Verification Report, composite cooperative surveillance

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Abstract

This document explains in detail the results of the validations of the Composite Cooperative Surveillance prototypes developed in the context of the project 15.04.02. It addresses the verification objectives and verification exercises applicable to NATS, Indra and DFS platforms and compiles the results and analysis of those validations.

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This deliverable consists of SJU foreground.

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Executive summary

This document analyses the results of the exercises performed during the Verification activities for the Composite Cooperative ADS-B/WAM prototypes under study in the context of the 15.04.02 project.

A high level description of the verification activities were performed in the different platforms (NATS-CRISTAL, INDRA and DFS) and their schedules were also included in deliverable 15.04.02 D10 Technical Report, Composite cooperative surveillance trials (Ref. [10]) After that, the document lists the global verification results, as well as conclusions and recommendations for each verification exercise.

Consequently, this report aims to describe more in detail the results given in that previous document and study the conclusions and recommendations for further development of the composite cooperative surveillance systems.

The low-level requirements of the validation exercises are the ones defined in the deliverable 15.04.02 D08 Technical report, Composite Cooperative Surveillance prototype (Ref. [8]) of the project 15.04.02. Verification objectives and test exercises that are validated in D10 and D11 were defined in the 15.04.02 D09 Verification Plan, Composite cooperative surveillance (Ref. [9]).

1 Introduction

1.1 Purpose of the document

The purpose of this document is to provide detailed results of the Verification Plan and Technical Report applicable to Composite Cooperative Surveillance System prototypes (NATS, INDRA and DFS platforms) under study in the context of the project P15.04.02.

It analyses the result of the verification activities defined in the D10 Technical Report (Ref. [10])

1.2 Intended readership

The audience of this document includes:

- ANSPs
- Project 15.01.06 Spectrum Management & Impact Assessment members
- Project 15.01.07 CNS System of System definition and roadmap project members
- Project 15.04.02 Integrated Surveillance sensor technologies project members
- Projects 15.04.05a and 15.04.05b Surveillance ground system enhancements for ADS-B members
- Project 15.04.06 Improved 1090MHz ADS-B Ground station capacity and security members
- Standardization bodies (EUROCAE WG51SG4 and others)

1.3 Structure of the document

This document is divided into six chapters:

Chapter 1 Is the introduction of the document.

Chapter 2 Provides the context of the NATS-CRISTAL, Indra and DFS systems introducing them in terms of validation platform and coverage.

Chapter 3 Describes on high level the verification activities performed for the different platforms

Chapter 4 Explains the verification results and findings for the different verifications and validations.

Chapter 5 Lists conclusions and recommendations that have been raised after the execution of the verification and validation activities.

Chapter 6 Lists the particular applicable and reference documents.

1.4 Glossary of terms

A common understanding of the definitions of the following terms as applied in the context of this document is considered necessary:

- WAM system: Wide Area Multilateration System.
- Multilateration System: One method of locating an aircraft using the transponder signal is multilateration. In this technique, the transponder signal from the aircraft is received at multiple receivers at known locations. The signal arrives at the receivers at different times due to the different separation distances from the target. The TDOA can be calculated in a number of different ways, including cross-correlation of captured waveforms and differences between absolute Time of Arrival (TOA) measurements, and forms the basis of the

multilateration technique. (Note that in Multilateration System which uses active Interrogation, this so-called 'time-hyperbolic method' can also be augmented by other techniques).

A *Multilateration System* is any group of equipment configured to provide position and identification derived from target-transmitted signals using Time Difference of Arrival (*TDOA*) techniques.

- ADS-B: Automatic Dependent Surveillance – Broadcast (ADS-B) is a means by which aircraft, aerodrome vehicles and other objects automatically transmit and/or receive identification, position, velocity and additional data in a broadcast mode via a data link
- Composite Surveillance System: A Composite Surveillance system is also, more correctly, known as a Composite (ADS-B and WAM) Surveillance System.
- Composite (ADS-B and WAM) Surveillance System: A surveillance system which exploits the synergies between two similar but different surveillance techniques – ADS-B and WAM. In their standalone form they are both distributed cooperative surveillance systems. The term composite is used to signify that various system components, physical and logical, are shared. Shared information from WAM and ADS-B processing is used to supplement the basic levels of performance that are to be achieved by each system in their standalone mode in particular with respect to reducing WAM active interrogation rates, providing additional confidence information on ADS-B horizontal position information (including spoofing) and enhancing overall data continuity performance. For the aim of this project, the Composite Surveillance system is composed by a Composite Surveillance Sensor and a Multi sensor Tracker.
- Composite Surveillance Sensor: Surveillance elements that provide ADS-B, WAM and composite data flows.
- Multi Sensor Tracker: Central fusion node for the processing of the surveillance data.
- Ranging: Technique used in multilateration systems to determine the distance of a target to one or more transmitting elements.
- Partial position: In the scope of this document is defined as the points of the space for which their distance difference (and consequently the time difference of arrival (TDOA)) to two receivers is lower than a fixed value. This defines a number of hyperbolas on which the position is contained. Predicted Position: A position obtained from an extrapolation process when operating in periodic mode such that output data generated on each output period is applicable at the time of output. Two types are considered:
    - Smoothed Periodic Predicted Mode based on previous position detections of several output periods.
    - Consolidated Periodic Predicted Mode is based on previous position detections within the most recent output period.
- Pre-tracked Data: Data derived from a 'measurement' or a plot derived directly from 'measured' data i.e. not tracked, smoothed or predicted output at a periodic rate or data driven time-stamped with the time of applicability of the 'measurement'.
- Tracked data: Pre-tracked data that has had a supplementary tracking processing stage applied to it to obtain a predicted position.

1.5 Acronyms and Terminology

Term	Definition
ADD	Aircraft Derived Data
ADS-B	Automatic Dependent Surveillance - Broadcast

Term	Definition
AG	Air-Ground
ANSP	Air Navigation Service Provider
ARTAS	ATM suRveillance Tracker And Server
ASTERIX	All Purpose Structured EUROCONTROL Surveillance Information Exchange
ATC	Air Traffic Control
ATM	Air Traffic Management
BAR	Barometric Altitude Rate
BDS	Comm-B Data Selector
BVR	Barometric Vertical Rate
CASCADE	Co-operative ATS through Surveillance and Communication Applications Deployed in ECAC
CAT	Category
CAV	Coverage Assessment Volume
CMS	Control and Monitoring System (includes Remote Control and Monitoring)
CNS	Communications, Navigation & Surveillance
CPS	Centralized Processor System
CRISTAL	Co-operative Validation of Surveillance Techniques and Applications of Package I
DAP	Downlinked Aircraft Parameter
DF	Downlink Format
DFS	Deutsche Flugsicherung
DOD	Detailed Operational Description
DOP	Dilution of Precision
E-ATMS	European Air Traffic Management System
E-OCVM	European Operational Concept Validation Methodology
ETP	Expected Theoretical Precision
FMS_SFL	Flight Management System Selected Flight Level
FRUIT	False Replies Unsynchronized with Interrogator Transmissions

Term	Definition
GEN SUR SPR	Generic Surveillance Safety and Performance Requirements
GVA	Geometric Vertical Accuracy
IBP	Industrial Based Platform
ICAO	International Civil Aviation Organisation
INCS	Independent Non-Cooperative Surveillance
INTEROP	Interoperability Requirements
IRS	Interface Requirements Specification
LSB	Least Significant Bit
MCP_SFL	Mode Control Panel Selected Flight Level
MLAT	Multi-lateration
MRT	Multi-Radar Tracker
MSDF	Multi-Sensor Data Fusion
MSPSR	Mutli-Static Primary Surveillance Radar
MST	Multi-Sensor Tracker
MTBCF	Mean Time Between Critical Failure
MTTR	Mean Time To Repair
NACp	Navigation Accuracy Category - Position
NACv	Navigation Accuracy Category - Velocity
NATS	National Air Traffic Services
NIC	Navigation Integrity Category
NICbaro	Navigation Integrity Category - Barometric
NM	Nautical Mile (1852 metres)
NSA	National Supervisory Authority
NUCp	Navigation Uncertainty Category - Position
NUCr	Navigation Uncertainty Category - Velocity
OFA	Operational Focus Areas
OSED	Operational Service and Environment Definition

Term	Definition
PD	Probability of Detection
PIC	Position Integrity Category
PSR	Primary Surveillance Radar
RAI	Range from Active Interrogation
RF	Radio Frequency
RRRS	Radar Record and Replay System
Rx	Receiver
SDA	System Design Assurance
SESAR	Single European Sky ATM Research Programme
SESAR Programme	The programme which defines the Research and Development activities and Projects for the SJU
SIL	Source Integrity Level
SILsupp	Source Integrity Level supplement
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SJU Work Programme	The programme which addresses all activities of the SESAR Joint Undertaking Agency.
SPR	Safety and Performance Requirements
SSR	Secondary Surveillance Radar
SUT	System Under Test
TAD	Technical Architecture Description
TDOA	Time Difference of Arrival
TMA	Terminal Manoeuvring Area
TRL	Technology Readiness Level
TS	Technical Specification
Tx	Transmitter
TXU	Transmitting Unit
VALP	Validation Plan
VALR	Validation Report

Term	Definition
VALS	Validation Strategy
VLD	Very Large Scale Demonstration
VP	Verification Plan
VR	Verification Report
VS	Verification Strategy
WAM	Wide Area Multilateration
WGS84	World Geodetic System 84

2 Context of the Verification

2.1 The composite surveillance

Air traffic surveillance systems use both cooperative and non-cooperative techniques to locate aircraft. While non-cooperative techniques rely on the reflection of energy directed at the aircraft, cooperative techniques require the carriage of a transponder or transmitter device on board the aircraft. Systems using the signals broadcast from such transponders / transmitters are classified as a dependant technology, as the ground surveillance systems derive all surveillance information from the decoded message content to determine aircraft identity and 3D position.

The table below summarises the categories that the various existing and new ground-based air traffic Surveillance sensors fall into:

		Air traffic surveillance sensor
Independent Non cooperative		Primary Surveillance Radar (PSR) Multi-Static Primary Surveillance Radar (MSPSR) (Under development)
Cooperative	Independent	Secondary Surveillance Radar (SSR) (Mode A/C and Mode S) Wide Area Multilateration (WAM) system MultiLATeration (MLAT) system
	Dependent	Automatic Dependent Surveillance Broadcast (ADS-B)

Figure 1: Categories of air traffic surveillance sensors

SSR, ADS-B (Automatic Dependent Surveillance – Broadcast) and WAM (Wide Area Multilateration) systems are ‘Cooperative Surveillance Systems’, as they are reliant on signals broadcast from aircraft transmitters/transponders.

A Composite ADS-B and WAM Surveillance System is a surveillance system that exploits the similarities between the two surveillance techniques and combines them into a single system. The term composite is used to signify that various system components and data items are shared whilst ensuring that the required degree of channel autonomy/independence is retained.

2.2 Benefits offered by Composite (ADS-B and WAM) Surveillance

A Composite ADS-B and WAM Surveillance System is a surveillance system which is designed to exploit the synergies between two similar but different surveillance techniques – ADS-B and WAM.

In addition to cost savings, achieved through the co-mounting of system components into a single unit and the associated savings in terms of site costs, communications and efficient utilization of certain common components, the exploitation of synergies between the two surveillance techniques also supports a number of performance enhancements. These include:

- Use of ADS-B message information (excluding position) in the WAM system to support a reduction in the 1030 and 1090 MHz usage by the WAM components:
  - The use of ADS-B data to support passive acquisition of an aircraft reduces the 1030/1090 MHz footprint of a WAM surveillance system.
  - The commonality between aircraft derived parameters[1] that are available within an aircraft's ADS-B and Mode S transmission supports a reduction in the number of 1030 MHz interrogations made by the WAM surveillance channel.
  - Through the techniques described in the two bullet points above the performance of the WAM Surveillance Channel is enhanced from a 1030 MHz RF perspective. Of significant importance is the fact that overall ATM system performance is improved through reduced transponder occupancy and the consequent benefits this brings.
- The availability of 'raw' RF and timing data within the Composite Surveillance System provides information that is not available in other components of a surveillance infrastructure or in standard ADS-B receivers. The information can be used to derive additional indicators:
  - Ground based 'confidence/credibility' measure of the positional information contained within an aircraft's ADS-B messages based upon the timing data present in the system and derived through an analysis of the time at which ADS-B signals were received at 2 or more time synchronized receivers. Whilst this could be of particular interest during the transition to an ADS-B operational environment it also offers the potential of providing longer term benefits such as the early identification of anomalous avionic behaviour.
  - The credibility assessment can also provide a means to identify spoofed 'ADS-B transmissions' that have been maliciously introduced into the RF environment. This can be based upon the mechanism described above although the reception of an ADS-B signal at only 1 receiver when line of sight was expected from multiple sites can also provide a credibility indication.
  - The availability of additional data within the system can also be used to support optional means to provide additional security mitigation techniques in a cost effective manner - although these are currently considered as beyond the scope of this technical specification.
- A comparison of ADS-B and WAM data can be used to:
  - Support the initial tuning and commissioning of the WAM system.
  - Monitoring: by improving (long term) performance monitoring and alerting of faults in the WAM system. This includes supplementing the WAM channels BITE by using the comparison between the ADS-B position and WAM channel data (particularly concerning expected antenna coverage and time difference of arrival) to alert in the event of timing drift or component failure. For example, if a discrepancy is only apparent in part of the WAM coverage, then it is likely that it is due to a WAM failure condition.
- To improve the performance of the ADS-B channel:
  - By enabling the allowance of temporary (i.e. short- to medium-duration) reductions in ADS-B quality indicator values, in particular regarding the measurement integrity NIC bound. These temporary reductions would be mitigated by the establishment of an ADS / WAM cross-integrity containment bound that can be associated with the ADS-B data. It is to be noted that a failure in the ADS-B / WAM cross-integrity comparison indication does not take precedence over the ADS-B measurement integrity information (as it might be the WAM channel that is in failure);

[1] For consistency the term Aircraft Derived Data (ADD) is used within this document. This embraces the ADD broadcast within an ADS-B configuration and also the Downlinked Aircraft Parameters (DAPs) – a term used to denote the information extracted from BDS registers through Mode S Enhanced Surveillance (EHS)

- by resolving ADS-B data-to-track association issues related to non-unique 24-bit addresses;
- by calculating the (mean) ADS-B uncompensated latency that is induced on-board on the ADS-B horizontal position, i.e. in order to reduce the effects on the resulting along-track horizontal position error;

- Safety: by identifying incorrect ADS-B measurement integrity indications (i.e. under failed ADS-B / WAM comparison conditions);
- Security: by identifying spoofed ADS-B targets;
- Monitoring: by supporting the detection of ADS-B avionics anomalies, likely to be indicated by ADS-B / WAM comparison failure conditions sustained over a longer period.
- To keep the electromagnetic interferences as low as possible and to limit the transponder occupancy caused by a WAM system, the WAM part of the composite system may only be used for verification purposes for the position as well as secondary attributes. For the secondary attributes, especially the barometric altitude, which is of much more criticality than e.g. the callsign-in-flight, can be confirmed in a similar manner as if a rotating sensor would be present. For a single transceiver unit it is not possible to confirm the complete horizontal position, but proper ranging can be conducted. Even low interrogation rates as one interrogation per minute or two appear to be sufficient for this validation purpose. In this almost passive configuration the performance is achieved by ADS-B, the WAM system has a validation task to fulfil.

2.3 Maturity of the developed system

In the initial scope of this project, the aim is to study the feasibility of composite surveillance and the use of different validation methods to increase security, reduce spectrum load and increase the system performances. Indra upgraded their ADS-B or WAM systems with composite functionalities. In addition, different composite systems have been defined for each of the validation platforms. Project member NATS utilised their 'CRISTAL' ADS-B and WAM system to collate and analyse a large dataset of real world ADS-B data from a high-density environment to further assess the viability of the composite system concept.

This evolution of systems is in line with the EATM masterplan and with the surveillance roadmap and TAD defined by 15.01.07 CNS federating project in their documents. Please see references [11] and [12].

The following table identifies for each of the ATM Masterplan technologies in which the WP15.04.02 project is involved, the key deliverables and the continuation in SESAR2020.

ATM Master Plan technology	WP15 SUR Project(s)	WP15 SUR Projects Key Deliverables	Continuation in SESAR 2020
Ground Based Composite WAM/ADS-B	▪ 15.04.02	• Products • Technology validation • Requirements • Technical specifications (to feed EUROCAE Working Groups) • Interface definitions	Yes, PJ14-04-03. Security, composite surveillance

Ground Based Multi Static Primary Surveillance Radar	▪ 15.04.02	• Technology validation • Technical specifications (to feed EUROCAE Working Groups)	Yes, PJ14-04-03. INCS, Composite surveillance…
Ground Based Rationalisation of conventional surveillance infrastructure	▪ 15.04.02 ▪ 15.04.05 ▪ 15.04.06 ▪ 15.04.03	• Feasibility • Road mapping • Requirements	Yes, PJ14 solutions 14-01-01 & 14-01-03

Table 1: WP15.04.02 project main technologies delivered

In addition, the following table summarizes the status of the ATM Masterplan SUR related enablers addressed in the WP15.04.02 project and the maturity assessment of the technology at the end of SESAR1.

Code	Name	WP contribution	Maturity at WP start	Maturity at WP end
CTE-S02c	Multi Static Primary Surveillance Radar	Establishment of design targets for the performance parameters that multi-static independent non-cooperative surveillance (INCS) systems are to meet to ensure such systems are capable of addressing emerging performance requirements and supporting future ATC operations. Definition of the Operational Service and Environment Definition for the application(s), which were determined to place demanding requirements upon such systems. Identification of capabilities, such as the means to be able to provide an indication of the height a non-cooperative target is flying at. Definition of standards, including the ASTERIX format. Implementation of new functionalities.	TRL 1	TRL 3
CTE-S06	Composite WAM/ADS-B	Creation of specifications for the Composite Cooperative Surveillance System (WAM/ADS-B). Definition of requirements derived from different standards and guidance material, including ED-142 and ED-129 and provision of feedback for new EUROCAE versions. Study on benefits offered by composite surveillance, such as: Reduction in the 1030 and 1090 MHz spectrum, information provision not available without composite surveillance and several improvements in performance, security and safety. Definition of system objectives and test exercises in order Validate & verify system operation.	TRL 1	TRL 5

Table 2: WP15.04.02 project – ATM Masterplan new related enablers

As can be seen, the level of maturity is not based on E-OCVM levels (V3, V4, V5...) due to the difficulty of measuring. Instead, the SJU proposed at WPL21 to use Technology Readiness Levels (TRL) instead of the E-OCVM for assessing the maturity of System Enablers. This proposal was agreed and the Action WPL21/A3 & WPL22/A1 objective was to provide a checklist that can help determining the progress in terms of maturity of SESAR technological solutions (e.g. CNS enablers).

The principles of the maturity based on TRL can be summarized in the following points.

- TRL criteria shall take into consideration:
  - the maturity of the SESAR Technological solution itself;
  - the "maturity" of the environment in which the SESAR Technological solution (system enabler) is verified e.g. laboratory, IBP, ...
- Key maturity transitions considered so far are: End of TRL-2 (V1), End of TRL-4 (V2) & End of TRL-6 (V3)
- TRL-7 / V4 not included at this stage but it is required to be considered in further evolutions:
  - Link to Very Large Scale Demonstrations VLDs in SESAR 2020 i.e. Proof of Concept. They require a first industrialization process at "proof of concept certification" level.

E-OCVM and TRL maturity levels can be mapped, even if not covering either the same scope or the same objective. In the Part 19 of European Commission Decision C (2014)4995 of 22 July 2014 (Horizon 2020 Work Programme 2014-2015) can be found a short definition of the different TRL levels:

TRL	TRL Definition	Equivalent in E-OCVM	Detailed information
TRL-1	Basic principles observed		
TRL-2	Technology concept formulated	V1	• Initial description available (basic architecture, major functions, interfaces) • Mock-up / analytical tools are developed/used for simulation or analysis of the solution • Paper/analytical/modeling/simulation studies
TRL-3	Experimental proof of concept		
TRL-4	Technology validated in lab	V2	• Technical feasibility in a laboratory environment • Stand alone Prototyping & Laboratory Tests

TRL	TRL Definition	Equivalent in E-OCVM	Detailed information
			• Initial definition of functional and performance requirements / contribution to standards
TRL-5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)		
TRL-6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	V3	• Technical feasibility in a Industrial Based Platform (IBP) e.g. integrated with other solutions • Prototype & Live Trials on IBP (relevant end-to-end environment). • Final definition of requirements / contribution to standards
TRL-7	System prototype demonstration in operational environment	V4 (VLD)	
TRL-8	System complete and qualified		
TRL-9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)		

Table 3: TRL levels definition

2.4 NATS – CRISTAL, Description of System

To undertake the verification and validation activities exploring the potential for a combined WAM and ADS-B system to offer 3NM separation services in High Density airspace within the CASCADE CRISTAL RAD HD project; a Thales Air Systems Wide Area Multilateration Air/ground Surveillance System (MAGS) was installed to provide coverage over the London Terminal Manoeuvring Area (LTMA).

The receiver / interrogator configuration of the CRISTAL system was modified from the base configuration used within the CRISTAL RAD HD project validation activities.

The modification made under the auspices of project 15.04.02 included:

- The re-installation of a previously decommissioned receiver at a new site to the North West of cluster to provide additional coverage and improved WAM DOP,
- The redeployment of the interrogator from a site with a sectorial antenna to an omni antenna to facilitate range aided multilateration testing.
- The deployment of a new receiver to the South West of the cluster, to improve low level coverage and improve the WAM DOP through an improved geometry of contributing receiver solutions.

These modifications were mainly implemented to improve the DOP of the WAM system and improvement of the low level coverage within the LTMA. Furthermore the redeployment of the interrogator was undertaken to facilitate the assessment of range aided mulitlateration to extend the volume of coverage, which would not have been possible with the directed sectorial antenna of the base configuration.

It should be noted that the CRISTAL WAM system is primarily passive, relying on replies to 1030MHz solicitation by other interrogators, as well as ADS-B messages. Where aircraft are within coverage of the sole interrogator, the system will utilise its own interrogations to obtain, identity, Mode C and Mode S DAP registers BDS 4,0, 5,0 and 6,0.

The list below provides details of the receiver locations and different antenna types that formed the CRISTAL RAD HD ADS-B/WAM network:

- Chedburgh; 6dBi omni antenna Rx,
- Greenford; 6dBi omni antenna Rx,
- Reigate; 6dBi omni antenna Rx,
- Ventnor; 12.65dBi diffused sector antenna Rx ,
- Winstone; 16.25dBi non-diffused sector antenna, Rx
- Daventry: 6dBi omni antenna Rx /Tx (200 W).
- Swingfield: 6dBi omni antenna Rx

These receivers should provide the following coverage at 1500ft ARP as show in Figure 2

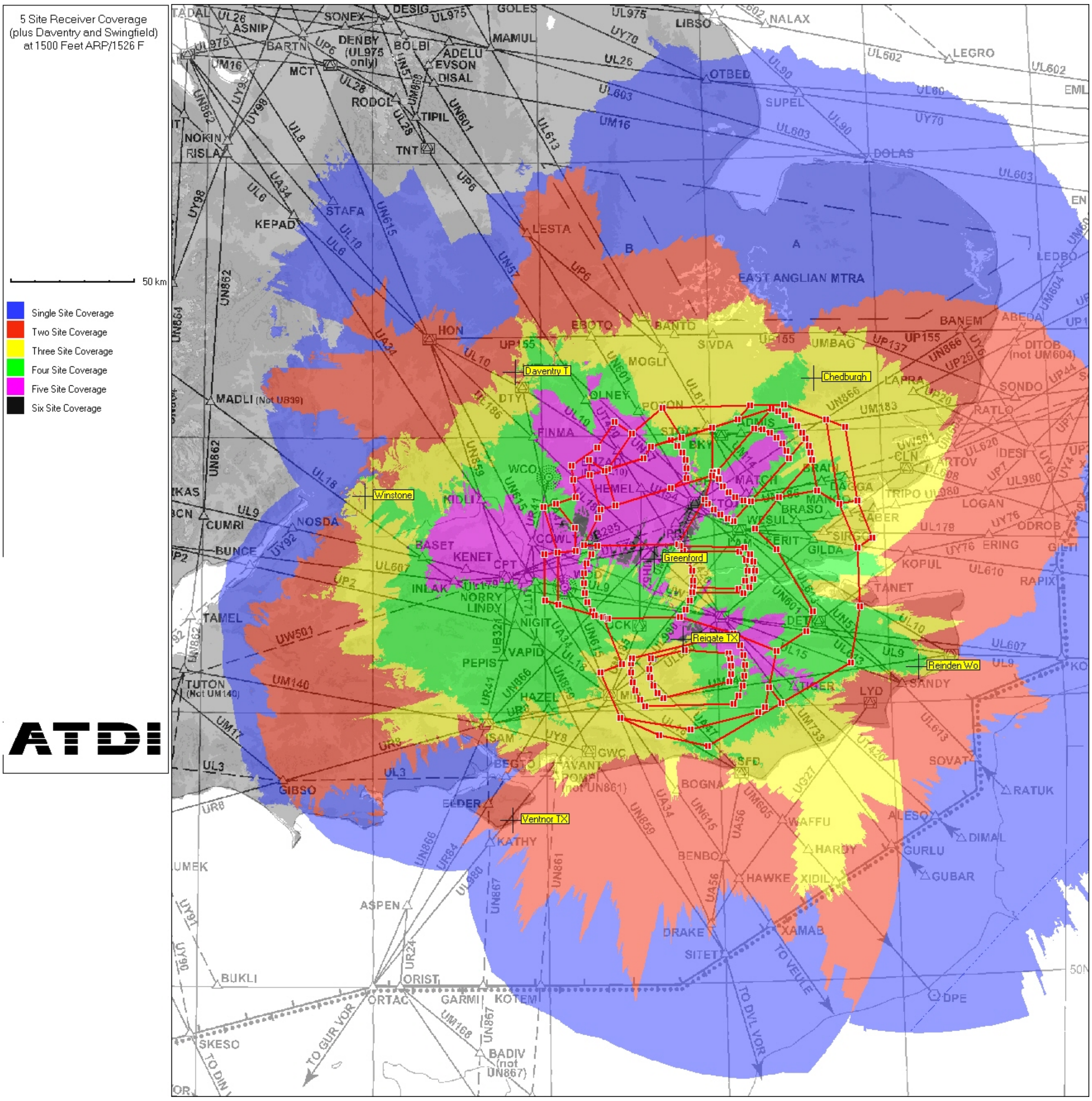

Figure 2: Theoretical coverage of CRISTAL ADS-B at 1500ft ARP / 2026 AMSL

Overall the modified ground station configuration for the system under test provided a high altitude footprint (at high altitude) of 150 x 170 NM, centred on the London TMA.

The analysis of the data collected by the CRISTAL ADS-B and WAM system will also utilise NATS MRT Mode S based radar data source to provide a baseline for use in the SASS-C analysis tool. A high level dataflow of the NATS validation platform is shown below in figure Figure 3.

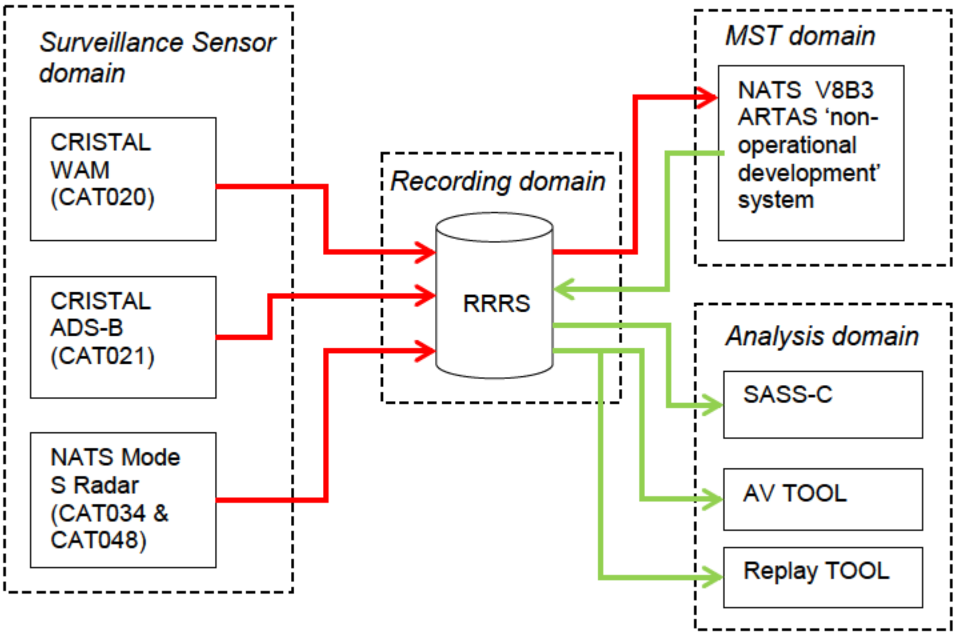

Figure 3: High-level components and data flow of NATS Validation Platform

It should be noted and as described in the deviations section of D10 [10] that the MST assessment aspect of the project using ARTAS V8B3 was not conducted.

2.5 Indra INDRA, Description of System

To evaluate the performances and behaviour of a composite WAM-ADSB surveillance system, an Indra WAM Surveillance System was installed to provide coverage over the Madrid (TMA). Indra installed five receiver stations, one of them with interrogation capability. For the deployment of the stations, the criterion of selection of the sites was performed according to the availability of Indra buildings in the Area. In many cases, locations are not optimal by Line of Sight, or for DOP calculations, but this will help to evaluate the improvements provided by a Composite system against a standard WAM system.

The main characteristics of the system are:

- System composed by 5 WAM-ADSB receivers
- System footprint size around 8x25Nm at Indra facilities
- Active WAM system, but passive operation will be under study.
- Central processor & CMS located in Torrejón
- Using Indra Company MetroLANs for communications with maximum four routing jumps (1MB bandwidth guaranteed).
- VPN over Indra network.

The list below provides details of the receiver sites; note that the deployment is installed at Indra Facilities.

- Torrejón; 5.5 dBi omni antenna Rx and 2dBi omni antenna TX(200watt),
- Edificio Triangulo - Alcobendas; 5.5dBi omni antenna Rx,
- Calle Alcalá - Madrid; 5.5dBi omni antenna Rx,
- Aranjuez; 5.5dBi omni antenna Rx ,
- San Fernando; 5.5dBi omni antenna Rx

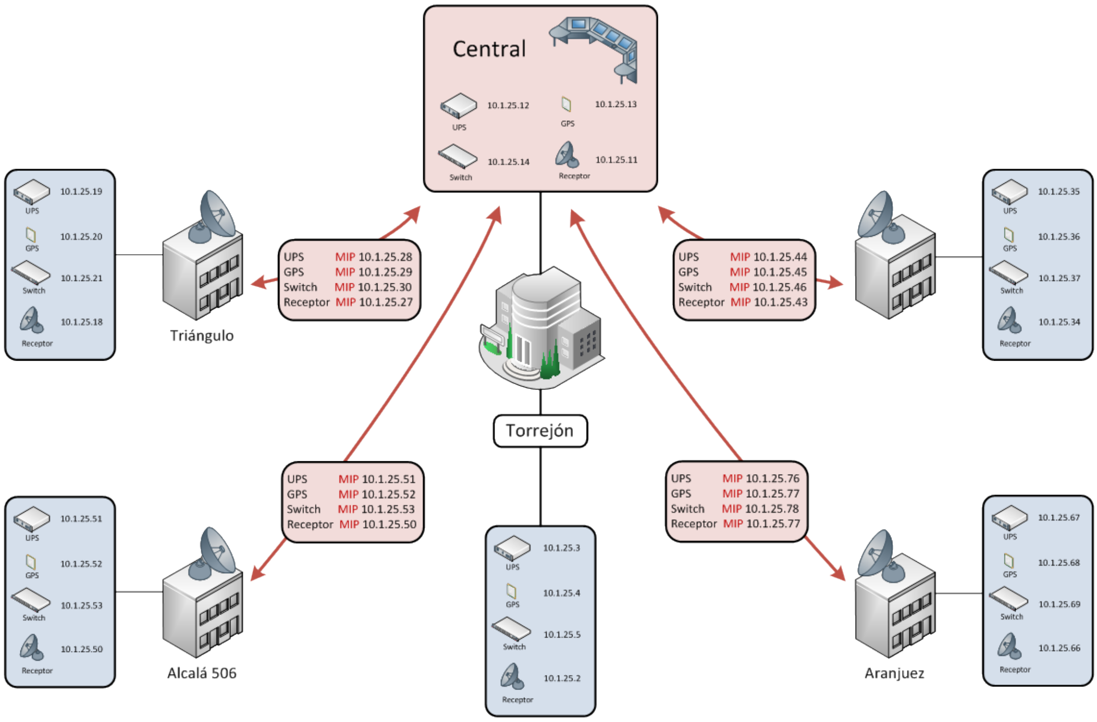

Figure 4: High level components and data flow of Indra Validation Platform

Figure 5: Location of the Receiver Stations with respect to Madrid airport

Coverage is limited by system deployment (locations are not optimal being that the sites are buildings inside Madrid Metropolitan area, except receiver 4 – Aranjuez that is about 25NM from Madrid).

- This produces some blind areas at low level, but will help to study benefits of composite surveillance. Good coverage is expected in South, West and East areas, worse at north.
- Good coverage of many sectors of the Madrid TMA
- Good coverage of en-route flights.
- Coverage overlapped with existing SSR & Mode S radars.
- Some blind spots, but will be good for data analysis with & without ADS-B information.

