Enclosure to Letter F064-L09-056
ENCLOSURE

On-Board Performance Monitoring and Alerting (OPMA)

Airborne System Calculations, Statistical Meaning and Relationships to Separation Standards Development

Michael Cramer

September 2009

Acknowledgments

The author would like to acknowledge Mr. Donald Pate, Federal Aviation Agency (FAA), Retired for various in-depth conversations on the analysis work at the International Civil Aviation Organization (ICAO) Separation and Airspace Safety Panel (SASP), Mr. Tass Hudak (MITRE) for compilation of existing standards, Mr. Nick Tallman (FAA) for consultation on the paper content and Mr. Madison Walton (FAA) for supplying the working papers and summaries from SASP-15.

Introduction

The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) was tasked with assessing the utility of "On-board Performance Monitoring and Alerting" in modern Flight Management Systems. This report defines this functionality, documents an initial assessment of its utility, and focuses on separation standards development questions that will need to be answered to gain separation benefit from this flight deck capability.

The term "On-board Performance Monitoring and Alerting" is fairly recent terminology used to label the alerting functions for navigation performance that are present in Required Navigation Performance (RNP) capable Area Navigation (RNAV) systems. The Performance Based Navigation (PBN) Roadmap and other sources have relied on the real-time estimation of the navigation performance achieved in these systems to derive benefits that could not be obtained simply with RNAV. This has already occurred in the approach navigation arena with the publication of FAA Orders 8260.52 U.S. Standard for RNP Approach procedures with Special Aircraft and Aircrew Authorization Required (SAAAR) and 8260.54A U.S. Standard for Area Navigation, and it is now being developed for enroute and terminal navigation as well. Several PBN operational concepts that are envisioned to produce benefits based on advanced avionics and procedures are dependent on reduced aircraft separation. How and to what degree these concepts can be realized depends on our ability to utilize on-board monitoring and alerting to safely reduce separation requirements from the standards and requirements for current operations. The basic question seems to reduce to what the RNP system of on-board performance monitoring and alerting introduces above and beyond what is required for RNAV operations to enable us to safely reduce separation standards or implement complex PBN procedures.

To help answer this question, this paper provides an overview of work currently being done at the International Civil Aviation Organization (ICAO) to quantify the use of OPMA and RNP to affect route separation standards for PBN applications, with comment on questions yet to be answered or addressed. It will then review the current methods used in RNP systems for navigation performance estimation, comparing them with each other and with the concepts of RTCA DO-236B Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation and drawing some inferences relative their underlying statistics. It will further discuss what these calculation methods might mean in the analysis of separation standards and how they may relate to obstacle assessments for RNP systems. Discussion of safety analysis and / or collision risk in terms of normal, rare-normal and non-normal performance of navigation systems will be tied into the alerting function and possible Automatic Dependent Surveillance Broadcast(ADS-B) functions. Possible corrective actions in the event of an alert or warning when using separation standards based on RNP will also be discussed. Finally, this report will reference a summary of all current separation requirements taken from FAA Order 7110.65 Air Traffic Control, and will attempt to probe the probable historical sources of those requirements. With this background the paper proposes questions and methods of analysis that might yield significant benefit results in the near term.

Survey of ICAO Work

Since the adoption of the PBN Manual and the initiation of RNP operations in the United States (US) and other States, the Separation and airspace Safety Panel (SASP) of ICAO has had project teams beginning to assess the safety cases for aircraft separation in PBN operations. Work on in-trail procedures for altitude changes, use of ADS-B for surveillance, use of lateral offsets enroute and implications for Reduced Vertical Separation Minimums (RVSM) has been in progress. There was a large amount of work done that resulted in a controversial recommendation to the Air Navigation Commission (ANC) prior to SASP-15, where it was proposed that Obstacle Clearance Areas (OCAs) be used as the basis for route separation in terminal airspace. While there is a large amount of information contained in various project team minutes and working papers, and the author of this paper has not had a chance to participate to the level that the Federal Aviation Administration (FAA) and other persons have, a review of significant papers brought out a few questions / observations.

Relative to the use of OCA for terminal separation for RNAV and RNP, the author in general agrees with the conclusions and recommendations of Working Paper (WP)/06 co-authored by Mr. Donald Pate and Dr. Richard Greenhaw (FAA); where more analysis and work is proposed for the use of OCAs in this manner. A missing element in the proposed analysis might be that the underlying properties of RNP systems are not addressed directly when speaking of analytical and statistical models. They address specific navigation methods, such as range / range methods using Distance Measuring Equipment (DME), and note that there are many variations of use of navigational aids. The requirements on RNP systems should allow for analysis in a way that fits all RNP systems regardless of underlying sensor sets, since they share common requirements on performance as described in the next section of this paper. This common requirements based characterization of RNP systems seems to be missing in other papers as well. Where the project team 8 final report fixed track to track separation at 7 nautical miles (NM) for RNAV-1 based on Gaussian assumptions for performance and the standard collision risk model, they have not yet accounted for the statistical containment integrity requirement on RNP system, nor for the alerting (more on this after discussion of the RNP systems themselves.

