Appendix B: Use of RNP Flight Management System Navigation Data as a Backup Source for ADS-B

B.1 Introduction

GPS or an augmented version of GPS navigation is the primary and preferred data source for airborne ADS-B surveillance due to its high precision, rapid update time, and availability of quality metrics for position error assessment. However, some back-up means of navigation is generally desirable in the event of loss of GPS signal availability, or in the rare event that GPS RAIM integrity monitoring is lost or of unsuitable quality, i.e. during occurrence of RAIM "holes". For modern air-transport category aircraft and many GA aircraft such as business jets, a Flight Management System (FMS) is provided that performs multi-sensor fusion of various aircraft and navigation sensors to derive a current "best" estimate of aircraft position and velocity states for aircraft guidance and control. In the event of loss of availability of GPS or other navigation signals, the FMS will choose alternate navigation sources such as DME-VOR, dual DME, LORAN, or Inertial Reference System (IRS) navigation sources as the basis for continuity of navigation and guidance functions. Since the FMS automatically selects the best available navigation sources and outputs the FMS navigation solution to other aircraft avionics, it is natural to consider the FMS navigation solution as a potential back-up source of ADS-B surveillance in the event of a loss of GPS function. However, the quality of the FMS navigation solution is in general unknown, and as a result such outputs are typically unsuitable for air-air or air-ground surveillance applications.

One class of FMS systems has evolved in recent years that characterize the quality of FMS navigation outputs, i.e. RNP or Required Navigation Performance systems. These systems explicitly characterize the accuracy and integrity of the horizontal and vertical position states output by the FMS, and provide performance guarantees on other navigation metrics such as availability and continuity of navigation function. As a result, the RNP based FMS systems are potentially suitable as back-up sources of surveillance information for ADS-B transmission to external users. This appendix provides guidance for use of such data as a back-up to GPS sources of state information for ADS broadcasts.

B.2 Background on FMS and RNP Multi-Sensor Navigation

B.2.1 FMS Based Horizontal Multi-Sensor Navigation

Since the early 1980's aircraft Flight Management Systems have performed multi-sensor navigation in order to provide best estimates of aircraft position and velocity states to the FMS guidance function, and for output to external avionics functions such as flight controls. Typically, the FMS provides either a priority scheme for selecting the best available navigation sensor, or provides sensor data fusion to compute a best estimate of navigation states given several sensors such as GPS, DME/DME, DME/VOR, and IRS. In air-transport category aircraft, the IRS system is used as a back-up sensor and is directly integrated with the other sensor modes, e.g. on current Boeing 737 FMS aircraft the available sensor modes are GPS/IRS, DME/DME/IRS, DME/VOR/IRS, LOC/DME/IRS, and IRS (free inertial mode). If the existing navigation signal, say GPS, is unavailable for some time period, then the IRS system is used to integrate the FMS navigation solution forward until the GPS signal is available again, or alternately, the pilot can select another sensor mode such as DME/DME/IRS radio updating if that mode is available.

Figure 1 shows a typical pilot Control Data Unit (CDU) position reference page for cockpit display of available navigation sources on a Boeing 737 aircraft. The first row of data denoted “FMC POS” contains the current aircraft latitude and longitude of the FMS horizontal position vector and ground speed outputs. The next two rows provide the Left and Right side IRS position and ground speed outputs, followed by the Left and Right side GPS sensor position outputs. Finally, the preferred means of radio updating, i.e. dual DME or VOR/DME is displayed in the last data row denoted “RADIO”. The pilot can select or change sensor updating modes, and specify a specific sensor for FMC position in the event that one of the sensors currently used in the FMC calculations is faulty or unreliable.

