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Technical Verification and Validation of TIS-B using VDL Mode 4

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Sammanfattning
Abstract

This report is a technical verification and validation of Traffic Information Service Broadcast (TIS-B) using the data link VDL Mode 4.

The main objective of the report is to examine the usefulness of TIS-B considering the results from tests performed in the Stockholm Terminal Area and for the Advanced Surface Movement Guidance and Control System (A-SMGCS) at Arlanda airport. The results are compared with the requirements that have been set by the standardisation organisations ICAO, RTCA, Eurocontrol and Eurocae. TIS-B is however such a new concept, so most of the operational requirements have not yet been defined.

The process for performing the evaluation of TIS-B involves three stages:
- Study the requirements on TIS-B, ADS-B, radar and A-SMGCS.
- Verify TIS-B by performing tests at Arlanda airport.
- Validate the results through analysis.

A theoretical study of slot allocation optimisation is performed to decide how the slot allocation is to be implemented.

The report includes a Functional Hazard Analysis (FHA). The FHA is done to see if the applications for TIS-B are ready for implementation or if more hazard preventing actions has to be taken, before any operational actions can be performed.

The report also involves a theoretical introduction to Air Traffic Management (ATM), Surveillance techniques and TIS-B.

All parts included in the report results in conclusions and recommendations regarding the TIS-B service.

Nyckelord
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VDL Mode 4, TIS-B, A-SMGCS, SCAA, Arlanda, Luftfartsverket, NUP II, STDMA, FHA, Transceiver, Slot allocation

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Abbreviations

ADS-B	Automatic Dependent Surveillance – Broadcast
A-SMGCS	Advanced Surface Movement Guidance and Control System
ASAS	Airborne Separation Assurance Systems
ASTERIX	All-Purpose Structured Eurocontrol Radar Information Exchange
ATCC	Air Traffic Control Center
ATM	Air Traffic Management
ATSAW	Air Traffic Situation and Awareness
AVOL	Aerodrome Visibility Operational Level
CCI	Co-Channel Interference
CD & R	Conflict Detection and Resolution
CDTI	Cockpit Display for Traffic Information
CNS	Communication, Navigation and Surveillance
CRC	Cyclic Redundancy Check
FHA	Functional Hazard Analysis
GLONASS	Global Orbiting Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground Station
GSC	Global Signalling Channel
HMI	Human Machine Interface
ICAO	International Civil Aviation Organisation
LFV	Luftfartsverket (SCAA)
LSC	Local Signalling Channel
MASPS	Minimum Aviation System Performance Standards
MSL	Mean Sea Level
NAC	Navigational Accuracy Category
NEAN	North European ADS-B Network
NEAP	North European CNS/ATM Application Project
NIC	Navigational Integrity Category
NM	Nautical Miles
NUP	NEAN Update Programme
PSR	Primary Surveillance Radar
RSC	Regional Signalling Channel
RTCA (inc.)	Requirements and Technical Concepts for Aviation
RTK	Real Time Kinematic
SCAA	Swedish Civil Aviation Administration (LFV)
SDPS	Surveillance Data Processing System
SIL	Surveillance Integrity Level
SMR	Surface Movement Radar
SSR	Secondary Surveillance Radar
STDMA	Self-Organising Time Division Multiple Access
SV	Service Volume
TCP	Transmission Control Protocol
TIS-B	Traffic Information Service - Broadcast
TIV	Traffic Information Volume
TMA	Major Terminal Area
UDP	User Datagram Protocol
UTC	Universal Time Co-ordinated
VDL Mode 4	VHF Digital Link Mode 4
VHF	Very High Frequency
VIP	VDL Mode 4 Interface Protocol

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Personal contacts:

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Executive Summary

This report is a technical verification and validation of Traffic Information Service Broadcast (TIS-B) using the data link VDL Mode 4.

The main objective of the report is to examine the usefulness of TIS-B considering the results from tests performed within the Stockholm Terminal Area and for the Advanced Surface Movement Guidance and Control System (A-SMGCS) at Arlanda airport. The results are compared with the requirements that have been set by the standardisation organisations ICAO, RTCA, Eurocontrol and Eurocae. TIS-B is however such a new concept, so most of the operational requirements have not yet been defined.

The process for performing the evaluation of TIS-B involves three stages:

- Study the requirements on TIS-B, ADS-B, radar and A-SMGCS.
- Verify TIS-B by performing tests at Arlanda airport.
- Validate the test results through analysis.

A theoretical study of slot allocation optimisation is performed to decide how the slot allocation is to be implemented.

The report includes a Functional Hazard Analysis (FHA). The FHA is done to see if the applications for TIS-B are ready for implementation or if more hazard preventing actions has to be taken, before any operational actions can be performed.

The report also involves a theoretical introduction to Air Traffic Management (ATM), Surveillance techniques and TIS-B.

All parts included in the report results in conclusions and recommendations regarding the TIS-B service.

1. Introduction

The way of managing air traffic communication, navigation and surveillance is changing. The traditional method for surveillance based on radar is unsatisfying when it comes to supporting the increasing number of aircrafts. Today, pilots and drivers handling ground vehicles have no tool that gives an overview of the targets surrounding them. The development goes towards implementation of Automatic Dependent Surveillance Broadcast (ADS-B), which is an application that enables pilots and air traffic controllers to see targets on a display with higher accuracy than radar. ADS-B also provides aircraft status and flight information. The parameters of interest are communicated using a data link of some sort. In order to be detected as an ADS-B target, a vehicle must be equipped with a specific transceiver. Before all vehicles have been equipped it could be an idea to have a service that enables equipped vehicles to see non-equipped vehicles. This service is TIS-B. TIS-B can be based on radar, Multilateration or re-broadcasted ADS-B data transmitted via the specific data link to the transceiver-equipped vehicles, offering a full surveillance picture.

1.1. Objective

The main objective of the work has been to examine the usefulness and implementation possibilities for TIS-B using VDL Mode 4. Tests have been performed in order to find out if data distributed with TIS-B fulfils the operational requirements. However, most of the operational requirements for TIS-B have not yet been defined. Therefore, existing requirements for Secondary Surveillance Radar (SSR), A-SMGCS and ADS-B have been taken into consideration.

The report deals with prior work and opinions on TIS-B from RTCA, Eurocontrol and others. Possible applications, such as Air Traffic Situation and Awareness (ATSAW) and Airborne Separation Assurance (ASAS) applications, for TIS-B have been considered. A theoretical study of slot allocation optimisation has given an understanding of the slot allocation problem.

1.2. Scope

The issues that are addressed in this report are the performance of TIS-B in Major Terminal Areas (TMA) as well as on the airport surface. The scope of the document can be seen in figure 1-1. The operational requirements of TIS-B that have been considered are expressed in terms of availability, integrity, latency, accuracy, continuity, coverage, capacity and monitoring.

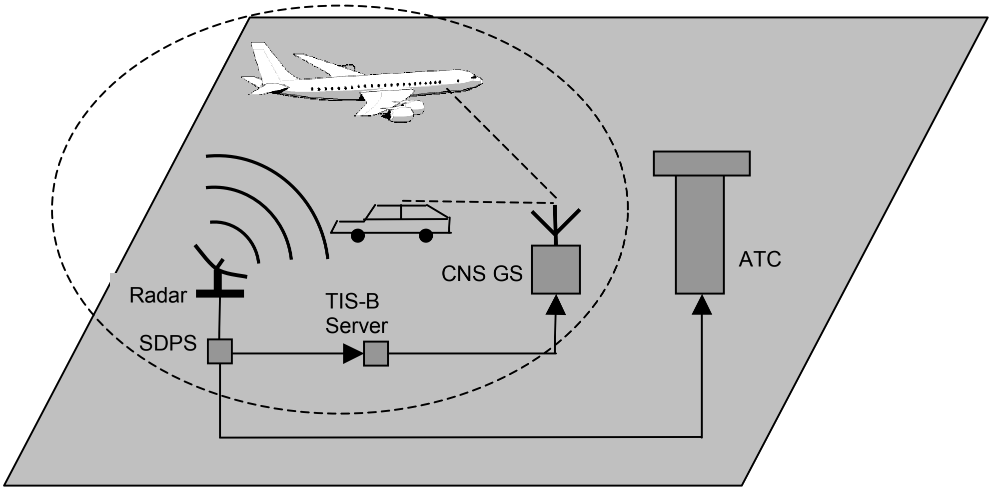

Figure 1-1. Scope of document within dotted circle.

1.3. Method

The main method for the technical verification and validation of TIS-B consists of three stages. The first stage is to make a theoretical study of the operational requirements of the surveillance methods: TIS-B, ADS-B, Radar and A-SMGCS. The second stage is to make plans for the tests at Arlanda airport and to implement these. The third stage is to evaluate the data collected in these tests. The work will conclude in opinions and recommendations concerning the TIS-B service.

The method for the theoretical optimisation of slot allocation is to evaluate different techniques through discussion and theoretical studies. Simple theoretical experiments will also be performed. The discussions and experiments will conclude in an understanding and a possible recommendation for the slot allocation process.

1.4. Revision

This report is revised and updated by the SCAA.

1.5. Audience

The audience for this report is the partners in the North European ADS-B Network Update Programme II (NUP II), the Swedish Civil Aviation Authorities (SCAA) as well as Linköpings Universitet.

2. Explanation of terms

Accuracy	Accuracy is a statistical measure of performance that describes how well a measured value agrees with a reference value. [Ref 1]
Availability	Availability is the ability of a system to perform its required function at the initiation of the intended operation. It is quantified as the proportion of the time the system is available to the time the system is planned to be available. [Ref 1]
Capacity	Capacity is the maximum number of simultaneous movements of aircraft and vehicles that the system safely can support within an acceptable delay commensurate with runway and taxiway capacity at a particular aerodrome. [Ref 1]
Continuity	Continuity is the probability of a system to perform its required function without unscheduled interruptions during the intended period of operation. [Ref 1]
En-route Airspace	En-route airspace is the volume of airspace outside terminal areas (see below), where the climb, cruise and descent phases of flight take place and within which various types of air traffic services are provided. [Ref 5]
EPOS	EPOS is a combination of GPS and differential corrections made available via the RDS channel all over Sweden through a customer subscription and using modified RDS receivers – EPOS receivers.
EUROCONTROL	EUROCONTROL is the European Organisation for the Safety of Air Navigation. It was founded in 1960 for overseeing air traffic control in the upper airspace of the member states. The most important goal today for EUROCONTROL is the development of a coherent and co-ordinated air traffic control system in Europe. Currently there are 29 member states.
Flight Level (FL)	Flight level is the name for the pressure altitude reported by an aircraft. It is measured in hundreds of feet, FL100 = 10 000 feet.
Global Signalling Channel (GSC)	The Global Signalling Channels are the two worldwide channels/frequencies (same frequencies all over the world) used for transmitting and receiving messages via VDL Mode 4. In complement to the GSCs, Local Signalling Channels can be used (see below).

Hold	As applied to air traffic, to keep an aircraft within a specified space or location which is identified by visual or other means in accordance with Air Traffic Control instructions.
ICAO	ICAO is the International Civil Aviation Organisation. It was founded in 1944 to develop the principles and techniques of international air navigation and to foster the planning and development of international air transport.
Integrity	Integrity is the probability that errors will be detected. For example a correct message must not be indicated as containing one or more errors, or a message containing one or more errors may not be indicated as being correct. [Ref 15]
Latency	Latency is the elapsed time between a system input and the corresponding system output. [Ref 1]
Local Signalling Channel (LSC)	A Local Signalling Channel is to serve as a complement to the Global Signalling Channel (see above) but with only local coverage, primarily close to major airports.
Major Terminal Area	A major terminal area is the volume of airspace surrounding one or more principal airports. The lateral extent will vary, depending on the disposition of airports within, or adjacent to the terminal area. The vertical dimensions will vary with the way the airspace and the procedures for handling the air traffic flow is organised.
Real Time Kinematic (RTK) GPS	Real Time Kinematic GPS is a high precision GPS equipment. At a well-defined reference position a station uses the carrier wave transmitted from the GPS satellite to calculate a very precise distance to the satellite. This calculation is then used by the aircraft GPS receiver to serve as a correction to the position calculated from the time received from the GPS satellites.
RTCA	RTCA, inc. is the Radio Technical Commission for Aeronautics. It was founded in 1935 and develops recommendations regarding communications, navigation, surveillance, and air traffic management (CNS/ATM) system issues. Most RTCA interests are U.S. government and business organisations.
Terminal Area	See “Major Terminal Area”, the term major is used when the terminal area surrounds one or more **major** airports. Around medium or smaller airports the term Terminal Area is used.

3. Air Traffic Management

Air Traffic Management (ATM) is often described in terms of Communication, Navigation and Surveillance (CNS). These three categories were formerly considered as independent and were handled separately. In the recent years however, these three categories have been merged together and are handled as one concept, CNS. It is very common to separate the three categories when an ATM system is analysed.

The main responsibility for ATM lies with the Air Traffic Control Centre (ATCC). This is where all decisions are taken concerning which flight paths the pilots shall use in order to obtain a well-organised traffic and to prevent collisions. One task for the air traffic controllers is to see to that the aircrafts in the air are separated from each other horizontally and vertically so that the minimum distances are not lower than what has been defined. The Tower control, controls that aircrafts and ground vehicles are separated on the airport surface.

3.1. Communication

In today's ATM systems 90 percent of the communication is done by voice. The voice communication is a limiting factor and has some disadvantages. Many accidents occur on behalf of poor communication between the participants on the airfield and in air space. In the future ATM systems, much of the communication is to be handled via data transmissions. This allows users to share the same channel instead of having the channel occupied by one user at the time. With a data link it would be possible to send text messages that would ensure that communication could not be misinterpreted, which can happen whilst using voice communication. This can be performed using broadcast transmissions, i.e. one-to-all communication or point-to-point transmissions, i.e. one-to-one communication. Eventually, in a more distant future, voice communication will only be used in non-routine and emergency situations.

3.2. Navigation

The navigation functions in today's ATM systems are insufficient for the needs of tomorrow. The systems that pilots use for navigation are based on old technique and can be quite expensive. Another common problem is that many aircrafts are put in hold, i.e. they are forced to circle around the airport waiting for permission to land. This results in large costs for the aviation companies. If the tools for navigation could be more efficient these companies could cut down their fuel costs considerably. To decrease the airborne time the aircrafts must fly as close to each other as possible. With today's tools for navigation and the regulations connected to them, it is difficult to achieve this. Applications where ADS-B is used will make it possible for pilots to fly shorter paths and closer to one another, resulting in shorter airborne time.

3.3. Surveillance

Surveillance functions of today's ATM systems are mainly managed with radar. Radar has some disadvantages compared to ADS-B, mainly poorer accuracy, but also limited coverage at low altitudes and on airport surfaces. TIS-B belongs to the surveillance category but the service might also be good enough for pilots to use for navigation in order to maintain minimum separation distances to other aircraft. Considering the fact that TIS-B is based on radar surveillance, it does not have the same accuracy as ADS-B and will not be as suitable for those applications as the ones where ADS-B will be used.

4. Surveillance

There are three ways to survey air traffic, traditionally using radar, which will be replaced to a greater or less extent by ADS-B. The third way is to use procedural surveillance, which involves surveillance by using radio communication systems. The first two surveillance techniques are described in section 4.1 and 4.2. The third technique is not described because of its irrelevance regarding TIS-B.

4.1. Radar surveillance

There are several kinds of radar equipment that can be used in flight surveillance.

4.1.1. Primary Surveillance Radar and Secondary Surveillance Radar

The most common radar equipment is the Primary Surveillance Radar (PSR) and the Secondary Surveillance Radar (SSR). The PSR is a system where a radar ground station transmits interrogation signals and calculates a distance to surrounding aircrafts hit by the signal. This calculation is based on the time it takes for the echoing signal to return to the radar ground station. No equipment onboard the aircrafts is needed. The SSR is a system where a radar ground station transmits interrogation signals to aircraft transponders. The aircraft transponder replies, and the distance is calculated based on the time it takes for the signal to reach the radar ground station. The aircraft transponder reply also contains other information. The content of the information depends on which mode of SSR that is used. These modes are described in table 4-1.

Mode	Content
A	Flight ID.
C	Flight ID and pressure-altitude measurement.
S	Flight ID, pressure-altitude measurement and other more specific information about the target.

Table 4-1. The different modes of SSR and their content.

4.1.2. Surface Movement Radar

The Surface Movement Radar (SMR) keeps track of the vehicles on the airport surface. The SMR can be of for example PSR type and provides surveillance information generally up to an altitude of approximately 300 feet.

4.1.3. Multilateration

Multilateration is used when a more accurate surveillance system than the PSR or the SSR is required. Multilateration is based on the SSR service. The SSR signals can be received by a collection of sensors. The different times of arrival, of the SSR signals to the sensors, are used to determine the position of the aircraft. The sensors receive time synchronisation from a Global Navigation Satellite System (GNSS) service. Multilateration is only used to a less extent on some major airports.

4.1.4. Surveillance Data Processing System

The Surveillance Data Processing System (SDPS), also referred to as the tracker, provides centralized processing of data from all the independent radar systems; PSR, SSR, SMR and Multilateration. The surveillance data is then distributed to the local Air Traffic Control Centre.

4.1.5. Advanced Surface Movement Guidance and Control System

A-SMGCS is the generic term for different integrated surveillance techniques that survey the airport surface such as the SMR. The A-SMGCS has four basic functions; surveillance, routing, guidance and control. According to ICAO there must be surveillance coverage over the complete airport surface. The height of the surveillance coverage area must cover the approach paths and helicopters flying at low altitude. The surveillance function must be able to deliver position and identification of all vehicles moving on the airport surface. The routing function shall supply the different vehicles with routing paths. The guidance function shall give the drivers of the vehicles clear directions of the paths they shall follow. The control function will supply the controller with information and analysis of the safety in the airport environment. [Ref 27]

4.2. Automatic Dependent Surveillance Broadcast

Automatic Dependent Surveillance Broadcast (ADS-B) is a surveillance application that automatically, via a data link, transmits different parameters of interest. Some parameters of interest are:

- Three-dimensional position
- Identification
- Velocity
- Time

ADS-B is automatic because it transmits automatically; there is no need for external stimulus. The service is dependent because it relies on on-board navigation sources and on-board broadcast transmission systems to provide surveillance information to other users.

In order to function as an ADS-B target, the aircraft or ground vehicle must be equipped with an ADS-B transceiver. Such a transceiver could be installed in all vehicles that use the airfield or airspace as their working space. Every vehicle with a transceiver automatically sends information in a given time interval. The whole system is dependent of information that comes from GNSS receivers. The GNSS can be the Global Positioning System (GPS), the Global Orbiting Navigation Satellite System (GLONASS) or others. In comparison with radar surveillance, ADS-B offers much better position accuracy because of the use of GNSS.

ADS-B enables air traffic controllers, pilots and people working on the airfield to get a better traffic awareness. A Cockpit Display of Traffic Information (CDTI) can be installed in the aircrafts on which the pilots can get information about other vehicles within their coverage area. A display can also be installed in a ground vehicle or in any other vehicle where the ADS-B information can be useful.

Figure 4-1 visualises the principle of ADS-B. The pilots of the two aircrafts can see each other as ADS-B targets.

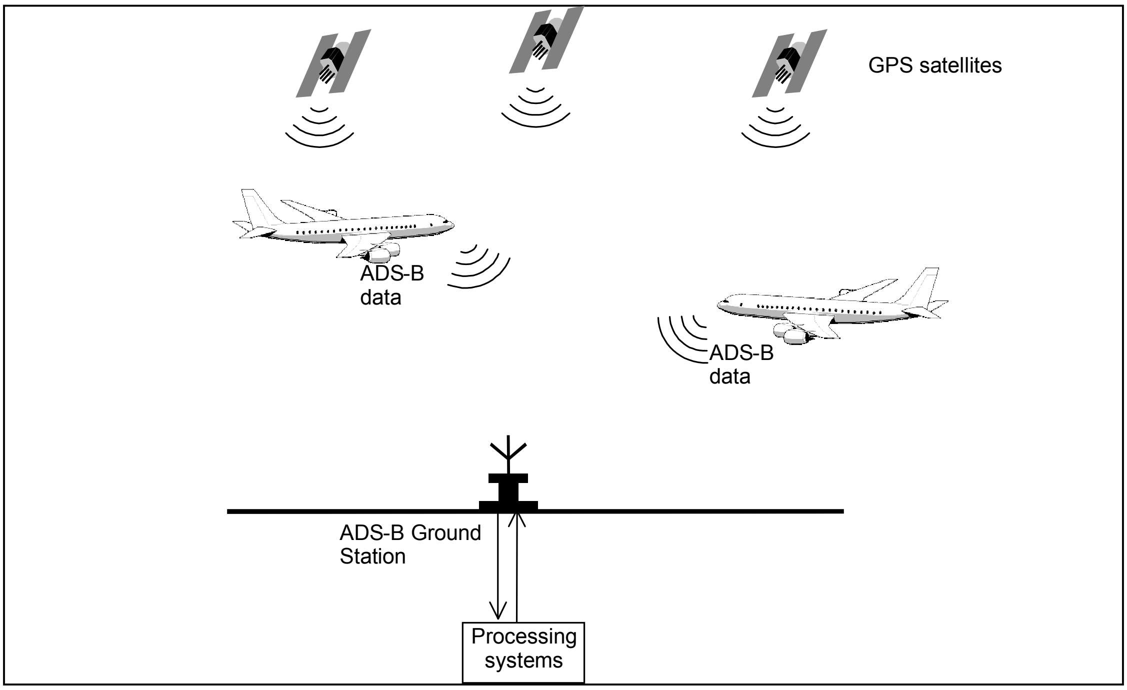

Figure 4-1. The principle of ADS-B.

In some areas, mainly at airports, there is need for a more accurate positioning system. In these areas the ADS-B service uses GNSS augmentation. A network of ground stations, with well-defined positions and overlapping coverage areas, serves as a reference point so that the vehicles can determine a more accurate position.

5. Traffic Information Service Broadcast

5.1. Overview

The purpose of Traffic Information Service Broadcast (TIS-B) is to provide a full surveillance picture to airborne systems. The service derives traffic information from one or more ground surveillance sources and broadcasts it to ADS-B equipped aircrafts or ground vehicles. There is no data transfer from aircraft to ground and there are no acknowledgements of the receipt of TIS-B messages. TIS-B could work as a tool to bridge the transition from radar based CNS to ADS-B based CNS.