Another area of investigation was an attempt to take data from flight tracks to substantiate RNP performance as Gaussian (or not) in WP/15. This is one of the first papers the author has seen that specifically recognizes the containment integrity requirement on RNP systems (10^{-5} per flight hour of exiting 2xRNP without an alert). The authors are rightly concerned that a Gaussian assumption for the TSE distribution shape could lead to under-estimation of collision risk if the assumption proves incorrect, since other distributions have heavier tails. They assert that no evidence exists that would validate the Gaussian assumption, which this author believes is incorrect. The aircraft manufacturers and avionics vendors have amassed statistical information based on very precise system and aircraft mathematical models that they use validate designs, and Monte Carlo simulations with enough samples to validate the Gaussian assumption in the tails have been done by engineering organizations within the OEMs and their suppliers. Such data should be made available to ICAO, something that The MITRE

Corporation might accomplish by de-identifying the data to protect proprietary information under our non-disclosure agreements with the the original equipment manufacturers (OEMs). In the data analysis in this reference paper, it did not appear that data used had been screened to assure that the systems were being flown in an automatic manner using autopilot lateral navigation (LNAV); historical data has shown that pilot flying, whether using the flight director or manually using the map, tends not to be Gaussian, so to truly assess RNP performance, autoflight must be in service to validate the assumption.

In summary it seems that the common characterization of RNP systems is not yet being recognized, particularly in application of the alerting function to non-normal performance (safety management system assessment) and in the application of containment integrity performance to normal and rare normal performance.

RNP Systems

Area navigation systems (both RNAV & RNP) share the same general characteristics in terms of navigational errors, but they are distinguished in other ways which will be discussed following a description of the general characteristics. An area navigation system is a two dimensional navigator, that is, it generates a system position in latitude / longitude and navigates over the surface of the earth by that means. Once the system position is estimated, the system can navigate along a defined path with a certain degree of accuracy. The general picture is seen below in Figure 1. The system position is navigated along the desired track by the RNAV system, and there is an area of uncertainty around the system position that will contain the true position of the aircraft. In general, the area (grey) that has a 95% probability of containing the true position is used to characterize the navigation system accuracy, but higher probability areas may also be defined as shown (orange ellipse), such as the 99.999% integrity of RNP systems. The realized path is the path that the aircraft actually traverses while the system position if flown along the desired track.

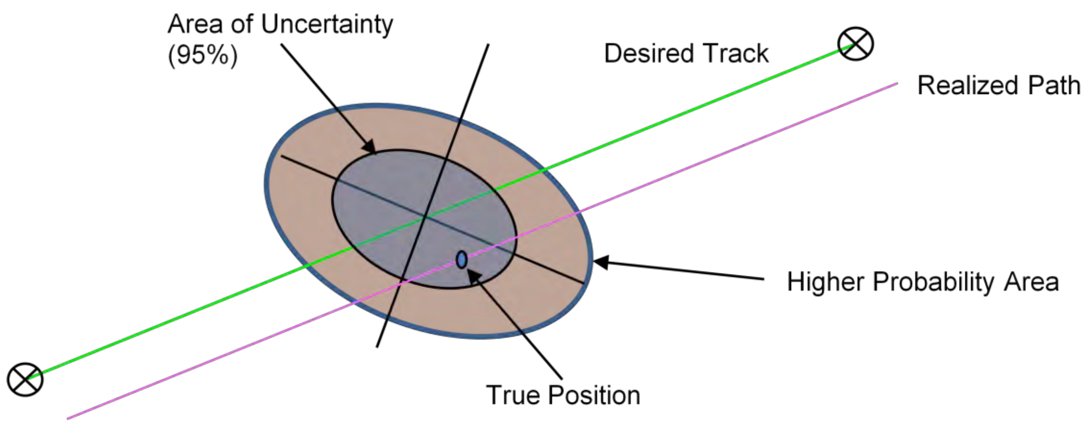

Figure 1 General Error Characteristics of RNAV

RNAV system performance (and subsequent route design) is based upon the 95% bound as shown in Figure 2 with the addition of “buffer” areas that are determined from the a priori statistics of navigation assuming various sensor mixes and from certain failure conditions..

