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RTCA Special Committee 186

Working Group 6

Verifying Performance of ADS-B Position Reporting: Experience From Capstone ADS-B "Radar-Like Services"

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1.0 Background

Data collection and analysis activities were conducted in support of certification of the downlinked ADS-B information to be used for the Capstone Radar-Like Services (RLS) function. These activities focused on the integrity and accuracy of the reported ADS-B information as well as monitoring for any other anomalies in the operation of the ADS-B avionics or ground stations. One objective of the study was to determine the condition under which a problem with the quality of a given track within the automation system should be annunciated. A key parameter examined in this regard was the Navigation Uncertainty Category of position (NUCp) value reported with each ADS-B message. The NUCp value to be reported with each ADS-B message is specified in RTCA DO-242[1] and shown here in Table 1. For the Capstone implementation the Horizontal Protection Level shown in the table is based on the GPS RAIM alarm limit per TSO C129.

Table 1. NUCp Values per RTCA DO-242

NAVIGATION UNCERTAINTY CATEGORY - Position			
CODING	MEANING		
NUC_P	Horizontal Protection Level		Altitude Type
0	Unknown or > 20 nmi	*AND*	Baro Altitude
1	< 20 nmi	*AND*	Baro Altitude
2	< 10 nmi	*AND*	Baro Altitude
3	< 5 nmi	*AND*	Baro Altitude
4	< 1 nmi	*AND*	Baro Altitude
5	< 0.5 nmi	*AND*	Baro Altitude
6	< 0.2 nmi	*AND*	Baro Altitude
7	< 0.1 nmi	*AND*	Baro Altitude

NOTE 1: In the table, the rows shown with a shaded background indicate the NUCp values which the Capstone equipment reports.

NOTE 2: Horizontal Protection Level: the radius of a circle in the horizontal plane (local plane tangent to the WGS-84 ellipsoid), with its center being at the true position, such that the probability that the indicated position lies outside this circle is 10^{-7} per flight hour. Since this allowed rate of "missed detection" of an integrity alert is so low, very conservative assumptions must be used in declaring an alarm condition.

NOTE 3: In the Capstone implementation, the baro altitude input has no influence on the NUCp determination

Capstone avionics employs GPS sensors certified for navigation under TSO C129. According to the TSO and the MOPS, these units are not required to provide an output of HPL directly, but are only required to issue an alarm based on a *pilot entered* navigation mode (enroute, terminal, non-precision approach). The manufacturer has therefore made some adaptation to enable the ADS-B NUCp reporting based on this GPS sensor.

For purpose of the Capstone RLS application, it was expected that the NUC 4 value would be the lowest (worst) value consistent with the separation standard (5 nmi) used

[1] The following is from DO-242 Section 2.1.2.2.4.1: "The NUC is reported so that the surveillance applications may determine whether the reported position has an acceptable level of integrity and accuracy for the intended use." It should be noted that some changes in the way this information is classified and reported are being considered in future revisions of DO-242.

for Capstone RLS. Any value lower (worse) than this is reported as a NUC 0, which for purposes of Capstone RLS, is planned to be interpreted as "integrity not available"[2].

2.0 Equipment Configuration

Figure 1 below provides a functional diagram of the Capstone ground system. The remotely deployed ground stations are known as Ground Broadcast Transceivers (GBTs). Each GBT site in Capstone employs redundant GBTs, each with independent satellite circuit (ANICS) connectivity to Anchorage Center. GBTs contain GPS sensors identical to those in the ADS-B avionics. At each site, each GBT has its own GPS antenna. GPS antennae are sited within 50' of each other at each site. GBTs are configured to report their position and NUC information in a fashion identical to an ADS-B report. This occurs in one of two ways. One is through special RF transmissions between the cosited GBTs—referred to as the Fixed ADS-B Beacon (FAB)[3]. The other is through self-generated status messages. Data used for the analysis was collected using the Micro-EARTS Continuous Data Recorder (CDR) function. The Micro-EARTS is the ATC automation system used at Anchorage Center.