The surveillance data for the service can be provided from SSR, PSR, SMR, ADS-B or Multilateration systems. The data is then distributed via ground stations to the receiving stations. Figure 5-1 shows the processing of surveillance data from a radar ground station and an ADS-B ground station to the TIS-B ground station. The pilots of the two ADS-B equipped aircrafts have the possibility to see each other as well as the non-equipped aircraft on the CDTI.

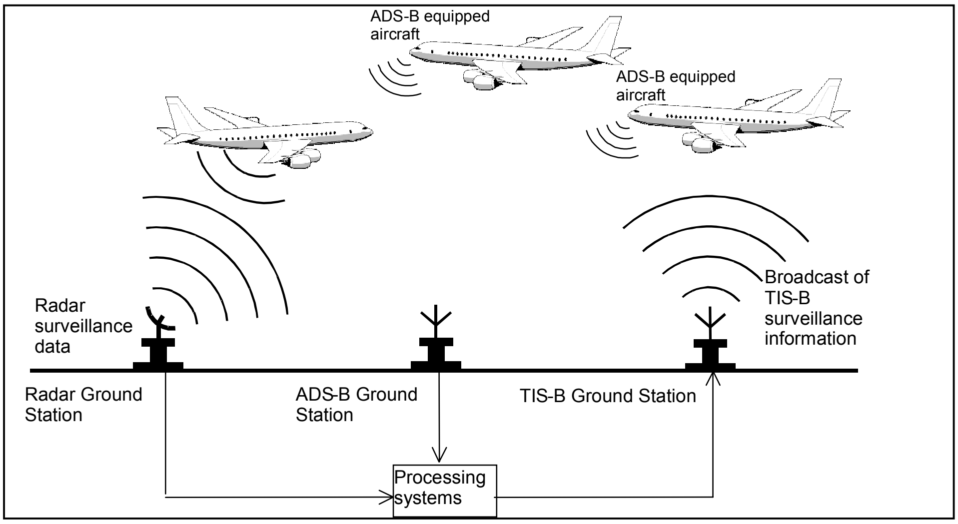

Figure 5-1. The principle of TIS-B.

5.2. Definitions of TIS-B services

According to Eurocontrol [Ref 7] a TIS-B service will be defined by:

- A Service Identifier.
- A TIS-B Service Volume (SV).
- A TIS-B Traffic Information Volume (TIV).
- The Service Track Selection Criteria.
- The Service Level.
- The Service Quality.

A Service Identifier is included within each TIS-B report. The TIS-B user will determine which services are required and will identify and select the appropriate TIS-B Services using the Service Identifier. The Service Volume and the Traffic Information Volume, more thoroughly described in section 5.4, are predefined volumes in which the TIS-B service is operating. The Service Track Selection Criteria defines which tracks, or targets, that are to be broadcast by the service. The Service Level defines which set of data items are to be sent in each TIS-B Report and at what frequency the TIS-B Reports are to be broadcast, and the Service Quality defines the expected availability, integrity, latency, accuracy, and report resolution for the service.

5.3. TIS-B message descriptions

The following section refers to the NUP TIS-B Service Description [Ref 2] construction of messages. Other organisations evaluating TIS-B, for example RTCA, have different approaches when it comes to constructing TIS-B messages.

5.3.1. Message types

The surveillance data broadcasted by the TIS-B ground station consists of two different types of messages; management and target messages.

The management messages contain all the relevant information concerning the TIS-B service and the details of the Traffic Information Volume (TIV) in which the TIS-B service is operating. The content of a TIS-B management message is described in table 5-1.

Management message
TIS-B message ID.
TIV ID.
TIS-B service version.
Update period.
Number of TIS-B targets sent last period.
Number of ADS-B targets in the TIV.
Accuracy of TIS-B targets last period.
Reference point (latitude).
Reference point (longitude).
Lower barometric altitude.
Upper barometric altitude.
Number of TIV vertices.
TIV Vertex latitude.
TIV Vertex longitude.

Table 5-1. Content of the management message.

Management messages are transmitted once each TIS-B update period. An update period is with advantage set equal to the time it takes for the radar to make a revolution. This time varies depending on what radar equipment is being used. Each TIS-B update period starts with a management message.

Target messages contain information about aircraft or ground vehicles. A unique code or “target identifier”, within the target message, identifies each target. The target identifier is the 24-bit ICAO address for aircrafts and an id set by the TIS-B server for ground vehicles. The target identifier assists target tracking in the airborne equipment because it will be able to associate information on the same aircraft in consecutive updates.

The target messages are divided into three groups:

- Aircraft target messages (airborne service).
- Aircraft target messages (ground service).
- Ground vehicle target messages.

The content of the different target message types differ according to table 5-2.

Data item	Aircraft target (airborne service)	Aircraft target (ground service)	Ground vehicle
TIS-B message ID	x	x	x
TIV ID	x	x	x
Target Identifier	x	x	x
Target identifier flag	x	x	-
Radar fusion flag	x	x	x
ADS-B fault flag	x	x	x
Latitude	x	x	x
Longitude	x	x	x
Barometric altitude	x	-	-
Altitude resolution flag	x	-	-
Ground speed	x	x	x
Ground track	x	x	x
Time stamp	x	x	-
Flight ID flag	x	x	-
Flight ID type	x	x	-
Flight ID - Callsign	x	x	-
Aircraft category	x	x	-

Table 5-2. Content of the different target message types.

The number of target messages sent from the TIS-B server to the CNS ground station depends on which mode the TIV is started. With the **full surveillance mode** all the targets within the TIV are transmitted. In the other mode, **gap filler mode**, only targets without functioning ADS-B equipment are transmitted. If the server is set for full surveillance there is a risk that ADS-B targets are displayed as two different targets because the plots are too far away from each other. Normally the plots should be fused.

5.4. Service Volume and Traffic Information Volume

There are two volumes of airspace that are of interest to users of TIS-B. These volumes are the Service Volume (SV) and the Traffic Information Volume (TIV). The Service Volume corresponds to the volume where the ground station network will provide reliable radio frequency coverage, that is, aircraft are guaranteed to receive the TIS-B service being broadcast. Outside the SV no TIS-B services can be offered. The Traffic Information Volume is defined as the volume of airspace where the surveillance infrastructure can provide reliable tracking of all targets. It should be mentioned that Eurocontrol defines both the terms TIV and SV, but NUP finds the SV as superfluous and uses the TIV as the only definition of airspace volumes in its service description.

5.4.1. Specification of the TIV

The following section refers to the NUP TIS-B Service Description [Ref 2] specification of TIV:s.

Each TIV must be determined with respect to the ground surveillance equipment that is available. If the TIV is too big, some targets located out of tracking range will not be taken into consideration. Consequently, each TIV will be individually configured based upon traffic conditions and surveillance infrastructure. A TIV can have a circular or polygon shape. The polygon could have up to 16 vertices with a minimum of 3 vertices. When defining TIV:s surrounding an airport it is preferred to separate airborne targets from ground targets by using one or more Air TIV:s as well as one or more Ground TIV:s, see figure 5-2. The surveillance data for the Air TIV:s are based on PSR and SSR and the surveillance data in the Ground TIV is based on surveillance data from the SMR.

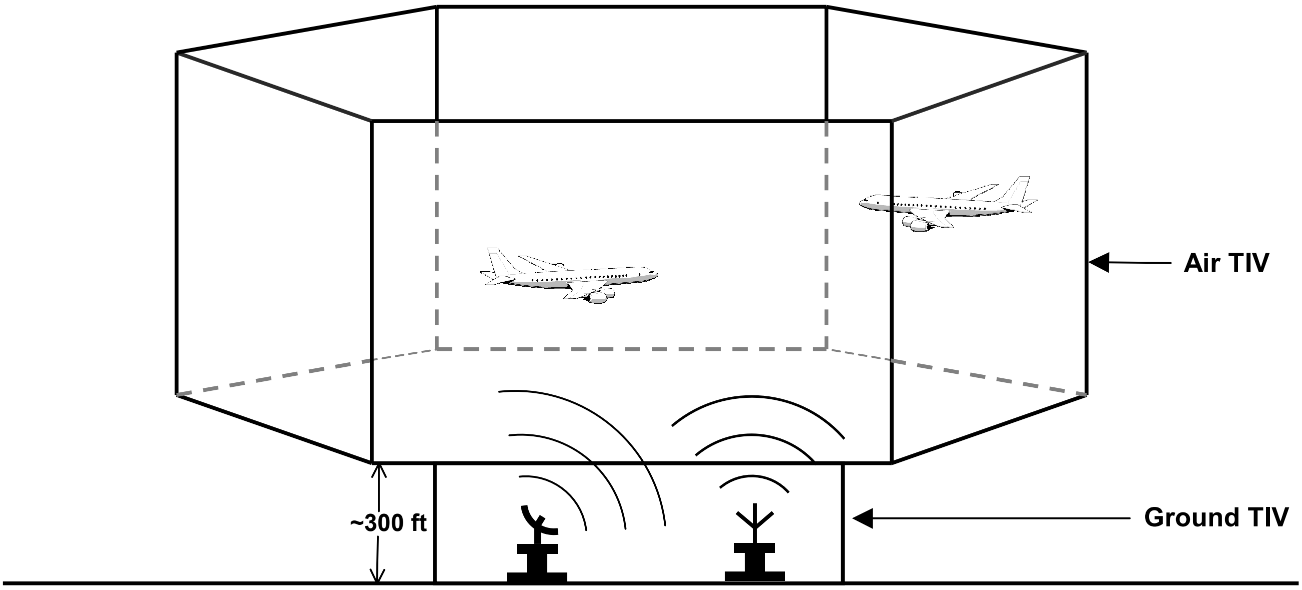

Figure 5-2. Example of polygon-shaped Traffic Information Volumes.

The target position, included in the target message, is communicated as an offset from a reference point connected to the TIV. The reference point, included in the management message, should not be more than 240 NM from any of the TIV boundary vertices. The advantage of using a reference point is that the number of bits in the target messages is reduced. All the targets shall be broadcasted with the same quality of service. The quality of service for the TIV should be determined according to the target with the lowest quality of service. In this way the target quality of service is the TIV's quality of service or better. [Ref 21]

The level of quality of traffic information provided by TIS-B is dependent on the number and type of ground sensors as sources for TIS-B and the timeliness of the reported data.

5.5. Possible Applications

5.5.1. Air Traffic Situation and Awareness

Air Traffic Situation Awareness (ATSAW) gives pilots and drivers of ground vehicles an overview of the traffic but does not provide any active separation. This means that no responsibility can be transferred from the controller to the pilot. With ATSAW a pilot would only be able to make decisions implicitly. An example would be if a pilot avoids entering a runway, although he has been given permission to enter it, because he sees another aircraft on the runway on his CDTI. An example where ATSAW using either ADS-B or TIS-B might have prevented a serious accident was the collision between an MD-87 and a Cessna on the Linate airport outside Milan in October 2001.

5.5.2. Airborne spacing

With airborne spacing, the responsibility for maintaining a distance from designated aircraft is delegated to the aircrew, but the responsibility for providing separation in accordance with applicable ATC separation minima still rests with the controller, who will monitor the spacing procedure.

5.5.3. Airborne Separation

Airborne Separation will play an important role in the future of ATM. This has to do with the fact that the number of aircrafts increases, which makes it harder to fulfil safety requirements. Airborne separation applications seek to increase pilots' situational awareness as well as to provide active airborne separation. The two services that support airborne separation are ADS-B and TIS-B. The question is whether TIS-B provides an accuracy that is good enough for it to be used for airborne separation applications.

With airborne separation, the separation responsibility relative to designated aircraft is delegated to the aircrew, and the controller does not need to monitor the procedure. [Ref 16]

5.6. Different approaches to TIS-B

There are mainly three different approaches to the usefulness of TIS-B. These approaches are:

- TIS-B could be used for advanced applications such as ASAS.
- TIS-B should only be used for ATSAW applications.
- TIS-B is a waste of the data link capacity and should not be used at all.

The different opinions of the usefulness of the TIS-B service depend on a number of aspects. Some are of the opinion that the precision of the radar systems is not reliable enough to perform advanced applications such as ASAS. The opinion that TIS-B only can be used for ATSAW applications is based on the poor accuracy of the radar systems. The opinion that TIS-B is a waste of capacity is also based on the accuracy issue. This opinion also points out that it is just a waste of time to develop a TIS-B service because in a near future every aircraft will have an ADS-B transceiver.

Dr. Andrew Zeitlin, co-chair of the RTCA 186 WG-2, believes TIS-B should serve as a supplement to ADS-B. “We cannot be sure that all aircrafts ever will be equipped with ADS-B. In order to complete the picture for an ADS-B user the TIS-B service must be present.” Zeitlin believes that TIS-B alone could provide the surveillance service where ADS-B has some limitations. This could be for example at the airport surface. With a Multilateration system the TIS-B service could have better accuracy, higher update rate and coverage of areas that might be blocked for ADS-B by buildings. Another example of TIS-B superiority could be in areas with multiple radars and a multi sensor tracker. In the upcoming TIS-B MASPS there will be a new service where the ADS-B broadcast will be received via one data link on the ground and rebroadcast the message on another link, according to Zeitlin. [Ref 29] It can be added that using DGPS would give better accuracy than with Multilateration, according to Hasslar. Zeitlin does not take DGPS into consideration.

Rudi Erhmanntraut, Eurocontrol, states in the paper “About Alternative Enablers for ASAS” that TIS-B does not fulfil the requirements and therefore there is no need for TIS-B [Ref 10].

RTCA says in the paper “Safety Assessments of ADS-B and ASAS” that ASAS applications should be performed with help of TIS-B but due to the uncertainty of the accuracy of the TIS-B service they do not state the advancement of the applications to perform. TIS-B should at least be used for ATSAW applications. [Ref 19]

Airbus states in the paper “Data Link Roadmap”, a summary of the things said on the second stakeholder workshop in February 2003, that TIS-B is a conceptually attractive system but they want to see the performance statistics before making a statement. [Ref 21]

According to Eurocontrol each individual track will need an indication of its accuracy. The current NUP TIS-B Service Description assumes that the level of track quality will be determined by its source, the SDPS. Eurocontrol states that the track quality can vary significantly between individual tracks depending on the quality of the input data from which the track is created. The applications will therefore need an indication of track quality per track, although this will clearly depend on the accuracy and integrity requirements of the chosen applications. [Ref 7]

RTCA has basically the same view as Eurocontrol when it comes to the quality of individual track accuracy. RTCA uses three indicators for describing the quality of tracks. These are described in section 7.2.2.

6. The VDL Mode 4/TIS-B technical equipment and protocols

6.1. Equipment

The providing of TIS-B data involves different stages of processing. Processing is done in the SDPS, the TIS-B server and the CNS ground station as well as in the ADS-B/VDL Mode 4 transceiver, according to figure 6-1.

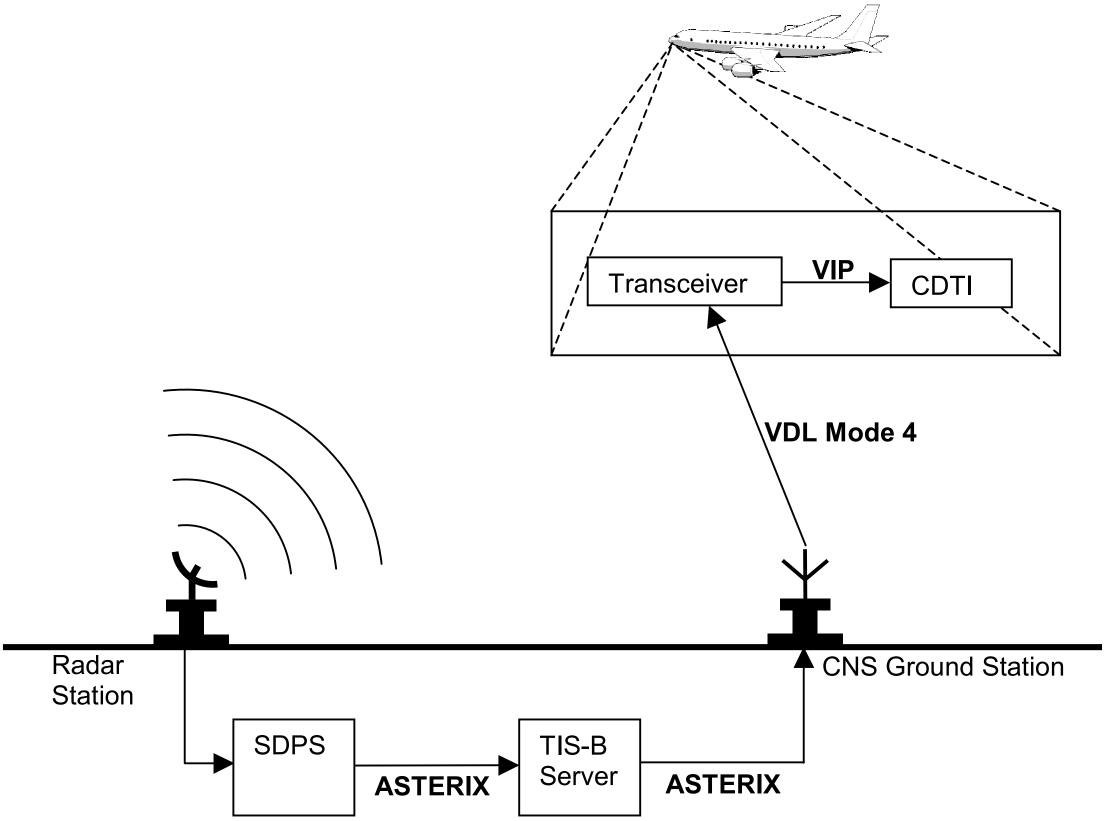

Figure 6-1. Processing of TIS-B data. The different protocols used are in bold style.

6.1.1. The SDPS

There are two trackers used for the tests; one providing data about the traffic on the ground and one providing data about airborne targets. These trackers are manufactured by the Dutch company HITT™.

6.1.2. The TIS-B Server and its connections

AerotechTelub™ manufactures the TIS-B server used for the verification and validation of TIS-B. This section refers to the TIS-B Server Functional Specifications Report [Ref 22].

The TIS-B server receives data from the SDPS. The TIS-B server delivers target messages containing data information about one aircraft or ground vehicle, and management messages containing information about the TIS-B service and the TIV, to the CNS Ground Station.

The main functions of the TIS-B Server is to:

- Receive target message and system track from the SDPS.
- Administrate TIV:s.
- Connect each track to a TIV.
- Connect each TIV to a primary CNS GS supporting it.
- Provide a gap filler or full surveillance picture for each TIV.
- Create a management message for each TIV and update period.

- Control status of TIS-B Service in the CNS GS.
- If the TIV is overloaded try to start an alternative smaller TIV else move the TIV to a secondary CNS GS, if defined.
- Send target messages and management messages to the CNS GS.
- To provide an HMI for TIS-B configuration and administration.
- TIS-B logging and statistics.
- SNMP (Simple Network Management Protocol) support.

The TIS-B server should be able to support up to 32 TIV:s and 32 CNS GS:s as well as up to 4 TIV:s per CNS GS. The TIS-B server should also be able to handle 1022 targets in one TIV and 110 targets in one TIV per second. Both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are supported. Port numbers and IP addresses are configured in a Human Machine Interface (HMI). The TIS-B server receives and delivers functionality reports from/to the Monitor and Control (M&C) device. If no data is received from the SDPS it will be considered as out of order. The TIV:s that are served from the SDPS will be terminated and an alarm will be sent to the M&C. The M&C delivers the alarm to the clients. The same scenario elapses when the TIS-B Server is having software failure, hardware failure or problem with the transmission. To get the service status of TIS-B the TIS-B server is connected to a Central Access Point Server (CAPS), which delivers ADS-B data from the Local Access Point Server (LAPS) at each CNS GS. Between the CAPS and the LAPS, there is a Regional Access Point Server (RAPS). The Interfaces between the server and the other participating parts, described above, is visualised in figure 6-2.

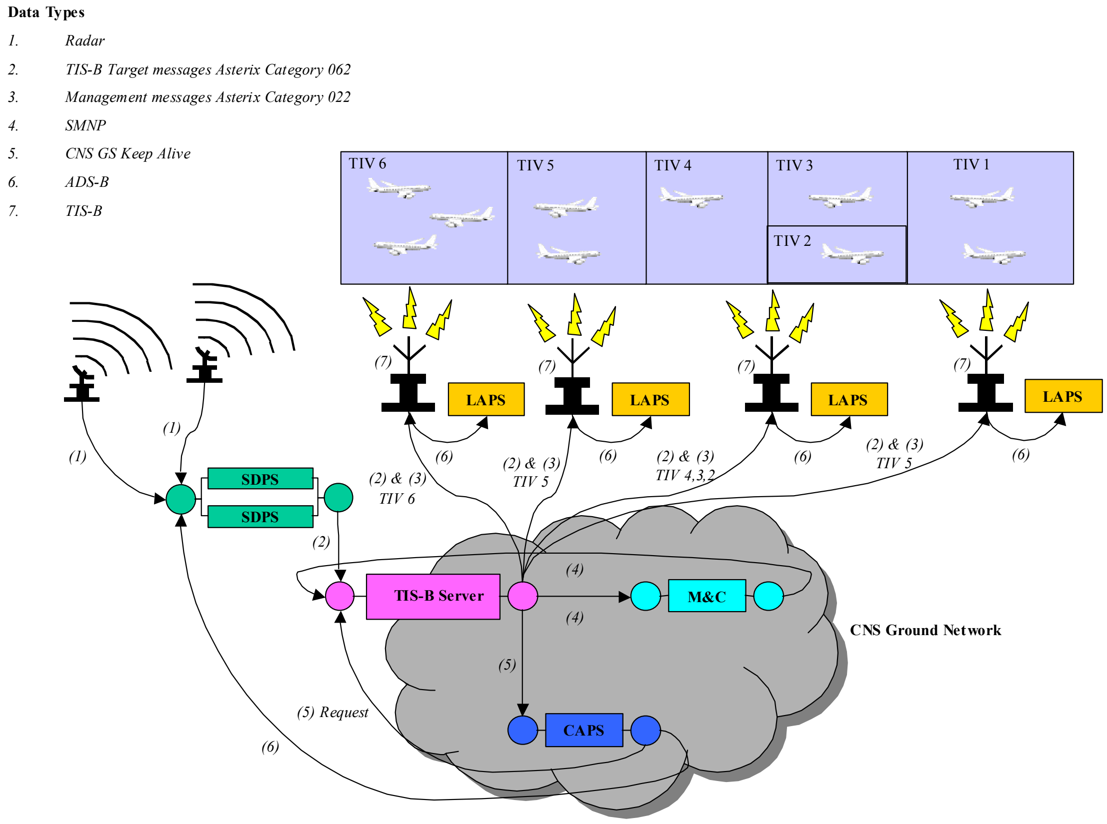

Figure 6-2. The TIS-B Server Interfaces.