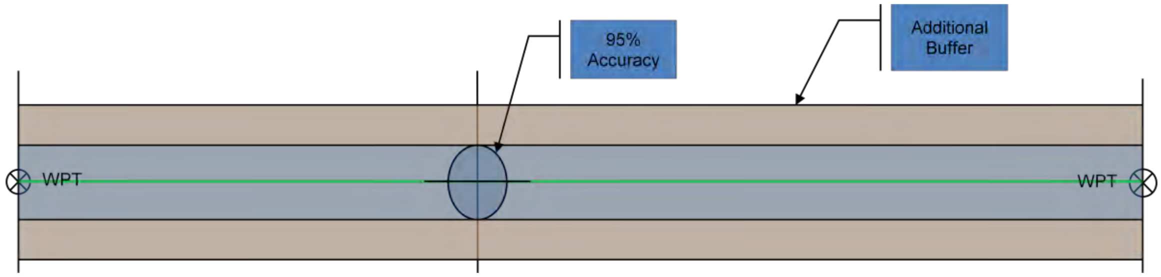

Figure 2 Example RNAV Route Design

The aircraft systems are assumed to meet these RNAV standards by prior testing. The system error model changes from a single sensor based model to one based on assumed methods such as range/range from Distance Measuring Equipment (DME) stations, or range/bearing from DME and Very High Frequency Omin-range (VOR) stations (e.g., DME/DME or DME/VOR). Assumptions of how the signals are combined to do RNAV are made, setting accuracy requirements, and the route width is not scalable. Systems are expected to meet a common standard of sustainable accuracies by flight phase which are fixed based on the sets of navigational aids assumed to be in use. These are directly related to criteria, e.g., 0.5 NM 95% accuracy is required in the terminal area using for systems using DME/DME. The difference between RNAV and sensor specific routings lies in the fact that the path can be fixed to arbitrary geographic points, not necessarily navaids. In the RNP model of RNAV systems, a scalable size parameter called the RNP value is provided to the airspace designer. By choosing the RNP (in NM), the designer chooses the width of the protected areas around the desired path to meet the operational considerations that the design is attempting to satisfy. As shown below in Figure 3, the route width is now tied to the RNP value, with both the 95% and the 99.999% boundaries specified at 1 and 2xRNP respectively.

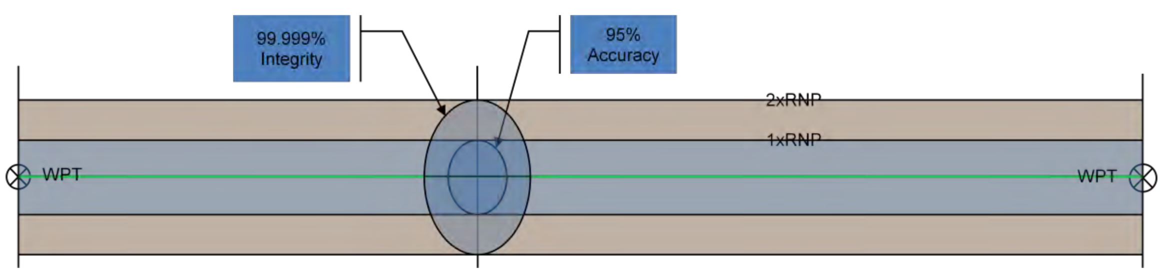

Figure 3 Example RNP(RNAV) Route Design

This choice of RNP value sets the required integrity and continuity performance that the aircraft navigation and control systems must meet to operate on the route or procedure, resulting in an airspace design that is not dependent on sensors by shifting that dependency to the operational approval of the navigation system and aircraft. In addition, as discussed in detail below, on-board computation of the real-time performance is required of RNP systems, along with alerting when the above diagramed route RNP value is not met.

Performance Computations and Definitions

Performance of RNP systems is quantified in terms of three navigational errors, the sum of which defines the total navigational error of the system.