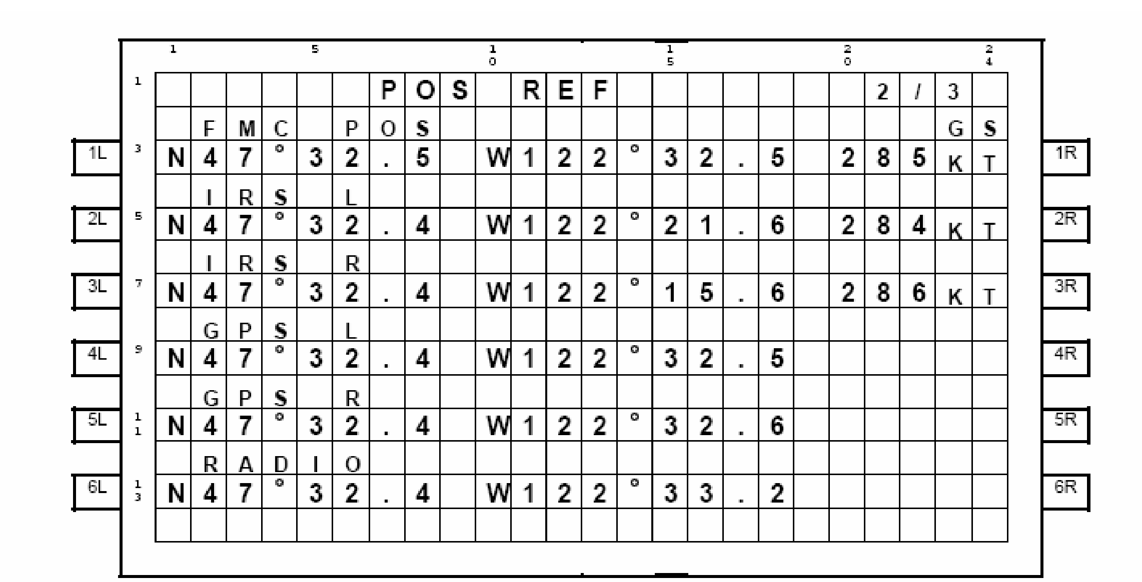

Figure B-1: Example Position Reference Page – Boeing 737 CDU

B.2.2 Vertical Channel Integration

The Baro vertical rate output from the Air Data Computer (ADC) has always been noisy and problematic as a source of vertical information for vertical flight controls. Consequently, the IRS sensor and the ADC are typically integrated in modern FMS aircraft to provide a more reliable vertical rate signal. One method of vertical integration is to use a complementary filter with input signals consisting of Baro altitude and rate, and IRS vertical acceleration and inertial vertical rate as constituents. Basically, the complementary filter provides a low-pass smoothing filter on the Baro inputs and acts As a high-pass filter on the IRS inputs, in order to compensate for Baro filter lag while simultaneously eliminating altitude bias in the IRS inputs. This integration may take place in the FMS or as a separate IRS/ADC pre-processor, prior to the FMS calculations. At any rate, the vertical outputs of the FMS are Baro altitude and altitude-rate. As a consequence, none of the geometric vertical outputs of the GPS sensors are used in air-transport category aircraft. For FMS aircraft without IRS sensors, it is possible to integrate the vertical channel GPS signals and the ADC in a complementary filter analogous to that described above. In this case, the GPS signals would be used to calculate an improved Baro vertical rate, and the output of the FMS would be the horizontal GPS states plus complementary filtered Baro altitude and vertical rate.

B.2.3 FMS / RNP Based Multi-Sensor Navigation

RNP based FMS systems utilize the precision of navigation inherent in modern FMS systems to fly intended paths within specified lateral or vertical containment regions, and with other specified navigation performance metrics. Required Navigation Performance (RNP) as defined by ICAO document 9650 is a statement of navigation system performance accuracy, integrity, continuity and availability necessary for operations within a defined airspace. Applications of RNP to date include the ability to fly precise lateral paths in mountainous terrain for non-visual approach and departure operations, precisely specified lateral and vertical paths for noise abatement in urban areas, and precise lateral containment for procedural separation of parallel tracks in en-route / oceanic airspace. In order to fly these procedures, an airplane must be certified to RNP standards consistent with the airspace routings for such procedures. For example, the Juneau, Alaska RNP approach requires an accuracy bound of 0.15 nm including navigation sensor accuracy, and lateral flight technical error. The use of RNP navigation replaces specification of detailed navigation and flight system hardware with generic RNP requirements, allowing avionics system designers to use different hardware architectures and avionics integration methods to achieve desired RNP levels.

