Proposed Revisions to ADS-B MASPS:
Integrity and Accuracy Monitoring

SC 186 WG-6, August 2001

1. Introduction

Since the publication of the ADS-B MASPS (RTCA DO-242, Ref.1), RTCA committee SC-186 has been developing Required Surveillance Performance characteristics for ADS-B applications and airborne separation assurance procedures. Two important performance parameters for any surveillance application are Accuracy and Integrity. Accuracy refers to the nominal bounds on position (or velocity) state estimates and is typically stated as a 95% containment limit for estimate uncertainty, given that the system is operating normally. Integrity on the other hand refers to the probability that an ADS-B state estimate (horizontal position or height) provides misleading information to an application without alerting. Integrity is typically measured in terms of a containment bound and the probability that the state estimate will fall outside the containment bound without crew alerting. An examination of the safety implications of proposed ADS-B applications has shown that up to three levels of Integrity[1] need to be considered for ADS-B applications, i.e.

- Nonessential - applications (such as visual acquisition) where minimal integrity is required since an undetected failure has only minor safety consequences,

- Essential – applications (such as some proposed paired separation procedures) where a basic level of Integrity (Probability level of 1x 10^{-5} /hr or less) is required to avoid major safety consequences resulting in increased workload for pilots and controllers when an undetected failure in the surveillance function occurs,

- Critical – applications (such as primary separation assurance procedures) where a high level of Integrity (Probability level of $1x10^{-7}$/hr or less) is required to avoid severe major safety consequences when an undetected failure in surveillance occurs.

This paper documents proposed revisions to the ADS-B MASPS for RTCA DO-242A which will provide necessary accuracy and integrity parameters for ADS-B state vector reporting, and for assessing whether proximate aircraft have sufficient accuracy and integrity to participate in selected separation applications. The MASPS revisions are specifically designed to accommodate the above levels of criticality. Initial applications are anticipated to require lower levels of integrity, i.e. nonessential for enhanced VFR applications and essential for near term IFR applications, but potential growth to critical applications is accommodated in the proposed MASPS revisions.

[1] The criticality levels used in this document, e.g. non-essential, essential, and critical, are intended to represent equipment categories defined by certification authorities, e.g. FAA Air Circular AC-25.1309 and RTCA DO-178B. ADS-B equipment will also need to meet corresponding certification standards for availability and other criteria.

2. Problem Statement

In the current version of the ADS-B MASPS (RTCA Document DO-242, Ref.1) horizontal position integrity and nominal position uncertainty of an ADS-B report are combined into a single Navigation Uncertainty Category (NUC_P). This method of transmitting horizontal position integrity and position accuracy has several major problems for surveillance and separation assurance processing:

(1) Navigation integrity and accuracy metrics need to be treated separately. In general performance characteristics for nominal accuracy and for integrity containment bounds are not functionally dependent. Many existing navigation systems such as dual DME systems do not monitor integrity using redundant sensors to estimate integrity containment. Such systems may perform tests to validate correct operation of the navigation sensor and reasonableness of the estimated positions, but may not have the ability to detect degraded sensor modes such as large multipath errors or station location errors. With the current MASPS, systems with inadequate integrity monitoring would presumably report a NUC_P of 0, indicating no known integrity limits. Systems that have the ability to detect large errors with high confidence could probably be certified to a large containment bound, e.g. a NUC_P of 2. With the current MASPS, nominal 95% position uncertainty would not be reported or known for such systems.

The Airborne Surveillance and Separation Assurance Processing (ASSAP) function will require an estimate of position uncertainty for each aircraft in track for multi-sensor data fusion and for monitoring aircraft separations. A 95% position uncertainty estimate is needed to represent nominal estimation uncertainty for these functions, e.g. generation of alerts for crew awareness of potential separation problems.

(2) The level of integrity needed, i.e. probability of position error exceeding the stated containment bound without warning, is dependent on the ADS-B application, with some applications requiring substantially lower integrity levels than others. The integrity level in the MASPS (10^{-7}per hour) is intended to reflect the signal-in-space integrity using a GPS based system with RAIM failure detection or WAAS or LAAS integrity monitoring. The overall navigation system containment bounds for the RAIM and WAAS GPS based systems are unlikely to achieve a certified integrity level greater than $1x10^{-5}$, consistent with requirements for navigation RNP.