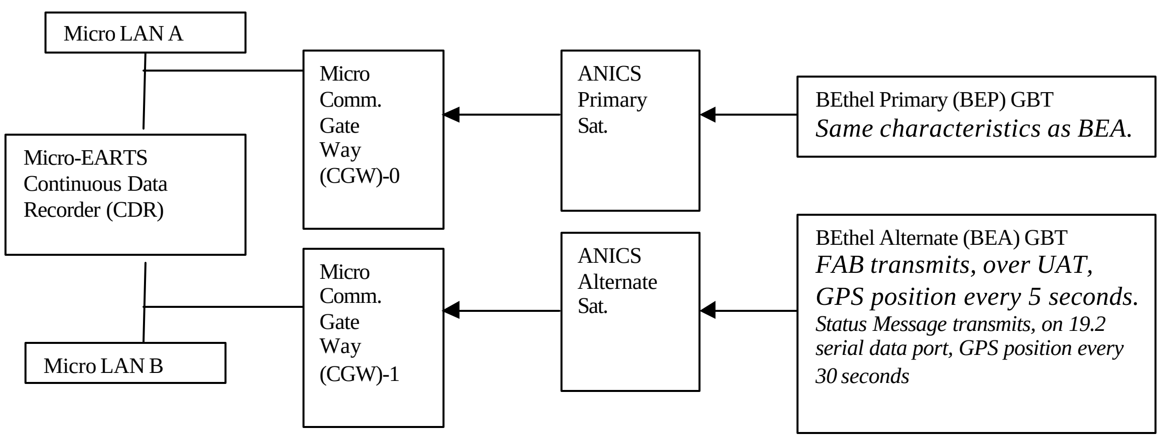

Figure 1 Capstone ADS-B Functional Diagram

3.0 Observations

The significant observations made from the data collection and analysis activity were as follows:

1. Rate of NUC 0 Occurrence: It was found that avionics (and the ground stations) experience and report "NUC 0" events at a rate high enough to be an operational concern if this were used as an indication of ADS-B service

[2] In Capstone a NUCp of 0 could be due to one of two factors: 1) the HPL is > 1.0 nmi (possibly due to RAIM unavailable); or 2) due to a failure of the primary GPS sensor, a backup GPS sensor is providing input to the ADS-B data link—derivation of the NUCp value is not provided from the backup sensor.

[3] The FAB bears some relation to the "parrot" used for monitoring SSR performance. In the case of Capstone the FAB is used to alarm failures of the GBT radio systems as well as GPS. (This is also referred to as the "Fixed ADS-B Parrot" within the FAA/MEARTS product team).

unavailability for ATC purposes. The reason for this is that unnecessary dropping of tracks from the air traffic controller's display would present a hazardous condition since this will tend to occur for all targets in an area for several minutes per event. This is similar to the nature of RAIM unavailability that could be expected of a GPS navigator of characteristics similar to that used for Capstone (7.5 degree mask angle, no baro aiding)

2. Observed Position Accuracy: Given this operationally unacceptable rate of low NUC value reporting, focus turned to examination of ADS-B position accuracy by comparing GPS position reports from the ground stations with the known surveyed locations of those ground stations. With the exception of one event, no position deviations greater than 70 m were observed over the entire period of time for which data were collected (continuously from 1 October through 31 October 2000). The exception was one event where a sudden position jump of approximately 2000 m was observed. This unexplained jump was seen in each of the two cosited GBTs; but not in either of the two aircraft in range at the time. Over several minutes, this position error slowly diminished. See Table 3 below.