The following figure shows the Wide Area Multilateration coverage obtained by the five ground receivers which have been listed above:

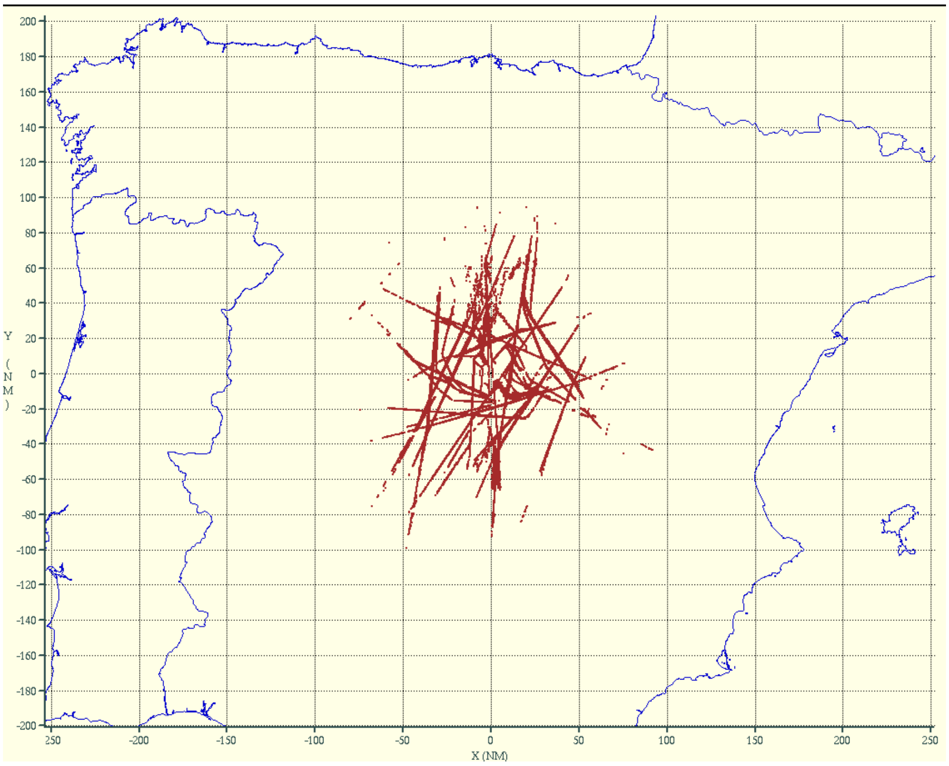

Figure 6: Real WAM Coverage of Indra Validation Platform

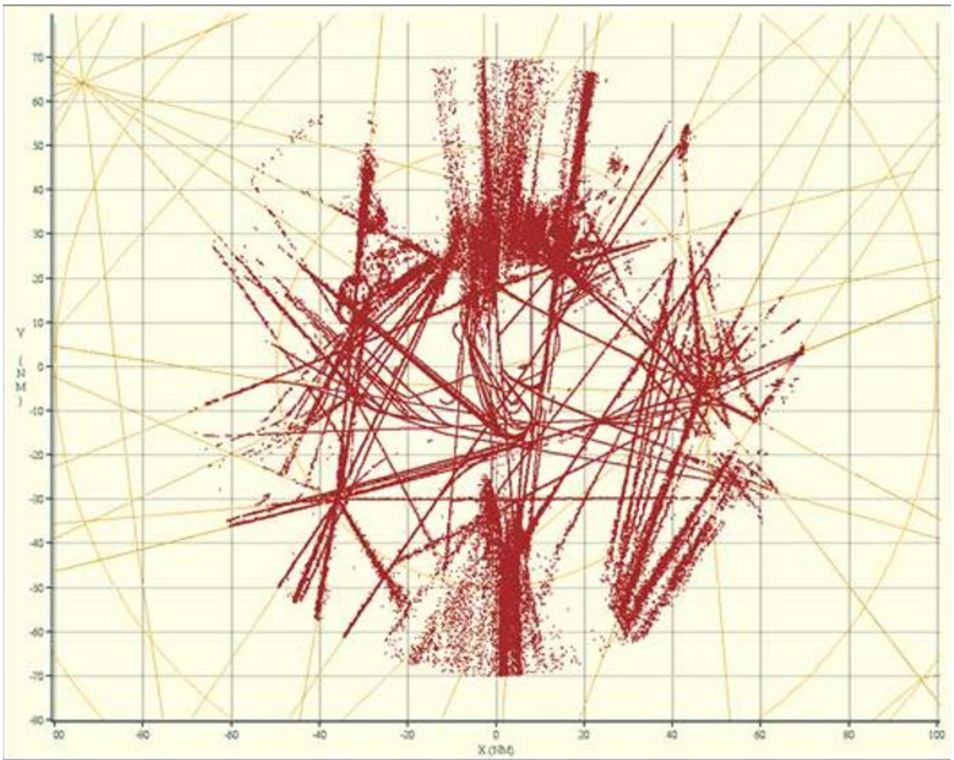

Figure 7: Real WAM Coverage of Indra Validation Platform (zoomed)

In **Figure 7** can be appreciated the effects of the system DOP shown in **Figure 8**

Due to the distribution of the receiving stations, DOP and system accuracy are not optimal (system is installed not following a DOP criteria), so evaluations have been limited to areas of good DOP. In areas of bad DOP (close to the North-South Axis), position based validations may provide incorrect results.

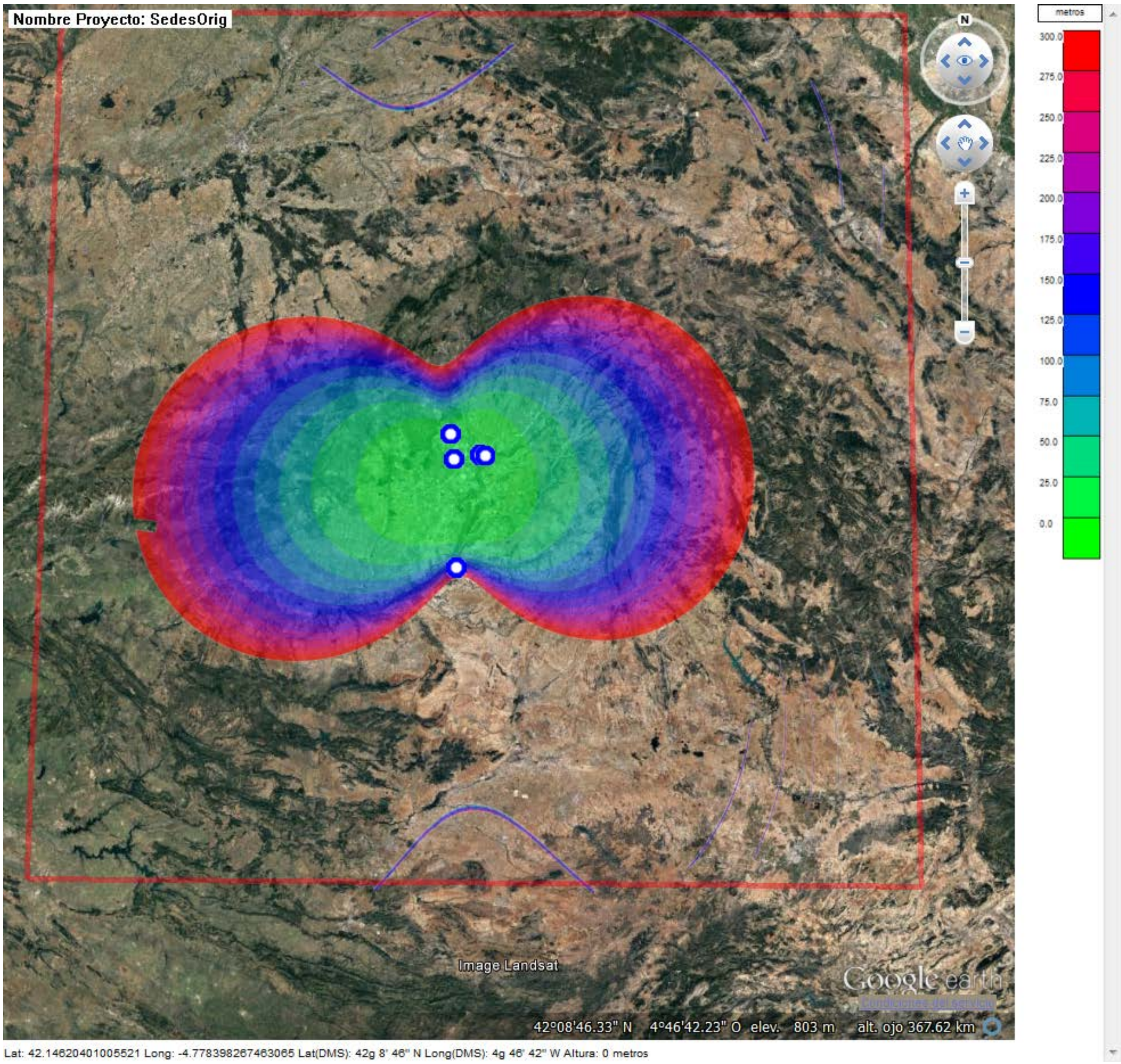

Figure 8: Calculated DOP in Indra environment

Indra verification tests have been carried out in the TMA of Madrid, one of the busiest areas of the Spanish air space.

The following pictures represent the sectors of the TMA and their upper/lower limits, the air space class, and also the danger/restricted/prohibited areas.

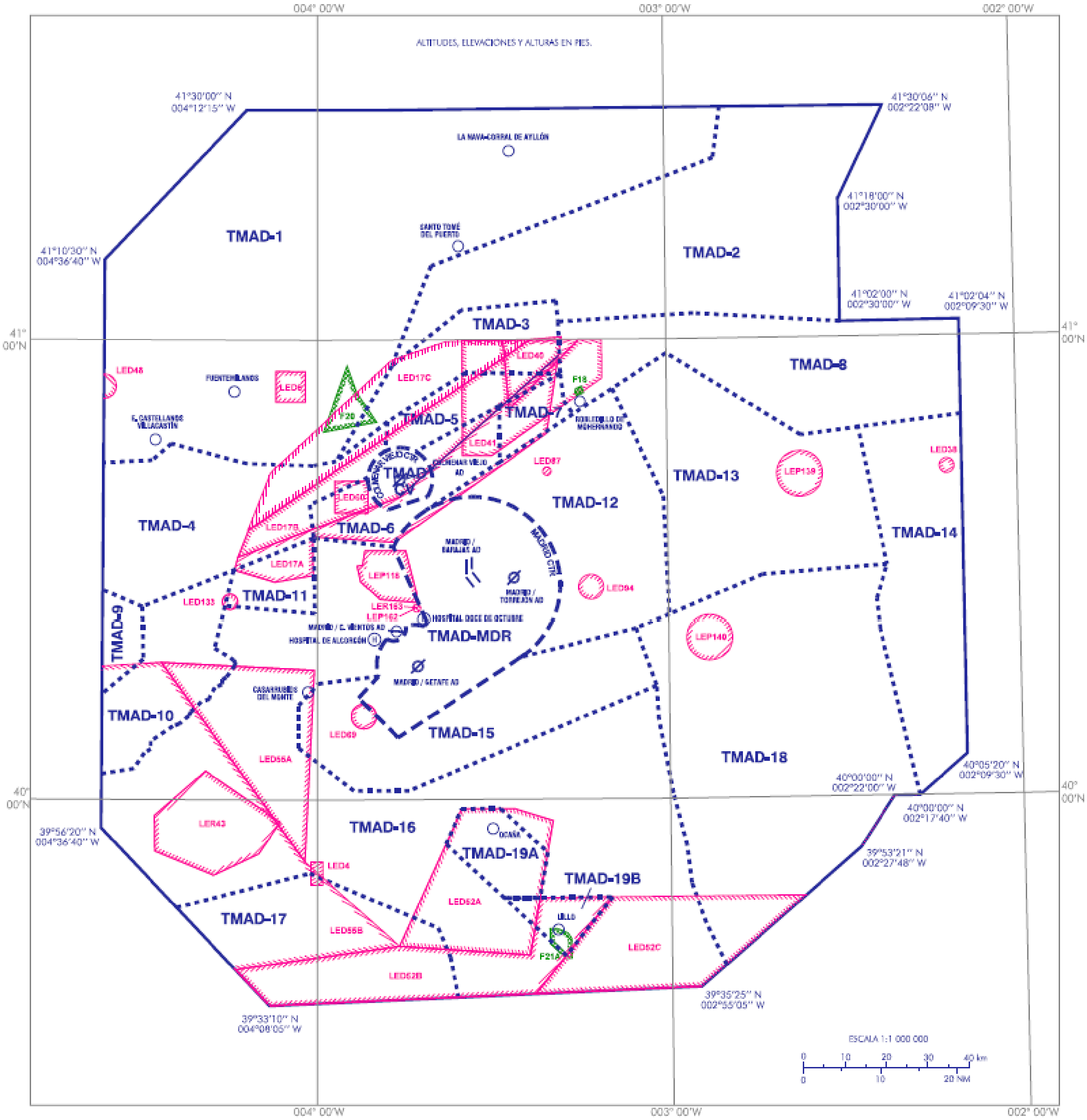

Figure 9: Madrid TMA airspace division

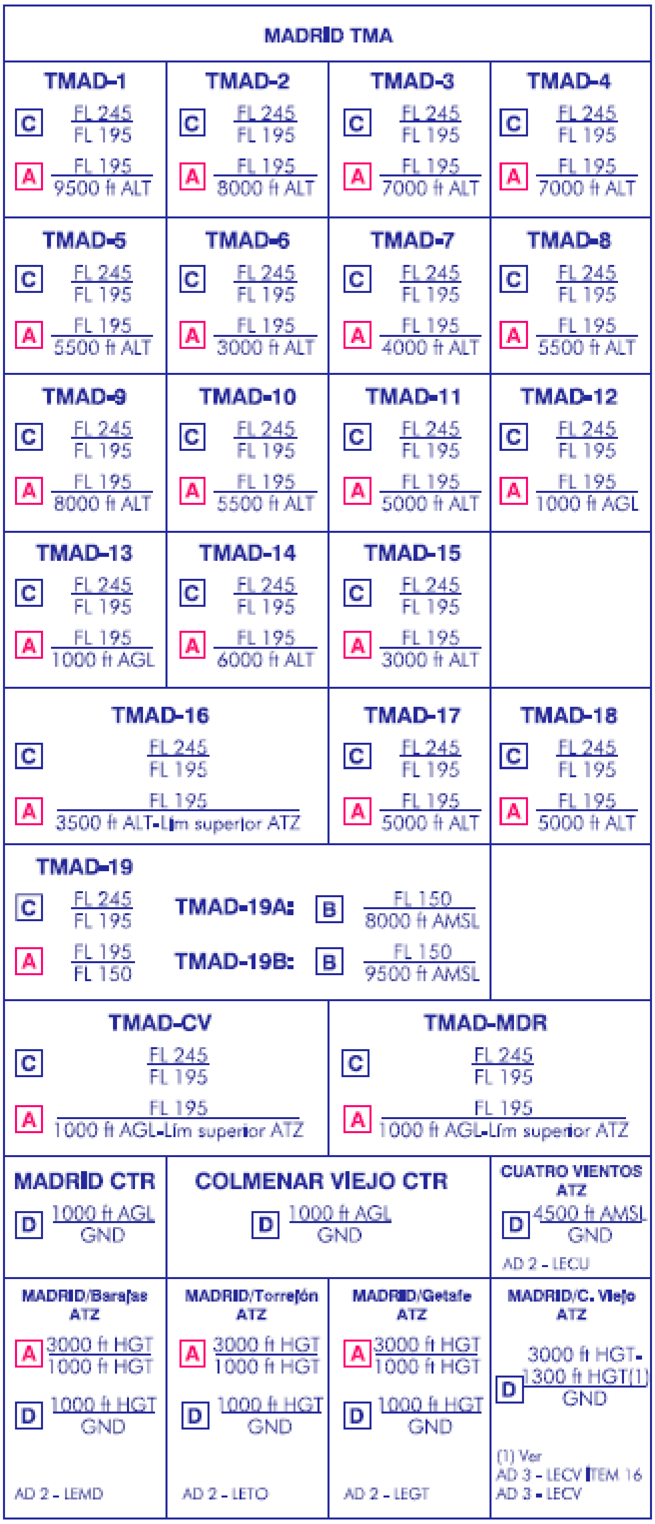

Figure 10: Madrid TMA upper and lower limits

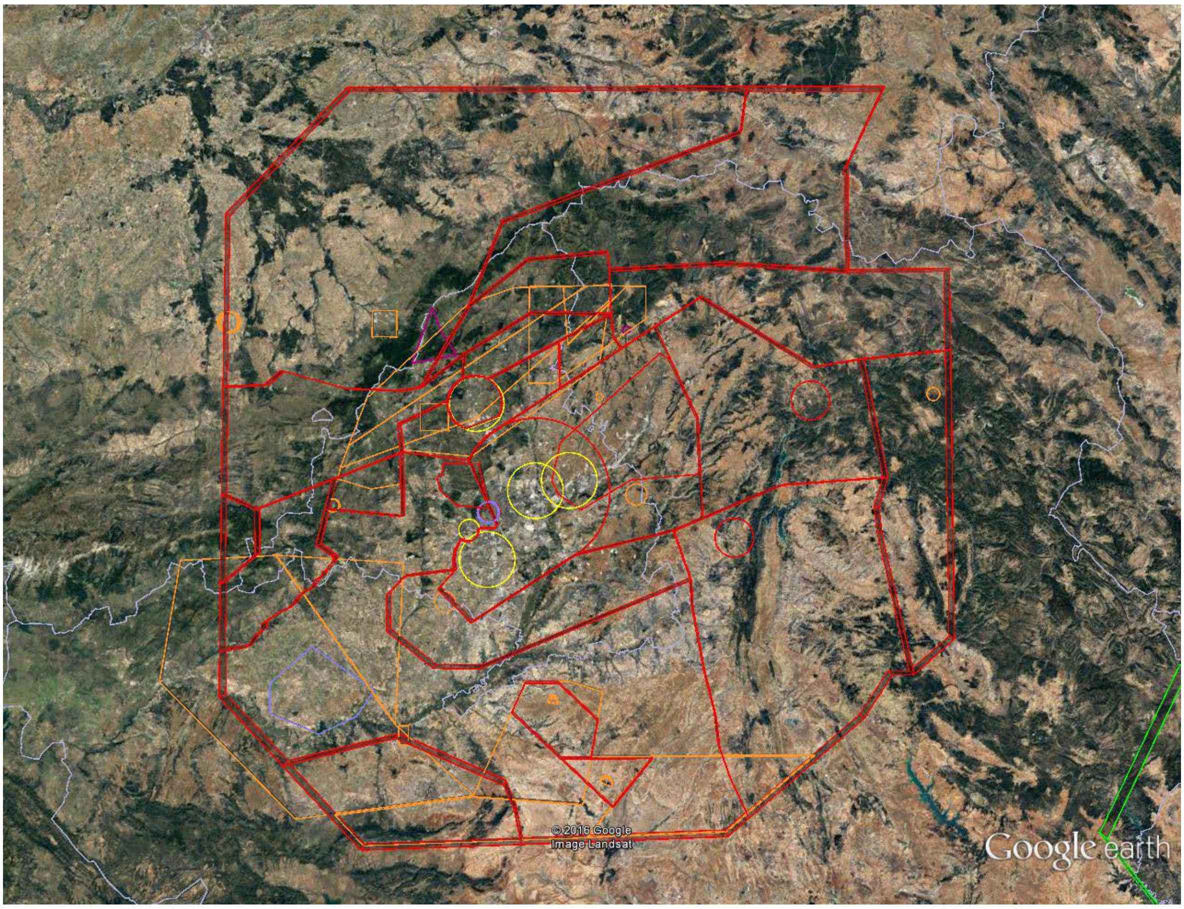

Figure 11: Madrid TMA in Google Earth

Given the location of the multilateration stations and the layout of buildings and the terrain level, the southern zone of the Adolfo Suárez Madrid-Barajas airport is the optimum multilateration area for climb, cruise and descent phases. The recorded data will be filtered to only represent the information of overflights and climbing/descending flights above a determined altitude.

In the next figure, it can be seen the Madrid TMA and the filtered area of the recorded data, a circle with a radius of 30NM and its centre slightly below the Madrid airport (the blue circle in the picture).

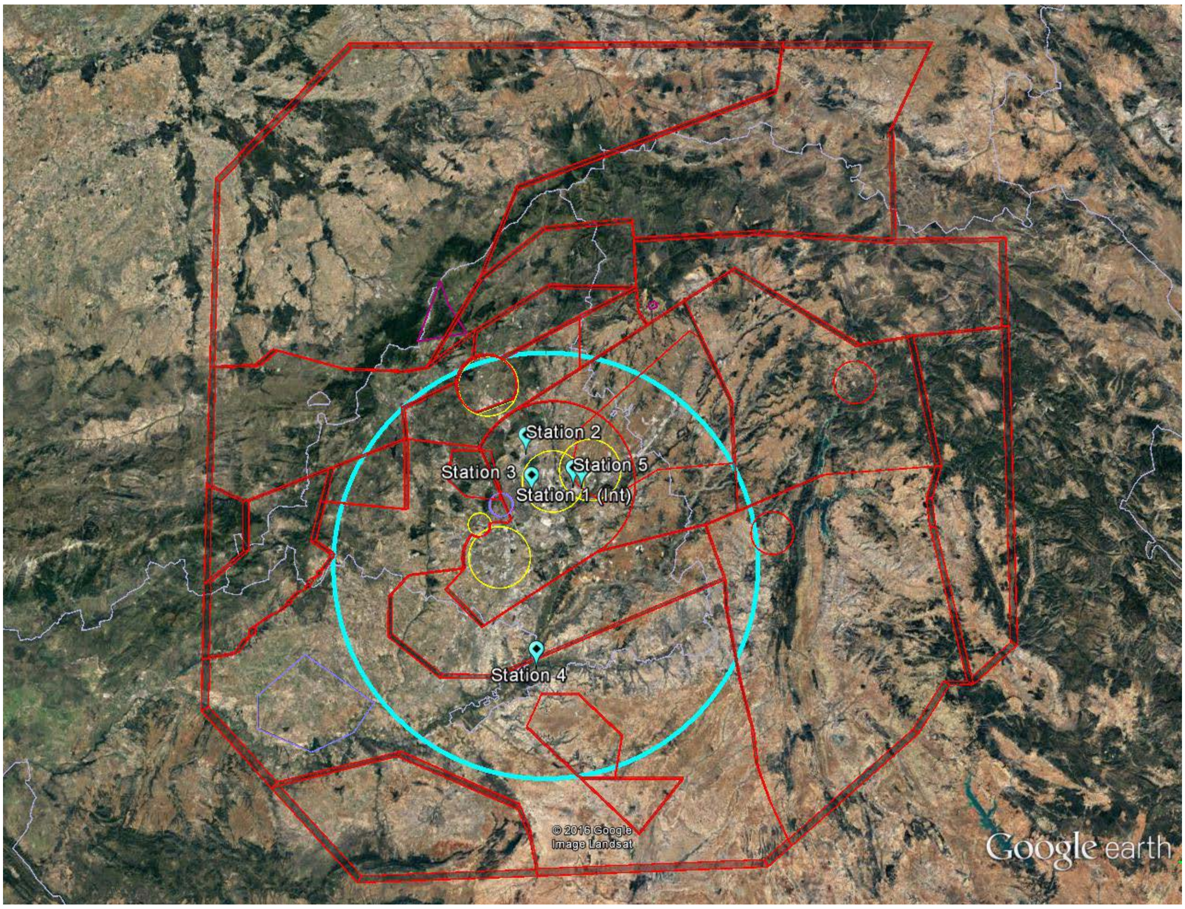

Figure 12: Indra verification environment

2.6 DFS, description of System

To evaluate the performances and behaviour of a composite WAM-ADSB surveillance system, the PHOENIX system was used in the System-House at DFS headquarter in Langen. The goal was to test the system for targets showing an error characteristic, which is expected to be present in real data only on very few occasions and is regarded as complementary task to the Indra measurement campaign conducted in Spain. It was chosen to rely solely on synthetic data for this purpose. Furthermore, real data are not expected to show a specific effect in its pure form. Both the data generation and data processing are decoupled from real time necessities.

The main characteristics of the system are:

- A synthetic data generator for providing Cat020 and Cat021 data amongst Cat001/Cat002 and Cat034/Cat048.
- An Analysis Working Position (AWP) for data inspection; especially for the Cat062 SP which contains data not addressed by the ASTERIX standard (e.g. ADS-B position or barometric altitude bias)
- A Multi-sensor data-fusion unit for data processing and validation purposes.

Figure 13 below provides an overview of the DFS 15.04.02 WP2 validation platform:

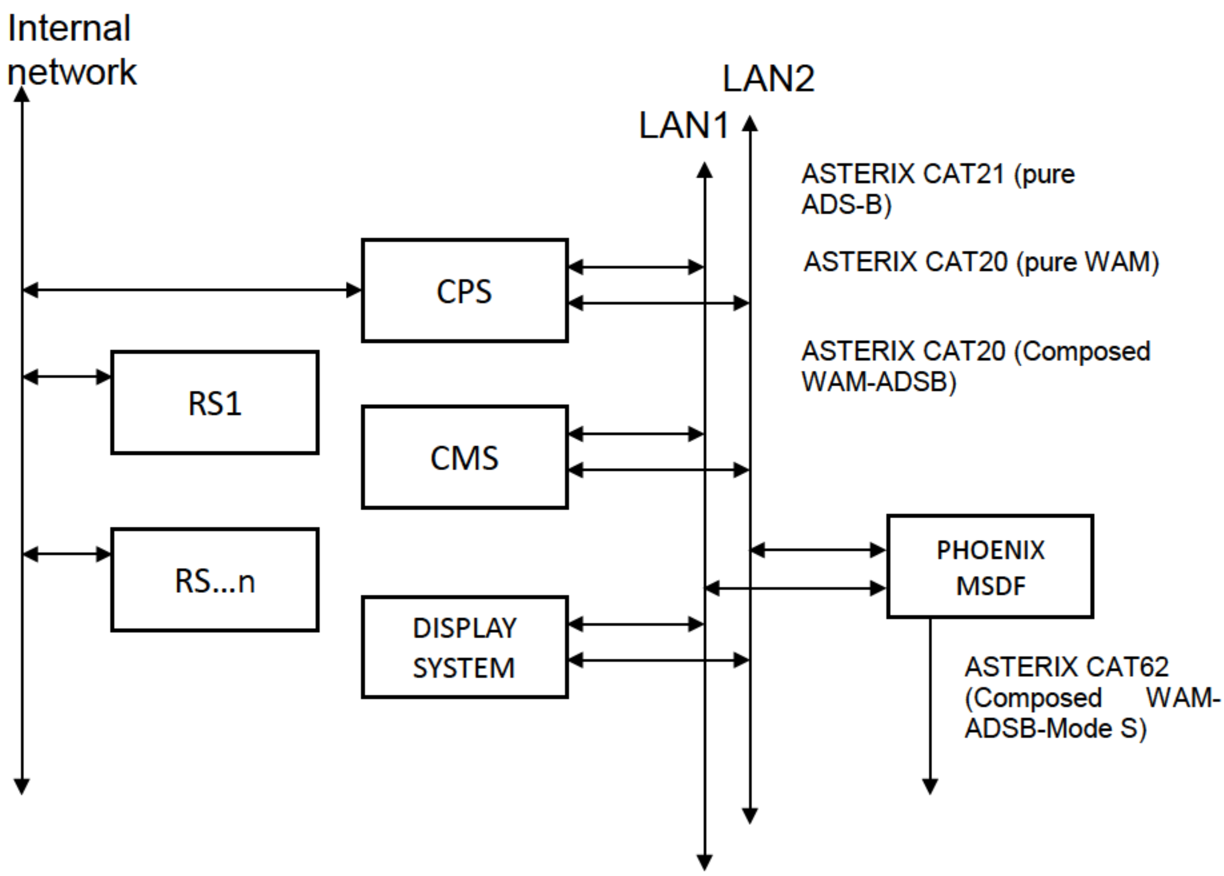

Figure 13: High level components and data flow of DFS Validation Platform

2.7 Summary of Verification Exercises, Verification Objectives and Success Criteria

A summary table is provided detailing the Verification exercises under the scope of the Verification Report.

Verification Exercise ID and Title	**EXE-15.04.02-D09-0010.0001 NATS Test platform interoperability**
Leading organization	NATS
Verification exercise objectives	OBJ-15.04.02-D09-0010.0000 OBJ-15.04.02-D09-0010.0010 OBJ-15.04.02-D09-0010.0020

Rationale	Function
Verification Technique	Real Traffic capture and user acceptance based on traffic replay
Dependent Verification Exercises	N/A

Table 4: Exercise 1 Concept Overview

Verification Exercise ID and Title	**EXE-15.04.02-D09-0020.0001 Validation by Ranging**
Leading organization	INDRA
Verification exercise objectives	OBJ-15.04.02-D09-0020.0000 OBJ-15.04.02-D09-0020.0010 OBJ-15.04.02-D09-0020.0020 OBJ-15.04.02-D09-0020.0030 OBJ-15.04.02-D09-0020.0040 OBJ-15.04.02-D09-0020.0050 OBJ-15.04.02-D09-0020.0060 OBJ-15.04.02-D09-0020.0090 OBJ-15.04.02-D09-0020.0120 OBJ-15.04.02-D09-0020.0150
Rationale	Function
Verification Technique	Real Time Simulation
Dependent Verification Exercises	N/A

Table 5: Exercise 2 Concept Overview

Verification Exercise ID and Title	EXE-15.04.02-D09-0020.0002 Validation by WAM
Leading organization	INDRA
Verification exercise objectives	OBJ-15.04.02-D09-0020.0050 OBJ-15.04.02-D09-0020.0060 OBJ-15.04.02-D09-0020.0070 OBJ-15.04.02-D09-0020.0100 OBJ-15.04.02-D09-0020.0130 OBJ-15.04.02-D09-0040.0060 OBJ-15.04.02-D09-0040.0070
Rationale	Function
Verification Technique	Real Time Simulation and Real Traffic
Dependent Verification Exercises	N/A

Table 6: Exercise 3 Concept Overview

Verification Exercise ID and Title	EXE-15.04.02-D09-0020.0003 Validation by partial position
Leading organization	INDRA
Verification exercise objectives	OBJ-15.04.02-D09-0020.0050 OBJ-15.04.02-D09-0020.0060 OBJ-15.04.02-D09-0020.0080 OBJ-15.04.02-D09-0020.0110 OBJ-15.04.02-D09-0020.0140
Rationale	Function
Verification Technique	Real Time Simulation and Real Traffic
Dependent Verification Exercises	N/A

Table 7: Exercise 4 Concept Overview

Verification Exercise ID and Title	EXE-15.04.02-D09-0020.0004 Height validation
Leading organization	INDRA
Verification exercise objectives	OBJ-15.04.02-D09-0020.0160 OBJ-15.04.02-D09-0020.0170 OBJ-15.04.02-D09-0020.0180 OBJ-15.04.02-D09-0040.0080 OBJ-15.04.02-D09-0040.0090 OBJ-15.04.02-D09-0040.0100 OBJ-15.04.02-D09-0050.0000
Rationale	Function
Verification Technique	Real Time Simulation and Real Traffic
Dependent Verification Exercises	N/A

Table 8: Exercise 5 Concept Overview

Verification Exercise ID and Title	EXE-15.04.02-D09-0020.0005 Identification
Leading organization	INDRA
Verification exercise objectives	OBJ-15.04.02-D09-0020.0160 OBJ-15.04.02-D09-0020.0170 OBJ-15.04.02-D09-0020.0180 OBJ-15.04.02-D09-0020.0190 OBJ-15.04.02-D09-0020.0230 OBJ-15.04.02-D09-0020.0240 OBJ-15.04.02-D09-0020.0250 OBJ-15.04.02-D09-0020.0260
Rationale	Function
Verification Technique	Real Time Simulation and Real Traffic
Dependent Verification Exercises	N/A

Table 9: Exercise 6 Concept Overview

Verification Exercise ID and Title	EXE-15.04.02-D09-0020.0006 Performance Monitoring
Leading organization	INDRA
Verification exercise objectives	OBJ-15.04.02-D09-0020.0200 OBJ-15.04.02-D09-0020.0210 OBJ-15.04.02-D09-0020.0220
Rationale	Function
Verification Technique	Real Time Simulation and Real Traffic
Dependent Verification Exercises	N/A

Table 10: Exercise 7 Concept Overview

Verification Exercise ID and Title	EXE-15.04.02-D09-0020.0007 PTE-DOP Data ages
Leading organization	INDRA
Verification exercise objectives	OBJ-15.04.02-D09-0040.0000 OBJ-15.04.02-D09-0040.0010 OBJ-15.04.02-D09-0040.0020 OBJ-15.04.02-D09-0040.0040 OBJ-15.04.02-D09-0040.0130 OBJ-15.04.02-D09-0040.0140 OBJ-15.04.02-D09-0040.0150
Rationale	Function
Verification Technique	Real Time Simulation and Real Traffic
Dependent Verification Exercises	N/A

Table 11: Exercise 8 Concept Overview

Verification Exercise ID and Title	EXE-15.04.02-D09-0030.0001 Data Processing
Leading organization	DFS
Verification exercise objectives	OBJ-15.04.02-D09-0030.0000 OBJ-15.04.02-D09-0030.0010 OBJ-15.04.02-D09-0030.0020 OBJ-15.04.02-D09-0030.0030
Rationale	Function
Verification Technique	Real Time Simulation
Dependent Verification Exercises	N/A

Table 12: Exercise 9 Concept Overview

Verification Exercise ID and Title	EXE-15.04.02-D09-0030.0002 Data Verification
Leading organization	DFS
Verification exercise objectives	OBJ-15.04.02-D09-0040.0050 OBJ-15.04.02-D09-0040.0110 OBJ-15.04.02-D09-0040.0120
Rationale	Function
Verification Technique	Real Time Simulation
Dependent Verification Exercises	N/A

Table 13: Exercise 10 Concept Overview

2.8 Choice of methods and techniques

The chosen methods for the verification activities are provided below:

Platform / Tool	Method or Technique
NATS	Real Traffic capture and user acceptance based on traffic replay
INDRA	Real Time Simulation and Real Traffic
DFS	Real Time Simulation

Table 14: Methods and Techniques

3 Conduct of Verification Exercises

3.1 Verification strategy of the project

This project has been organized in different deliverables: First, the requirements have to be defined and then, a verification strategy or plan is made in order to meet those requirements. In addition, two different tasks were defined: Task 05 is for high-level requirements and verification strategy and on the other hand, Task 06 is for low-level requirements and its verification exercises. Verification activities are included in parallel between tasks 06 & 07. Finally, the last Task 07 aims to produce the reports of the final tests and validation activities.