6.1.3. The CNS Ground Station for TIS-B

Thales ATM™ manufactures the CNS GS, viewed in figure 6-3, used for the verification and validation of TIS-B. The CNS GS shall broadcast the TIS-B data to the ADS-B users.

Figure 6-3. The CNS Ground Station and its antenna at Arlanda airport.

The TIS-B server shall transmit the TIS-B management message to the CNS GS via the ground network.

6.1.4. The VDL Mode 4 transceiver

The mobile transceiver that is used for this purpose is a product of CNS Systems™ and can easily be reconfigured for handling both ADS-B as well as TIS-B.

The transceiver is used for determining the position and time, managing transmissions on the data link and transmitting and receiving data. The VDL Mode 4 transceiver is visualised in figure 6-4.

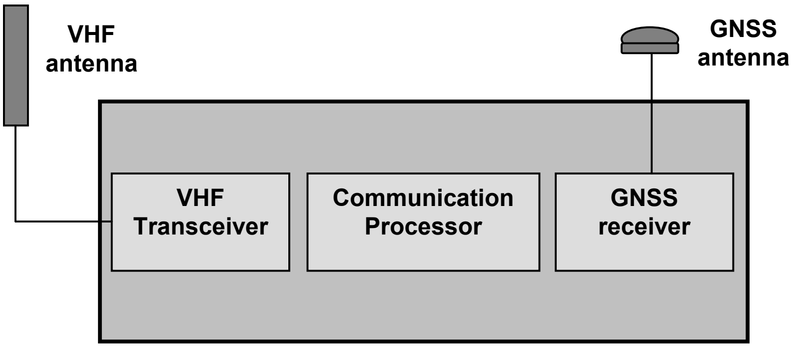

Figure 6-4. The VDL Mode 4 transceiver.

6.1.4.1. VHF transceiver

The VHF transceiver is used to communicate the position and other relevant information of the vehicle to other users as well as to receive data from other users. Depending on what application the transceiver is used for the transmitter power is in a range of 1-25 W.

6.1.4.2. GNSS receiver

The GNSS receiver provides position and time information all over the globe. Time inputs are typically obtained from GNSS but can also be obtained from another source, for example an on-board atomic clock.

6.1.4.3. Communication processor

The communication processor is a computer that co-ordinates the use of the communication channel. The communication processor is connected to the VHF transceiver and the GNSS receiver.

6.1.5. The CDTI

The CDTI provides a picture of the current traffic situation to the pilot. An example of how this is visualised can be seen in figure 6-5. The targets in the figure are shown with label and history track.

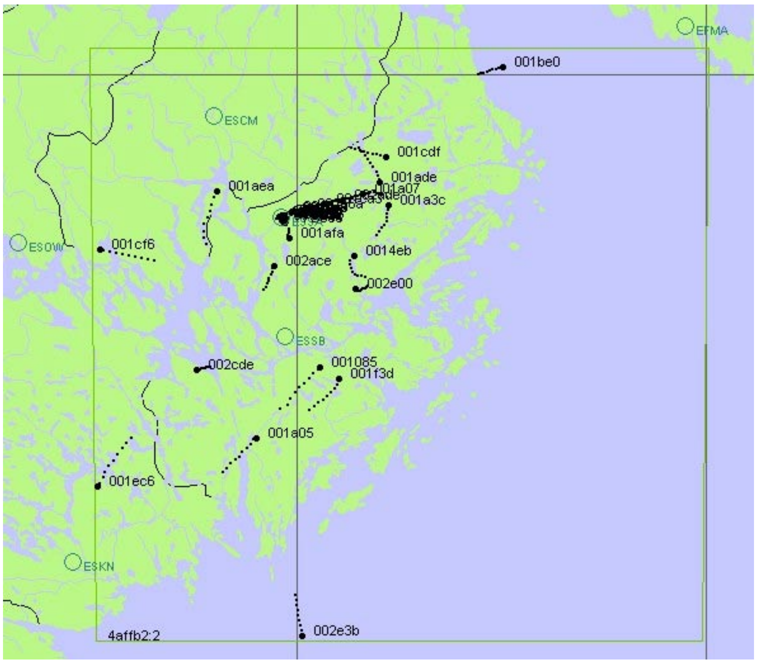

Figure 6-5. An example of visualisation of TIS-B targets in an HMI.

6.2. Protocols

The communication between the units are handled using different protocols, see figure 6-1. The different protocols used are:

- ASTERIX
- VDL Mode 4
- VIP

6.2.1. ASTERIX

The messages sent from the SDPS to the TIS-B server and further to the CNS GS is communicated using a protocol called ASTERIX (All-Purpose STructured Eurocontrol suRveillance Information Exchange). The ASTERIX radar data format is a protocol standardized by EUROCONTROL. The data comes in hexadecimal format and has a structure described in the TIS-B Server FSPEC, [Ref 4]. Target messages are category 062 and management messages are category 022 of the ASTERIX protocol.

6.2.2. VDL Mode 4

Messages transmitted from the CNS GS are provided in the VDL Mode 4 format. This format differs completely from the ASTERIX format but has a hexadecimal form as well. These messages are described in the TIS-B Service Description [Ref 2] and have not been set as a standard by any organisation but will be the basis of standardisation for ETSI later on.

6.2.3. VIP

The protocol used for communication between the transceiver and the CDTI is called VDL Mode 4 Interface Protocol (VIP). The messages in VIP format have the same structure as the messages in VDL Mode 4 format. The VIP format is recommended as a standard for VDL Mode 4 implementation.

In order to solve problems occurring with the TIS-B service it is vital to understand all of these protocols.

7. Requirements on surveillance data

The requirements on TIS-B data are mostly a translation of the radar surveillance system requirements. The limitations of TIS-B data is that it cannot be more accurate than the data the radar surveillance equipment delivers and it should not be any less accurate than what the radar surveillance can provide.

We will look at the following requirement parameters for TIS-B:

- Availability
- Integrity
- Latency
- Accuracy
- Continuity
- Coverage
- Capacity
- Monitoring

7.1. Availability requirements

7.1.1. Definitions

Availability is the ability of a system to perform its required function at the initiation of the intended operation. It is quantified as the proportion of the time the system is available to the time the system is planned to be available. [Ref 1]

The radar data processing system shall be considered unavailable if no processed radar data is produced for more than one time interval between information updates on the display. [Ref 5]

7.1.2. TIS-B

RTCA states that the availability of TIS-B is dependent on the availability of the ground based surveillance system and the TIS-B system functions. The availability requirements of the TIS-B system will be determined once the ASAS application requirements are defined. [Ref 17]

7.1.3. ADS-B

The availability factor for ADS-B shall be 99.996 percent of time for the end user according to ICAO [Ref 15] and 99.95 percent of the time according to Eurocontrol [Ref 8] and RTCA [Ref 18].

7.1.4. Radar

In order to specify the data availability requirements for SSR the data is categorised as full and essential. Full data performance means that all elements and functions of the radar chain are operating normally. Essential data performance (reduced performance) means that some elements of the radar chain are below full performance. Depending on the circumstances, the provision of a radar service may or may not be affected.

Full data are:

- Aircraft horizontal position and history.
- Aircraft identification.
- Aircraft vertical position.
- Specific indication of Mode A special codes.
- Ground speed.
- Status of the Track whether it is primary, secondary combined or extrapolated.

Essential data are:

- Aircraft horizontal position and history.
- Aircraft identification or Mode A code.
- Aircraft vertical position.

The full radar surveillance data availability shall not be less than 0.995, excluding periods of scheduled maintenance. This means that the maximum allowed time for interruption is a total of 44 hours per year. The essential radar data availability shall not be less than 0.99999, which means that there must not be interruptions for more than a total of 6 minutes per year. [Ref 5]

7.1.5. A-SMGCS

The availability of an A-SMGCS should be sufficient to support the safe, orderly and expeditious flow of traffic on the movement area of an aerodrome down to its Aerodrome Visibility operational Level (AVOL). [Ref 14]

7.2. Integrity requirements

7.2.1. Definitions

Integrity is the probability to have an error greater than a specified value without annunciation for a period longer than a specified time-to-alert. [Ref 6]

TIS-B System Integrity is the probability that hazardous or misleading information is inadvertently introduced into a TIS-B report while being processed by the TIS-B system. [Ref 17]

Integrity is the probability that errors will be detected. For example a correct message must not be indicated as containing one or more errors, or a message containing one or more errors may not be indicated as being correct. [Ref 15]

7.2.2. TIS-B

According to Eurocontrol [Ref 6] the integrity risk is generally characterised by:

- A probability (with respect to a given exposure time) of an error exceeding the containment bound for extreme errors.
- A containment bound for extreme error.
- A maximum time to alert.

According to RTCA the end-to-end integrity of the TIS-B system shall be 10^{-6} or better on a per report basis, which is the same requirement as for ADS-B. [Ref 17]

The latest ADS-B MASPS [Ref 6] introduces three indicators to qualify the accuracy and quality/integrity of each report. These are briefly described below:

NAC – The Navigational Accuracy Category defines the accuracy of both lateral and vertical information. NAC indicates the width of the 95 percent error bounds and is expressed, for both position (NAC_P) and rate (NAC_R), in a category value from zero to ten.

NIC – The Navigational Integrity Category specifies the containment radius for extreme errors and is used in conjunction with SIL, described below.

SIL – The Surveillance Integrity Level defines the probability of an error exceeding the containment radius described in NIC.

7.2.3. ADS-B

According to RTCA the end-to-end integrity of the ADS-B system shall be 10^{-6} or better on a per report basis [Ref 18]. According to ICAO the integrity of an ADS-B system shall be 10^{-7} or better on a per report basis [Ref 15].

7.2.4. Radar

According to ICAO the probability of detection should be greater than 95 percent. Protection against corruption of the data contained in Mode S interrogations and replies is provided by cyclic redundancy check procedures. The error rates shall be less than one detected error in 10^7 112-bit messages for Mode S. For Mode A and Mode C missing or invalid code should occur in less than 5 per cent probability in any scan. Reports with corrupted code for Mode A and Mode C should occur in less than 2 per cent in any scan. In a combined PSR/SSR the probability of detection is measured inside the volume of coverage and should be at least 95 percent. The probability of a false radar indication should be less then 0.1 percent. [Ref 12]

According to Eurocontrol the overall probability of detection should be greater than 97 percent and the false target reports should be less than 0.1 percent. [Ref 5]

7.2.5. A-SMGCS

The system design should preclude failures that result in erroneous data for operationally significant time periods. [Ref 14]

7.3. Latency requirements

7.3.1. Definitions

Latency is the elapsed time between a system input and the corresponding system output. [Ref 1]

TIS-B latency is the component of latency attributed to the TIS-B system, which is composed of ground and aircraft subsystems. The TIS-B latency is measured from the sensor Data TOA (i.e., time of measurement) to the TOA in the corresponding TIS-B Target Report that is presented to the Airborne Surveillance and Separation Processing subsystem. [Ref 17]

The latency of an ADS-B transmission is the time period from the time of applicability of the aircraft/vehicle position ADS-B report until the transmission of that ADS-B report is completed. [Ref 18]

7.3.2. TIS-B

According to Eurocontrol the latency shall be measured and be given a value (Lmaximum) that will show the maximum delta time between an input in the system and the related TIS-B output change delivered to the user. A value of the maximum “age” (Lmax age) of data will also be included. This will define when a data burst is to be considered of no use at the user level and therefore not be output by TIS-B. [Ref 6]

According to RTCA the TIS-B latency shall meet or exceed the latency requirements of the associated ASAS applications. It is assumed the ASAS application latency requirement will stipulate the maximum age of a measured target that can be to be used by an application. Future versions of RTCA MASPS may provide latency requirements on each subsystem. [Ref 17]

7.3.3. ADS-B

According to Eurocontrol [Ref 8] the latency of the system shall be 0.4 s in 95% on a per-report basis.

7.3.4. Radar

In SSR the latency is expressed in three terms:

- Transceiver reply delay – the time for the airborne SSR receiver to reply to the ground station
- Propagation time
- On site delay – the time, in seconds, between the time an object is detected until it starts being transmitted.

The transceiver reply delay should not be greater than 128 ±0.5 microseconds for Mode S transceivers. For the Mode A and B transceivers the transceiver reply delay should not be greater than 3 ± 0.5 microseconds. The maximum on site delay is 2 seconds. [Ref 5]

7.3.5. A-SMGCS

The latency and validation of surveillance position data for relevant aircraft and vehicles should not exceed 1 second. For the identification data the latency should not exceed 3 seconds. [Ref 14]

7.4. Accuracy requirements

7.4.1. Definitions

Accuracy is a statistical measure of performance that describes how well a measured value agrees with a reference value. [Ref 1]

7.4.2. TIS-B

According to Eurocontrol [Ref 6] the accuracy data to be checked is:

- Track horizontal position.
- Track geometric altitude.
- Track ground speed.
- Track angle.
- Track angle rate.
- Track vertical rate.
- Track position.
- Velocity.

7.4.3. ADS-B

According to RTCA horizontal position shall be communicated and reported with a resolution sufficiently fine that it does not compromise the one-sigma maximum ADS-B contribution to horizontal position error σ_{hp}= 20 m for airborne participants, or σ_{hp} = 2.5 m for surface participants. Geometric altitude shall be communicated and reported with a resolution sufficiently fine that it does not compromise the one-sigma maximum ADS-B contribution to vertical position error σ_{vp} = 30 feet for airborne participants. [Ref 18]

Requirements for horizontal position, horizontal velocity, vertical position and vertical velocity according to the SCAA can be found in table 7-1. [Ref 1] The accuracy parameters for ground applications shall be at least equivalent to SSR accuracy. CD & R is short for Conflict Detection and Resolution.

	CD & R
σ_{hp}	50 m
σ_{hv}	0.75 m/s
σ_{vp}	10 m
σ_{vv}	0.3 m/s

Table 7-1. Accuracy requirements on ADS-B.

7.4.4. Radar

The positional accuracy of the surveillance radar data available, at the control position, shall have an error distribution with a root mean square (RMS) value equal to or less than 500 metres for En-route airspace and equal to or less than 300 metres for major terminals areas. [Ref 5]

Surveillance information updates shall enable the display updates to be no more than 5 seconds for major terminal areas, and no more than 8 seconds in en-route airspace. A maximum of 2 successive updates by extrapolation is acceptable for positional data. Mode C shall not be extrapolated for display. [Ref 5]

The Eurocontrol requirement on ground speed is a maximum error of 20 m/s and 2° on ground track within TMA. [Ref 5]

7.4.5. A-SMGCS

According to ICAO [Ref 14] the reported velocity accuracy should be 1 knot in speed and ±1° in the direction of movement. The position horizontal accuracy should be ±7.5 meters. The vertical position accuracy should be ±10 meters.

According to Eurocae [Ref 20] the reported velocity accuracy should have a maximum error of 5 m/s in speed and ±10° in the direction of movement.

7.5. Continuity requirements

7.5.1. Definitions

Continuity is the probability of a system to perform its required function without unscheduled interruptions during the intended period of operation. [Ref 1]

7.5.2. TIS-B

According to Eurocontrol TIS-B service continuity is to be discussed whether it is airspace category/phase of flight dependent or not. [Ref 6]

The RTCA continuity requirements of the TIS-B system will be determined once the ASAS application requirements are defined. [Ref 17]

7.5.3. ADS-B

According to Eurocontrol [Ref 8] and RTCA [Ref 18] the continuity probability of an ADS-B system shall be 0.9998 or better. ICAO [Ref 15] specifies the continuity probability to be 0.99996.

7.5.4. Radar

No explicit requirements for continuity are present for radar.

7.5.5. A-SMGCS

No explicit requirements for continuity are present for A-SMGCS.

7.6. Coverage requirements

7.6.1. Definitions

Coverage for ADS-B is the operational geographic area (or volume) within which the system provides a service. [Ref 8]

7.6.2. TIS-B

No explicit requirements for coverage are present for TIS-B.

7.6.3. ADS-B

The limiting factor for ADS-B is the line of sight, the transmitting power of the aircraft transceiver and/or ground station and the sensitivity of the receiver. The signal should be strong enough to be received within a range of 200 Nautical Miles[1] (NM), assuming there are no obstacles in the line of sight.

7.6.4. Radar

Comprehensive and continuous radar coverage of high quality shall be constantly available in order to achieve radar operational separations of 3 NM, 5 NM and 10 NM. [Ref 12 and 3]

SSR should provide coverage under all weather conditions at all bearings and at all ranges between at least 1.85 km and the maximum operationally required range which is 200 NM for long-range systems and 80 NM for short-range systems, and at all operational altitudes up to at least 100 000 ft between at least the angles of elevation of 0.5 degree and 40 degrees. The horizontal

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[1] One nautical mile is approximately 1 852 meters.

extent of the coverage shall be at least 30 NM beyond the area of responsibility of the relevant Area Control Centre (ACC), except where this is impossible due to geographical limitations. [Ref 5]

The SSR should provide coverage between at least 0.5 and 40 degrees.
Within any one scan the false target count should be less than 2 per cent of the total target count. [Ref 12]

7.6.5. A-SMGCS

The A-SMGCS should cover at least the movement area. Within the required area of the aerodrome, surveillance should be provided up to an altitude so as to cover missed approaches and low level helicopter operations. Surveillance should also be provided for aircraft on approach to each landing runway direction, at such a distance that inbound aircraft can be integrated into an A-SMGCS operation and that aerodrome movements, including aircraft departure or aircraft crossing the relevant active runways can be managed. [Ref 14]

According to Eurocae [Ref 20] the coverage should be at least 5 NM.

7.7. Capacity requirements

7.7.1. Definitions

Capacity is the maximum number of simultaneous movements of aircraft and vehicles that the system safely can support within an acceptable delay commensurate with runway and taxiway capacity at a particular aerodrome. [Ref 1]

ADS system capacity is a combination of channel capacity over a geographic area over a number of channels (if appropriate). [Ref 8]

7.7.2. TIS-B

According to RTCA the TIS-B system shall be capable of meeting the capacity requirements in DO-242A §3.3.4 [Ref 18]. The TIS-B service will only have to accommodate the peak traffic densities postulated in the ADS-B MASPS (DO-242A) if there are no ADS-B equipped targets in the airspace serviced by the TIS-B system. [Ref 17]

7.7.3. ADS-B

According to RTCA the capacity shall be more than 1270 vehicles (within a Range of 200 NM) to satisfy the demand for the traffic situation in 2020. [Ref 18]

7.7.4. Radar

The ground station capacity requirements should be specified according to forecast local traffic density. A capacity of 400 aircraft per scan is sufficient for most areas of the world. [Ref 12]

7.7.5. A-SMGCS

The A-SMGCS should be able to handle all aircraft and vehicles that are covered by the A-SMGCS on the movement area at any instant in time. [Ref 14]

7.8. Monitoring requirements

An essential part of a surveillance system is to alert and to notify when something does not function as it should. The monitoring and alerting performance is dependent on the other requirements such as accuracy and latency.

7.8.1. TIS-B

No explicit requirements for monitoring are present for TIS-B.

7.8.2. ADS-B

No explicit requirements for monitoring are present for ADS-B.

7.8.3. Radar

No explicit requirements for monitoring are present for radar.

7.8.4. A-SMGCS

The probability of detection of an alert situation should be greater than 99.9%. The probability of false alert should be smaller than 10^{-3}. The maximum alert time, the time it takes from detection of an alert situation until a report is generated, should be less then 0.5 seconds. [Ref 20]

8. Error detection and error handling of TIS-B

The TIS-B service was not fully functional in the beginning of this project. It soon became obvious that some error detection and error correction had to be done before any tests of the service could be performed. With a fairly new system like TIS-B, it is not surprising that some system tuning is necessary. Error detection is time-consuming work and it took some time to understand the different stages and transformations of the TIS-B reports. The messages go through four different stages before they are displayed on the CDTI. It has been assumed that the data from the radar to the SDPS is correct. This assumption is based on existing studies and the fact that the air traffic controllers use this data.

Proper analyses of the data stream between the SDPS and the CDTI can only be done if the different interfaces between the different stages are understood. There are three different message encapsulations. These can be seen in figure 8-1.

The different message encapsulations are:

- ASTERIX (1)
- VDL Mode 4 (2)
- VIP (3)

Figure 8-1. The different stages and transformations of TIS-B messages.

8.1. Tools for analysis

When analysing extensive data it is necessary to have powerful tools for analysis. Some of the tools that existed did not meet our demands. Decoding programs for the different data encapsulations that can decode ASTERIX, VDL Mode 4 and VIP format have therefore been created. The programs have been programmed in C++. The output from these programs is text files with different data that have been imported and evaluated in Excel. To do these programs a lot of manual decoding had to be done.

8.2. The first flight trial

A first flight trial was performed at Arlanda airport the 4th of November 2003, in connection with the AVT demonstration 2 of ADS-B and TIS-B, a Eurocontrol project. The equipment was installed at the Arlanda Air Traffic Control Centre. There were two flight tests with three aeroplanes in each test. The aeroplanes should do different manoeuvres in order to demonstrate the possibilities for airborne separation assurance. One of the aeroplanes was equipped with EPOS, from which we got exact position-, ground speed-, ground track- and altitude data.

EPOS is a combination of GPS and differential corrections made available via the Radio Data System (RDS) channel all over Sweden through a customer subscription and using modified RDS receivers – EPOS receivers.

Data was logged in the TIS-B server, the CNS GS and at two different transceivers. One transceiver was located at the ATCC and the other one was located in the EPOS equipped aeroplane. The transceiver at the ATCC logged the VIP stream that was delivered to the CDTI. The other transceiver logged the VDL Mode 4 data stream that the transceiver received.

After the first flight trial there was a meeting with the other participants of the test to summarize the results of the trial. Some problems had been encountered in the test. Soon after we started analysing the log files we realized that the test could not be used as a valid test for the verification of TIS-B. We only had data from all of the logging stations for a time of approximately ten minutes, so the test could only be used to evaluate and discover different problems.

8.2.1. Possible problem solutions and observations from the first flight trial

There were problems encountered in both transceivers because they did not receive as many messages as expected. In the VIP format the data was heavily delayed but it had the same content as the log files in the CNS GS. The logging at the CNS GS indicated that a lot more messages had been transmitted than what had been received. The data from the log files from the aeroplane equipped with EPOS was decoded and analysed. The EPOS data was compared with the data delivered from the ground station.

