)^2);
A34_std=std(A34_corrected);
A_drms(12)=2*sqrt(A34_std(1)^2+A34_std(2)^2);

A41_std=std(A41_corrected); %standard deviation
A_drms(13)=2*sqrt(A41_std(1)^2+A41_std(2)^2); %2DRMS (2D)
A42_std=std(A42_corrected);
A_drms(14)=2*sqrt(A42_std(1)^2+A42_std(2)^2);
A43_std=std(A43_corrected);
A_drms(15)=2*sqrt(A43_std(1)^2+A43_std(2)^2);
A44_std=std(A44_corrected);
A_drms(16)=2*sqrt(A44_std(1)^2+A44_std(2)^2);
```

Figure 28. Calculating 2DRMS

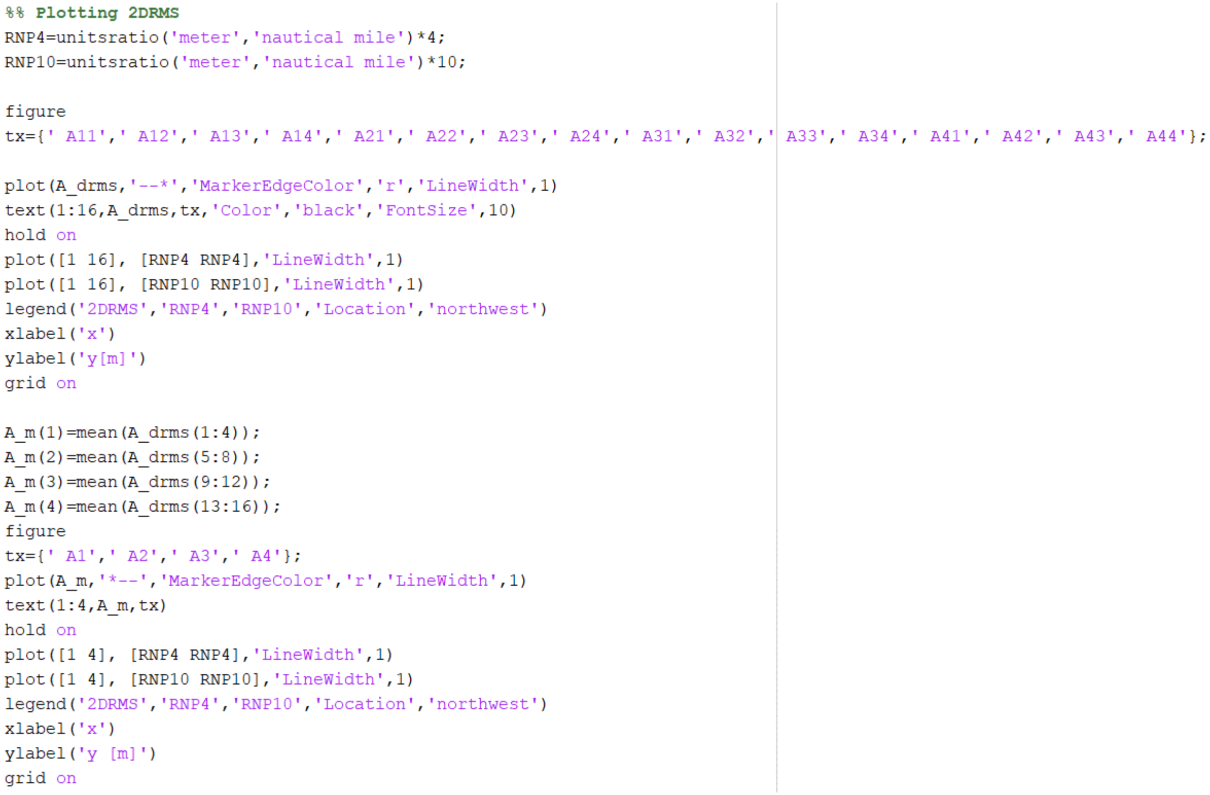
Plotting Results

The last step is to plot the results, see Figure 29. Firstly, the corrected aircraft’s positions are plotted into the Figure 36. Secondly, 2DRSM is plotted for each aircraft. Thirdly, the mean of the 2DRMS is calculated and plotted for each layer.



```
%% Plotting Results
hold on
plot(A11_corrected(:,1),A11_corrected(:,2),'o')
plot(A12_corrected(:,1),A12_corrected(:,2),'o')
plot(A13_corrected(:,1),A13_corrected(:,2),'o')
plot(A14_corrected(:,1),A14_corrected(:,2),'o')

plot(A21_corrected(:,1),A21_corrected(:,2),'o')
plot(A22_corrected(:,1),A22_corrected(:,2),'o')
plot(A23_corrected(:,1),A23_corrected(:,2),'o')
plot(A24_corrected(:,1),A24_corrected(:,2),'o')

plot(A31_corrected(:,1),A31_corrected(:,2),'o')
plot(A32_corrected(:,1),A32_corrected(:,2),'o')
plot(A33_corrected(:,1),A33_corrected(:,2),'o')
plot(A34_corrected(:,1),A34_corrected(:,2),'o')

plot(A41_corrected(:,1),A41_corrected(:,2),'o')
plot(A42_corrected(:,1),A42_corrected(:,2),'o')
plot(A43_corrected(:,1),A43_corrected(:,2),'o')
plot(A44_corrected(:,1),A44_corrected(:,2),'o')
```

Figure 295. Plotting Results



```
%% Plotting 2DRMS
RNP4=unitsratio('meter','nautical mile')*4;
RNP10=unitsratio('meter','nautical mile')*10;

figure
tx={' A11',' A12',' A13',' A14',' A21',' A22',' A23',' A24',' A31',' A32',' A33',' A34',' A41',' A42',' A43',' A44'};

plot(A_drms,'--*','MarkerEdgeColor','r','LineWidth',1)
text(1:16,A_drms,tx,'Color','black','FontSize',10)
hold on
plot([1 16], [RNP4 RNP4],'LineWidth',1)
plot([1 16], [RNP10 RNP10],'LineWidth',1)
legend('2DRMS','RNP4','RNP10','Location','northwest')
xlabel('x')
ylabel('y[m]')
grid on