This appendix is primarily concerned with providing guidance for conversion of available RNP metrics into accuracy and integrity metrics for ADS-B transmission of FMS state vector data, i.e. STP conversion of ANP and RNP metrics into HEPU, HEVU, and HPL (Rc) metrics for ADS-B broadcast of FMS position and velocity states.

RNP accuracy, denoted RNP-X for X nm position accuracy, is a 95% horizontal position bound centered on the computed FMS position that is required for navigation on a defined airspace or route segment. RNP-X indicates the required accuracy of a navigation system in normal operations, i.e. RNP-1 indicates a 1 nm accuracy bound. The actual navigation performance (ANP) is the computed navigation system accuracy for the FMS horizontal position and represents a radius of a circle centered on the FMS position such that the aircraft is inside the circle with 95% probability of better. The aircraft meets the current RNP accuracy requirement if ANP < RNP(X). Note: RNP-X is typically selected by the flight crew for a given region of flight, or provided by FMS default values, e.g. RNP-2 for domestic en-route airspace.

RNP integrity is represented by a horizontal containment radius (Rc) of a circle centered on the FMS position such that the probability of the true position lying outside the circle without being detected is improbable, i.e. less than 1E^-5 per hour. For RNP systems, pilot alerting of inadequate navigation performance is provided whenever ANP exceeds RNP. If ANP < RNP then RNP integrity is guaranteed at two times RNP, i.e. Rc <= 2*RNP(X). Consequently, ANP and RNP provide adequate metrics to determine navigation accuracy and integrity bounds, respectively, and for RNP-RNAV qualified systems, determine specific lateral containment bounds for route following as well.

Figure 2 shows an example of the RNP Progress Page on the pilot interface to the FMS system, i.e. the Control and Display Unit (CDU). On the left side of the display the RNP accuracy and ANP are displayed as "RNP / Actual". In the example, the aircraft is in Approach mode with default RNP = 0.5 nm and actual RNP = 0.21 nm. The Progress Page also shows a cross-track deviation or lateral FTE = 0.06 nm, and vertical channel RNP and ANP metrics. (The latter metrics are not currently needed for ADS-B transmissions of FMS state data.)

