Experimental ADS-B based surveillance

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Abstract— **This paper describes an ADS-B implementation in air-to-air and ground based experimental surveillance within a prototype ATM system. The relations between airborne and ground systems related to surveillance are detailed, and the prototype surveillance systems and their algorithms described. Their performance is analysed, based both on simulated and real data.**

ADS-B; TIS-B; Air Surveillance; Ground Surveillance

I. INTRODUCTION

The Automatic Dependent Surveillance-Broadcast (ADS-B) [3][4][5] is a key enabler for all future Air Traffic Management (ATM) proposals, as it allows for both ground and air surveillance. As the surveillance function is a prerequisite for separation assurance (airborne and in ground), and ground flight intent conformity checking, this is a critical technology for civilian air traffic control. It is foreseen that, in coordination with Wide Area Multilateration Systems and Mode S radar it will progressively phase out current Secondary Surveillance Sensors. As not every aircraft will be equipped with ADS-B enabling avionics, a complementary service to provide ground surveillance results (from other sensors) will have to be equipped to aircraft. This is the Traffic Information System-Broadcast (TIS-B) [6].

The research described in this paper has been performed within ATLANTIDA, an Spanish project aiming to implement a completely automatic prototype of an future ATM system with Unmanned Aircraft Systems (UASs). The proposed air and ground surveillance systems have been implemented for INDRA S.A. within this project and is integrated in the ATLANTIDA avionics and traffic management prototypes.

One novelty in ATLANTIDA is the integration of such a system in a complete Trajectory Based Operation (TBO) framework for ATM with an air-inclusive SWIM (System Wide Information Management) middleware connecting all ATM systems. This SWIM concept, also present in SESAR [1] and NEXTGEN [2], assumes all data interchange and information retrieval demands are covered with a unique communication infrastructure. ADS-B was implemented over a SWIM network comprising both ground and airborne equipment.

In ATLANTIDA the following objectives of an ADS-B/TIS-B based surveillance solution were investigated:

- Design of a SWIM oriented protocol for ADS-B. We defined new ADS-B messages and protocols for experimentation, as it is mainly a software-based solution using standard hardware and middleware, instead of current approaches based on the use of certified data-buses and hardware.
- Design and implementation of a complete ADS-B based ground surveillance, with all the typical surveillance functions (measurement association, track initiation and deletion, measurement filtering, integrity tests to increase reliability, ...) and additional procedures for ADS-B induced computational load management.
- Design and implementation of a complete ADS-B based air surveillance, with a functionality similar to ground surveillance, but with additionally stringent computational requirements, and with the particularity of being implemented in a mobile platform.
- Inclusion of new data formats providing on-board meteorological measurements to a ground facility, to enable high quality tuning of meteorological models.
- Inclusion of new data formats to enable air-to-air communication of aircraft intents, to support potential extensions of ATLANTIDA concept to ASAS (Airborne Separation Assurance Systems).

This paper starts (section II) with a brief introduction to currently available ADS-B and TIS-B technologies, and some related surveillance technologies. Then (section III) it will describe the relation of air and ground surveillance systems with other avionic and ATM systems. Based on previous requirements, it will define the new data formats and protocols to be used in ATLANTIDA and subsequent work (section IV). Sections V and VI will describe internal air-to-air and ground surveillance systems structure and algorithms. Finally, the paper will include a simulation based performance evaluation of the system in section VII; and it will draw some conclusions and describe future research lines in section VIII.

II. CURRENT ADS-B AND TIS-B IMPLEMENTATIONS

There are several competing technologies for ADS-B implementation. Next we are summarizing some of the most important points of those implementations, especially with regards to the information they may provide, and to the protocols related with this communication.

Mode S squitter (Also known as 1090 ES) is currently the most used ADS-B implementation. In fact, both SESAR [1] and NEXTGEN [2] take an approach of concentrating efforts on this technology, which can be installed and updated with minor changes into currently mandatory Mode S transponders (for a great part of the aircraft fleet).

The different messages available and their fields are described in ICAO Annex 10 [3]. All squitters contain unique ICAO address (Mode S) code identifying unequivocally the transponder/aircraft. The kind of information provided is basically kinetic (position, velocity).

There are mainly two kinds of protocols in Mode S squitter: based on quasi-periodic broadcast of messages, for most types of messages; and based on event driven broadcast of messages.