(3) A problem with the current definition of NUC_P in the DO-242 MASPS, especially as implemented in the DO-260 MOPS, is that receiving equipment cannot tell whether the NUC_P value is communicating an <u>integrity</u> bound (such as HPL) or an accuracy bound (such as EPU or HFOM). Indeed, the present DO-260 MOPS requires that the transmitted NUC_P value be determined by HPL if HPL is available to the transmitting ADS-B equipment, and by HFOM if HPL is not available. Consequently, there is no way for receiving equipment to tell whether a given NUC_P code describes an <u>integrity</u> bound (such as HPL) or an <u>accuracy</u> bound (such as HFOM).

Therefore, ADS-B applications that require knowledge of integrity of a transmitted position cannot be operationally approved based on the present use of NUC_P as defined in DO-242 and implemented in DO-260 – because they cannot be assured that a given NUC_P code does indeed convey an integrity limit. Likewise, applications that require knowledge of the accuracy of a transmitted position cannot be operationally approved based on DO-242 and DO-260 -- because they cannot be assured that a given NUC_P code does indeed convey an accuracy limit.

The RNP MASPS (RTCA Document DO-236A, Ref.2) use a lower integrity level of $1x10^{-5}$ for the probability of exceeding the RNP based containment bound. This integrity level is consistent with most IFR avionics, e.g. current navigation and Flight Management Systems. However, RNP based Navigation Integrity may be inadequate for critical level separation assurance applications since the integrity level represents a fleetwide average rather than a specific aircraft flight. This problem is illustrated with an example:

Suppose that an ADS-B system is based on a dual DME system with RNP-0.3 navigation capability, the exposure probability to a multi-path degraded DME range estimate is 0.001 for the navigation system, and the probability of missed detection for a DME error > 0.6 nmi containment bound is 0.001. Then, the average probability of obtaining a hazardously misleading DME solution is the joint product of the exposure probability and the missed detection probability, i.e.

Probability (undetected multi-path DME error > 0.6nmi) $= .001x\ .001 < 1x10^{-5}$.

In this case, navigation integrity for RNP-0.3 would be considered acceptable since the average probability of exceeding the 2*RNP containment bound without alerting is less than $1x10^{-5}$. However, on a specific flight path where serious multi-path conditions occur which can lead to large errors, the probability of an undetected large error is on the order of 0.001 which is two orders of magnitude larger than $1x10^{-5}$. Such a system would probably not be considered suitable for critical separation assurance applications. What appears to be needed for such applications is a stronger requirement on integrity monitoring. For example, one could require that the conditional probability of undetected large errors given any probable failure mode is less than $1x10^{-5}$, or alternately, that the integrity level be increased to $1x10^{-7}$ for such applications. The latter level of integrity monitoring may be more appropriate for higher integrity separation assurance applications.

One means to achieve higher integrity levels is to provide redundant means of estimating aircraft position, for cross-checking of ADS-B position reports. For example, the use of TCAS ranging data, or use of TIS-B position data derived from radar sensors could be a means of achieving higher integrity levels, based on cross-checking and monitoring of position differences between redundant surveillance sources. Of course, the containment value for such integrity monitoring needs to be determined such that the uncertainty in integrity cross-checking is properly accommodated.

3. Summary of WG-6 Proposed Revisions to the ADS-B MASPS

The revisions to the ADS-B MASPS proposed by WG-6 for DO-242A would transmit separate horizontal accuracy and integrity containment parameters in each ADS-B report and a Surveillance Integrity Level (SIL) reflecting an assured probability of not exceeding the containment radius for integrity. The first two parameters are designated Navigation Accuracy Category (NAC_P), and Navigation Integrity Category (NIC). The Navigation Accuracy Category (NAC_P) would exclusively refer to nominal position uncertainty at the 95% probability level and corresponds to standard RNP accuracy levels from RNP10 to RNP 0.1 and adds additional accuracy levels as shown in Table 1. For example, NAC_P=6 would identify the 95% horizontal position uncertainty as between 0.3 nmi and 0.1 nmi. Navigation Integrity Category (NIC) would indicate the containment bound for integrity monitoring in the same way that NUC_P is used in the current MASPS. However, the integrity level for NIC values will be indicated by one of four possible SIL values corresponding to (0) no integrity, (1) non-essential integrity, (2) essential level integrity, and (3) critical (severe major) level integrity.