A_m(1)=mean(A_drms(1:4));
A_m(2)=mean(A_drms(5:8));
A_m(3)=mean(A_drms(9:12));
A_m(4)=mean(A_drms(13:16));
figure
tx={' A1',' A2',' A3',' A4'};
plot(A_m,'*--','MarkerEdgeColor','r','LineWidth',1)
text(1:4,A_m,tx)
hold on
plot([1 4], [RNP4 RNP4],'LineWidth',1)
plot([1 4], [RNP10 RNP10],'LineWidth',1)
legend('2DRMS','RNP4','RNP10','Location','northwest')
xlabel('x')
ylabel('y [m]')
grid on
```

Figure 30. Plotting 2DRMS

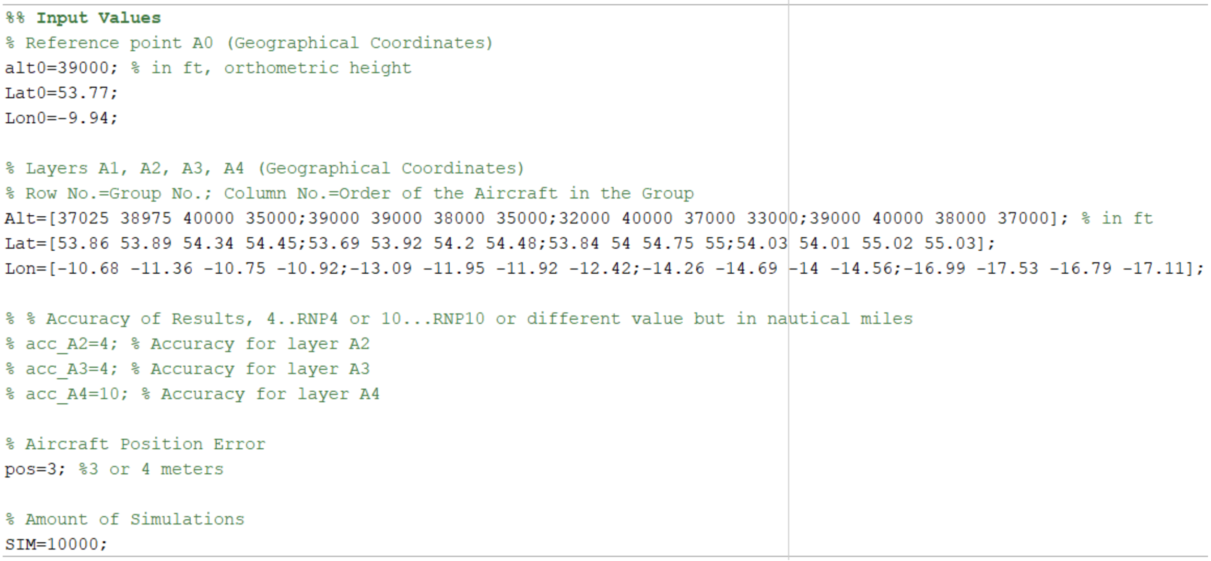
6.2 Model v5_4A

The script Model v5_A4 consists of the following sections: Input Values, Coordinates Transformation, Plotting Real Traffic Situation, Variables, Simulation, Processing Results, Plotting Results.

Only sections Input Values and Simulation are going to be described since the rest of the sections are entirely the same as in Model A3.

Input Values

The Input Values section, see Figure 31, is the same as in Model A3, except for the option to choose reference aircraft. This option is not implemented in this model since there is a different approach to choosing them.

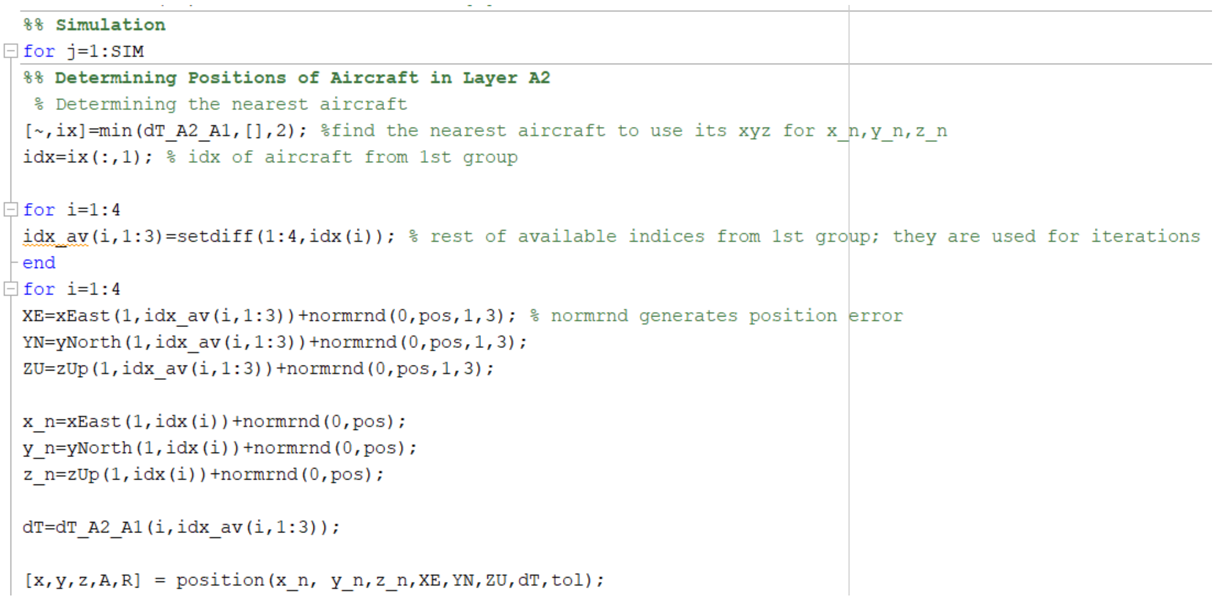


