CHALMERS

GPS for use in radar verifications and tests

An inventory of GPS-technique and development of a method for use in processing of position data in radar verifications and tests

Master of Science Thesis

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Cover: Photo of the author in a Swedish Air Force combat aircraft JAS 39A Gripen over the lake Vänern in southwest Sweden.

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Abstract

GPS has evolved as the dominating global positioning service since the official operational start-up in 1994. This is due to continuous technical upgrades accompanied by other competing and collaborating systems that have emerged during the period after launch of the GPS service. This has made and will probably continue to make satellite based navigation systems into every-day used applications in many different areas.

Raw GPS measurements can be refined with different techniques such as differential GPS and GPS combined with inertial measurements. An improvement in accuracy down to decimeter or centimeter level is possible under favorable conditions. GPS is however not entirely without cons. However, the benefits such as the flexibility gained from the global infrastructure and the all-weather capacity are unmatched especially in airborne and other dynamic applications.

Owing to the good properties of GPS, this technique together with enhancing methods is regularly used in several product tests and verifications at Saab Electronic Defence Systems. The position data from GPS is used as benchmark when verifying accuracy in radar sensor measurements. This applies both to ground based sensor systems as well as airborne sensor systems.

The report is directed to employees at Saab EDS for whom it serves two different purposes. The first part of the report is an inventory of existing position measuring equipment used at Saab EDS. This part, together with a general GPS walk-through in appendix, is an introduction of position measurement procedures used at the company. The second part develops, investigates and suggests a specific method to compare GPS position data with target data from a PS-05/A radar unit mounted on Saab Gripen fighter aircrafts. The method takes care of issues regarding data synchronization and incompatible position coordinates.

Keywords: GPS, Radar, Gripen, PS-05/A

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Sammanfattning

GPS har sedan den officiella uppstarten 1994 utvecklats till den dominerande positioneringstjänsten för global användning. Detta har åstadkommits genom kontinuerlig teknisk uppgradering av systemet åtföljt av andra konkurrerande och samarbetande system. Den här utvecklingen har gjort satellitbaserade navigeringstjänster till något som används i vardagen inom en mängd olika områden, och framstegen fortsätter.

Rådata från GPS-mätningar kan raffineras för ökad noggrannhet med olika metoder och tekniker som till exempel differentiell GPS, men även genom kompletterande mätningar med tröghetsnavigeringssystem. Under goda mätförhållanden är en förbättring av noggrannheten ned till decimeter- eller centimeternivå möjlig. GPS som mätmetod är dock inte helt utan svagheter, vilket delvis manifesteras i skiftande datakvalité. Styrkan ligger däremot i den flexibla användningen som åstadkoms genom att systemet erbjuder en global infrastruktur, samt genom att GPS fungerar under alla väderförhållanden.

På grund av de goda egenskaperna hos GPS så används denna positioneringsteknik tillsammans med raffineringsmetoder inom produkttester och verifieringar på Saab Electronic Defence Systems, EDS. Positionsdata från GPS-mätningar används för att verifiera noggrannhetskrav på mätningar gjorda av såväl markbaserade som luftburna radarsensorer.

Denna rapport är riktad till anställda på Saab EDS och tjänar två olika syften för dessa. Den första delen av rapporten är en inventering av befintlig GPS-mätutrustning som används på Saab EDS. Denna del tillsammans med en allmän beskrivning av GPS i bifogat appendix ska tjäna som en introduktion till de positionsmätningsprocedurer som används på företaget. Den andra delen av rapporten utvecklar, testar och föreslår en särskild metod för att jämföra positionsdata från GPS med radardata från radarenheten PS-05/A. Denna radar tillhör utrustningen på stridsflygplan av typ Saab Gripen. Metoden tar hand om kompatibilitetsproblem i tids- och positionsdefinitioner i GPS- och radardata.

Preface

This report is part of a master thesis work fulfilled at the department of Computer Science and Engineering, division of Networks and Systems, Chalmers University of Technology. The master thesis completes a Master of Science degree in Computer Science and Engineering. Most of the work is performed at Saab EDS Göteborg at the section for System Integration and Verification of airborne radars and responsible for the forward looking radar PS-05/A in service on the Saab Gripen fighter aircraft. The report is aimed for a reader with technical skills and knowledge in level of an undergraduate student.

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Last, but not least, I would like to thank my wonderful wife Jenny. Many thanks also to our respective families helping me and Jenny with child care and support.

List of Abbreviations and Concepts

ASCII	**American Standard Code for Information Interchange**: An encoding scheme for text characters in computers.
C/A	**Coarse/Acquisition**: An open GPS signal code for civilian use.
CDMA	**Code Division Multiple Access**: Method to share a band of frequencies by coding of the different signals.
CEP	**Circular Error Probability**: The radius of a circle where 50% of the population lies within.
CF	**CompactFlash**: Standard for removable memory cards.
COMET	Aircraft recording system for the Gripen fighter test aircrafts.
DGPS	**Differential GPS**: Enhancement method to the GPS system, including two or more GPS receivers.
DOP	**Dilution of Precision**: A time and space dependent value describing possible accuracy of GPS as a function of satellite geometry. DOP is sometimes split up into PDOP, HDOP, VDOP and TDOP describing satellite geometry influence on accuracy in position, horizontal position, vertical position and time respectively.
MS-DOS	**Microsoft - Disk Operating System**: A text based operating system on IBM PC computers and predecessor to the graphic user interfaces like Windows.
EDS	**Electronic Defence Systems**: A business area in the Saab AB Group.
EGNOS	**European Geostationary Navigation Overlay Service**: Satellite based augmentation service set up to improve navigation for GPS-users mainly in Europe.
FDMA	**Frequency Division Multiple Access**: Method to share a band of frequencies by splitting of the available bandwidth.
GALILEO	The European GNSS that is set out to be operational in 2014 (as of May 2010) and is a joint project of the European Space Agency (ESA) and the European Commission (EC).
GLONASS	**GLObal NAvigation Satellite System**: GNSS constructed by Russian governments.
GNSS	**Global Navigation Satellite Systems**: Family name for satellite based systems built mainly for positioning and with global coverage.

GPRS	**General Packet Radio Service**: Standard for data packet transfer, designed for 2G mobile networks.
GPS	**Global Positioning System**: The first operational GNSS with all-time global coverage. Built and managed by US governments.
GSM	**Global System for Mobile Communications**: 2nd generation (2G) mobile network systems with digital transmission of speech channels.
GUI	**Graphical User Interface**
HDF5	**Hierarchical Data Format 5**: File format standard designed for large sets of numerical data.
HOW	**Hand Over Word**: Telemetry word in GPS for synchronization etcetera.
IE	**Inertial Explorer**: Software from NovAtel providing post-processing capabilities of GNSS and inertial data.
IMU	**Inertial Measurement Unit**: Unit that reports measurements made by accelerometers and gyroscopes.
INS	**Inertial Navigation System**: System that uses instruments, same as in an IMU, to compute position, velocity and attitude of a craft by using a dead reckoning method.
L1	GPS signal frequency at 1575.42 MHz
L2	GPS signal frequency at 1227.60 MHz
MCS	**Master Control Station**: The main control center, situated in Colorado USA, from where NAVSTAR GPS is controlled.
MIL-STD-1553	**Military Standard 1553**: Serial bus standard developed by US Department of Defense for use in military avionics.
P(Y)	Encrypted GPS signal code for US military and governmental use solely.
PCMCIA	**Personal Computer Memory Card International Association**: Standard for interface between PC laptops and peripheral units.
PPS	**Precise Positioning Service**: The non-public service in GPS positioning.
PRN	**Pseudo Random Number**: Deterministic series of numbers that appear as if they would be random.
PS-05/A	Forward looking radar in service on the Saab Gripen combat aircraft.

RMS	**Root Mean Square**: Statistical measure that indicates the variation within a quantity.
RTC	**Real Time Clock**: The definition of time used by internal systems in the Gripen aircraft as it is referred to in this report.
SA	**Selective Availability**: Intentional error that was added to the civilian GPS signal to degrade performance in the positioning service. Removed by the US governments in May 2000.
SBAS	**Satellite Based Augmentation Service**: Family name of services that improve GPS receiver performance by additional satellite signals.
SC	**System Computer**: Central processing unit with interface to all other sub-systems onboard the Gripen aircraft.
SD	**Secure Digital**: Memory card format
SPAN	**Synchronized Position, Attitude and Navigation**: Positioning system from NovAtel including GNSS and IMU units integrated with each other.
SPS	**Standard Positioning Service**: Public GPS positioning service for civilian use. The domain of GPS used by most subscribers.
SQL	**Structured Query Language**: Computer language designed for managing of databases.
STT	**Single Target Track**: Air-to-air radar mode in PS-05/A focused on one prioritized target track.
SV	**Space Vehicle:** A commonly used abbreviation in the GPS area referring to the GPS satellites.
TOT	**Time of Travel**: The propagation time of an electromagnetic frequency signal.
USB	**Universal Serial Bus:** Computer interface specification for data transfer and electric power supply.
UTC	**Coordinated Universal Time**: Time standard used globally as reference time. A bit simplified, UTC is equal to Greenwich Mean Time (GMT).
VHF	**Very High Frequency**: Radio frequency band 30-300MHz used by e.g. FM radio transmissions.
VOR	**VHF Omnidirectional Radio range**: Radio navigation aid system for air traffic.

WAAS — **Wide Area Augmentation Service**: SBAS system built by US aviation authorities.

WGS84 — **World Geodetic System 1984**: Standard system for navigation and maps used in GPS.

Contents

1 INTRODUCTION......1

1.1 BACKGROUND......1
1.2 PURPOSE......2
1.2.1 GPS Inventory......2
1.2.2 Method for Comparison of Radar and GPS Data......3
1.3 METHODS......4
1.3.1 GPS Inventory......4
1.3.2 Method for Comparison of Radar and GPS Data......4
1.4 IMPLEMENTATION......4
1.4.1 GPS Inventory......4
1.4.2 Method for Comparison of Radar and GPS Data......5
1.5 SCOPE......5

2 GPS INVENTORY – EDS......6

2.1 GPS RECEIVER EQUIPMENT......6
2.1.1 GPS on Ground Based Sensors......6
2.1.1.1 Z-Xtreme from Ashtech......7
2.1.1.2 DL-V3 from NovAtel......8
2.1.1.3 SPAN-SE-D from NovAtel together with iIMU-FSAS from iMAR......9
2.1.2 GPS on Airborne Saab Gripen Test Aircrafts......10
2.1.2.1 GPS on High-Dynamic Airborne Systems......10
2.1.2.2 GPS on the Gripen Test Aircrafts......12
2.1.2.3 Thales Navigation - Ashtech DG16......13
2.2 GPS POST-PROCESSING METHODS......14
2.2.1 Differential GPS......14
2.2.1.1 DGPS – Ground Based Systems......14
2.2.1.2 DGPS – Gripen Test Flight......15
2.2.1.3 PNAV......15
2.2.1.4 GrafNav......15
2.2.2 GPS combined with INS – Gripen Test Flight......16
2.2.2.1 Gripen INS Unit......16
2.2.2.2 Inertial Explorer – Post Processing Software......16

3 METHOD FOR COMPARISON OF RADAR AND GPS DATA......17

3.1 INTRODUCTION TO GRIPEN RADAR TESTS......17
3.1.1 PS-05/A – Brief Facts......17
3.1.2 Integration of PS-05/A on Gripen......19
3.1.3 Radar Verification in General......20
3.1.4 Gripen Test Flights......21
3.1.4.1 Test Flight Geometry......21
3.1.4.2 Test Flight Recording - COMET......23
3.2 TRANSFORMATION OF COORDINATES......24
3.3 SYNCHRONIZATION OF DATA......25
3.3.1 Data Message from Radar......26
3.3.2 Data Message from INS......28
3.3.3 Synchronization Process......30
3.4 DISTANCE-TO-TARGET MEASUREMENTS......31
3.4.1 Target Position - Radar......31
3.4.2 Distance-to-target – Radar......31
3.4.3 Target and Fighter Position – GPS......32
3.4.4 Distance-to-target – GPS......32
3.4.5 Interpolation of GPS data......33
3.5 TEST OF COMPARISON METHOD......35
3.5.1 Determination of a Maximum Message Delay Time......36
3.5.2 Test Flight #1......39
3.5.3 Test Flight #2......41
3.5.4 Test Flight #3......43

4 CONCLUSIONS ... 45

4.1 GPS INVENTORY ... 45

4.1.1 Positioning for Ground Based Sensors ... 45

4.1.2 Positioning in Test Flight of PS-05/A ... 45

4.2 METHOD FOR COMPARISON OF RADAR AND GPS DATA ... 46

4.2.1 Transformation of Coordinates ... 46

4.2.2 Synchronization of Data ... 46

4.2.3 Test of Comparison Method ... 46

5 REFERENCES ... 47

6 APPENDICES ... 48

1 Introduction

1.1 Background

Saab Electronic Defence Systems (EDS) is a business area of Saab Group AB, a company with products, services and solutions ranging from military defense to civil security. Business area EDS is a provider of technical solutions in areas such as surveillance, threat detection and location. These technical solutions often include sensors using microwave technique, like radar units. This thesis work is accomplished at a section within EDS primarily working on integration and verification of PS-05/A. PS-05/A is a forward looking radar sensor integrated in the Saab Gripen fighter aircraft, mainly used by the Gripen pilot for target acquisition, ground mapping and weapon guidance.

The majority of the products from EDS in Göteborg use radar sensor technique. The main task of a radar sensor is to serve the user with position information on objects of interest within the radar search volume and range. During test and verification of radar systems, there is a need to evaluate sensor accuracy and precision. This is usually done in a comparison of sensor data with benchmarking data from an independent source. The prevalent method to retrieve benchmarking data for comparison with radar measurement data is to use satellite based navigation systems. Positional data on sensor as well as target object are measured by using a suitable satellite based navigation system, like GPS, see Figure 1-1.

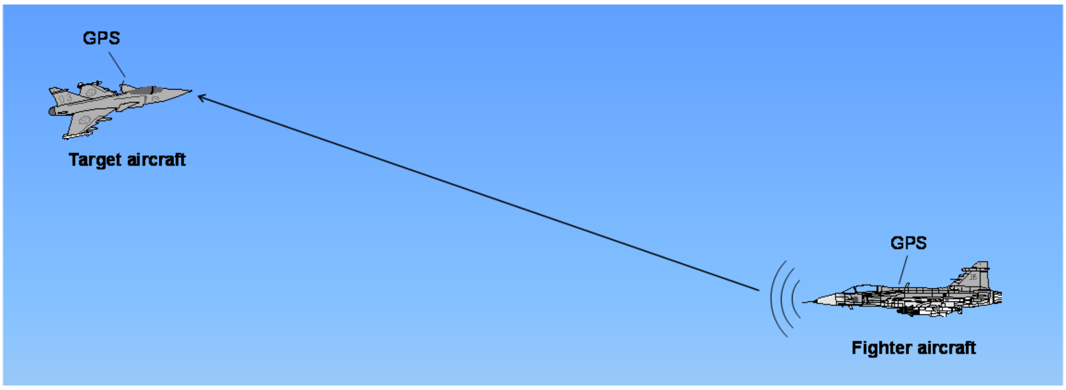

Figure 1-1: Gripen fighter and target – both equipped with GPS.