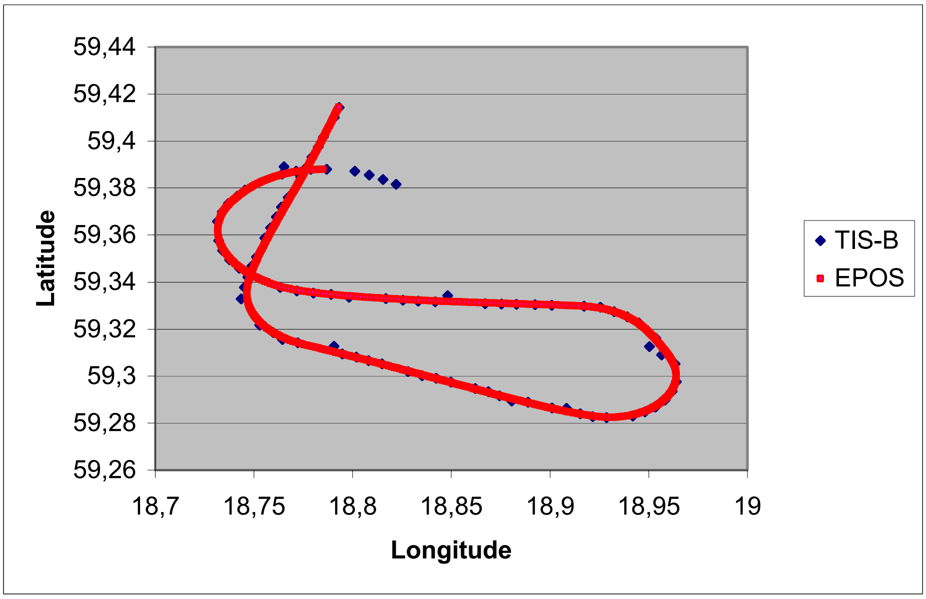


Figure 8-2. Comparison of positions in latitude and longitude for TIS-B and EPOS.

The latitude and longitude positions transmitted from the ground station seemed to be quite accurate, see figure 8-2. A number of random errors occurred but there were no extreme errors.

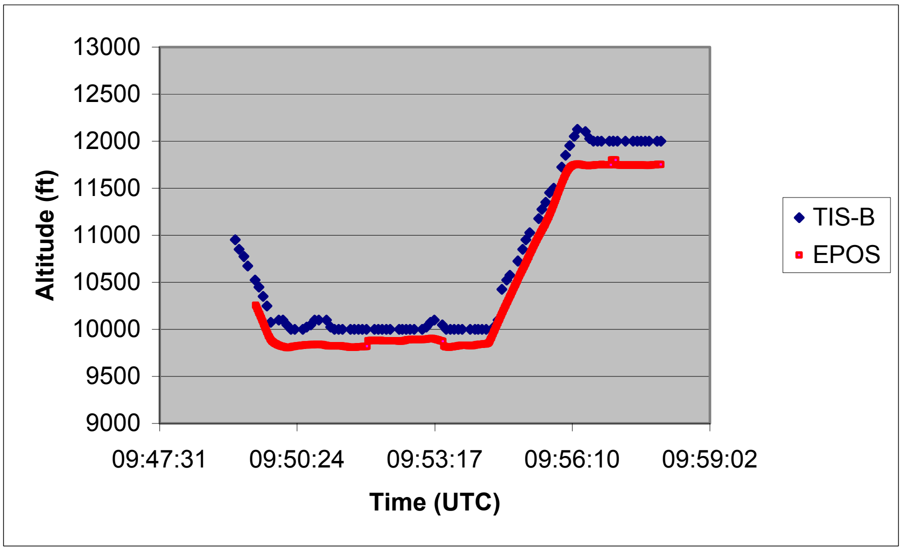


Figure 8-3. Comparison of altitude for TIS-B and EPOS.

The altitude seemed to be implemented the right way, see figure 8-3. There was a slight difference in the altitude curve, but the error is consequent, which indicates that the difference has to do with the barometric altitude-parameter in TIS-B. This parameter can vary depending on pressure and temperature.

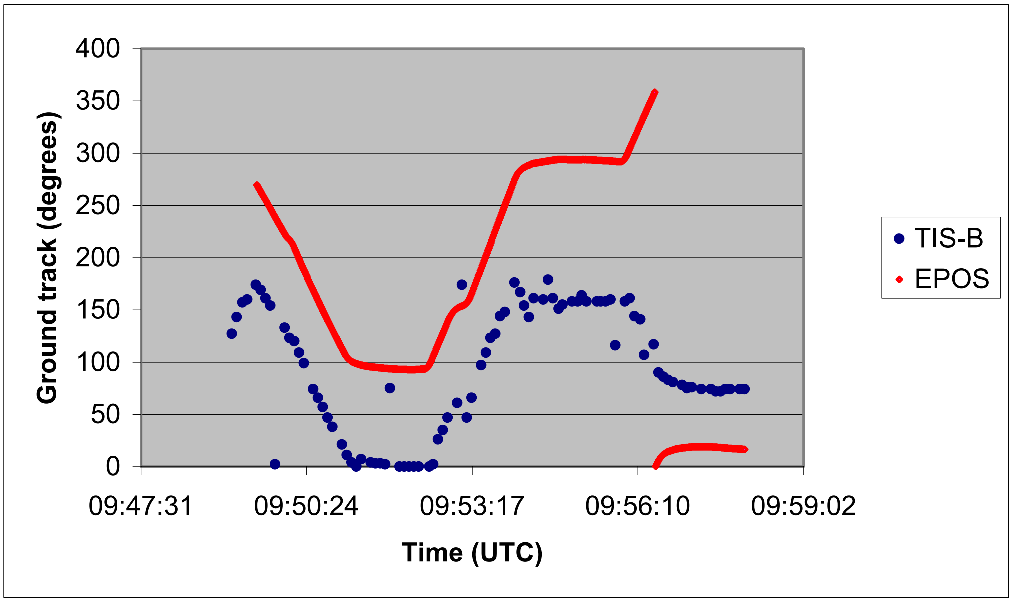


Figure 8-4. Comparison of ground track for TIS-B and EPOS.

The ground track seemed to be differing 90 degrees for the TIS-B service compared with EPOS, according to figure 8-4. As a logical consequence, the velocity vectors generated on the CDTI were completely out of course.

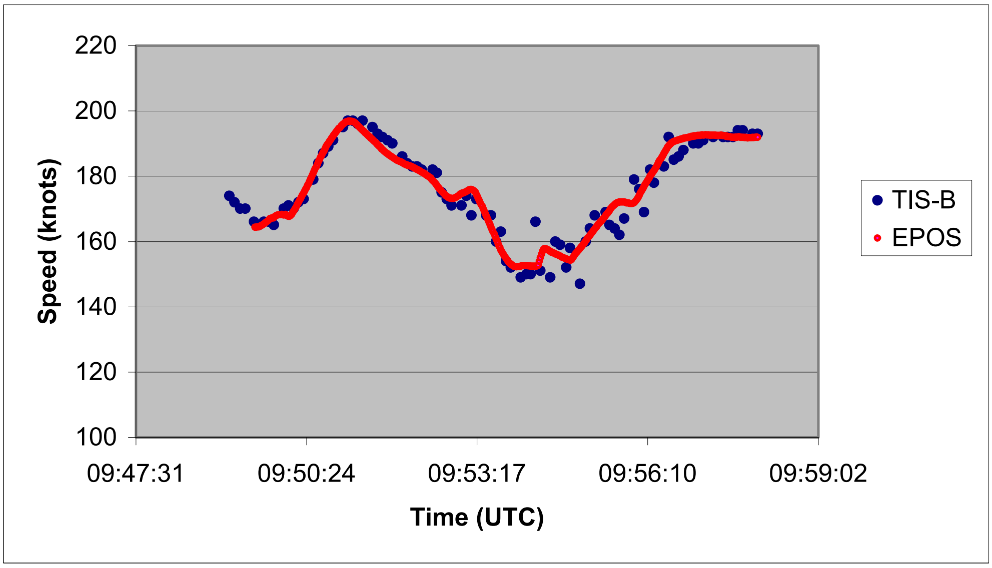


Figure 8-5. Comparison of ground speed for TIS-B and EPOS.

The ground speed seemed to be accurate, see figure 8-5. There were a few random errors but no extreme ones.

As mentioned earlier the CNS GS seemed to transmit all of the messages delivered from the server. The data transmitted seemed to be accurate except from the ground track. The data coming from the TIS-B server were analysed and the track angle calculated according to [Ref 11]. This angle was differing from the angle transmitted by the ground station. The problem was therefore located to the ground station.

The data item for velocity in the ASTERIX format is stored in y and x vectors.

One ASTERIX message received by the Ground station was decoded. The calculated track velocity had the values $V_x \approx 24.50$ m/s and $V_y \approx 94,75$ m/s, see table 8-1.

Format	Time	Latitude	Longitude	Ground speed	Ground track
ASTERIX	09:51:51	59.33	18.85	196	14.5
VDL 4	09:51:51	59.33	18.85	190	75.5

Table 8-1. Decoded data from one target message.

The angle between North (N) and the speed vector (V) should be $\alpha=\arctan(V_x/ V_y) \approx 14.5$. It seemed like there was a mix-up between the y-, and x-axis in the GS configuration. The result of using $\tan \alpha=(V_y/V_x)$ to calculate the ground track angle is incorrect. The implementation $\beta=\arctan(V_y / V_x)$, results in the other angle, $\beta \approx 75.5$. This is what was decoded from the ground station log file. The relation between vectors and ground track can be seen in figure 8-6.

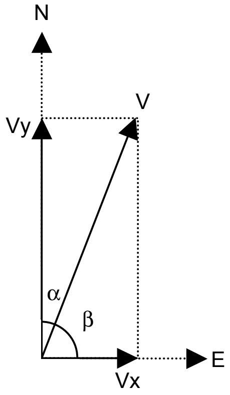


Figure 8-6. The relation between speed vectors and ground track angle α.

After having informed the manufacturer about the error when calculating ground track, they have corrected it in the ground station configuration files.

The management messages were analysed to determine if the number of TIS-B targets was accurate to the number of messages transmitted from the CNS GS. The log files from the CNS GS showed no sign of incorrect management messages. The ground station did not deliver any ground vehicle targets. Ground vehicles had been seen in prior logs, which made this problem difficult to understand. Analyses of different data streams showed that there were incoming ground vehicles to the TIS-B server but in the data stream delivered from the server there were none. The ground vehicles seemed to be transformed to aircraft targets. Analysing this problem led to the conclusion that the problem was located in the TIS-B server. There had been an update of the program files where something had gone wrong. A fix was developed and the ground vehicles started to show up again.

Time stamp was not used in the target messages transmitted from the ground station. Timestamp is an indication of latency in the ground system and should be used in the ground station. The timestamp should not however be delivered to the transceiver, according to the CNS GS manufacturer.

The parameter flight identification flag (fidflg) was almost always set to a 0, which means that the message does not contain any callsign, registration marking or mode A code. The only time we encounterd a fidflg set to a 1 was when an aircraft was ADS-B equipped. Aircraft ADS-B targets had fidflg=1 in every third message, which is the way it should be.

All of the aircraft TIS-B targets (air TIV) had radar fusion flag (rflg) set to a 1, which means that the target includes ADS-B as a source. This is incorrect; the targets in question should have the rflg set to 0. Aircraft TIS-B targets (ground TIV) had rflg=0, which means that the target is based only on radar or Multilateration data.

8.3. Further collection and analysis of data

8.3.1. Flight test

In the first flight trial there was a problem with lost messages between the CNS GS and the transceiver. There was an idea that the poor throughput was a result of the placement of the antennas. On the 29th of November an SCAA aircraft performed tests of the landing instrument systems at Arlanda airport. This event was taken as an opportunity to collect more data for error detection. Data was logged in the CNS GS and in a transceiver in the aircraft. The main objective of this test was to determine if the problem with disappearing messages could be blamed on the placement of the antennas.

8.3.2. Observations

Comparing the sent TIS-B reports from the ground station with the received reports at the transceiver showed that there still was a big loss of messages. The test was run in a 45-minute test period that started with a specific report, identical in the ground station and at the transceiver, and ended with another specific report. All of the reports that were decoded at the transceiver were identical to the reports that were sent. The total loss of reports was 60 percent. This showed that the problem with disappearing messages was located somewhere between the CNS GS and the transceiver.

When the difference between the TIV:s was analysed, it was noticed that the Air TIV had a much better throughput. There could be over 90 percent throughput in the air TIV and only 20 percent in the ground TIV. Could this have something to do with the update period, the TIV size or had it something to do with interference with the service INFO-B (Information Broadcast)?

ICAO	VIP/GS out	Time Interval
1140 (GVT)	40 %	09.33.00 – 09.50.00
7680 (GAT)	39 %	09.49.00 –10.17.00
1358 (GAT)	41 %	09.58.00 –10.10.00
4790 (AAT)	90 %	09.59.00 –10.24.00
2522 (GAT)	36 %	10.00.00 –11.11.00
3004 (GAT)	23 %	10.00.00 –11.11.00
7730 (AAT)	97 %	10.57.00 –11.07.00

Table 8-2. Presence of target messages.

8.3.3. Test with no INFO-B and a smaller TIV

On the 5th of December 2003 the INFO-B service was shut down. A smaller TIV was made and data in the CNS GS and in a transceiver was logged. The main objective of this test was to determine if the problem with disappearing messages had something to do with interference between TIS-B and INFO-B.

8.3.3.1. Observations

The results from the test showed that INFO-B and TIS-B did not interfere with each other. The problem with disappearing messages sustained. The conclusion from this was that the transmitting transceiver at the CNS GS was not transmitting all of the incoming messages. The problem was located in the CNS GS.

8.3.4. Test with updated configuring files for the CNS GS

On the 19th of January 2004 the configuration files to the CNS GS was updated so it could handle bit stuffing. In prior observations there had only been one target message per VDL 4 TIS-B message. Data was logged in the CNS GS and in a transceiver. The main objective of this test was to determine if the bit stuffing procedure worked properly.

8.3.4.1. Observations

The results from the test showed that the bit stuffing procedure worked properly and that the problem with the disappearing messages had now been solved.

8.3.5. Test with one channel dedicated for TIS-B

On the 29th of January 2004 a test was performed using one channel dedicated for TIS-B. The ADS-B equipped vehicles could not find an empty slot when TIS-B reserved 20 slots on the VDL 4 link. This problem did not however affect the TIS-B system in any way. The fault only affected ADS-B. The dedication of a single channel for TIS-B was just a simple solution to get the ADS-B system to work. The test also involved analysis of problems that had occurred with coordinates for the TIV.

8.3.5.1. Observations

The TIV displayed in the HMI did at some times change. When analysing the problem it was noticed that this occurred when the management message occurred in the end of the stuffed TIS-B message. This also affected the target messages that occurred last in the stuffed TIS-B message. Somehow the least significant bit in the last byte of the last message of the TIS-B message changed its value.

The TIV:s can only be set with the accuracy of 1/60° in the management message. This gives a minimum distance between the vertices with approximately 1 NM. In the server the TIV:s are set with better accuracy, with a minimum of approximately 40 meters between the vertices. If a small complicated TIV, less than 1 NM between vertices, is implemented in the server it will be displayed incorrectly in the HMI. The vehicles are however displayed correctly. To solve this problem the management message has to be changed so it can display smaller and more complex TIV:s. Another solution to the problem is to set a filter in the server so that unwanted target messages do not appear on the HMI.

9. Verification and Validation of TIS-B data

9.1. Arlanda airspace environment description

The tests performed in this study have all taken place in the Arlanda environment. This has to do with the fact that the only ground station for transmitting TIS-B in Sweden today is located at Arlanda airport. Three SMR stations survey surface movements at Arlanda. Each SMR station is located near one of the three runways. The SMR stations can be seen in figure 9-1. Two of the runways have the direction 01-19 and one has the direction 08-26. There are two SSR stations that survey the movements within the Stockholm TMA. These stations are located approximately 20 kilometres northeast of Arlanda and between 30 to 40 kilometres north of Uppsala. Since the variations of the terrain are small, the VHF coverage in the Stockholm TMA is good. Stockholm TMA extends from 1200 ft MSL to FL95.

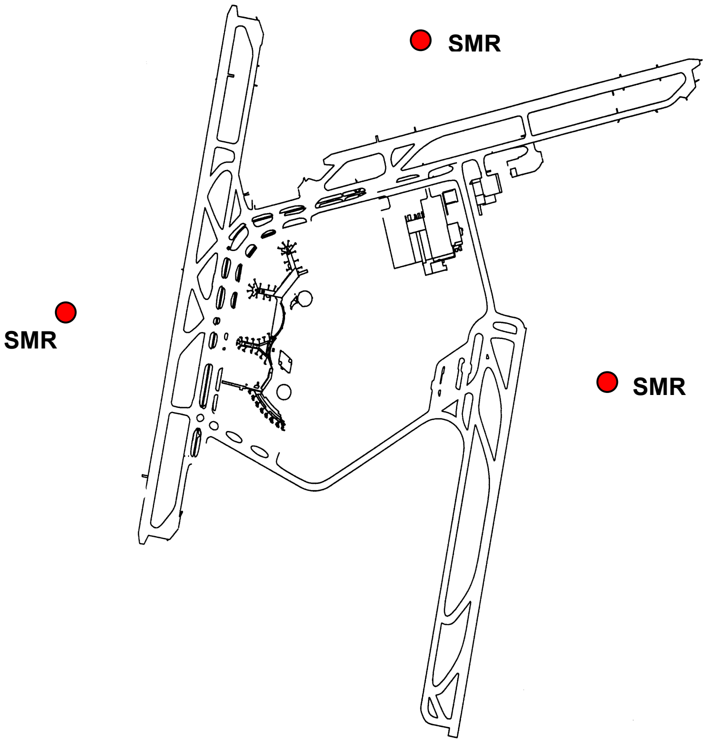


Figure 9-1. The location of the SMR stations at Arlanda.

The tests have been performed for A-SMGCS and Major Terminal Areas within the Stockholm TMA and at Arlanda airport.

9.2. Availability

9.2.1. Verification

In order to obtain useful availability data, the system has to be analysed for a long period of time. The availability of the TIS-B service has been measured by using two reference objects at Arlanda airport, according to figure 9-1. There are three SMR stations at Arlanda airport, which have been able to detect these two objects. Unfortunately there were some problems encountered with the software used for logging VIP when this test was performed. Therefore, data from the driving test has been used instead. The extent of this data, logged for approximately three hours and fifteen minutes, is not by near sufficient to determine the availability of the system. It will however give an indication of the availability, but further testing is necessary. The analysed TIS-B data has been recorded at one receiving VDL Mode 4 transceiver located in building B0003, see figure 9-1.

Availability is calculated using the formula $A = \dfrac{MTBCF}{MTBCF + MDT}$

MTBCF = Mean Time Between Critical Failure
MDT = Mean Down Time

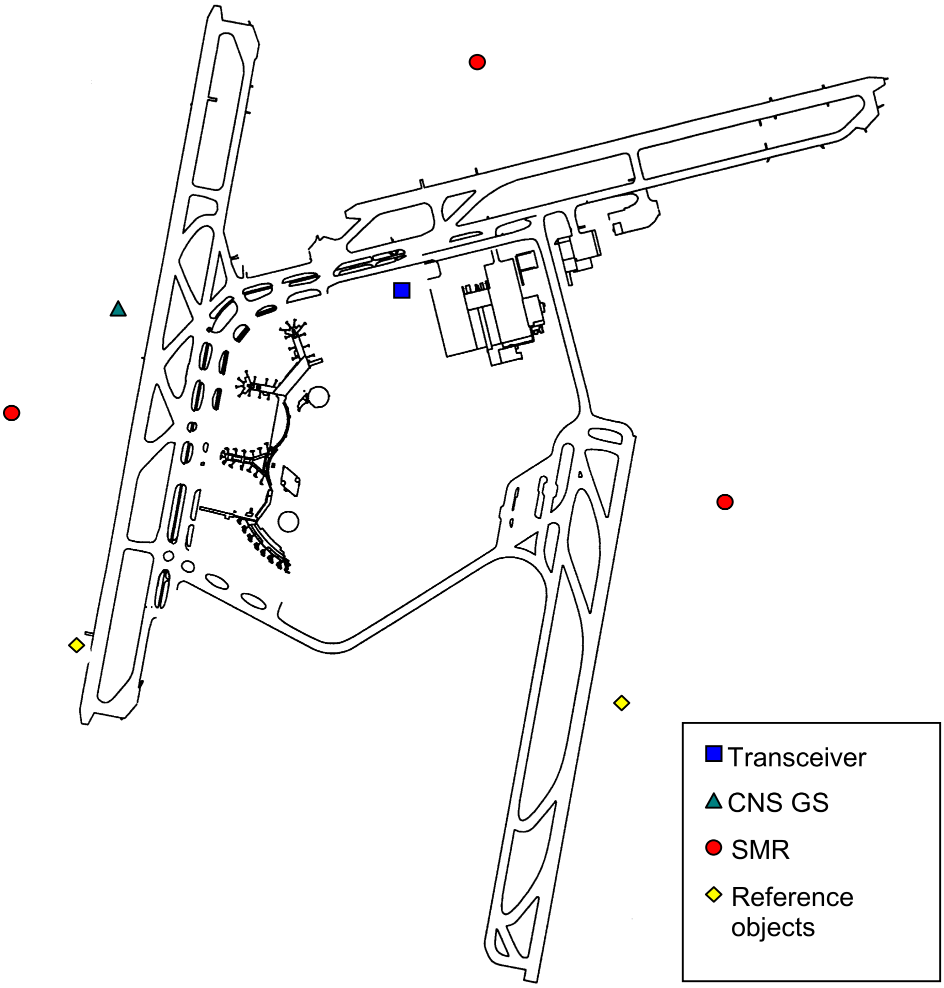


Figure 9-2. The location of transceivers, reference objects and SMR stations.

The system has been considered unavailable if more than two following TIS-B messages were missing in the transceiver. If the radar and the ADS-B service have fulfilled that requirement, so should the TIS-B service.

9.2.2. Validation

10 076 respectively 10 272 target messages for the two reference objects have been taken into consideration. The results can be seen in table 9-1.

	Reference object 1	Reference object 2
Availability	95.07 %	95.25 %

Table 9-1. TIS-B availability.

If the results are compared with the availability requirements for ADS-B, it is obvious that the system must be improved. However, the poor result could depend on that the total time for the test has been too short. One separate occasion of unavailability could have had large impact on the whole result.

9.3. Integrity

Is the transmitted message the same as the received message? Bit errors and calculation errors can occur during the data process.