```
%% Input Values
% Reference point A0 (Geographical Coordinates)
alt0=39000; % in ft, orthometric height
Lat0=53.77;
Lon0=-9.94;

% Layers A1, A2, A3, A4 (Geographical Coordinates)
% Row No.=Group No.; Column No.=Order of the Aircraft in the Group
Alt=[37025 38975 40000 35000;39000 39000 38000 35000;32000 40000 37000 33000;39000 40000 38000 37000]; % in ft
Lat=[53.86 53.89 54.34 54.45;53.69 53.92 54.2 54.48;53.84 54 54.75 55;54.03 54.01 55.02 55.03];
Lon=[-10.68 -11.36 -10.75 -10.92;-13.09 -11.95 -11.92 -12.42;-14.26 -14.69 -14 -14.56;-16.99 -17.53 -16.79 -17.11];

% % Accuracy of Results, 4..RNP4 or 10...RNP10 or different value but in nautical miles
% acc_A2=4; % Accuracy for layer A2
% acc_A3=4; % Accuracy for layer A3
% acc_A4=10; % Accuracy for layer A4

% Aircraft Position Error
pos=3; %3 or 4 meters

% Amount of Simulations
SIM=10000;
```

Figure 316. Input Values (Model 4A)

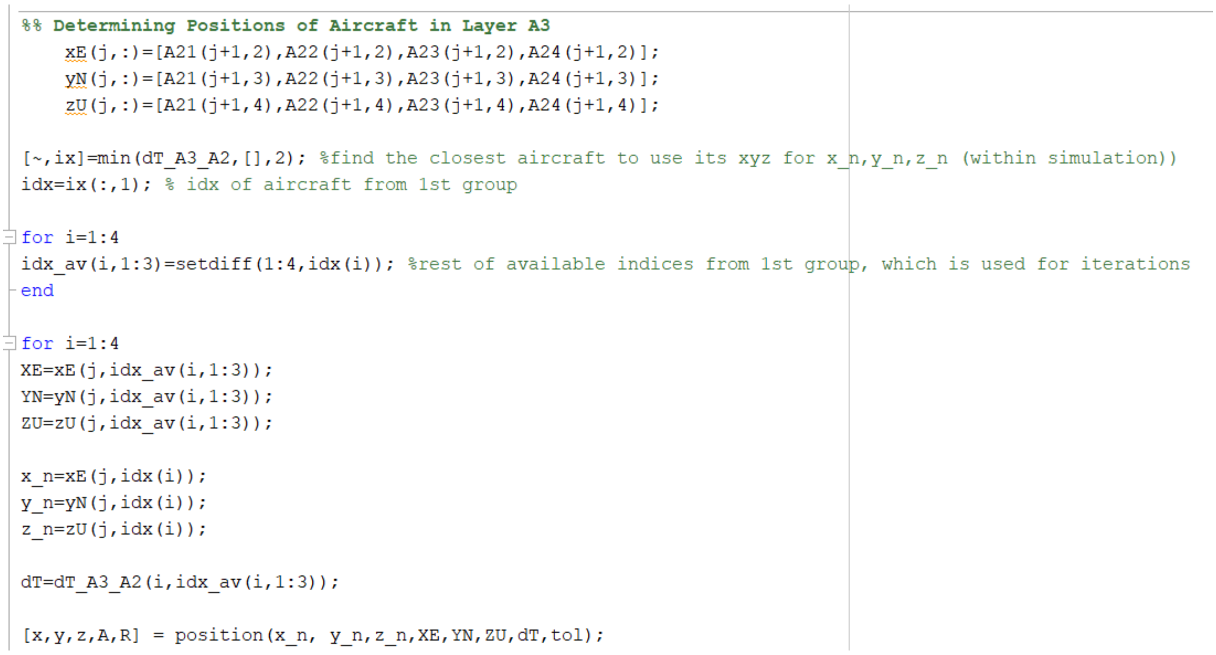
Simulation

Within this section, the nearest aircraft is determined based on the smallest time distance between the layers A1 and A2, see Figure 32. Matrix indices of the shortest distances are saved in the variable ‘idx’, which is used to find the available indices of aircraft from layer 4. The principle is the same also for Layer A3 and A4, only instead of indexing into matrices xEast, yNorth and zUp, it is indexed into xE, yN and zU, see Figure 33. The rest is the same as in Model 3A.



```
%% Simulation
for j=1:SIM
%% Determining Positions of Aircraft in Layer A2
 % Determining the nearest aircraft
[~,ix]=min(dT_A2_A1,[],2); %find the nearest aircraft to use its xyz for x_n,y_n,z_n
idx=ix(:,1); % idx of aircraft from 1st group

for i=1:4
idx_av(i,1:3)=setdiff(1:4,idx(i)); % rest of available indices from 1st group; they are used for iterations
end
for i=1:4
XE=xEast(1,idx_av(i,1:3))+normrnd(0,pos,1,3); % normrnd generates position error
YN=yNorth(1,idx_av(i,1:3))+normrnd(0,pos,1,3);
ZU=zUp(1,idx_av(i,1:3))+normrnd(0,pos,1,3);

x_n=xEast(1,idx(i))+normrnd(0,pos);
y_n=yNorth(1,idx(i))+normrnd(0,pos);
z_n=zUp(1,idx(i))+normrnd(0,pos);

dT=dT_A2_A1(i,idx_av(i,1:3));

[x,y,z,A,R] = position(x_n, y_n,z_n,XE,YN,ZU,dT,tol);
```

Figure 327. Simulation (Model 4A)



```
%% Determining Positions of Aircraft in Layer A3
    xE(j,:)=[A21(j+1,2),A22(j+1,2),A23(j+1,2),A24(j+1,2)];
    yN(j,:)=[A21(j+1,3),A22(j+1,3),A23(j+1,3),A24(j+1,3)];
    zU(j,:)=[A21(j+1,4),A22(j+1,4),A23(j+1,4),A24(j+1,4)];