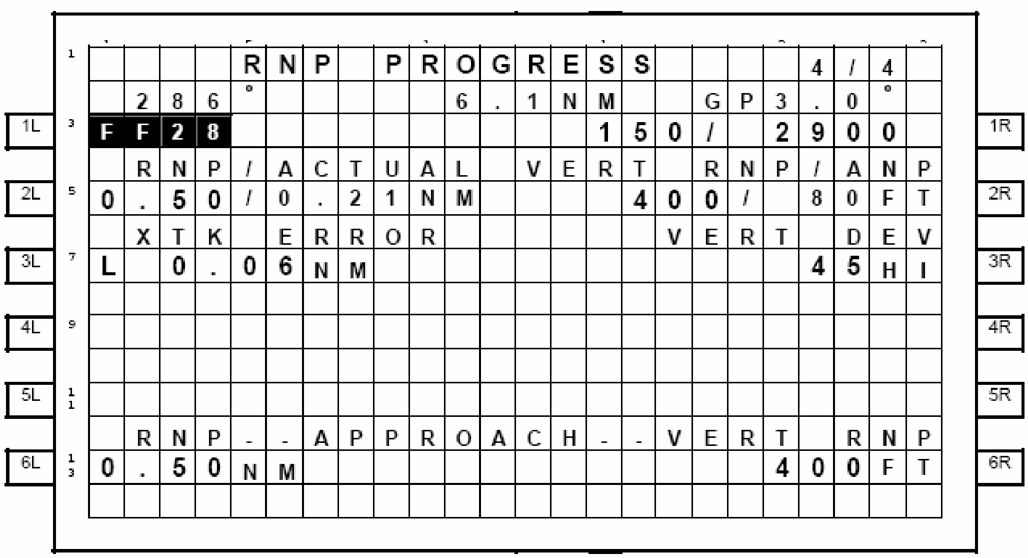

Figure B-2: Example RNP Progress Page on a 737 CDU

B.3 Guidance for use of FMS/RNP Navigation Sources for ADS-B

B.3.1 Overview of GPS Primary and FMS Backup Data Source Selection

The GPS sensor output is generally preferred to using FMS state data, even if the GPS sensor is the primary Navigation sensor used for the FMS Navigation solution. There are several reasons why GPS is preferred: (1) the GPS quality metrics such as HFOM and HPL are generally more accurate and less conservative than the FMS ANP and RNP quality metrics, and (2) the GPS sensor provides a precise estimate of time-of-measurement, whereas the FMS does not output the measurement time to other avionics since it outputs state data at a relatively high data rate, e.g. 10 hz data rate for modern FMS systems. Moreover, on some aircraft, the GPS sensors are not integrated into the FMS navigation solution, and are primarily used for other functions such as ADS-B surveillance and enhanced ground proximity warning. In this case, the GPS sensors will in general produce position estimates that are much more accurate than those derived using traditional navigation sources such as DME/DME and IRS sensors.

Nonetheless, there are situations where GPS is not available or is not desirable as a data source for ADS-B use. The latter situation occurs when there are insufficient GPS satellites for RAIM based integrity monitoring, or the satellite geometry is poor resulting in large GDOP values and in large HPL values. For navigation functions where high accuracy is needed, predictive RAIM is generally required so that alternate procedures can be used during those times when RAIM monitoring is inadequate. However, modern FMS systems generally can 'coast through' such periods using multi-sensor integration methods to back-up the GPS sensor and assure availability and continuity of the navigation solution, although at a somewhat reduced accuracy level. Consequently, RNP based FMS systems that quantify the current accuracy level of the navigation solution can provide a valuable back-up to the GPS sensor in these situations.

The proposed airborne architecture for using GPS and FMS based data sources for ADS-B is shown in Figure B-3. The GPS data source for ADS-B can be either the same sensor selected for integration into the aircraft navigation solution, or can be another, standalone GPS sensor. In any case, the geometric position and velocity states from this GPS and the GPS accuracy and integrity metrics, e.g. HFOM, VFOM, HPL, and VPL are input into the STP interface for ADS-B transmission. Baro Altitude is input directly from the air data computer and is the same sensor output selected by the flight crew for transponder output of pressure altitude. The Flight Management Computer also inputs the FMS position and velocity states to the STP function, together with currently displayed ANP and RNP, and the IRS /air data derived Baro vertical rate. In addition to the primary content from the FMC and other sensor interfaces, additional discrete values are output indicating validity of sensor outputs, type of sensor data, if GPS data, whether WAAS or LAAS capable, and for the FMC output may include bits indicating which sensors contribute to the selected navigation solution. The STP function then selects the GPS or FMC horizontal position and velocity, selects either a geometric vertical rate or a Baro vertical rate for ADS-B transmission, and computes various quality metrics that determine the state vector metrics NACp, NACv, NIC, and SIL transmitted in the ADS-B messages. The following sections describe the calculation of the quality metrics and the selection of the GPS or FMC states for ADS-B output. Note: Although ANP and RNP metrics and other FMC parameters shown below are available on special FMS data buses for pilot displays, some of the parameters shown flowing between the FMC and the STP function may not be available on current data buses, i.e. using general purpose ARINC 429 data buses.