The next figure summarizes the organization described above:

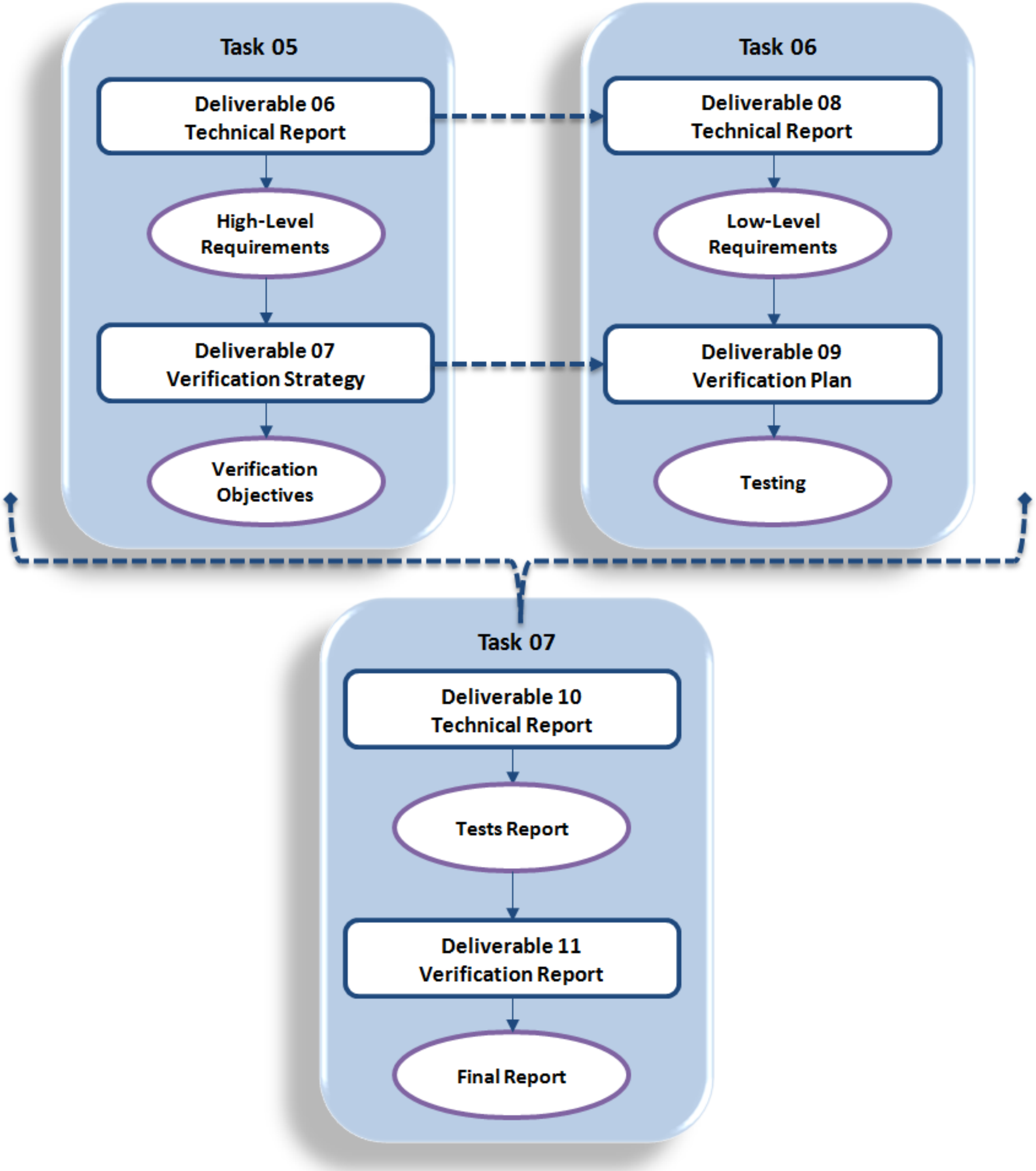

Figure 14: Verification organization of the project

This report aims to analyse and study that the prototypes developed by the project members NATS, Indra and DFS are implemented in accordance with the technical specifications defined in previous deliverables ([6][7][8][9][10]). It is the final process that ensures that each solution complies with the expected needs.

All verification exercises followed the same verification process, defining a list of several exercises to be executed in a test environment in order to produce reports which point out those prototypes are suitable for the validation and integration phases.

Each manufacturer has been in charge of running the verification test in appropriate scenarios to demonstrate the correct implementation of the requirements and objectives.

3.2 Verification Exercises Preparation

In case of simulated data, the preparation of the different Verification Exercises is explained in the section “Precondition(s)” provided in each Verification Exercises Report located in D10 deliverable (Ref. [10]).

In case of real traffic data, the preparation is explained in the following sections of the document.

3.3 Verification Exercises Execution

The execution of the NATS verification exercises related to the User Acceptance Testing was performed on 14th July 2016. Data collection to support the WAM accuracy and probability of update assessment was taken on the 15th May 2016. Data to support the assessment of the ‘Identity, Mode C and Mode A, was based on 43 days between the 28th of April 2016 and the 31st of May 2016. The ADD- DAP study comprised of data taken from 7 days of nearly contiguous recordings[2] from the 13th – 18th and 20th July 2016.

The execution of the Indra verification exercises using the data simulator was performed from 15th to 27th June 2016. The real traffic recordings were performed in different days of July and August 2016.

The execution of the DFS Data Processing verification exercise was performed on 4th June 2016 and the Data Verification exercise was performed on 15th June 2016.

[2] The 19th July 2016 was not available for analysis, so the 20th July 2016 was used in its place.

3.4 Deviations from the Planned Activities

In previous deliverables of this project, the idea was to integrate both INDRA and DFS validation platforms into one.

Nevertheless, after some discussions among the project members we decide not to do that due to several difficulties in the integration and information exchange procedures.

Therefore for the sake of a better work efficiency, the INDRA and DFS validation platforms are divided now and the verification exercises will be performed separately with INDRA focusing on a mix of real and synthetic data and DFS on synthetic data only as complementary campaign. A first set of system requirements were derived from the EUROCAE documentation already existing and that is related to WAM and ADS-B systems. For the aim of the project, not all requirements included in such document will be tested, as they are considered as a baseline for the project. The analysis will be focused on the evaluation of the performances of the prototypes and the capability of improvement using the described techniques (e.g. DAPs, use and creation of ADD, and use of composite WAM – ADS-B data).

Project members NATS were unable to execute two aspects of the planned work package activities; the ARTAS V8B3 integration and associated assessment and the range aided multilateration assessment. The ARTAS integration could not be conducted due to resource commitments of the specialist NATS staff required. The range aided mulitlateration assessment was not conducted due to unanticipated delays in activating the interrogator at the new ground station location, leaving insufficient time to conduct that aspect of the trial and assessment.

In the context of this document, the deviations noted above did not directly impact the three NATS platform verification objectives under consideration. However, as the project progressed and the options for solutions for displaying the ADS-B and WAM data to users for acceptance was explored in more detail it became apparent that the use of the NATS Space facility and integrated real time simulation suite would not be able to provide a sufficient fidelity display for the resource available to the project. Instead a smaller 'portable solution using the same core software components as the Space facility was progressed. As such, the verification objectives assessed within EXE-15.04.02-D09-0010.0001 refer to the portable solution rather than the originally anticipated NATS Space Facility solution.

A consequence of the 'portable' solution was that it replayed the data locally rather than streaming it from the RRRS. The successful replay will note this as a 'PASS' in the verification exercise report but will note that it was not strictly applicable.

4 Verification Results

4.1 Summary of Verification Exercises Results

In general, verification exercises results are in line with the expectations.

DFS

For the DFS platform, in this exercise the system has been tested using synthetic scenarios. The focus was to validate the ADS-B position and barometric altitude using mainly WAM as complementary sensor technology. It was shown that a real time monitoring of these bias values is feasible conducted directly by the MDSF data processing unit. Furthermore, it could be demonstrated that it is possible to validate the provided accuracy of a sensor (a.k.a. accuracy of accuracy). This evaluation of the provided accuracy shows great potential especially in the handling of sensors with a strongly fluctuating accuracy from two contemporary measurements e.g. MSPSR.

INDRA

For the Indra platform, in these exercises, the system have been tested using pre-configured scenarios in order to create anomalies in operation and discrepancies that may not appear with real traffic. In the following sections graphics, statistics and different comparison charts will provide more information: For example, it will be possible to compare the results of the verifications (Full WAM, Partial WAM, Ranging ...) with different types of ADS-B versions and if version 0 targets have worse performance than version 2 targets.

NATS

The verification of the NATS replay platform for the user acceptance testing passed all of the verification objectives in the exercise. The following section documents the results of the user acceptance test undertaken with the NATS replay platform, in addition to the comparative analysis of real world values of ADS-B and WAM ASTERIX data items pertinent to composite cooperative surveillance. This study also documents the results of the other NATS low-level objectives described in D08.

In the next tables, the results of the different Verification Exercises have been summarised. The results have been assessed against the success criteria and project members have decided if the Verification objective analysis status per Verification exercise is Pass or NOK.

The explanation about Pass and NOK is provided below:

- Pass: Verification objective achieves the expectations, i.e. verification exercise results achieve success criteria.
- NOK: Verification objective does not achieve the expectations, i.e. verification exercise results do not achieve success criteria.

Verification Exercise ID	Verification Objective ID	Verification Objective Title	Success Criterion ID	Success Criterion	Exercise Results
EXE-15.04.02-D09-0010.0001	OBJ-15.04.02-D09-0010.0000 OBJ-15.04.02-D09-0010.0010 OBJ-15.04.02-D09-0010.0020	NATS UAT CAT020 NATS UAT CAT021 NATS UAT CAT062	SUC-15.04.02-D09-0010.0000 SUC-15.04.02-D09-0010.0010 SUC-15.04.02-D09-0010.0020	Meet the “Pass Criteria”	**PASS**
EXE-15.04.02-D09-0020.0001	OBJ-15.04.02-D09-0020.0000 OBJ-15.04.02-D09-0020.0010 OBJ-15.04.02-D09-0020.0020 OBJ-15.04.02-D09-0020.0030 OBJ-15.04.02-D09-0020.0040 OBJ-15.04.02-D09-0020.0050 OBJ-15.04.02-D09-0020.0060 OBJ-15.04.02-D09-0020.0090 OBJ-15.04.02-D09-0020.0120 OBJ-15.04.02-D09-0020.0150	ADS-B position comparison 1 ADS-B position comparison 2 ADS-B position comparison 3 ADS-B position comparison 4 ADS-B position comparison 5 Output Comparison information 1 Output Comparison information 2 Output Comparison information 5 Output Comparison information 8 Output Comparison information 11	SUC-15.04.02-D09-0020.0000 SUC-15.04.02-D09-0020.0010 SUC-15.04.02-D09-0020.0020 SUC-15.04.02-D09-0020.0030 SUC-15.04.02-D09-0020.0040 SUC-15.04.02-D09-0020.0050 SUC-15.04.02-D09-0020.0060 SUC-15.04.02-D09-0020.0090 SUC-15.04.02-D09-0020.0120 SUC-15.04.02-D09-0020.0150	Meet the “Pass Criteria”	**PASS**
EXE-15.04.02-D09-0020.0002	OBJ-15.04.02-D09-0020.0050 OBJ-15.04.02-D09-0020.0060 OBJ-15.04.02-D09-0020.0070 OBJ-15.04.02-D09-0020.0100 OBJ-15.04.02-D09-0020.0130 OBJ-15.04.02-D09-0040.0060 OBJ-15.04.02-D09-0040.0070	Output Comparison information 1 Output Comparison information 2 Output Comparison information 3 Output Comparison information 6 Output Comparison information 9 Evaluation of functions 2 Evaluation of functions 3	SUC-15.04.02-D09-0020.0050 SUC-15.04.02-D09-0020.0060 SUC-15.04.02-D09-0020.0070 SUC-15.04.02-D09-0020.0100 SUC-15.04.02-D09-0020.0130 SUC-15.04.02-D09-0040.0060 SUC-15.04.02-D09-0040.0070	Meet the “Pass Criteria”	**PASS**
EXE-15.04.02-D09-0020.0003	OBJ-15.04.02-D09-0020.0050 OBJ-15.04.02-D09-0020.0060 OBJ-15.04.02-D09-0020.0080 OBJ-15.04.02-D09-0020.0110 OBJ-15.04.02-D09-0020.0140	Output Comparison information 1 Output Comparison information 2 Output Comparison information 4 Output Comparison information 7 Output Comparison information 10	SUC-15.04.02-D09-0020.0050 SUC-15.04.02-D09-0020.0060 SUC-15.04.02-D09-0020.0080 SUC-15.04.02-D09-0020.0110 SUC-15.04.02-D09-0020.0140	Meet the “Pass Criteria”	**PASS**
EXE-15.04.02-D09-0020.0004	OBJ-15.04.02-D09-0020.0160 OBJ-15.04.02-D09-0020.0170 OBJ-15.04.02-D09-0020.0180 OBJ-15.04.02-D09-0040.0080 OBJ-15.04.02-D09-0040.0090 OBJ-15.04.02-D09-0040.0100 OBJ-15.04.02-D09-0050.0000	Use of ADS-B non-position data 1 Use of ADS-B non-position data 2 Use of ADS-B non-position data 3 Evaluation of functions 4 Evaluation of functions 5 Evaluation of functions 6 Initial Validation Conditions for	SUC-15.04.02-D09-0020.0160 SUC-15.04.02-D09-0020.0170 SUC-15.04.02-D09-0020.0180 SUC-15.04.02-D09-0040.0080 SUC-15.04.02-D09-0040.0090 SUC-15.04.02-D09-0040.0100 SUC-15.04.02-D09-0050.0000	Meet the “Pass Criteria”	**PASS**

Verification Exercise ID	Verification Objective ID	Verification Objective Title	Success Criterion ID	Success Criterion	Exercise Results
		Pressure Altitude 1			
EXE-15.04.02-D09-0020.0005	OBJ-15.04.02-D09-0020.0160 OBJ-15.04.02-D09-0020.0170 OBJ-15.04.02-D09-0020.0180 OBJ-15.04.02-D09-0020.0190 OBJ-15.04.02-D09-0020.0230 OBJ-15.04.02-D09-0020.0240 OBJ-15.04.02-D09-0020.0250 OBJ-15.04.02-D09-0020.0260	Use of ADS-B non-position data 1 Use of ADS-B non-position data 2 Use of ADS-B non-position data 3 Validation Check for Aircraft Identification WAM performance Monitoring 4 WAM performance Monitoring 5 WAM performance Monitoring 6 WAM performance Monitoring 7	SUC-15.04.02-D09-0020.0160 SUC-15.04.02-D09-0020.0170 SUC-15.04.02-D09-0020.0180 SUC-15.04.02-D09-0020.0190 SUC-15.04.02-D09-0020.0230 SUC-15.04.02-D09-0020.0240 SUC-15.04.02-D09-0020.0250 SUC-15.04.02-D09-0020.0260	Meet the “Pass Criteria”	**PASS**
EXE-15.04.02-D09-0020.0006	OBJ-15.04.02-D09-0020.0200 OBJ-15.04.02-D09-0020.0210 OBJ-15.04.02-D09-0020.0220	WAM performance Monitoring 1 WAM performance Monitoring 2 WAM performance Monitoring 3	SUC-15.04.02-D09-0020.0200 SUC-15.04.02-D09-0020.0210 SUC-15.04.02-D09-0020.0220	Meet the “Pass Criteria”	**PASS**
EXE-15.04.02-D09-0020.0007	OBJ-15.04.02-D09-0040.0000 OBJ-15.04.02-D09-0040.0010 OBJ-15.04.02-D09-0040.0020 OBJ-15.04.02-D09-0040.0040 OBJ-15.04.02-D09-0040.0130 OBJ-15.04.02-D09-0040.0140 OBJ-15.04.02-D09-0040.0150	Uncertainties in position 1 Uncertainties in position 2 Uncertainties in position 3 Uncertainties in position 5 Evaluation of functions 9 Evaluation of functions 10 Evaluation of functions 11	SUC-15.04.02-D09-0040.0000 SUC-15.04.02-D09-0040.0010 SUC-15.04.02-D09-0040.0020 SUC-15.04.02-D09-0040.0040 SUC-15.04.02-D09-0040.0130 SUC-15.04.02-D09-0040.0140 SUC-15.04.02-D09-0040.0150	Meet the “Pass Criteria”	**PASS**
EXE-15.04.02-D09-0030.0001	OBJ-15.04.02-D09-0030.0000 OBJ-15.04.02-D09-0030.0010 OBJ-15.04.02-D09-0030.0020 OBJ-15.04.02-D09-0030.0030	Surveillance Sensor ASTERIX Output 1 Surveillance Sensor ASTERIX Output 2 Surveillance Sensor ASTERIX Output 3 Surveillance Sensor ASTERIX Output 4	SUC-15.04.02-D09-0030.0000 SUC-15.04.02-D09-0030.0010 SUC-15.04.02-D09-0030.0020 SUC-15.04.02-D09-0030.0030	Meet the “Pass Criteria”	**PASS**
EXE-15.04.02-D09-0030.0002	OBJ-15.04.02-D09-0040.0050 OBJ-15.04.02-D09-0040.0110 OBJ-15.04.02-D09-0040.0120	Evaluation of functions 1 Evaluation of functions 7 Evaluation of functions 8	SUC-15.04.02-D09-0040.0050 SUC-15.04.02-D09-0040.0110 SUC-15.04.02-D09-0040.0120	Meet the “Pass Criteria”	**PASS**

Table 15: Summary of Verification Exercises Result

4.1.1 Unexpected Behaviours/Results

No problems have been registered during the performance of the verification exercises.

4.2 NATS Verification Report

4.2.1 Analysis Supporting Cooperative Composite Surveillance

The NATS CRISTAL platform THALES MAGS (Multilateration ADS-B Ground Surveillance) comprised of 7 receivers detailed in section 2.4 was used to collect a large dataset of overlapping CAT021 ADS-B and CAT020 WAM messages covering the London Terminal Manoeuvring Area.

The following assessments compared the values of the CAT020 WAM messages with CAT021 ADS-B messages.

In total 43 days of overlapping ADS-B and WAM data were recorded, resulting in 241,371,078 CAT021 ADS-B messages and 121,156,658 CAT020 WAM messages, of which 68,795,149 could be compared; this equates to 28.5% of the total number of ADS-B CAT021 messages and 56.8% of the total number of WAM messages.

The assessment compared the Mode A code, FL and Aircraft Identification (ACID) derived from ADS-B and WAM.

4.2.1.1 Mode A Assessment

Of the 68,795,149 comparisons (from all versions of ADS-B), the Mode A of the WAM (I020-070) matched the Mode A of the ADS-B (I021-070) on 7,251,383 (10.54%) instances. However it should be noted that of the 68,795,149 CAT021 ADS-B reports used in the comparison, 61,540,698 (89.45%) did not report Mode A. Where a Mode A code was available for comparison, all but 3,068 matched, equating to 0.042% of the messages that provided Mode A code.

For aircraft broadcasting that they were ADS-B Version 2, there were 6,089,871 messages available for comparison, of which 6,086,942 (99.95%) had a match. Only 73 messages did not match in the analysis. The 6,089,871 Version 2 messages represent 8.85% of the 68,795,149 messages covering all versions of ADS-B.

The 'whitelist' Version 2 ADS-B aircraft had a similar result, with 2,878,968 messages available for comparison, with 2,878,517 (99.98%) matching. 37 messages did not match.

4.2.1.2 ACID Assessment

Aircraft ID (ACID) is reported within ASTERIX as field I020-220 for WAM and I021-170 for ADS-B.

As for the Mode A assessment, including all versions of ADS-B, there were 68,795,149 messages available for comparison. Of these messages 68,790,934 (99.994%) matched, with 4,215 messages not matching. The aircraft that reported as Version 2 matched for 99.988% (6,089,149 of 6,086,942 messages) while the whitelist 'verified as Version 2' gave a result of 99.987% (2,878,600 of 2,878,968 messages).

4.2.1.3 Flight Level Assessment

Non-QNH corrected barometric Flight Level (FL) information (Mode C) is provided in ASTERIX fields I020-090 for WAM and I021-145 for ADS-B.

Including all versions of ADS-B, 68,756,154 messages had FL information equating to 99.943% of the 68,795,149 messages.

Figure 15 illustrates that 97.224% of the messages where within ±25ft, and 99.852% were within ±50ft.

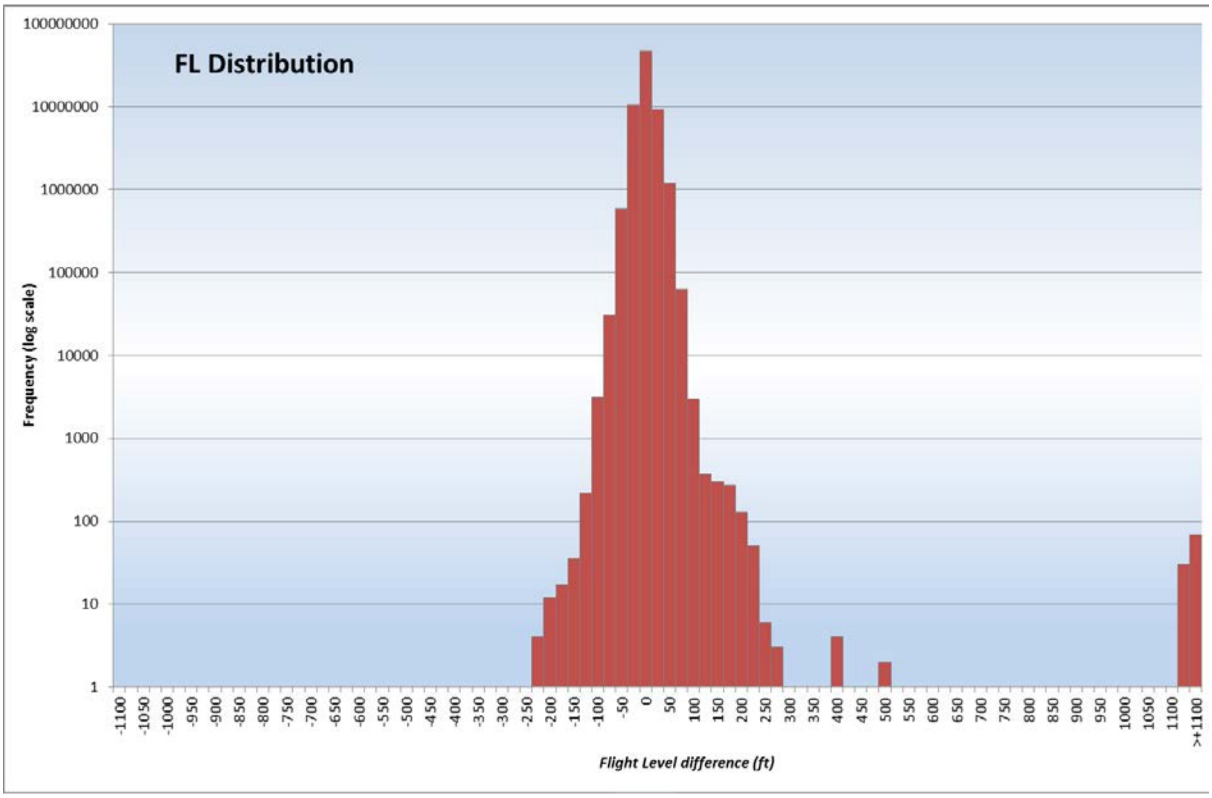

Figure 15: FL difference from all airframes

The distributions for the airframes reporting as Version 2 and verified as Version 2 in the whitelist were extremely similar to that shown in Figure 15, albeit for reduced numbers (6,084,55 messages for airframes reporting V2 and 2,876,886 messages on the whitelist). The distributions for the airframes reporting as Version 2 is shown in Figure 16.

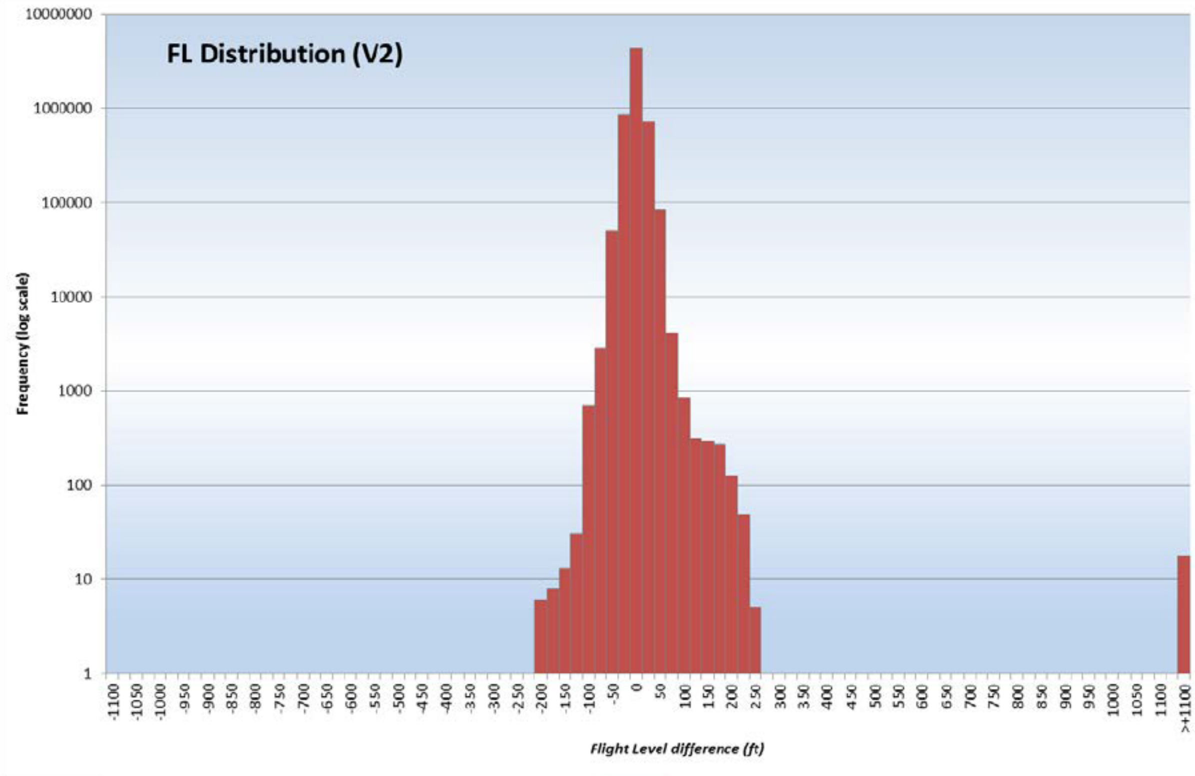

Figure 16: FL difference from airframes reporting as V2 ADS-B

4.2.2 Analysis of ADDs & DAPs

The Downlinked Aircraft Parameter (DAP) extraction was an additional activity to assess whether there were any notable discrepancies between the parameters downlinked via Mode S interrogations of BDS registers 4,0 5,0 and 6,0 against the Aircraft Derived Data (ADDs) broadcast in the ADS-B message elements relating to Extended Squitter BDS registers 0,9 and 6,2.

Table 16 below summaries the theoretical compatibility between the DAP values extracted via interrogation and the ADD values broadcast by ADS-B aircraft.

DAP NAME	Register	ASTERIX Item	ADD NAME	Register	ADS-B Version (0,1,2)	CAT021 Item Name	ASTERIX Item
MCP/FCU SELECTED ALTITUDE	4,0	020-250	MCP/FCU SELECTED ALTITUDE (&SELECTED ALTITUDE TYPE bit)	6,2	2	Selected Altitude	021-146 / 021-148
FMS SELECTED ALTITUDE	4,0	020-250	MCP/FCU SELECTED ALTITUDE (&SELECTED ALTITUDE TYPE bit)	6,2	2	Selected Altitude	021-146 / 021-148
BAROMETRIC PRESSURE SETTING (BPS)	4,0	020-250	BAROMETRIC PRESSURE SETTING	6,2	2	RE field item	021-RE

DAP NAME	Register	ASTERIX Item	ADD NAME	Register	ADS-B Version (0,1,2)	CAT021 Item Name	ASTERIX Item
STATUS OF MCP/FCU MODE BITS VNAV MODE ALT HOLD MODE APPROACH MODE	4,0	020-250	STATUS OF MCP/FCU MODE BITS, AUTOPILOT ENGAGED, VNAV MODE ENGAGED ALTITUDE HOLD MODE APPROACH MODE	6,2	2	Selected Altitude	021-146
TARGET ALT SOURCE (&STATUS OF TARGET ALT SOURCE BITS)	4,0	020-250		6,2	1		021-148
ROLL ANGLE	5,0	020-250	N/A	N/A	N/A	Roll Angle	021-230
TRUE TRACK ANGLE (TTA)	5,0	020-250	EAST-WEST VELOCITY	~0,9	0, 1, 2	Airborne Ground Vector	021-160
GROUND SPEED (GSPD)	5,0	020-250	EAST-WEST VELOCITY	0,9	0, 1, 2	Airborne Ground Vector	021-160
TRACK ANGLE RATE (TAR)	5,0	020-250	EAST-WEST VELOCITY	~0,9	0, 1, 2	Track Angle Rate	021-165
TRUE AIRSPEED (TAS)	5,0	020-250	AIRSPEED	0,9	0, 1, 2	True Airspeed	021-151
MAGNETIC HEADING (MAG)	6,0	020-250	HEADING	~0,9	0, 1, 2	Magnetic Heading	021-152
INDICATED AIRSPEED (IAS)	6,0	020-250	AIRSPEED	0,9	0, 1, 2	Air Speed	021-150
MACH	6,0	020-250	N/A	N/A	N/A	Air Speed	021-150
BAROMETRIC ALTITUDE RATE (BAR)	6,0	020-250	VERTICAL RATE (&SOURCE BIT FOR VERTICAL RATE))	0,9	0, 1, 2	Barometric Vertical Rate	021-155
INERTIAL VERTICAL VELOCITY	6,0	020-250	VERTICAL RATE (&SOURCE	~0,9	0, 1, 2	Geometric Vertical Rate	021/157

DAP NAME	Register	ASTERIX Item	ADD NAME	Register	ADS-B Version (0,1,2)	CAT021 Item Name	ASTERIX Item
(IVV)			BIT FOR VERTICAL RATE))				

Table 16: DAP - ADD cross reference matrix

The NATS CRISTAL platform provides ASTERIX CAT020 edition 1.5 for WAM and CAT021 edition 2.1 for ADS-B.

4.2.2.1 Assessment Overview

The ADD- DAP study comprised of data taken from 7 days of nearly contiguous recordings[3] from the 13th – 18th and 20th July 2016. This 7 day dataset comprised of 17,890,860 CAT021 ASTERIX ADS-B messages and 8,899,450 ASTERIX CAT020 WAM messages. However it should be noted that the DAPs were only available within a subset of the CAT020 messages; i.e. those within coverage of the Daventry interrogator ground station.

This unfiltered dataset includes airframes broadcasting all three versions of ADS-B. Although 15.04.02 is aimed at validating requirements for an SPIIR ADS-B Version 2 mandated environment, this assessment also studied the ADD- DAP compliance performance for all versions of ADS-B. To specifically assess the V2 (DO-260B / ED-102A) ADD - DAP compliance, a EUROCONTROL 'whitelist' (complied at the end of 2015) of known 'verified' V2 installations was used. Separately the Version 2 flag in the ADS-B messages was also used to assess whether there was a difference in compliance between verified V2 airframes and airframes that report V2 capability.

4.2.2.2 BDS 4,0

The total number of CAT020 messages containing BDS 4,0 information was 67,901.

Of the 67,901 messages:

- 67,589 (99.54%) provided the MCP/FCU SELECTED ALTITUDE (in I020-250),
- 4,845 (7.14%) provided the FMS SELECTED ALTITUDE (in I020-250),
- 64,943 (95.64%) provided the BAROMETRIC PRESSURE SETTING (BPS) (in I020-250),
- All 67,901 (100.00%) were 'MCP Mode Unknown' (BDS 4, 0 bit 48=0).

By comparison, including for all versions of ADS-B, there were 17,890,860 CAT021 messages, of which:

- 470,760 (2.63%) provided MCP_SFL selected altitude information,
- 25,067 (0.14%) provided FMS_SFL selected altitude information,
- 9,312 (0.05%) provided ALT_HOLD selected altitude information,
- 463,225 (2.59%) provided Barometric Pressure Setting information.

As noted in Table 16, the selected altitude and related BPS information is only contained within the Version 2 ADS-B message set, explaining the low percentage of all ADS-B messages recorded within the dataset.

The comparison assessment between the BDS 4, 0 derived from WAM and corresponding ADD messages in ADS-B only evaluated messages where an airframe with the same Mode S address (ICAO 24 bit address I020-220 and I021-080) was received by the WAM system and then the ADS-B system within 1 second. This time bound reduced the messages for direct comparison to:

- 5, 320 (7.835% of BDS 4,0 messages) with MCP_SFL selected altitude information,

[3] The 19th July 2016 was not available for analysis, so the 20th July 2016 was used in its place.

- 781 (1.150% of BDS 4,0 messages) with FMS_SFL selected altitude information.
- 0 ALT_HOLD with selected altitude information,
- 5, 172 (7.617% of BDS 4,0 messages) with Barometric Pressure Setting information.

The distributions of the difference between the ADD MCP_SFL minus the DAP MCP_SFL is shown in Figure 17. The distribution for the ADD minus DAP FMS_SFL is shown in Figure 18, while the ADD BPS minus DAP BPS distribution is shown in Figure 19.