Position measurements with use of a satellite based navigation system in test and verification activities are standard procedure today. It is standard procedure not only at EDS, but also widespread among many other commercial actors and governmental activities dealing with same positioning issues. However, before satellite navigation was developed, the retrieval of positional data on moving objects, sensors and targets, was associated with complicated and quite slow processes. These difficulties were especially characterized during position measurements of airborne objects. These measurements formerly demanded great resources in measuring equipment and also large amount of manual post-processing of data.

After the satellite based NAVSTAR Global Positioning System (GPS) was set operational in the early 1990's, position data was all of a sudden possible to retrieve in a significantly less complicated and less expensive process compared to older methods. However, not with the high accuracy during the first years as is possible now. But the last ten years the accuracy in data delivered by GPS equipment has increased to a preciseness that in several cases by far exceeds accuracy requirements of most radar sensors. This trend has made GPS measurements the predominant choice of positioning method during radar system development. On top of this there are several GPS data processing and refining methods able to improve accuracy even more compared to what the receiving equipment delivers.

The thesis work is divided into two separate parts. The first part is an inventory of GPS techniques in general. The general inventory is accompanied by a local inventory of how GPS is used at EDS today. This first part aims to introduce GPS positioning methods for a broader range of employees at Saab EDS. The later part takes aim on the specific GPS measurements that are done during Saab Gripen Fighter test flights. In this part a suitable method is developed describing how GPS position data could be used in Gripen radar test and verification procedures.

1.2 Purpose

The purpose of this thesis work is to mainly split in two. The first part is an inventory of the GPS area as a whole and aims to serve as guidance for general GPS understanding. But it is also an inventory of existing GPS equipment at Saab EDS. The second part will look into the special case of GPS measurements at Saab Gripen test flights. We will find a possible method to use GPS measurements when testing, evaluating or verifying the PS-05/A-radar.

1.2.1 GPS Inventory

GPS in General

Engineers from Saab EDS regularly execute GPS measurements as well as use data from previous GPS measurements. It is desirable for Saab that the engineers working with GPS equipment and GPS data have a good basic understanding of the GPS system. For this reason this report explains fundamental and essential facts about GPS for a reader with basic technical skills.

GPS Inventory at Saab EDS

The thesis report is also intended to be used at Saab EDS as a more practical guideline. A guideline aimed for people using available GPS equipment for position measurements during system tests and verification. The question that this part of the report considers is: -What equipment and software is available at the company and to what degree can they help me solve a specific positioning task? Any presumptive GPS user at the company should with this report be able to get a quick and brief idea of existing systems at the company. The focus is particularly set on accuracy in output data as well as system properties and limitations regarding usability. Furthermore, available software at Saab EDS used for improving GPS data accuracy should be introduced and described in terms of improved level of accuracy.

1.2.2 Method for Comparison of Radar and GPS Data

The main goal of this part of the thesis work is to find a suitable method to compare GPS data and radar data. The suggested method will take care of existing problems regarding synchronization and different position coordinate frames between radar and GPS data. The purpose of developing this method is that it later can be used during evaluation and verification of other radar measurement quantities of interest, although these quantities are not covered in this work.

Evaluation of target position data from the PS-05/A radar can be done by comparing it with position data measurements from another source. In order to evaluate target position data that by default is radar relative, there is a need to have absolute position data on both the radar unit as well as the target. Position data on both the Gripen fighter aircraft carrying the PS-05/A radar as well as the airborne target aircraft are orderly and as default collected through GPS measurements during Gripen test flights. There are also methods used at Saab to refine GPS position data. These methods may refine data to a degree of accuracy where it is assumed to correspond to Saab's demands on accuracy level in position data from radar measurements. However, a comparison of radar data and GPS data is not a straight forward operation. This is due to two major circumstances which come from the fact that data from radar and GPS are different in terms of position coordinate frames and definition of time.

Transformation of Coordinates

GPS data and radar data from test flights are expressed by position coordinates in different reference systems. GPS position data refer to the WGS84 coordinate system. WGS84 is a globally used standard instance of a normal geographic coordinate system used on most maps. A position in the WGS84 system is expressed by three quantities, longitude, latitude and altitude [1]. Radar data are instead expressed in a local 3-dimensional Cartesian coordinate system. Either GPS positions or target positions in radar data has to be transformed to the other set of coordinates in order for them to be comparable with one another. For further introduction of the two coordinate systems see chapter 3.2.

Time Synchronization of Data

Valid time for GPS data samples are set by using universal time coordinated (UTC) definition of time. Radar data on the other hand is set to an internal aircraft definition of time with no obvious connection to UTC. A comparison of the two entities needs the two data sets to be synchronized in time. The purpose of this part is therefore to find a suitable method to synchronize the two different definitions of time.

Method to Evaluate Radar Data – Distance-to-target Measurements

A method to compare radar quantities with GPS measurements can be developed when radar and GPS data are set into comparable position coordinate frames as well as synchronized by the same definition of time. One of the most interesting measurement quantities for any military radar unit is the ability to measure distance to target with best possible accuracy. This part aims to find a suitable method to evaluate distance-to-target measuring. The method is applied on test flight data to verify the functionality of the method itself.

1.3 Methods

1.3.1 GPS Inventory

GPS in General

The report aims to describe and cover the GPS area in general and consequently the work starts off with an extensive study of GPS literature, articles, and papers as well as published material on official GPS internet sites.

GPS Inventory at Saab EDS

Information for the next part, focusing on GPS receivers and software used at Saab, is gathered with help from, and in cooperation, with employees working with GPS applications at both Saab EDS in Göteborg and Saab Aeronautics in Linköping. Furthermore, product manuals together with other printed and internet based material from manufacturers have been studied to gather information on the different products subject to the local GPS receiver and refining software inventory.

1.3.2 Method for Comparison of Radar and GPS Data

Transformation of Coordinates

Transformation of any position coordinates from one coordinate system to another are done by commonly used algorithms from the Swedish mapping, cadastral and land registration agency, Lantmäteriet. Lantmäteriet is an accepted authority in the area of position measurements why these algorithms are assumed to be sufficient for this work.

Time Synchronization of Data

Radar data and GPS data is possible to be synchronized in time if a useful link between the two different definitions of time can be found. Such link is assumed to exist and be found in data from test flight recordings. This process needs a relative deep knowledge regarding the in-flight recording system used during test flights.

Method to Evaluate Radar Data – Distance-to-target Measurements

A comparison is done visually by plotting of radar data, with GPS data set as reference, during three radar exposure intervals.

1.4 Implementation

1.4.1 GPS Inventory

GPS in General

Study of GPS in general is performed to get an overall understanding of the system, its facilities and limitations. All adequate general GPS information is compiled into Appendix A. Appendix A is aimed to serve as a GPS reference for the main report, but can also be used as optional reading by any other reader that wants a brief walk-through of GPS and satellite navigation theory. Appendix A describes the GPS system through its history, system properties, functionality and also future development in the area of global navigation satellite systems (GNSS).

GPS Inventory at Saab EDS

The available GPS measuring equipment used during live tests at Saab EDS are reviewed including properties such as measurement accuracy stated by the manufacturer. But the chapter also covers any requirements on peripheral equipment such as power adapters and data logging devices. Requirements on peripherals may affect measurements practically and/or introduce limitations in challenging environments.

The next step is to look at GPS data refining processes to get an understanding of how position data can be more precise compared to raw data. Different software solutions are studied during this phase.

1.4.2 Method for Comparison of Radar and GPS Data

GPS data and radar data from test flights are delivered to EDS in a packed format not suitable for processing or analysis. For processing and analysis of radar data Mathworks Matlab is a commonly used software environment at EDS. Matlab is also chosen for this part of the thesis work.

The first step is to transform the GPS and radar data from the original HDF5 format to a manageable format before any data processing and analysis can be done. The analysis of data is done in Mathworks Matlab software and for that purpose the data sets are added into compatible databases with specially designed scripts.

Transformation of Coordinates

Scripts for use in Matlab environment are written during the thesis work to transform position data according to algorithms from Lantmäteriet described in Appendix B.

Time Synchronization of Data

All data messages transmitted in the aircraft bus-system are recorded in special test flight equipment. The registration equipment is synchronized with the UTC definition of time and marks all incoming messages with time of arrival in UTC. This time-stamp on messages that includes information on internal aircraft time is intended to be used as a link between the two different definitions of time and thus also for synchronization between them if the link is useful.

Method to Evaluate Radar Data – Distance-to-target Measurements

The radar distance-to-target estimate over time is visually displayed by plotting all radar measurement samples on a picture of a fighter aircraft to get a quick view of how the measurements are distributed. This picture is completed with a histogram to describe the spread of the measurements.

1.5 Scope

Verification of GPS measurements with any other positioning method to determine the absolute accuracy in GPS data is of course desirable. However this work will not cover position measurements by any other method than GPS, as this requires more resources and time than available in a master thesis work.

2 GPS Inventory – EDS

This chapter is a reviewing inventory of available GPS equipment, GPS data processing methods used for test and verifications of the PS-05/A radar and ground based systems developed at Saab EDS.

2.1 GPS Receiver Equipment

2.1.1 GPS on Ground Based Sensors

Tests and verifications of ground based sensor systems can take place in different terrains and elements. The basic idea during test and verification of these systems is to compare relative position measurements from the sensor with absolute position measurements from GPS equipment. Sensor systems in subject to tests are either static placed on ground or mounted on an off-shore operating vessel in a more dynamic environment. The targets that are subject to the sensor measurements are in most cases airborne vehicles of any kind, but can also be ships. In tests and verification of the systems there is a need to have position data on both sensor and target for comparison with sensor measurements.

GPS measurements for ground based sensor verification are done with different sets of equipment. The receivers are from different manufacturers and thus afflicted with different behaviors. This chapter will be a walk-through of available GPS equipment on Saab EDS including important system properties and expected quality in output data together with brief pros and cons of the different systems.

2.1.1.1 Z-Xtreme from Ashtech

Satellite Tracking: 12 channel simultaneous GPS satellite tracking.

Log Function: PCMCIA card slot for internal removable storage.

Log Setup: Setup of log variables can be done via the front panel but also from a PC via serial port.

Power Supply: Built-in battery providing up to 10 hours of operation. For longer operation or back-up power there is also an input for external power +10 to +28V DC.

Operation Setup: Since the data log is stored internally it only needs one connection in form of satellite signal input from the antenna. It is possible to connect the receiver to a PC on a serial link for parameter settings before and during operation but most of the parameters can be set via the receiver front panel.

Output Data: Downloading of data is done from receiver to PC over serial link or direct from the PCMCIA memory card if the PC has a driver to read that type of memory card. Downloading of data must be done with Ashtech software and the procedure results in binary and ASCII-files each containing different parts of measurements.

Position accuracy - Manufacturer Technical Specification:

Stand-alone	N.A.
DGPS	< 1 m RMS

2.1.1.2 DL-V3 from NovAtel

Satellite Tracking: GPS and GLONASS satellites simultaneously tracked on 72 available channels.

Log Function: Compact Flash (CF) card slot for internal removable storage availability or connection to an external PC.

Log Setup: Connect receiver to PC installed with NovAtel software to edit log variables.

Power Supply: External power +9 to +28V DC.

Operation Setup: If logging to internal CF-card is done the receiver unit only needs connection to GNSS antenna and external power from an adapter. For external logging a PC is connected to the receiver via Ethernet, USB, Bluetooth or serial port and the NovAtel software is used to administrate the process. When downloading data from the internal CF-card after measurements are completed, the NovAtel software is also used.

Output Data: If internal CF-card logging is used the download of data is either done by direct receiver connection to PC or by putting the CF-card in a card reader connected to the PC. Output data has to be subject to further analysis or post-processing by using for example the GrafNav software from NovAtel.

Position accuracy - Manufacturer Technical Specification:

Stand-alone L1	1.8 m RMS (single frequency)
Stand-alone L1/L2	1.5 m RMS (dual frequency)
DGPS	0.45 m RMS

2.1.1.3 SPAN-SE-D from NovAtel together with iIMU-FSAS from iMAR

Satellite Tracking: GPS and GLONASS satellites simultaneously tracked on 72 available channels.

Log Function: Secure Digital (SD) card slot for internal removable storage supplemented with real-time logging on external PC.

Log Setup: Receiver setup is made from PC using NovAtel CDU (Control and Display Unit) software.

Power Supply: External power +9 to +30V DC.

Operation Setup: Receiver is connected to one or two antennas and IMU. PC may be connected for log functions and receiver monitoring

Output Data: Measurement output data can be stored on the SD-card or logged in real-time on a PC. Data format for each variable-file can be set to either binary or ASCII.

Two-antenna Installation: The SPAN system is able to install with two antennas to enable a heading output from a static system.

GPS/INS Integration: The NovAtel SPAN system is able to combine two completely different technologies in a single measuring unit. SPAN uses GNSS measurements from GPS and GLONASS (if available) together with inertial measurements forming an integrated GNSS/INS system. Inertial measurements are carried out by an IMU (inertial measurements unit) connected to the SPAN GNSS receiver. For position solution a SPAN system can use the two measurements in a combined position solution but also provide the user with a GPS-only position. The SPAN implementation at EDS is a SPAN SE-D receiver together with the inertial measuring unit iIMU-FSAS from the German company iMAR. The receiver has a two-antenna installation giving the availability to present the direction, or heading, of the SPAN system installation. The heading is derived from base-line calculation from the two antennas using their respective geographic positions.

Position accuracy - Manufacturer Technical Specification:

GPS only

L1	1.8 m RMS (single frequency)
L1/L2	1.5 m RMS (dual frequency)
DGPS	0.45 m RMS

GPS/INS [2]

North	0.038 m RMS
East	0.034 m RMS
Height	0.033 m RMS

2.1.2 GPS on Airborne Saab Gripen Test Aircrafts

In verification and tests of various systems onboard an aircraft, like the Saab Gripen fighter, there are quite often demands to continuously be able to record where in space and time the aircraft is. Determination of the relative or absolute position of a flying object is, however, not an elementary task. The dynamic airborne environment of a fighter aircraft introduces a few additional constraints compared to a static ground based environment.

- A relatively long distance to any observer of the object results in great impact for errors in angular measurements.

- The lack of reference objects close to an object flying in free space gives no ability to compare aircraft position with other fixed objects.

- Relative high speed on the object leads to strict timing requirements to get adequate accuracy in position measurements.

The history of aircraft position measurements at Saab involves methods such as photogrammetry and theodolite measurements. Both of them require quite extensive measuring equipment as well as a large number of operating people. Furthermore, these methods were bound in geography to a predetermined area where equipment used for the measurements was installed. This made all positioning measurements on airborne objects quite inflexible and complex. These methods also demand a clear line-of-sight, leading to lot of constraints on suitable weather during measurements. Since GPS can produce positional data with high accuracy it is now the back-bone in position measurements in Gripen flight test and verification programs. GPS is also versatile as it is global and all-weather operational. Cost effectiveness for users are also substantial as the infrastructure including satellites and ground installations is already in place and provided by other interests.

2.1.2.1 GPS on High-Dynamic Airborne Systems

Compared with most other environments where GPS is used, the airborne platform and the environment where it operates is a challenging one with special properties. These challenges together with demands on data response time and quality set the standard for what equipment and methods to be used in airborne positioning.