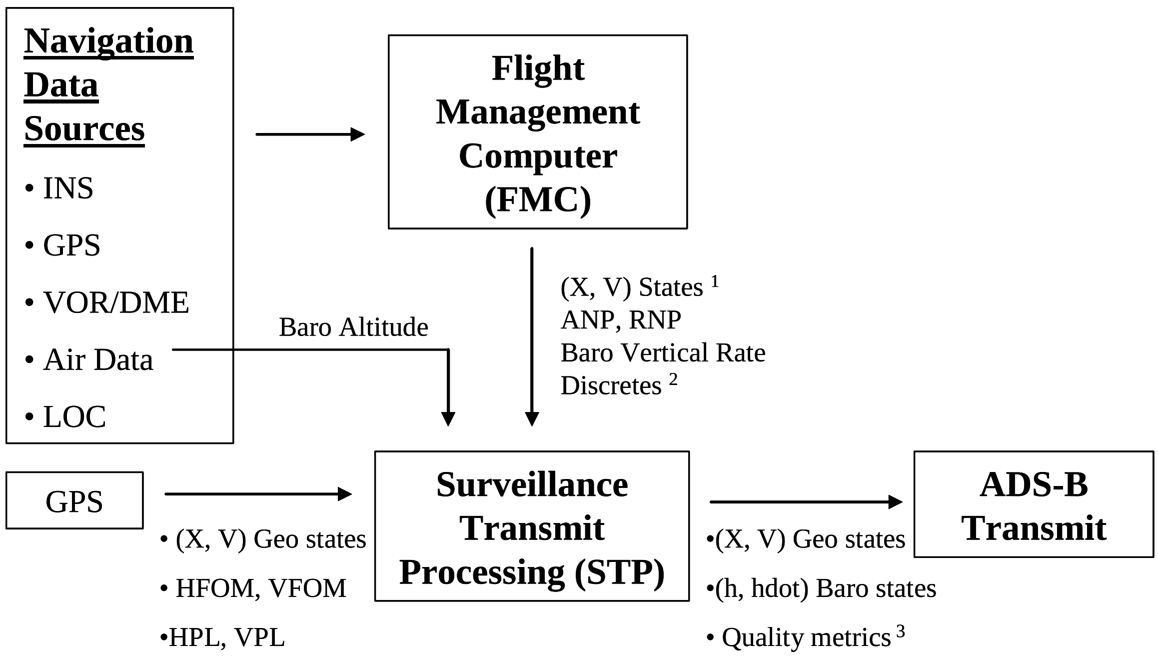

Figure B-3: Airborne Architecture for GPS Primary and FMS/RNP Backup for ADS-B

Notes: 1) Selected FMC navigation states are output at ~ 10 hz rate with no time mark.
2) Discretes are binary data that may include FMC NAV data sources in use.
3) Quality metrics include HEPU, VEPU, HPL, VPL*, HEVU, and VEVU*, where the * (vertical) metrics are not output for FMC selected states .*

B.3.2 Calculation of Horizontal Accuracy Metric (HEPU) for RNP Data Sources

The primary source of position accuracy available from the FMS is the ANP metric. For GPS updating of the FMS navigation solution, the ANP metric may be a conservative estimate of HEPU, i.e. for 737 RNP based FMS systems, the following bound is valid when GPS is the primary source of horizontal position: HEPU <= 0.64 * ANP.
Since the FMS navigation solution is primarily a backup to the primary GPS sensor for ADS-B transmissions, it is recommended to use the more conservative and generic bound

HEPU <= ANP,

since the more conservative bound is valid for all RNP aircraft types and for all modes of FMC navigation updating. Consequently, the ANP metric can be encoded as the estimate of HEPU or ‘EPU’ on an ARINC data bus. If the FMS is selected as the source of ADS-B position, then VEPU is not relevant for NACp encoding since the vertical FMS outputs are based on pressure altitude, and ANP is then the sole basis for encoding NACp.