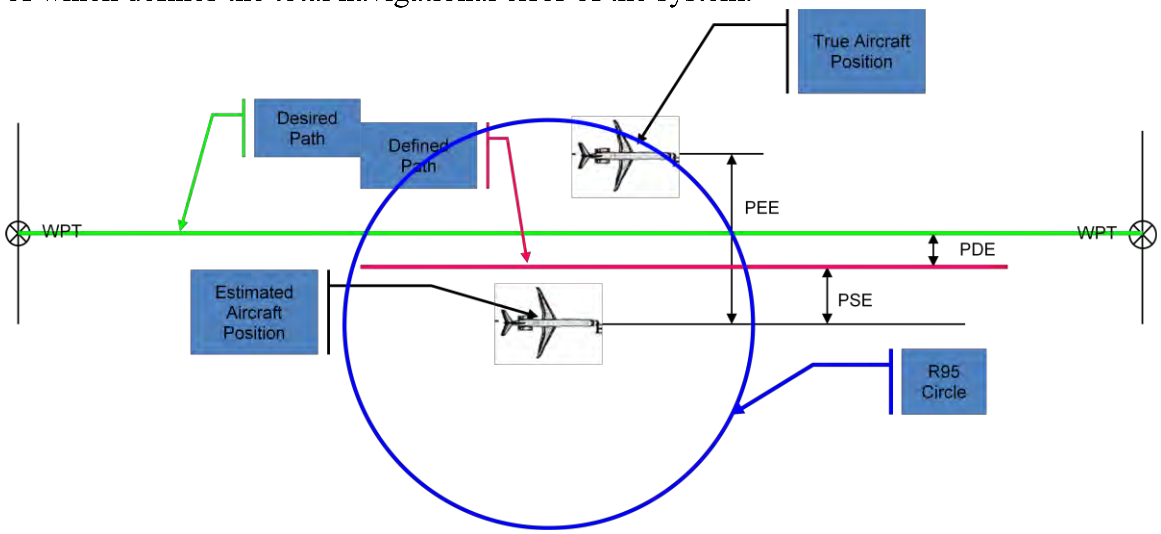

Figure 4 Lateral Navigation Errors

Referring to Figure 4, we begin with the green "desired path", which is the ground track that the designer wants the aircraft to traverse. The navigation system will compute a replica of that path, the "defined path" in red, and the Path Definition Error (PDE) is the abeam distance between the two paths at any point. In general, this error is the smallest of the three, and it vanishes when the airborne system uses the same coordinate system and computations as the designer to define the path. The navigation system computes a location for the aircraft, the estimated position, and attempts to keep that position on the defined path (red); any error in this is the Path Steering Error (PSE) which results from the flight control system responses. This error is dependent on the type of control, the control gains, and the mode of operation at any given time. The final error of navigation is the unknown difference between the estimated position and the true position of the aircraft; called Position Estimation Error (PEE) this error is dependent upon sensors and the statistical combination of measurements, as well as dynamics of flight. Total System Error (TSE) is the sum of these three, and forms the basis for performance estimation and monitoring, and the R_{95} circle notionally indicates that the TSE will be less than the radius of the circle 95% of the time, a key parameter in alerting.

Key RNP RNAV Requirements

The Minimum Aviation System Performance Standard (MASPS), DO-236B, requires that an RNP RNAV system provide an Estimate of Position Uncertainty (EPU) defined as follows:

> "EPU is a measure based on a defined scale, in nautical miles, which conveys the current position estimation performance."

It is important to note that in the requirement text, there is no specified statistical level associated with EPU. There is however a requirement that such a measure is available continuously in flight to the flight crew:

> "Each navigation system operating in RNP airspace shall make available a continuous estimate of its horizontal position uncertainty under the prevailing conditions of flight. Prevailing conditions include airborne equipment condition, airborne equipment in use, and external signals in use."

Specific numerical requirements are levied on the TSE of the navigation system as accuracy, integrity and continuity requirements based on the RNP value as follows:

> "Each aircraft operating in RNP airspace shall have total system error components in the cross track & along track directions that are less than the RNP value 95% of the flying time", and

For a containment limit = 2*RNP:

> "The probability that the total system error of each aircraft operating in RNP airspace exceeds the specified cross track containment without annunciation shall be less than 10^{-5} per flight hour" (the integrity requirement) and
> "The probability of annunciated loss of RNP capability (for a given RNP type) shall be less than 10^{-4} per flight hour" (the continuity requirement).

These are the relevant requirements that most RNP system manufacturers have been working to satisfy in their navigation systems.

Statistical Performance Estimation

The early (pre-DO 236) RNP systems provided an estimate of navigation performance which they labeled Actual Navigation Performance, or ANP. This value was a conservative estimate of the radius of a circle centered on the current estimated position that had a 95% probability of containing the true position (sometimes called R_{95}). The RNP value was at that time representative of the permissible 95% horizontal position error allowable in the navigation system, so comparison of the two values (RNP to ANP) provided an indirect measure of compliance.

However, as noted above, the requirements in DO-236() are stated as bounds on TSE relative to the RNP value:

1. 95% accuracy (along and cross track) < RNP value
2. 99.999% integrity (cross track) < 2xRNP value

The significance of this is that both ANP and EPU were designed as statistical bounds on position estimation error, not total system error, therefore, ANP (EPU) does not account for PDE or PSE directly. This means that they do not provide a direct method of monitoring compliance with the above stated requirements on TSE.