Below are two examples of what problems an airborne GPS receiver has to deal with. Generally it is difficult to get transparency in how receiver manufacturers tackle these problems. However, usually the product manual states any limits of the operational envelope of the receiver. The operational envelope of a GPS receiver is typically limited by several physical conditions, as for example temperature and acceleration. Outside the envelope the product cannot be guaranteed full performance.

Interrupted line-of-sight to satellite

For a maneuvering aircraft in general and military fighters in particular, turns and other dynamics leads to that the aircraft continually will experience a lot of different attitudes. This means that it may rotate around all three axes in space during dynamic flight phases. With a single roof-top installed antenna, as it is on the Gripen, the best conditions for satellite acquisition are when flying straight forward in level flight with the antenna pointing straight up. The roof-top antenna is an obvious design choice since most of the airborne time is done in level flight even on a dynamic platform like a combat aircraft. The antenna on the Gripen has an approximate coverage of 180˚.

This makes signal propagation to the antenna difficult when satellites are located in relative position under the fuselage, see Figure 2-4. That happens for example nearly always in hard turns when banking angles are approximately 90˚. Even if the receiver has signal acquisition from eight or more satellites before turning, this constitutes a problem since time of re-acquisition on each signal usually is in order of 10-20 seconds. This makes the number of valid signals for a given moment in time during a hard turn drastically lower and sometimes below the required number of four satellite signals. A receiver does not deliver any positional data during a period with three or less satellite signals tracked. This result in a gap in the position data trajectory produced during a test flight.

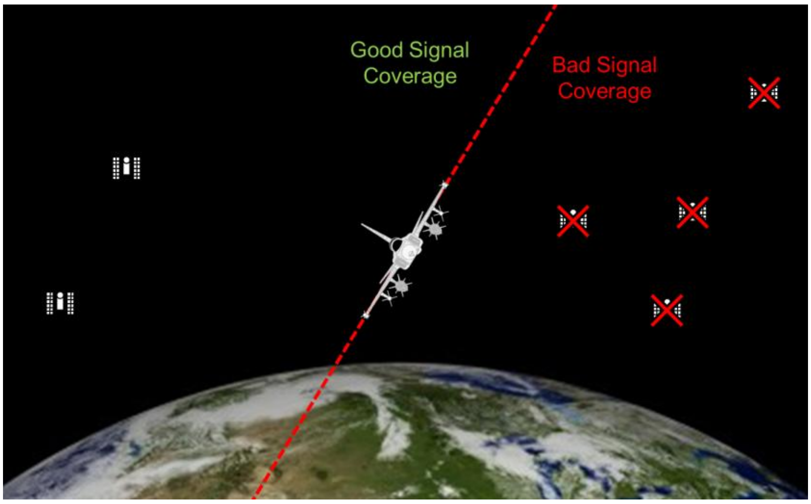

Figure 2-1: A turning aircraft with a partially shaded GPS antenna.

However, this problem can be dealt with by using other measuring methods during periods of loss of GPS data. One solution is to use inertial navigation techniques with use of gyros and accelerometers in a dead-reckoning method to update positional data until GPS data is available again. The Gripen aircraft regularly uses the dead-reckoning method with its Inertial Navigation System (INS) that can deliver fully autonomous navigational data during GPS outages as well as combine it with GPS positioning. This can be done in real time or by post-processing of data.

Lateral accelerations/High G-force

During any acceleration, a GPS receiver will experience a slight frequency shift of the satellite signal carrier as a result of the Doppler Effect. This can be challenging for any GPS receiver not constructed for these events. A normal handheld GPS receiver in low dynamic environments will not experience this effect to any great extent. On the contrary, a GPS receiver for use with military fighters with lateral accelerations up to 9G in turns must deal with the Doppler Effect in an acceptable way. One way to deal with frequency shifts is to make the bandwidth for signal tracking wider. Opposed to this more dynamically robust method stands the fact that a wider bandwidth leads to increased thermal noise sensitivity for GPS receivers [3].

2.1.2.2 GPS on the Gripen Test Aircrafts

To obtain sufficiently precise position measurements from flight tests of the Gripen fighter there are installations of an additional GPS receiver on board the designated test aircrafts. The additional receiver is a Thales DG16 unit with characteristics according to the manufacturer that fully covers the whole Gripen flight envelope. This means that the receiver characteristics are sufficient to all possible speeds, accelerations and altitudes for the Gripen aircraft.

DG16 shares GPS antenna with the integrated GPS unit and is placed on the upper ridge of the aircraft fuselage and the antenna installation point is where all GPS data refer to as aircraft position, see Figure 2-5. Since the DG16 is installed as a one-antenna receiver it may suffer from interrupted line-of-sight problems during aircraft maneuvering. This problem may cause passages with no GPS positioning during data collection due to not enough number of satellites within visible range. Since re-acquisition of satellite signals can take 10-20 seconds, a hard maneuvering Gripen fighter will have problem to regain sufficient number of satellite signals for any given moment during maneuvering.

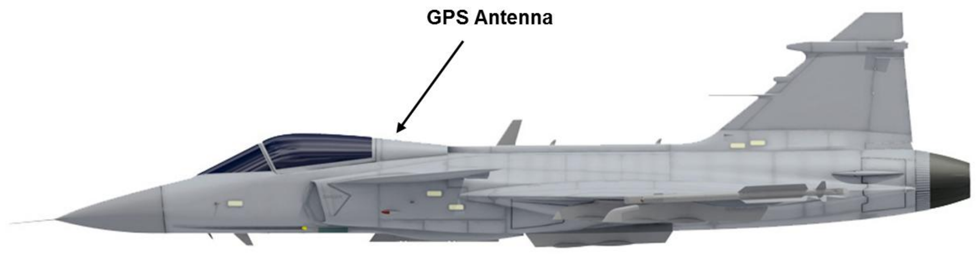

Figure 2-2: Schematic picture of GPS antenna position on Saab Gripen.

2.1.2.3 Thales Navigation - Ashtech DG16

Thales DG16 GPS receivers are installed in Saab Gripen test aircrafts where it serves as the main source of position data after test flight sorties. DG16 was launched in 2001 and has been in use in Gripen test flights since 2004. The version installed in the Gripen is a stand-alone receiver encapsulated in a hard case with 3 serial RS-232 ports for communication.

DG16 has 12 channels for simultaneous track of the L1 signal from 12 different satellites. The DG16 unit is functional within whole of the Gripen aircraft envelope and is serviceable, meaning that it gives valid output data as long as it gets enough satellite signal input not suffering from any line-of-sight problems.

Output Format

Output from DG16 integrated in the Gripen is configured to be written on a serial RS-232 port in binary "Ashtech Real Time" format. The position data is in form of records containing data on all satellites currently receiving information from. The satellite data is specifying distance to satellite, DOP-value and more. The valid GPS-time is then attached to each record for users to know when measurements were made.

<u>DG16 Data record</u>

- GPS-time
- Satellite #, Distance to Sat #, DOP, …
- Satellite # + 1, Distance to Sat # + 1, DOP, …
- ...
- Satellite # + n, Distance to Sat # + n, DOP, …

Position accuracy - Manufacturer Technical Specification

Acceleration (max):	20 g in tracking capability
Speed (max):	514 m/s (1,000 knots)
Altitude (max):	18287 m (60,000 feet)

Position Accuracy:

Autonomous:	CEP: 3.0 m (RMS: 3.57 m) [3]
Differential:	CEP: 0.40 m (RMS: 0.48 m) [4]

2.2 GPS Post-Processing Methods

What has been described in previous chapters concerning data quality is what can be achieved with measurements from a single stand-alone GPS receiver. However, GPS data can be refined using post-processing methods if supplementing measurements has been done simultaneous to the original measurements. Position data quality can be improved to some degree depending on refining method and quality on additional measurements. Two different methods of position measurement refining are available at Saab for use on data from tests and verifications at EDS. The dominating method is differential GPS and that is normally used as standard during all tests. The other method is to combine GPS measurements with inertial measurements consisting of gyro- and accelerometer measurements.

2.2.1 Differential GPS

One of the most common GPS refining methods is differential GPS (DGPS). DGPS can be explained as a family name of several related procedures. Common to all DGPS procedure is that position measurements are corrected for errors introduced by for example atmospheric delays, satellite clock biases and satellite position inaccuracies. The DGPS procedures include at least two receivers to reach desired result, a rover receiver and a minimum of one reference receivers. The rover receiver is making measurements on the unknown location and the reference, or base, receivers are placed on well-known positions, preferably not too far from the rover receiver. The reference receiver is usually only one set of equipment placed on a single location. But in some installations there can be several reference receivers forming a grid with a more advanced DGPS capability.

The differential correction in DGPS is generally done by using the additional simultaneous measurements from the reference receiver. These additional measurements result in a continuous error estimate covering the interval of interest that can be used for the differential correction as described in Appendix A.

Standard procedure at EDS for all measurements in focus during the thesis project is post-processing of GPS data with differential methods. Compared to stand-alone GPS measurements, with a typical accuracy in position somewhere below 10 meters, the differential methods can offer position measurements of a decimeter level [4]. As it is a well-established, precise and a rather easy-to-use method, DGPS has become the choice for positioning in many system tests at Saab.

Differential processing of data is done post tests using various software solutions described below.

2.2.1.1 DGPS – Ground Based Systems

Position measurements during tests of ground based systems are by default done with DGPS methods. For this reason a reference station is always placed on a suitable site among several pre-defined locations for logging of additional differential measurements. Position data from the reference station must be recorded during the whole interval where DGPS processed position data is wanted. Therefore a reference station must be up and running during the whole test interval.

The post-processing of reference and rover GPS data after tests of ground based systems is done in either PNAV 2.2.1.3 or GrafNav 2.2.1.4 described in respective chapters.

2.2.1.2 DGPS – Gripen Test Flight

Measurement of reference position data during Gripen test flights is carried out through a GPS reference station with an Ashtech DG16 receiver. This receiver is similar to the airborne receiver installed in the Gripen and positioned right by the runway at Saab airport in Linköping during operation. The measurements are logged to be used later for refinement of GPS data from the aircraft with DGPS post-processing.

The post-processing of differential GPS data is done with the GrafNav tool from NovAtel using the GPSRefinery GUI. The process is standard procedure after all flight tests and the EDS PS-05/A verification section are regularly subscribers of the DGPS data. The GPS data sets that are delivered to EDS includes 3-dimensional position, UTC-timing, velocity estimate, number of tracked satellites as well as quality measures all sampled in 1-2 Hz frequency. GPS data recording covers the whole flight sortie from power up to shut down of aircraft systems.

For more GrafNav information see 2.2.1.4 GrafNav chapter.

2.2.1.3 PNAV

The Ashtech PNAV (Precise Differential GPS Navigation and Surveying) software is designed for differential post-processing and runs in a MS-DOS environment. The only GPS data format that PNAV processes is binary files produced as output from the relatively older Ashtech GPS receivers. The program is not very instructional but a quite fast tool to use for the experienced user.

The accuracy in position data from PNAV varies from case to case since accuracy in the output depends on many external variables. However, the reference manual states accuracy in position within 1-3 meters RMS, according to the manufacturer's technical specifications. This level of accuracy will be achieved with at least 5 satellite locks, PDOP < 4, separation between reference and rover receiver < 10 km and C/A code phase tracking. Verification of PNAV accuracy has been done at Saab Aeronautics. Position data for this verification was taken from airborne GPS receivers and benchmarking data was measured with photogrammetry. The verification showed accuracy in position down to 1.0 meters RMS, cited in [6].

2.2.1.4 GrafNav

GrafNav is a Windows based differential GPS post-processing software from Waypoint Consulting, a group within the NovAtel Company. GrafNav uses a lot more GUI (Graphic User Interface) features and solutions compared to the MS-DOS based PNAV software.

The accuracies in position output are, in the dynamic user case, stated in the product specification to be below 10 cm with a 10 km long baseline during carrier phase tracking. The code phase tracking accuracy is not stated but according to a study at Saab Aeronautics cited in [6] the accuracy of code phase tracking positioning on an airborne fighter is comparable to that of PNAV and then approximately 1.0 meters.

2.2.2 GPS combined with INS – Gripen Test Flight

During favorable conditions there can be large benefits in combining output data from GPS and INS described more in detail in appendix A. A possible GPS/INS solution is provided for in the Gripen test aircrafts. This solution is a post-processing method using data from the test aircraft GPS receiver together with the standard built-in INS unit.

2.2.2.1 Gripen INS Unit

The Gripen aircraft has an INS unit responsible for run-time position estimation during test flights as well as normal operations in non-test flight configurations. The position estimate from the INS unit with support from a GPS receiver is a provider of position data to all Gripen sub-systems. This GPS receiver is not to be confused with the extra GPS receiver in test aircrafts that instead produces position data for post sortie analysis only.

The INS is physically fixed to the aircraft to be able to record all changes in speed and attitude. With three gyros and three accelerometers the INS unit measures rotation around three axes and also accelerations along same three axes. The gyro measurements can track all changes in attitude of the aircraft. Aircraft attitude is determined by how it is orientated relative another reference system which usually is a system fixed to the Earth. With gyro measurements the INS is able to measure how the local aircraft reference system is angularly orientated relative to a geo-fixed reference system. With accelerometer and gyro measurements the INS unit can calculate position changes over time to keep track of how the aircraft reference system is moving within the geo-fixed system by using a dead-reckoning method. The gyros and accelerometers together form a navigation solution that can keep track of aircraft position during operation after first being initialized in an alignment procedure.

In-flight navigation in all Saab Gripen test aircrafts is carried out by the INS unit. During test flight this unit also provides the test registration system with raw inertial measurements from accelerometers and gyros. The inertial measurement data may be processed after test flight sorties together with GPS data using GPS/INS post processing software.

2.2.2.2 Inertial Explorer – Post Processing Software

The Inertial Explorer (IE) software from NovAtel is developed for post-processing of data from GNSS (Global Navigation Satellite System) measurements together with data from an IMU (Inertial Measurement Unit). For post-processing of Gripen test flight position data the input to IE are GNSS data from the Thales DG16 GPS unit and IMU data from the integrated INS unit.

The product specifications of Inertial Explorer state that IE may produce position data with accuracy down to 1 cm horizontally and 1.5 cm vertically during full GPS coverage and otherwise good conditions. It is very hard to verify this statement in the special case of position measurements on an airborne Gripen aircraft due to lack of comparable metrics with accuracy good enough to serve as benchmark. However, in comparisons between data from IE and theodolite measurements with an accuracy of 0.5 meter, IE shows very good performance. Thus we assume that IE has a better position accuracy output compared to what GrafNav produces from test flights.

3 Method for Comparison of Radar and GPS Data

3.1 Introduction to Gripen Radar Tests

Chapter 3.1 covers general facts about the radar unit PS-05/A. The chapter also includes a description of the integration in the Gripen aircraft. Furthermore, flight test of the radar unit is described briefly together with a description of how data is recorded during these tests.

3.1.1 PS-05/A – Brief Facts

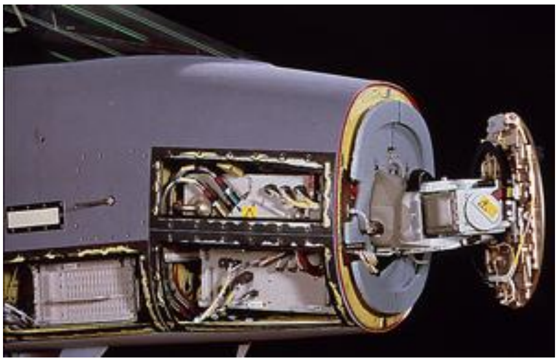

Figure 3-1: Installation of PS-05/A on a Saab Gripen.