VDL Mode 4 [5] is a VHF data link technology, also standardized by ICAO, and designed to support CNS/ATM digital communications services. In the Surveillance Domain it is being investigated as a candidate ADS-B data link (in complement to 1090 ES) to support ADS-B applications. It provides means for the periodic transmission of quite a lot of cinematic and intent related information potentially using broadcast, multicast, or addressed communication procedures. It can also define event driven procedures for the transmission of data.

The UAT system [4] is specifically designed for ADS-B operation. UAT has lower cost and greater uplink capacity than 1090 ES. UAT not only provides ADS information: users have access to ground-based aeronautical data and can receive reports from proximate traffic (FIS-B and TIS-B). In the United States the UAT link is intended for general aviation aircraft. From a controller or pilot standpoint, the two links operate similarly. Each aircraft broadcasts UAT ADS-B Messages once per second to convey kinetic state and other information.

TIS-B is the broadcast of traffic information to ADS-B-equipped aircraft from ADS-B Ground based transponders (GBTs). The source of this traffic information is derived from air traffic surveillance radars or other surveillance sensor such as Wide Area Multilateration (WAM). TIS-B is intended to provide ADS-B-equipped aircraft with a more complete traffic picture in situations where not all nearby aircraft are equipped with ADS-B. This advisory-only application will enhance a pilot's visual acquisition of other traffic. There are implementations and research on TIS-B based on the three previous technologies (Mode S squitter, VDL and UAT).

Although not properly ADS/TIS-B, there are some other surveillance technologies directly related to ADS-B. Those are the surveillance technologies related to ADS-C (ADS - Contract [7]), Mode S applications[3] and Airborne Collision Avoidance System (ACAS[3]). Those surveillance technologies are based on the use of several information registers within the Mode S transponder, and they are used for some other applications. The definition of ATLANTIDA surveillance messages and modes of operation also took into account the information provided by those systems.

III. ATLANTIDA SURVEILLANCE DESCRIPTION

ATLANTIDA Surveillance infrastructure is based on the definition of two interrelated systems, one deployed on airborne platforms (SURAIR), and another one compiling data from all aircraft on ground (SURGND). Next figure shows the main relations between SURAIR and SURGND systems and surrounding ATLANTIDA systems.

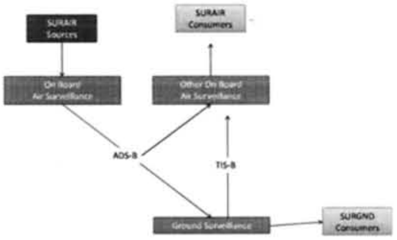

Figure 1: Overall ATLANTIDA Surveillance architecture

The main role of ground surveillance (SURGND) in ATLANTIDA is creating an air picture situation to be used by ground ATM systems. Its main data source is SURAIR, and its main information consumer is Traffic manager (TM), which provides this information, integrated with trajectory information, to other subsystems, and also performs negotiation of trajectories with aircraft, automated conflict detection and resolution procedures, etc. SURGND also provides traffic information (tracks) to Remote Flight Manager (RFM), which can act as a means for the remote control of the UAS. Ground surveillance also communicates with CNSPM system (Communication/Navigation/Surveillance Performance Monitoring System) to enable its assessment of surveillance function, and with DMET (Meteorological) system to provide meteorological samples to improve trajectory predictions in the whole ATLANTIDA system. It provides Air surveillance with TIS-B data of aircraft, and can manage TIS-B data rate. In order to perform time-synchronized hybrid simulations for experimentation, it will be connected to a simulation control engine. Additionally, it can be adapted to surveillance context and can record data for the experimental analysis.

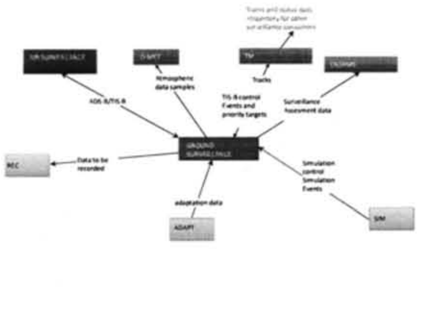

Figure 2: Ground Surveillance relation with other systems

Next figure comprises the most relevant relations of air surveillance (SURAIR) with surrounding systems.