B.3.3 Calculation of Horizontal Velocity Metric (HEVU) for RNP Data Sources

In this document, we recommend that HEVU be limited to a value such that the accuracy metric NACv =1. The reason is that in the case that GPS is not being used for FMS position updating, the IRS sensor is likely the primary source of horizontal velocity data. Current IRS sensor accuracy when unaided by external position updating is on the order of 6 m/s (95% probability) or better. This results in a NACv =1 estimate as a worst case for FMS velocity accuracy. Although it is recommended to simply set HEVU to 6 m/s or any other value between 3.0 and 10.0 m/s for ADS-B calculation of NACv, it is possible to do somewhat better when GPS updating of the FMC navigation solution. In this case, the calculation of HEVU can use the methodology shown in row 1 of Table 2.2.4.6-2, i.e. it is possible to achieve a NACv =2 when GPS updating. However, this means that one of the discrete outputs from the FMC shown in Figure B-3 is an indicator whether GPS updating occurs or not. Although not recommended due to increased complexity, it is feasible to use the methodology shown in Table 2.2.4.6-2 with HFOM replaced by ANP to achieve somewhat smaller HEVU values when GPS updating.

B.3.4 Calculation of Horizontal Integrity Metric (HPL / Rc) for RNP Sources

As stated in the previous section B.2.3, the horizontal containment radius Rc for RNP based systems is bounded by

Rc <= 2*RNP,

provided ANP <= RNP, where RNP denotes the current displayed RNP value in the FMS progress page. In the case that ANP > RNP, then an RNP integrity alarm is issued to the pilot and the containment radius in that case is set to unknown. In some cases, such as when doing GPS updating, the generic bound above can be decreased. For example, when GPS updating with an RNP based 737 aircraft, the containment radius is bounded by Rc <= 1.8* ANP < 2* RNP whenever ANP <= RNP. For simplicity, it is recommended to use the generic bound above rather than airplane specific bounds, since the generic bound is valid for all aircraft types and navigation modes satisfying RNP RNAV standards, i.e. DO-236B RNP MASPS and DO-283A RNP MOPS. The corresponding certified probability level for RNP containment is SIL=2, since containment is assured at the 10^-5 per hour level. Note: since current minimum RNP values are >= 0.1 nm, the smallest integrity bound in current RNP aircraft is 0.2 nm (370.4 m). Consequently, the maximum NIC value for current FMS / RNP navigation systems is NIC = 7.

B.3.5 Calculation of HEPU, HEVU and HPL for non-RNP FMS Sources

The calculation of quality metrics, and in particular integrity for non-RNP FMS systems is somewhat problematic. Nonetheless, for minor level surveillance applications or for applications where high accuracy is not required, such systems may be used to back-up a primary or stand-alone GPS sensor. For traditional FMS navigation sources such as dual-DME and DME-VOR with IRS fall-back, the navigation accuracy of such systems can be estimated or bounded, provided the specific sensor mode in use for navigation is indicated to the STP module.

For dual DME and DME-VOR systems, one-sigma bounds on horizontal position accuracy are provided in DO-236B, Appendix C. Assuming Gaussian error distributions on DME and VOR sensor errors, the 95% accuracy metric for these navigation sources can be estimated using

HEPU = 2* sigma(horizontal position),

where specific equations are provided in the above referenced document for dual DME and DME-VOR systems, and worst case observation geometries in terms of operating ranges and angular separations can be used to bound the HEPU calculation. A similar approach can be used for other sensors such as GPS and DME / Localizer navigation solutions.

The calculation of velocity accuracy is similar to that above for RNP FMS systems, i.e. assuming that an IRS sensor is part of the FMS navigation solution, then a fixed bound based on IRS velocity error can be used, e.g. HEVU = 6 m/s for modern Boeing FMS aircraft.

The calculation of HPL or containment radius Rc for non-RNP sources is problematic since integrity is not typically established on the basis of a containment metric. However, it may be possible to compute an upper bound on containment integrity for navigation sources such as DME, VOR, and LORAN that perform external monitoring of signals in order to validate sensor functioning. For dual DME systems with angular extent between 30 degrees and 150 degrees, and for DME-VOR systems with VOR range not exceeding 20 nm, external sensor monitoring yields a maximum error before sensor shutdown not exceeding 2 nm. In this case an HPL <= 2 nm (NIC =4) with a SIL=1 can likely be justified. (SIL =2 values for major level applications such as separation assurance would likely require some form of cross-sensor monitoring since an external monitor only validates the integrity of signal-in-space and not receiver processing and navigation solution processing.)