[~,ix]=min(dT_A3_A2,[],2); %find the closest aircraft to use its xyz for x_n,y_n,z_n (within simulation))
idx=ix(:,1); % idx of aircraft from 1st group

for i=1:4
idx_av(i,1:3)=setdiff(1:4,idx(i)); %rest of available indices from 1st group, which is used for iterations
end

for i=1:4
XE=xE(j,idx_av(i,1:3));
YN=yN(j,idx_av(i,1:3));
ZU=zU(j,idx_av(i,1:3));

x_n=xE(j,idx(i));
y_n=yN(j,idx(i));
z_n=zU(j,idx(i));

dT=dT_A3_A2(i,idx_av(i,1:3));

[x,y,z,A,R] = position(x_n, y_n,z_n,XE,YN,ZU,dT,tol);
```

Figure 33. Simulation (Model 4A, Layer A3)

7 Results

Monte Carlo simulation has been applied to both proposed models to find the positioning accuracy. For both models, the number iterations were set to 10 000.

For model each model different simulations were run to compare the different effect of different values for the first iteration.

The “y” axis represents the value of 2DRMS.

7.1 Model A3

As can be seen on the figures below, the position error rises with each layer. The figure below, displays 2DRMS for each aircraft. It is visible, that after applying the 2DRMS,, all layers fulfil the requirements of RNP4. It is important to mention, that by removing the outliers the results are influenced, e.g. in layer A4 approximately 1/3 of position results were removed, which with 10 000 simulations is around 3000 results, for layer A3 it was around ¼ of results removed and for A2 it was approximately 1/10. See Figure 34, Figure 35 and Figure 36.

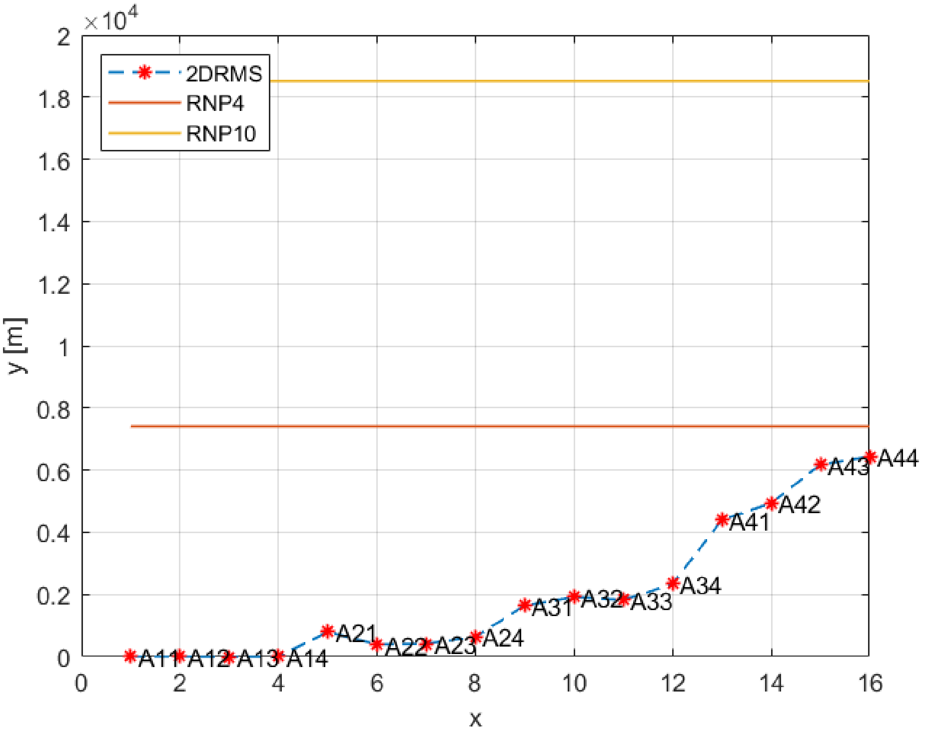


Figure 348. Model A3 2DRMS (All Aircraft)

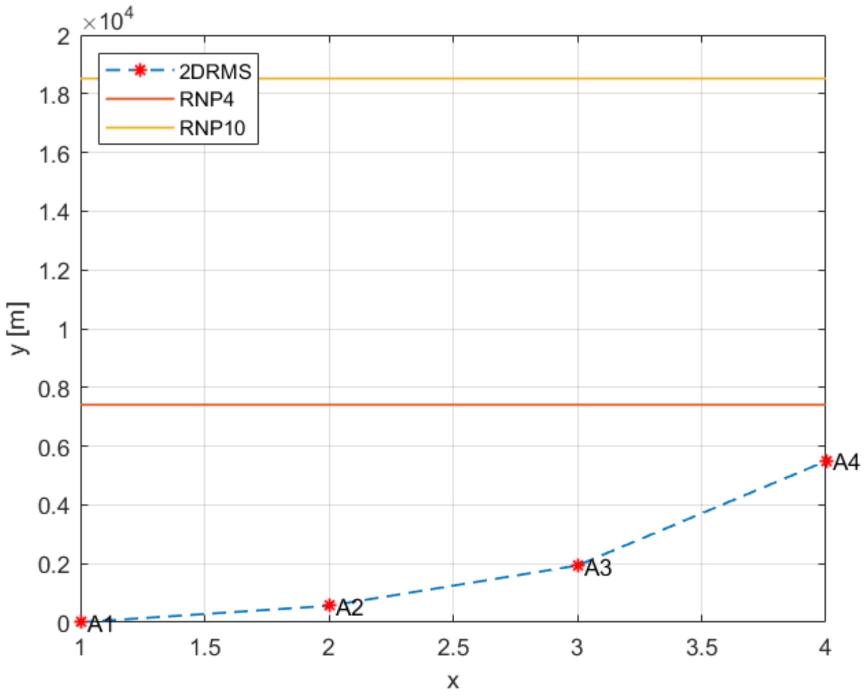


Figure 35. Model A3 2DRMS (Layers)

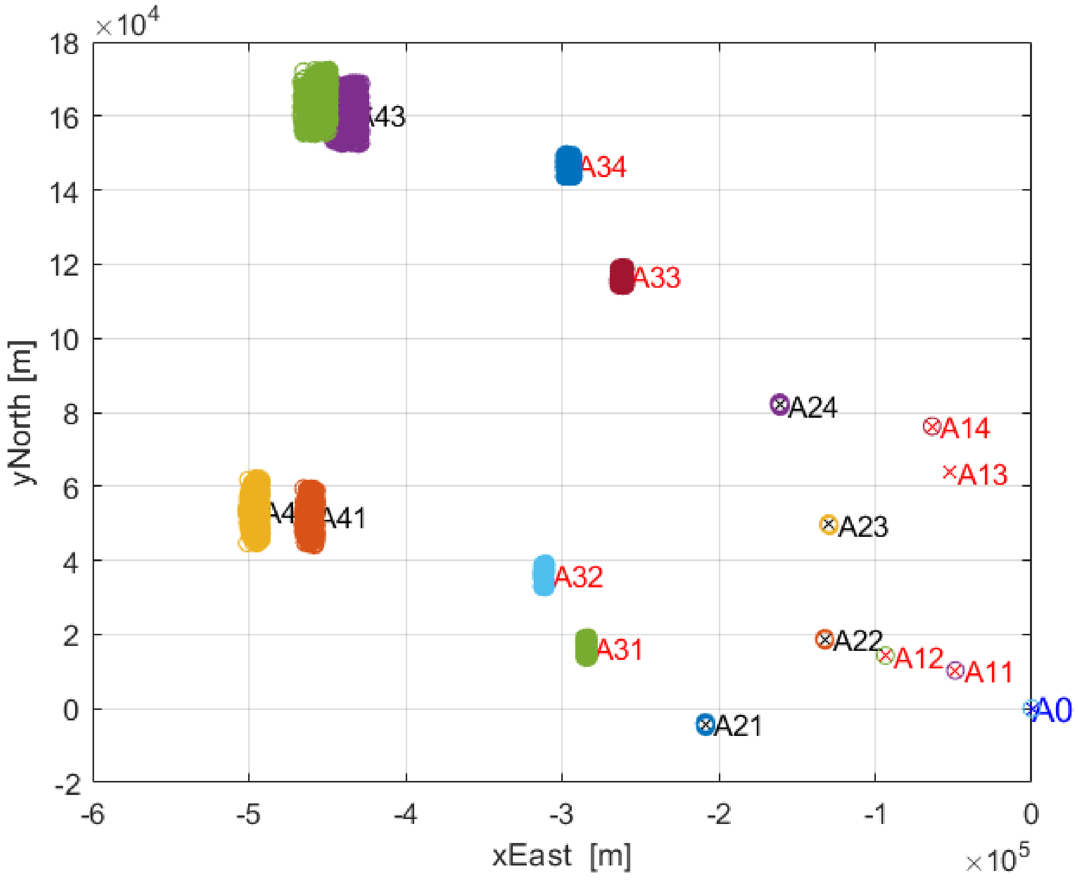


Figure 36. Model A3 Results

7.2 Model A4

Comparing results of this model, which is using different method for choosing reference aircraft, the worsening of results is noticeable and expected, as by using the reference position of computed aircraft the position error rises.

The number of outliers is approximately same as for model A3. Layer A2 fulfills requirements of RNP4, A3 fulfills requirements of RNP 10 and A4 is extremely far from RNP10. See Figure 37 and Figure 38 , Figure 39, Figure 40.

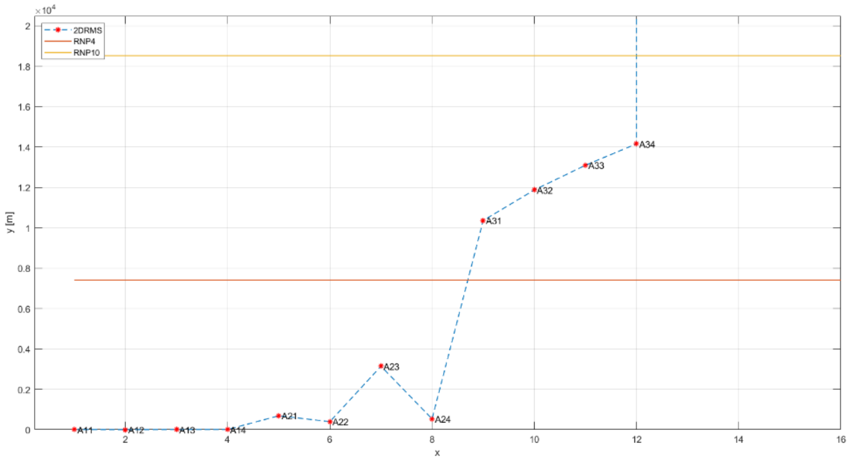


Figure 37. Model A4 2DRMS (All Aircraft)

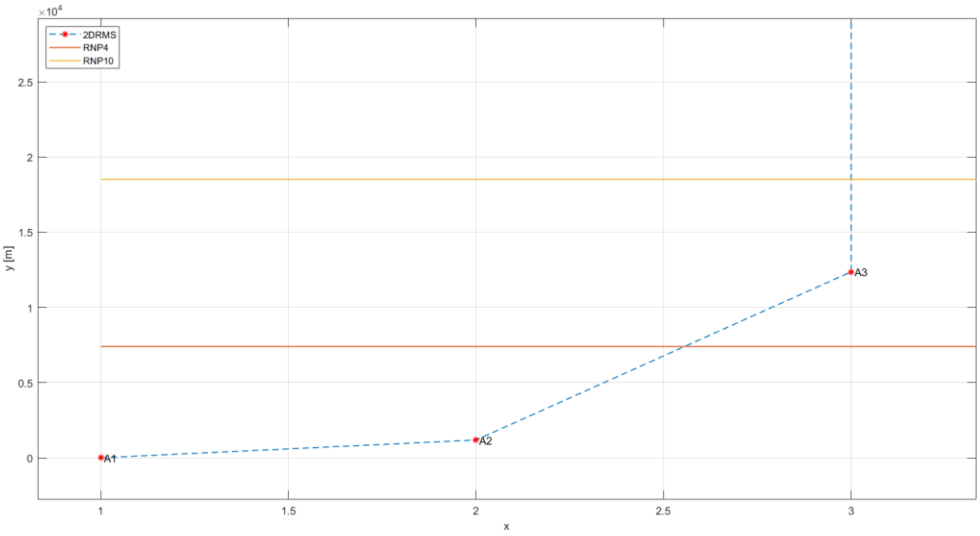


Figure 389. Model A4 2DRMS (Layers)

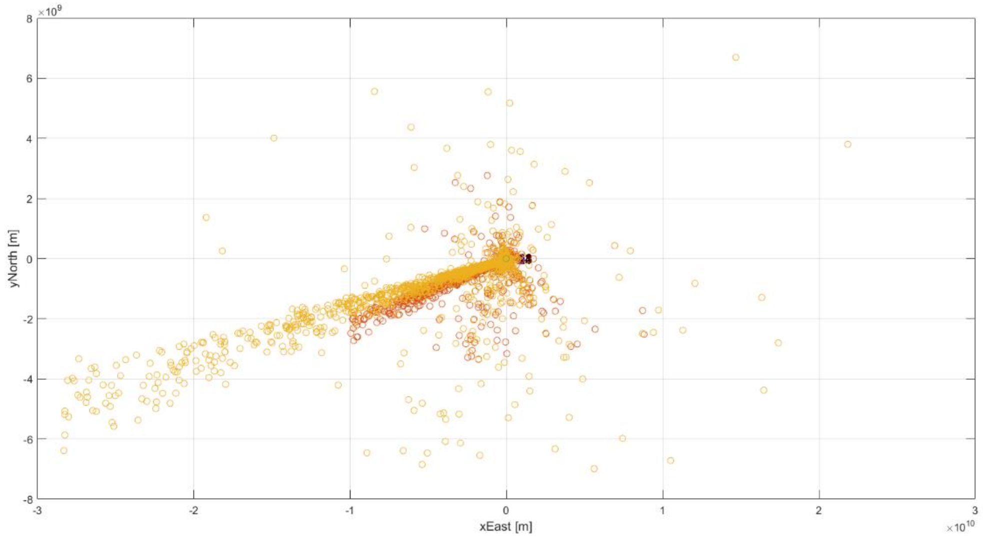


Figure 39. Model A4 Results

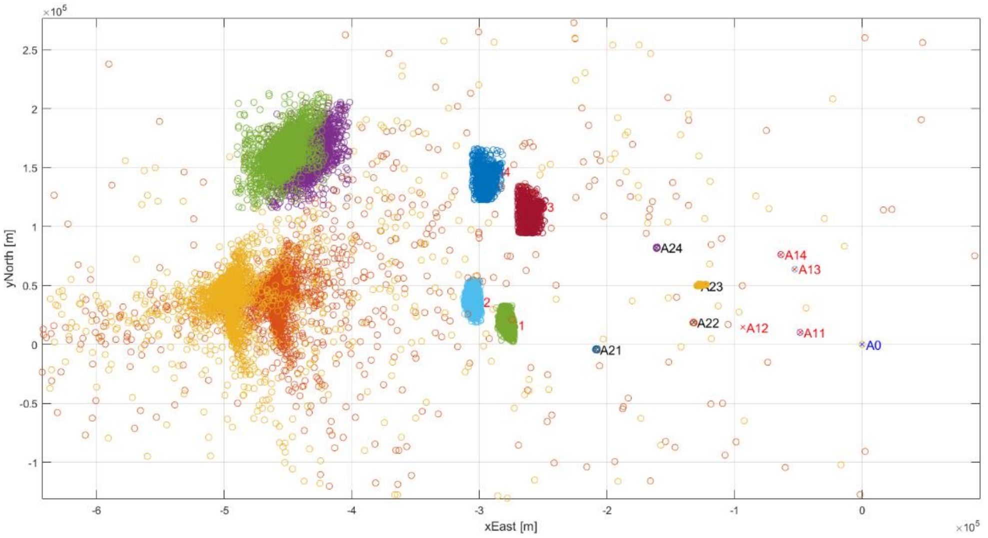


Figure 40. Model A4 Results (Detailed)

7.3 Implementation in real life situations

It is important to mention how both proposed models could be applied in real life. Speaking of Model A3, all the layers fulfil both, the RNP 4 and RNP 10. However, it is important to mention, that the results fulfil the requirements only after removing the outliers. Therefore, an APNT system using this method must be able to calculate and correctly evaluate the extreme values. Since Model A4 fulfils the RNP4 only till second layer and RNP 10 till third layer, it is questionable if such a system would be worth it in low density area.

8 Conclusion