The PS-05/A is a Pulse Doppler forward looking radar working on the X-band. It is in service on the Saab Gripen fighter aircraft since 1992 and installed in the front part of the aircraft, see Figure 3-1. The PS-05/A unit is a radar unit with multi-mode functionality. That is the radar has the ability to switch mode depending on how the pilot sets the system to optimize it for different mission types. The radar functionalities include air, ground and sea target acquisition, ground mapping, weather mapping as well as link functions for use in missile guidance. In air-to-air mode the radar provides guidance on target position for pilot as well as for sensors and weapon systems. The target information includes distance, relative angular direction and velocity on the target together with a lot of internal system data.

In a very short explanation of radar physics a radar unit can find and sort out objects or targets within its range through three steps:

1. The radar emits an electromagnetic signal in a precisely specified direction.
2. If the signal hits any reflecting surface on its way a portion of the signal energy may be reflected back to the emitting radar.
3. The signal answer that is received by the radar is analyzed and the reflecting surface is determined to have a position relative to the radar given by signal travel time, the speed of light and the direction of the radar.

The amount of energy reflected back to the radar ( ) is given by the general radar equation in free space stated below. As given by the equation the received energy ( ) is inversely proportional to distance-to-target here denoted as range ( ). The equation will not be explained in any other detail here. The interested reader is recommended to continue with reference literature on the matter [7].

General Radar Equation.

As mentioned earlier PS-05/A is a Pulse Doppler radar unit. The radar looks for any possible frequency shift of the received signal to improve target acquisition properties compared to older radar techniques. When a radar pulse hits an object that has a relative velocity towards or away from the radar emitter the frequency of the reflected signal will be slightly shifted compared to the emitted signal. This frequency shift is the result of the Doppler Effect. Doppler radars use this effect to filter out moving objects from the massive background noise reflected from the ground. The filter algorithms use the fact that the ground below the aircraft has a well-known relative velocity. By this filtering the radar can sort out objects that after further analysis may be recognized as targets on ground or in the air [8].

3.1.2 Integration of PS-05/A on Gripen

The Gripen fighter aircraft is a fourth generation combat aircraft meaning, in one sense, a fully integrated system with all sub-systems controlled by a system computer (SC). This design principle is sometimes popularly described as a system of systems and stands in contrast to earlier generations of combat aircrafts. Sub-systems in former combat aircrafts were not integrated to the same level as in the Gripen, but were instead more of stand-alone systems. The integrated design principle in a modern combat aircraft gives accessibility to information between different sub-systems. It also gives the SC an ability to use input data from different sources in data fusion processes to enhance the decision support for the pilot. Transmission of information between the different systems is physically implemented in a military standard MIL-STD-1553 bus-system. The SC has a role of being both bus-controller and hub for the 1553-buses during normal operation, and the SC regularly processes data from all the sub-systems.

PS-05/A is a vital sensor system on the Gripen as it gathers information from beyond pilot visual range. This information is visualized on graphic displays to support situation awareness for the pilot. Data from the radar unit is also delivered to other sub-systems for use in weapon preparation for example. The radar unit is fully integrated as one of the sub-systems on board the aircraft giving that all key information on targets and radar status may be transmitted to the SC as well as to other systems. Transmission of radar data is carried out via the 1553 bus-system. This fact will prove to be very valuable for a fast and relatively easy access to radar data used in this work.

Figure 3-2: Cut-away picture of a Saab Gripen fighter.

3.1.3 Radar Verification in General

There are several means to verify a radar unit like the PS-05/A. This chapter will not cover any deeper analysis of the various aspects on radar verification. But it is justified to clarify what basic and important quantities that any radar measure and hence what quantities that usually are verified on a radar unit. These quantities are namely interesting when doing a comparison of radar and position data.

What generally can be said about fundamental properties in the output of any radar unit is that the more predominant ones are accuracy in angular, distance and velocity measurements as well as possible detecting range. There are of course other important aspects as for example robustness but during an established target tracking phase the velocity and position measurements are of greatest interest.

One way to verify accuracy in distance and angular measurements can be made by comparisons between data from the radar with data from a completely different source. This can be achieved by retrieving comparison data from position measuring systems mounted on both carrier of radar unit and target object. When verifying a certain level of accuracy in radar data it is obvious that the accuracy level in the benchmarking position data must be at least better. Therefore position data with accuracy on a preferably higher level than the specified radar accuracy is desirable when doing a measurement comparison.

In this work the benchmarking data is solely taken from GPS measurements made during the test flight sorties.

3.1.4 Gripen Test Flights

Most of the tests during aircraft development are done in simulated environments but some tests have to be done in a real operational context during flight. The Saab Flight Test & Verification department at Saab Aeronautics in Linköping is responsible for test flights of the Gripen aircraft. Flight tests of PS-05/A are performed by staff from this department but the geographic location for test sorties can be other than Linköping depending on type of flight test.

3.1.4.1 Test Flight Geometry

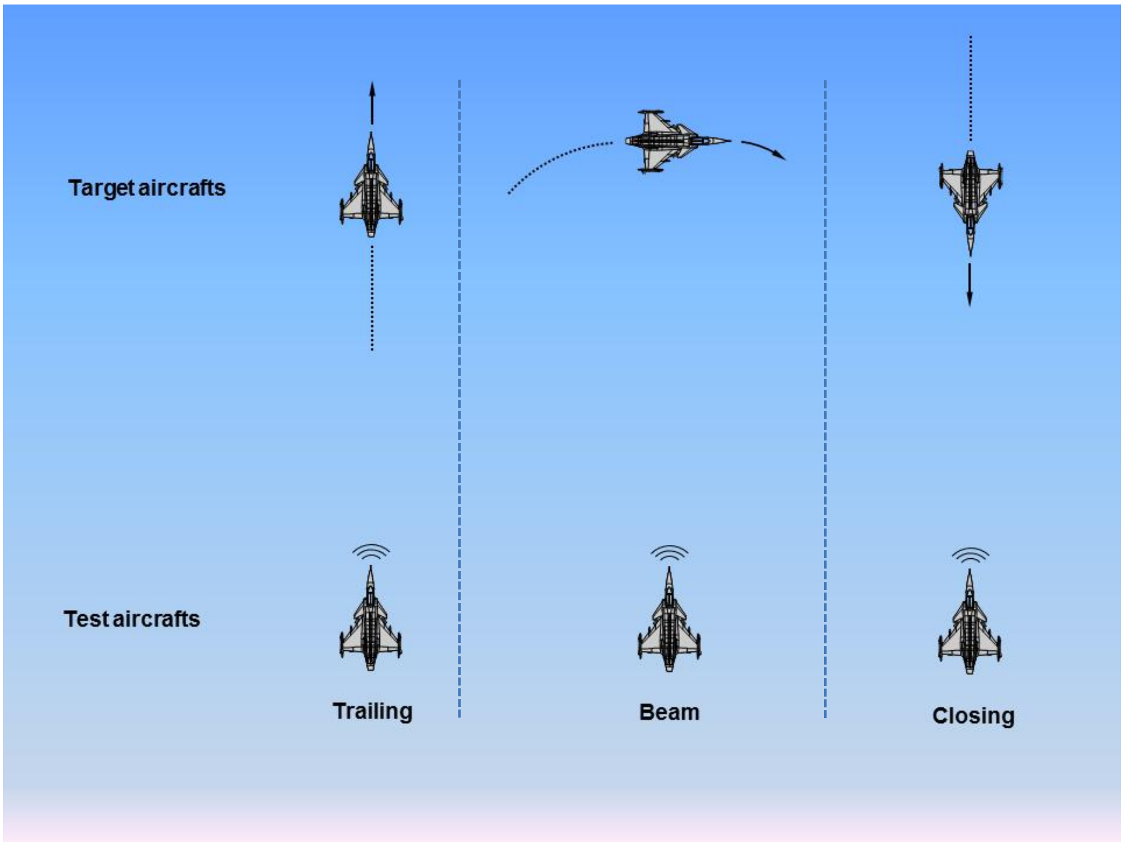

Figure 3-3: Examples of different relative geometries.

As described earlier the PS-05/A is a forward looking radar unit. That is why radar data on any target can only be measured when the aircraft carrying the radar is pointing toward a target within radar range and aspect limitations. On the contrary the target may have any attitude around all three axes. This leads to geometrical requirements on the aircraft trajectories during radar test flights where target aircraft need to be somewhere in front of the test aircraft during a radar test exposure, see Figure 3-3.

Depending on what aspect angle the radar sees a target, see Figure 3-4, the amount of reflected radar energy received by the same radar unit may differ a lot. This phenomenon is quantified by the radar cross section concept. Although radar cross section is expressed by square measures it does not reflect the exact physical area of an object seen from a certain view. Instead it indicates the radar reflection properties of an object seen from different aspect views. It is dependent on, for example, how the object is shaped and from what materials it is built. Furthermore the center-point of reflection on an object may also differ due to aspect angle. Relatively small changes in aspect can lead to major changes in radar response in a non-uniform and also hard to predict dependency [7]. Therefore dynamic aircraft trajectories on either test or target aircraft during radar measurements can be somewhat challenging as the dynamics will have some influence on measurements. For this work, when looking at accuracy down to meter-level, we try to use test flight phases with low-dynamic radar exposures that aims for low fluctuations in radar cross section area during the exposure.

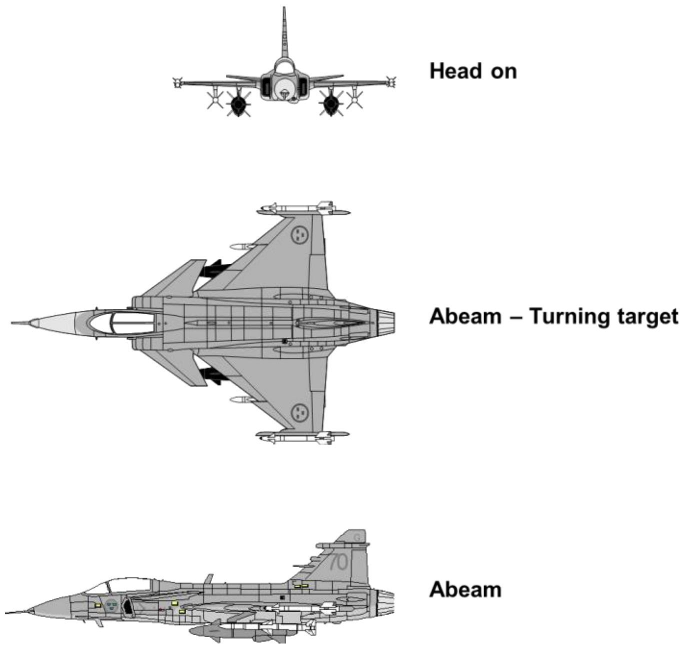

Figure 3-4: Picture exemplifying 3 different aspect angle views on an aircraft, in this figure exampled with a Gripen.

3.1.4.2 Test Flight Recording - COMET

In test flights the Gripen aircrafts use the COMET recording system. The COMET system records all traffic on the bus-system for post-flight evaluations, as described in Figure 3-5. Along with many other inputs COMET saves all message records that are transmitted on the buses and gives them a time stamp indicating when it arrived to COMET. The time stamping function is synchronized with GPS time and marks all incoming data records with arrival time referred to UTC. UTC is a time standard that is widely used as the leading reference time in the world. GPS time is easily converted to UTC and therefore most GPS receivers present time with UTC used as base.

Radar data with target information are transmitted from the radar unit to the system computer on the bus system in a pre-set and uniform frequency rate. These bus transfers entail that all transmitted radar data are recorded in COMET. COMET is not the only recording system for radar data during a test flight sortie. But it is the most suitable for the purpose of this work since COMET data have all parameters of interest and are relatively easy to access. Normal procedure after radar flight tests sorties having been run by Saab Aeronautics in Linköping is that recorded data sets from COMET are delivered to Saab EDS in Göteborg. These data sets are then subject to further analysis of radar behavior and performance.

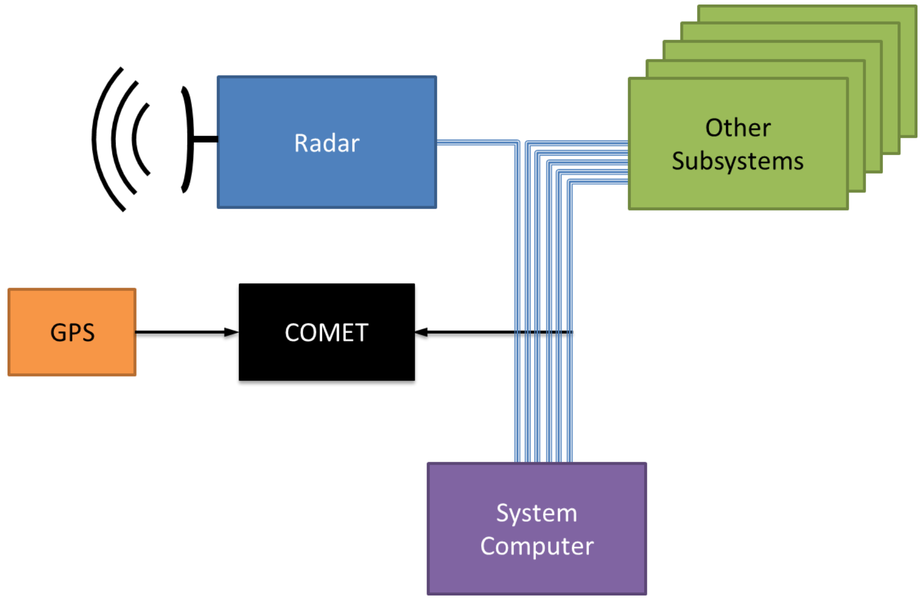

Figure 3-5: Schematic picture with COMET and aircraft infrastructure.

3.2 Transformation of Coordinates

GPS position data are represented by geodetic polar coordinates using the WGS84 datum where a position is set by its longitude, latitude and altitude values, see Figure 3-6. Polar coordinates are not a good representation of position data when they are subject to mathematical analysis. Instead they need to be transferred into a Cartesian coordinate system, see Figure 3-6. Transformations are done by Matlab scripts using formulas in Appendix B. The coordinates are expressed in a geocentric Cartesian system with Earth center as origin after transformation is done.