There are two main roles of air surveillance:

- ADS-B message broadcasting enabling all other surveillance functions, both on air and on ground. To do so it obtains kinetic and meteorological information from navigation (NAVAIR) and status and intent information from Flight Manager (FM) systems, and controls the broadcasting rate
- Creating an air picture situation local to aircraft to be potentially used by air automation systems. In this role, its main data sources are air surveillance for ADS-B and ground surveillance for TIS-B, and its main information consumer is Flight Manager (FM), which could provide this information, integrated with trajectory information, to other subsystems. Air surveillance also communicates with FDRS (Flight Data recording System) to enable offline surveillance quality assessment.

In order to be able to perform time-synchronized hybrid simulations for experimentation, it will be connected to the same simulation control engine as ground surveillance.

Figure 3: Air Surveillance relation with other systems

IV. ATLANTIDA ADS-B AND TIS-B MESSAGES AND PROTOCOLS

ATLANTIDA ADS-B and TIS-B data formats are an extension of available ADS-B and TIS-B formats to include new fields of interest for short term and medium term trajectory prediction. They are:

- Aircraft mass.
- Intent information, in a much more detailed format than previous systems. The format used for Aircraft intent is derived from AIDL specification from Boeing [11]. This is the key element enabling ADS-B based predictions potentially enhancing current ASAS applications.
- Attitude information
- Aerodynamic configuration (Flaps, Landing Gear, ... state)

All messages in ATLANTIDA are managed by a SWIM system. It comprises two modes of operation, one based on the broadcasting of messages (using a DDS approach, based on RTI [10] middleware) and another one based on a request-reply protocol (using CORBA). This ATLANTIDA SWIM system not only covers ground systems, but also air-ground and air-to-air communications. ADS-B/TIS-B is implemented with SWIM middleware making use of publish-subscribe paradigms based on DDS.

Table 1 describes ATLANTIDA ADS-B and TIS-B data formats.

Table 1. Message formats

Message	Field	Description
adsb_intent	**callsign**	Identification of the aircraft
	creation_time	Time of contracted intent creation
	initial_conditions	Initial conditions are needed to calculate the predicted trajectory based on the aircraft intent
	intent	Intent information. It is a complex field describing the contracted trajectory in a reproductible manner
adsb_kinetic	**callsign**	Identification of the aircraft
	creation_time	Reference time of navigation data
	kinetic_state	Includes 3D geodetic position, groundspeed, heading, attitude (Euler Angles), barometric height
	performance_cat	ADS-B performance categories, such as NIC, NAC or SIL
adsb_meteo	**callsign**	Identification of the aircraft
	creation_time	Reference time of metorological data
	static_pressure	
	temperature	
	wind_speed	
adsb_status	**callsign**	Identification of the aircraft
	creation_time	Time of status measurement creation
	mass	Full aircraft plus payload plus fuel mass
	configuration	Aerodinamic configuration
tisb_kinetic	**callsign**	Identification of the aircraft
	creation_time	Reference time of navigation data
	kinetic_state	Includes 3D geodetic position, groundspeed, heading, barometric height
	performance_cat	Synthetic ADS-B performance categories, such as NIC, NAC or SIL

V. AIR SURVEILLANCE STRUCTURE AND ALGORITHMS

The structure of air surveillance system is depicted in next figure.

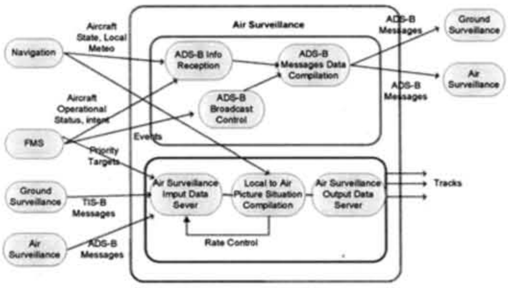

Figure 4. Air Surveillance internal structure

The air surveillance system is mainly divided into two parts to be described next:

- ADS-B messages compilation and broadcast
- Surrounding aircraft Air surveillance.

A. ADS-B compilation and broadcast

This function is necessary for the implementation of both ADS-B based air and ground surveillance. Air surveillance receives ADS-B data from Flight manager (FM) and navigation systems. This function must maintain a copy in a set of internal registers of the last data of a given kind received. ADS-B messages are broadcasted at a potentially variable data rate, depending on potentially time-changing FM requirements. ADS-B messages are broadcasted through SWIM.

B. Surrounding aircraft air surveillance

This function is in charge of obtaining the local to aircraft air picture. It contains three steps:

- Air surveillance input data server: This subsystem is in charge of receiving ADS-B and TIS-B messages. If the aircraft is receiving ADS-B messages from a given aircraft (its identifier may be used for it) TIS-B messages should be discarded.
- Air picture situation compilation, to be described in detail later.
- Air surveillance output data server: it is in charge to communicate results of the air surveillance function to FM. It actualizes periodically the track states, synchronized in time, to feed the FM.