Referring back to the "open" definition in DO-236() EPU must be based on a "defined" scale, must convey current <u>position</u> estimation performance, and no further specification is made. This "open" definition, plus the fact that it reflects <u>position</u> estimation performance, leaves much to choice during implementation.
To understand how RNP systems are computing estimates and alerting requires an examination of differing 2-D accuracy measures, and an examination of the difference in

the computational characteristics between navigation mode based and blended measurement methods.

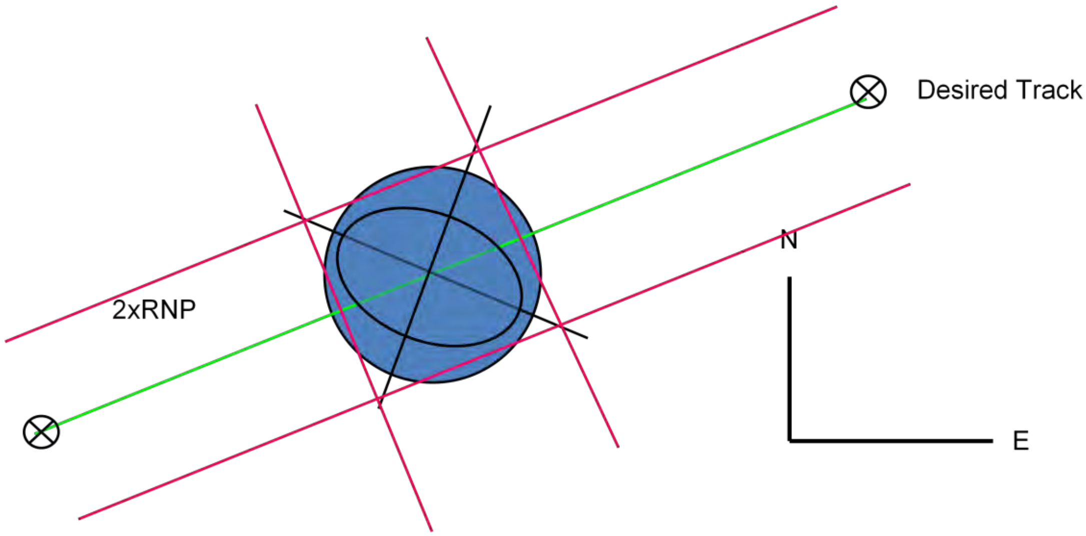

Figure 5 Bivariate Distribution Alignment

An important characteristic of most navigation systems is that the performance statistics are Gaussian (normal), as shown by analysis and validated by testing. Many millions of Monte Carlo simulation runs have been made using the full aircraft dynamic models and the exact algorithm models for the avionics. The methods of position estimation utilized generally result in elliptical error distributions (bi-variate normal) whose principal axes are not aligned with either track or N-E coordinate frames as shown in Figure 5 above. Since the DO-236 requirements are individually applied to the along track and cross track errors (red lines in the diagram) system designs have evolved to the use of circular regions of constant probability (ANPs or EPUs) for comparison to RNP values.

For a 2D navigation error distribution, complexities arise even if the distribution is Gaussian in both directions; we will review the two that are in use in RNP systems currently being produced. The three most common circular measures of performance are:

- 2-drms – twice the "distance root-mean-squared"
- R_{95} - radius of a circle equal to 95% probability
- Circular Error Probable (CEP) – radius of a circle equal to 50% probability

However, only the first two are used in RNP RNAV systems, CEP is not used in any of these and so will not be discussed.

The 2-drms method begins with the basic 2σ error ellipse (P = 0.86) defined by the two orthogonal Gaussian distributions, see Figure 6. The diameter of the circle is calculated as the RMS value for the two axes of the ellipse, i.e., $2\text{drms} = [(2\sigma_x)^2 + (2\sigma_y)^2]^{1/2}$. The probability value contained in the circle depends on the ratio σ_y/σ_x as shown in the table contained in the figure. If the two axes are equal, the distribution ellipse becomes a circle and the 2drms boundary contains 98.2% of the probability. This statistic forms the basis for the Dilurion of Precision (DOP) characteristics used in Global Positioning Systems (GPS) performance descriptions.