The aim of this thesis was to design and evaluate an alternative navigation solution model extending the availability of the terrestrial concepts in the oceanic and remote areas as a possible GNSS backup in case of the GNSS interference.

The input data for the model proposal was a real traffic situation consisting of five layers of the aircraft. The first layer, layer A0, contains only one row, which means that there is only one aircraft. The coordinates of the aircraft A0 were used as the point of origin for the East North Up (ENU) coordinate system that was used for this model. The layers A1, A2, A3 and A4 consist of four rows each. The first layer is used as a reference for the other three layers.

One of the important questions when designing this model was to choose the values for the first iteration leading to the aircraft computed position. Multiple possibilities were simulated. The reason for this was to propose a model where the last known position of the aircraft is not necessary, and therefore it offers another backup layer, but it increases the dependency on the surrounding aircraft and the accuracy of their position information.

One of the proposed options was to use the point of origin, which was almost immediately rejected, as the point of origin was for the layers A3 and A4 too far, and therefore the inaccuracy was quite high. The next choice was to find an imaginary center of gravity of the polygon shaped by the aircraft in the previous layer (e.g. when trying to allocate the aircraft in the layer A2, the center of gravity was inside the polygon created by all four aircraft in the layer A1). This solution was more accurate than using the point of origin, nevertheless the position error was still enormous. This type of solution also showed to be too complicated as there was another, better thought of which point is the best for the first iteration and will lead to an accurate solution. This leads to an option which, at the end, was modelled and evaluated.

The talk is about the Model A4. In this model the four aircraft from the previous layers are evaluated in terms of the time distance from the aircraft which needs to be located. The aircraft closest in time is then interrogated to obtain information about its coordinates. These are used as the position of the searched aircraft or the first iteration. The Monte Carlo simulation, consisting of 10 000 iterations, was applied to evaluate the position accuracy. The first two layers, A1 and A2, fulfil the requirements of the RNP 4. It is necessary to mention that around 1% of the computed results for the layer A1 and between 10 to 20 % for the layer A2 were treated as outliers and therefore removed. The third layer fulfils the requirement of the RNP 10, with 10-20% of the removed outliers. The fourth layer, the A4, is far beyond fulfilling any of these specifications with around 50% being removed.