9.3.1. Verification

The verification of integrity has been performed theoretically. To identify bit errors, a Cyclic Redundancy Check (CRC) is used. The CRC adds 16 bits to the TIS-B message, which makes it possible to determine if data is corrupt. A one-bit error results in a one-bit change in the calculated CRC. The probability of error detection for the CRC is $1 – 0.5^r$, where r is the length of the CRC in bits. [Ref 25]

9.3.2. Validation

The integrity of a 16 bit CRC is $1 – 0.5^r = 1 – 0.5^{16} = 0.999985$. Since there are no requirements on TIS-B regarding integrity, the value 0.999985 is compared with the ICAO integrity requirements on ADS-B stated in section 7.2.3, which is 0.9999999. The conclusion is that a 16-bit CRC is not good enough to meet the requirements on ADS-B integrity. A solution would be to use a 24-bit CRC in stead, which gives an integrity value of 0.99999994.

9.4. Latency

9.4.1. Verification

The time window from when the target is detected by the radar until it is received by the VDL Mode 4 transceiver has been checked. Latency has been tested in the driving test and in the flight test described in appendix 2 and 4. TIS-B data has been logged in the server and at the VDL Mode 4 transceiver.

The Time of Track Information parameter in the ASTERIX format is specified as the number of seconds after midnight. It has 24 bits and the least significant bit is 1/128 s. The VDL Mode 4 Time Stamp parameter in the VIP format is specified as the number of seconds since 2000-01-01 and rounded off to an integer. As a consequence the accuracy in the validation of latency is ± 0.5 s.

9.4.2. Validation

9.4.2.1. Ground targets

Analysis of 330 target reports has resulted in latency with a mean value of 0.93 ±0.066 seconds within a 95% confidence interval.

Part Time	Definition of Part Time	Note	Latency [s]
Data processing time	The time from when the radar detects the target until it is sent from the CNS GS.		0.93 ±0.066
Propagation time	The time from when the message is sent from the CNS GS until it is received in the transceiver.		< 0.0015

Table 9-2. TIS-B latency for ground targets.

The latency is distributed according to figure 9-2.

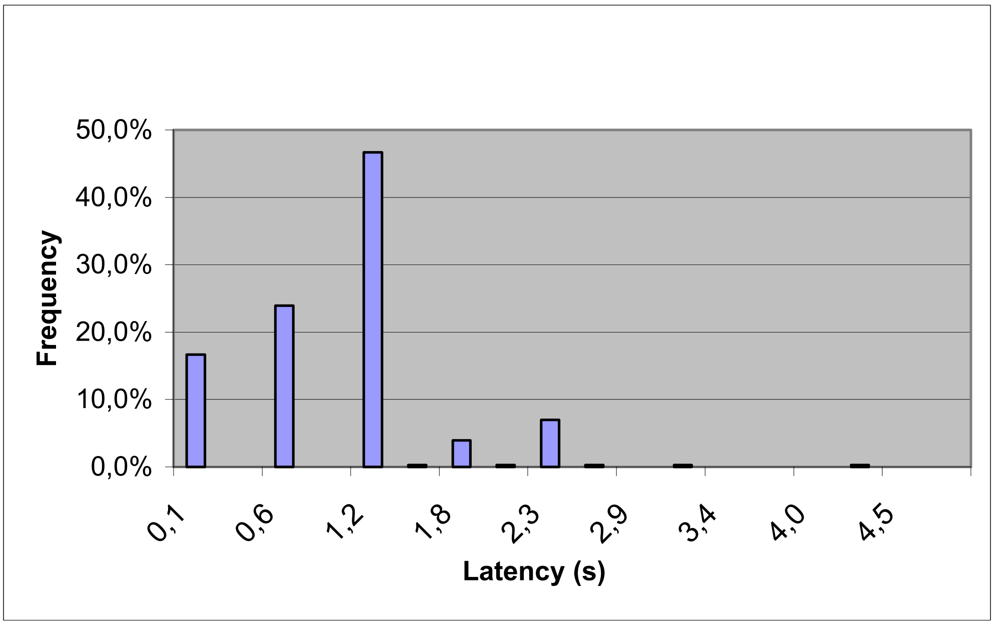


Figure 9-3. Distribution of latency for ground targets.

9.4.2.2. Airborne targets

Analysis of 814 target reports resulted in a latency with a mean value of 4.45 ±0.37 seconds within a 95% confidence interval. The fact that the ARTAS tracker only sends information about all scanned targets once every sixth second has major impact on the latency aspect. However, if this value could be changed in order to get a higher update rate, it would to reduce the latency of the complete system. It has not been possible to do this for these tests.

Part Time	Definition of Part Time	Note	Latency [s]
Data processing time	The time from when the radar detects the target until it is sent from the CNS GS.		4.45 ±0.37
Propagation time	The time from when the message is sent from the CNS GS until it is received in the transceiver.		< 0.0015

Table 9-3. TIS-B latency for airborne targets.

The latency is distributed according to figure 9-3.

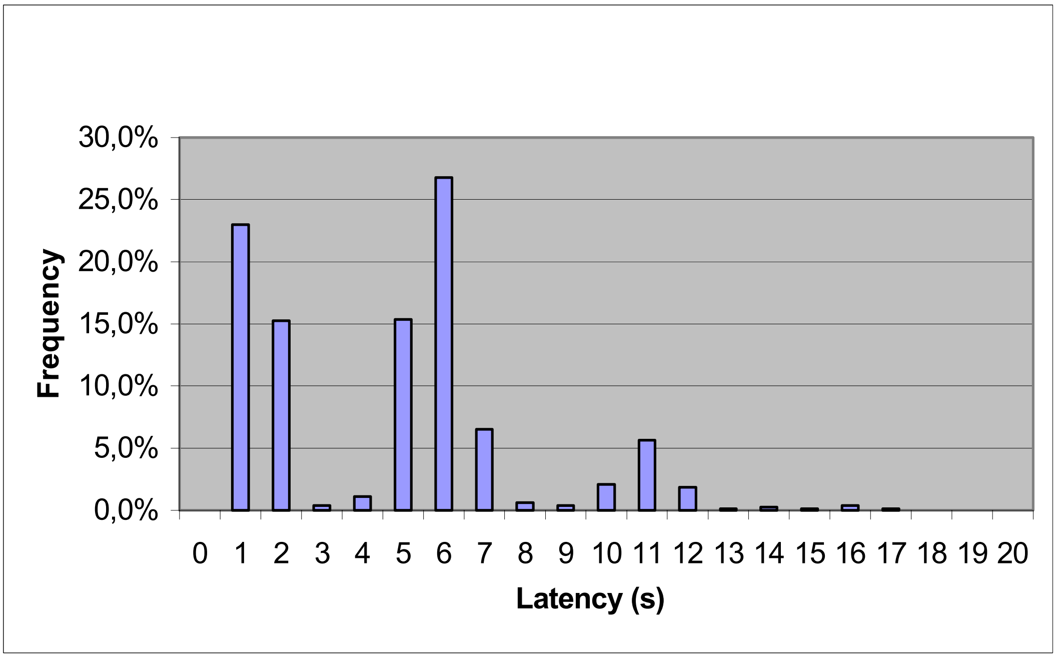


Figure 9-4. Distribution of latency for airborne targets.

9.5. Accuracy

9.5.1. Verification of Position Accuracy

In order to verify the position accuracy three different tests have been performed. The first test is a driving test at Arlanda airport. A vehicle equipped with RTK GPS has been used to define positions along a driven route. The positions have been recorded as well as the TIS-B data received by a VDL Mode 4 transceiver. The log files have been compared in order to determine the position accuracy at the airport surface. For further information about the driving test at Arlanda airport, see appendix 2.

The second test has been performed within the Stockholm TMA. The RTK-equipped aeroplane has performed testing of the Instrument Landing System on Arlanda and has flown according to the path in figure 9-4. The three-dimensional positions have been recorded as well as the TIS-B data received by the VDL Mode 4 transceiver. The log files have been analysed in order to determine the position accuracy in the TMA. For further information about the flight test at Arlanda airport, see appendix 4.

The third test is a static target test at Arlanda airport. TIS-B data has been recorded during a period of time.

9.5.2. Validation of Position Accuracy

9.5.2.1. Ground targets

495 position reports have been taken into consideration. The position error has a mean value of 21.37 ±1.92 meters within a 95% confidence interval.

Position error [m]	Measurements [%]
< 7.5	4.7
< 20	58.1
< 40	96.1
> 40	3.9

Table 9-4. TIS-B position error in the driving test.

As mentioned earlier there are no specific requirements on TIS-B concerning accuracy. Since the ICAO requirements on radar for A-SMGCS is a maximum error of 7.5 meters, only 4.7% of the TIS-B reports fulfil these requirements. The position error depends to a large extent on latency.

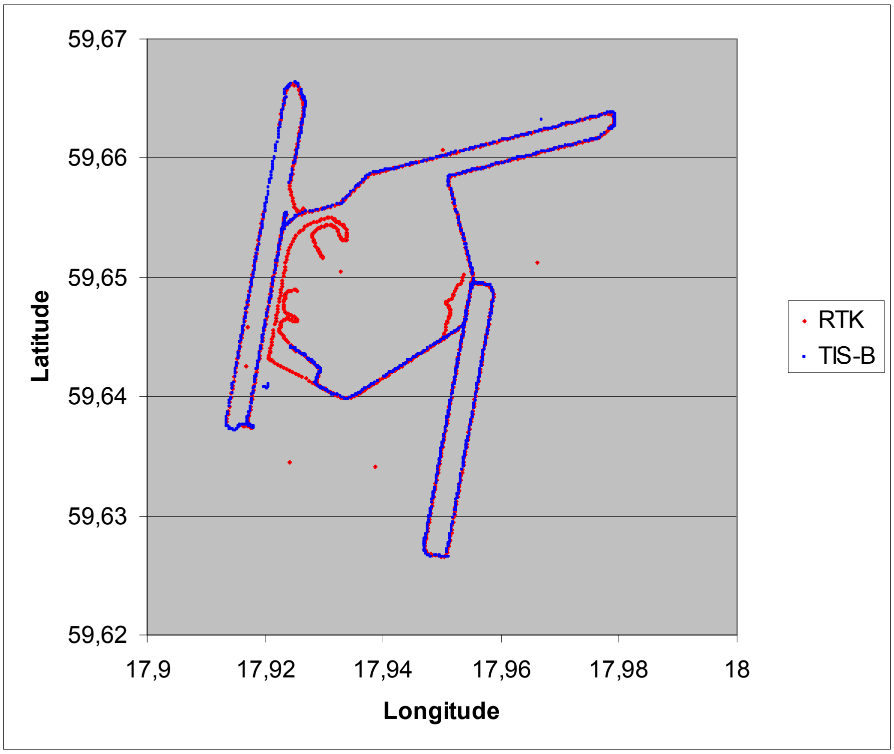


Figure 9-5. TIS-B and RTK GPS positions in the driving test.

9.5.2.2. Airborne targets

304 reports have been compared in the flight test concerning position accuracy. The position error has a mean value of 513.57 ±34.98 meters within a 95% confidence interval.

Position error [m]	Measurements [%]
< 300	21.4
< 500	56.3
< 1000	93.5
> 1000	6.6

Table 9-5. TIS-B position error in the flight test.

Table 9-5 shows that there are some reports with significant difference in position accuracy. The position error depends to a very large extent on latency. As mentioned earlier, the requirement on radar within TMA is a maximum error of 300 meters. This requirement is only fulfilled for 21.4% of the reports. The minimum separation distance in en-route airspace is 5 NM, approximately 9.3 kilometres. The TIS-B accuracy should be good enough for aircrafts to keep this minimum distance.

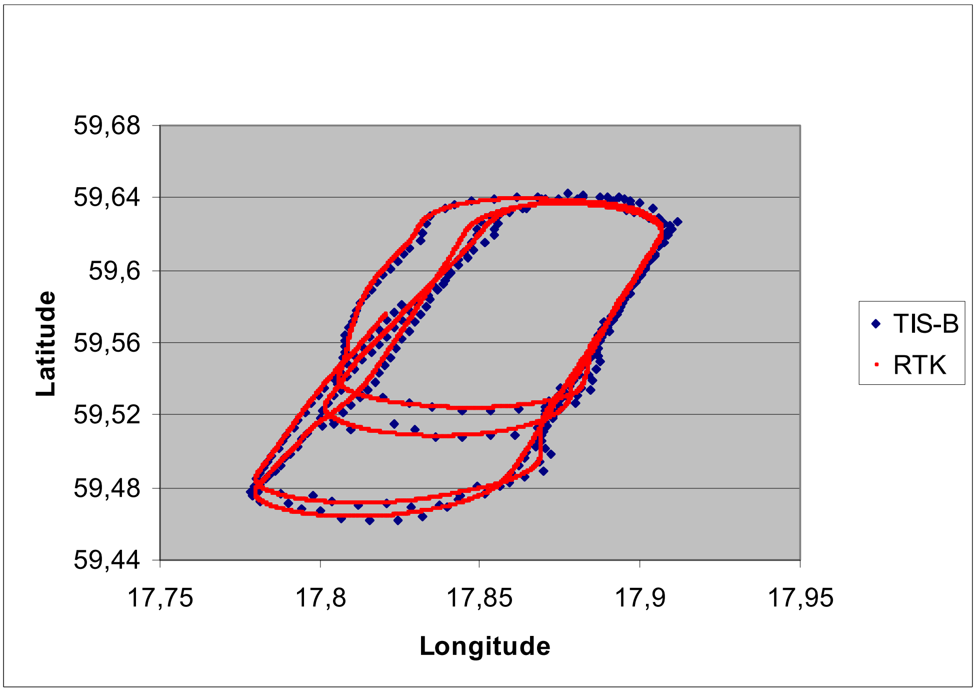


Figure 9-6. TIS-B and RTK GPS positions in the flight test.

9.5.2.3. Static targets

4540 position reports have been compared in the static target test. The position error has a mean value of 2.52 ±0.017 meters within a 95% confidence interval.

Position error [m]	Measurements [%]
< 7.5	100.0

Table 9-6. TIS-B position error in the static target test.

The test shows that the ICAO requirement on radar for A-SMGCS, a maximum error of 7.5 meters is fulfilled.

9.5.3. Verification of Ground Speed Accuracy

In order to determine the speed accuracy, RTK GPS has been used in the driving test and in the flight test. RTK GPS data has been recorded in the vehicle as well as TIS-B data received by the VDL Mode 4 transceiver. For further information about the driving test and the flight test, see appendix 2 and 4.

9.5.4. Validation of Ground Speed Accuracy

9.5.4.1. Ground targets

462 reports have been taken into consideration. The speed error has a mean value of 2.80 ±0.45 knots within a 95% confidence interval.

Speed error [knots]	Measurements [%]
< 1	19.7
< 10	94.6
> 10	5.4

Table 9-7. TIS-B ground speed error in the driving test.

The ICAO A-SMGCS requirement on speed, a maximum error of 1 knot, is fulfilled in 19.7% of the reports. The Eurocae requirement, a maximum error of 5 m/s (10 knots), is fulfilled in 94.6% of the reports.

9.5.4.2. Airborne targets

280 reports have been compared in the flight test. The speed error has a mean value of 11.70 ±1.10 knots within a 95% confidence interval.

Speed error [knots]	Measurements [%]
< 10	53.9
< 40	99.9
> 40	0.1

Table 9-8. TIS-B ground speed error in the flight test.

Table 9-8 shows how the ground speed differs in the TIS-B log file and the RTK GPS data log file. Again, most of the difference has to do with the latency aspect. The Eurocontrol requirement for radar within TMA, a maximum error of 20 m/s (40 knots), is fulfilled in 99.9 % of the reports.

9.5.5. Verification of Direction of movement Accuracy

In order to determine the direction of movement accuracy, the RTK GPS log files and the TIS-B log files from the flight test have been compared. At the time when the test was performed there was still an error in the configuration of the CNS GS, which resulted in an incorrect ground track angle. It has been possible to calculate the correct ground track angle in the analysis.

9.5.6. Validation of Direction of movement Accuracy

245 reports have been compared in order to analyse the direction of movement accuracy. The error has a mean value of 7.42 ±1.29 degrees within a 95% confidence interval.

Ground track error [degrees]	Measurements [%]
< 2	37.1
< 10	76.7
> 10	23.3

Table 9-9. TIS-B ground track error in the flight test.

The Eurocontrol requirements are fulfilled in 37.6% of the reports, according to table 9-9. The poor result depends to a large extent on that the update of ground track angle is delayed because of latency, which is evident when the aircraft turns. The kind of flight that has been logged is not fully representative considering that the aircraft makes many sharp turns that would not occur as frequently in a “normal” flight. In order to obtain better direction of movement accuracy the latency in the system must be reduced.

9.5.7. Verification of altitude accuracy

In order to determine the altitude accuracy, the RTK GPS log files and the TIS-B log files from the flight test have been compared.

9.5.8. Validation of altitude accuracy

The result of comparison of 280 reports can be seen in table 9-10. The altitude error has a mean value of 96.02 ±12.09 feet within a 95% confidence interval.

Altitude error [feet]	Measurements [%]
< 30	18.4
< 100	72.5
> 100	27.5

Table 9-10. TIS-B altitude error in the flight test.

There are no requirements on TIS-B concerning altitude accuracy available but for ADS-B the error should not be more than 30 feet according to RTCA. This requirement is only fulfilled in 18.4% of the reports. Latency has had much effect on the result.

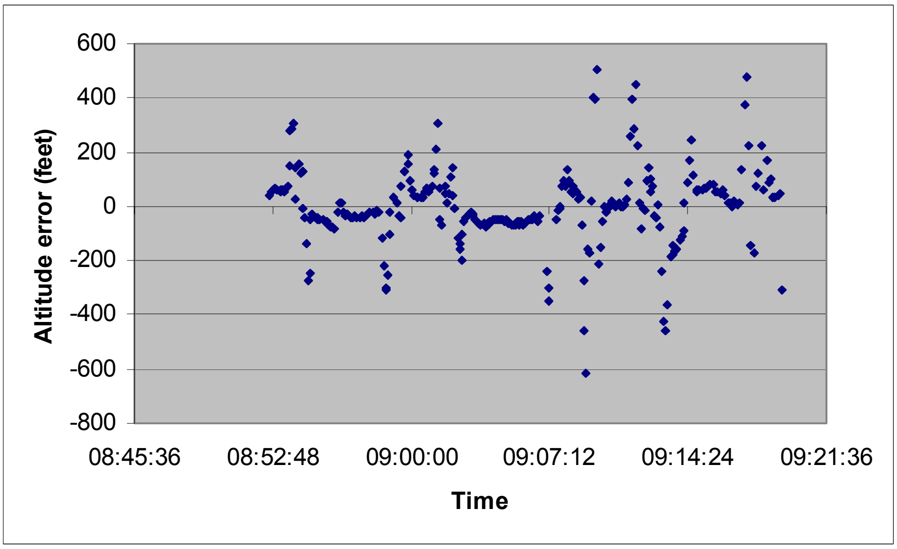


Figure 9-7. TIS-B altitude error in the flight test.

9.6. Continuity

9.6.1. Verification

The principle for testing continuity is the same as for availability. Two objects that can be detected by the SMR have been placed at Arlanda airport for a longer period of time. The location of the objects can be seen in figure 9-1. TIS-B data received by the VDL Mode 4 transceiver has been recorded and analysed. The system has been considered as being discontinuous if more than two following TIS-B messages are missing. Again, since the time for logging has been too short, the result is only an indication of the continuity performance of TIS-B.

Continuity is calculated using the formula $C = e^{-\frac{t_c}{MTBCF}}$

t_c = critical time = 3 seconds for ground targets

9.6.2. Validation

10 076 respectively 10 272 target messages for the two reference objects have been taken into consideration. The results can be seen in table 9-11.

	Reference object 1	Reference object 2
Continuity	99.25 %	99.46 %

Table 9-11. TIS-B continuity.

There are no continuity requirements present for TIS-B, but comparison with the ADS-B requirements shows that the continuity must be improved. Further testing of continuity must be performed in order to obtain more valid results.

9.7. Coverage

9.7.1. Verification

The TIS-B coverage for the airport surface should be the same as the SMR coverage and the radio frequency coverage of the ground station. The test has been performed by driving a vehicle along the route in figure 9-2. Data from the on-board transceiver has been recorded as well as TIS-B data received by the second transceiver.

9.7.2. Validation

The TIS-B coverage is satisfying, according to figure 9-2. The reason that there are missing TIS-B reports at some places, depends on that these areas have been removed in the SDPS by using a filter. The coverage of the CNS GS on Arlanda airport should be satisfying everywhere where aircrafts are in movement, according to Eriksson and Lundmark [Ref 14].

9.8. Capacity

9.8.1. Verification

At this moment the TIS-B server can reserve 40 slots on the VDL 4 link for TIS-B messages. This means that there can be a maximum of 242 airborne aircraft targets with an update rate of one report every six seconds. Alternatively there can be a maximum of 84 Ground Aircraft targets or 116 Ground vehicle targets with an update rate of one report per second.

Target	Update period [s]	Maximum number of targets
Airborne Aircraft Targets	6	484
Ground Aircraft Targets	1	84
Ground Vehicle Targets	1	116

Table 9-12. The maximum number of TIS-B targets having a capacity of 40 slots.

9.8.2. Validation

The number of slots should be enough to fulfil the requirement of complete surveillance of Arlanda airport and airspace.

9.9. Monitoring

9.9.1. Verification

During the tests, the Human Machine Interface (HMI) “Multimode CATS”, by Carmenta™, has been monitored and there has been an alert message when there are fewer TIS-B targets than expected. There is also a time out function so that targets that have not updated their position information in a given time interval still can be seen in a different colour. The monitoring device is however dependent on the information of the management message, which is directly dependent on the data delivered from the tracker.

In the practical tests, the number of target messages in the VIP log files has been compared to the “number of targets”-parameter in the management message.

9.9.2. Validation

The total number of target messages received by the transceiver is approximately 99.9% of what has been indicated in the management messages. We consider the monitoring functions of the system as satisfying. No direct requirement is however present today.

10. TIS-B slot allocation optimisation

The following section is based on information in the NUP TIS-B service description [Ref 2].

There are two factors determining the number of slots needed in a VDL Mode 4 frame when transmitting TIS-B reports. The first factor is the actual number of targets that are sent. The other factor is the management message that is sent one time every update period. With this message the recipient receives information concerning which traffic information volume each target is associated with. Management messages can have a size of between 96 and 384 bits. The number of slots needed is dependent of how many vertices the TIV has. With the term “TIS-B report” we refer to all of the messages that are transmitted during one second.