Next we will detail Air picture situation compilation, depicted in figure 5.

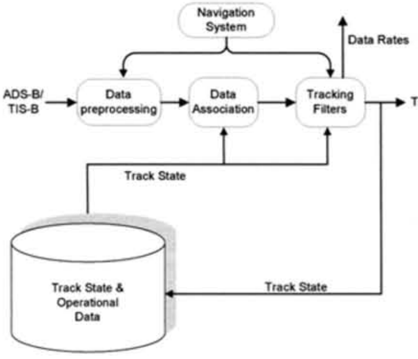

Figure 5. Air Picture situation architecture

The preprocessing consists in the coordinate transformation and the error covariance estimation for ADS-B kinetic messages. Tracking is performed in stereographic plane whose tangential point is a position near the aircraft position, which jumps every few minutes following aircraft motion. We convert both position and ground speed and track angle information from geodetic coordinates to stereographic projection.

The accuracy of ADS-B position and velocity reports will be expressed in tracking coordinates, taking into account the error models of ADS-B: Accuracy expressed typically following Navigation Accuracy Category (RTCA 260-a) will be translated to a measurement covariance matrix for horizontal position and a variance for vertical position. Therefore, after pre-processing we will have position and velocity measures with their assumed covariances. TIS-B messages will not be filtered, and therefore it is not necessary to assess their accuracy.

After preprocessing, measurement to track association must be performed. The association process among target reports (ADS-B or TIS-B) and tracks has been reduced to a code association (using the ICAO 24 bits address). There are track initiation & termination procedures both for ADS-B and TIS-B messages based surveillance. In both cases, a track will be initiated once a message with a new code is received. Track closing procedure is based on track age (time from last track update). Additionally, means for converting TIS-B based tracks in ADS-B based tracks and vice versa are defined based on time without ADS-B messages. There are independent filters for horizontal relative position and for geometric and barometric height.

Each track has associated information, which is maintained by the tracking function. Only 3D Position and ground velocity are considered for tracking. Other information, from other ADS-B messages, will be updated directly in the track state but not considered for tracking. The horizontal tracking filter is of Kalman type due to airborne low processing capabilities. It has a residual based maneuver detector, increasing acceleration variance in a piecewise constant white acceleration model [8] during a fixed time interval after maneuver detection. There are two independent vertical tracking filters: for barometric and geometric heights respectively. Both filters will be also of Kalman type.

Based on the quality of the estimated track, tracking function computes and communicates to the surveillance input data server the data rate necessary to maintain track quality, to reduce SURAIR computational needs.

VI. GROUND SURVEILLANCE STRUCTURE AND ALGORITHMS

Ground Surveillance architecture is depicted in next figure. It is built around the Air Picture Situation Compilation system, which obtains the current Air Picture Situation for all targets.

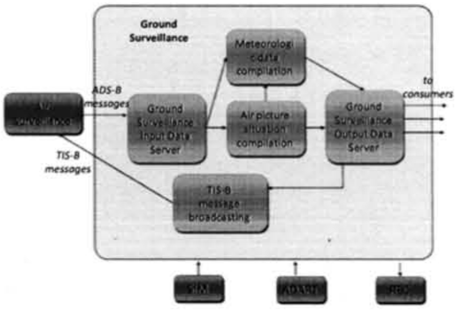

Figure 6. SURGND Architecture

In ATLANTIDA not only the processing of ADS-B has been addressed, but additionally the integration with other surveillance systems studied, although not implemented.

The main parts of SURGND are:

- Ground Surveillance Input Data Server: This subsystem is in charge of receiving ADS-B messages and discarding repeated messages. ADS-B measures are provided to different subsystems: Kinetic and status messages are provided to Air Picture Situation compilation block while Meteorological messages are provided to Meteorological Data Compilation.
- The Air picture situation block executes the three central processes of figure 7. It is a system similar to SURAIR Air Situation Picture Compilation, but with the following differences:
    - It does not process intent information messages
    - It has no need to change tracking reference position along time, as it is fixed
    - Due to additional computational resources, pre-processing, data association and tracking filters may be enhanced versions of those in SURAIR.
- Meteorological Data Compilation: SURGND receives Meteorological info ADS-B messages, and sends meteorological samples to DMET.
- Ground Surveillance Output Data Server. The output data server block is in charge to periodically communicate results of the surveillance function to other actors in ATM systems.
- TIS-B Control and message broadcasting, from current tracks, managing publication period to control SURGND load.