In addition, the NUC_R velocity value in the current MASPS is renamed NAC_V, since this parameter reflects a 95% accuracy bound on horizontal velocity vector.

The reason for transmitting and maintaining both an accuracy NAC and an integrity NIC is that these parameters play different roles in the separation assurance process. Typically, the sensor uncertainty values (including velocity uncertainty NAC_V) are used to predict potential conflicts and to select alarm thresholds. Separation standards and procedures for assuring safe separation between aircraft are based on the integrity and containment bounds of the sensors used to assure separation. Procedural separation, for example, is typically based on the integrity of the airborne horizontal and vertical sensors for flying intended path routings. Both accuracy and integrity are needed elements for Required Surveillance Performance (RSP). User applications requiring similar sensor accuracy may be expected to levy substantially different requirements on integrity, depending on application criticality and the safety consequences of hazardously misleading information.

For GPS based systems satisfying the WAAS MOPS (RTCA DO-229B, Ref.3), the 95% accuracy values used to compute NAC_P are output as the Horizontal Figure of Merit (HFOM), and for systems requiring geometric altitude, the Vertical Figure of Merit (VFOM). Similarly, the NIC categories are determined by the Horizontal Protection Limit (HPL), and for applications requiring geometric altitude, the Vertical Protection Limit (VPL). For other navigation sensors, e.g. VOR, DME, and Loran systems, horizontal accuracy and containment values are output as Estimated Position Uncertainty (EPU) and containment radius (Rc), and may be estimated consistent with the methods for RNP determination (RTCA DO-236A, Ref.2).

The proposed criteria for Navigation Accuracy Category (NAC_P), Navigation Integrity Category (NIC), and Surveillance Integrity Level (SIL) are summarized below:

Table 1: Proposed Navigation Accuracy Category – Position

NAC_P	Horizontal Error (95%)	Vertical Error (95%)	Comment
0	EPU ≥ 10 nmi	-	Accuracy Unknown
1	EPU < 10 nmi	-	RNP-10 Accuracy
2	EPU < 4 nmi	-	RNP-4 Accuracy
3	EPU < 2 nmi	-	RNP-2 Accuracy
4	EPU < 1 nmi	-	RNP-1 Accuracy
5	EPU < 0.5 nmi	-	RNP-0.5 Accuracy
6	EPU < 0.3 nmi	-	RNP-0.3 Accuracy
7	EPU < 0.1 nmi	-	RNP-0.1 Accuracy
8	EPU < 0.05 nmi	-	e.g. GPS
9	EPU < 30 m	-	e.g. GPS (No SA)
10	HFOM < 10 m	VFOM < 15 m	e.g. WAAS
11	HFOM < 3 m	VFOM < 4 m	e.g. LAAS

Table 2: Proposed Navigation Integrity Category – Horizontal Position

NIC	Horizontal Containment	Comment
0	Unknown	No containment
1	Rc < 20 nmi	RNP-10 containment
2	Rc < 8 nmi	RNP-4 containment
3	Rc < 4 nmi	RNP-2 containment
4	Rc < 2 nmi	RNP-1 containment
5	Rc < 1 nmi	RNP-0.5 containment
6	Rc < 0.6 nmi	RNP-0.3 containment
7	Rc < 0.2 nmi	RNP-0.1 containment
8	Rc < 0.1 nmi	e.g. RAIM - GPS
9	Rc < 75 m	Future system
10	Rc < 25 m	e.g. WAAS HPL
11	Rc < 7.5 m	e.g. LAAS HPL
12-15	future expansion	

The surveillance integrity levels (allowable probability of exceeding the associated NIC containment value without alerting) are defined by the following categories:

SIL = 0   1 - No integrity (non-interfering level)
1   1×10^{-3} - Non-essential level
2   1×10^{-5} - Essential level
3   1×10^{-7} - Critical level

The above probability values are per flight hour or per operation for separation assurance applications. The SIL values are expected to represent certification values and are unlikely to change unless a different NAV source is being used.

It is proposed to move the NIC, NAC_P, NAC_V, and SIL parameters into the Mode Status Report, since these parameters are likely to change slowly or rarely, during routine operations. However, the Mode Status report must be updated promptly if a change occurs in any or these parameters.