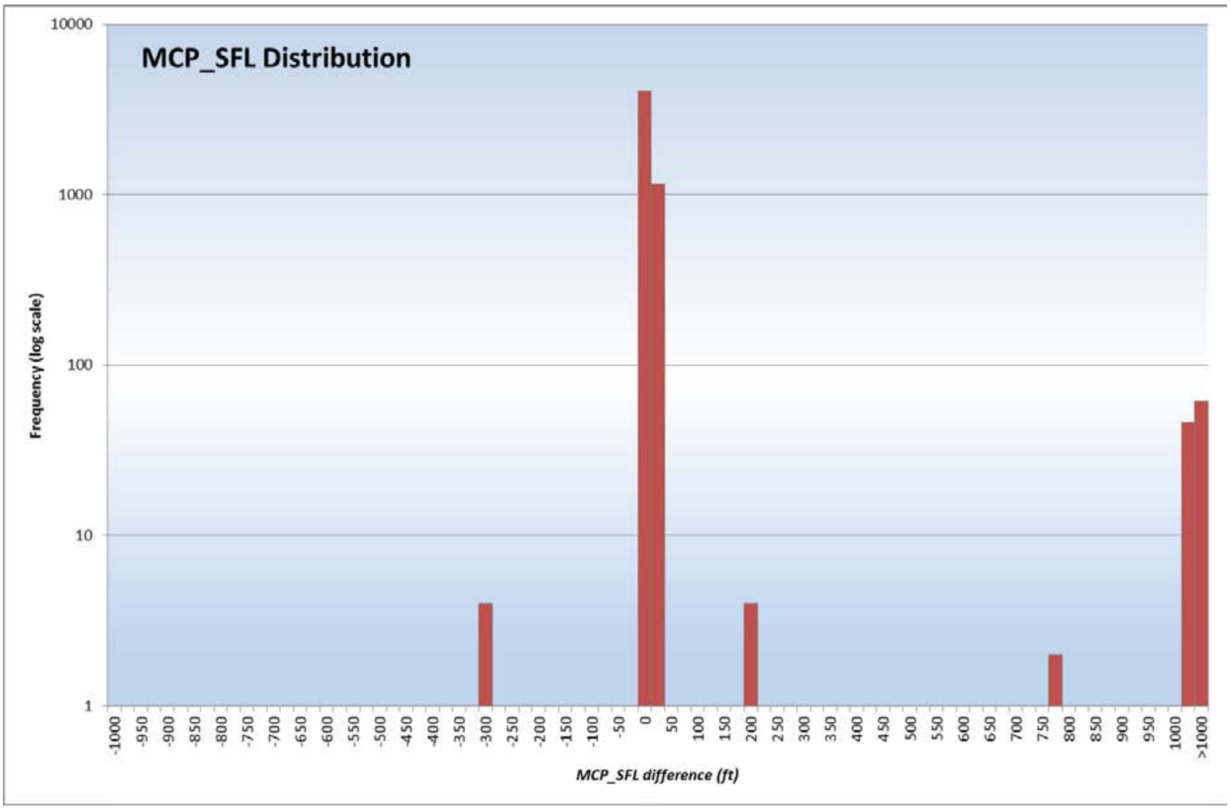

Figure 17: ADD - DAP MCP_SFL difference distribution

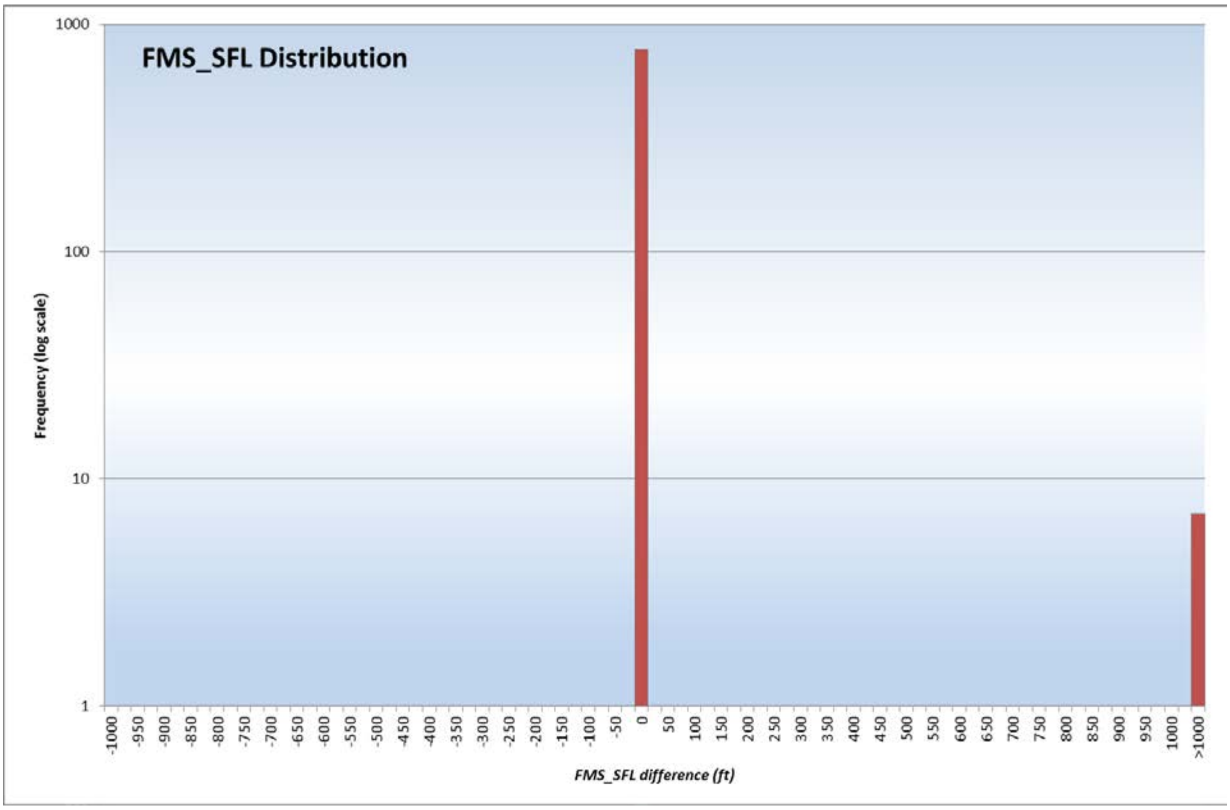

Figure 18: ADD - DAP FMS_SFL difference distribution

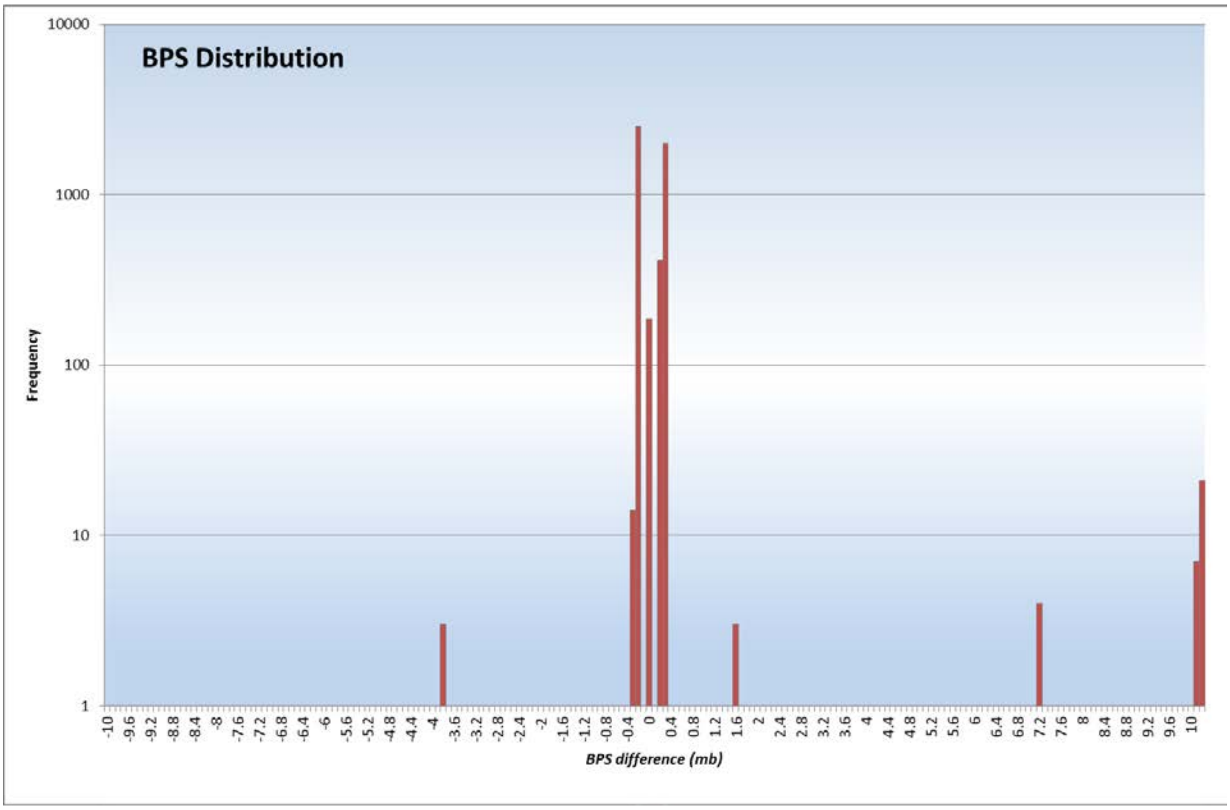

Figure 19: ADD - DAP BPS difference distribution

For the MCP_SFL comparison assessment (Figure 17); 5,199 of the 5,320 (97.73%) messages are within 25ft.

For the FMS_SFL comparison assessment (Figure 18); 772 of the 781 (98.85%) messages values are identical (0ft difference).

For the BPS comparison assessment (Figure 19); 5,134 of the 5,172 (99.27%) message are within ±0.3 mb.

Slightly less MCP_SFL messages were compared for the airframes that reported they were Version 2, with only 5,205 messages compared, with no significant differences to the distribution of that shown in Figure 17. No FMS_SFL messages were compared, while as expected there was no change for the number of BPS messages compared as this value is only available in Version 2 ADS-B.

The whitelist used to identify verified Version 2, further restricted the available number of plots for comparative analysis, resulting in 2,332 MCP_SFL messages for comparison and 2,327 BPS messages.

Of these 2,332 MCP_SFL Version 2 whitelist messages, 2,305 (98.842%) where within 25ft, while 2,315 (99.48%) of the BPS messages where within ±0.3mb.

4.2.2.3 BDS 5, 0

The assessment recorded 68,238 CAT020 messages that provided BDS 5, 0 reports in the dataset used.

Of these 68,238 reports:

- 68,053 provided Roll Angle (99.729% of all BDS 5, 0 messages),
- 67,446 provided True Track Angle (98.839% of all BDS 5, 0 messages),
- 67,315 provided Groundspeed (98.647% of all BDS 5, 0 messages),
- 63,289 provided Track Angle Rate (92.747% of all BDS 5, 0 messages),
- 67,250 provided True Airspeed (98.552% of all BDS 5, 0 messages).

By comparison, for all versions of ADS-B, there were:

- 5,174,795 CAT021 messages containing Track Angle (28.924% of all CAT021 messages),
- 5,174,795 CAT021 messages containing Groundspeed (28.924% of all CAT021 messages),
- 98 CAT021 messages containing True Airspeed (0.001% of all CAT021 messages).

The comparison assessment between the BDS 5, 0 derived from WAM and the corresponding ADD messages in ADS-B only evaluated messages where an airframe with the same Mode S address (ICAO 24 bit address I020-220 and I021-080) was received by the WAM system and then the ADS-B system within 1 second. Furthermore for this assessment the ADS-B 'Track Angle' data item was compared to the DAP 'True Track Angle' data item.

This time bound reduced the messages for direct comparison to:

- 67,333 (98.674% of BDS 5, 0 messages) for comparison of the Track Angle,
- 67,202 (98.482% of BDS 5, 0 messages) for comparison of the Groundspeed.

The distribution of the difference between the ADD and the DAP for True Airspeed is shown in Figure 20.

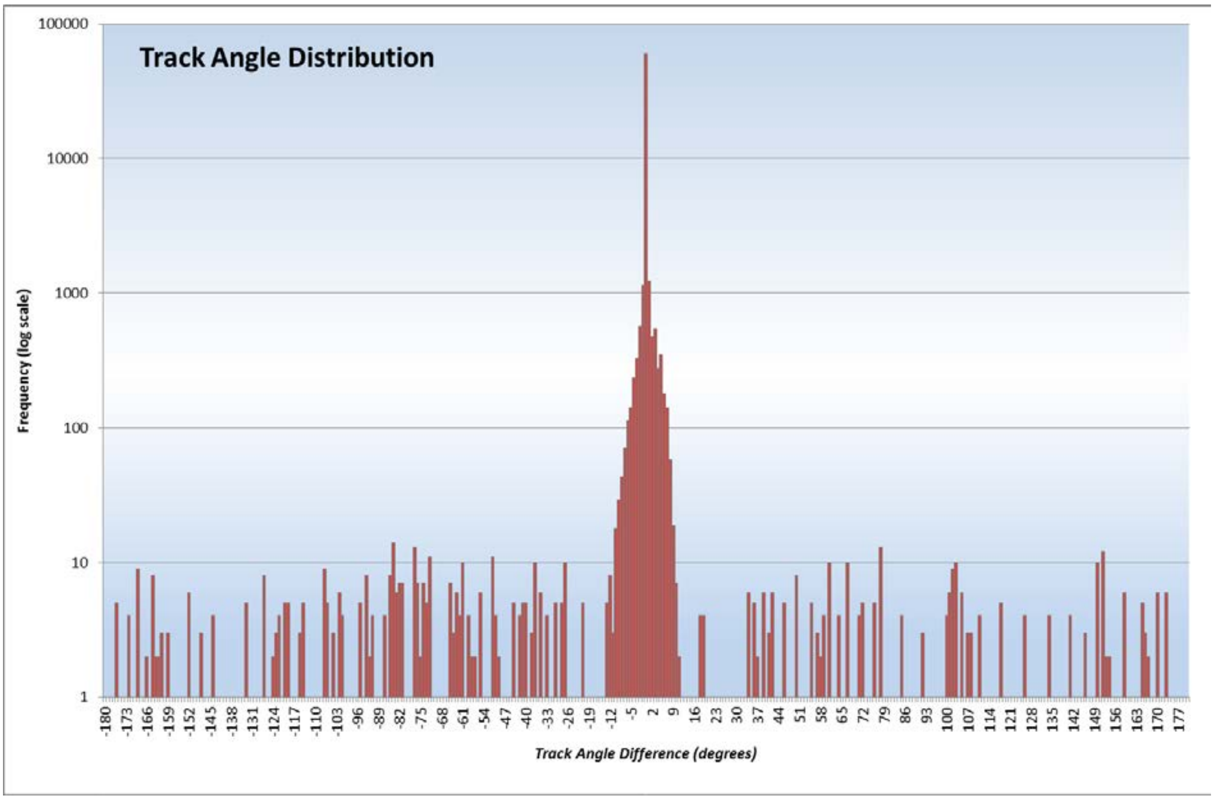

Figure 20: ADD - DAP Track Angle difference distribution

This assessment found that 90.15% of the ADD and DAP values for the Track angle are the same, with 98.03% within ±5° and 99.03% within ±10°. Beyond ±10° the difference between the ADD and DAP value for the Track Angle does not appear to follow a defined distribution, but instead would appear to be more consistent with low level noise. It should be noted that the distribution is not quite uniform, with a steeper drop off for positive differences (the difference was calculated as ADS-B Track Angle minus DAP True Track Angle).

Both Version 2 specific comparisons had similar distributions to those including all versions of ADS-B (aircraft broadcasting Version 2 shown in Figure 21).

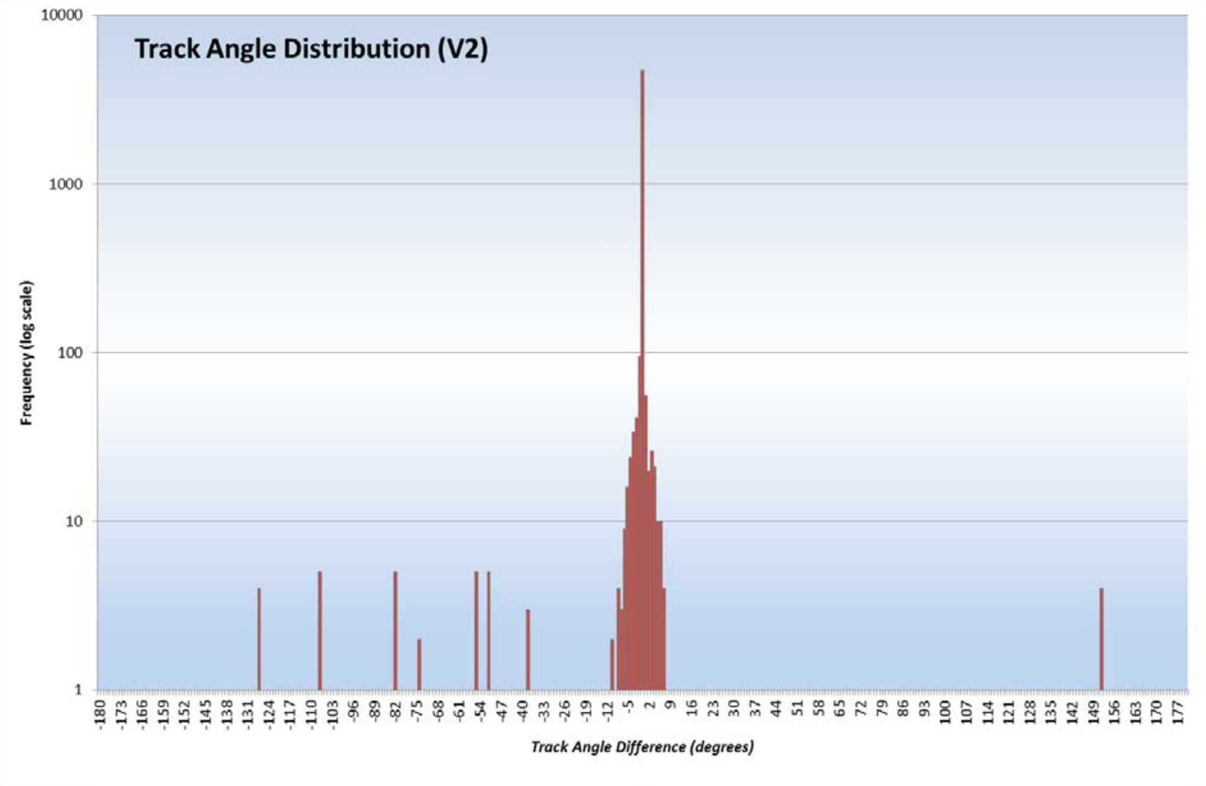

Figure 21: ADD - DAP Track Angle difference distribution for airframes reporting as Version 2

For the Groundspeed comparison the difference was calculated for the ADD Groundspeed minus DAP Groundspeed. Figure 22 shows the distribution from this comparison assessment.

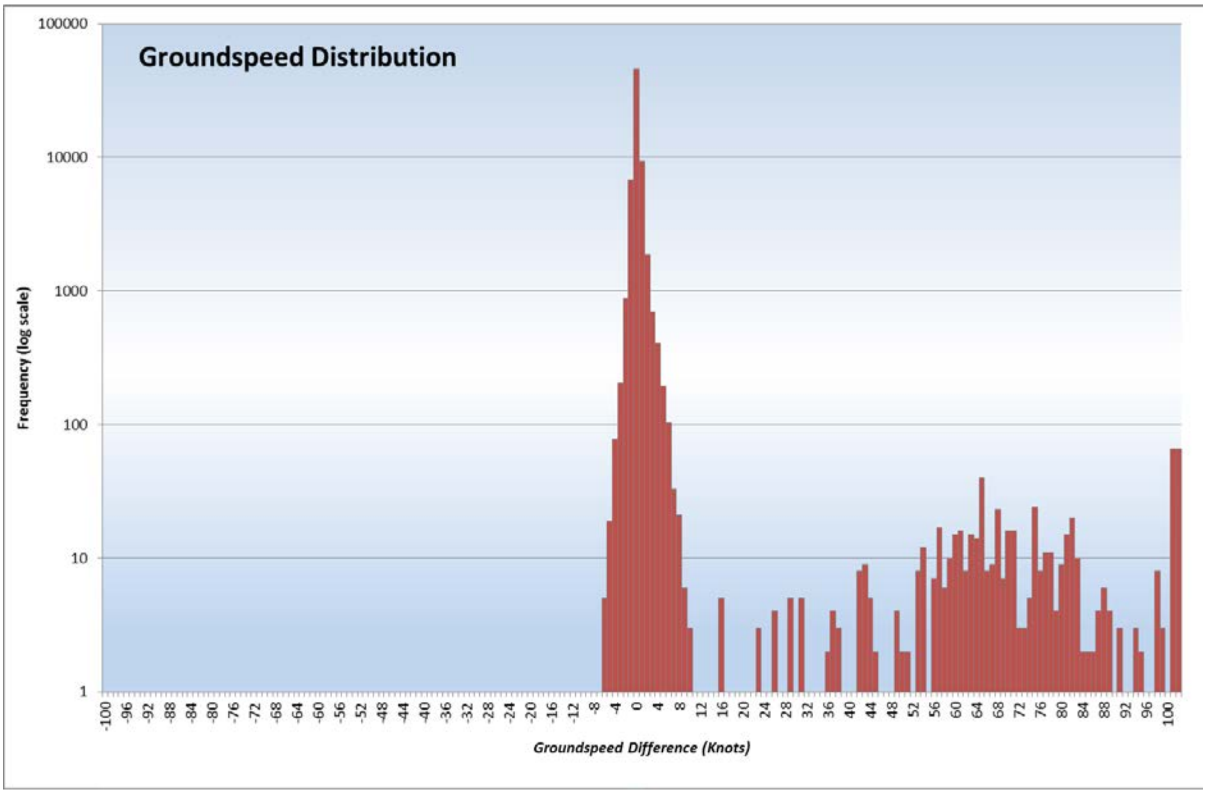

Figure 22: ADD - DAP Groundspeed difference distribution

The assessment indicates that although 98.87% of the values were between ±5 Knots, there was a small skewed flat distribution centred around +65 knots and nearly 100 additional plots greater than ±100 knots different.

Both Version 2 specific comparisons had similar distributions, albeit for smaller samples (5,159 for the Version 2 reporting aircraft (see Figure 23) and 5,144 for the whitelist verified Version 2 airframes).

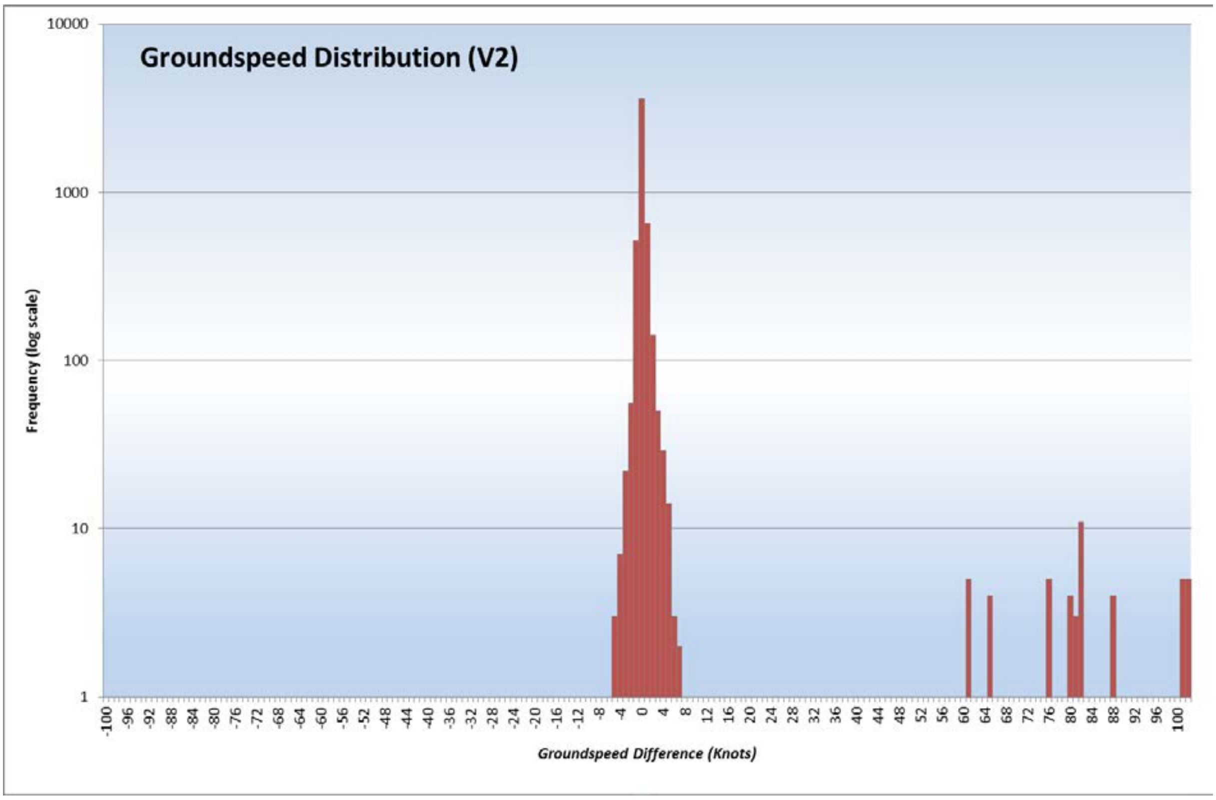

Figure 23: ADD - DAP Groundspeed difference distribution for airframes reporting as Version 2

4.2.2.4 BDS 6, 0

For the BDS 6, 0 assessment there were 70,449 CAT020 messages containing BDS 6, 0 reports. Of which;

- 70,194 (99.638%) contained Magnetic Heading,
- 69,611 (98.810%) contained Indicated Airspeed,
- 69603 (98.799%) contained Mach number,
- 70,092 (99.493%) contained Barometric Altitude Rate (BAR),
- 69,258 (98.309%) contained Inertial Vertical Velocity.

Within all of the ADS-B ASTERIX messages, there were;

- Only 93 that contained Magnetic Heading[4]
- 566,545 that contained Barometric Vertical Rate (BVR).

Of these datasets there was a subset of 7,301 instances of BAR and BVR from the same airframes at the same time (within 1 second). Of the 7,301, messages, 3,916 (53.64%) were from airframes reporting they were Version 2 ADS-B, despite the fact that Version 2 aircraft represent less than 10% of the current ADS-B fleet and this ADD data item should be available in all versions of ADS-B.

The distribution for the difference between the two measurements is shown (ADD BVR minus DAP BAR) below in Figure 24.

[4] It is unknown whether this was from a single airframe.

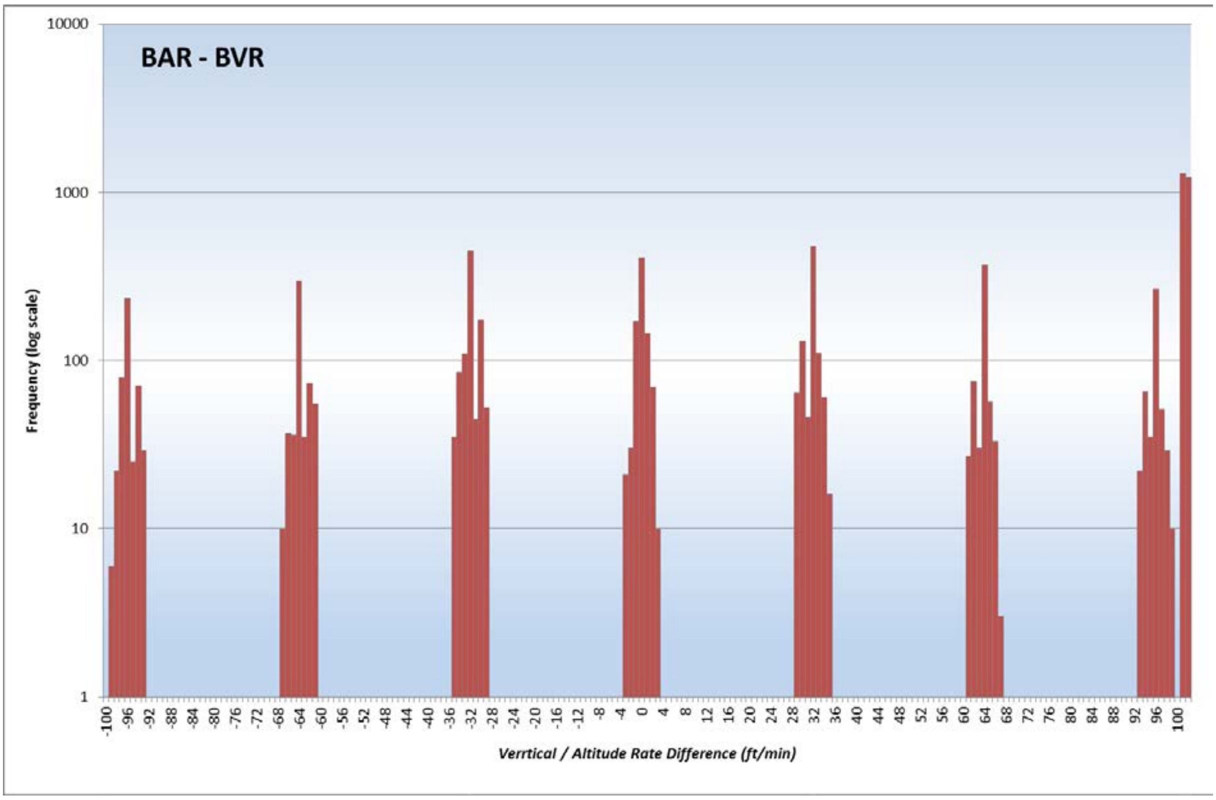

Figure 24: Distribution of ADD BAR minus DAP BVR

It should be noted that the Least Significant Bit (LSB) of the BAR DAP is 32ft/min, while the LSB of the BVR ADD item is 64ft/min. This difference leads to the distributions around quantisation's of 32ft./min as observed in Figure 24. The same distribution is also observed in Figure 25 for airframes reporting as Version 2 ADS-B.

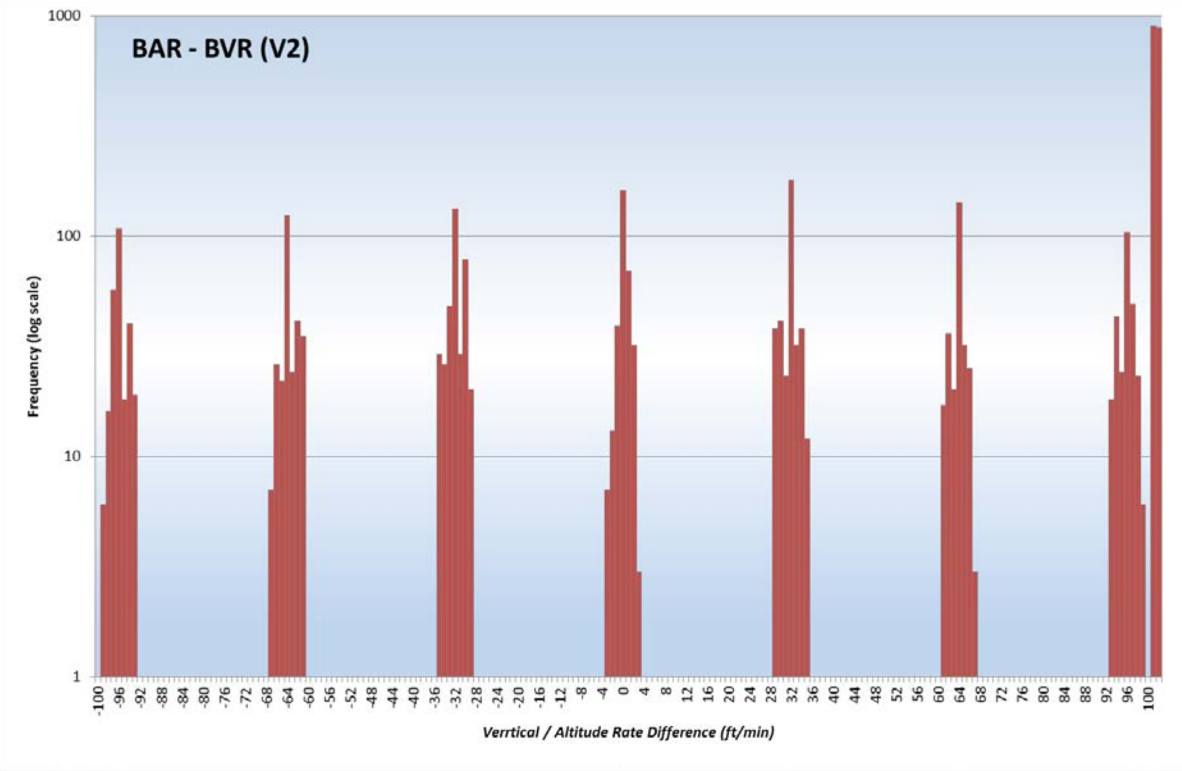

Figure 25: Distribution of ADD BAR minus DAP BVR for aircraft reporting at Version 2

Unfortunately the range of the 'bins' used within this aspect of the assessment was not wide enough to identify where the majority of the differences between the two measurements from the ADD and DAP tails off as the two columns on the far right indicating the <-100ft/min and >+100ft/min are just under 10 times as large as the peaks around the 32ft/min quantisation's. However, it should be noted that in Figure 24, the central distribution around 0 ft/min only contains 11.6% of all of the plots, suggesting the difference between the BAR and BVR is wide.

4.2.3 WAM Accuracy & Detection

Due to difficulties encountered with incorporating the ADS-B data recorded on the CRISTAL Platform into SASS-C version 6.7.0.4040, it was not possible to conduct the accuracy and detection and therefore separation standards analysis for UK ADS-B data. Instead, only the validated WAM in CAT020 ed1.5 format provided by the CRISTAL platform (THALES MAGS with 7 receivers) was analysed.

The analysis was based on a four hour dataset from 15/05/16 10:00 – 13:00 and analysed in SASS-C against NATS CAT0562 track data from Mode S radars.

Figure 26 displays a sample of the 'validated' WAM coverage received in the CRISTAL system.

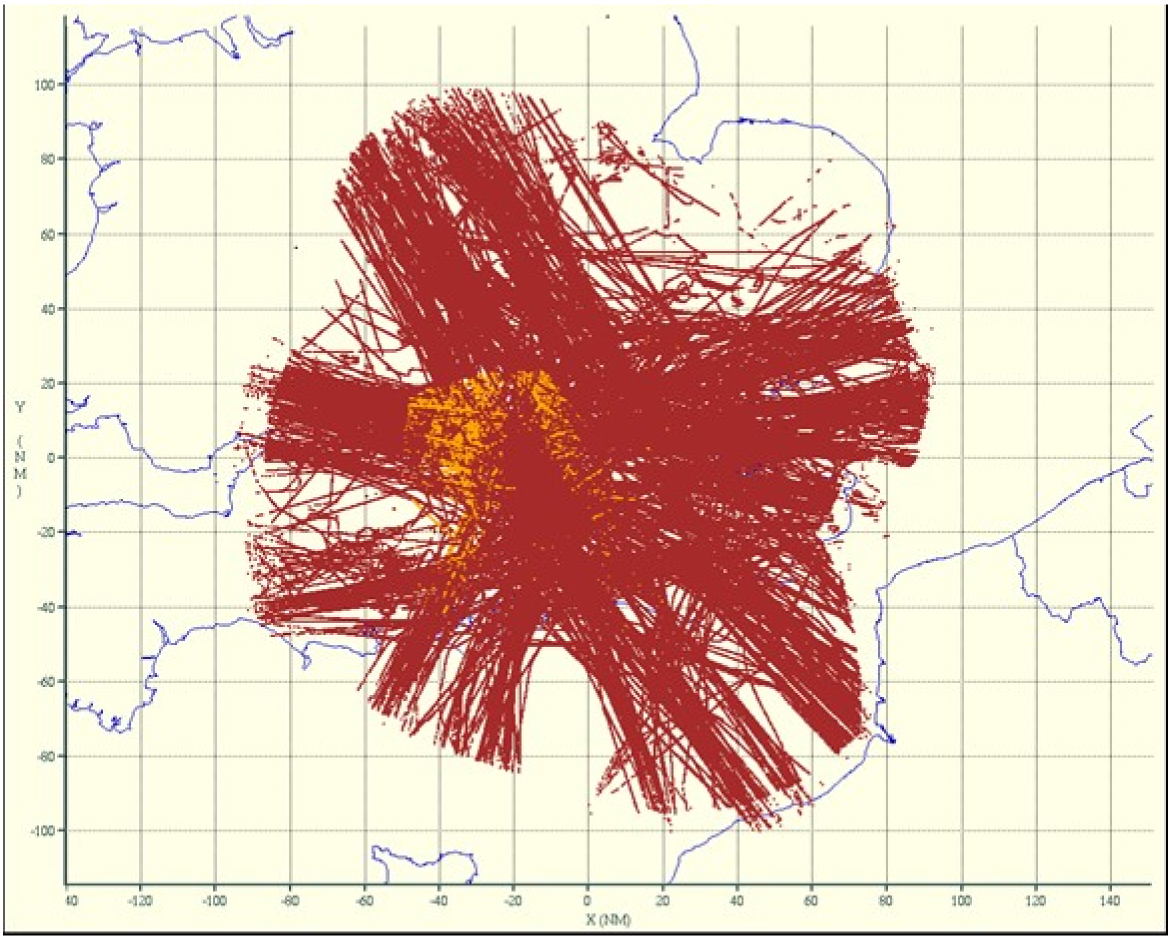

Figure 26: Sample of WAM plots from CRISTAL validation platform to show validated plot coverage.