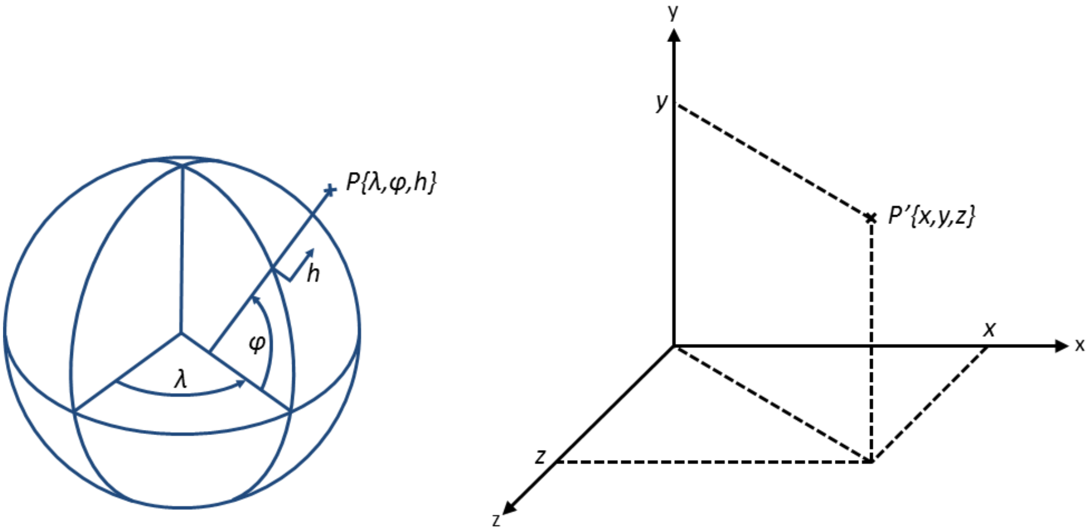

Figure 3-6: Polar coordinate system (left) and Cartesian coordinate system (right).

The radar on the other hand uses a local Cartesian coordinate system from the very beginning when describing target positions in information messages to other aircraft sub-systems. This coordinate system is referred to as the 9R-system which is used and defined internally at Saab. The difference of the 9R-system compared to a geocentric system is that coordinates from the radar refers to a local aircraft origin instead of Earth center. The axes of this local system are not necessarily parallel to any geocentric system either but they are parallel to a Saab defined geocentric 0-system. The local 9R-system for radar data leads to the fact that we do not need to know the absolute position of the test aircraft to calculate the distance-to-target from radar data.

The position coordinates from the radar as well as the GPS position coordinates, after transformation, are not represented in the same coordinate systems though they are all expressed by Cartesian coordinates. However, since we only need the distance between test and target aircrafts for the later comparison no further transformation has to be done since we can calculate respective distances using their own coordinate systems.

3.3 Synchronization of Data

Comparison of GPS and radar data cannot be done unless they are synchronized in time. Valid time for GPS data samples is only expressed in UTC. Radar data messages with target information are instead tagged with valid time expressed by the internal aircraft real time clock (RTC) as reference. RTC is a definition of time used in several aircraft systems on the Gripen for internal synchronization within time dependent sub-systems. RTC is initiated and set to zero when the aircraft is powered up before engine start. During aircraft operation all the internal clocks are frequently synchronized by a central time manager on board the aircraft. The time manager for RTC does not synchronize with any other reference time and therefore RTC time is running independent to UTC.

Nevertheless, the two sets of measurements from GPS and radar have to be set in the same definition of time in order to allow any comparison between the two. Therefore a transformation of the time reference of either one of the data sets is needed. However this transformation of time reference is not an elementary operation since it does not exist any obvious links between the two definitions of time. The strategy for solving this problem is to transfer the valid time for radar data from RTC to UTC since GPS data with valid time in UTC constitutes the benchmarking data for this comparison. Thus the problem of synchronization is to find a sufficiently strong dependency that links RTC to UTC. This dependency could possibly be found in COMET data recordings because all recorded data, including radar data are marked with arrival time expressed in UTC.

When looking at all recorded message traffic in COMET data the only connection between RTC and UTC could be found in a few of all the different types of data messages. These messages are tagged with valid data time set in RTC. The COMET recording time is controlled by GPS and expressed in UTC and used as time stamp for all recorded messages in COMET. One way to connect the two definitions of time is by looking at dependencies in valid time and recording time on a suitable data message type and from that determine the offset time between RTC and UTC. The offset between valid time in RTC and recording time in UTC for a data message is composed by the general RTC/UTC offset time added to the delay time derived from the transmission between radar unit and COMET.

3.3.1 Data Message from Radar

The first attempt in search of a link between RTC and UTC is by looking at one of the target data messages from the radar with information on RTC. The message type that is chosen, in this report named RR_DATA, contains data on target position together with some other information on the tracked target. The message type also contains valid time for target data and that time is expressed in RTC, see Figure 3-7. When this message is transmitted to the SC it is also recorded in COMET, see Figure 3-8. When recorded in COMET the message is marked with a recording time expressed in UTC. This means that from the recorded COMET-version of this message there is an ability to get both RTC and UTC times, see Figure 3-9.

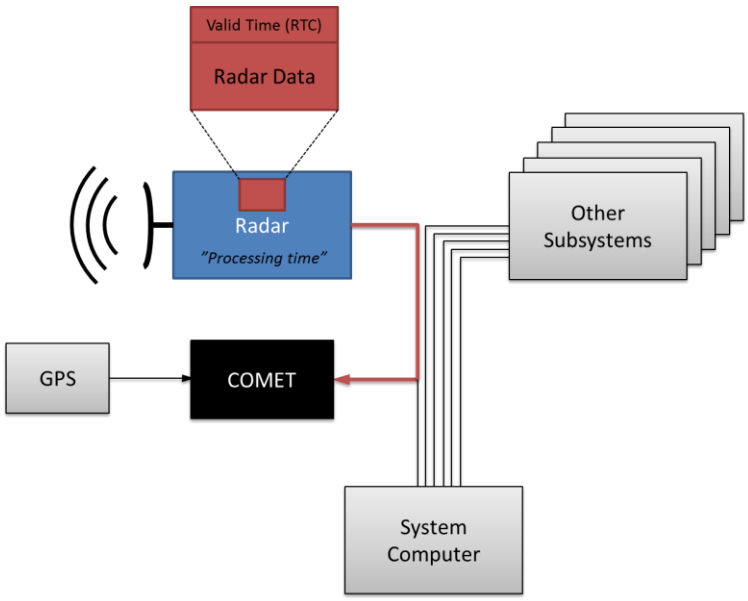

Figure 3-7: RR_DATA message created at radar unit.

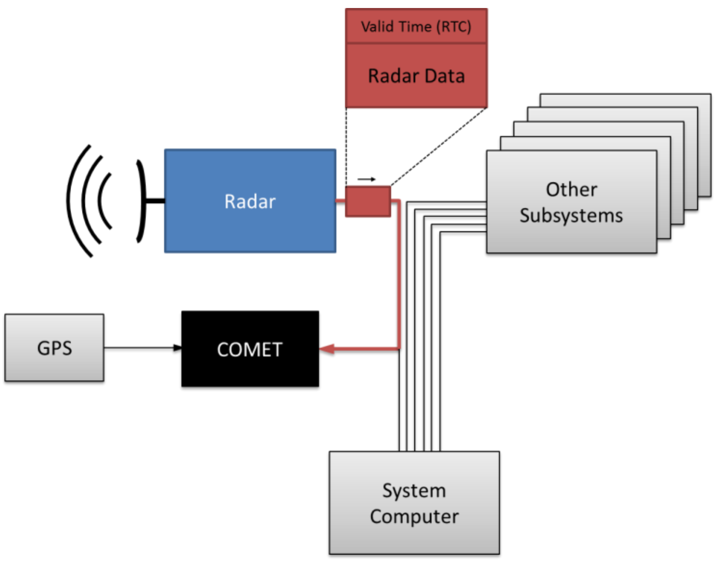

Figure 3-8: RR_DATA message transmitted on the bus-system.

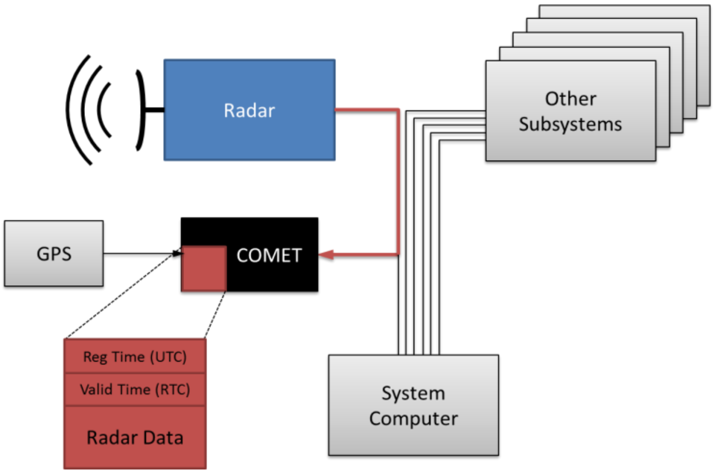

Figure 3-9: RR_DATA message stored in COMET recording system.

However, when observing this target data message in Matlab it becomes apparent that the difference in time between RTC and UTC values over time is seemingly random with limits beyond the acceptable, see Figure 3-12. The time span between valid data time and recording time is varying depending on different elapse time during signal- and data processing of target data in the radar before transmission to SC. The elapsed time entails the target data to be transmitted on the bus with a varying delay. Thus the dependency between valid data time and recording time in this message type clearly is unsuitable in transformation of RTC to UTC timeframe.

3.3.2 Data Message from INS

Since data messages from the radar suffers from varying delays due to processing time there is a need to find another data message recorded in COMET for which we could determine the delay within an acceptable interval. For this purpose a candidate message from SC to radar with position data readings from the INS (Inertial Navigation System) unit is found. For this report the message is named INS_DATA, see Figure 3-10. The data in INS_DATA is in contrast to radar target data in RR_DATA not subject to any processing after valid time is set and thus not suffering from any delay other than transmission time to COMET recording. The INS_DATA message type contains a valid data time expressed in RTC and since it is recorded in COMET it is also marked with a recording time expressed in UTC why it can serve as a link between the two definitions of time, see Figure 3-11.

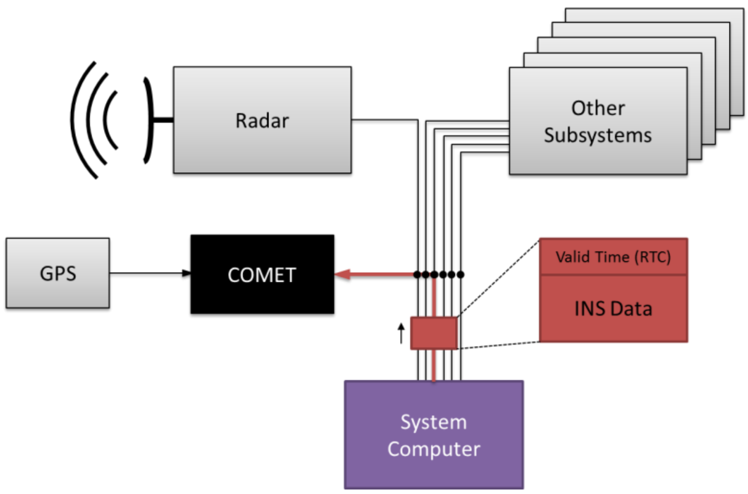

Figure 3-10: INS_DATA message transmitted on the bus-system.

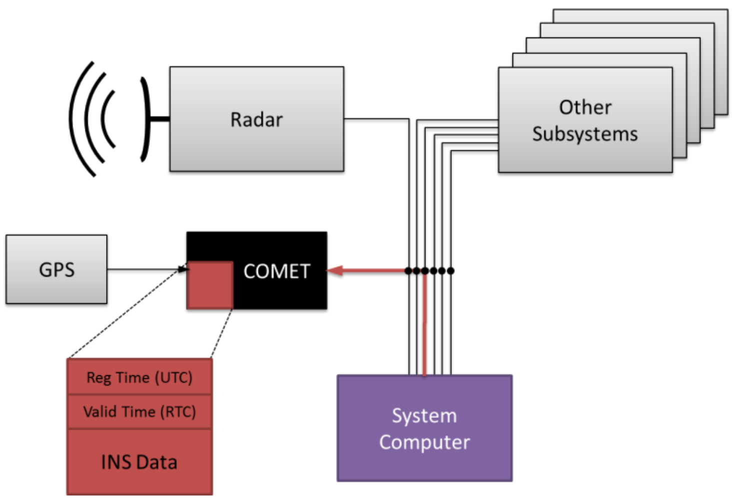

Figure 3-11: INS_DATA message stored in COMET recording system.

The delay time between valid time and recording time for the INS_DATA message is by experience and rightly assumed to have a length of maximum one message cycle. However this assumption will be tested when evaluating one of the test flights in chapter 0. The INS_DATA messages are transferred at a rate of 60Hz giving a message cycle of ~16.7 msec. If not taken into account, this delay will introduce a minor synchronization fault after a transfer of radar data from RTC to UTC. The delay will result in a distance offset between radar measured distance and the benchmarking GPS/INS measured distance with a size depending on relative speed between test aircraft and target aircraft. This means that a time delay leads to a shorter radar distance with two aircrafts relatively departing from each other, and respectively a longer radar distance with two aircrafts closing in relative distance.

Fig 3-12 shows offset time between COMET recording time and valid data time for both RR_DATA and INS_DATA messages. Initial offset time (t) on the y-axis is the offset time for the first recorded INS_DATA message in the interval. This offset for any test sortie is typical counted in days since recorded GPS time refers to seconds of week initiated at 00.00h between Saturday and Sunday and valid time is initiated at power up before engine start. Fig 3-12 shows that RR_DATA not only suffers to a delay approximately 100 ms longer than the INS_DATA message but also that the delay is varying much more than the delay of the INS_DATA. The slope that can be observed on INS_DATA and to some extent also on RR_DATA can be explained by the slight difference in clock rate between RTC and UTC.

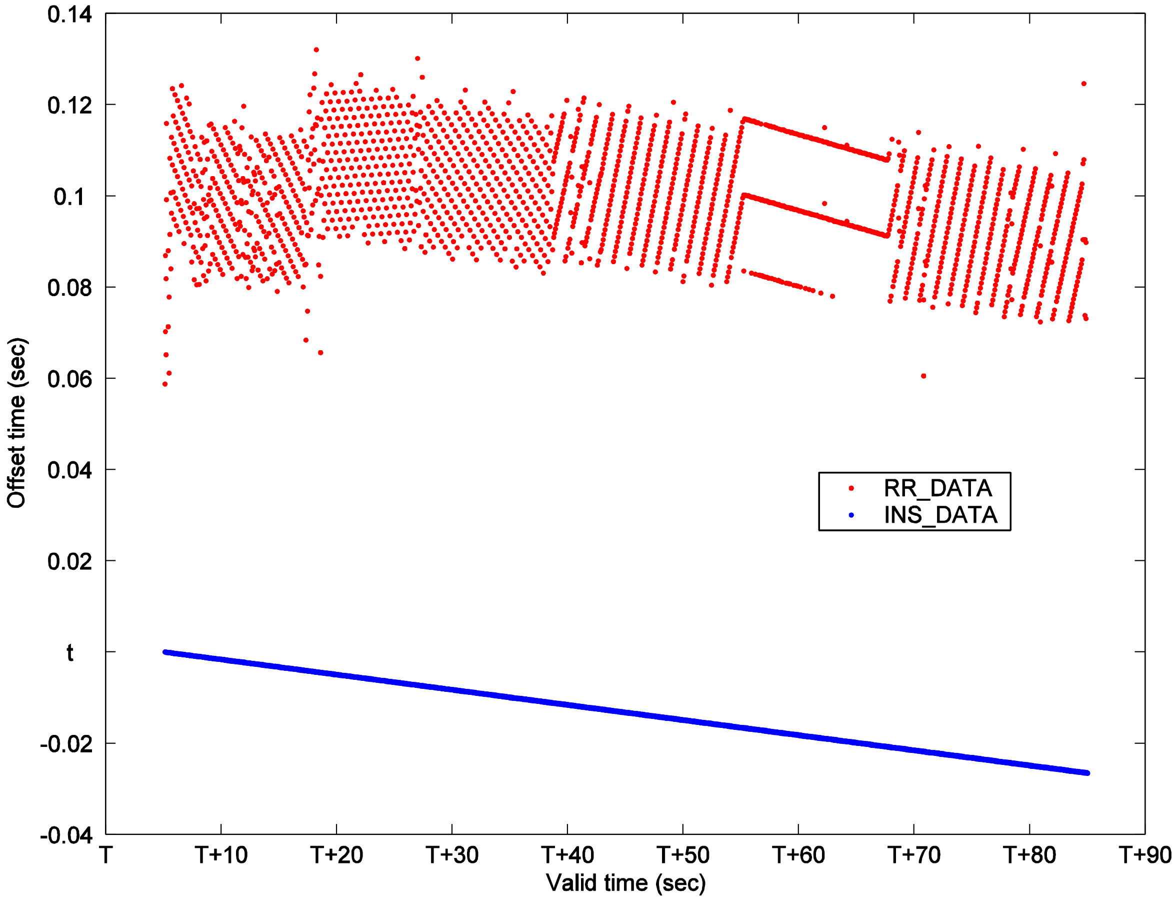

Figure 3-12: Offset between recorded time and valid time for RR_DATA and INS_DATA.