The second designed model, the Model A3, uses the last known position of the searched aircraft (before the GNSS unavailability) as an input for the first iteration. The convenience of this model is in its lower dependency on the other aircraft as it uses its own coordinates for the computation. The accuracy of this was much better than the accuracy of the previous model. All four layers fulfil the requirements of the RNP 4. Regarding the removed outliers, 1% was removed in the layer A1, 10-20% in the layer A2, 30% in the layer A3 and nearly 50% in the layer A4.

In conclusion, both of the models require some improvements if they should be considered for implementation in real traffic situation. One of the possible solutions how to increase the accuracy of the models could be if the aircraft constantly interrogated the surrounding aircraft and precisely eliminated the outliers.

The proposed models could be useful as they could serve as a comparison for future solutions. I am going to use this experience and the gained knowledge for my future studies. This thesis highly contributed to my professional and academic development.

9 Bibliography

[1] ICAO. (2017). GPS Interference/Signal Degradation in Manila, Philippines Affecting Flight and ATM Operations. International Civil Aviation Organization. Regional Preparatory Group (RPG) Meeting for WRC-2019. Bangkok, Thailand. https://www.icao.int/APAC/Meetings/2017%20RPGITUWRC19/WRC19RPG42-GNSS_Interference_Philippines_CharlemagneGilo.pdf

[2] ICAO. Working paper, Assembly – 40th Session, A40-WP/188. *An Urgent Need to Address Harmful Interferences to GNSS.* Presented by the International Federation of Air Traffic Controllers' Association (IFATCA), the International Federation of Air Line Pilots' Associations (IFALPA) and the International Air Transport Association (IATA). 2019. [Accessed 2020-12-01]. Available at: https://www.iata.org/contentassets/e45e5219cc8c4277a0e80562590793da/address-harmful-interferences-gnss.pdf

[3] S. Han, Z. Gong, W. Meng, C. Li and X. Gu. *Future Alternative Positioning, Navigation, and Timing Techniques: A Survey.* In IEEE Wireless Communications, vol. 23, no. 6, pp. 154-160, December 2016, DOI: 10.1109/MWC.2016.1500181RP. [Accessed 2020-12-01]. Available at: https://ieeexplore.ieee.org/document/7593455

[4] FAA. Advisory Circular 91-70B: *Oceanic and Remote Continental Airspace Operations* [online]. 2016. [Accessed 2020-08-09]. Available at: https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1030086

[5] ICAO Doc 9613: *Performance-based Navigation (PBN) Manual*. International Civil Aviation Organization, Montreal, 3rd Edition, 2008. ISBN 978-92-9231-198-8

[6] FAA. Advisory Circular 91-70B: *Oceanic and Remote Continental Airspace Operations* [online]. 2016. [Accessed 2020-08-09]. Available at: https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1030086

[7] ICAO Annex 10. *Aeronautical Telecommunications*: *Volume IV – Surveillance and Collision Avoidance Systems.* International Civil Aviation Organization, 4th Edition, 2007.

[8] EUROCONTROL. *ACAS Guide – Airborne Collision Avoidance.* 2017. [Accessed 2020-12-01]. Available at: https://www.eurocontrol.int/publication/airborne-collision-avoidance-system-acas-guide