The metrics used in the assessment were taken from a subset of ESASSP [19] criterion and summarised below in Table 17. Due to the limited resource available for the assessment, only six key criterion were used in this assessment.

The WAM data assessed was restricted to the 'validated WAM plots' within defined 'Coverage Assessment Volumes' (CAVs). Two CAVs were required to differentiate the London Terminal Control coverage requirements for low level airspace and high level airspace. These are referred to as 'TC Lower CAV' and 'TC Upper CAV'.

ESASSP Assessment Criterion	Description	Evaluation Criteria
ESASSP -3N_N-R2	Probability of update of horizontal position	**Greater than or equal to 97% for 100% of the flights, any flight below 97% shall be investigated as defined in R22**
ESASSP -3N_N-R3	Ratio of missed 3D position involved in long gaps (larger than 16.5 s = 3 x 5 s + 10%)	**Less than or equal to 0.5 %**
ESASSP -3N_N-R4	Horizontal position RMS error	**Less than or equal to 300 metres global and less than 330 metres for 100% of the flights, any flight below 550 m shall be investigated as defined in R22**
ESASSP -3N_N-R7	Probability of update of pressure altitude with correct value	**Greater than or equal to 96 % global**
ESASSP -3N_N-R14	Probability of update of aircraft identity with correct value	**Greater than or equal to 98 % global**
ESASSP -3N_N-R15	Ratio of incorrect aircraft identity	**Less than or equal to 0.1 %**

Table 17: ESASSP Criterion used in NATS WAM Accuracy and Detection assessment

The results of the assessment are provided in Table 18.

			TC Lower			TC Upper			TC Upper 'Mod'		
ESASSP assessment criterion		Target	WAM 1s	WAM 4s	WAM 6s	WAM 1s	WAM 4s	WAM 6s	WAM 1s	WAM 4s	WAM 6s
3N_C-R2	PU % Overall	97	90.74%	98.99%	99.33%	89.16%	98.72%	97.17%	93.24%	99.35%	99.51%
	Pu % FL20 - 30		68.66%	91.92%	93.72%	n/a	n/a	n/a	n/a	n/a	n/a
	Pu % FL30 - 40		79.73%	97.64%	98.90%	n/a	n/a	n/a	n/a	n/a	n/a
	Pu % FL40 - 50		87.85%	99.59%	99.85%	87.29%	98.15%	98.89%	87.43%	98.44%	98.96%
	Pu % FL50 - 60		92.84%	99.84%	99.95%	90.56%	99.19%	99.43%	90.69%	99.32%	99.54%
	Pu % FL60 - 70		94.01%	99.86%	99.93%	91.14%	99.06%	99.27%	91.29%	99.10%	99.36%
	Pu % FL70 - 80		94.67%	99.81%	99.93%	92.61%	99.35%	99.24%	92.65%	99.03%	99.24%
	Pu % FL80 - 90		95.22%	99.94%	99.99%	94.22%	99.03%	99.22%	94.33%	99.18%	99.25%
	Pu % FL90 - 100		95.32%	99.99%	100.00%	93.37%	98.64%	98.98%	93.57%	98.94%	99.11%
	Pu % FL100 - 195		97.31%	99.99%	100.00%	92.35%	99.14%	98.54%	94.85%	99.53%	99.63%
	Pu % FL195 - 250		n/a	n/a	n/a	75.13%	96.78%	88.40%	92.37%	99.70%	99.84%
	Chains below 97% PD	0	366	12	1	320	53	50	303	2	1
3N_C-R3	3D gap ratio	<0.5%	5.00%	0.16%	0.03%	7.35%	2.44%	2.49%	2.85%	0.10%	0.07%
	3D gap Misses		25669	229	24	34708	3441	2078	12728	133	53
	3D gap returns		512758	139935	75243	471934	140656	83468	446378	135103	75460
3N_C-R4	Horizontal Errors average	<330m	61.4			61.1			60.1		
	returns		449924			428720			414808		
	chains		769			753			750		
3N_C-R7	Correct Mode C	>96%	99.98	100.00%	99.99%	99.99%	100.00%	100.00%	99.99	100	100

			TC Lower			TC Upper			TC Upper 'Mod'		
ESASSP assessment criterion		Target	WAM 1s	WAM 4s	WAM 6s	WAM 1s	WAM 4s	WAM 6s	WAM 1s	WAM 4s	WAM 6s
3N_C-R14	Correct mode A >1000ft	>98%	100	99.99%	100.00%	100.00%	100.00%	100.00%	100	100	100
3N_C-R15	Incorrect and validated mode A >1000ft	<0.1%	0	0.00%	0.00%	0.00%	0.00%	0.00%	0	0	0

Table 18: Results of WAM Accuracy and Detection Asssment

The results of the high level ESASSP analysis for the WAM provided by the CRISTAL platform (shown in Table 18) indicate that the performance for WAM provided at a 1 second update rate would not be able to support 3NM separation within the three coverage assessment volumes (CAVs) defined for the analysis.

For the ‘TC Lower’ CAV the six ESASSP requirements are met for the WAM update rates of 4 and 6 seconds, with the exception of the probability of update (PU) between FL20 and FL30 which falls below the 97% requirement in both instances. At this altitude, the majority of commercial air traffic is either departing or arriving London terminal airfields. The configuration of the groundstation network for CRISTAL is not ideally suited for such low level coverage as all but two of the groundstations are located at a considerable distance from the terminal airfields. As such, the line-of-sight (LOS) at low level near the airports to three or more of the receivers is unlikely, leading to the poor probability of update observed.

The ‘TC Upper’ CAV which does not extend as low (FL40), was able to meet the probability of update requirements for the majority of the volume, with the exception of the highest area extended out to the east of the CAV, where the PU target was not met. This region is over the North Sea, with the receivers providing the coverage all located inland to one side, and all at considerable distance from the area.

Although this region is part of London Terminal Control airspace, it is not part of the London Terminal Manoeuvring Area (LTMA). Restricting the eastern extent of this coverage volume to only include the TMA aspect, and thereby removing the ‘off shore’ coverage, led to a slightly smaller ‘TC Upper Mod’ CAV that was able to meet all of the PU requirements at all levels assessed.

ESASSP assessment criterion 3N_C-R3 which is the ‘3D gap ratio’ was also not met for the TC Upper CAV, but was met for the TC Upper Mod CAV for the 4 and 6 second update ratios.

It should also be noted that the placement of the groundstations was not optimal for the performance of the CAVs, but instead constrained by site availability and access. However, the analysis shows that the sub-optimal sites are still able to provide a surveillance (based on the six ESASSP requirements assessed) suitable for a 3NM separation service over the majority of the LTMA and London Terminal Control area of responsibility.

ESASSP assessment criterion 3N_C-R4 which requires that the Horizontal Errors average less than 330m, was met within all three CAVs analysed, where the average error was 61.4m within ‘TC Lower’, 61.1m within ‘TC Upper’ and 60.1m within ‘TC Upper Mod’. The following three figures and key, display the accuracy analysis plots by 10NM x 10NM cells.

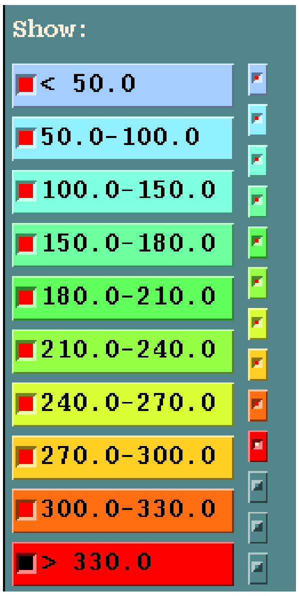

Table 19: Accuracy Analysis colour key

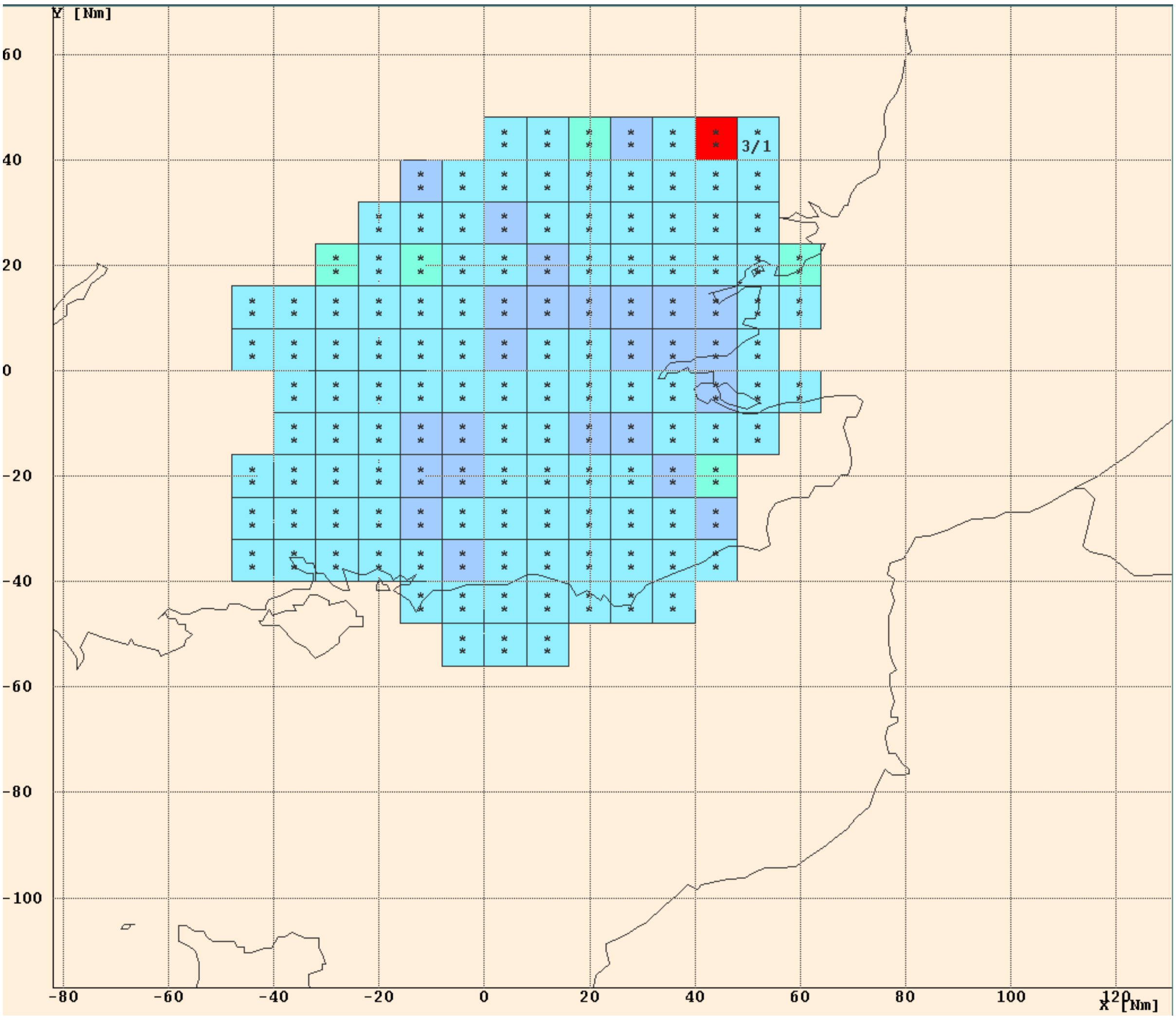

Figure 27: TC Lower CAV Accuracy, note red square caused by 2 random returns.

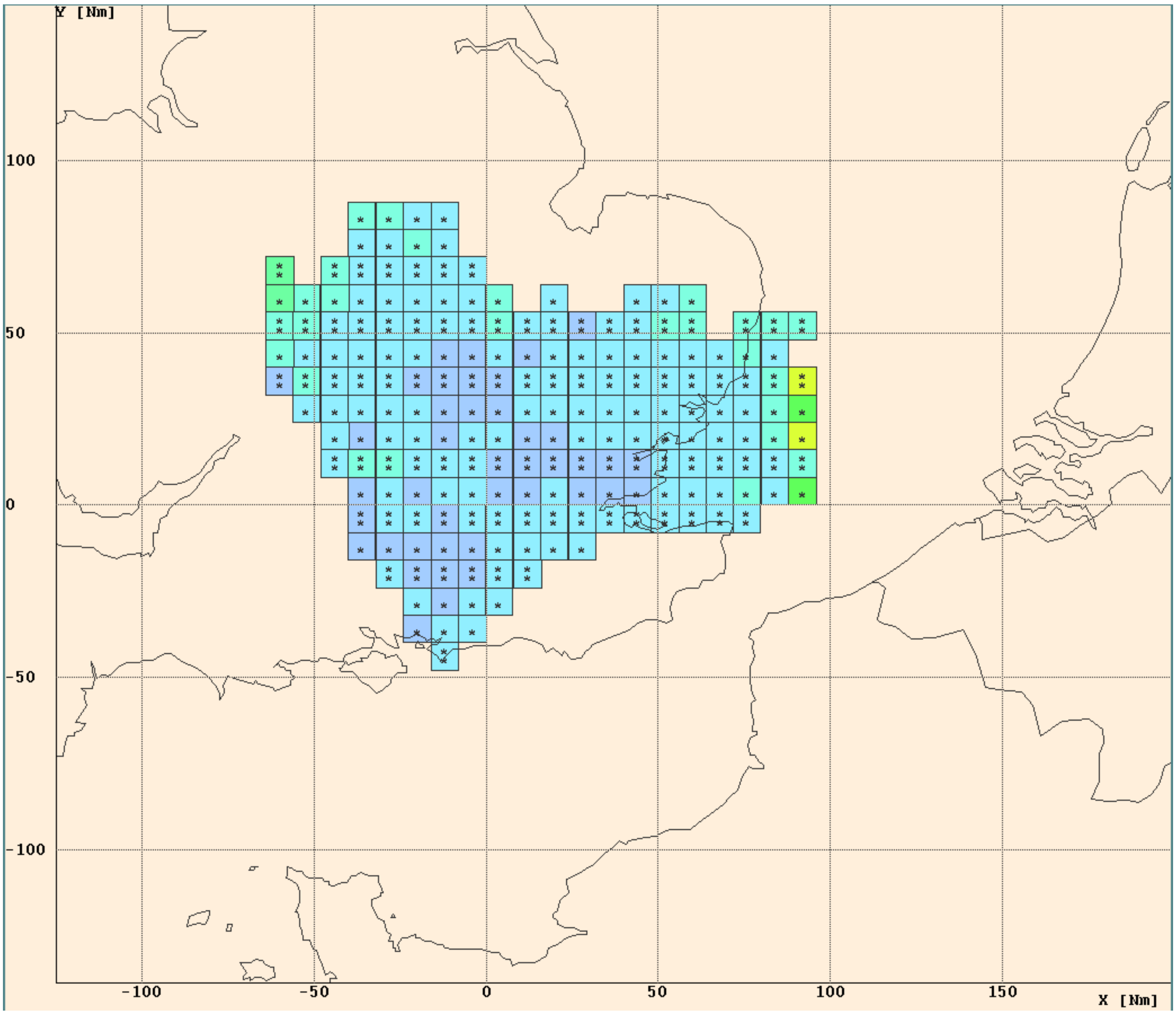

Figure 28: TC Upper CAV accuracy analysis, note lower PU to Eastern edge of volume

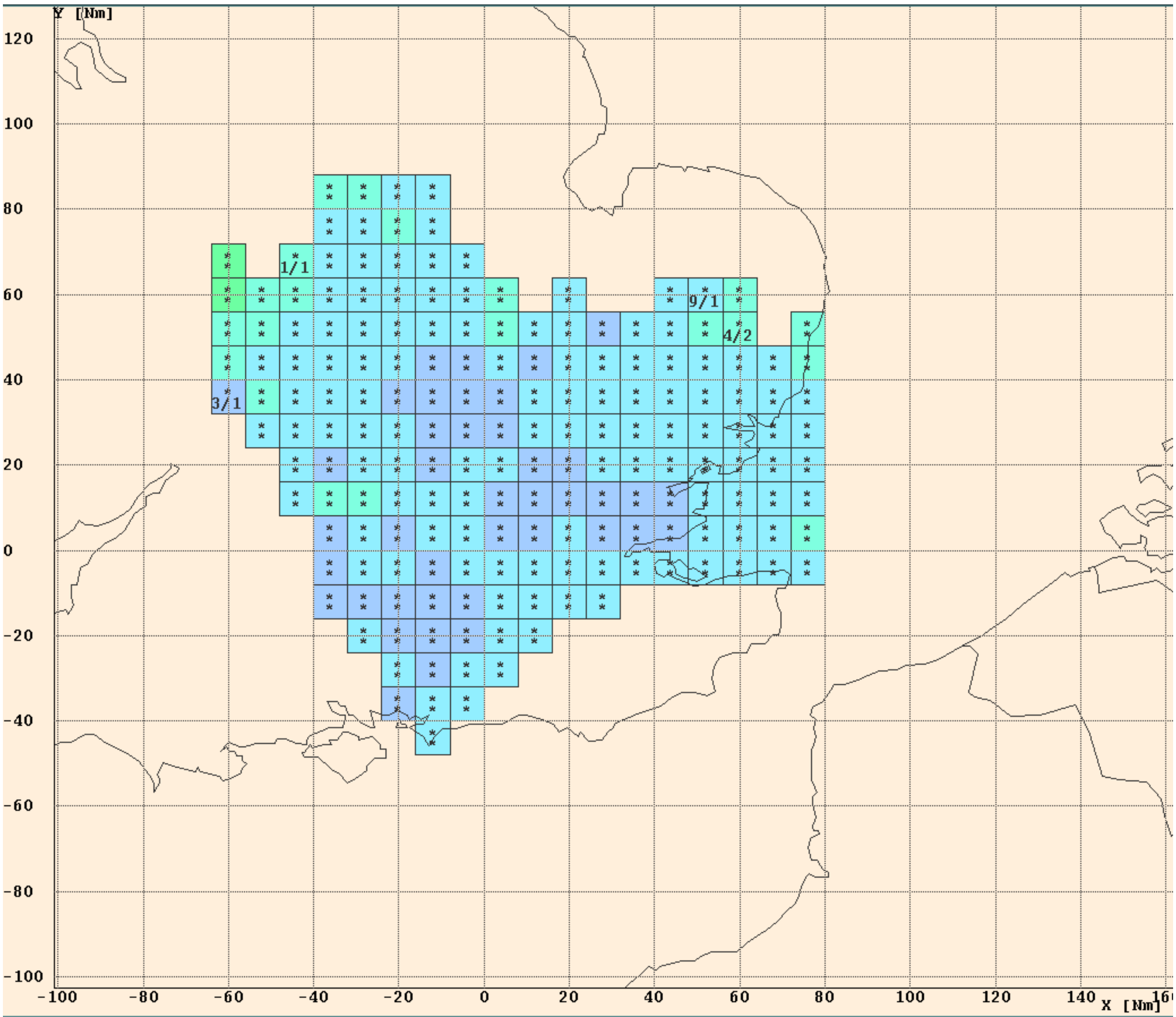

Figure 29: TC Upper 'Modified CAV' Accuracy -removing 'Clacton' area to East of TMA

4.2.4 User Acceptance Trial

The original intent of this particular trial was to demonstrate the multi-surveillance tracker (MST) concept side by side with the existing NATS multi-radar tracker (MRT) situation display picture in front of operational staff to provide validation through expert judgement. User acceptance trials are necessary to provide assurance of controller confidence in the surveillance picture provided by ADS-B and WAM.

As the project progressed it became apparent that the original intent and method of displaying the ADS-B and WAM data would not be possible as firstly, the integration with the MST did not take place and secondly, the use of the NATS Space facility and integrated real time simulation suite would not be able to provide a sufficient fidelity display for the resource available to the project.

Instead a smaller ‘portable solution using the same core software components as the Space facility was progressed and used within the trials.

Figure 30: Setup for User Acceptance Testing, large display for CAT021 and smaller laptop display for CAT020

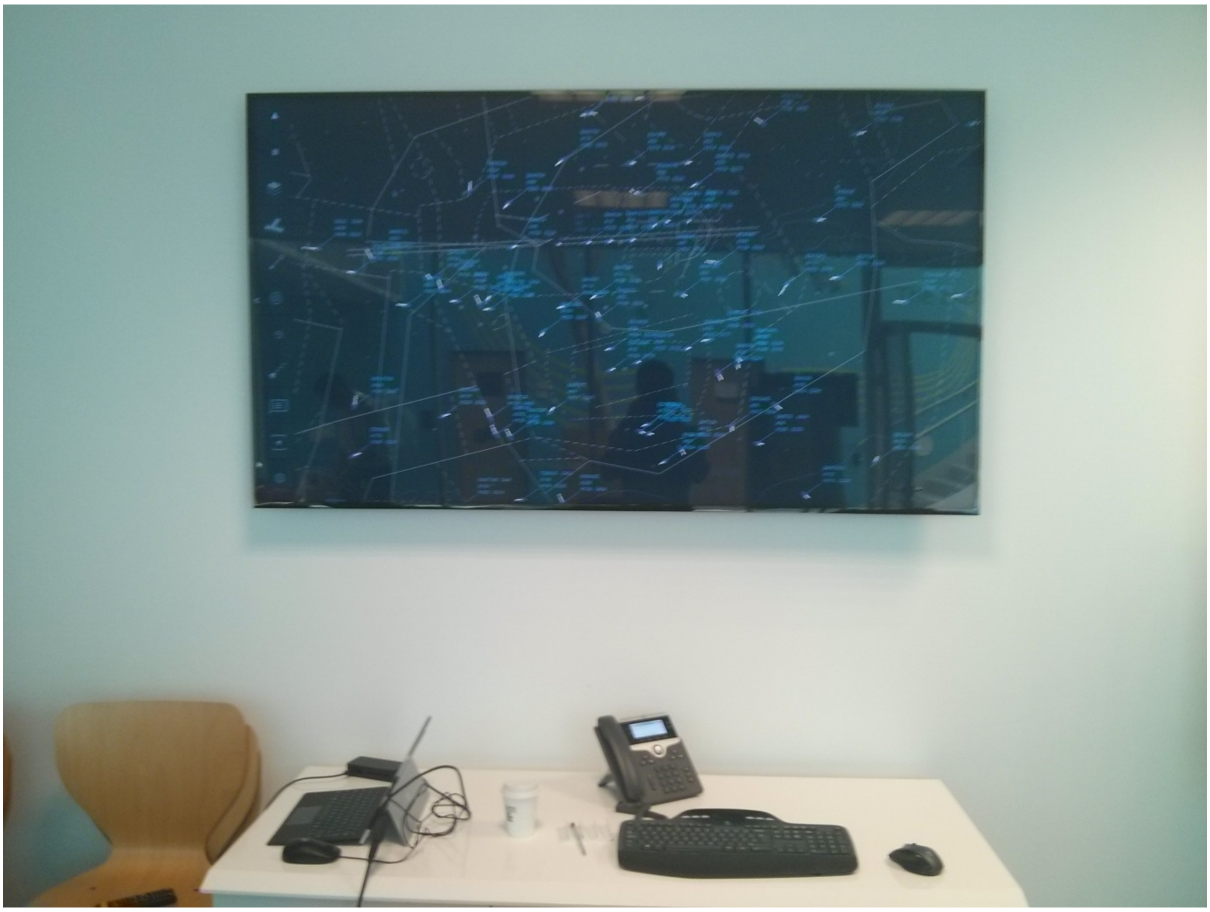

Figure 31: Close up of recorded CAT021 represented on display for user acceptance testing

The feedback from the UAT was primarily received through completion of questionnaires that asked the following questions:

ADS-B
After viewing the **ADS-B** Replay, what are you views on the following aspects?

- Would you be happy trusting the aircraft to provide its position?
- Track Offsets (for older Version 0 airframes reporting incorrect position)?
- 1 Second Update rate
- Track Jitter
- Track heading or Track Angle
- Turn Delay / Aircraft manoeuvring characteristics
- Does the ADS-B track picture have any unexpected attributes compared to the track picture you are used to? Please describe/list.
- Do the tracks provide you with confidence that they are displaying the position of the aircraft correctly?

WAM
After viewing the **WAM** Replay, what are you views on the following aspects?

- 1 Second Update rate
- Track Jitter
- Track heading

- Turn Delay / Aircraft manoeuvring characteristics
- Does the ADS-B track picture have any unexpected attributes compared to the track picture you are used to? Please describe/list.
- Do the tracks provide you with confidence that they are displaying the position of the aircraft correctly?
- Any other comments for either ADS-B or WAM (please state which).

Eight Questionnaires were completed by the expert judgement staff. The following list summarises the responses received for the display for ADS-B data:

ADS-B

- Would you be happy trusting the aircraft to provide its position?
  - All eight respondents provided a comment on this question, with half responding positively.
- Track Offsets (for older Version 0 airframes reporting incorrect position)?
  - Only three respondents provided a comment, of which two were negative and one was intermediate.
- 1 Second Update rate
  - All but one of the respondents provided a comment this question and five (71.4% of the respondents) provided a positive comment.
- Track Jitter
  - Half of the respondents provided a comment or a 'N/A' answer. The split between, positive, intermediate, negative and not applicable was even with one response each.
- Track heading or Track Angle
  - This question also generated few responses, with only three completed comments, of which one was positive, one intermediate and one 'not applicable'.
- Turn Delay / Aircraft manoeuvring characteristics
  - Of the two responses returned for this question, one was positive the other was intermediate.
- Does the ADS-B track picture have any unexpected attributes compared to the track picture you are used to? Please describe/list.
  - Of the three responses returned, the result was even between, positive, intermediate and negative.
- Do the tracks provide you with confidence that they are displaying the position of the aircraft correctly?
  - Four of the five responses returned for this question were positive (80%), while the other was intermediate, indicating an overall positive response for this question.

Plotting the completed graded results of the ADS-B specific questions provides the following Figure 32.

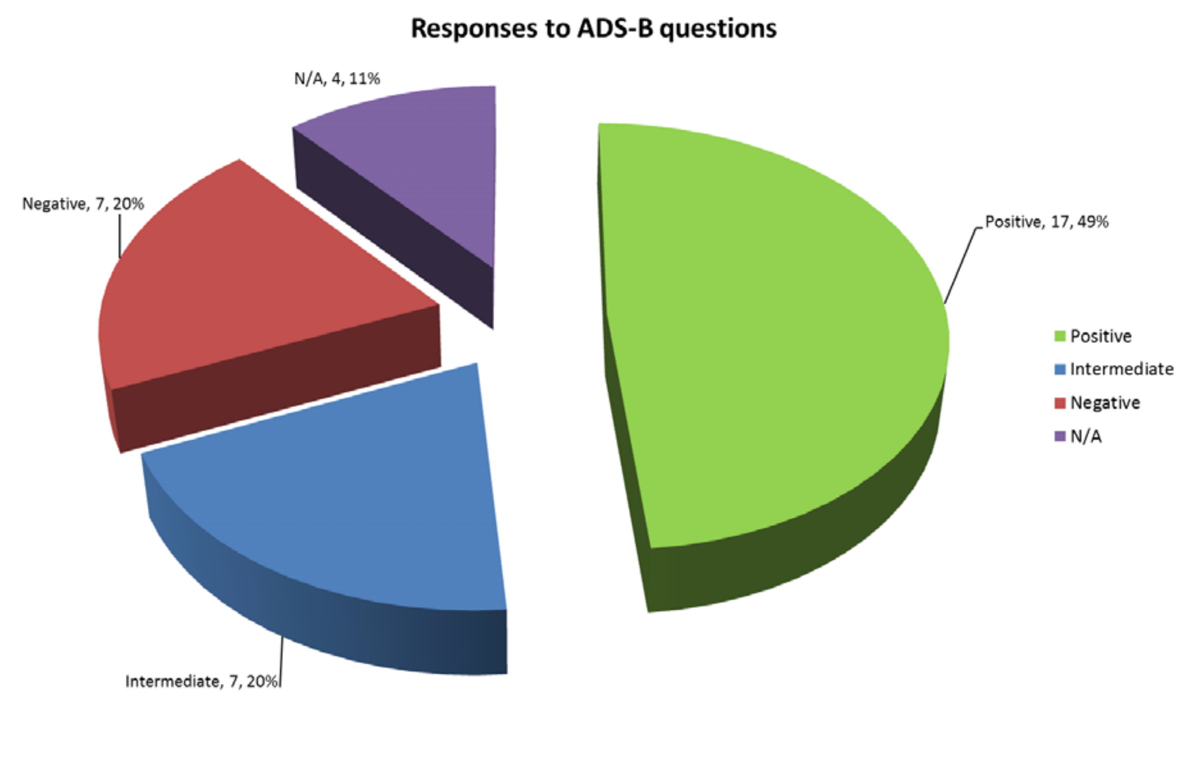

Figure 32: Results for completed ADS-B specific questions

Overall, just under half of the completed responses were positive compared to 20% negative, with a further 20% 'intermediate'.

The following graded responses were received for the WAM display:

WAM
After viewing the **WAM** Replay, what are you views on the following aspects?

- 1 Second Update rate
  - All five of the responses returned for this question were positive, indicating that the opinion of the expert group was a 1 second update rate would be beneficial.
- Track Jitter
  - Only three of the responses provide a comment for this question, with one positive, one intermediate and one not applicable. This opinion of this aspect of the surveillance source is inconclusive.
- Track heading
  - Of the two responses received, one was positive, while the other was not applicable to the aspect under consideration.
- Turn Delay / Aircraft manoeuvring characteristics
  - The one received response was positive for this question.
- Does the ADS-B track picture have any unexpected attributes compared to the track picture you are used to? Please describe/list.
  - Two responses were received for this question, one was summarily assessed as intermediate, while the other was generally negative.
- Do the tracks provide you with confidence that they are displaying the position of the aircraft correctly?

  - All three of the responses received for this question were positive in response, suggesting the expert group were confident in the surveillance picture provided by WAM.
- Any other comments for either ADS-B or WAM (please state which).
  - Three of the five responses received for this question were positive, one was intermediate and the last was described as ‘not applicable’.

Plotting the completed graded results of the WAM specific questions provides the following Figure 33.

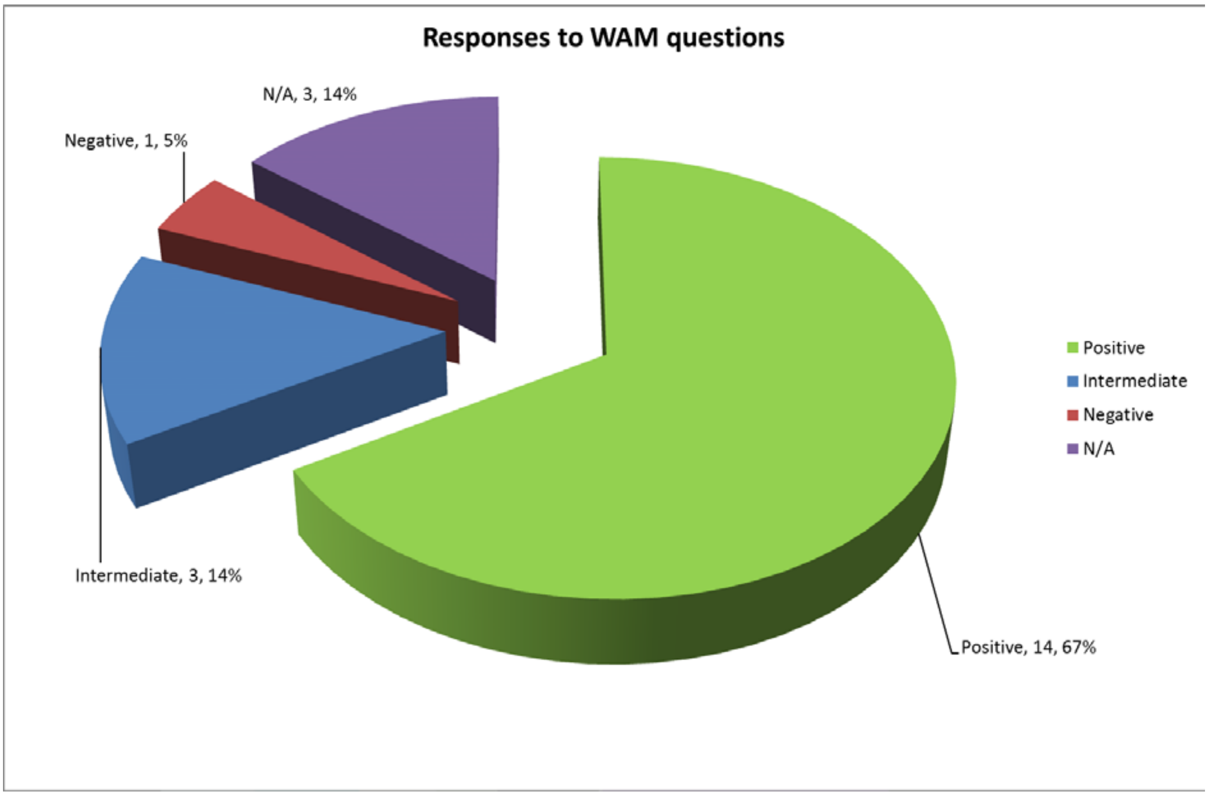

Figure 33: Results for completed ADS-B specific questions

For these questions, the majority of the responses (67%) were positive of WAM data and characteristics, with only 5% negative and 14% intermediate.

Overall combing the general grading of the completed responses for both sets of questions provides Figure 34 indicating an overall positive response to the ADS-B and WAM data and its characteristics.