σ_y/σ_x	P
0	0.954
0.5	0.969
1.0	0.982

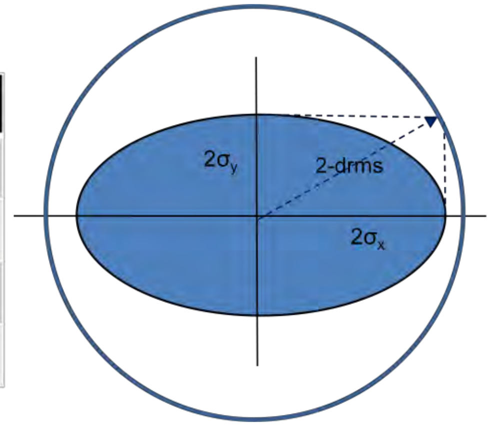

Figure 6 2-DRMS Method of Bounding Error

The 95% circle is also used in some RNP systems. It is also based on the error ellipse from the bivariate distribution of navigation errors. In Figure 7, the 95% ellipse is shown for comparison to the circle. The table shows how the R_{95} circle is related to the principal axis of the ellipse, the probability level is always 95%. Complex calculations result in the radii shown based on ratio of σ_y/σ_x, for all ratios σ_y/σ_x the probability in the circle is 95% and for low values of the ratio, parts of the 95% ellipse can be outside the circle.

σ_y/σ_x	R_{95}/σ_x
0	1.96
0.5	2.036
1.0	2.45

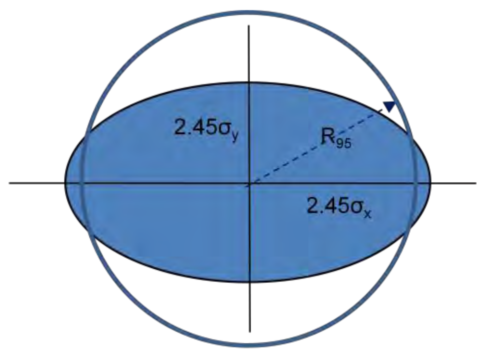

Figure 7 R_{95} Method of Bounding Error

From the tables, it can be seen that 2-drms is always larger than R_{95}, which results in a conservative estimate of the 95% bound on the navigation error. The 2-drms circle ranges from a value of 95.4% up to a 98.2% probability of containing the true position of the aircraft. R_{95} always has a probability of containing the truth equal to 95% for all distributions. At the limiting cases we have the following:

For $\sigma_y/\sigma_x = 0$, the distribution is linear

$$2\text{-drms} = 2\,\sigma_x \;\&\; R_{95} = 1.96\,\sigma_x$$

For $\sigma_y/\sigma_x = 1$, the distribution is circular

$$2\text{-drms} = 2\sqrt{2}\,\sigma \;\&\; R_{95} = 2.45\,\sigma$$

These measures are the two most commonly used in RNP systems to compute ANP (EPU).

Implementation is airborne systems can be made "inclusinve" or conservative by using the 2-drms measure as noted above (that is, for nearly circular distributions it is equivalent to a 98% accuracy circle). It can also be made conservative in the R_{95} case by choosing to always use the factor of 2.45 as the multiplier for the larger axis of the ellipse (equivalent to 95% only if the sigmas are equal). As can be seen from the table, if the ellipse is elongated by a factor of 0.5, the multiplier 2.45 is greater than the 2.036 needed to reach 95%, and so includes a higher percentage of the probability. Both of these methods have been used in airborne system according to a survey of manufacturers which was performed via interviews during the manufacturer site visits for the FMS differences testing during 2009. The addition of a multiplier to the 2.45 is also common to assure that even for a circular distribution the probability is higher than 95%.

RNP System Alerting

There are two distinct methods in current use for performing system navigation. Position estimates, and consequently the estimates of performance for the positions can be generated by utilizing one external navigation source at a time (mode based systems), or by blending of all available navigation sources (blended systems). The method used has an effect on performance (ANP or EPU) calculations in the on-board system that needs to be understood to utilize the system.

Systems that navigate in unique "modes" calculate performance (ANP) based strictly on that mode of operation. This means that the ANP when operating in one mode will only reflect the sensors in use at the time. For instance, when operating in a GPS mode, such a system will match its ANP value to some derivative of the GPS performance (Horizontal Dilution of Precision, HDOP or the Hroizontal Integrity Limit, HIL in some fashion, but it will not reflect any other sensors that might be used when the mode is switched. In addition to GPS updating modes, methods such as range / range, range / bearing, range / localizer and Inertial Reference System (IRS) are other possible modes of operation, and they are independent of each other. When such a system "switches" modes, the ANP calculations and value will change to reflect the new mode, and, more significantly, the ANP may be allowed to "step" to the new value immediately. There can be assumptions made to introduce a rate of change limit, and in these cases the ANP will move "smoothly" to the new value. This type of operation has resulted in limitations in RNP procedure designs as reflected in the requirement to disallow DME updating as a reversion to GPS on an RNP SAAAR approach for some systems. Whole state or error state blended systems contain a dynamic "model" of the navigation state (position / velocity for whole state or navigation errors for error state versions) that is a continuously updated function of time. Individual measurements related to system position are used to "update" the model at some predetermined rate, and the model carries the state forward in time in the absence of measurements to fill in between them or extrapolate after they are lost. A feature of the state space model is that the state covariance matrix carries estimates of the navigation accuracy along with the states themselves. So for instance in an IRS error model, not only are the IRS errors estimated, but their standard deviations are estimated as well (based on a Gaussian distribution for the errors). A main feature of these methods is that changing sensors in the mix does not change the method of computing performance, and there is automatic smoothing of switches due to the dynamics of the model. In these cases, the performance estimate (ANP) will depend on the covariance matrix of the position errors which contains the dimensions of the error ellipse shown in previous discussion. In one major system, ANP = $2.45\sigma_x$, and since this applies to a circular distribution ($\sigma_y/\sigma_x = 1$) it is conservative for all lower ratios which provides margin for PSE.