[9] ICAO Doc 9924: *Aeronautical Surveillance Manual*. International Civil Aviation Organization, Montréal, Quebec, Canada, 1st Edition, 2011. ISBN 978-92-9231-690-7

[10] FAA. Advisory Circular 91-70B: *Oceanic and Remote Continental Airspace Operations* [online]. 2016. [Accessed 2020-08-09]. Available at: https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1030086

[11] NAT Doc 007: North Atlantic Operations and Airspace Manual. ICAO EUR/NAT Office, Paris, V.2019-2.

[12] ICAO Doc 9863: *Airborne Collision Avoidance System (ACAS) Manual.* International Civil Aviation Organization, Montréal, Quebec, Canada, 1st Edition, 2006.

[13] Flightradar 24 [online]. [Accessed 2020-06-20]. Available at: https://www.flightradar24.com/

[14] Pleninger, Stanislav. *ADS (Automatic Dependent Surveillance).* Presentation presented at: [CNS Systems Course at Faculty of Transportation Sciences, Czech Technical University in Prague; Academic Year 2013/2014; Prague, Czech Republic].

[15] ICAO. Doc 4444. *Procedures for Air Navigation Services – Air Traffic Management.* 16th Edition, 2016. ISBN 978-92-9258-081-0.

[16] ICAO. Doc 9849. *Global Navigation Satellite System (GNSS) Manual.* 2nd Edition. 2012.

[17] Pleninger, Stanislav. *Hyperbolické navigační systémy.* Presentation presented at: [ZLT Course at Faculty of Transportation Sciences, Czech Technical University in Prague; Academic Year 2010/2011; Prague, Czech Republic].

[18] VITAN, Valeriu, Gerhard BERZ, Luca SAINI, Jean-Pierre ARETHENS, Boubeker BELABBAS, Petr HOTMAR. *Research on alternative positioning navigation and timing in Europe. In: 2018 Integrated Communications, Navigation, Surveillance Conference (ICNS) [online].* IEEE, 2018, 2018, 4D2-1-4D2-17 DOI: 10.1109/ICNSURV.2018.8384887. ISBN 978-1-5386-5679-2. [Accessed 2020-08-10]. Available at: https://ieeexplore.ieee.org/document/8384887/

[19] RAMOS GÁLVEZ, José. Alternative Means of Navigation for GNSS Backup in Aviation. Prague, 2019. Master´s Thesis. Faculty of Transportation of Sciences. Supervisor: Doc. Ing. Jakub Kraus, Ph.D. Co-Supervisor: Ing. Tereza Topková

[20] GUERMAH, B., H. EL GHAZI, T. SADIKI, S. REBOUL, and E. AHOUZI. *An Approach to Compute and Modelize Multipath Errors for GNSS Positioning in urban environment* [online]. NGNS CONFERENCE. 2016. [Accessed 2020-08-10]. Available at:

https://www.researchgate.net/publication/311935462_An_Approach_to_Compute_and_Modelize_Multipath_Errors_for_GNSS_Positioning_in_urban_environment/figures?lo=1

[21] FAA. Advisory Circular 91-002: *Aircraft and Operators approval for RNAV5 operation.* [online]. 2012.

[22] Scientific American. GPS is easy to hack, and the U.S. has no backup. [Accessed 2020-11-28]. Available at: https://www.scientificamerican.com/article/gps-is-easy-to-hack-and-the-u-s-has-no-backup/

[23] OSTROUMOV, I. V. and N. S. KUZMENKO. Performance analysis of passive positioning by Distance Measuring Equipment and Automatic Dependent Surveillance Broadcast data. In: 2018 International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo) [online]. IEEE, 2018, 2018, s. 1-5 [Accessed 2020-08-02]. DOI: 10.1109/UkrMiCo43733.2018.9047607. ISBN 978-1-5386-5264-0. Available at: https://ieeexplore.ieee.org/document/9047607/