4. Comments on Alternative Proposals for Replacing NUC_P in DO242 MASPS

Several alternative proposals were considered by WG-6 that would simplify the representation of position containment by deleting either the NIC category or the NAC category. These proposals were not considered adequate by the committee for the following reasons:

- Delete NIC and broadcast NAC only: This proposal was rejected on the basis that the integrity of a position estimate cannot be estimated based on a NAC value reflecting 95% uncertainty for normal operations. For example, with a dual DME system there is no redundant information to detect anomalies in position estimates, e.g. large multi-path errors. Thus it is not possible to take a NAC uncertainty value and multiply by some fixed number to estimate integrity containment radius.

- Delete NAC and broadcast NIC only: This proposal was rejected on the basis that the integrity of a position estimate may not adequately reflect normal sensor performance. For many navigation sources such as LORAN and dual DME, there simply is insufficient redundancy to assure a reasonable size integrity containment radius, i.e. most systems would either output no integrity or extremely conservative values which could be orders of magnitude larger than typical errors in normal operation. Similarly, for GPS systems satisfying the recent DO-229B WAAS MOPS, in certain geometries where a minimal number of satellites is in view, the HPL containment radius can grow and become much larger than the nominal HFOM accuracy level. This reflects the fact that the GPS solution is probably very accurate, but the sensor system cannot detect GPS failures and provide alerting of integrity failures unless the resulting position errors are very large. For many applications, accuracy tolerances are relatively small, e.g. see Table 3-4 in the current DO-242 MASPS. The use of Integrity as a substitute for accuracy would significantly reduce availability and continuity of operations for virtually all the applications studied to date, and would eliminate many potential navigation sources for ADS-B broadcast.

5. References

(1) Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B), RTCA Document DO-242, SC-186, Feb. 1998.

(2) Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation, RTCA Document DO-236A, SC-181, Sept. 2000.

(3) Minimum Operational Performance Standards for Global Positioning System / Wide Area Augmentation System Airborne Equipment, RTCA Document DO-229B, SC-159, October 1999.

Appendix A: Default Conversion of NUC^P and NIC Values for DO-260 MOPS Equipment

Backward compatibility and interoperability of older DO-242 MASPS equipment is an important issue in implementing the proposed MASPS changes. Table 3 shows the proposed conversion for a Version 1 1090 MHz ADS-B receiving subsystem to interpret the NUC_P codes that it receives from a Version 0 1090 MHz ADS-B transmitting subsystem. Similarly, Table 4 shows the proposed conversion of a version 1 NIC code into a transmitted NUC_P value for version 0 receiving equipment. Other ADS-B systems may need to build similar conversion tables for interpreting NUC_P codes and converting to NIC/NAC/SIL values, and *visa versa*, and for interpreting other format changes for compatibility with DO-242A MASPS requirements.

Table 3: Interpretation of NUC_P Codes from Version 0 1090 MHz Transmitting Subsystems When Received by Version 1 or Above 1090 MHz ADS-B Receiving Subsystems.

Values Sent By Version 0 Transmitting Subsystem			Values Inferred by Version 1 or Above Receiving Subsystem		
Message Type[1]	Message Type Code	NUC_p	NAC_P	NIC	SIL[2]
All	0	0	0 (EPU ≥ 10 nmi)	0 (R_C ≥ 20 nmi)	0 (No Integrity)
Surface position	5	9	11 (HFOM < 3 m)	11 (R_C < 7.5 m)	1 (“3 nines”)
Surface position	6	8	10 (HFOM < 10 m)	10 (R_C < 25 m)	1 (“3 nines”)
Surface position	7	7	8 (EPU < 0.05 nmi)	8 (R_C < 0.1 nmi)	1 (“3 nines”)
Surface position	8	6	0 (EPU ≥ 0.05 nmi)	0 (R_C ≥ 0.1 nmi)	0 (No Integrity)
Airborne with Baro	9	9	11 (HFOM < 3 m)	11 (R_C < 7.5 m)	1 (“3 nines”)
Airborne with Baro	10	8	10 (HFOM < 10 m)	10 (R_C < 25 m)	1 (“3 nines”)
Airborne with Baro	11	7	8 (EPU < 0.05 nmi)	8 (R_C < 0.1 nmi)	1 (“3 nines”)
Airborne with Baro	12	6	7 (EPU < 0.1 nmi)	7 (R_C < 0.2 nmi)	1 (“3 nines”)
Airborne with Baro	13	5	6 (EPU < 0.3 nmi)	6 (R_C < 0.6 nmi)	1 (“3 nines”)
Airborne with Baro	14	4	5 (EPU < 0.5 nmi)	5 (R_C < 1.0 nmi)	1 (“3 nines”)
Airborne with Baro	15	3	4 (EPU < 1.0 nmi)	4 (R_C < 2.0 nmi)	1 (“3 nines”)
Airborne with Baro	16	2	2 (EPU < 4.0 nmi)	2 (R_C < 8 nmi)	1 (“3 nines”)
Airborne with Baro	17	1	1 (EPU < 10 nmi)	1 (R_C < 20 nmi)	1 (“3 nines”)
Airborne with Baro	18	0	0 (EPU ≥ 10 nmi)	0 (R_C ≥ 20 nmi)	0 (“No Integrity”)
Airborne with GPS altitude	20	9	11 (HFOM < 3 m, VFOM < 4 m)	11 (R_C < 7.5 m)	1 (“3 nines”)
Airborne with GPS altitude	21	8	10 (HFOM < 10 m, VFOM < 15 m)	10 (R_C < 25 m)	1 (“3 nines”)
Airborne with GPS altitude	22	TBD	0 (EPU ≥ 10 m or unknown)	0 (R_C ≥ 25 m or unknown)	0 (No Integrity)