An aircraft target message including Flight ID has a size of 153 bits. An aircraft target message without Flight ID has a size of 104 bits. The Flight ID must be transmitted every third update period. Aircrafts on the ground have a target message size of 148 or 99 bits. Ground vehicle target messages have a size of 85 bits, see table 10-1.

	Aircraft target messages (airborne service)	Aircraft target message (ground service)	Ground vehicle target message
Flight ID included	153	148	-
Flight ID excluded	104	99	85

Table 10-1. Size of target messages.

Every TIS-B burst begins with some filling and synchronisation parameters, which consist of 144 bits. As a consequence, the first slot in a TIS-B burst can contain 104 bits of information. The following slots in the burst can contain 248 bits of information.

10.1.1. Transmission methods

Different methods for transmitting TIS-B reports can be used. There are two extreme case methods. With the first of these methods one TIS-B report is transmitted once every radar update period. This message will contain all targets detected by the radar during the period of time it takes for the radar to make a revolution. The advantage with this method is that it gives an optimal slot usage based on the co-ordination algorithm. The disadvantages are that the method causes long update delays for some targets and that it results in an inhomogeneous structure in the superframe. There is also a greater risk of bit error rate, which results in that all of the information in that particular burst is lost.

With the second extreme case method TIS-B reports are transmitted each second during the radar update period. This results in shorter delays for the target updates and the superframe gets a more homogenous structure. The disadvantage with the second method is that it is not as slot efficient as the first.

The best solution is to find a method with a slot usage that is satisfactory and at the same time obtain a reduction of latency.

10.1.2. Static reservation and dynamic allocation

Static reservation, dynamic allocation or both could be used to allocate slots for TIS-B reports. In a static system the number of available slots in every update interval is predefined. The number of slots must be sufficient to supply the maximum traffic intensity. In a static system there are always slots available but it requires a lot of capacity since slots might be reserved without being used. In a dynamic system the number of available slots will change depending on the traffic density and intensity. The slots will be assigned when a vehicle of interest enters the coverage area. This system saves capacity but the continuous change in the number of needed slots will be a problem when allocating the slots.

10.2. Experiments

In this section a number of theoretical experiments has been done in order to see how different systems react to different traffic situations. The systems will be evaluated theoretically and by simulation with the TIS-B slot allocation simulation program, “*Device For Slot Allocation (DFSA)*”.

Suppose that we have a TIV with six vertices. The update interval for the tracker is set to six seconds. Targets are reported each second. The management message consists of 204 bits and is transmitted once every update period. It is transmitted in the first TIS-B burst in the update period. Two slots are needed in order to fit the management message. We only use airborne targets because these are the largest message types. The target messages consists of 104 or 153 bits depending on if the flight ID is included or not. Figure 10-1 shows how the radar picture is divided into six areas.

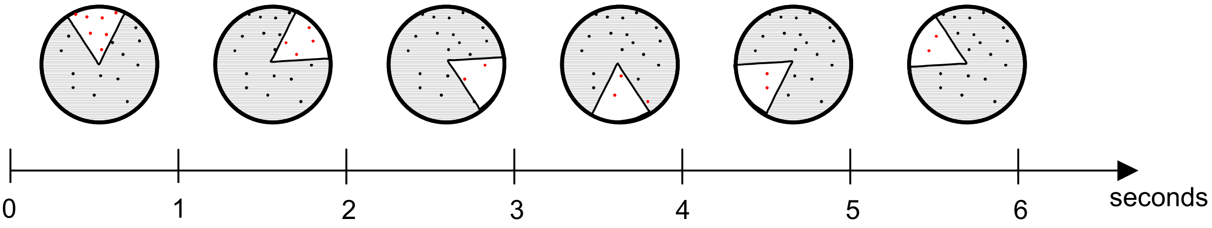


Figure 10-1. Separation of a radar revolution into six areas.

All calculations performed in the experiments can be seen in appendix 5.

10.2.1. Experiment 1 – Static system with six reserved slots per second

Area	Number of targets
1	9
2	5
3	4
4	1
5	2
6	9

Table 10-2. Target distribution – experiment 1.

Conditions: We use a static system with the number of targets as represented in table 10-2. The number of reserved slots is 6 per second. This will give us the capacity to transmit 9 airborne targets per second when a management message is included. If the system is working properly no delay will occur.

Second						
1	▨	▨	▨	▨	▨	▨
2	▨	▨	▨			
3	▨	▨	▨			
4	▨	▨				
5	▨	▨				
6	▨	▨	▨	▨	▨	

Rest (nr of targets)
0
0
0
0
0
0

Table 10-3. Slot usage – experiment 1.

Conclusion: 21 slots of the 36 available are used. No targets are delayed.

10.2.2. Experiment 2 – Static system with four reserved slots per second

Conditions: From experiment 1 we can see that we did not use all the available slots. The system works correctly but uses a lot of slots that could be used for other applications. In this experiment we decrease the number of reserved slots to 4 per second and the number of targets is the same as in experiment 1. The system should work correctly but we should get some latency.

Second					Rest (nr of targets)
1	🟦	🟦	🟦	🟦	4
2	🟦	🟦	🟦	🟦	2
3	🟦	🟦	🟦		0
4	🟦	🟦			0
5	🟦	🟦			0
6	🟦	🟦	🟦	🟦	2
7	🟦	🟦	🟦	🟦	6
8	🟦	🟦	🟦	🟦	4
9	🟦	🟦	🟦	🟦	2
10	🟦	🟦	🟦		0
11	🟦	🟦			0
12	🟦	🟦	🟦	🟦	2

Table 10-4. Slot usage – experiment 2.

Conclusion: We use 21 slots of the 24 available at the most. 14 targets have a one-second delay in update period 2.

10.2.3. Experiment 3 – An extensive number of targets in a static system with four reserved slots per second

Area	Number of targets
1	9
2	5
3	4
4	15
5	2
6	9

Table 10-5. Target distribution – experiment 3.

Conditions: The number of reserved slots is 4 per second. We use the number of targets represented in table 10-5. The same number of targets as in experiment 2 is used in all areas of the radar revolution except area number 4 where suddenly 15 airborne targets enter. In this experiment the number of airborne targets are 44.

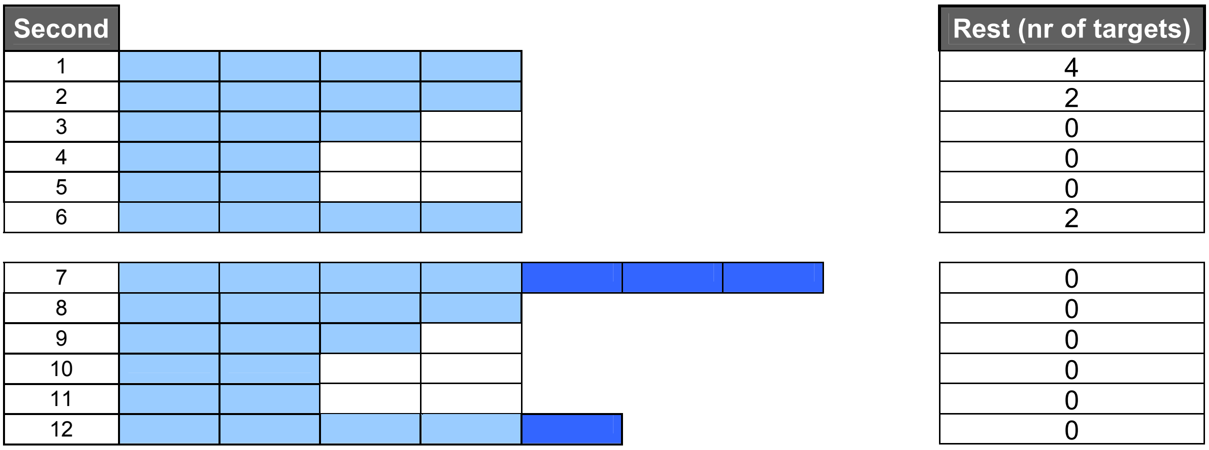
Second					Rest (nr of targets)
1	🟦	🟦	🟦	🟦	4
2	🟦	🟦	🟦	🟦	2
3	🟦	🟦	🟦		0
4	🟦	🟦	🟦	🟦	8
5	🟦	🟦	🟦	🟦	4
6	🟦	🟦	🟦	🟦	6
7	🟦	🟦	🟦	🟦	10
8	🟦	🟦	🟦	🟦	8
9	🟦	🟦	🟦	🟦	5
10	🟦	🟦	🟦	🟦	13
11	🟦	🟦	🟦	🟦	9
12	🟦	🟦	🟦	🟦	11
13	🟦	🟦	🟦	🟦	15
14	🟦	🟦	🟦	🟦	13
15	🟦	🟦	🟦	🟦	10
16	🟦	🟦	🟦	🟦	18
17	🟦	🟦	🟦	🟦	14
18	🟦	🟦	🟦	🟦	16

Table 10-6. Slot usage – experiment 3.

Conclusion: The system fails to update all the targets in one revolution. This leads to accumulating latency. Only three revolutions have been simulated, approximately 18 seconds, and the maximum latency is already 3 seconds. This experiment shows the importance of setting a maximum number of targets when using the static system. If the maximum number of targets are exceeded the TIV should be compressed.

10.2.4. Experiment 4 – Semi-dynamic system with four reserved slots per second and a dynamic allocation with a 1-second delay.

Conditions: In order to decrease the delay we reserve 4 static slots per second and the server reserves as many extra slots needed in each area in the previous update interval plus the rest from the last area in the first area of the following revolution. The number of targets is the same as in experiment 1.



Second								Rest (nr of targets)
1	▨	▨	▨	▨				4
2	▨	▨	▨	▨				2
3	▨	▨	▨					0
4	▨	▨						0
5	▨	▨						0
6	▨	▨	▨	▨				2
7	▨	▨	▨	▨	■	■	■	0
8	▨	▨	▨	▨				0
9	▨	▨	▨					0
10	▨	▨						0
11	▨	▨						0
12	▨	▨	▨	▨	■			0

Table 10-7. Slot usage – experiment 4. The slots with dark blue colour have been dynamically allocated.

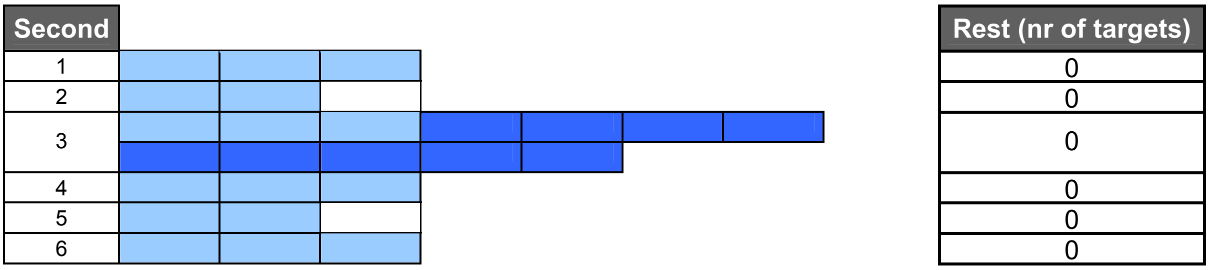
Conclusion: We need to reserve 4 slots dynamically. A disadvantage could be that the different bursts have inhomogeneous size. A difficulty is to predict the change of the number of targets in each area between each update interval. Another difficulty is to reserve slots for a large burst in the event of an extensive number of targets in one area of the radar revolution.
One idea is to log positioning data during one week and let the static reservation for the coming week be based on the logged data. Another idea is to use extrapolation to determine the number of targets in each area for the next update interval.

10.2.5. Experiment 5 - Semi-dynamic system with three reserved slots per second

Area	Number of targets
1	3
2	1
3	16
4	4
5	2
6	4

Table 10-8. Target distribution – experiment 5.

Condition: Static reservation of 3 slots per second and dynamic allocation. Suppose that there are never more than 3 free slots in a row in each 75-slot frame. The other slots have already been reserved by for example ADS-B.



Second								Rest (nr of targets)
1	▒	▒	▒					0
2	▒	▒						0
3	▒	▒	▒	■	■	■	■	0
	■	■	■	■	■			
4	▒	▒	▒					0
5	▒	▒						0
6	▒	▒	▒					0

Table 10-9. Slot usage – experiment 5.

Conclusion: It is difficult to make up a number of available slots in the frame that are not already occupied by for example ADS-B reports. With these conditions the number of slots used is 25. The high number of slots depends on the using of four bursts in area number 3, since every burst includes the filling and synchronisation parameters that represent 144 bits.

10.3. A scenario at Arlanda airport during peak hour

In order to present a scenario with real traffic, TIS-B data for the air TIV has been logged for 20 minutes at Arlanda airport during peak hour. The locations of the targets have been put together in a diagram, which shows the spreading of the targets during each minute, according to figure 10-2.

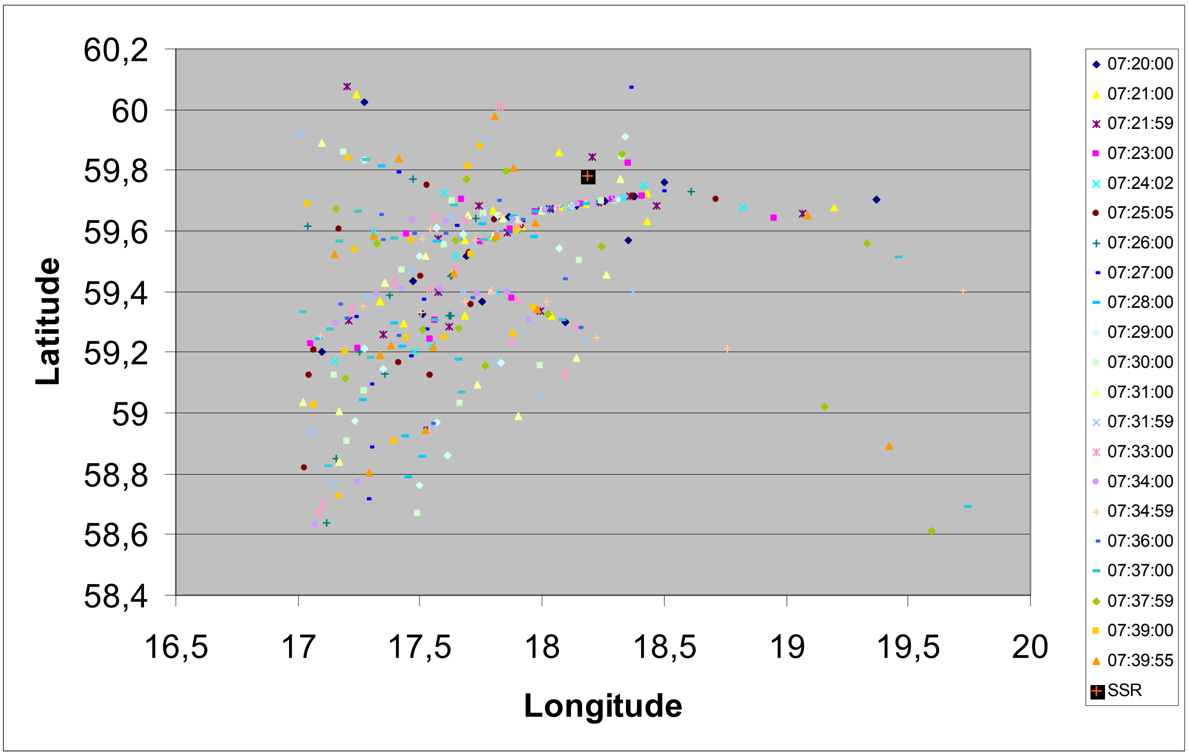


Figure 10-2. The location of airborne targets during each minute in a 20-minute interval.

The next step has been to draw a circle with the SSR in the middle and divide it into six areas, each representing the area that is swept over by the SSR during one second. The result is concluded in table 10-10.

	1	2	3	4	5	6
07:20:00	0	4	2	9	1	0
07:21:00	0	4	1	9	2	0
07:22:00	0	3	1	9	2	1
07:23:00	1	3	1	10	1	0
07:24:00	0	3	1	9	2	0
07:25:00	0	2	1	11	2	0
07:26:00	0	1	1	10	2	0
07:27:00	1	1	1	10	1	0
07:28:00	0	0	1	14	1	0
07:29:00	1	1	0	15	1	0
07:30:00	1	0	2	11	2	0
07:31:00	0	1	2	12	1	0
07:32:00	0	1	2	10	3	0
07:33:00	0	0	3	13	2	0
07:34:00	0	0	0	15	1	0
07:35:00	0	1	2	12	0	0
07:36:00	0	0	2	11	2	0
07:37:00	0	2	1	9	4	0
07:38:00	1	1	3	8	3	0
07:39:00	0	0	0	12	4	0
07:40:00	0	2	0	10	4	0

Table 10-10. The number of airborne targets in each area during each minute.

Table 10-10 shows how the concentration of targets can differ to a large extent in each area of the radar revolution. If static reservation of slots would be used for this kind of traffic scenario the number of slots to reserve would have to be adjusted to the maximum number occurring, which is 15.

Second									Rest (nr of targets)
1	🟦	🟦							0
2	🟦								0
3									0
4	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	0
5	🟦								0
6									0

Table 10-11. Slot usage – static reservation of 8 slots per second.

If the worst minute, 08:29:00, is taken into consideration and static reservation is used, there would be a need to reserve 9 slots each second, see table 10-11. This would be a very inefficient method since 23 slots are reserved but not used in the entire update period. On the other hand, no target reports will be delayed.

Second						Rest (nr of targets)
1	🟦	🟦				0
2	🟦					0
3						0
4	🟦	🟦	🟦	🟦	🟦	6
5	🟦	🟦	🟦	🟦	🟦	0
6						0

Table 10-12. Slot usage – static reservation of 5 slots per second.

Using static reservation of 5 slots per second would improve the slot efficiency. The result would be only 17 unused slots. 6 targets would have a one-second delay, which might be acceptable.

11. Functional Hazard Analysis

The Functional Hazard Analysis (FHA) answers how safe the system needs to be. We have made worst-case assumptions and only consider one function at a time and not combinations of several functions. Historic data and competent advisors have been used to determine the severity and frequency of a disabled function. The FHA is based on the descriptions of FHA in the documents “Air Navigation System Safety Assessment Methodology” [Ref 9] and “JAR 25.1309” [Ref 23].

The objectives of the FHA have been to:

- Identify all potential failures associated with the system.
- Determine the safety consequences of failure occurrence and to identify potential hazards.
- Assess the severity associated with each hazard.

For each of the system functions following steps have been performed:

- Identify potential failures: What could go wrong with the system?
- Identify potential hazards: What could happen if something goes wrong and does it affect the safety of aircraft operations?
- Assess severity of hazards: How bad would the effect of the hazards be?
- Specify safety objectives: How often can the hazards be tolerated?

11.1. Severity Categories

To indicate the severity of a hazard, five different categories have been used. The categories have been given a number of 1-5, where 5 is the most severe. The severity categories are shown in table 11-1 [Ref 9].

Severity Category	Description
No effect (1)	
Minor (2)	Failure conditions which would not significantly reduce aeroplane safety, and which involve crew actions that are well within their capabilities. Minor failure conditions may include, for example: • Slight reduction of safety margins. • Slight increase in workload for the air traffic controller and/or the flight crew.
Major (3)	Failure conditions which would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example: • A significant reduction in safety margins or functional capabilities. • A significant increase in workload for the air traffic controller and/or the flight crew.
Hazardous (4)	Failure conditions which would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be: • A large reduction in safety margins or functional capabilities, • Physical distress or higher workload such that the flight crew cannot be relied upon to perform their task accurately or completely.
Catastrophic (5)	Failure conditions, which would prevent continued safe flight and landing.

Table 11-1. Severity categories.

11.2. Frequency categories

The frequency of the hazard have been determined with four different categories given numbers from 1-4 where 4 is the most frequent. In the risk matrix used by the SCAA there are six different frequency categories but we use this simplified one so that we easier can address different hazards. The frequency number together with the severity number results in the risk of the hazard. In the tables below the different frequency categories are shown. Table 11-2 shows the qualitative description of the categories and table 11-3 shows the quantitative description of the categories [Ref 9].

Frequency Category	Description
Extremely Improbable (1)	So unlikely that they are not anticipated to occur during the entire operational lifetime of the system.
Extremely Remote (2)	Unlikely to occur when considering the total operational lifetime of the system, but nevertheless, has to be considered as being possible.
Remote (3)	Unlikely to occur during the total operational lifetime but which may occur several times when considering the total operational lifetime of all systems.
Probable (4)	Anticipated to occur one or more times during the entire operational lifetime of each system.

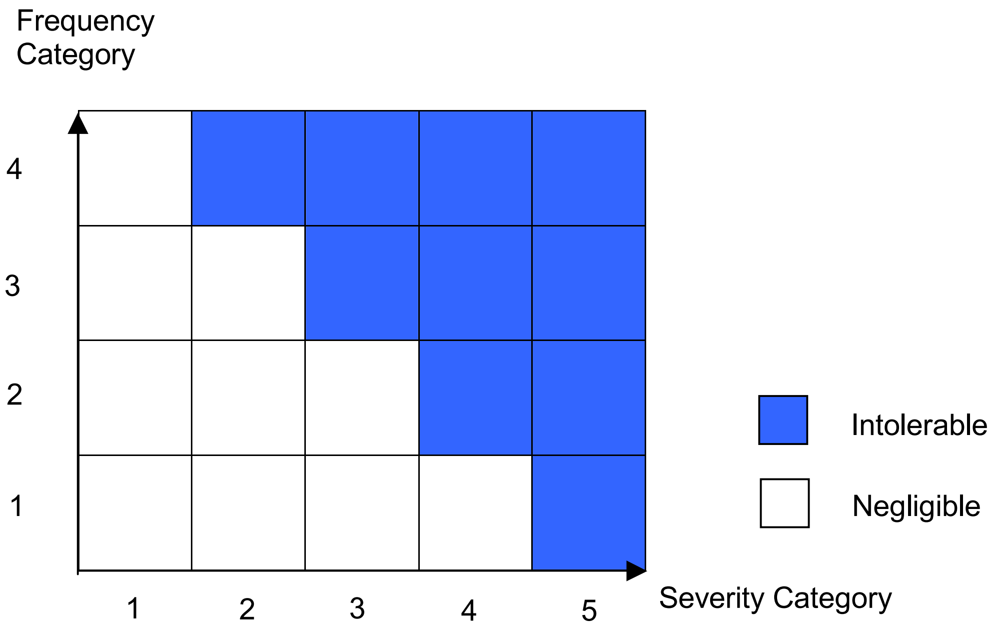
Table 11-2. Qualitative frequency categories.