3.3.3 Synchronization Process

The dependency between RTC and UTC is in this work considered to be linear as they basically are two clocks running in parallel. The strategy for finding a polynomial describing the dependency between the two is to use the polyfit function in Matlab. As input for the polyfit function RTC and UTC values from INS_DATA messages during the current radar exposure interval are taken, following the conclusions made in Ch. 3.3.1-2. Polyfit returns a first degree polynomial as output that describes the linear function . This first degree polynomial is found with the polyfit function in Matlab by use curve fitting of input data in a least square sense. This first degree polynomial will also take care of any indifference in clock rates between RTC and UTC that can be observed in fig 3-12.

What is important to know is that this linear dependency includes the unknown delay time from valid data time to recording time that the recorded INS_DATA message is subject to. However the approach is that by the comparison of radar and GPS data in the later test we will get a chance to determine this delay time with better accuracy.

3.4 Distance-to-Target Measurements

Accuracy in radar data can be distinguished in different measurements as for example distance, velocity and angle of aspect. This test serves only as guidance for future work on how to use GPS data together with radar measurements. The focus is set on radar measurements made on distance-to-target and is a test of the correctness in data transformations made in our method. The choice that is made to only look at distance-to-target measurements is done because that is the most straightforward calculated quantity of them all, at the same time as it fully serves the purpose of the test.

3.4.1 Target Position - Radar

The data sets from the radar are in HDF5 format. This is a file format designed for large data structures. Scripts for putting HDF5 data into databases are available at EDS and used to unpack data for further analyze in local evaluation environments. Most of data analysis during the thesis work is done in Mathworks Matlab environment with data retrieved from the databases created in earlier steps described above.

The interesting radar data for use in the test of our method is filtered out in several stages using Matlab. To do this filtering several scripts had to be written. These scripts remove any irrelevant data like empty messages containing zeros. They also eliminate radar target data with inferior quality compared to best available target data. The result of this extraction of relevant data is a vector with elements containing all radar estimations of target position from a specified radar exposure interval. All position estimates are also tagged with a valid data time. These scripts had to be written before a useful analyze of target data could be done with Matlab.

3.4.2 Distance-to-target – Radar

The radar describes target position relatively the test aircraft in three dimensions.

The calculation of the Euclidian distance is done by:

where:

Test Aircraft Position =

Target Aircraft Position =

The distance-to-target calculation is done for all radar position estimates from the radar exposure interval resulting in a vector with distance-to-targets tagged with valid times.

3.4.3 Target and Fighter Position – GPS

Previously in 2.2.2.2 we assumed that position data from post-processed GPS and INS data probably was the most accurate position data set that could be produced from Gripen test flights. Therefore the choice is to evaluate radar data using GPS/INS position data as benchmark whenever it is available. This position quality is only available for one of the test exposures and for the other two we use DGPS position data instead, with nearly the same accuracy

GPS and INS position data from flight tests are post-processed with NovAtel Inertial Explorer and the result is delivered in text-files specifying GPS/INS-filtered positions in 2Hz sample frequency. If there is a lack of post-processed GPS/INS data from test flights we choose to use differential processed GPS data from GrafNav instead.

3.4.4 Distance-to-target – GPS

Calculation of distance-to-target from GPS data can be done in the same way as for radar data by using the same formula for the Euclidian distance.

Where:

Test Aircraft Position =

Target Aircraft Position =

3.4.5 Interpolation of GPS data

There is a need to interpolate one of the datasets after distance-to-target is calculated from both radar and GPS data. This is because the distance-to-target samples from the two different sources, GPS and radar, do not match in time, see Figure 3-13. The GPS samples are in either 1Hz or 2Hz and suitable to be linearly interpolated over all radar samples resulting in synchronized distance-to-target values from both GPS and radar measurements as shown in Figure 3-14.

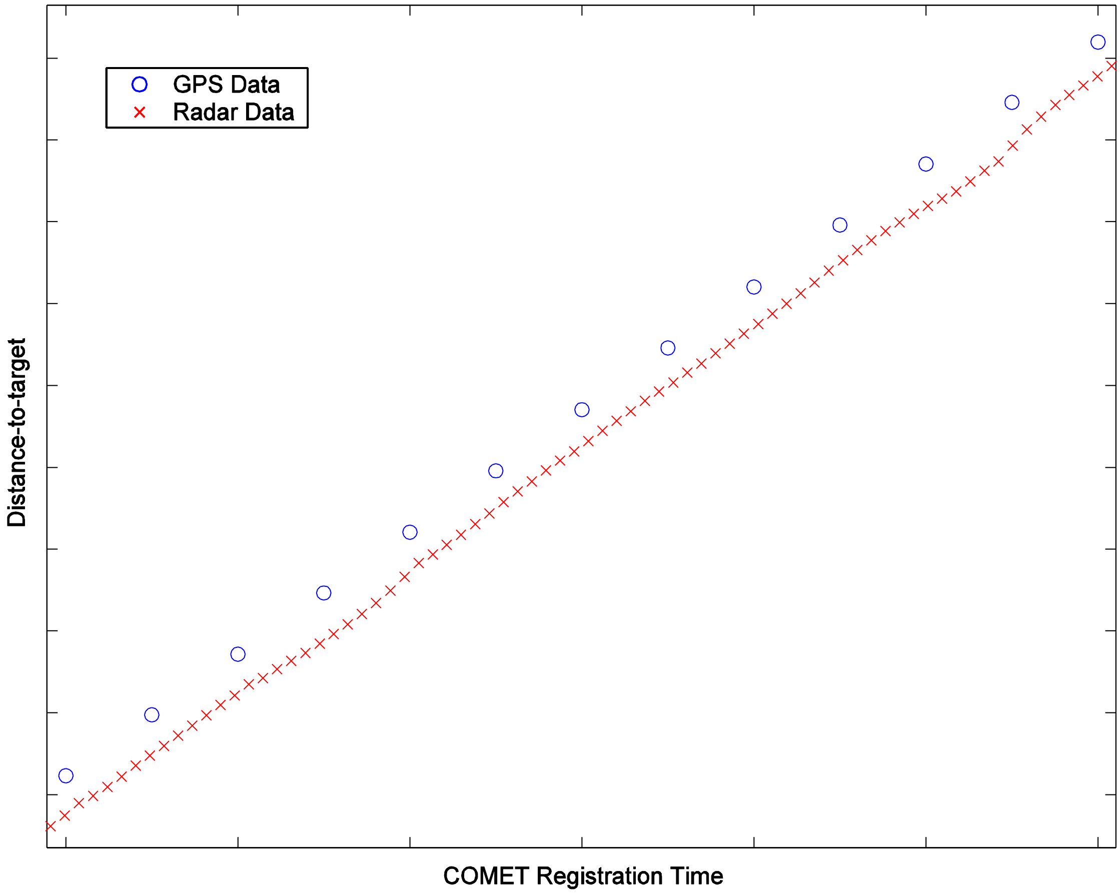

Figure 3-13: Example with radar and GPS data before interpolation of GPS data.

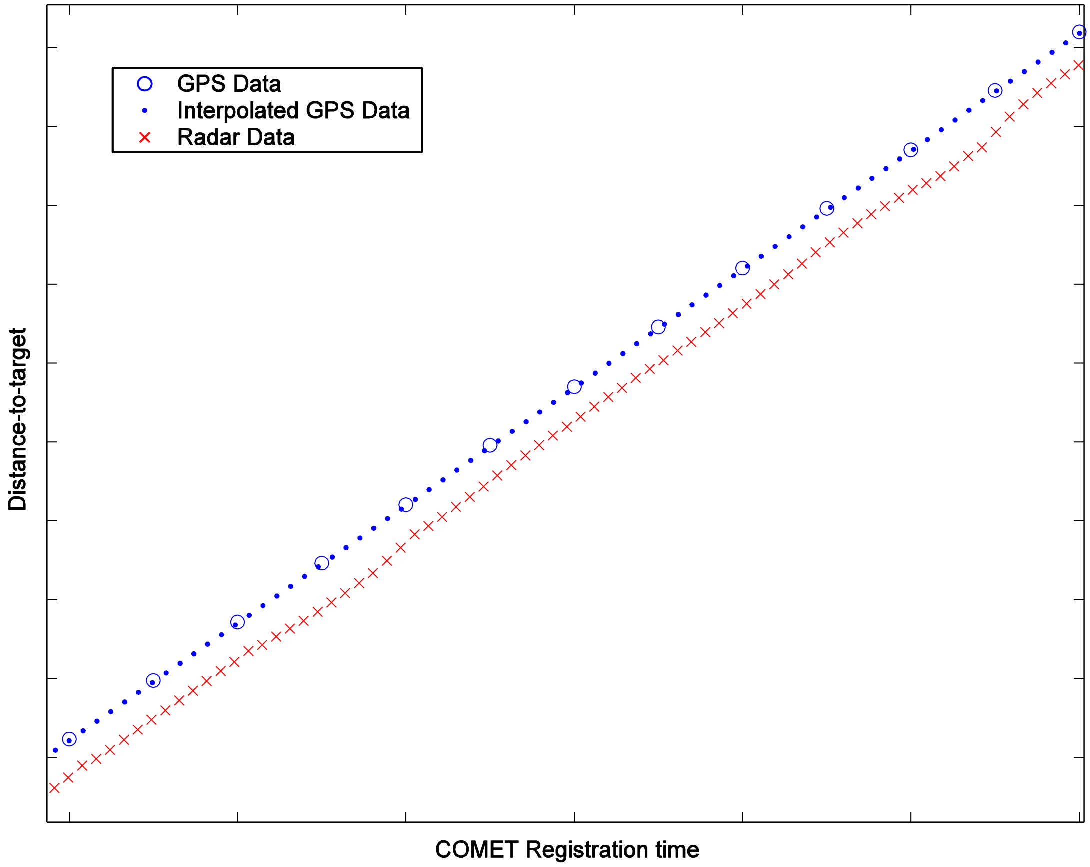

Figure 3-14: Example with radar and GPS data after linear interpolation of GPS data.

3.5 Test of Comparison Method

Numerous of test flights have been carried out through the years since early development of the PS-05/A. Focus in this test lies solely at distance-to-target radar measurements and for that we need radar data from test flight phases with best possible data quality. The best quality in target data as well as highest data update rate is achieved when the radar works in Single-Target-Track-mode (STT). This mode is optional for the pilot during any phase when a target is locked on. STT-mode means that the radar only tracks a single target and spends no time in search of any other target leading to a higher update rate of the tracked target.

For this test we will look at three different test flights with slightly different setup premises. By looking at different geometries and speeds we can draw conclusions of the correctness of the method not afflicted with errors origin in the character of the test flight or other anomalies derived from shifting aspect angles. Also, by looking at one closing setup with high relative velocities on test aircraft and target aircraft we may draw conclusions on and determine what delay times the previous time synchronization are afflicted with.

The test is done with comparisons between radar measured distance-to-target and GPS measured distance-to-target. The three test flight phases have durations between 45 and 80 seconds. GPS distance-to-target is set as benchmarking distance. Radar measured distance is then compared to GPS by looking at both the distribution of radar distance measurements and the position of the mean radar distance during the interval. For this test we assume the radar reflection point of the target aircraft is positioned at the average radar distance measured during the test exposure interval. The radar reflection point is then compared to where the aircraft is positioned according to GPS measurements. In this comparison the reflection point should be somewhere on the target aircraft, and if not, the comparison method may be considered as improperly designed. Notable in these tests is that we assume both radar and GPS data to be of sufficient accuracy and that the tests only check the accuracy of the method itself.

To ensure that the comparison method is correct during all possible conditions, it would have been desirable to have a significantly larger number of test flights to test the method on. However, it was hard to find test flight phases with appropriate conditions to use for test of the method. It was also a time consuming and thorough manual process that the data sets had to undergo before data could be used. This is why the thesis work only includes three different test flight setups.

Notable in the comparisons in this report is that target aircraft pictures are not to scale schematic models of the original target aircrafts. All metrics of the models are also removed. These measures have been taken due to the consideration of product confidentiality.

3.5.1 Determination of a Maximum Message Delay Time

When looking at a static exposure with no relative velocity between test aircraft and target aircraft a delay, whether it is taken care of or not, will not affect a comparison of measurements since the distance-to-target is constant. However by looking at a dynamic exposure setup the differences in GPS and radar measurements will increase according to the magnitude of the delay and relative velocity. For this reason the first test flight evaluated is one with two closing aircrafts.

Test Flight #1: The conditions on this test flight exposure are favorable to determine the maximum delay time of the INS_DATA message and understand how UTC and RTC are related. The conditions for the determination are good since the relative speed between the aircrafts is high which leads to large differences in radar and GPS distance estimates when introducing a relatively minor delay time. A delay time will introduce a shift in radar distance estimate for a given point in time. This shift corresponds to the distance travelled by the two aircrafts during that delay time, see Figure 3-15. Estimation of maximum delay time of the INS_DATA message is done by observing three different assumed values of the delay. These values correspond to 0, ½ and 1 message cycle (0 ms, 8 ms and 16 ms).