Notes: (1) *Surface position messages, airborne messages using Baro altitude and airborne messages using GPS altitude are differentiated by a message type code for DO-260 ADS-B systems.*

(2) *A Default SIL value of 1 is assumed when NUCp cannot be unambiguously translated as a containment bound. Higher SIL values may be achievable for specific system implementations.*

Table 4: Interpretation of NIC Codes (from Version 1 or Above 1090 MHz Transmitting Subsystems) When Received by Version 0 1090 MHz Receiving Subsystems.

Type Code in Message From Version 1 Transmitting Subsystem	NIC Value from Version 1 or Above Transmitting Subsystem	NUC_P Value Assumed by Version 0 Receiving Subsystem
0	0 (R_C unknown or ≥ 20 nmi)	0 (HPL ≥ 20 nmi , or HFOM ≥ 10 nmi)
5	11 (R_C < 7.5 m)	9 (HPL < 7.5 m, or HFOM < 3 m)
6	10 (R_C < 25 m)	8 (HPL < 25 m, or HFOM < 10 m)
7	8 or 9 (R_C < 0.1 nmi)	7 (HPL < 0.1 nmi, <u>or</u> HFOM < 0.05 nmi)
8	0 (R_C ≥ 0.1 nmi)	6 (HPL ≥ 0.1 nmi, <u>or</u> HFOM ≥0.05 nmi)
9	11 (R_C < 7.5 m)	9 (HPL < 7.5 m, <u>or</u> HFOM < 3 m)
10	10 (R_C < 25 m)	8 (HPL < 25 m, <u>or</u> HFOM < 10 m)
11	8 or 9 (R_C < 0.1 nmi)	7 (HPL < 0.1 nmi, <u>or</u> HFOM < 0.05 nmi)
12	7 (R_C < 0.2 nmi)	6 (HPL < 0.2 nmi, <u>or</u> HFOM < 0.1 nmi)
13	6 (R_C < 0.6 nmi)	5 (HFOM < 0.25 nmi, <u>or</u> HPL < 0.5 nmi)
14	5 (R_C < 1.0 nmi)	4 (HPL < 1.0 nmi, <u>or</u> HFOM < 0.5 nmi)
15	4 (R_C < 2 nmi)	3 (HPL < 2 nmi, <u>or</u> HFOM < 1.0 nmi)
16	2 or 3 (R_C < 8 nmi)	2 (HPL< 10 nmi, <u>or</u> HFOM < 5.0 nmi)
17	1 (R_C < 20 nmi)	1 (HPL < 20 nmi, <u>or</u> HFOM < 10 nmi)
18	0 (R_C ≥ 10 nmi)	0 (HPL ≥ 20 nmi, <u>or</u> HFOM ≥ 10 nmi)
20	11 (R_C < 7.5 m)	0 (HPL and HFOM unknown)
21	10 (R_C < 25 m)	0 (HPL and HFOM unknown)
22	**TBD** (R_C ≥ 25 m)	0 (HPL and HFOM unknown)