Frequency Category	Description
Extremely Improbable (1)	Failure condition frequency is less than 10^{-9} per hour.
Extremely Remote (2)	Failure condition frequency is between 10^{-9} and 10^{-7} per hour.
Remote (3)	Failure condition frequency is between 10^{-7} and 10^{-5} per hour.
Probable (4)	Failure condition frequency is more than 10^{-5} per hour.

Table 11-3. Quantitative frequency categories.

11.3. Hazard classification scheme

The hazard classification scheme in figure 11-1 [ref 23] shows if the hazard is negligible or intolerable. A simplified risk matrix has been used to see if the hazard is to be considered or not.



Frequency Category	1	2	3	4	5
4	⬜	🟦	🟦	🟦	🟦
3	⬜	⬜	🟦	🟦	🟦
2	⬜	⬜	⬜	🟦	🟦
1	⬜	⬜	⬜	⬜	🟦

🟦 Intolerable
⬜ Negligible

Figure 11-1. Hazard Classification scheme.

11.4. Different TIS-B applications

There are four main applications for TIS-B, which will be considered. These applications are:

- ATSAW.
- Airborne Spacing.
- Airborne Separation.
- Airborne Self-Separation.

The applications transfer different amount of responsibility to the aircrew. The transfer of responsibility for the applications is explained in table 11-4.

Application	Responsibility
ATSAW	No transfer of responsibility. The responsibility lies on the air traffic controller.
Airborne Spacing	The responsibility for maintaining a distance from designated aircraft is delegated to the aircrew, but the responsibility for providing separation in accordance with applicable ATC separation minima still rests with the air traffic controller, who will monitor the spacing procedure.
Airborne Separation and Airborne Self Separation	The separation responsibility relative to designated aircraft is delegated to the aircrew, and the controller does not need to monitor the procedure.

Table 11-4. The relation between application and responsibility.

Figure 11-2 [Ref 24] shows in which flight phase the different applications are to be used.

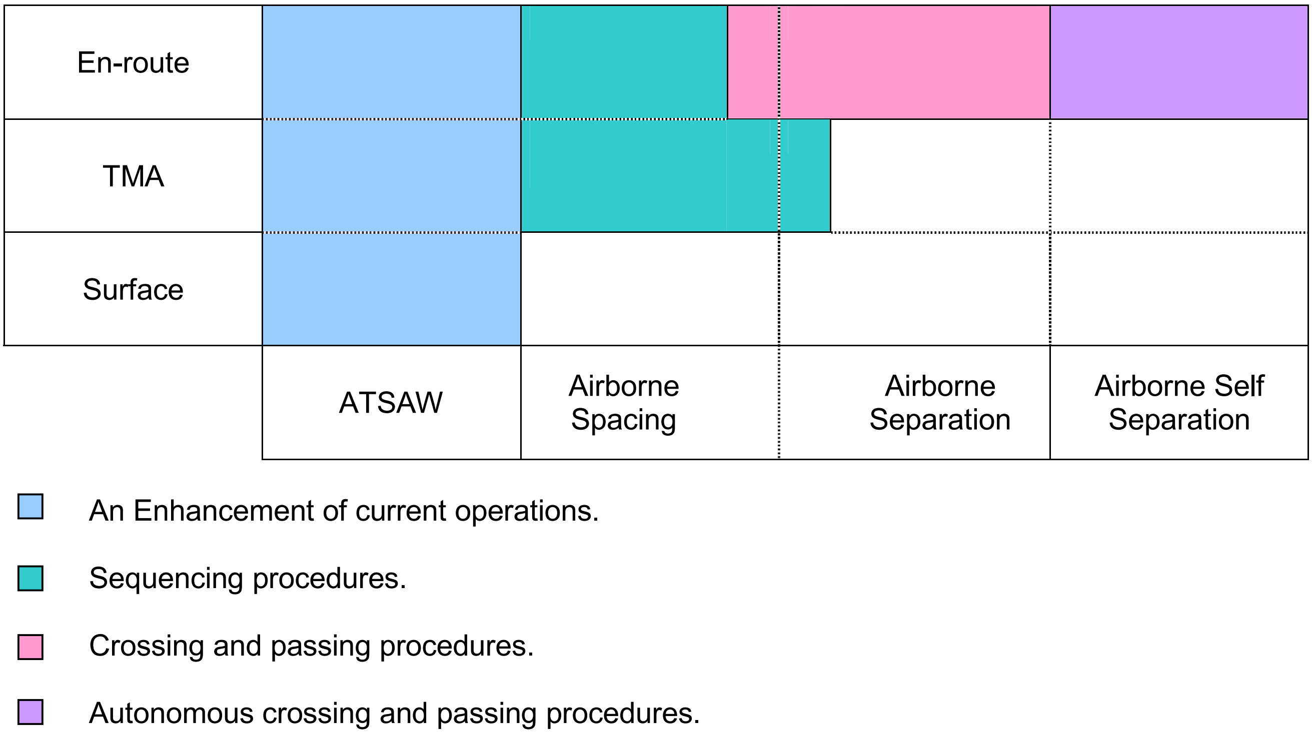


Figure 11-2. Different Applications for different flight phases.

11.5. The FHA meeting

The FHA meeting took place in the SCAA, Norrköping, on the 25th of February.

Participants on the meeting were:	Matts Eriksson	Ground Station expert.
	Daniel Fredriksson	TIS-B technical specialist.
	Göran Hasslar	TIS-B expert / Safety engineer.
	Per-Ola Kårbro	Aeronautical expert.
	Anne-Lovise Linge	ADS-B and VDL 4 expert.
	Anders Schweitz	TIS-B technical specialist.

The meeting began with a short introduction of the meaning of the FHA. After the introduction the severity and frequency categories were presented. We then began an open discussion considering the hazards of the TIS-B system. The TIS-B system was divided into seven parts:

- Radar
- SDPS
- TIS-B Server
- Ground station
- Data link
- Transceiver
- HMI

Through the open discussion several hazards were identified and addressed. The hazards were collected in a hazard assessment table, concluded in chapter 11.6. Some of the discussed issues can be seen in the chapters 11.5.1 - 11.5.7.

11.5.1. Radar

If the radar system is completely out of order it will disable TIS-B. The ADS-B equipped vehicles will no longer be able to see the non-equipped targets. If there are false plots it could have impact on the pilot's decision making. This means that the pilot will contact the air traffic controller to get information what kind of object it is. Many pilots might inquire for the same information, resulting in a higher workload for the controller. It must be determined whether all targets detected by the radar should be transferred to the end user or only the targets that have a label. If the pilot would put too much trust in TIS-B he/she might hesitate if a target shows up on the HMI, whilst doing some kind of manoeuvre. If the seen target is only a ghost target the pilot might lose confidence in the system. Landing is especially critical if the pilot sees a target located on the runway on his HMI and acts on his own initiative although the controller has informed him that the runway is free. The pilot could for example do a go-round. This would however be an incorrect action by the pilot since the controller must always be relied on. If an ADS-B aircraft performs self-separation and the TIS-B target that is being followed is lost this can be critical. It is uncertain if TIS-B will ever fulfil the requirements to be used for self-separation. First of all every aircraft in the airway must be equipped with an SSR transponder. There must be rules for fallback if the TIS-B target is lost so that the risk of an accident is avoided. If the radar misses one update for one target this should not have any significant consequence. However if the target is not detected by radar for several update periods the risk increases.

11.5.2. SDPS

If the output data from the SDPS differs from the input data, then there might be some consequences that are difficult to foresee. The probability that this error occurs is very low. Moreover, if the SDPS is temporarily out of function it will have the same consequences as when the radar is not functioning.

11.5.3. TIS-B server

The same problems as the ones identified for the SDPS can occur. Another identified possible problem is that TIV:s might be overloaded resulting in that the TIV will not be shown on the HMI at all. There might also be problems with ground targets that are displayed as aircraft and the other way around. The consequences should be minor. Pilots that come from one TIV and enters another where the surveillance mode (gap filler or full surveillance) is not the same should not be a problem. This is however not an error mode, just an aspect that could affect the pilot.

11.5.4. Ground station

If the ground station does not transmit all messages, this should be indicated in the HMI, since the number of targets would not correspond with the number of targets parameter in the management message. The output data might differ from input data here as well but the probability of this is low. Another possible error could be that TIV:s are transmitted from the wrong ground station, which could lead to some confusion.

11.5.5. Data link

The data link can be overloaded. This should not occur if the configuration is correct.

11.5.6. Transceiver

The transceiver should only receive TIS-B reports and deliver it to the HMI. The transceiver could stop working or deliver incorrect data to the HMI.

11.5.7. HMI

If the server is set for full surveillance there is a risk that ADS-B targets are displayed as two different targets because the plots are too far away from each other. Normally the plots should be fused. It is important for a correct traffic scenario that the accuracy of the targets is high and that latency is low.

11.6. Hazard Assessment

Function:	Name of the analysed function.
Failure Mode:	For each function, the failure mode considered.
Flight phase:	Considered flight phase, if the effects are dependent on the flight phase.
TIS-B Function:	Considered TIS-B function, if the effects are dependent on the function. The functions considered are: Airborne Traffic Situational Awareness, Airborne Spacing and Airborne Separation.
Operational consequences:	Description of operational effects of failure(s).
Hazard Description:	Description of effects on the safety of Air Navigation Services, and potential effects on aircraft operations, considering adverse operational and environmental conditions.
Severity Category:	Severity of the hazard and the rationale for its classification.
Frequency Category:	Frequency of the hazard.
Risk:	The risk of the hazard, negligible or intolerable.

Function	Failure mode	Flight phase	TIS-B Function	Operational consequences	Hazard description	Severity category	Frequency category	Risk
Radar	Out of order/Unavailable		ATSAW	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	1	3	*Negligible*
			Spacing	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	2	3	*Negligible*
			Separation	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	5	3	**Intolerable**
	False plots	TMA	ATSAW	False data is seen on the HMI. Which results in a false traffic scenario.		1	3	*Negligible*
		En-Route	Spacing	False data is seen on the HMI., which results in a false traffic scenario.		2	1	*Negligible*
		En-Route	Separation	False data is seen on the HMI, which results in a false traffic scenario.		5	1	**Intolerable**
	Lost Update		ATSAW	The data seen on the HMI is old.	More than two subsequent updates are lost.	1	4	*Negligible*
			Spacing	The data seen on the HMI is old.	More than two subsequent updates are lost.	2	4	**Intolerable**
			Separation	The data seen on the HMI is old.	More than two subsequent updates are lost.	4	4	**Intolerable**
SDPS	Out of order/Unavailable		ATSAW	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	1	3	*Negligible*

Function	Failure mode	Flight phase	TIS-B Function	Operational consequences	Hazard description	Severity category	Frequency category	Risk
			Spacing	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	2	3	*Negligible*
			Separation	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	5	3	**Intolerable**
	Sent data differs from received data.		ATSAW	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	1	1	*Negligible*
			Spacing	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	2	1	*Negligible*
			Separation	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	5	1	**Intolerable**
Server	Out of order/Unavailable		ATSAW	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	1	3	*Negligible*
			Spacing	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	2	3	*Negligible*
			Separation	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	5	3	**Intolerable**
	Sent data differs from received data.		ATSAW	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	1	1	*Negligible*
			Spacing	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	2	1	*Negligible*
			Separation	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	5	1	**Intolerable**

Function	Failure mode	Flight phase	TIS-B Function	Operational consequences	Hazard description	Severity category	Frequency category	Risk
	One of two adjacent TIV:s are unavailable.		ATSAW	No data is seen in one of the TIV:s, which results in a compressed traffic scenario.		1	2	*Negligible*
			Spacing	No data is seen in one of the TIV:s, which results in a compressed traffic scenario.		2	2	*Negligible*
			Separation	No data is seen in one of the TIV:s, which results in a compressed traffic scenario. Self-separation cannot be used.		5	2	**Intolerable**
	An aircraft is visualised as a Ground vehicle.			The aircraft is taken for a ground vehicle.		1	2	*Negligible*
	The TIV should be Gap Filler but is Full Surveillance.			All targets are transmitted as TIS-B targets.		1	4	*Negligible*
Ground Station	Out of order/Unavailable		ATSAW	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	1	3	*Negligible*
			Spacing	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	2	3	*Negligible*
			Separation	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	5	3	**Intolerable**
	Sent data differs from received data.		ATSAW	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	1	1	*Negligible*
			Spacing	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	2	1	*Negligible*

Function	Failure mode	Flight phase	TIS-B Function	Operational consequences	Hazard description	Severity category	Frequency category	Risk
			Separation	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	5	1	**Intolerable**
	Missing capacity.		ATSAW	All data is not sent.	All of the targets are not transmitted.	1	3	*Negligible*
			Spacing	All data is not sent.	All of the targets are not transmitted.	2	3	*Negligible*
			Separation	All data is not sent.	All of the targets are not transmitted.	5	3	**Intolerable**
	TIV sent by wrong Ground Station.		ATSAW	No data can be seen on the HMI.		1	3	*Negligible*
			Spacing	No data can be seen on the HMI.		2	3	*Negligible*
			Separation	No data can be seen on the HMI.		5	3	**Intolerable**
	Old data is sent instead of the new.		ATSAW	Non-accurate data is seen on the HMI, which results in a false traffic scenario.		1	3	*Negligible*
			Spacing	Non-accurate data is seen on the HMI, which results in a false traffic scenario.		2	3	*Negligible*
			Separation	Non-accurate data is seen on the HMI, which results in a false traffic scenario.		5	3	**Intolerable**
Data link	Out of order/Unavailable		ATSAW	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	1	3	*Negligible*
			Spacing	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	2	3	*Negligible*

Function	Failure mode	Flight phase	TIS-B Function	Operational consequences	Hazard description	Severity category	Frequency category	Risk
			Separation	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	5	3	**Intolerable**
Transceiver	Out of order/Unavailable		ATSAW	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	1	3	*Negligible*
			Spacing	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	2	3	*Negligible*
			Separation	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	5	3	**Intolerable**
	Sent data differs from received data.		ATSAW	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	1	1	*Negligible*
			Spacing	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	2	1	*Negligible*
			Separation	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	5	1	**Intolerable**
HMI	Out of order/Unavailable		ATSAW	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	1	3	*Negligible*
			Spacing	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	2	3	*Negligible*
			Separation	No data can be seen on the HMI.	Unavailable for at least 30 seconds.	5	3	**Intolerable**
	Sent data differs from received data.		ATSAW	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	1	1	*Negligible*

Function	Failure mode	Flight phase	TIS-B Function	Operational consequences	Hazard description	Severity category	Frequency category	Risk
			Spacing	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	2	1	*Negligible*
			Separation	Non-accurate data is seen on the HMI, which results in a false traffic scenario.	Consequent repeated error.	5	1	**Intolerable**
	High Latency of TIS-B reports.		ATSAW	The data is old and the position on the HMI is non-accurate.	The latency is greater than the requirements.	1	3	*Negligible*
			Spacing	The data is old and the position on the HMI is non-accurate.	The latency is greater than the requirements.	2	3	*Negligible*
			Separation	The data is old and the position on the HMI is non-accurate.	The latency is greater than the requirements.	5	3	**Intolerable**
	Low accuracy of TIS-B targets.		ATSAW	The position on the HMI is non-accurate.	The accuracy is lower than the requirements.	1	3	*Negligible*
			Spacing	The position on the HMI is non-accurate.	The accuracy is lower than the requirements.	2	3	*Negligible*
			Separation	The position on the HMI is non-accurate.	The accuracy is lower than the requirements.	5	3	**Intolerable**
	ADS-B targets are sent as TIS-B targets.		ATSAW	If there are major position differences between ADS-B and TIS-B data two targets will occur.		1	3	*Negligible*
			Spacing	If there are major position differences between ADS-B and TIS-B data two targets will occur.		2	3	*Negligible*
			Separation	If there are major position differences between ADS-B and TIS-B data two targets will occur.		5	3	**Intolerable**

12. Conclusions

This project has involved extensive research, tests and analyses. These three activities have given a complete picture of the TIS-B service and an understanding of its possibilities and problems. It is however difficult to determine how good the performance has been because of the lack of dedicated TIS-B requirements. On the other hand, the verification and validation has given guidelines to requirements and future implementation of TIS-B.

We see a possible use of TIS-B in a not too distant future. ADS-B will not be completely implemented for several years. TIS-B can provide users of ADS-B with a full surveillance picture. This could perhaps speed up the implementation of ADS-B. TIS-B is today the only solution that enables a full surveillance picture for these users. When pilots are offered a visualisation of the whole traffic scenario, the commands from the air traffic controller might be easier to understand. We also believe that the number of misunderstandings will decrease. If ADS-B is implemented without TIS-B functionality one problem can be that pilots will rely too much on the HMI and forget about the vehicles that have not been equipped with ADS-B.

During the tests many problems with the system have been discovered. A lot of them have been solved during this project. Some problems are however still to be taken care of. The biggest problem with the system is latency. After having evaluated position accuracy for moving targets it has become clear that the latency of the system contributes heavily to the poor accuracy. Because of high latency the targets are displayed with a plot that differs too much from the actual location of the target. A longer update interval of the radar and higher velocity of the targets results in that the problem has most impact for the air TIV. The ARTAS SDPS is sending all of the target messages in one batch, every sixth second, which has lead to the conclusion that there can be a delay of almost six seconds in the ARTAS SDPS before the target reports are sent to the server. If this delay could be removed the result would be a faster system that hopefully would deliver more accurate information to the users of the system.

We are positive to extrapolation of the position of targets. This would give a more continuous traffic scenario and would serve as a backup solution when updates are missing. The rules of how long the extrapolation will occur without any updates must be decided. This is affected by how many parameters that will be used for TIS-B targets. In order to use extrapolation for a longer period of time, it might be necessary to use the parameters angle rate and vertical rate. Our recommendation is to only extrapolate up to three updates. A longer time of extrapolation would be hazardous and give the participants a false picture of the traffic scenario.

We believe that the HMI should be capable of displaying more complex and smaller TIV:s. This is mainly a problem for the ground TIV. With a more complex TIV it would be easy to exclude non-interesting areas on the airport. Only the runways, taxiways and the aprons of the airport would be included in the TIV. We believe that it is very important that not used information is not transmitted on the data link. If the structure of the TIS-B management message cannot be changed it is recommended to have a filter in the server, which removes unwanted areas of the airport.

12.1. Slot allocation optimisation

The slot allocation should with preference be implemented with a semi-dynamic algorithm. The number of statically reserved slots is dependent of the need for every single TIV and should therefore be set according to the prevailing traffic conditions. A possible solution would be to reserve space for the mean value of the number of movements per day and let the overload of targets be reserved dynamically. With a self-learning mechanism, the Ground station could learn how many slots to be reserved at different times of a given time period. This demands that the traffic scenario to some extent repeats itself.

12.1.1. Static system

A static system is very reliable and simple to implement. With an overview of the traffic intensity it is easy to create a static system with efficient capacity. The limited space in the air interface is however a limiting factor. It is not slot efficient to transmit a big load of data with every transmission. Because the static system must be designed to cope with the heaviest traffic intensity it will, most of the time, be over-dimensioned and occupy space on the data link.

12.1.2. Dynamic System

A dynamic system always uses the exact number of slots needed to transmit data for all targets in the coverage area. The dynamic system is therefore, in theory, very slot efficient and occupies only the space, on the data transmission link, that it needs. The disadvantage with this method is that on a heavily used frequency the space will be limited. If no space is available or if the available slots are scattered in frequency this method will be very complex and slot demanding.

12.1.3. Semi-dynamic system

The semi-dynamic system is a combination of the static and the dynamic system. The number of static slots reserved can be considered according to the normal traffic intensity. If there is need for more slots the dynamic part of the system will allocate free slots and use these for the transmission. The disadvantages with the system are the same as for the two other systems but when combined the severity of these disadvantages reduces.

12.1.4. A self-learning mechanism

Using a static or semi-dynamic system the server could be self-learning and be able to compute approximately how many slots that are needed to fulfil the traffic requirements. This could be done using either a schedule for expected traffic intensity or by using the traffic information from the last minutes. The different update intervals can have different capacity requirements. The server should reserve the average number of slots needed in the different update intervals. In a static system there is also need to reserve some extra capacity so that high traffic intensity also could be served.

12.2. FHA

In the FHA we have come to the conclusion that TIS-B is ready to be implemented for ATSAW applications, despite high latency. Before any airborne spacing procedures can be performed there is need for more research. There is especially need for fallback procedures that prevent unnecessary risks when more than two sub-sequent messages from the radar are lost. If TIS-B is to be implemented for airborne separation applications it must be ensured that the information seen on the HMI is accurate.

12.2.1. ATSAW

No intolerable hazard for the ATSAW application has been found. TIS-B can be suitable for ATSAW applications.

12.2.2. Airborne Spacing

One intolerable hazard for the spacing application has been identified if more than two sub-sequent updates from the radar are lost. This hazard could be eliminated with for example extrapolation. The extrapolation should however not be used during a longer period of time. When testing has been done and fallback procedures have been developed, TIS-B can be suitable for spacing applications.

12.2.3. Airborne separation

For the Airborne separation application several hazards have been found. The self-separation application delegates the responsibility to the aircrew and the information seen on the HMI must therefore be highly accurate and with low latency. If TIS-B is to handle self-separation, a lot of research has to be done and fallback procedures must be developed.

13. Recommendations for further work

This chapter includes recommendations for further work. There are mainly three areas where actions and further investigation is necessary:

- Reduction of latency. This factor has significant contribution to position-, ground speed-, ground track- and altitude accuracy. This problem is most significant for targets in the air TIV. The best way to reduce latency would be to increase the update rate of the tracker, if possible, since all target positions are sent to the TIS-B server only once per update interval.
- Further discussion about how suitable TIS-B is for ATSAW-, airborne spacing- and airborne separation applications.
- Perform tests where the number of slots are determined using the same principles as in chapter 10. Today it is only possible to use static reservation. A compromise between efficient slot usage and reduction of delayed target reports must be found. A semi-dynamic solution would be attractive if the server could handle it.
- Perform new tests for availability and continuity in order to obtain more valid results.
- Evaluate the use of extrapolation of TIS-B target positions.

Appendix 1 - VDL Mode 4

VDL Mode 4 is a time-critical VHF data link that provides communication between mobile stations such as aircraft and airport surface vehicles as well as between mobile stations and fixed ground stations.