3. Consistency of NUC Reporting:
   a) Apparent inconsistencies in NUC calculation are indicated by some observed reduced NUC value events that deviate from a sidereal day pattern. In Table 2 below the decreased NUC values appear at approximately the same sidereal time for 5 days. Note, however, that the period of reduced NUC values at approximately 2200 UTC on the 27th does not occur at the same sidereal time.
   b) Cases could be found where the reported NUCp appeared inconsistent relative to the known satellite availability and geometry corresponding to the time and place of the event (see Table 2). In Table 2, the predicted Geometric Dilution of Precision (GDOP), Horizontal Dilution of Precision (HDOP) and Satellites in view are consistently worse during the 1700 and 2200 time frames than that of the 1200 and 1400 time frames. Yet, the NUC reported for the 24th 25th and 26th 1700 and 2200 time frames are 4 while the NUC reported for the 1200 and 1400 time frames are 0.

Date	Source		Time of Event	Event Conditions				Time of Event	Event Conditions				Time of Event	Event Conditions				Time of Event	Event Conditions			
24 Feb 01	A/C	NUC	No aircraft in range					No aircraft in range					No aircraft in range					22:49	0	4	5	6
		# a/c																		8		1
	GBT NUC		12:44	0 (1 min)				14:36	0 (2 min)				17:44	4 (5 min)				22:49	4 (4 min)			
	Sat Prediction		12:45	3.4/1.5/11				14:45	2.4/1.2/9				17:48	4.0/1.9/8				22:50	5.1/2.5/7			
25 Feb 01	A/C	NUC	No aircraft in range					No aircraft in range					No aircraft in range					22:45	0	4	5	6
		# a/c																		1		
	GBT NUC		12:40	0 (1 min)				14:34	0 (8 min)				17:40	4 (5 min)				22:45	4 (4 min)			
	Sat Prediction		12:42	3.4/1.5/11				14:42	2.4/1.2/9				17:44	4.0/1.9/8				22:46	5.1/2.5/7			
26 Feb 01	A/C	NUC	No aircraft in range					No aircraft in range					17:36	0	4	5	6	22:41	0	4	5	6
		# a/c													1				1	6		
	GBT NUC		12:36	0 (1 min)				14:28	0 (10 min)				17:36	4 (5 min)				22:41	4 (4 min)			
	Sat Prediction		12:36	2.9/1.3/11				14:40	2.4/1.2/9				17:41	4.0/1.9/8				22:41	5.1/2.5/7			
27 Feb 01	A/C	NUC	No aircraft in range					No aircraft in range					No aircraft in range					22:27	0	4	5	6
		# a/c																	2			
	GBT NUC		12:32	0 (1 min)				14:24	0 (6 min)				17:32	0 (1 min)				22:27	0 (9 min)			
	Sat Prediction		12:32	2.9/1.3/11				14:37	2.4/1.3/9				17:37	4.1/1.9/8				22:37	5.1/2.5/7			
28 Feb 01	A/C	NUC	No aircraft in range					No aircraft in range					17:28	0	4	5	6	22:33	0	4	5	6
		# a/c													1				5			
	GBT NUC		12:28	0 (1 min)				14:20	0 (9 min)				17:28	0 (1 min)				22:33	4 (4 min)			
	Sat Prediction		12:27	2.9/1.3/11				14:32	2.4/1.2/9				17:33	4.1/1.9/8				22:33	5.1/2.5/7			

Table 2. Comparison of Aircraft-Reported NUC with GBT-Reported NUC and GPS Constellation Data during Sidereal Events

In Table 2, three sources are monitored for four event time frames across five days. The three sources are: 1) Number of aircraft in range reporting for each possible NUC value, 2) the NUC value reported in the GBT status message, and 3) GPS data from the China Lake web site containing the GDOP/HDOP/ # of Sat. in view during the time of the event. Time is in UTC. Note that for many of the events no aircraft were in range.

c) ADS-B position deviation from the surveyed position was also found to be uncorrelated with the NUC value reported. The following observations were made:

- All NUC 0 events were found to have position accuracy comparable to those with NUC values of 4, 5 and 6 (within 70 m)
- The single 2000 m sudden jump event was reported with NUCp as high as 6. This position jump was to some degree reproduced in the laboratory by the manufacturer with a GPS simulator driving the Capstone avionics.

See Table 3 below.