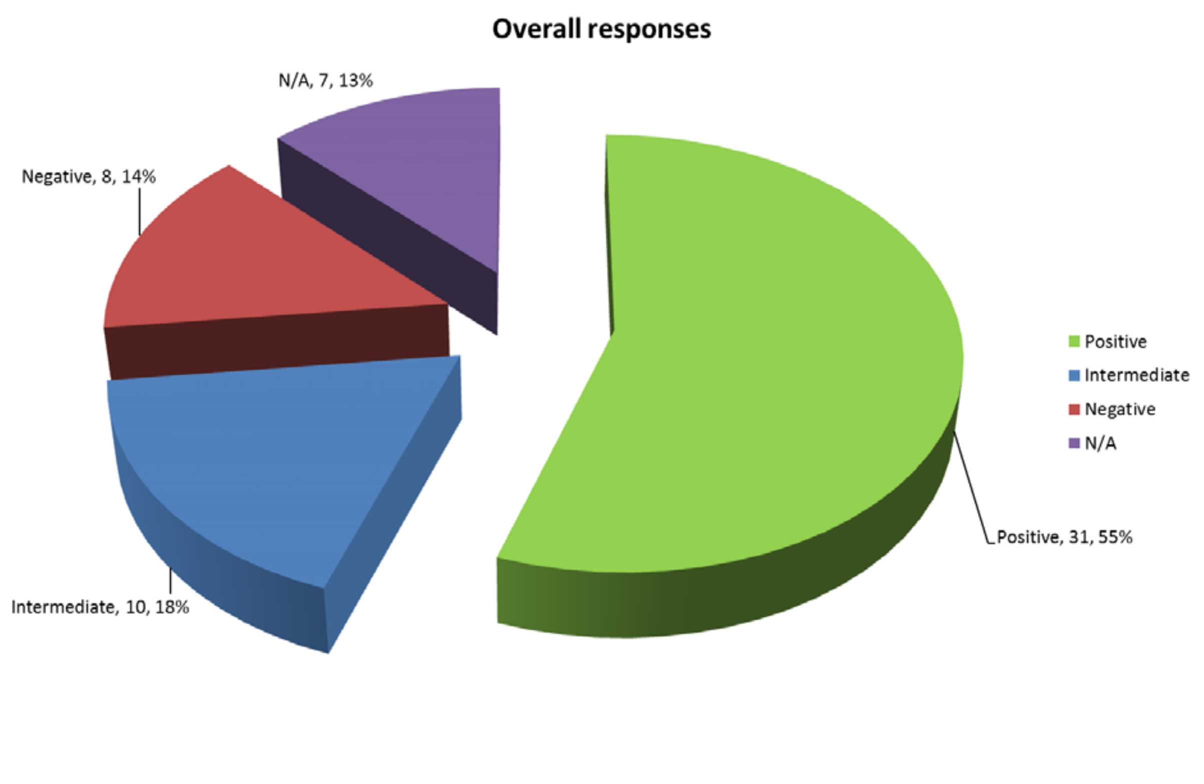

Figure 34: Overall completed results

When combined with the verbal feedback and written comments from the questionnaires the following themes are observed:

The dependent nature of ADS-B whereby the surveillance position is provided by the aircraft rather than independently determined by ground based sources was highlighted as a concern by the operational expert judgement group. It should be noted that the situation display used in the UAT included ADS-B V0 aircraft, of which a few could be observed during the replay to have systematic lateral offsets from the actual position of the aircraft (as visually identified by an offset from the extended centreline on approach to EGLL). It is assumed that these 'Version 0' airframes were broadcasting position based on Inertial Reference Systems rather than GPS. Although the 15.04.02 project analysis assumes Version 2 will be mandated, as it currently stands there will likely be exemptions to this mandate as well as aircraft that could be in a fault state, therefore the transmission of incorrect positions could still occur. As such, the ADS-B position validation techniques identified within the 15.04 projects will be necessary to identify such instances before the confidence of the operational staff for the suitability of using ADS-B for separation services is attained.

Although not an issue directly related to the ADS-B or WAM data, the possibility to provide update rates greater than that of existing rotating short and long range radar was explored by the validation as it would be applicable to the intended application. *[It should be noted that the results from section 4.2.3 were not available for the UAT.*] Overall the responses to the questionnaires were favourable, however it was noted that if implemented, the track history / trail dots HMI would need to be long enough to facilitate the controller to observe the track heading / motion of aircraft. It was also noted several times that the increased and closely spaced trail dots did not allow the controllers to quickly ascertain the speed of the aircraft as they do today, as such, despite providing a higher fidelity of aircraft motion, the additional plots would likely reduce a controllers situational awareness. It was however recognised that the additional fidelity of the tracks could benefit short term trajectory based controller tools, such as facilitating safety nets for independent parallel approaches.

Several comments were received in relation to the use of the ADS-B and WAM data in non-separation service uses. The use of the data was linked the extended coverage provided by the ADS-B when compared to the existing secondary surveillance coverage which is artificially limited.

4.3 Indra Verification Report

All the reported in the sections below and the recordings made have been done taking into account that there is increasing pressure for ATM to improve the manner in which the RF spectrum currently assigned to it is managed and used. This is coming not only from parties external to ATM but the increasing use of the 1030/1090 MHz band is also increasing pressure from within.

The RF spectrum is core to the correct functioning of all surveillance techniques and technologies. Demands upon the spectrum need to be managed and improvements need to be made to accommodate the increasing demands being placed upon it – both from within ATM and from external sources.

These are the main reasons why the recordings of the targets have been done in passive mode, using the Extended Squitter for the acquisition of the targets. In this way, the spectrum of the TMA environment is not affected. However, for the Ranging Validation the active mode has been necessary.

Recordings have been performed during one week, with different system configurations (passive and active system).

In total more than 13 Million reports have recorded during one week reports have been recorded.

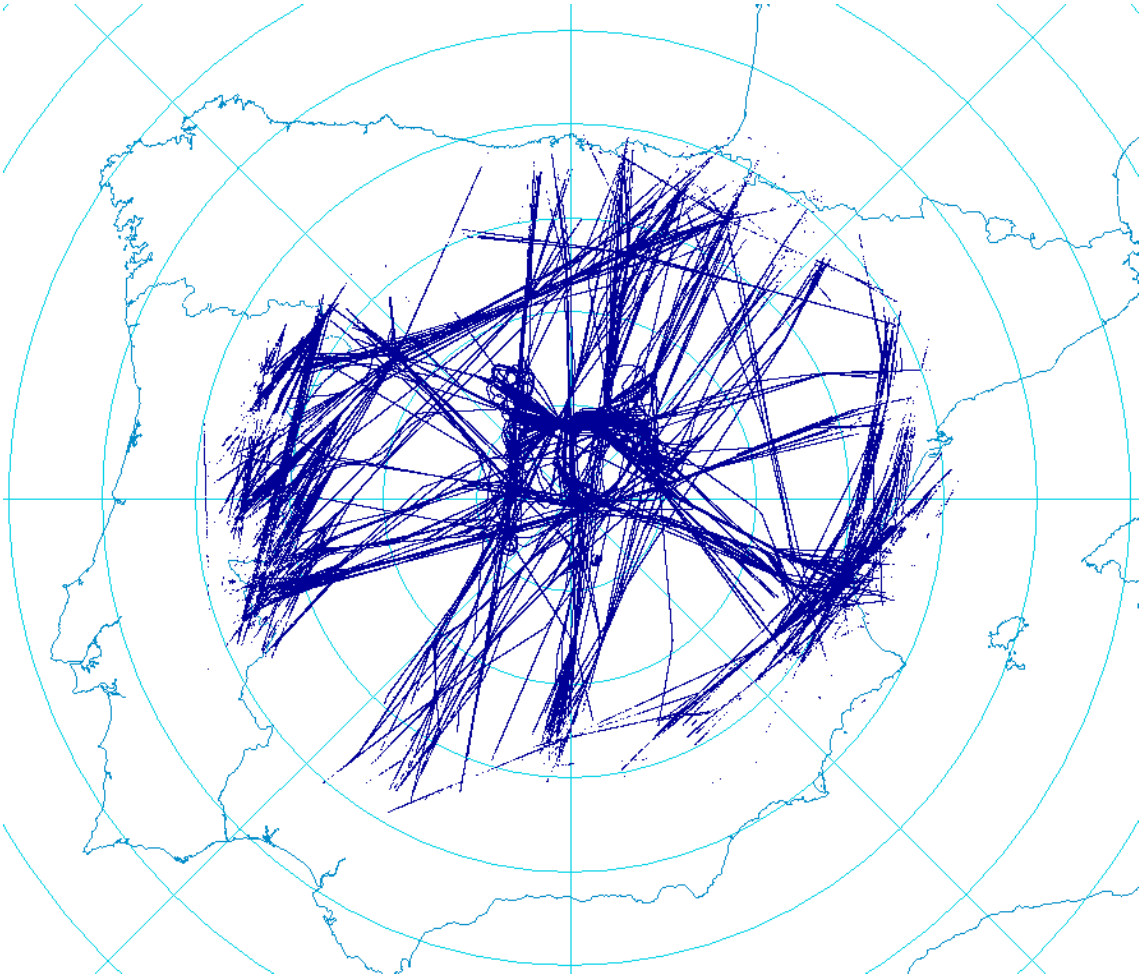

Figure 35: Recorded targets without filter

Indra test system is installed in the surroundings of Madrid, and provides coverage to an extension around 30NM of the system geographical centre. Data for analysis has been filtered to this maximum range, in order to have all functionalities available (only one interrogator is installed). In Altitude, data has been also filtered, as approaching flights to Madrid airport are not normally detected in the final phase, as there is not line of sight with enough receivers for multilateration.

After this data filtering, an outcome of data between 3 and 4 Million reports have been analysed for each of the different validations.

Recorded Reports	13125393
Recording duration	72
Range filter	< 30NM
Altitude filter	> 4000ft
Filtered reports Full-Wam	4035488
Filtered reports partial position	4035488
Filtered reports RAI/ModeA/C/Callsign	3498564

Table 20: Total number of Reports

4.3.1 Comparison of ADS-B and WAM lateral positions

This Section describes the objectives and principles of the comparison of an aircraft's ADS-B lateral position against its independently determined WAM position. It indicates the error characteristics that need to be taken into account in determining an appropriate difference threshold and containment bound. A simple method of doing this is described, but implementers are free to design their own method to better satisfy the same requirements for their system.

The objective of the ADS-B / WAM comparison is to determine whether or not the two positions agree, but within certain bounds and probability. In principle, the 2D position difference between ADS-B and WAM positions at the same time of applicability are tested against a threshold value, but what is an appropriate threshold value? Indeed, an appropriate threshold value needs to take account of the likely position errors on both ADS-B and WAM position measurements.

When both ADS-B and WAM systems are in their nominal (no fault) state and therefore working within their expected position measurement performance limits, there will generally be some difference between their positions because of normal measurement errors in each position. Consequently, in the nominal state, there will be some probability that the difference between the two positions will happen to exceed the threshold – this is referred to as a "false alert" (i.e. a significant difference is flagged, but there are no faults in either ADS-B or WAM systems). The probability of a false alert will depend upon the relative magnitudes of the threshold and the expected position errors distributions in each source. The expected probability of false alert is therefore a configurable system parameter that will control the position difference threshold.

If there is a fault in the ADS-B position source (either from an undetected GPS satellite fault or some other systematic aircraft installation fault), then there is likely to be some sustained bias error in the ADS-B position:- this is of course what we want to detect by comparison against the WAM position. However, because of the normal measurement errors, there will be some lower limit to the magnitude of the fault bias error that can be detected without excessive false alerts. Consequently, it is important to qualify the extent to which the comparison is able detect a fault bias and it is here that the notion of the containment bound is used. The containment bound defines the magnitude of a sustained position fault bias that can be detected (or not detected) with a certain required probability. Conventionally, this probability is expressed as a "missed alert" probability. Again, the containment bound will depend upon the magnitudes of normally expected position measurement errors an indeed, as shown in this Section, it can be simply derived from the position difference threshold.

4.3.2 Normal Measurement Errors

The difference threshold value that is needed for the comparison of positions must take into account the normally expected uncertainties in the position information from both ADS-B and WAM. The normal errors will include contributions from:

<u>Expected accuracy of ADS-B position source.</u>

ADS-B position accuracy is conventionally defined by the 95% error radius and this is qualified by NACp in ADS-B version 1 onwards. For version 0, there is no accuracy qualifier, but a worst case accuracy can be derived from the NUC integrity qualifier (i.e. accuracy = NUC/2).

However, for various reasons, the NACp (and NUCp) qualifier gives very conservative position accuracy values that are not truly representative of the real accuracy of the GPS source. Consequently, it may be better to use a configurable default parameter for a more realist, yet still conservative, accuracy value for ADS-B.

[Note the NACp accuracy qualifier is not sent in the same message as position, so an earlier value has to be maintained or an assumed default accuracy value used].

The 2D (radius) accuracy errors from the ADS-B GPS source are assumed to be Rayleigh distributed. There is no other information sent to describe the component errors in any finer detail, so it is simply assumed that the errors in each dimension (x,y) are the same and can be modelled as independent Gaussian distributions with the same standard deviations. From the statistical properties of Rayleigh and Gaussian distributions it can be shown that:

ADS component errors $\sigma Ax = \sigma Ay = Ra / 2.45$;

where Ra is the 95% accuracy radius.

Expected accuracy of WAM position measurement.

Inherently, the WAM system must be able calculate its expected accuracies from knowledge of the receiving geometry (i.e. DOP) and its expected uncertainties in measurements of time of arrival. Indeed, the expected accuracies in each dimension and also the co-variance are values that are needed for output in WAM reports (in ASTERIX category 20 items).

In this Section, for simplicity and conservatively, we assume that the WAM errors are over-bounded by a circular error and so the errors in each dimension are the same (i.e. $\sigma Wx = \sigma Wy$). Furthermore, it is simply assumed that the errors in each dimension are independent Gaussian distributions (as assumed for ADS-B accuracy above).

Of course, the WAM manufacturer is free to take advantage of the better internal knowledge of the WAM accuracy components (including co-variances) and also may have a better knowledge of the expected accuracy error distribution in practice, in particular if it is significantly non-Gaussian.

Nominal bias limits in WAM position

In practice, the WAM position may have some residual systematic bias that cannot be completely known or eliminated by the system itself. However, the possible extent of a bias is expected to be limited by the system design tolerances and capabilities of any self-calibration methods (such as using known transponders). The possible magnitude and direction of such biases is variable and is likely to depend upon the measurement geometry (i.e. DOP).

Consequently, a potential bias limit for a WAM position measurement can be determined from internal knowledge of the WAM system.

Since the direction of the possible WAM position bias is unknown, it is simply added to the difference threshold (because the direction of the WAM bias could be opposite to the direction of the ADS-B position).

Effects of uncompensated latencies in the ADS-B position

Aircraft ADS-B installations are allowed a limited amount of uncompensated latency:

- Maximum 0.6s allowed in ED-161 & EASA CS-ACNS (version 2)
- Maximum 1.5s allowed in ED-126 & EASA AMC 20-24 (version 0/1)

Uncompensated latency means that the ADS-B position is old by an uncertain amount – this produces an aircraft-dependent along-track error proportional to speed.

Most conservatively, the worst case ADS-B latency could be assumed and latency × speed simply added to the position difference threshold. However, the worst-case latency with typical aircraft speeds produces relatively large position uncertainties (as compared to the typical ADS-B GPS source and WAM position accuracies). Consequently, it is advantageous for the fidelity of the position comparison to model the uncompensated latencies in ADS-B more realistically.

Practical measurements of compliant installations indicate that the uncompensated latency time error may be conservatively modelled as bias of 0.25s with a standard deviation of 0.15s.

The standard deviation × speed can be combined statistically with the ADS-B position source accuracy standard deviation to degrade overall ADS-B accuracy slightly (i.e. resultant sum of squares).

Although Bias × speed may be used to compensate the ADS-B position along track, it may be simplest and most conservative to add this margin to the difference threshold.

The assumed compensated latency time bias and standard deviation should be made ADS-B version dependent parameters.

Furthermore, in areas of good accuracy WAM, the difference between ADS-B and WAM positions in the along-track direction can beaveraged over a number of successive measurements to form a dynamic estimate of the uncompensated latency time bias for the aircraft. Consequently, by obtaining a better estimate of uncompensated latency time bias, a more effective comparison could be made (i.e. a smaller comparison difference threshold could be used for the same false alert rate and this reduces the declared containment bound).

4.3.3 WAM Validation results

When an ADS-B equipped aircraft is within the coverage of a sufficient number of WAM receivers, it is possible for the WAM system to determine a position independently from the position information in the ADS-B messages.

In the WAM Validation, the aircraft horizontal position transmitted by the ADS-B position messages and as decoded by the composite system and is compared against the position, determined by multilateration techniques in the system for the same aircraft where there is sufficient reception from multiple receivers.

Before the ADS-B position data item can be considered to be used in the WAM track, the WAM derived position of the ADS-B data message must associate with an existing WAM track. Depending upon the ADS-B version, the use of the applicable ADS-B data item by WAM is subject to validation.

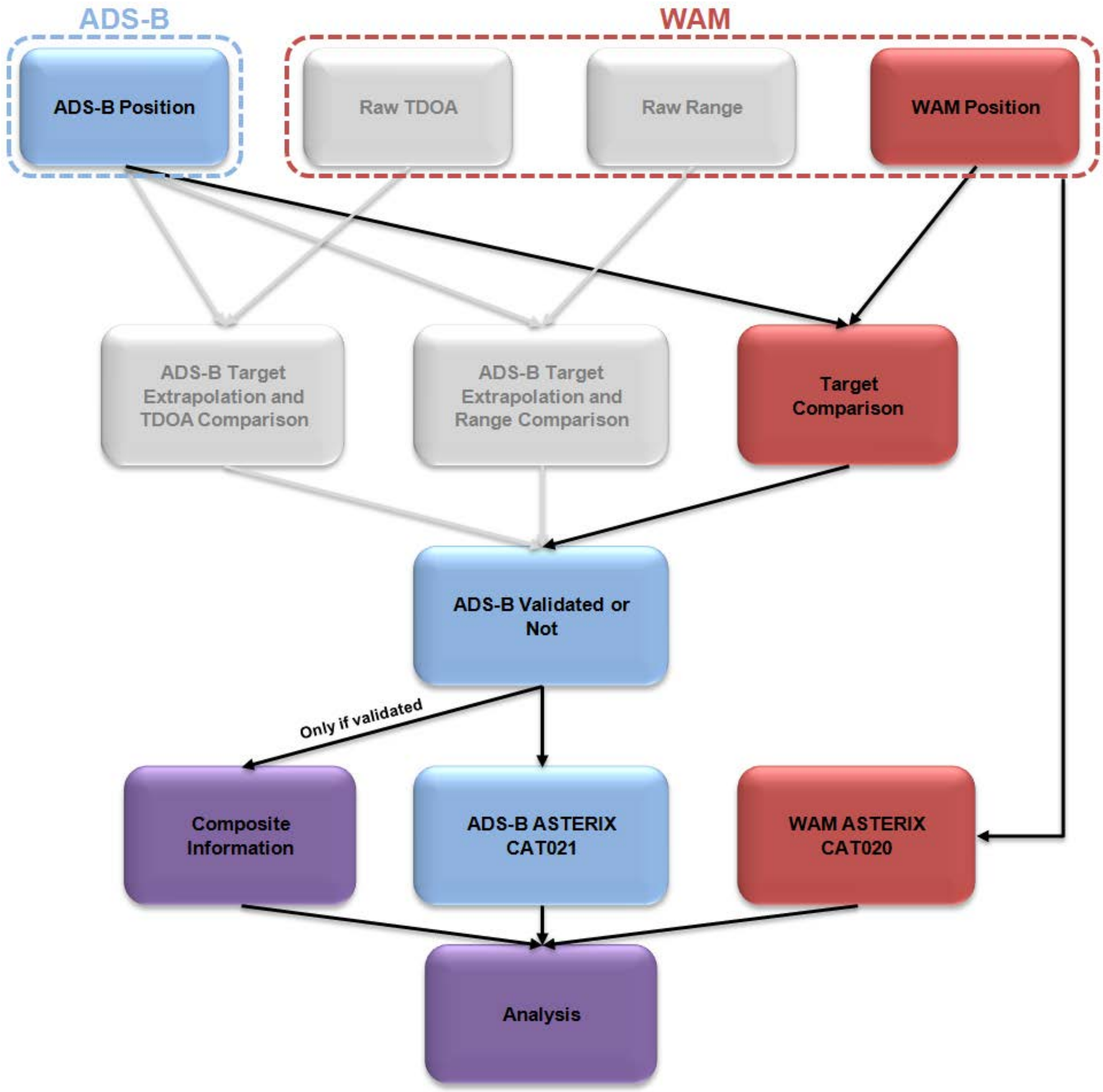

Figure 36: Indra System Architecture (WAM)

For this validation, a real traffic recording of +72h has been realised. After the recording, a post-processing filter has been done in order to study only a good coverage area for the multilateration of the targets in the apron and overflights in the TMA of Madrid (approx. 30NM excluding the targets on ground in the Adolfo Suárez Madrid-Barajas airport).

The ASTERIX file of the filtered data has been analysed, giving the following results of the validation:

Total of Recorded Messages	13125393
Recording duration	72

Range filter	<30NM
altitude filter	>4000ft
filtered messages for analysis	**4035488**

Table 21: Total number of reports

Of the filtered data, statistics have been generated in global and for each of the different transponder versions for the WAM validation, with the following results:

	TOTAL REPORTS	
Not Validated	18,91%	763111
Validated & Not Valid	2,17%	87570
Validated & Valid	78,92%	3184807
		4035488

	VERSION 0		VERSION 1		VERSION2	
Not Validated	19%	697736	18%	14528	18%	50847
Validated & Not Valid	2%	73446	7%	5650	3%	8475
Validated & Valid	79%	2901112	75%	60532	79%	223162
		3672294		**80710**		**282484**

Table 22: WAM validation statistics

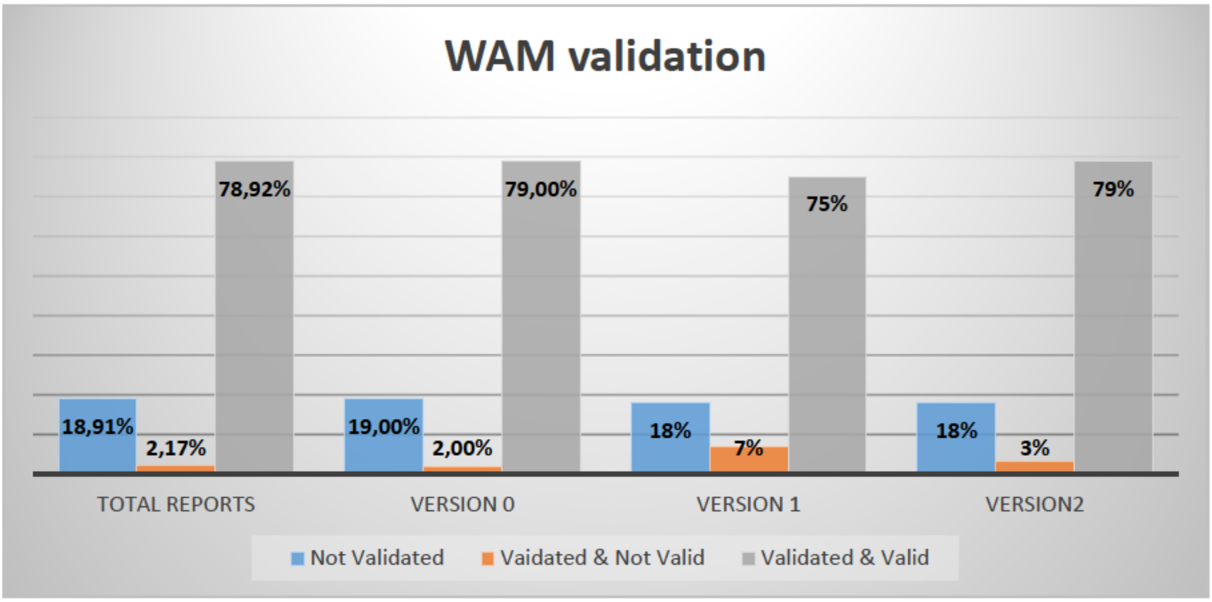

Figure 37: Statistics of WAM Validation

As can be seen in the previous figures, a high amount of the received messages are validated and valid. Thresholds for the validations have been set dynamically and based on the ADS-B quality indicators and also on the expected WAM accuracy.

The not validated messages are from targets with not a very good coverage area due to terrain, buildings, and other conditions, for which it´s not possible to compare ADS-B and WAM plots.

4.3.4 Partial Position Validation results

Comparison with Partial Position

In the case of only two WAM receivers of an ADS-B message, their time difference of arrival (TDOA) defines a hyperbola on which the ADS-B position should agree within the normally expected WAM and ADS-B uncertainties. In this case, the difference of concern is between the ADS-B position and its closest point on the hyperbola, as illustrated in the Figure below.

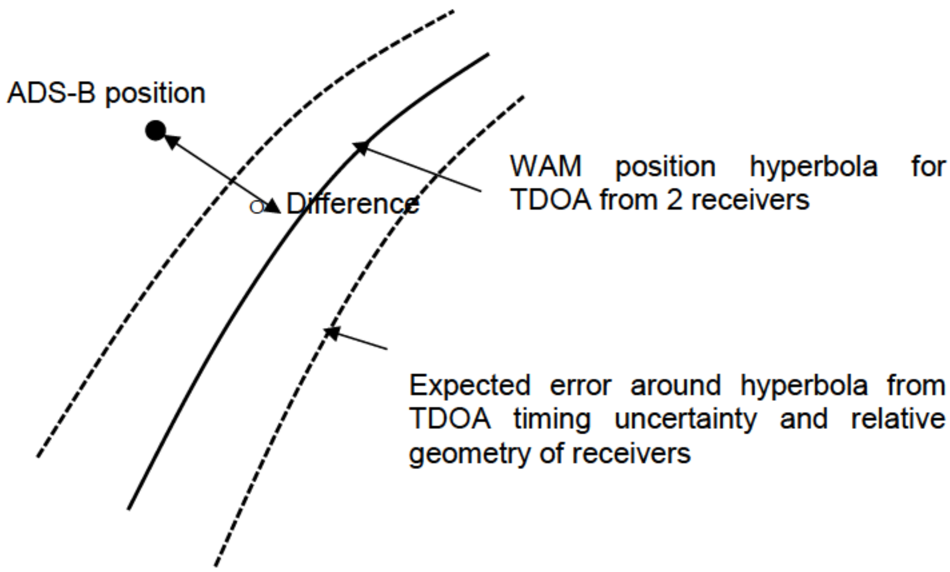

Figure 38: Illustrating TDOA hyperbola in the vicinity of the ADS-B position

The difference threshold (D) is determined from the combination of the expected errors from ADS-B accuracy and the WAM errors in the direction normal (90°) to hyperbola at its closest point to the ADS-B position.

As before, the ADS-B accuracy is assumed circular and Rayleigh distributed, so the error in any one direction is assumed Gaussian (σA) where:

σA = Ra/2.45;   and Ra is the 95% accuracy radius.

For WAM, the error in the direction normal to the hyperbola is determined from knowledge of the expected time measurement accuracy of TDOA and the geometry of the ADS-B position with respect to the receivers. It is assumed here that this error is represented by a Gaussian with standard deviation σW.

[Details of how to determine the WAM error from TDOA and geometry should not need to be given because it is in the domain of the WAM manufacturer].

Hence, in the nominal (no-fault) situation, the combined effect of the independent WAM and ADS-B Gaussian errors will produce a Gaussian difference distribution with standard deviation σd, where $\sigma d^2 = \sigma W^2 + \sigma A^2$.

Consequently, the probability of false alert (Pfa) for a difference threshold of D is given by the cumulative distribution function CDF(σd, D).

e.g. D=3.5σ,	Pfa = 4.6E-4
D=4σ,	Pfa = 6 E-5

However, a further margin needs to be added to the threshold to allow for the possible biases in WAM position and ADS-B uncompensated latency. As before, most conservatively, it is pessimistically assumed that the biases could all be aligned in the same direction as the WAM to ADS-B position difference. Hence, the biases are simply added to the difference threshold (D) as initially determined above, i.e.

$$D \leftarrow D + BA + BW + BE;$$

Where BA, BW and BE are biases as described previously.

It is possible for the WAM system to evaluate the integrity of the position information in the ADS-B messages, even when there are as few as two receivers. The time difference of arrival will define a hyperbola in space where the position of the aircraft should coincide (this is referred to generally below as a “partial position”). This validation is candidate to detect transmissions simulating targets transmitting incorrect position information (intentionally or not) for which it would be difficult to obtain a complete multiaterated position.

In the Partial Position (TDOA) Validation, the aircraft horizontal position transmitted by the ADS-B position messages and as decoded by the composite system is compared against the partial position determined by multilateration techniques in the system for the same aircraft.

In this case of a partial position hyperbola, as determined by the TDOA from two receivers, the difference of concern is essentially the length of the normal (90°) line from the hyperbola to the ADS-B position. Consequently, the difference threshold will depend upon all the error uncertainties from each measurement resolved along this direction.

To minimize the error component produced by the ADS-B in the case of a partial position hyperbola, the difference between the ADS-B position and the intersection of the normal line to the partial position hyperbola shall be compared against a threshold taking account of all the normally expected uncertainties in both measurements.

This approach will provide the best case error for the comparison.

As can be appreciated in Figure 39, the validation of ADS-B information will be performed at sensor level. Depending if the information is validated or not, there will be two cases:

- If the ADS-B information is validated, there will be three output dataflows: pure WAM dataflow in ASTERIX Category 020, One for ADS-B data in ASTERIX Category 021, and another for the composite information (ASTERIX Category 020 with different SIC-SAC codes).
- If the ADS-B information is not validated, in this case there will be only the ADS-B data in ASTERIX Category 021 and the pure CAT020 for WAM

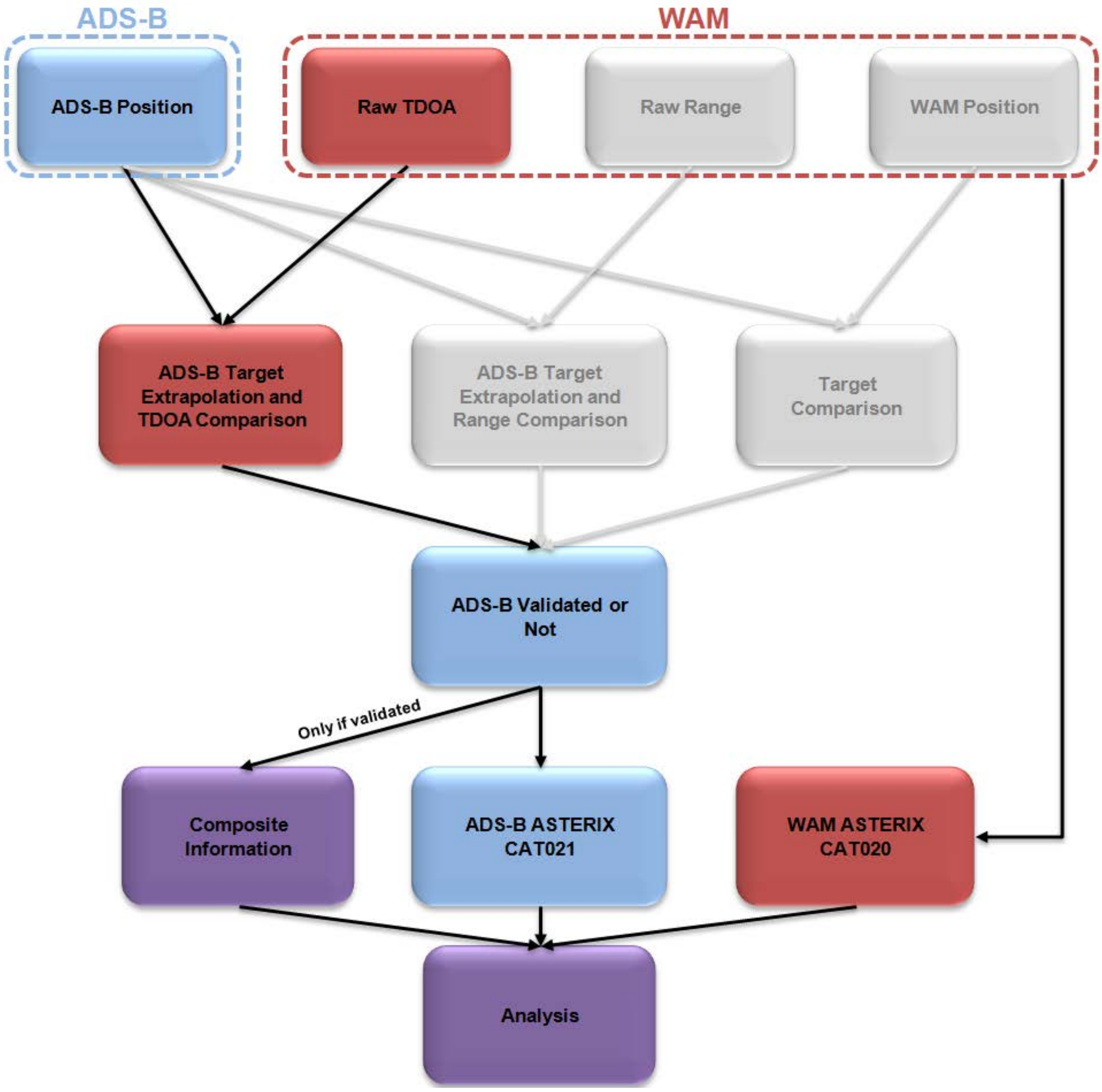

Figure 39: Indra System Architecture (Partial Position)

For this validation, a real traffic recording of +72h has been realised. After the recording, a post-processing filter has been done in order to study only a good coverage area for the multilateration of the targets in the apron and overflights in the TMA of Madrid (approx. 30NM excluding the targets on ground in the Adolfo Suárez Madrid-Barajas airport).