For applications that require higher integrity, e.g. SIL=2 or more precise containment Rc, it is recommended that multiple surveillance sources be used to enhance integrity, i.e. by appropriate multi-sensor processing within the ASSAP system or within ground automation systems. For example, one potential means to achieve a more precise HPL, say on the order of 2*HEPU with SIL=2 integrity level, would be to monitor position differences from non-RNP position sources versus TIS-B, TCAS, or other sensor position inputs to ASSAP capable of independent monitoring of aircraft position. Such multi-sensor processing may be considered in future standards documents if additional GPS backup sources are needed for more advanced ADS-B applications.

B.3.6 GPS / FMS Data Source Selection

One or more GNSS sensors and the FMS navigation solution may be sent simultaneously to the STP function to enhance availability of state data for ADS-B transmission. In the case that there are several data sources, the STP function must select one of those sources for output to the ADS-B transmit function. The recommended data source for horizontal position and velocity in most cases is the primary GNSS input source as identified by installation parameters or as selected by the pilot as the primary sensor for aircraft navigation. If this data source is not available, i.e. the input source is invalid, or if the containment integrity of this source is unknown or substantially larger than that of another input source, then an alternate data source should be selected, i.e. another data source that contains valid state data and has the smallest containment integrity (HPL metric) of the available data sources.

There are several mechanisms that can cause source selection to switch to the FMS or another GNSS sensor. If the satellite geometry for the GNSS sensors is poor, i.e. there are insufficient satellites with adequate observation geometry for expected RAIM performance, then the HPL metric from the GNSS sensor(s) can become very large for some time period until additional satellites become available for the RAIM calculations. Such "RAIM holes" can last several minutes, reducing availability and continuity of critical ADS-B operations. If an RNP based FMS is used as a backup during such conditions, then continuity of ADS-B operations is greatly enhanced. The reason is that the IRS system acts as a short term backup to the GNSS sensor. For example, during a RAIM hole or loss of GNSS inputs, the typical value of ANP for an RNP based B-737 aircraft increases at an observed rate of about 0.02 nm per minute during such conditions. This means that accuracies on the order of 0.1 nm and containment radius on the order of 0.2 nm (NIC=7) can be maintained for several minutes during such an event, if the STP switches from a GNSS sensor to a low RNP FMS position source. Similarly, if one or more GNSS sensors become unavailable due to signal interference or sensor failure, then ADS-B continuity of state data is assured by switching to the FMS source. In the event of an extended duration outage of GNSS sensors, the pilot may switch to another navigation source such as DME/DME/IRS navigation mode and increase the RNP value consistent with the current ANP of that data source, e.g. to RNP = 0.5 nm if ANP < 0.5 nm. In that case, ADS-B operations could continue after loss of the GNSS sensors with an increased HPL = 2*RNP.

The actual algorithm for FMS source selection should be based on position integrity, not accuracy, since the former is more important for critical separation applications. If source selection is based on HPL, then a threshold value on the order of delta_HPL >=0.05 nm is recommended for switching from a GNSS source to the FMS output, i.e.

HPL(GPS) >= HPL(FMS) + 0.05 nm. This is to prevent rapid alteration of data sources when the two HPL values are nearly equal. In the event that the FMS source has been selected for some time, it is recommended to change back to a GNSS data source when the HPL value for a GNSS source drops below that of the FMS. Additional guidance and requirements on source selection are discussed in section 2.2.3.8 of the STP MOPS.

If a GNSS sensor is selected for providing ADS-B state vector outputs, then the geometric altitude and vertical altitude rate values for that sensor should be selected for ADS-B transmission. Otherwise, if the FMS navigation states are selected for ADS-B output, then the vertical rate from the FMS (with pressure vertical rate type indicated to the ADS-B transmit function) should be selected for ADS-B output. The FMS pressure altitude is not selected in that case, however, since the air data sensor selected for transponder altitude is always used, when available, as the basis for ADS-B baro altitude.