Fixed ADS-B Beacon (FAB) data collected on 10-01-00 through 10-31-00				
FAB NUCs Reported and Average Position Deviation from the surveyed point in Meters	**BEA**		**BEP**	
Total FAB Reports at NUC 0 & Average Deviation	582	13.3m	538	19.8m
Total FAB Reports at NUC 4 & Average Deviation	1612	13.8m	1692	12.6m
Total FAB Reports at NUC 5 & Average Deviation	20127	13.3m	22521	13.7m
Total FAB Reports at NUC 6 & Average Deviation	480599	12.6m	463189	12.6m
Total Number of FAB Reports Between 10-1 & 10-31	502920		487940	
Percentage of FAB Reports at NUC 0	.12		.11	
Percentage of FAB Reports at NUC 4	.32		.35	
Percentage of FAB Reports at NUC 5	4.00		4.62	
Percentage of FAB Reports at NUC 6	95.56		94.93	
FAB Positions Reported				
Total # of Positions Reported > 1 nm from survey	3		9	
Total # of Positions Reported > .5 < 1 nm from survey	10		7	
Total # of Positions Reported >.2 < .5 nm from survey	1		0	
Total # of Positions Reported < .2 nm from survey	502906		487924	
Percentage Total # of Positions Reported > 1 nm	.0006		.0018	
Percentage Total # of Positions Reported > .5 < 1 nm	.0020		.0014	
Percentage Total # of Positions Reported >.2 < .5	.0002		0	
Percentage Total # of Positions Reported < .2	99.9972		99.9967	
Max. from Survey Point in meters less 10-17 anomaly	45.82		69.15	
Max. from Survey Point in meters during 10-17 anomaly	2147.42		2778.78	

Table 3. NUC and Position Accuracy Results from FAB Reports

4. ADS-B Time of Applicability: Capstone ADS-B messages are transmitted once per second. Each transmitted message has a time of applicability at the start of the UTC second just prior to the transmission. Any failures in the avionics to consistently apply the proper time of applicability will translate into an uncompensated position error within the ATC automation system. To verify this aspect of the avionics operation, ADS-B reports from an aircraft equipped with Capstone avionics was examined in a controlled flight test at FAATC during April 2000. This was performed with the use of a NIKE radar used to establish the "truth" position at a 10 hz update rate for comparison with the 1 hz ADS-B information. The recorded NIKE data samples closest to the UTC one second tic, consistently showed the best position agreement with the ADS-B data. This agreement was within 30 m for all flight data collected (approximately 1 hour at speeds of approximately 200 kts).

5. Lag in NUCp Calculation: Discussions with the equipment manufacturer indicated that the NUCp value contained some lag because the ADS-B equipment varied the alarm level in order to determine the "best" alarm level achievable in the current condition. This is done as part of the adaptation of the TSO C129 receiver mentioned in Section 1 above. This seemed to agree with our observations of NUCp excursions between extremes that usually transitioned through the values 0-4-5-6 and 6-5-4-0.

4.0 Conclusions

1. The Capstone ADS-B reported positions were consistently of much greater accuracy than air traffic control radar-derived positions for aircraft more than approximately 5 nmi from the radar. Figure 2 shows the comparison of ADS-B with an operational enroute radar partially covering the Capstone area. This is the data as it was seen by the Micro-EARTS system and is taken from the CDR. GPS Selective Availability was off during the period of this data collection.