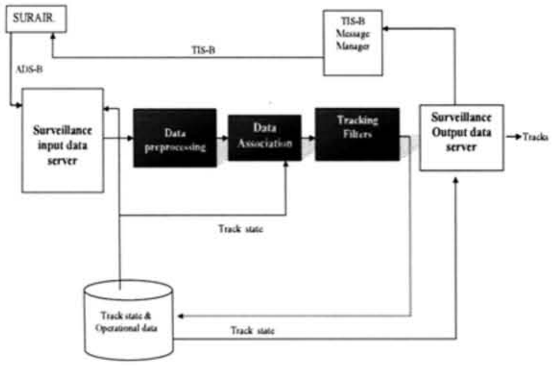

Figure 7. Air Picture situation architecture

The tracking filter is the key process in SURGND. This filter process the time ordered sequence of ADS-B reports by the same target. There are independent filters for horizontal relative position and for geometric and barometric height. The state estimated by this tracking filter (central state) is the base for the extrapolation to the demanded time done by the publication sub-function. The horizontal tracking filter is of IMM [9] type: a set of Kalman filters adapted to different movement models whose outputs are combined as a function of residual error (difference between predicted position by the filter and measures). This filter has many advantages: i) has a quickly response to target maneuvers, ii) has an automatic estimation of the MOF and iii) has an estimation of the quality of the estimated state. Additionally, there are two independent vertical tracking filters: for barometric and geometric heights respectively. Both vertical and horizontal tracking filters can process position and speed measurements.

Based on the quality of the estimated track, tracking function computes and communicates to the surveillance input data server the data rate necessary to maintain track quality. In this case, the data server prunes input reports to adapt the input data rate higher than the demanded one.

VII. PERFORMANCE EVALUATION

Here some representative results both from SURGND and SURAIR simulated and experimental results have been summarized. An example of simulated scenario is depicted in next figure, where two aircraft follow an encounter geometry with maneuvers with transversal accelerations in the order of 3 m/s^2. Trajectory A is the one in blue, while trajectory B is depicted in red.

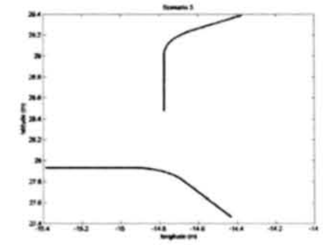

Figure 8. ADS-B simulation scenario using simulation data

The results, in terms of RMS of the error, can be seen for SURGND in next figures, along time. Blue lines represent measurement error while red lines filtered error. These results were obtained for GPS with differential corrections and quantification steps leading to a measurement RMS in position in the order of 30-40 m, and of 0.3-0.4 m/s in velocity components. Figure 9 shows the improvement in position (longitude), while figure 10 shows the improvement in velocity (groundspeed) for trajectory A.

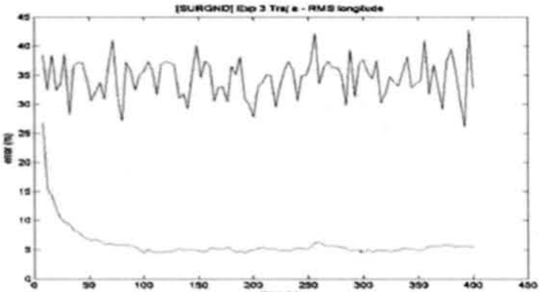

Figure 9. Position Error RMS

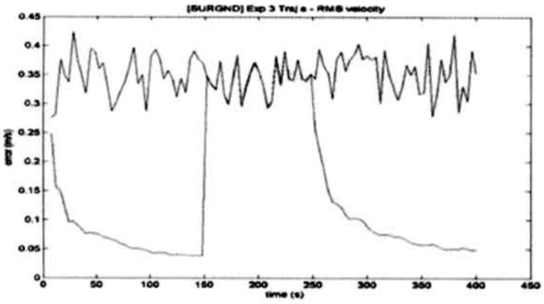

Figure 10. Velocity Error RMS

The filter reduces both position and velocity errors to negligible values in non-maneuvering conditions. In maneuvering conditions the filter maintains measurement velocity errors while improving position estimates.