[24] KIM, Euiho. *Analysis of DME/DME Navigation Performance and Ground Network Using Stretched-Front-Leg Pulse-Based DME*. Sensors [online]. 2018, 18(10) [Accessed: 2020-08-02]. DOI: 10.3390/s18103275. ISSN 1424-8220. Available at: http://www.mdpi.com/1424-8220/18/10/3275

[25] Pleninger, Stanislav. *DME (Distance Measuring Equipment).* Presentation presented at: [CNS Systems Course at Faculty of Transportation Sciences, Czech Technical University in Prague; Academic Year 2018/2019; Prague, Czech Republic].

[26] ICAO Doc 9613: *Performance-based Navigation (PBN) Manual*. International Civil Aviation Organization, Montreal, 3rd Edition, 2008. ISBN 978-92-9231-198-8

[27] Civil Aviation Safety Authority (2017). Chapter 6 Performance-based navigation. [online] Civil Aviation Safety Authority. [Accessed 2020-11-29]. Available at: https://www.casa.gov.au/book-page/chapter-6-performance-based-navigation

[28] Radartutorial.eu. Primary Surveillance Radar (PSR) vs. Secondary Surveillance Radar (SSR). [Accessed 2020-11-26]. Available at: https://www.radartutorial.eu/02.basics/PSR%20vs.%20SSR.en.html

[29] HELFRICK, Albert. *Question: Alternate position, navigation timing, APNT? Answer: ELORAN.* In: 2014 IEEE/AIAA 33rd Digital Avionics Systems Conference (DASC): 2014 IEEE/AIAA 33rd Digital Avionics Systems Conference (DASC) [online]. B.m.: IEEE. Available at: doi:10.1109/dasc.2014.6979452 [Accessed 2020-12-01]

[30] NASA´s Aviation Safety Reporting System. (2019). Controlled Flight Toward Terrain (CFTT). ASRS. Callback, Issue 473. [Accessed 2020-11-15]. Available at: https://asrs.arc.nasa.gov/docs/cb/cb_473.pdf

[31] Kroese, D. P., Brereton, T., Taimre, T., & Botev, Z. I. (2014). *Why the Monte Carlo method is so important today. Wiley Interdisciplinary Reviews: Computational Statistics, 6(6), 386–392.* doi: 10.1002/wics.1314

[32] Dekking, Michel (2005). A Modern Introduction to Probability and Statistics. Springer. pp. 181–190. ISBN 9781852338961. [Accessed 2020-11-26]. Available at:https://cis.temple.edu/~latecki/Courses/CIS2033-Spring13/Modern_intro_probability_statistics_Dekking05.pdf

[33] MathWorks, The official home of MATLAB software, Available at https://www.mathworks.com/products/matlab.html

[34] GPS World. GNSS Position Navigation Timing. GPS accuracy: Lies, damn lies and statistics. [Accessed 2020-11-14]. Available at: https://www.gpsworld.com/gps-accuracy-lies-damn-lies-and-statistics/

[35] Langley, R. (2013). The mathematics of GPS. University of New Brunswick. [Accessed 2020-11-27]. Available at: http://gauss.gge.unb.ca/gpsworld/EarlyInnovationColumns/Innov.1991.07-08.pdf

[36] Flightradar 24 [online]. [Accessed 2020-06-20]. Available at: https://www.flightradar24.com/

[37] Coodinate Systems [online]. [Accessed 2020-08-08]. Available at: http://www.dirsig.org/docs/new/coordinates.html

[38] GISGeography. GPS Accuracy: HDOP, PDOP, GDOP, Multipath & the atmosphere. [Accessed 2020-08-06]. Available at:

https://gisgeography.com/gps-accuracy-hdop-pdop-gdop-multipath/