The ASTERIX file of the filtered data has been analysed, giving the following results of this validation:

ASTERIX file of the filtered data has been analysed, giving the following results of the validation:

Total of Recorded Messages	13125393
Recording duration	72
Range filter	<30NM
altitude filter	>4000ft
filtered messages TDOA	**4035488**

Of the filtered data, statistics have been generated in global and for each of the different transponder versions for the TDOA validation, with the following results:

	TOTAL REPORTS	
Not Validated	17,03%	687244
Validated & Not Valid	2,25%	90798
Validated & Valid	80,72%	3257446
		4035488

	VERSION 0		VERSION 1		VERSION2	
Not Validated	17%	624290	15%	12106	18%	50847
Validated & Not Valid	2%	73446	6%	4843	3%	8475
Validated & Valid	81%	2974558	79%	63761	79%	223162
		3672294		**80710**		**282484**

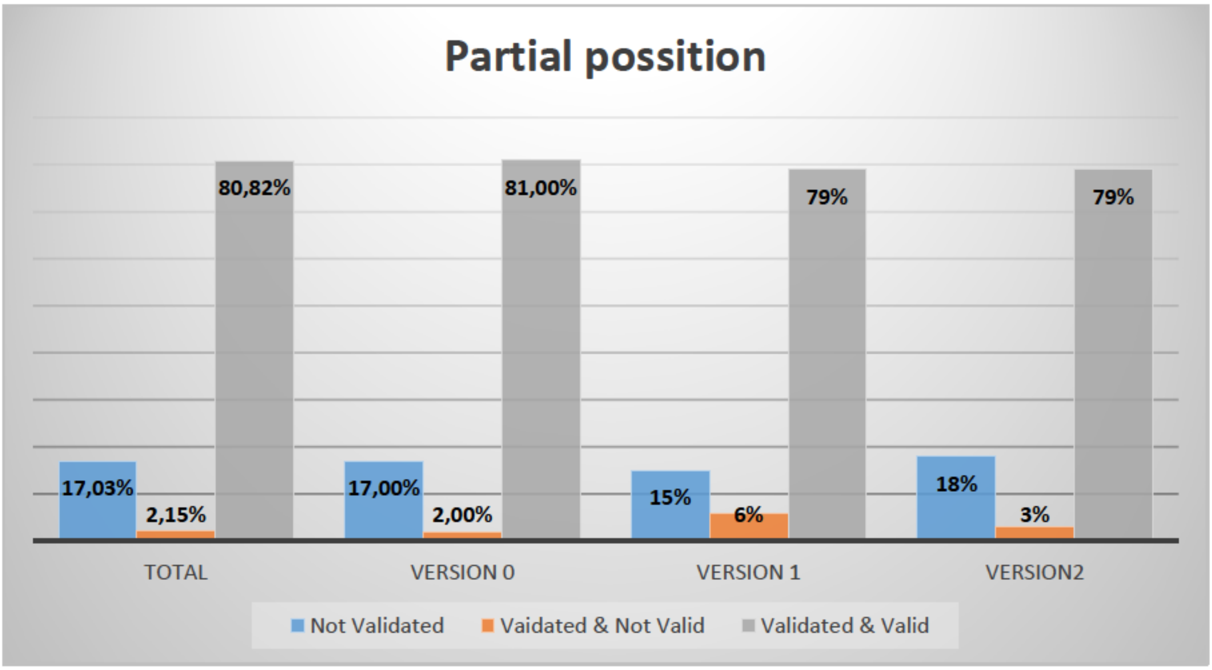

Figure 40: Statistics of TDOA Validation

As can be seen in the previous figures, most of the received messages are validated and valid, mainly due to the adequate location and operation of the receiver stations. Number of validated reports increase in relation to the WAM validation, which is expected as there are areas in the coverage were targets are nor received in enough number of receiver stations to be multlaterated. Can be appreciated that number of validated & valid for partial position is bigger in comparison with WAM validation. This is also expected as this kind of validation is less strict in terms of accuracy than the WAM validation.

4.3.5 Ranging Validation results

In the Ranging Validation, the aircraft horizontal position transmitted by the ADS-B position messages and decoded by the composite system is compared against the range determined by ranging techniques in the system for the same aircraft.

Before the ADS-B data item can be considered to be used in the WAM track, the WAM derived position of the ADS-B data message must associate with an existing WAM track. Depending upon the ADS-B version, the use of the applicable ADS-B data item by WAM is subject to validation. This is to be performed at different times, as follows:

1. Initial validation – WAM tracks initially obtain the data item by active interrogations. Subsequently, after the data item value has been initially established, it is then permissible to check that this data agrees with the same data obtained passively from ADS-B squitters. If agreement is successful, then the ADS-B data item can be used subsequently instead of making further WAM interrogations for the same data.

2. Periodic re-validation – at predetermined time intervals after successful initial validation, the WAM obtains the data item again by an active interrogation to check against the ADS-B data again. If successful, then the ADS-B data continues to be used or otherwise, the WAM channel reverts to obtaining the data item by active interrogations and any further use of the ADS-B data item will be subject to initial validation again.

Figure 36 represents the Indra combined system architecture. There are two different information flows: One from the ADS-B source and a second from the WAM sensor.

As can be appreciated in Figure 41, the validation of ADS-B information is performed at sensor level. Depending if the information is validated or not, there will be two cases:

- If the ADS-B information is validated, there will be three output dataflows: pure WAM dataflow in ASTERIX Category 020, One for ADS-B data in ASTERIX Category 021, and another for the composite information (ASTERIX Category 020 with different SIC-SAC codes).
- If the ADS-B information is not validated, in this case there will be only the ADS-B data in ASTERIX Category 021 and the pure CAT020 for WAM

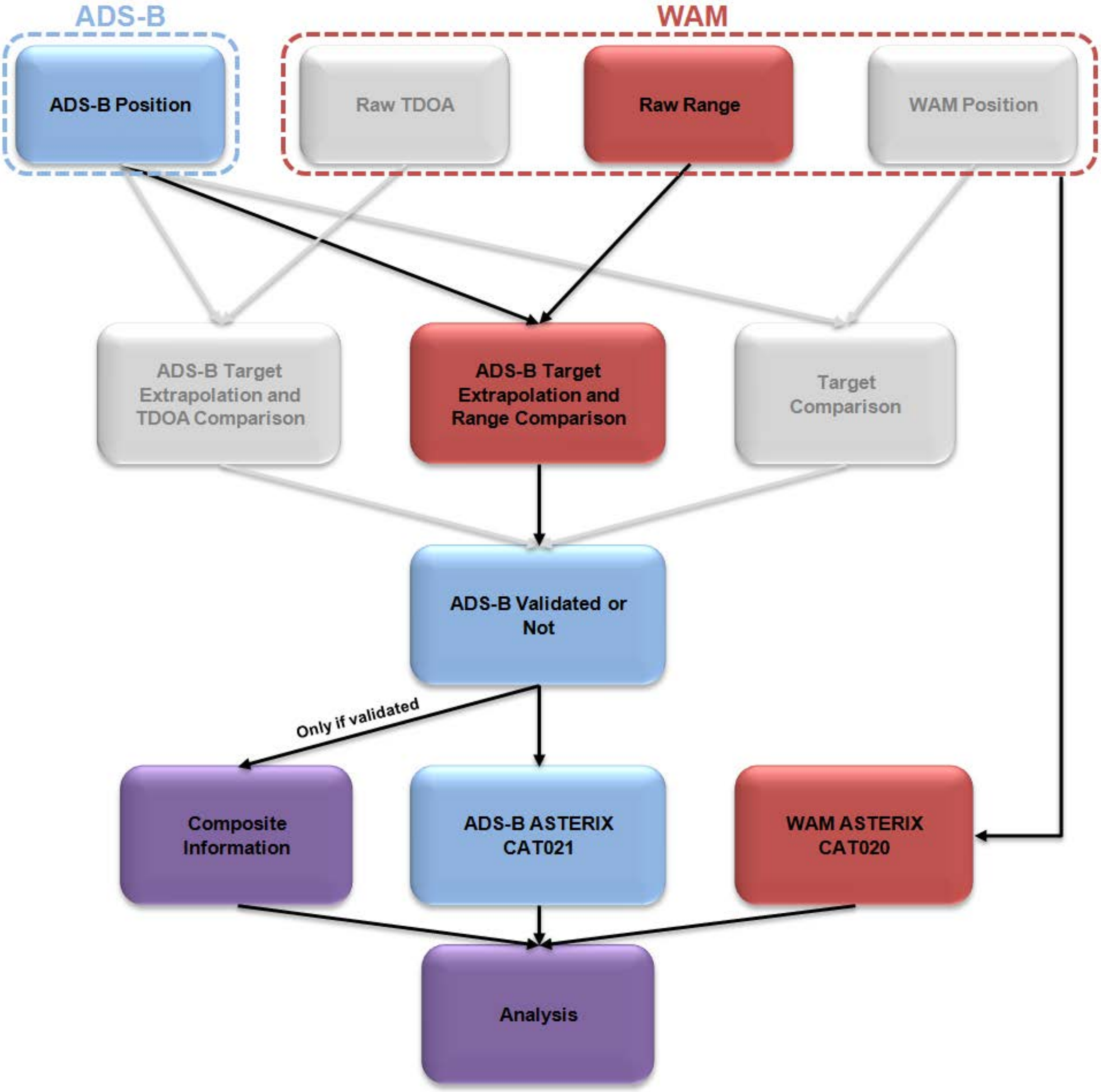

Figure 41: Indra System Architecture (Ranging)

As explained above, congestion of the RF environment is already becoming a problem area in dense traffic (e.g. the environment for these verification exercises) and ground system areas and, unless appropriate mitigations including rationalisation are introduced, it will continue to get worse and could eventually compromise system performance.

During the different validations, Indra has performed active validations with real traffic and also passive excersies, using a target simulator to introduce errors into the system.

Of the filtered data, statistics have been generated in global and for each of the different transponder versions for the RAI validation, with the following results:

		TOTAL REPORTS	
Not Validated	17,07%	597205	17,07%
Validated & Not Valid	2,08%	72770	2,08%
Validated & Valid	80,85%	2828589	80,85%
			3498564

	VERSION 0		VERSION 1		VERSION2	
Not Validated	17%	547175	17%	5948	18%	44082
Validated & Not Valid	2%	64374	3%	1050	3%	7347
Validated & Valid	81%	2607130	80%	27989	79%	193471
		3218679		**34986**		**244899**

Table 23: RAI validation statistics

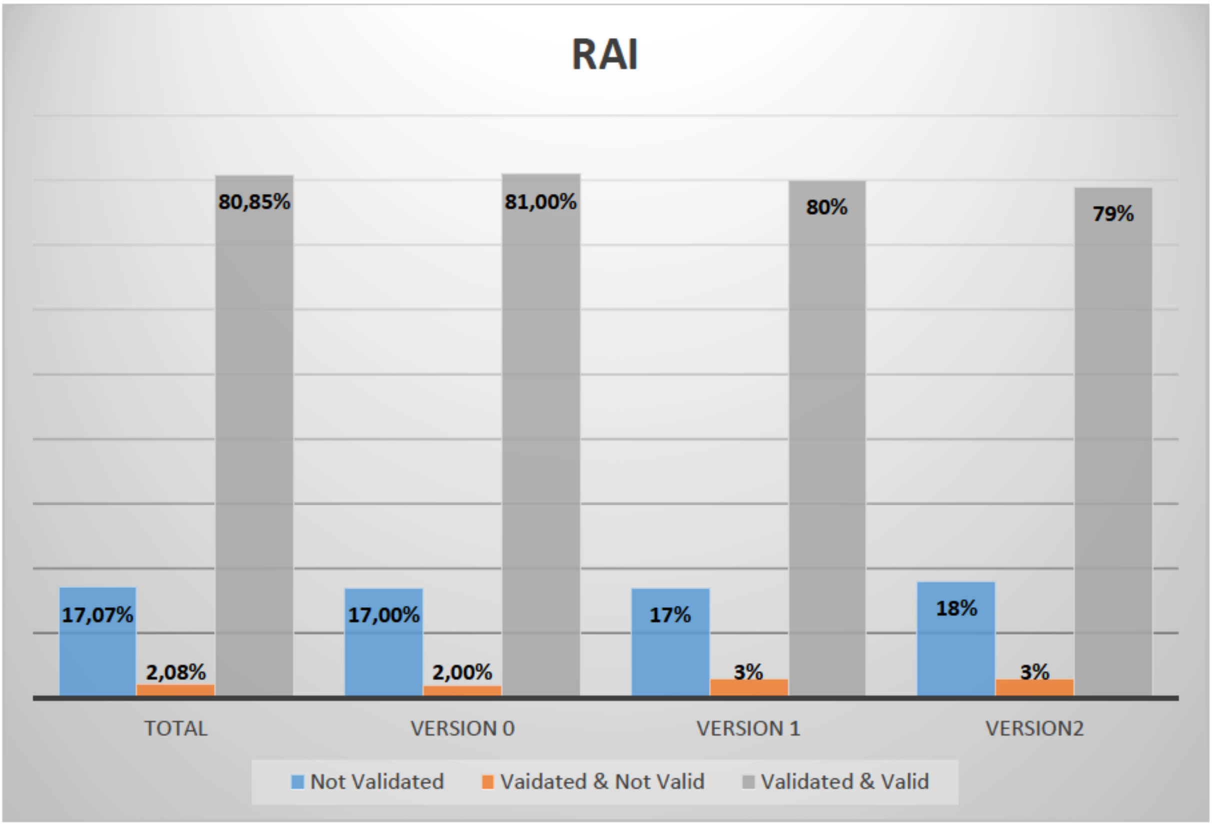

Figure 42: Statistics of RAI Validation

As can be seen, global values are similar to the obtained by other validation methods.

Using Traffic Simulator different errors can be introduced in the simulated targets. For this Ranging Validation, a study with simulated targets flying over areas transmitting good positions and suddenly introducing position errors.

In the following figure, two simulated targets are shown. The target IBE1111 has no errors with a validated/valid state in the ranging validation during all the simulation, except in the poor coverage area with a non validated status. On the other hand, IBE2222 has no errors as the previous target until one point in which is introduced a position error (out of the threshold. In that moment, the ranging validation of the targets indicates validated/invalid state and later.

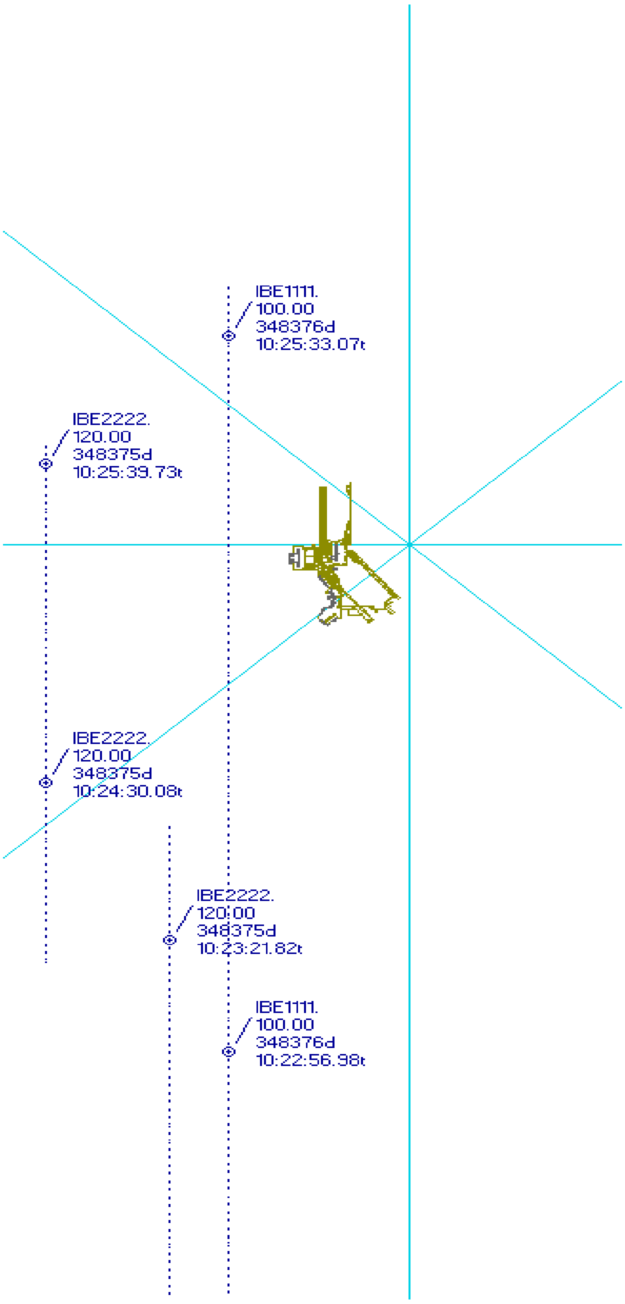

Figure 43: Ranging validation with induced-errors

4.3.6 Height Validation results

In the altitude validation, there are three main aspects to be considered:

The WAM track have initialised the track Pressure Altitude information using at least 2 active interrogations.

Validation Check for Pressure Altitude

The comparison of pressure altitude values from ADS-B and WAM needs a tolerance margin to allow for fluctuations in value due to quantisation and also to take account of possible changes in altitude between the times of applicability of the data item. *[Also to allow for uncompensated latency time in ADS-B].* Consequently, the altitude tolerance margin (∆A) could be considered as:

$$\Delta A = P1 + P2^{*}\Delta t$$

where P1 and P2 are system parameters and ∆t is the time difference. [*Typical values would be P1=100ft, P2=100ft)].*

The validation check of Pressure Altitude data requires the values from WAM and ADS-B to be within a certain tolerance margin.

The tolerance margin between Pressure Altitude values from WAM and ADS-B takes account of possible differences in altitude values due to uncertainties in quantisation and timing.

However, the allowable time difference (∆t) needs to be within a reasonable limit for the altitude validation check to be appropriate.

The validation check of Pressure Altitude requires the time difference between the ADS-B and WAM values to be less than a parameter amount. (Otherwise the check is considered as unsuccessful)

Periodic re-validation check

After initialisation and successful validation, the WAM system actively interrogates for Pressure Altitude information at a periodic time interval determined by a system parameter.

In case of unsuccessful comparison outcome, the WAM track re-initialises the Pressure Altitude information using active interrogations.

In case of loss of Pressure Altitude for longer than a parameter time, the system returns to initial validation conditions before attempting ADS-B data validation.

		TOTAL REPORTS	
Not Validated	17,07%	17,05%	596505
Validated & Not Valid	2,08%	2,10%	73470
Validated & Valid	80,85%	80,85%	2828589
			3498564

	VERSION 0		VERSION 1		VERSION2	
Not Validated	17%	547175	15%	5248	18%	44082

Validated & Not Valid	2%	64374	5%	1749	3%	7347
Validated & Valid	81%	2607130	80%	27989	79%	193471
		3218679		**34986**		**244899**

Table 24: Height validation statistics

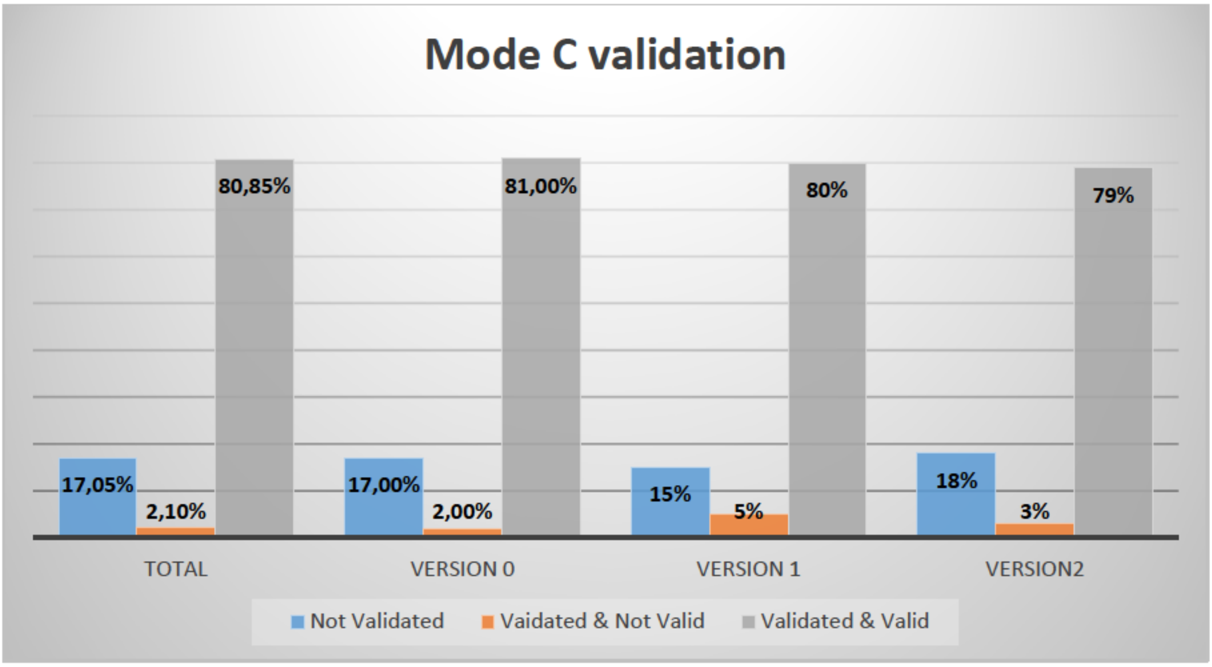

Figure 44: Statistics of Mode C Validation

In this Data Simulator two targets were created for study:

- Target A: Its Code C from squitter coincides with Code C from Mode S replies.
- Target B: Its Code C from squitter doesn't coincide with Code C from Mode S replies.

The following figures show the Data Simulator options and windows:

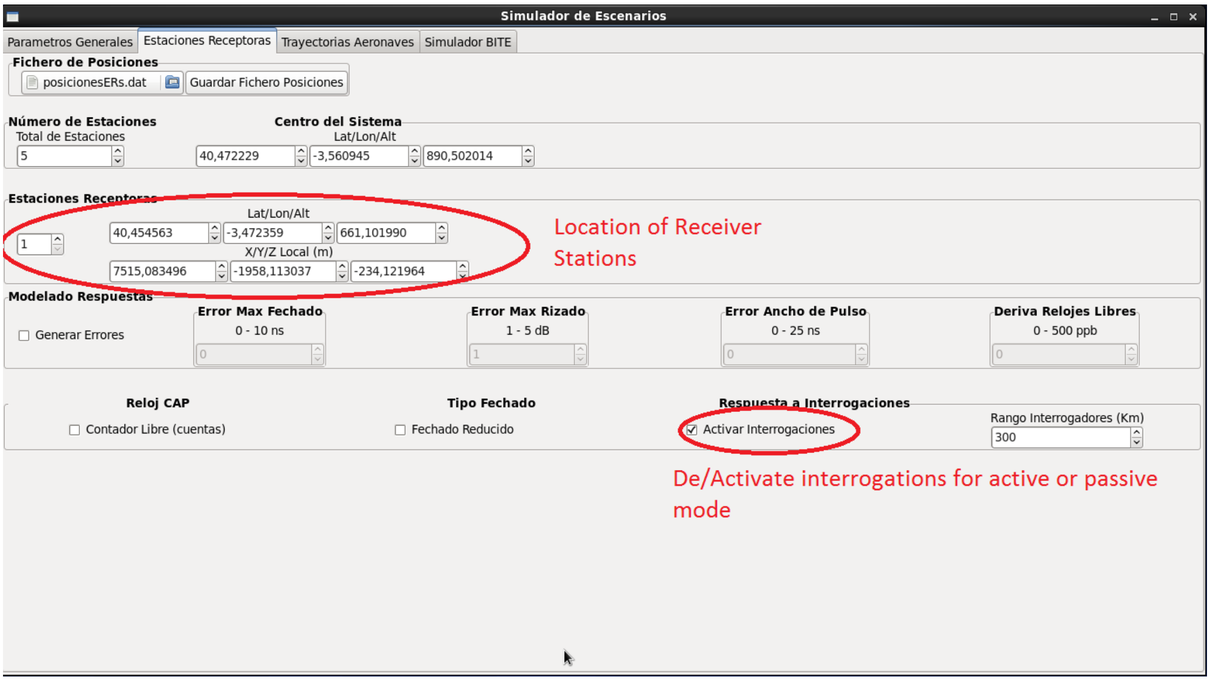

Figure 45: Receiver Stations configuration

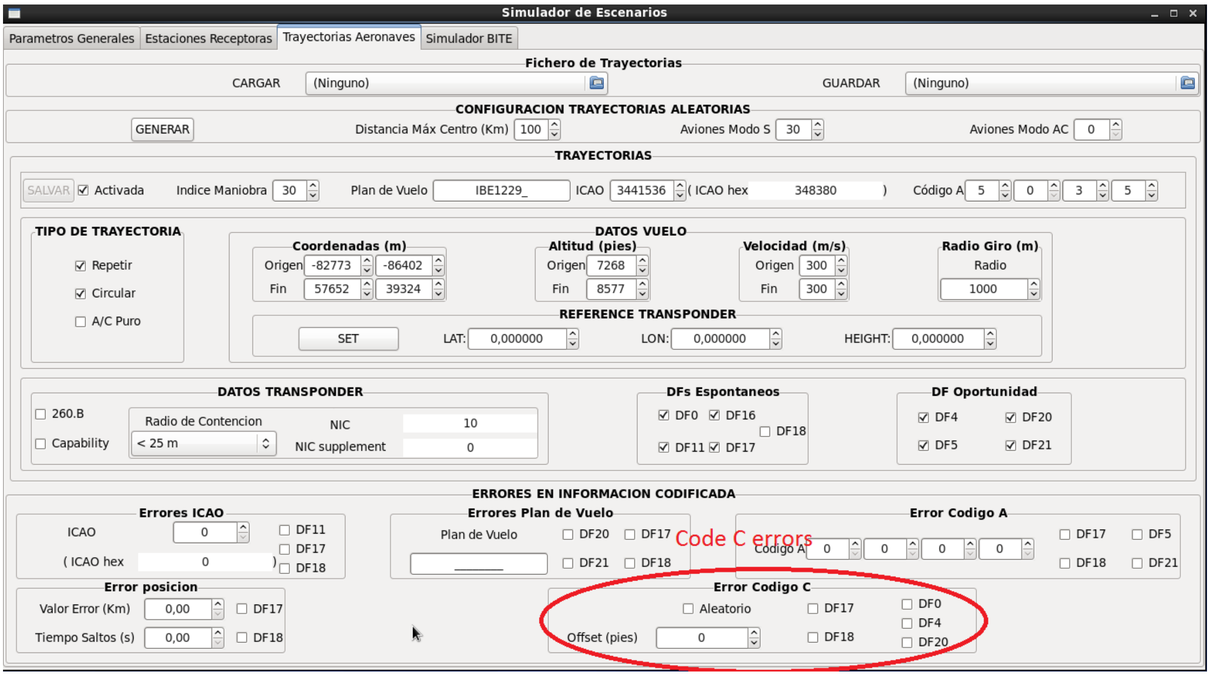

Figure 46: Aircraft configuration for Height Validation

After activating the feature “Height Validation” in the composite system and configuring the Recording Tool to capture ASTERIX reports, the test scenario with targets is can be introduced.

Then, by comparison of the recorded data against the known mobiles information, verify that:

Target A:

- There are more C codes in Composite ASTERIX CAT020 output than in standard ASTERIX CAT 020. That means a correct behaviour.
- During the simulation, if interrogations are activated, the code C information is OK. This can be checked during the simulation in the Multi-Radar Display, giving an alert to the user.
- During the simulation, if interrogations are deactivated, the code C information is lost in ASTERIX CAT020 (after 30 second approx.). This can be checked during the simulation in the Multi-Radar Display, giving an alert to the user.

Target B:

- There will be the same number of C Codes in both ASTERIX CAT020 flows. In addition, Code C messages from ASTERIX CAT021 are different from previous ones that only are received from interrogations. These conditions mean an incorrect behaviour.
- During the simulation, if interrogations are activated, the code C information is OK only in ASTERIX CAT020. This can be checked during the simulation in the Multi-Radar Display, giving an alert to the user.
- During the simulation, if interrogations are deactivated, the code C information is lost in ASTERIX CAT020 (after 30 second approx.) This can be checked during the simulation in the Multi-Radar Display, giving an alert to the user.

As conclusion, validation for mode C codes follow the same behaviour of other validations and can be used to reduce the rate if interrogations to an aircraft. Also, this validation can be used to provide an alert function in the Multi-Radar Display that warns to the user in cases when anomalies in the Code C are detected.

4.3.7 Identification Validation results

In the identification validation, there are three main aspects to be considered:

Initial Validation Conditions for Aircraft Identification

The WAM system initialises the track Aircraft Identification information using at least 2 active interrogations giving the same Aircraft Identification.

Validation Check for Aircraft Identification

The validation check of Aircraft Identification data requires the values from WAM and ADS-B to be the same.

Periodic re-validation check

After initialisation and successful validation, the WAM system actively interrogates for Aircraft Identity information at a periodic time interval determined by a system parameter.

In case of unsuccessful comparison outcome, the WAM system re-initialises the Aircraft Identity information using active interrogations.

In case of a loss of Aircraft Identity information for longer than a parameter time, the system returns to its initial validation conditions before attempting ADS-B data validation.

		TOTAL REPORTS	
Not Validated	17,07%	17,02%	595561
Validated & Not Valid	2,08%	2,05%	71616
Validated & Valid	80,85%	80,93%	2831388
			3498564

	VERSION 0		VERSION 1		VERSION2	
Not Validated	17%	548785	15%	5143	17%	41633
Validated & Not Valid	2%	62764	4%	1504	3%	7347
Validated & Valid	81%	2607130	81%	28338	80%	195920
		3218679		**34986**		**244899**

Table 25: Mode A validation statistics

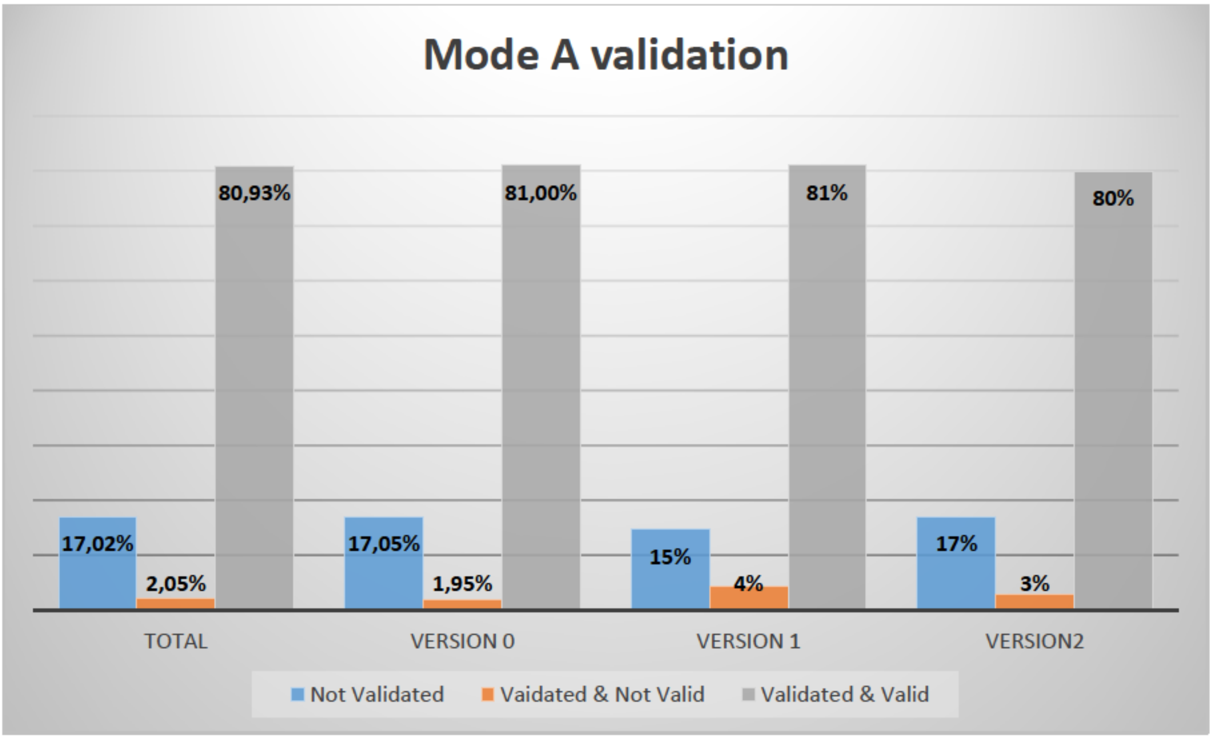

Figure 47: Statistics of Mode A Validation

In this Data Simulator two targets were created for study:

- Target A: Its Code A from squitter coincides with Code A from Mode S replies.
- Target B: Its Code A from squitter doesn't coincide with Code A from Mode S replies.

The following figures show the Data Simulator options and windows:

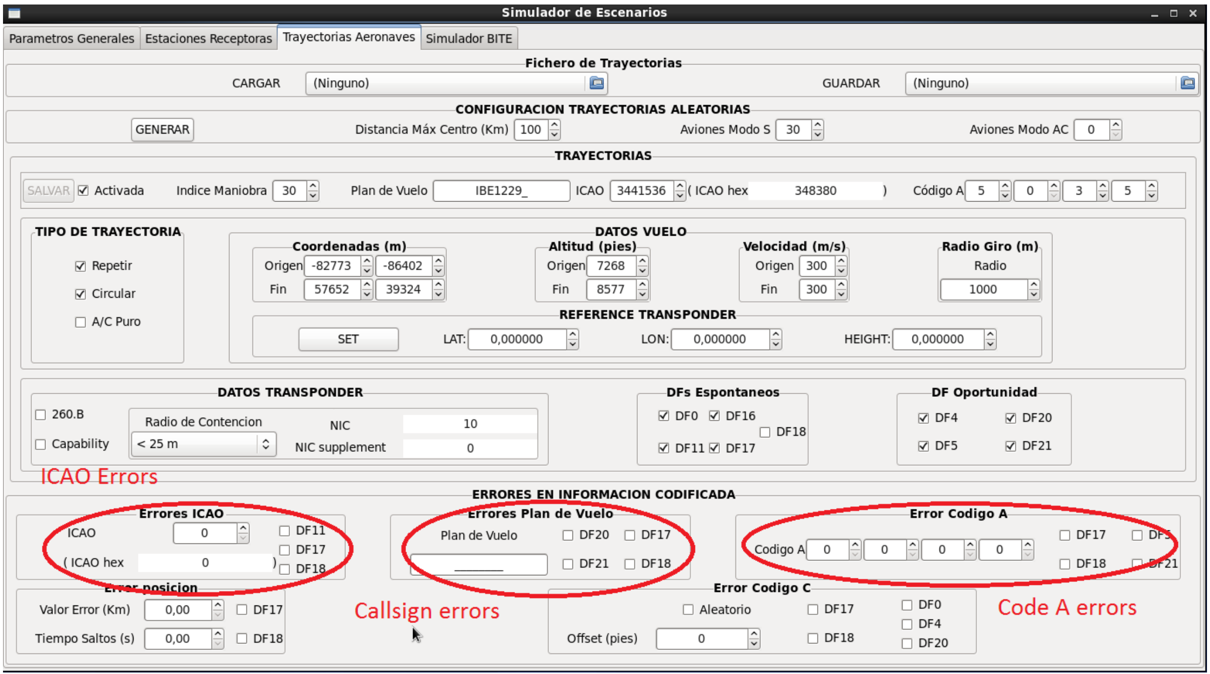

Figure 48: Aircraft configuration for Identification Validation

After activating the feature “Identification Validation” in the composite system and configuring the Recording Tool to capture ASTERIX reports, the test scenario with the two previous targets is can be introduced.

Then, by comparison of the recorded data against the known mobiles information, verify that:

Target A:

- There are more A codes in ASTERIX CAT020 Composite than in standard ASTERIX CAT 020 WAM.
- During the simulation, if interrogations are activated, the Code A information is OK. This can be checked during the simulation in the Multi-Radar Display, giving an alert to the user.
- During the simulation, if interrogations are deactivated, the Code A information is lost in ASTERIX CAT020 (after 30 second approx.). This can be checked during the simulation in the Multi-Radar Display, giving an alert to the user.