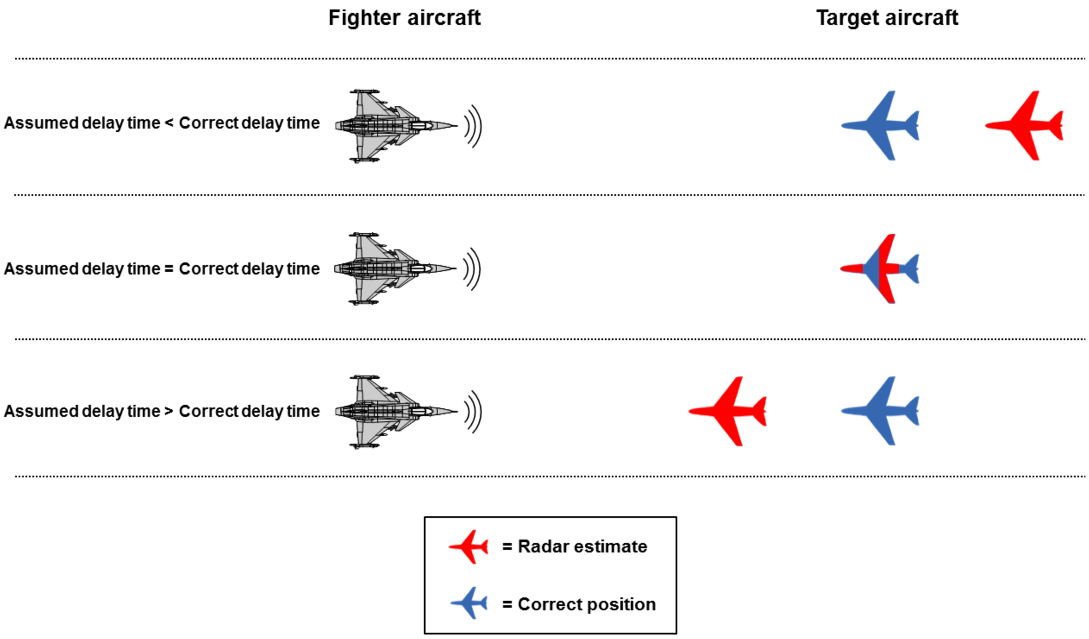

Figure 3-15: Radar estimates with different delay assumptions.

Assumption #1: Message delay = 0 ms

When setting message delay time to 0 ms the average of distance-to-target measurements gives that a probable radar reflection point on the target aircraft for this radar exposure is behind the nose cone of the target aircraft, see Figure 3-16.

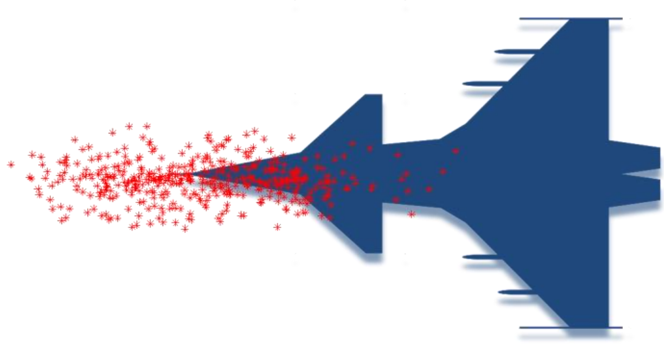

Figure 3-16: Radar distance-to-target plot - Test flight #1 with 0 ms message delay.[1]

Assumption #2: Message delay = 8 ms

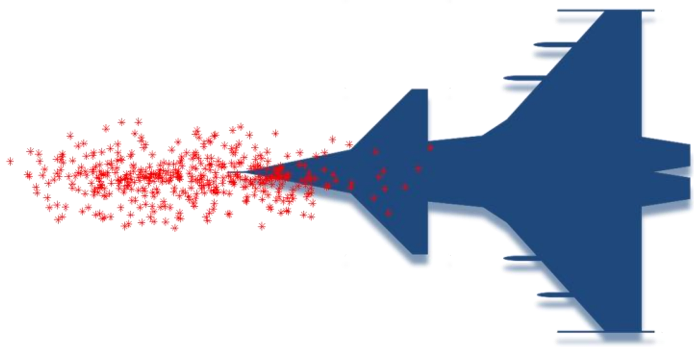

Figure 3-17: Radar distance-to-target plot - Test flight #1 with 8 ms message delay.[1]

With an assumed delay of 8 ms the probable radar reflection point is located in front of the aircraft, see Figure 3-17. This is a physically unlikely reflection point since it is positioned outside the aircraft fuselage. This observation also speaks for a delay time closer to zero than 16 ms.

[1] The 1-dimensional data is on purpose randomly spread out in the vertical dimension to better visualize the density.

<u>Assumption #3:</u> Message delay = 16 ms

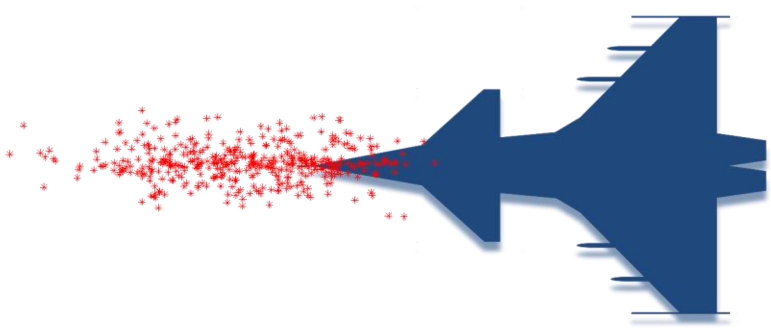

Figure 3-18: Radar distance-to-target plot - Test flight #1 with 16 ms message delay.[1]

This assumption moves the reflection point further away from the target aircraft nose cone. This estimated reflection point is well in front of the target aircraft and therefore not likely to represent a correct assumption of delay time, see Figure 3-18.

Conclusions regarding delay time: When assuming delay times of 8 or 16 ms the radar reflection point is positioned in front of the aircraft. From this we draw the conclusion that the correct delay time probably is somewhere between 0 and 8 ms.

Let us assume that an error of 8 ms would be introduced in our comparison method. What could the maximum error from this be in evaluation of a test flight?

The minimum resulting position error would be 0 in a setup with radar and target without any relative position change. Large position errors are instead obtained with high-speed closing, or departing, aircrafts. Let us say that two aircrafts are closing with speeds at 200 m/s, a normal aircraft speed in test flight. These aircrafts would then have a relative speed of 400 m/s. With an error of 8 ms these aircrafts are falsely assumed to be m closer than in reality, see Figure 3-15. 3.2 m is then the maximum position error during normal test flight conditions. Errors of this magnitude can be ignored for this work since they only may appear with closing aircrafts, and as they are significantly smaller than the length of the target aircrafts. Therefore a message delay of 0 ms will be assumed for the continuation of this work.

3.5.2 Test Flight #1

Test Flight	**#1**
Exposure	#15
Test Aircraft	Blue Trajectory
Target Aircraft	Red Trajectory
Target Tracking	STT-mode
Distance	~ 35.000 – 15.000 meter
Aspect to Target	Frontal
Duration	~ 45 seconds
Position Data	DGPS

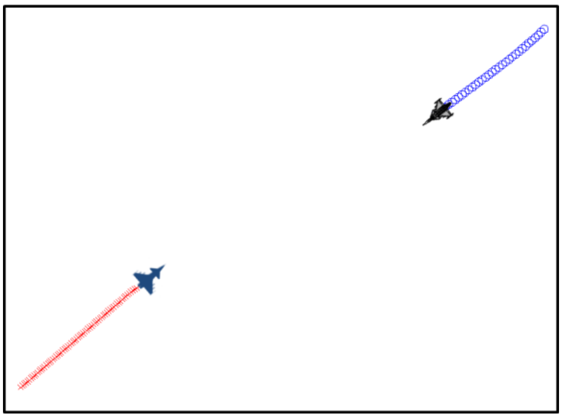

Figure 3-19: Setup geometry – Test flight #1.

Exposure setup: During this radar exposure the aircrafts are closing in distance where they are heading towards each other aiming for a frontal merge, see Figure 3-19. The exposure starts on a distance of 35.000 meter and ends at a distance of approximately 15.000 meter. The duration of this closure of 20.000 meter is 45 seconds therefore giving an average relative speed of nearly 450 m/s.

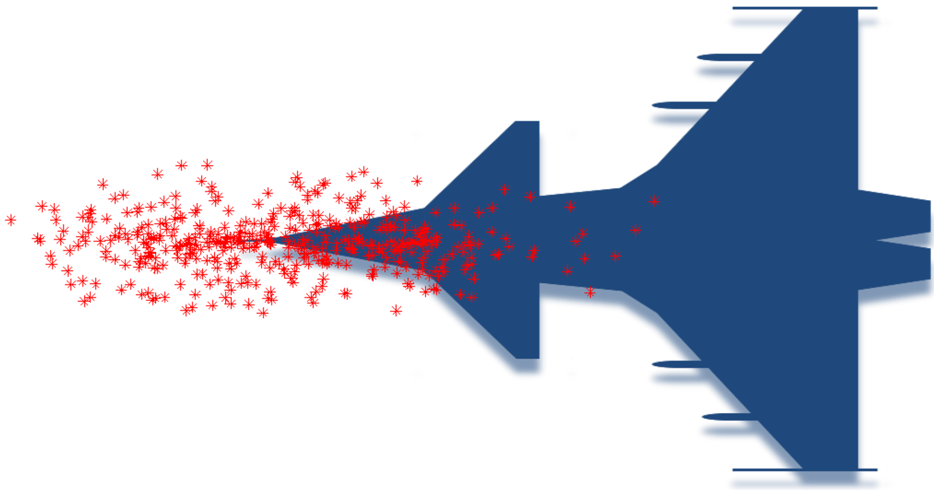

Figure 3-20: Radar distance-to-target plot - Test flight #1.[2]

[2] The 1-dimensional data is on purpose randomly spread out in the vertical dimension to better visualize the density.

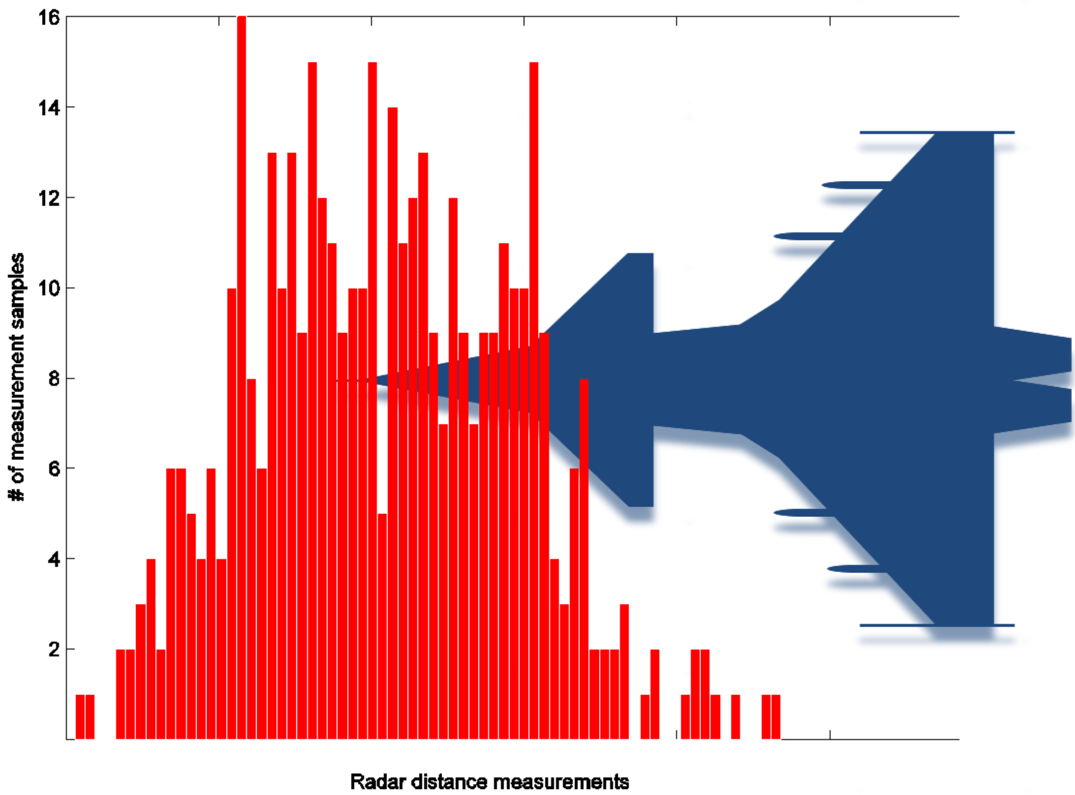

Figure 3-21: Radar distance-to-target histogram - Test flight #1.

Observations: The distance measurement samples are spread with most of them lying within a range of one target aircraft length, see Figures 3-20 and 3-21. The average radar measured distance is right behind the aircraft nose.

3.5.3 Test Flight #2

Test Flight	**#2**
Exposure	#13
Test Aircraft	Blue Trajectory
Target Aircraft	Red Trajectory
Target Tracking	STT-mode
Distance	~ 18.000 meter
Aspect to Target	Trailing
Duration	~ 50 seconds
Position Data	DGPS

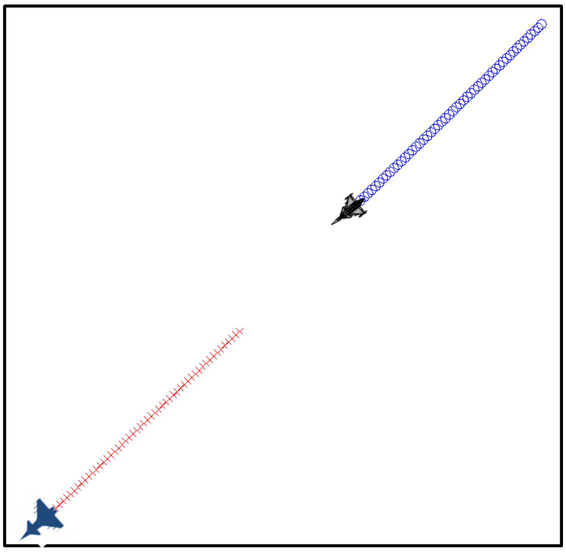

Figure 3-22: Setup geometry – Test flight #2.

Exposure setup: This radar exposure includes a target trailed from behind, see Figure 3-22. The velocities on the two aircrafts are nearly the same giving a quite stationary relative geometry between the two with a low relative speed. The distance between the two aircrafts is about 18.000 meter during the entire exposure.

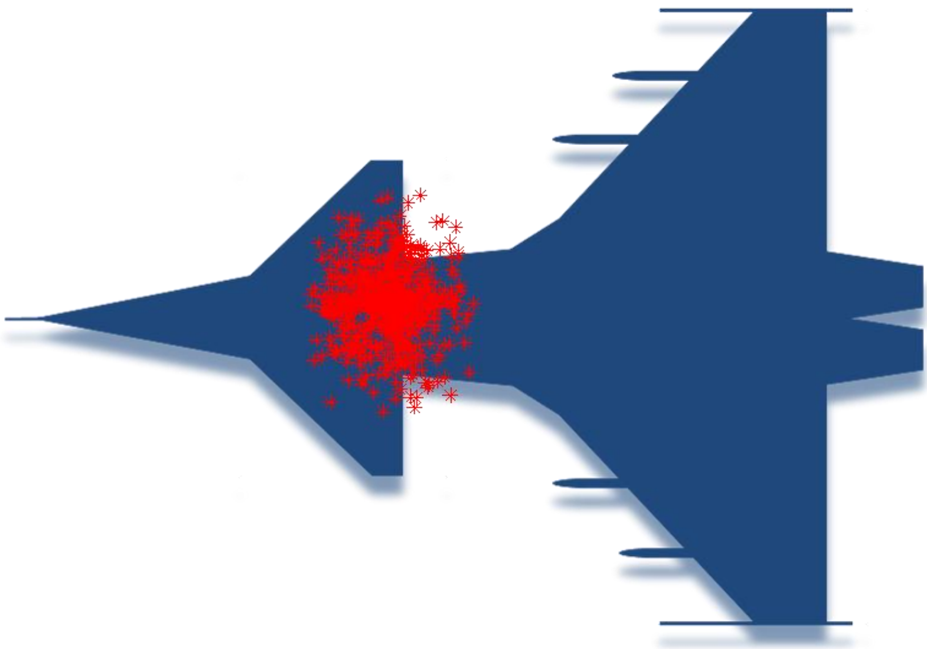

Figure 3-23: Radar distance-to-target plot - Test flight #2.[3]

[3] The 1-dimensional data is on purpose randomly spread out in the vertical dimension to better visualize the density.