In all systems, there is a conservative factor applied to the computed variances of PEE to allow margin for PSE. This is clearly shown in the Boeing Navigation System Analysis documents for each of their aircraft, which are public documents. Other systems manufacturers were interviewed and found to do essentially the same. The size of the factor is determined by how big an allowance is needed for PSE in the various flight operational modes for steering. In the Boeing documents this results in a minimum RNP that can be supported in each autopilot mode (LNAV autopilot, LNAV flight director or manual) and sensor mix. The final result is that each system, when alerting that ANP>RNP is factoring for TSE, and telling the crew when the containment integrity (10^{-5} at 2xRNP) is not being met. This results in the UNABLE RNP message or equivalent in each system.

The UNABLE message referred to above is not only navigation performance alerting provided by RNP systems. There are warnings relative to RNP values in the database and manually entered values; for instance if a manually entered RNP exists and the database calls for a smaller on as the aircraft moves along the path, a warning is generated to be sure the crew are aware. When flying a database value, if the crew enter a larger value, a warning is generate, again to assure that the crew are doing the correct thing. More automatic warnings are also generally in use, such as multiple sensor comparisons warnings. Many systems compare sensors such as IRS to IRS, IRS to FMS, FMS to GPS, FMS to radio (range/range or range/bearing) and FMS to FMS (dual system). Each of these differences is typically compared to the RNP value in use, with the exception of the IRS comparisons. Each of these, if exceeding the threshold, will warn that there is a potential for navigation error which needs to be checked by the crew. Data can be provided on map displays and/or Control Display Units (CDU) showing relative locations of each position used for comparisons to help diagnose the problem and the crew can select or deselect individual navaids or updating sources (GPS, VOR and DME) in some systems. Overrides can also be done by crew re-initialization and control of single / dual operation in dual systems. There are many layers of protection relative to the RNP value not only based on the performance level achieved, but on non-normal occurances as well. All of this needs consideration in any analysis of separation standards, as will be discussed in the next sections of this paper.

Separation Analysis and RNP Systems

Performance Classification and Detection

Separation standards depend on analysis of the combination of navigation system / aircraft performance, crew performance, and the monitoring or surveillance available where and when the operations are taking place. **Error! Reference source not found.** below attempts to capture the trade-offs among them in a qualitative way to help frame the rest of the discussion.

Table 1 Performance Characteristics

Performance	*Description*	*Monitoring / Detection*
Normal	**Bounded by 95% TSE, all systems operating normally with full availability of signals in space etc. The 95% value scales the total system error distribution given the type and no other constraining factors.**	**Historically derived from testing and assumed to be valid if the system is operating without failure indication. In RNP systems, a value is computed real time and displayed.**
Rare-normal	**Reflects "tails" of the TSE distribution; it is possible for TSE to enter this region during normal operation with no failures and full availability. Typical levels are 10^{-3}, 10^{-5}, 10^{-7} and 10^{-9} depending on the effect of an undetected excursion into this region as defined in AC 25-1309a (minor, major, hazardous, catastrophic).**	**Historically derived from analysis and assumed valid if the system is operating normally. In RNP systems there must be less than 10^{-5} per hour probability that TSE exceeds 2xRNP without an alert. Since TSE cannot be observed, an alert means 10^{-5} is not met. Actual excursions can be detected by independent surveillance, but not dependent surveillance (ADS-B).**
Non-normal	**These effects are driven by failure conditions in hardware or software that can be either latent and undetected or detected by the onboard systems through various means within the avionics. Crew errors also fit into this category.**	**System safety assessments and the certification process reduce or provide mitigation for this type of error. Detection through either dependent or independent surveillance is possible.**

Collision Risk vs. Safety Assessment

To derive separation standards, Collision Risk Modeling (CRM) and Safety Assessment (Safety Management System or SMS in the US) are applied to the avionic systems and to the operation using known and assumed attributes. Aspects of the performance classes in **Error! Reference source not found.** lend themselves to one method or the other, as shown in Table 2.