Target B:

- Code A information from ASTERIX CAT021 are different from ASTERIX CAT020. These conditions mean an invalid trajectory.
- During the simulation, if interrogations are activated, the Code A information is OK only in ASTERIX CAT020. This can be checked during the simulation in the Multi-Radar Display, giving an alert to the user.
- During the simulation, if interrogations are deactivated, the Code A information is lost in ASTERIX CAT020 (after 30 second approx.) This can be checked during the simulation in the Multi-Radar Display, giving an alert to the user.

As conclusion, validation for mode C codes follow the same behaviour of other validations and can be used to reduce the rate if interrogations to an aircraft. Also, this validation can be used to provide an alert function in the Multi-Radar Display that warns to the user in cases when anomalies in the Code A are detected.

For the case of ACID information, statistics are also very similar:

		TOTAL REPORTS	
Not Validated	17,07%	17,05%	596505,162
Validated & Not Valid	2,08%	2,08%	72700,1599
Validated & Valid	80,85%	80,87%	2829288,71
			3498564

	VERSION 0		VERSION 1		VERSION2	
Not Validated	17%	547175	15%	5248	18%	44081,9064
Validated & Not Valid	2%	64374	3%	980	3%	7346,9844
Validated & Valid	81%	2607130	82%	28688	79%	193470,589
		3218679		**34986**		**244899**

Table 26: ACID validation statistics

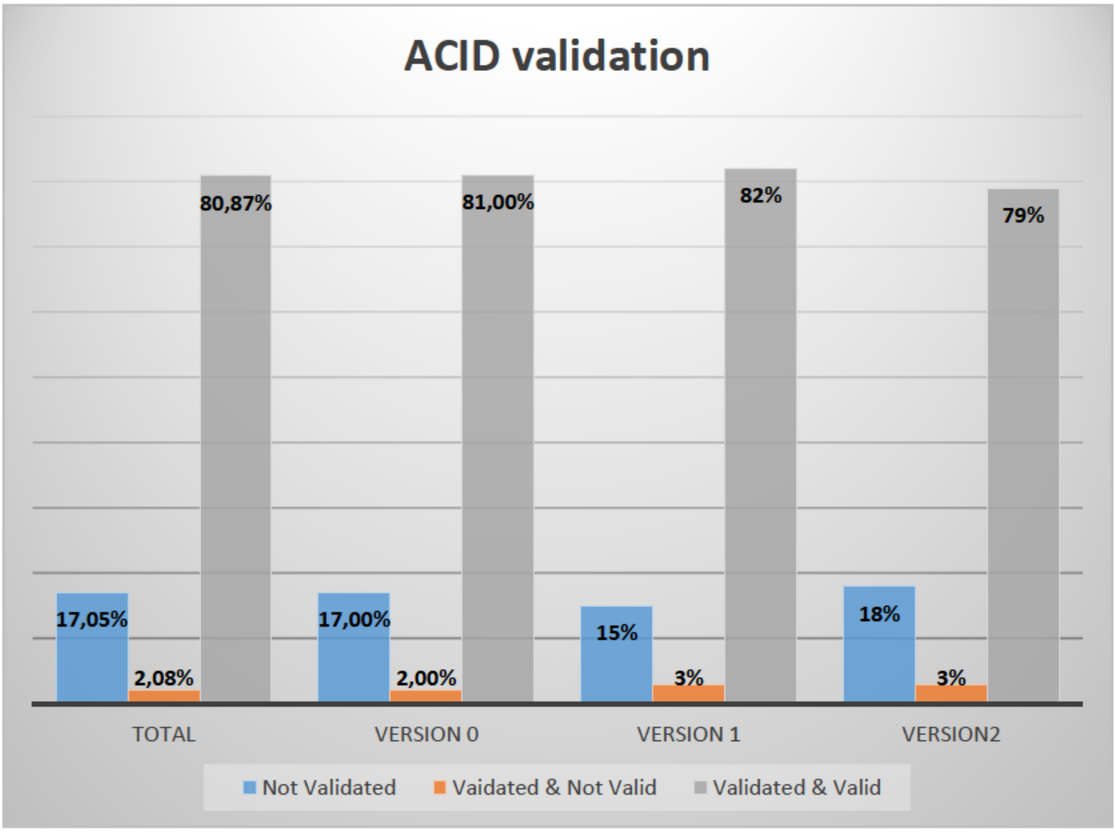

Figure 49: Statistics of ACID Validation

4.3.8 Performance Monitoring results

The monitoring of the system performance is based on the analysis of the validations in quasi real time.

For this purpose, the system divides the coverage in different sectors and analyses the evolution of the validations results for them. Once an anomaly is detected, system provides an alert.

While the system is working properly, percentage of positive validations is stable for each area. Due to some factors (jamming of signals, signal blockings, system failures…) performance of the system may decrease for certain areas. System may alert about malfunction of system, but if some receiver is not working properly due to jamming, it may be difficult for the system to report this.

The aim of this performance monitoring based on validation results is to detect situations that are not directly affecting to the system operation (system failures) but to the behaviour of the system due to external elements, as jamming or others.

To verify this, we have selected a coverage volume with good performance, and at certain moment in time, we have introduced a noise signal into one of the receivers with influence in the volume under study. This noise is simulating a jamming signal but may also be any other external factor.

We can appreciate that the % of validated & valid reports decreases for this volume as we introduce the noise on the receiver, and we can also see the alert generated by the system.

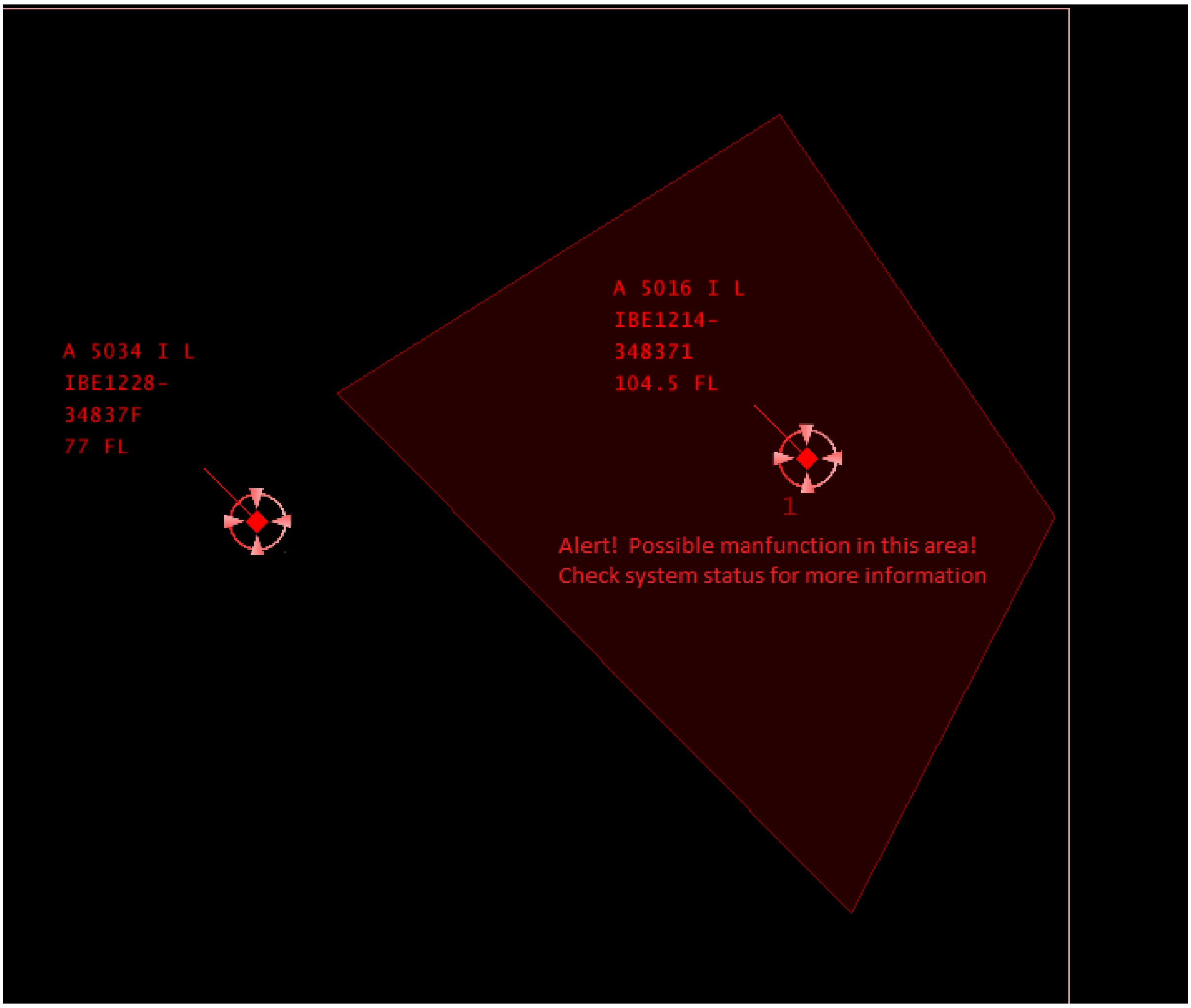

Figure 50: Alert of performance monitoring

4.3.9 Quality Indicators comparison results

As complementary information for this document, a study of the different quality indicators included in the I021/090 data item has been made. The sample for these statistics is the same that the previous sections, a real traffic recording of 72h.

In most of the cases, the targets with better quality indicators showed a better performance and results in the different validations.

For more information about the quality indicators and the information they provide, please see [14].

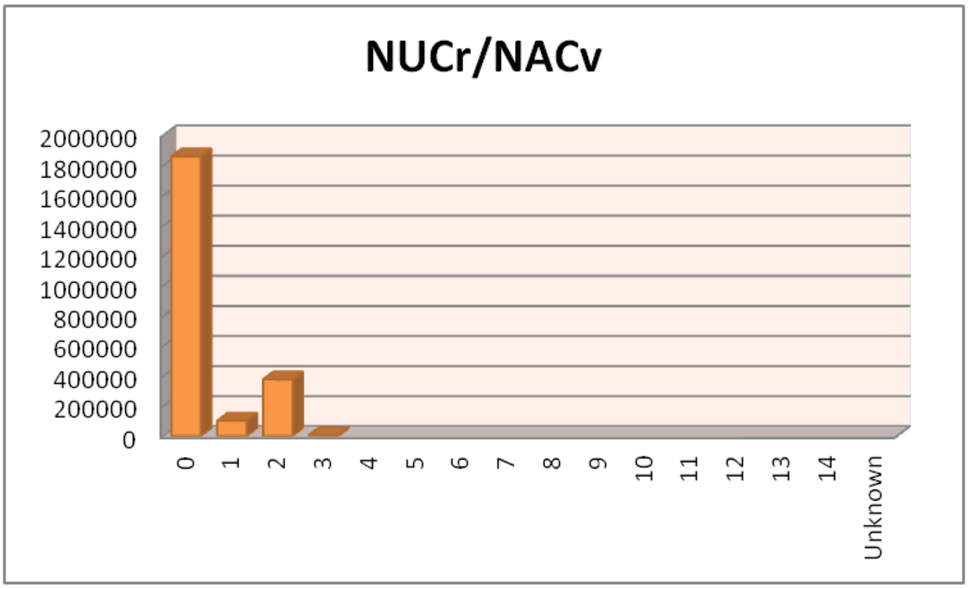

Figure 51: NUCr/NACv Statistics

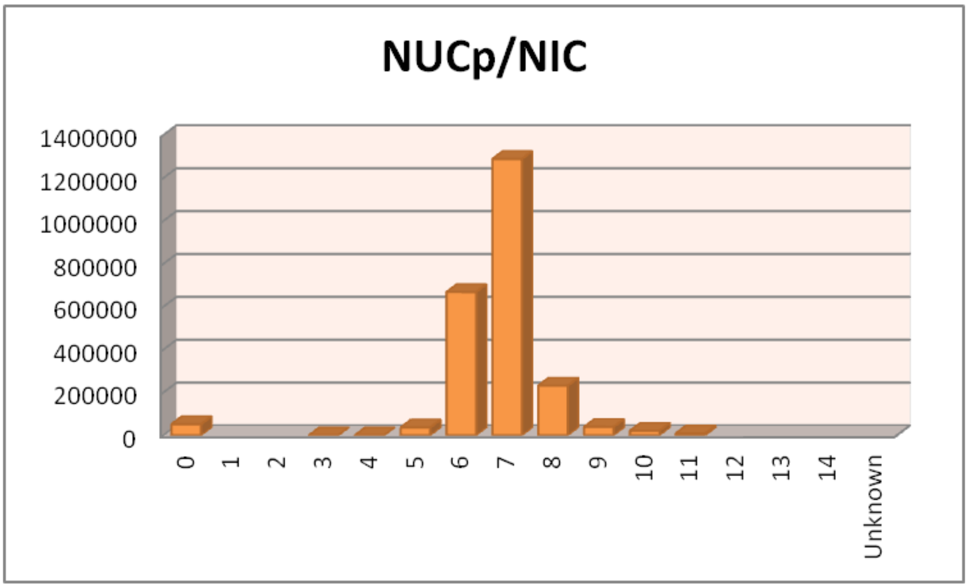

Figure 52: NUCp/NIC Statistics

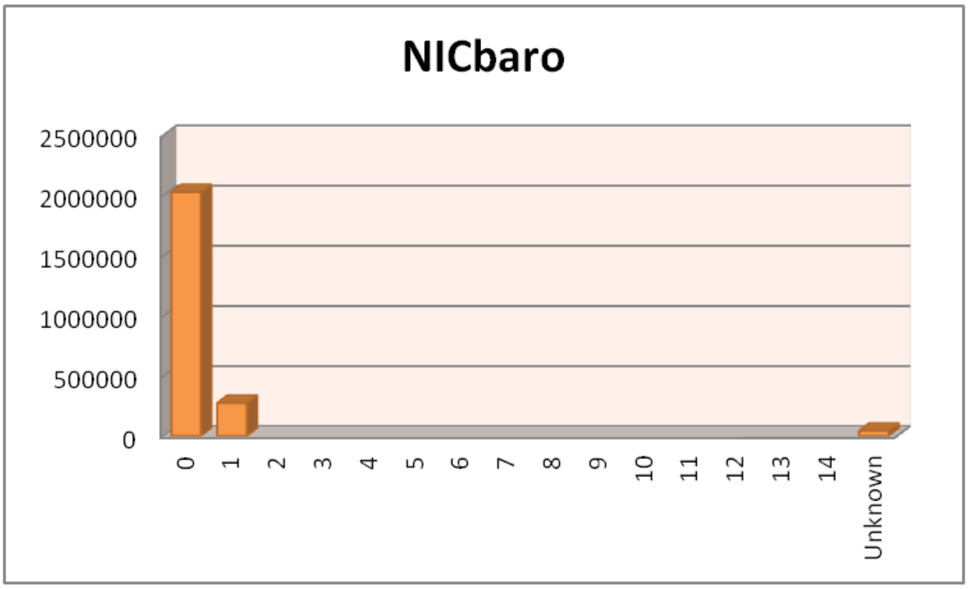

Figure 53: NICbaro Statistics

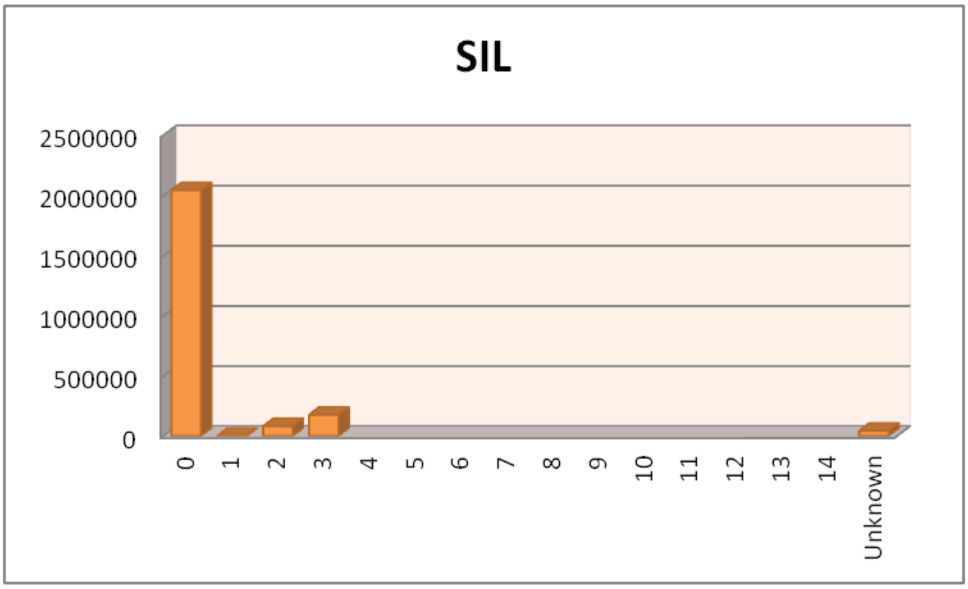

Figure 54: SIL Statistics

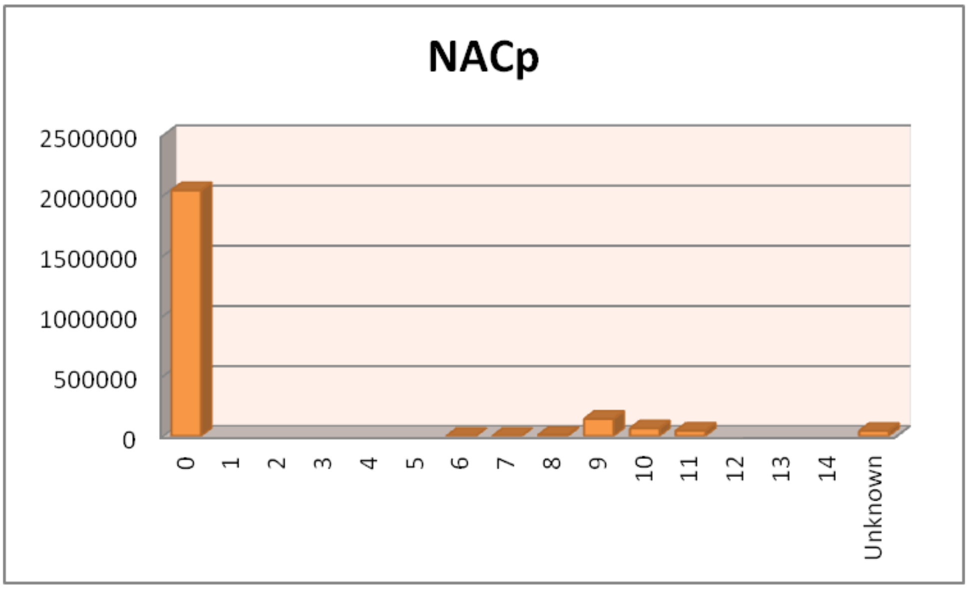

Figure 55: NACp Statistics

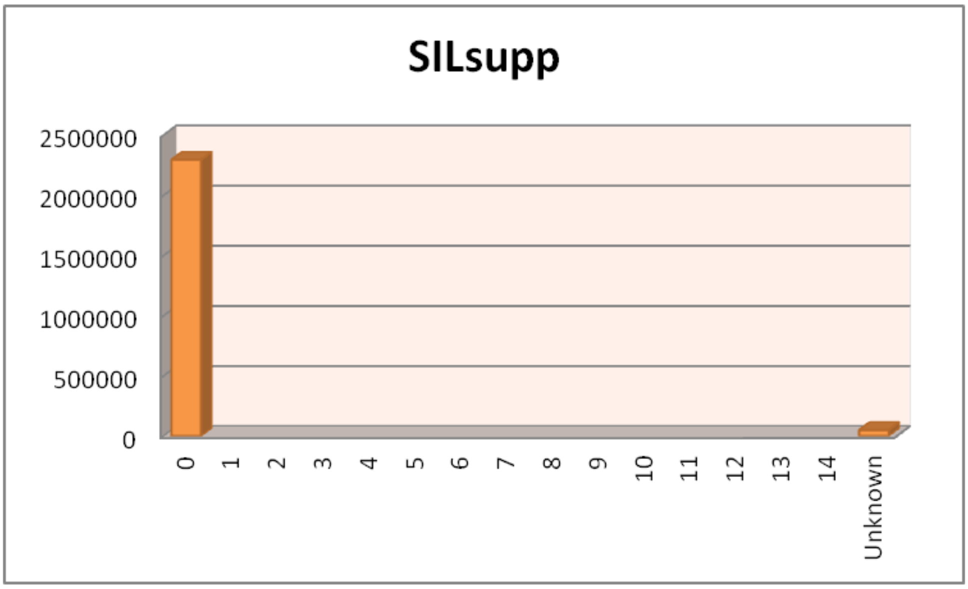

Figure 56: SILsupp Statistics

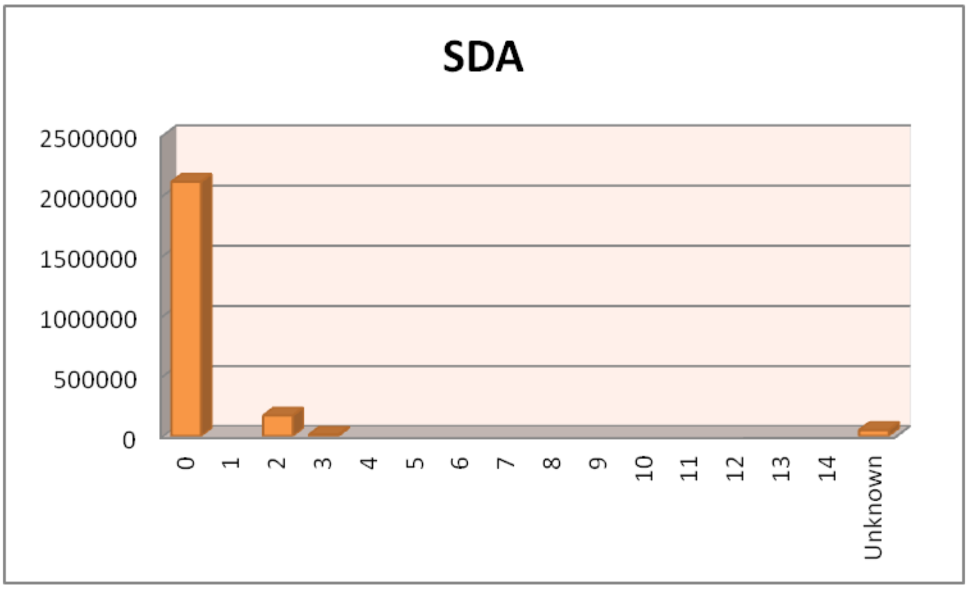

Figure 57: SDA Statistics

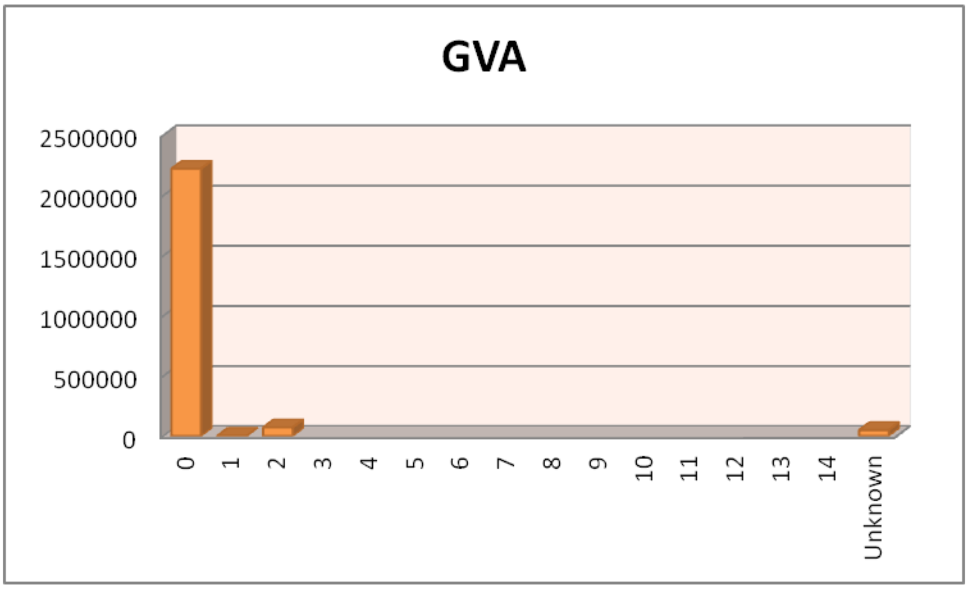

Figure 58: GVA Statistics

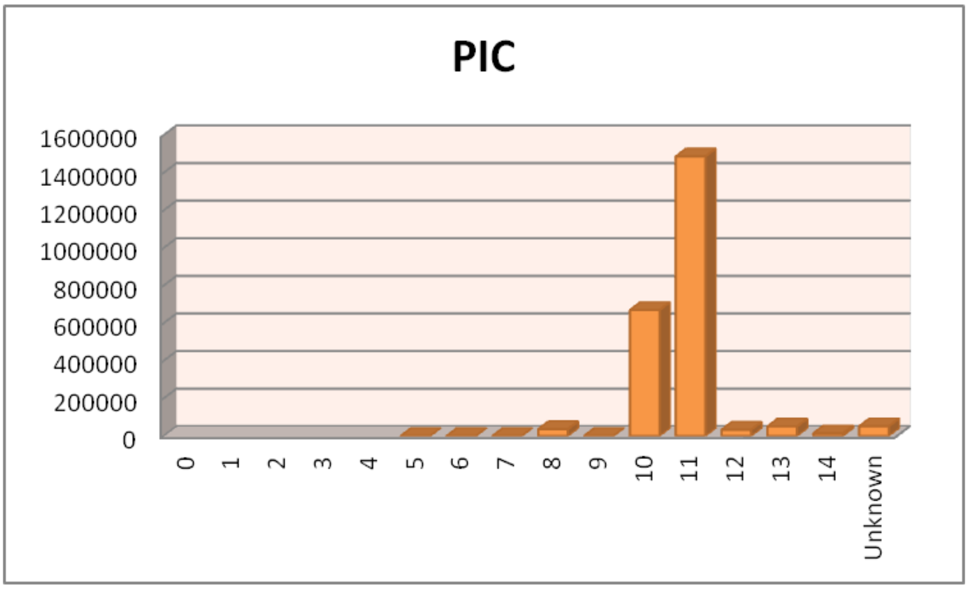

Figure 59: PIC Statistics

4.4 DFS Verification Report

4.4.1 ADS-B Barometric Height Error

According to [13] the provided barometric altitude of ADS-B is cross-validated with other secondary surveillance sensors like secondary radar and WAM. The designated data category for WAM, Cat020, does not support any information on the origin of the barometric altitude data. Hence the barometric altitude provided by cat020 might have its origin in ADS-B and would therefore be not suitable for validation of the ADS-B barometric altitude. This property is sensor dependent and hence it was made configurable, whether the WAM barometric altitude data is used for ADS-B barometric altitude validation purposes. In case the deviation exceeds a configurable threshold e.g. ±500 ft, the altitude discrepancy flag I062/200 (ADF) is set by the tracker.

For contradiction altitude measurements the altitude tracker would have difficulties to estimate directly a proper rate of climb and descent without compensation of this bias. Therefore the proposed algorithm does not apply temporal alignment of the measured barometric altitude values between ADS-B and radar plots. The residual between ADS-B and non ADS-B barometric altitude with its designated accuracy is used as pseudo measurement for a Kalman tracking filter that estimates the mean difference of the barometric altitude. Potential time differences are taken into account by an increased measurement noise based on the maximal expected rate of climb and descent.

The resulting barometric altitude residual is suitable for bias compensation purposes to achieve a stable climb and descend rate even in case of a significant deviation between the barometric altitude derived from ADS-B and secondary radar or WAM. This is a feed forward compensation and hence no feedback loop is introduced in the estimation of the rate of climb and descent.

This behaviour was tested in Verification Exercise EXE-15.04.02-D09-0030.0002 Data Verification with the scenarios ADSB/SCN2118 (ADS-B Barometric Altitude Bias - WAM before ADS-B), ADSB/SCN2119 (ADS-B Barometric Altitude Bias - WAM after ADS-B).

4.4.2 ADS-B Position Error

For position estimation purposes, ADS-B depends on an accurate position solution provided by the GPS system. Therefore a monitoring between the ADS-B and non-ADS-B position is implemented. If the difference between the ADS-B position and other position sources is small, ADS-B and non ADS-B plots contribute to the same track. Due to the assumed good accuracy of ADS-B, it is likely that the position of such a multi sensor track is dominated by the ADS-B data.

For estimating a potential ADS-B position bias, the mean residual between the track position and ADS-B plot position and the mean residual between the track position and non ADS-B plots are estimated separately. Two Kalman tracking filters, one for the ADS-B residual; one for the non ADS-B residual, are applied to calculate the mean residuals. The ADS-B position bias is given by the difference between the estimated two mean residuals.

This behaviour was tested in Verification Exercise EXE-15.04.02-D09-0030.0002 Data Verification with the scenarios ADSB/SCN2130 (ADS-B Position Bias - WAM before ADS-B), ADSB/SCN2131 (ADS-B Position Bias - WAM after ADS-B).

4.4.3 Accuracy of Accuracy

The provided accuracy of a WAM plot, e.g. by I020/500 or I020/RE is, similar as the position, a measurement itself and hence should be validated on its accuracy. The proposed evaluation of the provided accuracy is based on the accuracy used by the tracker for processing a specific plot, which might be a modified version (e.g. scaled) of the provided accuracy.

The test to evaluate the provided accuracy is based on the following 3 steps:

- Perform a chi-square test on each measurement
- Count how often it was successful and how often not
- Compare it to the expectation

The chi-square test has to take into account plot and track accuracy. To get rid of the impact of the plot under test with respect to the reference trajectory, the sensor under test should be set to InhibitTracking. Due to the additional uncertainty of the reference track, the chi-square test is slightly conservative. The quantile of the chi-square test is configurable. After counting of the successes and failures of the chi-square test, it has to be compared to the expected result of the chi-square test. The comparison step is currently done manually by the user.

This behaviour was tested in Verification Exercise EXE-15.04.02-D09-0030.0002 Data Verification with the scenario ADSB/SCN2204

5 Conclusions and recommendations

5.1 Conclusions

The results obtained after the different verification exercises indicate that the development of the platforms has been properly performed and the results are as expected.

Position based validations enhance system security, making possible to detect targets transmitting incorrect positions, may it be intentionally or not.

Validation techniques used for composite surveillance are valid methods to reduce interrogations and to enrich the quantity of data of a WAM system without the need of a continuously active interrogation system that increases the use of the RF spectrum.

Also validation techniques are considered a good method to evaluate the performance of the system and to identify external threats that may affect to the system.

The analysis indicates that the data items provided by ADS-B are suitable for supplementing the data items within WAM, with; over 99.9% of Mode A and ACID information where supplied within ADS-B messages matched that of the WAM derived data and over 99.5% of barometric Flight Level information being within ±50ft of the WAM Mode C data. Similarly, the analysis shows promise in the compatibility of several ADS-B Aircraft Derived Data items and Mode S Downlinked Airborne Parameters, although the limited data sample available in the assessment cannot provide a high level of significance to the results for this aspect of the analysis.

The further developed and adapted infrastructure consisting of data generator, sensor, MSDF and analysis tools provides powerful means for rapid prototypical development in future research projects.

5.2 Recommendations

This section contains recommendations for next activities to be performed in composite systems.

A complete integration of different systems would result in a better surveillance of the airspace, with higher values of accuracy, reliability and feasibility.

Reduction of RF spectrum is one of the critical and more important aspects of composite systems. Integration of ADS-B data in other independent sensors, such as Mode S radar, WAM or MLAT can reduce the use of interrogations by each system, reducing the total number of signals in the space and therefore reducing the likelihood of causing FRUIT, as well as reducing the use of the transponders on board, which in some saturated areas can be a problem.

Work developed in this project is in close relationship with EUROCAE activities. It should be continued with future activities after the closure of this project, providing an exchange of information between EUROCAE and SESAR projects.

Information obtained in this project will provide valuable feedback to the federating projects (e.g. 15.01.07s) for adapting their verification strategies (if applicable) and/or TAD, CNS roadmaps.

Using this project information as feedback to WP03 or B projects could improve the surveillance view and future developments.

It is recommended that evaluation and development of composite systems in it´s different possibilities is further studied in the expected SESAR2020 activities.

6 References

6.1 Applicable Documents

[1] Template Toolbox 03.01.03
https://extranet.sesarju.eu/Programme%20Library/SESAR%20Template%20Toolbox.dot

[2] Requirements and V&V Guidelines 03.01.00
https://extranet.sesarju.eu/Programme%20Library/Requirements%20and%20VV%20Guidelines.doc

[3] Templates and Toolbox User Manual 03.01.01
https://extranet.sesarju.eu/Programme%20Library/Templates%20and%20Toolbox%20User%20Manual.doc

[4] European Operational Concept Validation Methodology (E-OCVM) - 3.0 [February 2010]

[5] EUROCONTROL ATM Lexicon
https://www.eurocontrol.int/lexicon/lexicon/en/index.php/SESAR

6.2 Reference Documents

The following documents were used to provide input/guidance/further information/other:

[6] 15.04.02 D06 Technical Report, Composite cooperative surveillance studies

[7] 15.04.02 D07 Verification Strategy, Composite cooperative surveillance

[8] 15.04.02 D08 Technical report, Composite cooperative surveillance prototype

[9] 15.04.02 D09 Verification Plan, Composite cooperative surveillance

[10] 15.04.02 D10 Technical report, composite cooperative surveillance trials

[11] 15.01.07 D02-02 Integrated CNS Roadmap

[12] 15.01.07 D01-01 CNS Technical Architecture Document

[13] Safety, Performance and Interoperability Requirements Document for Enhanced Air Traffic Services in Radar-Controlled Areas using ADS-B Surveillance (ADS-B-RAD) published September 9, 2009 as RTCA DO-318 and EUROCAE ED-161 (RFG)

[14] EUROCAE ED-102A with Corrigendum 1 – Minimum Operational Performance Specification for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) & Traffic Information Services – Broadcast (TIS-B), January 2012;

[15] EUROCAE ED-142 – Technical Specification for Wide Area Multilateration (WAM) Systems

[16] EUROCAE ED-129B – Technical Specification for a 1090 MHz Extended Squitter ADS-B Ground System

[17] EUROCONTROL Specification for Surveillance Data Exchange ASTERIX Part 12 Category 21 ADS-B Target Reports v2.4, June 2015

[18] EUROCONTROL Specification for Surveillance Data Exchange ASTERIX Part 14 Category 20 Multilateration Target Reports v1.9, March 2015

[19] EUROCONTROL Specification for ATM Surveillance System Performance (ESASSP), Volume 1, Ed 1.1 September 2015

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