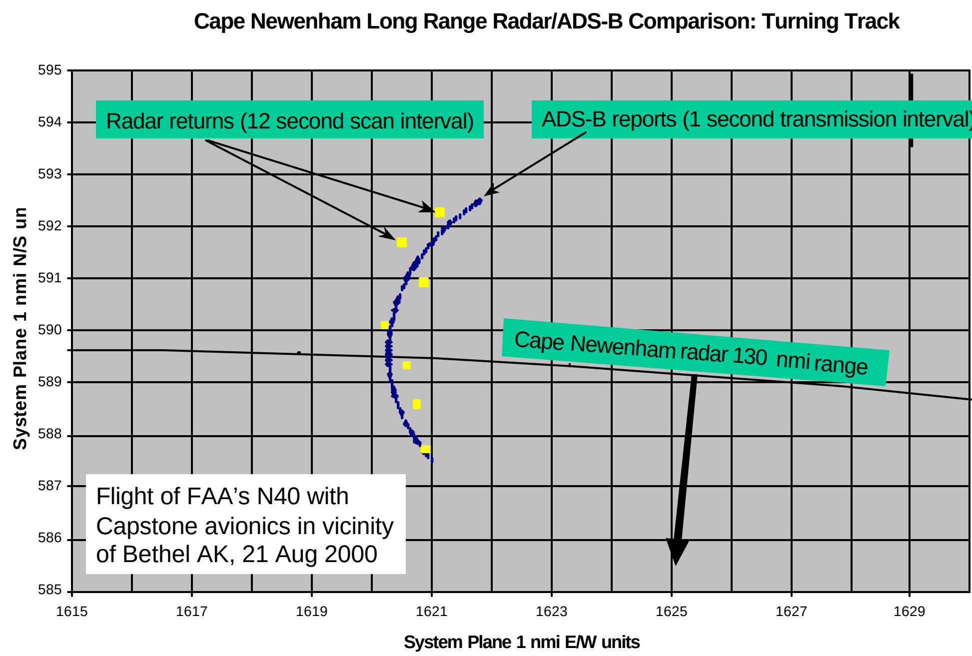

Figure 2. ADS-B and Radar Surveillance for Test Target as Seen by the Micro-EARTS

2. Use of the Capstone reported NUCp as the sole indicator of ADS-B service availability on a report-by report basis is unacceptable for ATC purposes. This is due to the following factors:
   - the rate of occurrence of the NUC 0 (no integrity) events observed and the operational disruption these events would cause (preventing track initiation or inhibiting track update or both) if they were used as a criteria for disqualifying an ADS-B report for display to the controller, AND
   - the apparent inconsistencies observed in NUC reporting, AND
   - that the NUC value is determined by monitoring RAIM alarm limits iteratively, rather than by a direct indication of the HPL applicable to the current ADS-B message. This results in some additional latency of the reported NUCp value
3. The lack of an acceptable avionics self-reported integrity containment estimate in each ADS-B report can be partially compensated for with a combination of the techniques listed below:

- By monitoring the GPS reported position of the surveyed ground stations and alarming when that position exceeds an established tolerance. This provides some assurance of detecting satellite failures affecting the Capstone area. Use of actual GPS reference stations would be even more effective. The FAA's MicroEARTS program office (AUA-650) has requested support to obtain a more comprehensive GPS monitoring capability for the Capstone area.
- Position errors from a single aircraft such as the single 2000 m position jump seen from the ground station discussed above, will be detected by the tracker within the ATC automation system. Specifically, a track discontinuity of this magnitude will result in the established track being coasted, and a new track being established at the new displaced position thus alerting the air traffic controller. However, this functionality will provide only limited protection from GPS errors. Smaller or slowly worsening error situations might go undetected for extended periods of time.

5.0 Final Thoughts

1. Some of the behavior of the NUCp values observed may be due to the use of a GPS sensor built for navigation to TSO-C129/DO-208 and its adaptation to ADS-B use. In particular, these units are not required to provide an output of HPL directly, but are only required to issue an alarm based on a *pilot entered* navigation mode (enroute, terminal, non-precision approach). In the future, GPS sensors built to TSO-C146/DO-229—with or without WAAS coverage—may be better suited to ADS-B use. These units meet a slightly faster time to alarm (satellite failure determination) requirement and the Class Beta units can provide an HPL indication directly.

2. However, even with the new sensor type, any potential latency of the reported NUC (HPL) value should be well understood and accounted for. Under TSO C146/DO-229, the time to alarm requirement is 8 seconds using FDE (when WAAS not available). Does this mean a misleading NUC value reported by ADS-B would be allowed for up to 8 seconds? Would this be acceptable for some (or all) ADS-B applications?