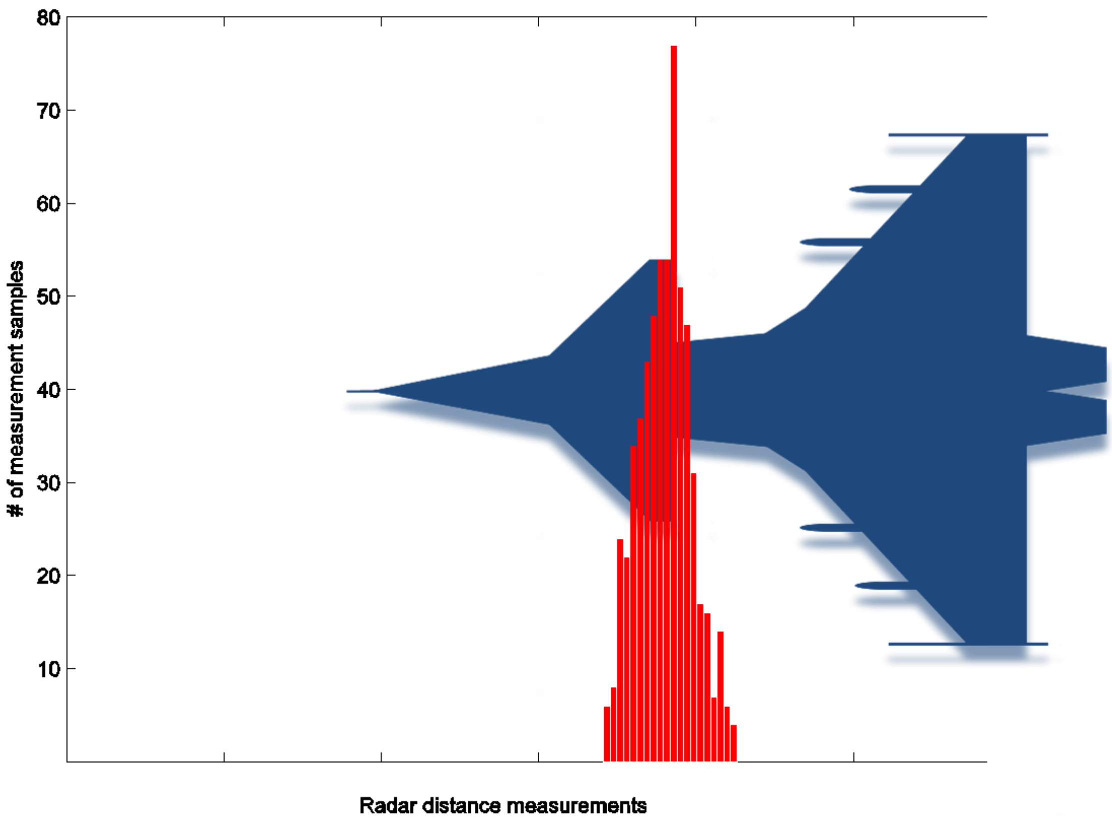

Figure 3-24: Radar distance-to-target histogram - Test flight #2.

Observations: The relative velocity between the aircrafts is near zero during this exposure. Therefore the INS_DATA message delay time will not afflict the radar distance-to-target estimate to any greater extent. What can be observed on the radar plot is that the radar measured distance-to-target samples from this exposure are very closely gathered relatively the target aircraft length, see Figures 3-23 and 3-24.

3.5.4 Test Flight #3

Test Flight	**#3**
Exposure	#8
Test Aircraft	Blue Trajectory
Target Aircraft	Red Trajectory
Target Tracking	STT-mode
Distance	~ 3.000 – 5.000 meter
Aspect to Target	Trailing
Duration	~ 80 seconds
Position Data	GPS/INS

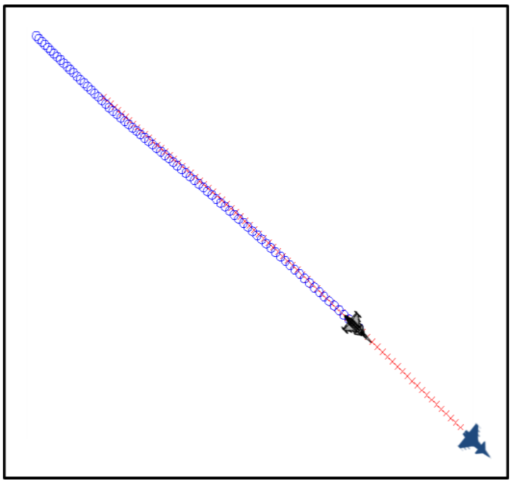

Figure 3-255: Setup geometry – Test flight #3.

Exposure setup: The phase is during exposure #8 of test flight #3, right after take-off where the test aircraft trails the target aircraft with radar locked on to the target in STT-mode, see Figure 3-25. The trajectories of the two aircrafts result in radar aspect angles where the radar looks at the target from behind during the entire phase. The phase is about 80 seconds long and the two aircrafts remains in nearly same aspect angles during the whole phase. There are slight changes in altitude and speed on both aircrafts. However, these dynamic changes are not considered to affect radar measurements in any greater extent as aspect angle is nearly static during the entire phase. The gap between the aircrafts increases from at first approximately 3000 meters to later about 5000 meters. This is the result when the target first has a relatively higher speed but later on decelerates to a speed less than that of the test aircraft and thus the gap between the aircrafts slightly closes.

Observations: The relative velocity between the two aircrafts is rather low. Therefore any position error from synchronization will not affect the reflection point estimate to any greater extent. The distance-to-target plot shows that most of the radar estimates lies within a distance comparable to one target aircraft length, see Figures 3-26 and 3-27.

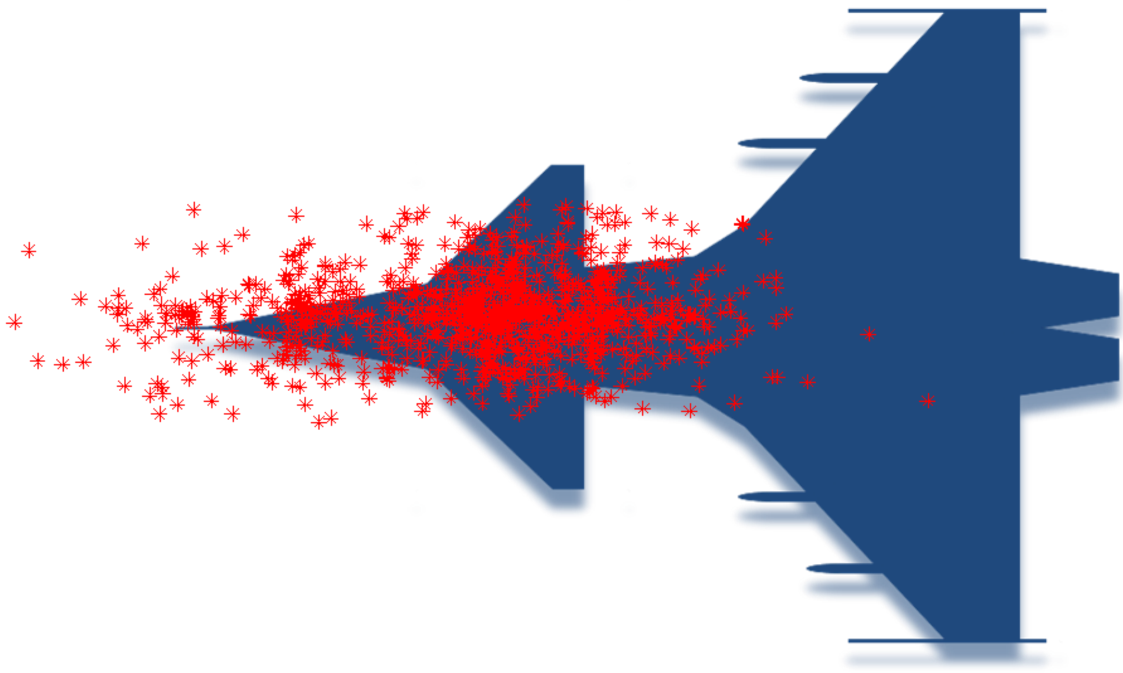

Figure 3-26: Radar distance-to-target plot - Test flight #3.[4]

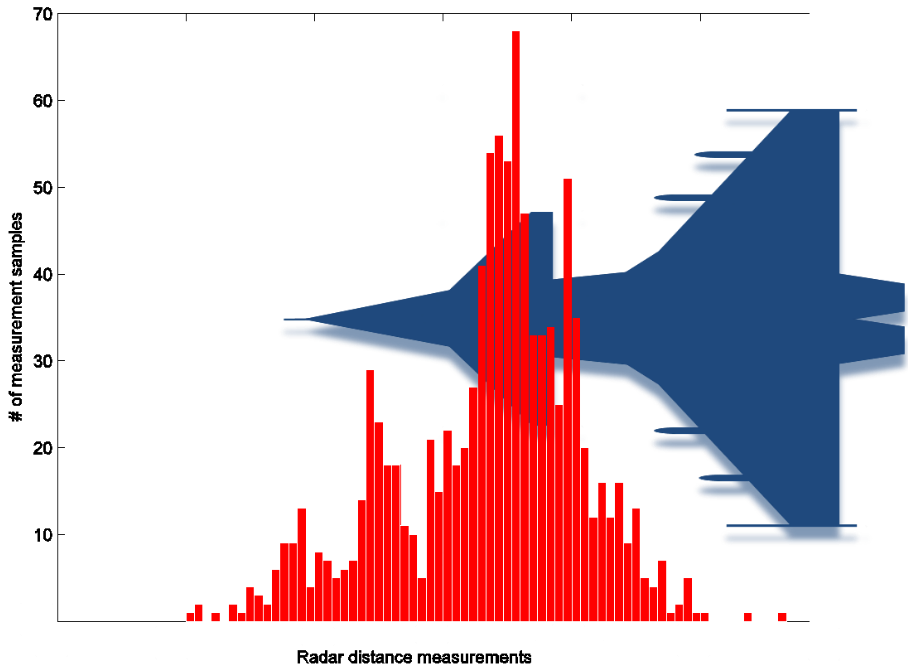

Figure 3-27: Radar distance-to-target histogram - Test flight #3.

[4] The 1-dimensional data is on purpose randomly spread out in the vertical dimension to better visualize the density.

4 Conclusions

4.1 GPS Inventory

4.1.1 Positioning for Ground Based Sensors

In tests of ground based sensors at EDS there is regularly need for position measurements on sensors and targets for later comparison with sensor data. These position measurements are primarily done by using three different sets of GPS receiver equipment. The accuracy of these sets of equipment is very much dependent on environmental factors which are the case with any other GPS receiver as well. Anyway, the position data tend to be on a level that is good enough for the tests that they are part of

- **Ashtech Z-Xtreme**

This receiver is easy to use since it does not need any external power source. The log-functions are also managed internally and therefore this receiver only needs an antenna to be set operational for basic use. After measurements are done the receiver is not that easy to use anymore since the operator has to connect it to a PC on a serial link with special software from the manufacturer installed on the PC.

- **NovAtel DL-V3**

The DL-V3 can log data to a CF-card making it quite flexible in use both during measurements and post-operation. The receiver needs an external power source during operation why it gets a bit more impractical compared to the Z-Xtreme with internal battery.

- **NovAtel SPAN SE-D**

This receiver is very much like the DL-V3 receiver when used without INS. However for use with INS integrated and with two-antenna installation it takes a lot more preparatory work for adjustments and I would not recommend an installation of the SPAN/INS combination when needing a quick system setup. However, when the system is up and running with all calibrations done it is a very potent set of measuring equipment.

4.1.2 Positioning in Test Flight of PS-05/A

The standard procedure for retrieval of position data to EDS from test flights is DGPS. There is however another method available including inertial measurements available at Saab Aeronautics that could be used for the Gripen test aircraft and also for the target if that is a Gripen aircraft as well. This GPS/INS combined method ensure better continuity in data as the output data of this method does not suffer from GPS signal outages. The accuracy is also assumed to be better to some extent. It is hard to determine the exact accuracy but it is assumed to be down in level of 0.5 meter during favorable conditions.

I would suggest that the GPS/INS combined method would be used on a more regular base as it is a relatively quick process to use it on data from a Gripen test aircraft.

4.2 Method for Comparison of Radar and GPS Data

The method suggested for evaluation of radar data by using GPS measurements is depending on what the evaluation aims at. The method in this thesis work only aims at distance-to-target measurements. There could be several other evaluations on radar measurements such as accuracy in angle and velocity. However, the least common divider for any radar data evaluation consist of the two steps listed below. These steps are therefore used in the method that this work suggests as a comparison method.

4.2.1 Transformation of Coordinates

GPS use polar coordinates in the global standard system, WGS84, to specify any position. The GPS coordinates are transferred into a Cartesian coordinate system with a transformation method recommended by the Swedish authority in the area of mapping, Lantmäteriet. Position coordinates expressed in a Cartesian system is a qualifier to be able to do any mathematical manipulations and analysis on the data. Regarding position data from the radar, these coordinates are already expressed in a Cartesian system and does not need any transferring before analysis.

The transformation method of GPS position data to Cartesian coordinates is, in this work, assumed to be assured in terms of quality. This assumption is made since the formulas used are stated by a recognized authority, Lantmäteriet.

4.2.2 Synchronization of Data

The position coordinate incompatibility found a quite straight forward solution. But the data synchronization was instead a more troublesome area. The problem consisted of different definitions of time for GPS and radar data regarding valid time. Radar data was set in a local aircraft definition of time and GPS data was set in the globally used UTC definition of time. The challenge was to get the two data sets into the same comparable definition of time.

By using a third data entity from the aircraft system radar data was transferred to the UTC definition of time. This transformation could be done by using message traffic with the third data entity sent on the aircraft bus-system. This bus-traffic is recorded during test flights for post flight evaluations and could therefore be investigated in this thesis work.

4.2.3 Test of Comparison Method

The method was tested on three different test flight setups with high quality radar data and favorable GPS conditions. The test was a comparison between GPS data, set as benchmark, and radar data. Radar data was plotted onto a stylistic target aircraft model. Plots were made showing both radar measurements, sample for sample, but also as a histogram. For all three test flights the average distance-to-target from radar data coincided with some part of the target models, which positions were decided from GPS data.

From this the conclusion is drawn that the method is usable under comparable conditions to the three above. However, I would recommend further testing of the method in other test flight setups to better ensure functionality of it.

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6 Appendices

Appendix A – Overview of GPS

Appendix B – Coordinate Transformation