The results for the same scenario for SURAIR are pretty similar. The main difference is a bias term of up to 0.3° in bearing, due to the mismatch between local horizontal planes of the aircraft. This bias disappears for near aircraft.

Finally, we also assessed performance of surveillance with respect to communication delays, which may have an impact in the desired rapid maneuver detection. The different colors in next figure are related to different combinations of origin aircraft and destination (other aircraft or ground surveillance).

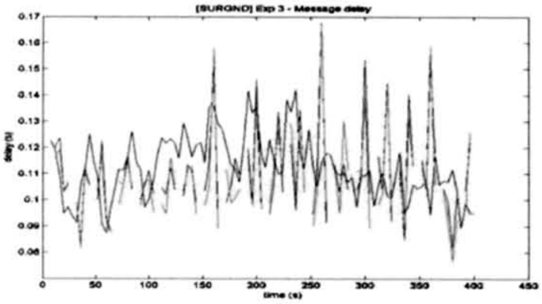

Figure 11. Mean Communication delays

From those results, its is clear less than 0.2 seconds delay is guaranteed for ADS-B messages, leading to high quality of surveillance in ATLANTIDA deployments.

VIII. CONCLUSION AND FUTURE WORK

This paper details the experimental development of an air-ground surveillance system to be integrated in ATLANTIDA system. Our simulated data shows it will fulfill even the most demanding surveillance accuracy requirements. Real data were not available yet, although the system is integrated with the rest of ATLANTIDA avionics and ATM systems.

Some key features of the proposed experimental deployment are:

- Support for new data types of interest for TBO using advaneed trajectory prediction infrastructures, especially for air-to-air trajectory negotiation, such as intent, dynamic state, aircraft configuration, … ATLANTIDA ASAS applications were not finally implemented, although SURAIR system provides the technological support for the definition of air-to-air intent based short and medium term negotiations.
- Air inclusive SWIM integrated communications
- Integration in complete prototype ATM system (ATLANTIDA). Specifically, ground surveillance was integrated in an adapted version of operational surveillance system (AIRCON) and with traffic management tools
- Experimental orientation, enabling data recording for analysis, integration in simulated environment, …
- Air surveillance is integrated in low cost PC-based avionics platform including a GNSS based navigation system, a fully automated Flight Management System, data recording support, an emergency and alert support system, …

Regarding R&D lines, the following ideas may drive future enhancements of aircraft surveillance:

- Extension of air surveillance applications, especially those related to coordinated maneuvers and delegation of responsibility to aircraft pilots.
- Extension of the use of intent information to reduce prediction error in maneuvers. Reduced versions of aircraft intent could be used for this extrapolation, enabling higher performance short-term conflict alerts.

As a conclusion, it is clear ADS-B must be improved to include new information enabling for accurate trajectory prediction to enable new applications. The final format of the intent/trajectory information to be interchanged is directly related to the negotiation procedures in ATM system.

REFERENCES

[1] SESAR Consortium website.

[2] Next Generation Air Transportation System (NGATS) Institute website.

[3] ICAO Annex 10: Aeronautical Telecommunications. Volume IV. Surveillance Radar and Collision Avoidance Systems

[4] Manual on the Universal Access Transceiver (UAT): Detailed Technical Specifications, Edition 1. Revision 3.2 2 March 2005. ICAO

[5] Manual on detailed technical specifications for the VDL Mode 4 digital link. Draft 2.1. 25 November 2003. EUROCAE.

[6] Technical Verification and Validation of TIS-B using VDL Mode 4. NEAN Update Program

[7] FANS-1/A Operations Manual. Version 4.0. Effective1. 28 September 2006

[8] Y. Bar-Shalom, ed., Multitarget-Multisensor Tracking: Applications and Advances, Vol. II, 1992, Massachusetts, Artech House.

[9] Kirubarajan T., Bar-Shalom, Y, 1999, Precision large scale air traffic surveillance using IMM/assignment estimators. IEEE Transactions on Aerospace and Electronic Systems. Jan. 1999. Vol: 35 , Issue 1, pp 255-266.

[10] http://www.rti.com/

[11] J. Lopez-Leones, M. Vilaplana, E. Gallo, F. Navarro, and C. Querejeta,, 2007, "The Aircraft Intent Description Language: A key enabler for air-ground synchronization in Trajectory-Based Operations", Digital Avionics Systems Conference, DASC '07. IEEE/AIAA 26th, 2007, pages. 1.D.4-1-1.D.4-12