Table 2 Applicability of Error/Failure Analysis

Performance	*Detected Failure*	*Undetected Failure*
Normal & Rare-normal	***Symptom*: Aircraft excursion from planned track or non-compliance with RNP value** ***Detection*: 1) Independent surveillance. Crew can detect PSE, external tracking (radar) can detect unknown PEE. 2) RNP systems "detect" and alert when Prob(TSE > 2xRNP) > 10^{-5} as described in the RNP systems section of this paper. Safety assessment can be used to determine hazard and appropriate action based on the higher probability of TSE > 2xRNP realizing that a large TSE need not be present for the alert.** ***Separation analysis:* Safety assessment of effect and recovery.**	***Symptom:* In normal unfailed operation, RNP systems meet the accuracy and integrity level of the RNP for the operation. However there is a finite probability of TSE being too large but not detected.** ***Detection:* Not detected.** ***Separation Analysis:* Collision risk modeling should be used with the probability distribution of the TSE to help define separation requirements. If the distribution is Gaussian, the controlling parameter is the 10^{-5} at 2xRNP. Need to validate the statistical model used.**
Non-normal	**Internal to the aircraft, there can be many combinations of detected system failures which are analyzed during certification. There can also be crew errors that affect the flight path of the aircraft.** ***Symptom:* Aircraft departure from planned track in a manner that may threaten loss of separation.** ***Detection:* Surveillance, either dependent or independent, and/or crew monitoring of PSE.** ***Separation Analysis:* Safety**	**System safety assessments and the certification process reduce or provide mitigation for system or crew faults/errors that could go undetected.** ***Symptom:* Aircraft departure from planned track in a manner that may threaten loss of separation.** ***Detection:* Not detected.** ***Separation Analysis:* Safety assessment of risk.**

	assessment of effect and recovery.

Comparison of the two tables, and the work at ICAO reviewed in the first section of this paper, shows areas where further work may be useful in establishing separation standards based on RNP systems with OPMA capability. Some of the work is in progress at ICAO, and some connections are yet to be explored. The following are some suggestions:

1) One ICAO paper began to explore the containment integrity requirement for RNP systems, but but asserted that there is really no way to know for sure that the probability distribution of TSE is Gaussian. An effort should be undertaken with OEMs and avionics vendors to provide data to substantiate the distribution. Simulation data from high fidelity simulations should suffice, with validation of the conclusions from carefully screened data collection from aircraft operations.
2) The safety assessment needs to postulate meaningful errors that could occur in RNP systems operation in the three ususal modes, manual flight, LNAV on flight director and LNAV on autopilot. This may result in restrictions of the mode of operation allowed in support of certain separation standards for RNP routes.
3) The “UNABLE RNP” alert needs to be understood in the context of an increased probability that TSE will exceed 2xRNP, rather than in the context of an actual tracking error. This should be included in the SMS not the CRM.
4) Use of dependent surveillance is seen in the preceding tables to be unusable in the detection of normal and rare-normal operation due to being directly linked to the navigation system error which is unknown to the avionics. This needs to be understood in the context of how operations are monitored. Dependent surveillance CAN be used to detect non-normal operation.
5) The connection to analysis used to establish OCAs must be made as recommended by Pate and Greenhaw in their working paper. We believe that the missing element from the OCA analysis is the safety assessment of non-normal operation and operation with an UNABLE RNP alert.

With the addition of this work, data could be provided to ICAO SASP to further take advantage of RNP operations and system characteristics in the performance based airspace of SESAR and NextGen.

Order 7110.65 Separation References and OPMA

A matrix containing all references to a separation distance was compiled as a reference during the development of this paper. It contains the paragraph reference and supporting external reference, where known, and it captures the conditions under which each separation standard is applied. As an aid to understanding the historical development of these separation standards, MITRE has begun to research the origins of these standards, however that work is incomplete should continue.

Based on the survey of ICAO work at SASP, and on the observations and explanations of RNP and its attendant alerting, it would seem that a “new” paragraph is needed in the separation criteria to specifically handle RNP systems. The RNP systems were defined and designed to provide an “UNABLE RNP” indication, analogous to the “flag” the drops to alert the crew that the localizer or glideslope are inoperative on their ILS. In the approach domain the response for both systems is the same, discontinuation of the approach. Use of the RNP values (or multipliers of them) for route separation covers the normal (and rare-normal), or unfaulted operation of the system, and the separation needed is a function of the statistics of the navigation. However, per the questions raised above, that is not the whole basis for separation. That is why this paper has pointed out the limitations of dependent surveillance (cannot detect errors due to normal or rare normal operation but can detect faulted operation such as pilot error), and the need for assessment of realistic faulted operational scenarios to complete the analysis of separation.