VDL Mode 4 transmits data in a 25 kHz channel and uses a medium access method called Self-organising Time Division Multiple Access (STDMA). STDMA divides the channel into segments. The biggest segment is called a superframe and it consists in turn of time slots. A superframe has 4500 time slots and each slot has a length of 13.33 ms. Each slot offers an opportunity for a station to transmit. The maximum allowed length for a transmission is one second, which results in that the maximum number of time slots per transmission is 75, see figure A-1. In VDL Mode 4, the time slots are synchronised to Universal Time Co-ordinated (UTC). The term self-organising refers to the use of a set of protocols, for example the periodic broadcast protocol, which is described in section A.1.2.

VDL Mode 4 operates within the spectrum band 108-136.975 MHz. Two Global Signalling Channels (GSC) will be allocated for worldwide use. Local Signalling Channels (LSC) and Regional Signalling Channels (RSC) might also complement these channels at airports with high-density traffic.

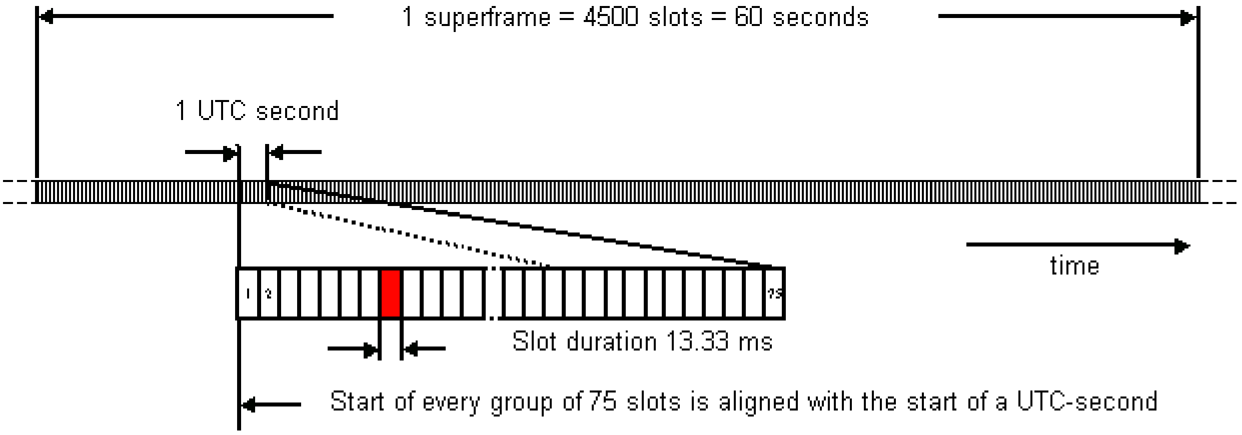


Figure A-1. The frame structure in VDL Mode 4.

A.1. Slot allocation

When transmitting a burst of data over VDL Mode 4, slots must be reserved. To make it possible for the stations to agree on which slots to use, their transmissions must be co-ordinated. Each station maintains a reservation table that contains all reservations made by other stations. When the link load increases and all slots are reserved, the stations are forced to reuse slots.

A.1.1. Slot reuse

There are two types of slot reuse, automatic and intentional. The automatic reuse will occur due to line of sight limitations or due to dissipation of signal power in the atmosphere. The intentional slot reuse consists of two guiding principles. The principles used are the Robin Hood and the Co-channel interference protection (CCI) principle. The Robin Hood principle allows a station operating on a busy channel to use slots previously reserved by another broadcasting station as long as it chooses the slots where the most distant station is broadcasting, see figure A-2. This results in a reduction of broadcast length of the transmitting station.

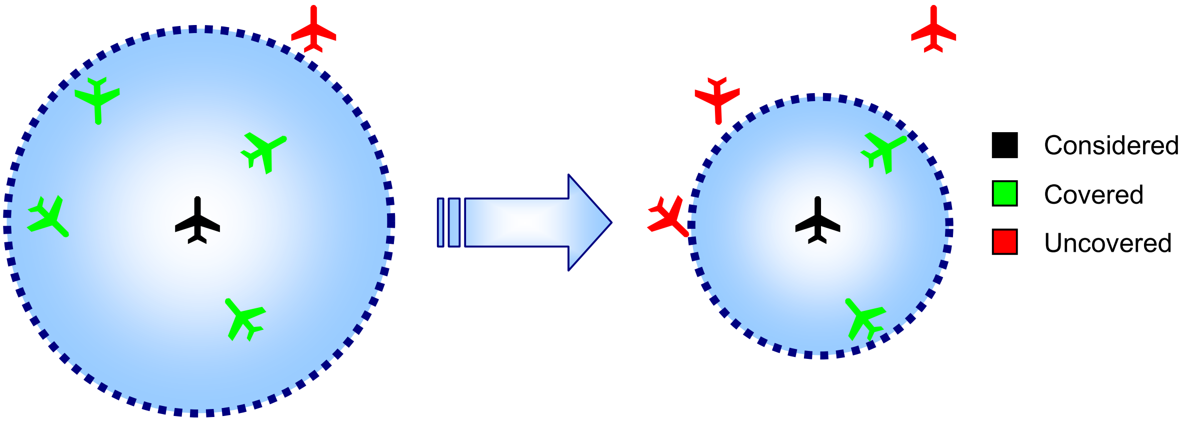


Figure A-2. Slot reuse using the Robin Hood principle.

The CCI protection principle allows slots, previously reserved for point-to-point communication between two stations, to be used by another station. VDL Mode 4 defines a measure of the CCI on the basis of free space attenuation. Discrimination of a station can occur as long as interfering signal strengths are differing with 12 dB, which is equivalent of a range ratio of 3 between the stations. In figure A-3, station 1 can transmit a message to station 2 using the same slots as station 3 transmitting to station 4 if the signal strength received by station 2 and 4 are differing with 12 dB. This is equal to that the distance between station 1 and 4 is 3 times greater than the distance between station 1 and 2 [Ref 1].

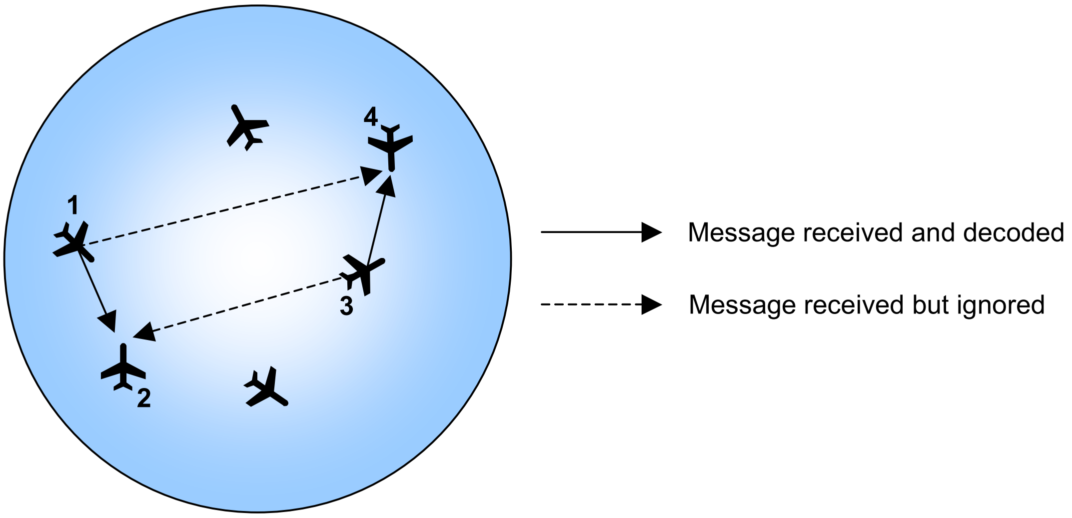


Figure A-3. The principle of Co-channel interference.

A.1.2. Periodic broadcast protocol

VDL Mode 4 supports a number of slot access mechanisms called reservation protocols. These protocols can be both autonomous and controlled access to data link resources. The most important autonomous protocol is the periodic broadcast protocol. This protocol supports the broadcast of identity and position to all other stations within the coverage area. Each station periodically broadcasts:

- Station ID
- Position information
- Control information for the periodic broadcast protocol

Each of the stations in the coverage area can build up their reservation table using the information broadcasted via the message. All stations occupy a particular slot and make reservations for the same slot in the next superframe. They also indicate which slot they will be moving to in future superframes via the periodic offset parameter. The assignment of slots is dynamic and the current stations change their slot at regular intervals between 4 and 8 minutes using the slot-time-out counter. The purpose of this is to avoid that when two aircrafts approach each other, they will not share the same slot or slots and garble each other's position reports. New stations entering the coverage area will continuously enter the slot structure with their own broadcasts. The reservation of slots and the change of slot number is visualized in figure A-4.

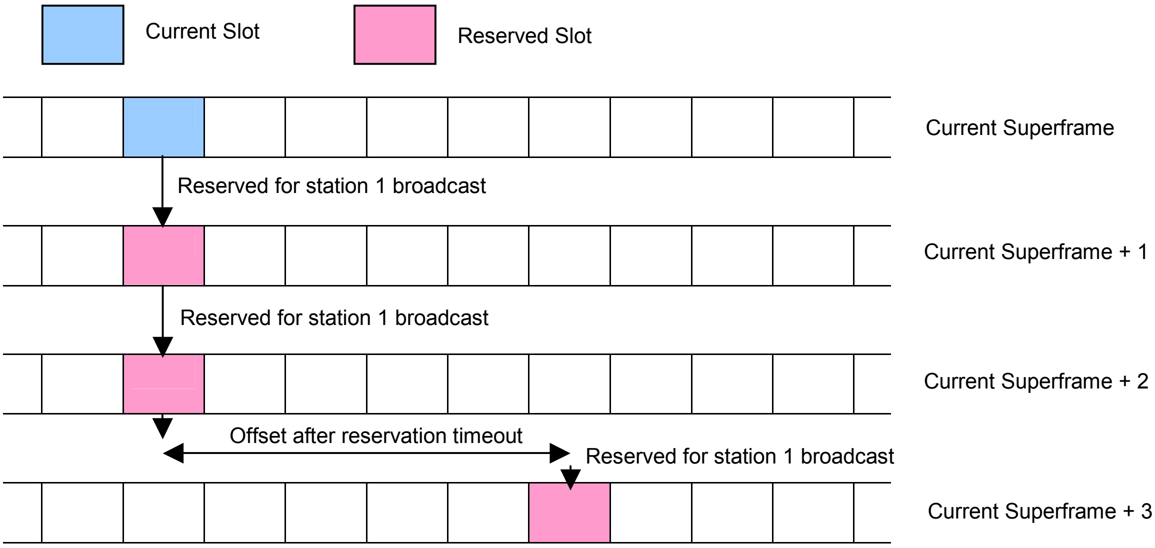


Figure A-4. The principle of slot allocation in VDL Mode 4

The selection of slots in the periodic broadcast protocol is a process in two stages. In the first stage the entering station, station A, will look for a slot to transmit in. Station A can only take an already reserved slot if another station, station B, is using the slot for a CCI protected point to point transmission and is more than 300 nautical miles away. If station A cannot find a slot that satisfies these criteria's it will search for an empty slot. If it finds just one empty slot station A will use it. If station A finds several unused slots it will randomly select one. If station A cannot find an empty slot it will move to the second stage, which forces station A to take an already reserved slot by a station that uses it for any broadcast transmission. Station A will select a slot used by the most distant station. [Ref 1]

Appendix 2 – Driving test at Arlanda airport

Categories: Accuracy
Coverage
Latency

Conditions

Date and time: 2004-02-11 13:00-15:00
Location: Arlanda airport, Stockholm

Participants

Supervisors: Daniel Fredriksson ASD/MAC, Anders Schweitz ASD/MAC
Other participants: Andreas Lindberg Swedia Networks

Equipment

A/V: Type: Car

Transceiver:
(RMS)
Type: NiTS VDL 4000/GA
Part number: 4000-10-10
Serial number: 3.25-4000-1111
Software: SW-4000-10-3.1, Update 1.3.3
VHF antenna type: Magnetfoot
VHF antenna position: Long: 17.5650 Lat: 59.3930
GPS type: Jupiter TU30-D400-021
GPS antenna type: Magnetfoot
GPS antenna position: Long: 17.5650 Lat: 59.3930

Settings:
Frequency T_x: 136,950 MHz and 136,975 MHz
Power T_x: 35 dBm (3,2 W)
Frequency R_{x1}: 136,950 MHz
Frequency R_{x2}: 136,975 MHz

RTK:
(Vehicle)
Type: Ashtech Z-Extreme
VHF antenna type: Ashtech
VHF antenna position: Vehicle roof
GPS antenna type: Magnetfoot
GPS antenna position: Vehicle roof

Logging equipment 1:
(Vehicle)
Data to log: RTK
Computer: Psion
Software: Pocketlogr
Software developer: N/A
Logging rate: 2 s.

Logging equipment 2:
(TIS-B Server)
Data to log: TIS-B (ASTERIX)
Computer OS: Windows NT
Software: LogUDP
Software developer: AerotechTelub

Logging equipment 3:

(RMS)

Data to log:	TIS-B (VIP)
Computer:	Compaq Armada
Computer OS:	Windows 2000
Software:	DumpVIP
Software developer:	CNS Systems

Test procedure

The test procedure involves driving a vehicle at Arlanda airport.

Checklist	
Start recording of TIS-B data in the TIS-B server	☐
Start recording of data in the transceiver	☐
Start recording of RTK GPS in the vehicle	☐
Start driving test according to driving description	☐

Appendix 3 - Static target test at Arlanda airport

Categories: Availability
Continuity

Conditions

Date and time: 2004-02-11 – 2004-02-19
Location: Arlanda airport, Stockholm

Participants

Supervisors: Daniel Fredriksson ASD/MAC, Anders Schweitz ASD/MAC
Other participants: Johan Abrahamsson, Swedia Networks

Equipment

Transceiver:
(RMS)
Type: NiTS VDL 4000/GA
Part number: 4000-10-10
Serial number: 3.25-4000-1111
Software: SW-4000-10-3.1, Update 1.3.3
VHF antenna type: Magnetfoot
VHF antenna position: Long: 17.5650 Lat: 59.3930
GPS type: Jupiter TU30-D400-021
GPS antenna type: Magnetfoot
GPS antenna position: Long: 17.5650 Lat: 59.3930

Settings:
Frequency T_x: 136,950 MHz and 136,975 MHz
Power T_x: 35 dBm (3,2 W)
Frequency R_{x1}: 136,950 MHz
Frequency R_{x2}: 136,975 MHz

Logging equipment 1:
(RMS)
Data to log: TIS-B (VIP)
Computer: Compaq Armada
Computer OS: Windows 2000
Software: DumpVIP
Software developer: CNS Systems

Checklist	
Determine exact locations of the reference objects	☐
Start recording of data in the transceiver	☐

Appendix 4 - Flight test in the Stockholm TMA

Categories: Accuracy
Coverage
Latency

Conditions

Date and time: 2004-02-04 08:00-10:00
Location: Arlanda airport, Stockholm

Participants

Supervisors: Daniel Fredriksson ASD/MAC, Anders Schweitz ASD/MAC
Other participants: Peter Lukic ASD/NAL

Equipment

A/V:	Type:	Beech King Air B200, Raytheon
RTK receiver:		
(Aircraft)	Model:	Ashtech Z-Extreme
	Positioning mode:	Real-Time Code Differential
	Antenna:	N/A
Transceiver:	Type:	NiTS VDL 4000/GA
	Part number:	4000-25-10
	Serial number:	3.25-4000-1111
	Software:	SW-4000-10-3.2
	VHF antenna type:	Magnetfoot
	VHF antenna position:	Long: 17.5640 Lat: 59.3880
	GPS type:	Jupiter TU30-D400-021
	GPS antenna type:	Magnetfoot
	Antenna position:	Long: 17.5640 Lat: 59.3880
	Settings:	
	Frequency T_x:	136,950 MHz and 136,975 MHz
	Power T_x:	30 dBm
	Frequency R_{x1}:	136,825 MHz
	Frequency R_{x2}:	136,950 MHz
Logging equipment 1		
(Aircraft)	Data to log:	RTK GPS
	Computer:	N/A
	Computer OS:	N/A
	Software:	N/A
	Software developer:	N/A
	Logging rate:	0.1 s
Logging equipment 2:		
(TIS-B Server)	Data to log:	TIS-B (ASTERIX)
	Computer OS:	Windows NT
	Software:	LogUDP
	Software developer:	AerotechTelub

Logging equipment 3:

Data to log: TIS-B (VIP)
Computer: Compaq EVO N610c
Computer OS: Windows 2000
Software: DumpVIP
Software developer: CNS Systems

Test procedure

The test procedure involves a flight within the Terminal Area.

Checklist	
Start recording of TIS-B data in ASTERIX format using LogUDP.	☐
Start recording of TIS-B data in VIP format using DumpVIP	☐
Start recording of RTK data in the aircraft	☐
Start flight test	☐

Appendix 5 – Slot allocation calculations

The following expression has been used to represent a TIS-B report with n targets:
Filling and synchronisation message size + management message size + target$_1$ message size + target$_2$ message size +…. + target$_n$ message size = Total number of bits for the TIS-B report (Number of targets in the report, Number of slots needed for the report)

The TIS-B burst representation for a burst containing a management message and 5 targets, two with flight ID and three without, is represented in this way:
144+204+153+104+104+153+104= 966 bits (5 targets, 4 slots)

Experiment 1
1: 144+204+153+104+104+153+104+104+153+104+104=1431 bits (9 targets, 6 slots)
2: 144+153+104+104+153+104=618 (5 targets, 3 slots)
3: 144+104+153+104+104 = 609 (4 targets, 3 slots)
4: 144+153=297 (1 target, 2 slots)
5: 144+104+104= 352 (2 targets, 2 slots)
6: 144+153+104+104+153+104+104+153+104+104=1227 (9 targets, 5 slots)

Experiment 2
1: 144+204+153+104+104+153+104= 966 bits (5 targets, 4 slots) **Rest 4**
2: 144+104+153+104+104+153 +104+ 104 = 970 (4+3 targets, 4 slots) **Rest 2**
3: 144+153+104+104+153+104+104=866 (2+4 targets, 3 slots)
4: 144+153=297 (1 target, 2 slots)
5: 144+104+104=352 (2 targets, 2 slots)
6: 144+153+104+104+153+104+104+153=966 (7 targets, 4 slots) **Rest 2**

7: 144+204+104+104+ 153+104+104=917 (2+3 targets, 4 slots) **Rest 6**
8: 144+153+104+104+ 153+104+104+104* =970 (6 + 1 targets, 4 slots) **Rest 4**
9: 144+153+104+53+104+104+153=915 (4+2 targets, 4 slots) **Rest 2**
10: 144+104+104+153=505 (2+1 targets, 3 slots)
11: 144+104+104=352 (2 targets, 2 slots)
12: 144+153+104+104+153+104+104+104*= 970 (7 targets, 4 slots) **Rest 2**

Experiment 3
1: 144+204+153+104+104+153+104=966 (5 targets, 4 slots) **Rest 4**
2: 144+104+153+104+104+153+104+104=970 (4+3 targets, 4 slots) **Rest 2**
3: 144+153+104+104+153+104+104=866 (2+4 targets, 3 slots)
4: 144+153+104+104+153+104+104+104*=970 (7 targets, 4 slots) **Rest 8**
5: 144+153+104+153+104+104+153=915 (6 targets, 4 slots) **Rest 2+2**
6: 144+104+104+153+104+104+153+104=970 (2+2+3 targets, 4 slots) **Rest 6**

7: 144+204+104+153+104+104+153=966 (5 targets, 4 slots) **Rest 1+9**
8: 144+104+104+153+104+104+153+104=970 (1+6 targets, 4 slots) **Rest 3+5**
9: 144+104+153+104+104+153+104+104=970 (3+4 targets, 4 slots) **Rest 1+4**
10: 144+153+104+104+153+104+104+104*=970 (1+4+2 targets, 4 slots) **Rest 13**
11: 144+153+104+153+104+104+153 =915 (6 targets, 4 slots) **Rest 7+2**
12: 144+104+104+153+104+104+153+104=970 (7 targets, 4 slots) **Rest 2+9**

13: 144+204+104+153+104+104+153=966 (2+3 targets, 4 slots) **Rest 6+9**
14: 144+104+104+153+104+104+153+104=970 (6+1 targets, 4 slots) **Rest 8+5**
15: 144+104+153+104+104+153+104+104=970 (7 targets, 4 slots) **Rest 1+5+4**
16: 144+153+104+104+153+104+104+104*=970 (1+5+1 targets, 4 slots) **Rest 3+15**
17: 144+153+104+153+104+104+153=915 (3+3 targets, 4 slots) **Rest 12+2**

18: 144+104+104+153+104+104+153+104 =970 (7 targets, 4 slots) **Rest 5+2+9**

Experiment 4

1: 144+204+153+104+104=709 (3 targets, 3 slots)
2: 144+153= 297 (1 target, 2 slots)
3: 144+104+104+153+104+104+153+104=970 (7 targets, 4 slots) **Rest 9**
4: 144+104+153+104+104+153+104+104=970 (7 + 0 targets, 4 slots) **Rest 6**
5: 144+153+104+104+153+104+104+104*=970 (6 + 1 targets, 4 slots) **Rest 1**
6: 144+153+104+153+104+104=762 (1 + 4 targets, 4 slots)

Experiment 5

1: 144+204+153+104+104=709 (3 targets, 3 slots)
2: 144+153=297 (1 target, 2 slots)
3: 144+104+104+153+104+104=713 (5 targets, 3 slots) **Rest 11**
144+153+104+104+153=658 (4 targets, 3 slots) *Dynamically Allocated*
144+104+153+104+104+153=658 (4 targets, 3 slots) *Dynamically Allocated*
144+104+104+153=505 (3 targets, 3 slots) *Dynamically Allocated*
4: 144+104+104+153+104=609 (4 targets, 3 slots)
5: 144+104+153=401 (2 targets, 2 slots)
6: 144+104+104+153+104=609 (4 targets, 3 slots)

The Arlanda scenario

Static reservation of 8 slots:
1: 144+204+104=452 (1 target, 2 slots)
2: 144+104=248 (1 target, 1 slot)
3:
4: 144+153+104+104+153+104+104+153+104+104+153+104+104+153+104+104=2153 (15 targets, 8 slots)
5: 104+153=257 (1 target, 2 slots)
6:

Static reservation of 5 slots:
1: 144+204+104=452 (1 target, 2 slots)
2: 144+104=248 (1 target, 1 slot)
3:
4: 144+153+104+104+153+104+104+153+104+104=1227 (9 targets, 5 slots) **Rest 6**
5: 144+153+104+104+153+104+104+153=1019 (6+1 targets, 5 slots)
6: