TECHNICAL MEMORANDUM
OU/AEC 08-12TM15689/0004-1

ASSESSING THE VALIDITY OF USING ACTUAL NAVIGATION PERFORMANCE (ANP) INFORMATION FOR SUPPORTING DESIGNATED FLIGHT INSPECTION OPERATIONS

The Federal Aviation Administration (FAA) Aviation System Standards (AVN) has RNP capable aircraft that utilize ANP, and this situation is the motivation for conducting an assessment regarding the use of ANP estimates for flight inspection related applications. The Avionics Engineering Center was tasked to support this assessment effort. The tasking consisted of providing an ANP seminar and assessing the suitability of ANP as a truth reference system for flight inspection applications. This report documents the work performed, provides a summary of the ANP tutorial material developed under this task order, and presents the results of the assessment to determine the suitability of ANP as a truth reference system for flight inspection applications. Conclusions regarding the suitability of an ANP-based system for supporting flight inspection applications are presented.

by

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Task Order 0004 – Final Project Report

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I. INTRODUCTION

The National Airspace System (NAS) is moving towards a performance-based architecture as a means of achieving increased capacity, efficiency, safety, and security [1]. Navigation, communication, and surveillance concepts are being defined based on performance standards and associated metrics instead of particular technologies or equipment suites. Area Navigation (RNAV) and Required Navigation Performance (RNP) are the enabling components for performance-based navigation.

RNAV refers to a navigation method that enables the aircraft to fly from point-to-point along any desired flight path as long as the following two requirements are satisfied. First, the flight path must be within the coverage of the navigation aids being used by the aircraft navigation suite. Second, this navigation suite must meet the minimum performance requirements specified for the procedure being flown or airspace utilized. One can think of RNP as an RNAV operation with a requirement for on-board monitoring of navigation performance. That is, the capability to determine in real time the Actual Navigation Performance (ANP), identify for the pilot whether the performance requirement is being met, and ensure the overall containment of the flight operation.

Typically, ANP is an estimate of the actual achieved performance based on statistical analysis of the sensor data, as well as other supporting information in some instances. This estimate is also referred to as Estimated Position Uncertainty (EPU). Ensuring the estimate is representative of the actual performance requires that both the assumptions made regarding senor error distribution and characteristics, as well as the associated analysis techniques, are valid.

The Federal Aviation Administration (FAA) Aviation System Standards (AVN) has RNP capable aircraft that utilize ANP, and this situation is the motivation for conducting an assessment regarding the use of ANP estimates for flight inspection related applications [2]. The Avionics Engineering Center (Avionics) at Ohio University was tasked to support this assessment effort. Under the initial tasking Avionics personnel were tasked to review ANP related materials obtained as either Government Furnished Information (GFI), from publicly available documents, and information to be obtained from equipment manufacturers. The results of this literature search effort indicated that the publicly available information was not sufficient for supporting this study. Thus, the initial Task Performance Work Statement was modified and the generation of ANP tutorial information was included in the tasking [3]. The revised tasking consisted of the following three major elements: 1) Providing an ANP seminar; 2) Assessing the suitability of ANP as a truth reference system for flight inspection applications; and 3) The delivery of a project report.

The purpose of this report is to document the work performed, summarize the ANP tutorial material developed under this task order, present the results of the assessment to determine the suitability of ANP as a truth reference system for flight inspection applications; and, provide conclusions based on the findings of this assessment.

II. ANP TUTORIAL

Performing the assessment discussed in the preceding section requires a sufficient understanding of ANP, including the reliability and accuracy of the estimate and standardization of equipment performance requirements among equipment manufacturers. Although Avionics personnel assigned to this task have significant experience with flight inspection methodologies and requirements, there was no one on staff with significant ANP experience. Thus, Avionics was tasked at the beginning of this effort to seek out and work with an ANP subject matter expert to develop an ANP tutorial briefing, as well as host an ANP tutorial (i.e., a seminar).

A. ANP Tutorial Development

Avionics and AVN personnel worked jointly to identify and select an ANP subject matter expert, and Mr. Michael Cramer of Cramer Consulting, Inc. was selected to lead the tutorial development effort. The tutorial that was developed is intended to provide one with a conceptual understanding of ANP, typical implementation schemes, performance variations among implementation schemes, verification results, and reference material that can be used to obtain a more detailed understanding of ANP [4-8]. The tutorial material was developed in stages. At each stage of development, the draft material was initially reviewed by Avionics personnel, then Avionics and Cramer Consulting personnel worked jointly to revise the draft material, which was then submitted to the FAA for review and comment. The final tutorial material was delivered to the FAA in Microsoft PowerPoint file format on 5 May 2008, and a second delivery occurred on 28 July 2008 (see section II.B). This material addresses the following thirteen topics:

1) What is ANP;
2) Actual Navigation Performance (ANP) and relationship to Estimate of Position Uncertainty (EPU) as defined in RTCA DO-236;
3) ANP versus RNP (i.e., similarities/differences);
4) Relevant literature, public domain reports, and RTCA documents such as DO-236, DO-200, DO-283;
5) Statistical techniques and sensor models used to produce ANP estimates including the Kalman filter approach;
6) Difference in calculation of ANP/EPU by different flight management system (FMS) manufacturers;
7) ANP accuracy performance bounds (best/worst case) and reliability based on current technology;
8) The role of flight guidance systems/flight technical error (FTE), if involved in ANP/EPU calculations;
9) ANP/EPU change as navigation system source changes (i.e., GPS, DME/DME, VOR/DME, IRU sensor hierarchy);
10) Effect of navigation database errors on ANP, such as incorrect DME facility latitude/longitude. (i.e., DME facility moved, but latitude/longitude not updated in database);

11) How performance degradation due to environmental effects such as multipath or atmospheric effects is addressed;
12) Verification methodologies employed; and,
13) Published verification results including certification data packages that may have been previously submitted to FAA for certification.

B. ANP Tutorial/Seminar

The ANP tutorial was provided by Mr. Mike Cramer of Cramer Consulting on the afternoon of 8 May 2008. The tutorial was provided at the Airman's Record Building, Mike Monroney Aeronautical Center, Oklahoma City, Oklahoma. The participants included approximately 30 FAA and three Avionics personnel.

Subsequent to the tutorial in Oklahoma City, the tutorial material was revised to address minor editorial corrections noted during the presentation of the material. The revised tutorial material, in Microsoft PowerPoint file format, was delivered to the FAA on 28 July 2008. A copy of the tutorial slides is provided in the Appendix.

III. ANP SUITABILITY FOR FLIGHT INSPECTION SYSTEM APPLICATIONS

As previously mentioned, AVN has RNP capable aircraft that utilize ANP. This situation is the motivation for conducting an assessment to identify the potential benefits, as well as potential barriers to using ANP estimates for flight inspection related applications. The objective is to compare the capabilities provided by being ANP equipped to the functional requirements for a flight inspection system. The ANP tutorial material was generated to provide one with a conceptual understanding of ANP, including its capabilities and performances. Thus, this material serves to define the capabilities that will be assessed against functional requirements for a flight inspection system. FAA Order VN 8200.8, Flight Inspection Program Standards and the United States Standard Flight Inspection Manual serve as the basis for defining those functional requirements [9, 10].

Two potential applications were identified based on comparison of ANP capabilities to functional requirements for a flight inspection system. One application is supporting National Airspace System (NAS) infrastructure evaluations; the second is supporting truth reference system applications.

A. Infrastructure Evaluations

Candidate infrastructure evaluations were included in the ANP tutorial material and are summarized herein. These evaluations could include validating the availability of the navigation signal in space, or the more interesting application of validating the minimum supported RNP for a given route or procedure.

For this later application, one would need ANP data as a function of location along the route or procedure being evaluated. Determining the minimum supported RNP requires an assessment of the collected ANP data to the RNP values used to design the route or procedure. To determine the minimum supported RNP, the assessment must account for variation of system performance over time, such as those due to variation in satellite position. Similarly, it must account for Path Steering Error (PSE) in various steering modes, as well as account for performance variations due to the use of available sensor combinations. Each of these factors depends heavily on the *a priori* assumptions and methods used to derive the ANP estimate.

This situation brings the question: Once an infrastructure evaluation is performed using one particular ANP system (i.e., flight inspection), are the results obtained applicable to other systems (i.e., NAS users)? To determine the answer to this question, answers to questions like the following are needed:

1) Are the sensor error models compatible?
2) Are the data rejection techniques comparable?
3) Are the operational modes and/or sensor combinations compatible?
4) Is the sensor blending for these combinations similar or comparable?
5) Are the ANP values meaning (e.g., statistical bound used) similar or the same?

The answer to these questions must be yes for the results obtained using one system to be applicable to another. It is felt that this is likely not the case at this writing. This situation may be due to the "open" definition of ANP/EPU in RTCA DO-236, which states it's a measure based on the defined scale, in nautical miles, which conveys the current position estimation performance. Other than it shall be continuously available in flight, no further specification is provided. This "open" definition provides the system designer with much latitude regarding the choices made during the design and implementation of an ANP/EPU system.

B. Truth Reference System

The objective of conducting flight inspections is to evaluate flight procedures to ensure safety, flyability, and human factors [9,10]. As listed in the flight inspection manual, the following assessments are included in a flight inspection evaluation:

1) Procedure design must meet obstacle clearance requirements;
2) The applicable navigation system(s) must meet performance requirements and must be suitable for supporting the intended procedure;
3) The procedure design is sufficiently simple so charting complexities can be kept to a minimum for human memory considerations;
4) Navigation charts must properly portray the procedure and be easily interpreted;
5) Aircraft maneuvering must be consistent with safe operating practices for the category of aircraft intending to use the procedure;
6) Cockpit workload must be at an acceptable level;

7) Runway markings and lighting must meet the applicable requirements;
8) Communications are adequate; and,
9) Radar coverage is available, when required.

Accomplishing assessment #2 includes the evaluation of Navigation System Error (NSE) against performance requirements. This evaluation process includes the comparison of the guidance or position information provided by the sensor or system being evaluated to that obtained from what is commonly referred to as a truth reference system. Simply stated, a truth reference system is another independent sensor or source of aircraft position with an accuracy known to be notably better than the sensor or system under evaluation. This might be a single system or device such as an optical tracking system (e.g., theodolite) or a multi-sensor, on-board autonomous system. The truth reference system may operate in the same coordinate system as the sensor or system being evaluated, or in a different coordinate system. Coordinate conversion of the truth reference system position information is performed in the latter case to obtain reference position fixes in the same coordinate system as the sensor or system being evaluated.

There are two situations to be considered in assessing the suitability of using ANP information to support truth reference system applications. One is when the ANP information is derived using a sensor or system that operates in the same coordinate system as the navigation sensor or system being evaluated. The other is when the ANP information is derived using a sensor or system that operates in a coordinate system different than that of the sensor or system being evaluated.

1. Same Coordinate System

When the ANP information is derived using a sensor or system that operates in the same coordinate system as the sensor or system being evaluated, the ANP estimates can be used to evaluate the accuracy performance of the sensor or system being inspected. There are implementation matters that need to be considered, such as how one would use a horizontal ANP estimate for evaluating cross-track and along-track errors. However, such discussion is outside the scope of this study, thus it will not be addressed herein.

It is important for this study to note that Order VN 8200.8 requires AVN to document the accuracies achieved for the reference systems being used and to ensure those accuracies are compliant with those required for the system being inspected [9]. Once the initial accuracy or measurement uncertainty has been verified, configuration control is required to ensure any subsequent changes do not affect the capability of the system to meet measurement accuracy requirements. It is the author’s opinion that the two requirements discussed in the preceding sentences are both reasonable and essential requirements for consistently obtaining high-fidelity NSE measurements. This opinion is based on the author’s own flight measurement experience as gained by working on projects such as those described in References 11 - 21. Further, it is the author’s understanding that ANP equipment are not produced with the intent to support true reference system applications, but to provide aircrews a means of monitoring compliance with RNP requirements.

Although in this situation it may be theoretically possible to produce an ANP system suitable for truth reference system applications, the “open” definition in RTCA DO-236 and the relatively larger commercial customer base may provide practical barriers in this situation.

The discussion has been conceptual in nature to this point. A simple example will be taken to illustrate the types of considerations that may impact the ability to use the information obtained from an ANP-based system for supporting truth reference system applications. Depending on sensor data rates, types of sensors used, etc., filtering, averaging, or integration for some number of samples or length of time may be performed as part of the ANP estimation process. In this example, we start with the true aircraft position and “unfiltered” sensor or measured aircraft position (see Figure 1). Then NSE data ($Error_1$) are generated by a point-by-point differencing of the sensor and true aircraft position. To gain insight into the effect filtering or averaging can have on the data reduction process, a filtered sensor data set is generated by averaging the data using a 0.01-second sliding window. Then, a second NSE ($Error_2$) trace is generated by point-by-point differencing of the filtered sensor data and true aircraft position data. The $Error_1$ and $Error_2$ traces show different characteristics. Figure 2 – Figure 6 show the effect for intervals of 0.1, 0.5, 1, 5 and 10 seconds, respectively. These examples are taken for illustrative purposes only and are not representative of any ANP system implementation. Similarly, this example points out that care must be taken when filtering of the truth reference data is performed or in selecting or specifying minimum data rates.

2. Difference Coordinate System

When the ANP information is derived using a sensor or system that operates in a coordinate system different than that of the sensor or system being evaluated, the ANP information cannot be used directly to evaluate the accuracy performance of the sensor or system being inspected. This is because the ANP estimate is for a coordinate system different from that of the sensor or system being evaluated. Since this information is an estimate of position uncertainty and not a position estimate, coordinate conversation of the estimate is not possible. In this situation, the ANP estimate might be used as a means of monitoring the quality of the position information being used via coordinate conversion to produce truth reference information.

Similarly, any ANP system used for this situation must meet the requirements set forth in Order VN 8200.8. Although it may be theoretically possible to produce an ANP system suitable for this application, the “open” definition in RTCA DO-236 and the relatively larger commercial customer base may provide practical barriers in this situation.

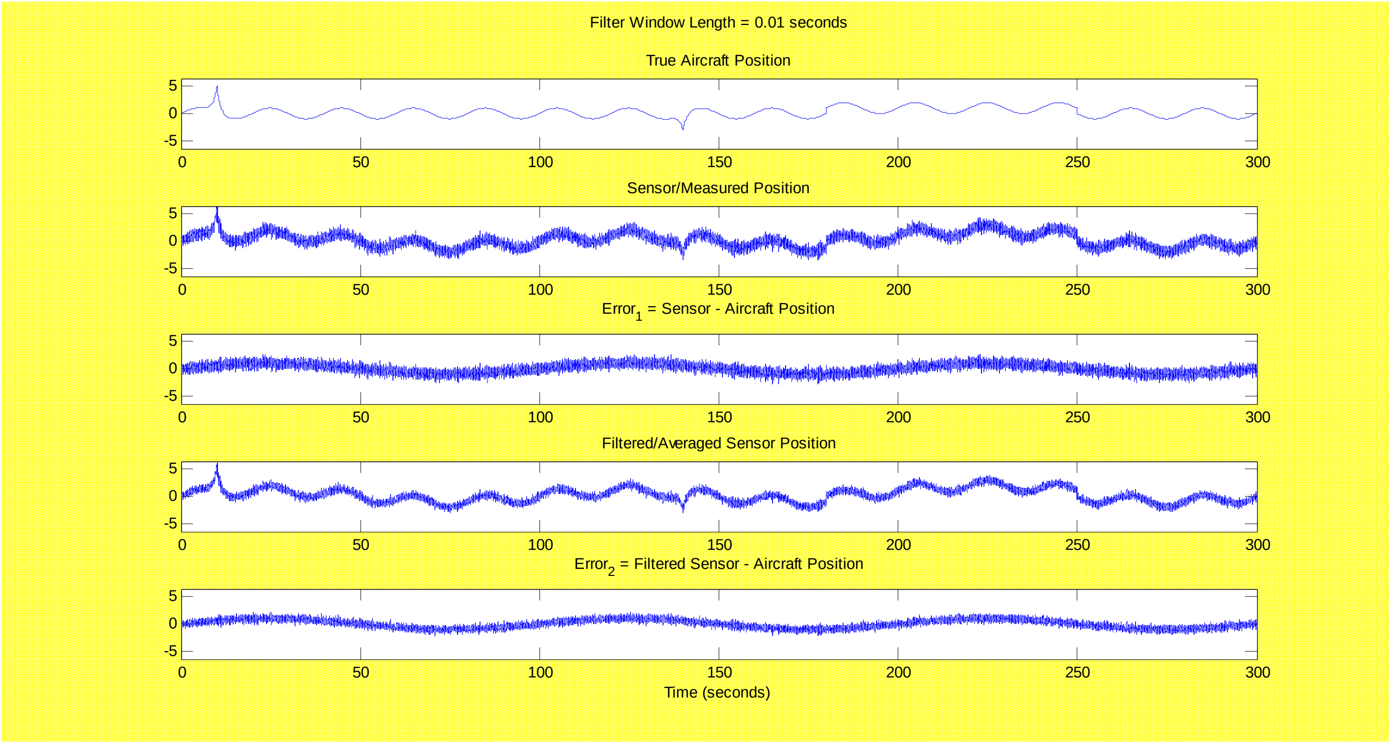

Figure 1. Example of Filtering Effects, 0.01-Second Interval.

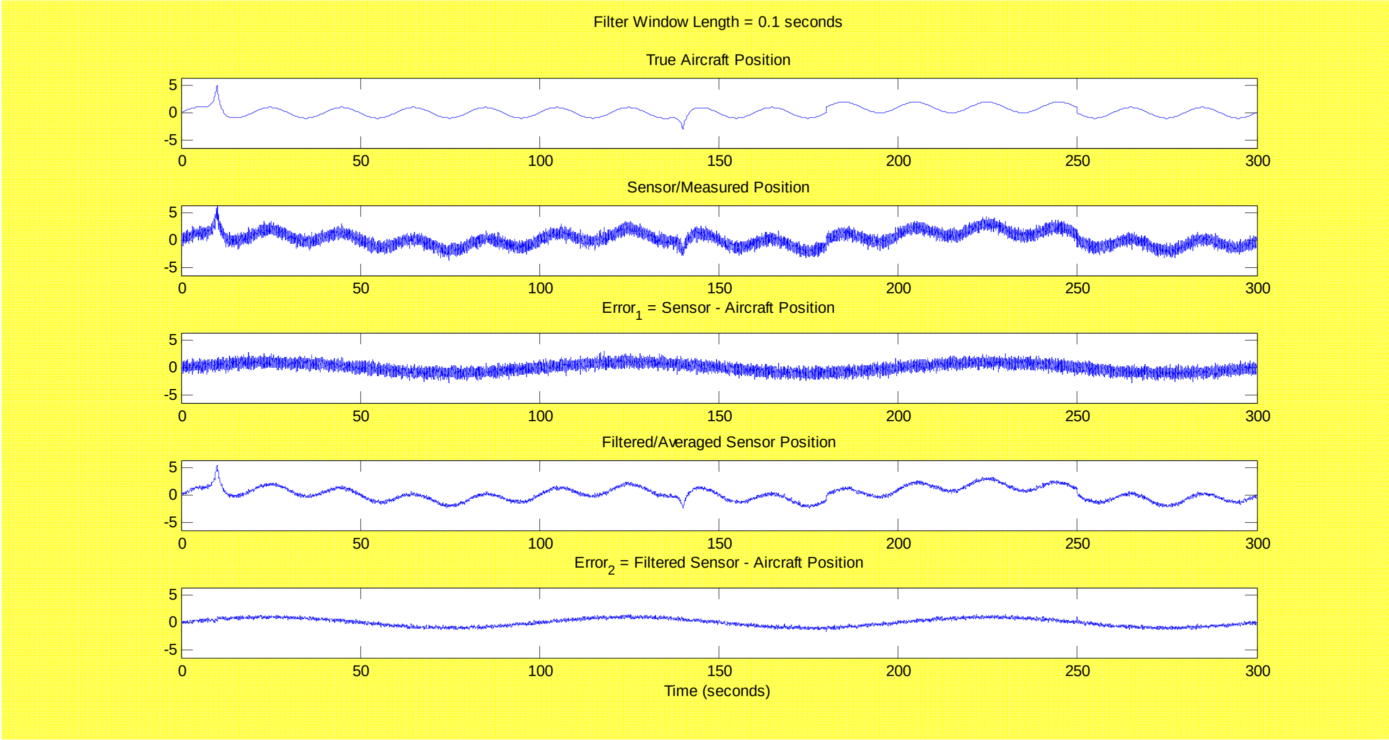

Figure 2. Example of Filtering Effects, 0.1-Second Interval.

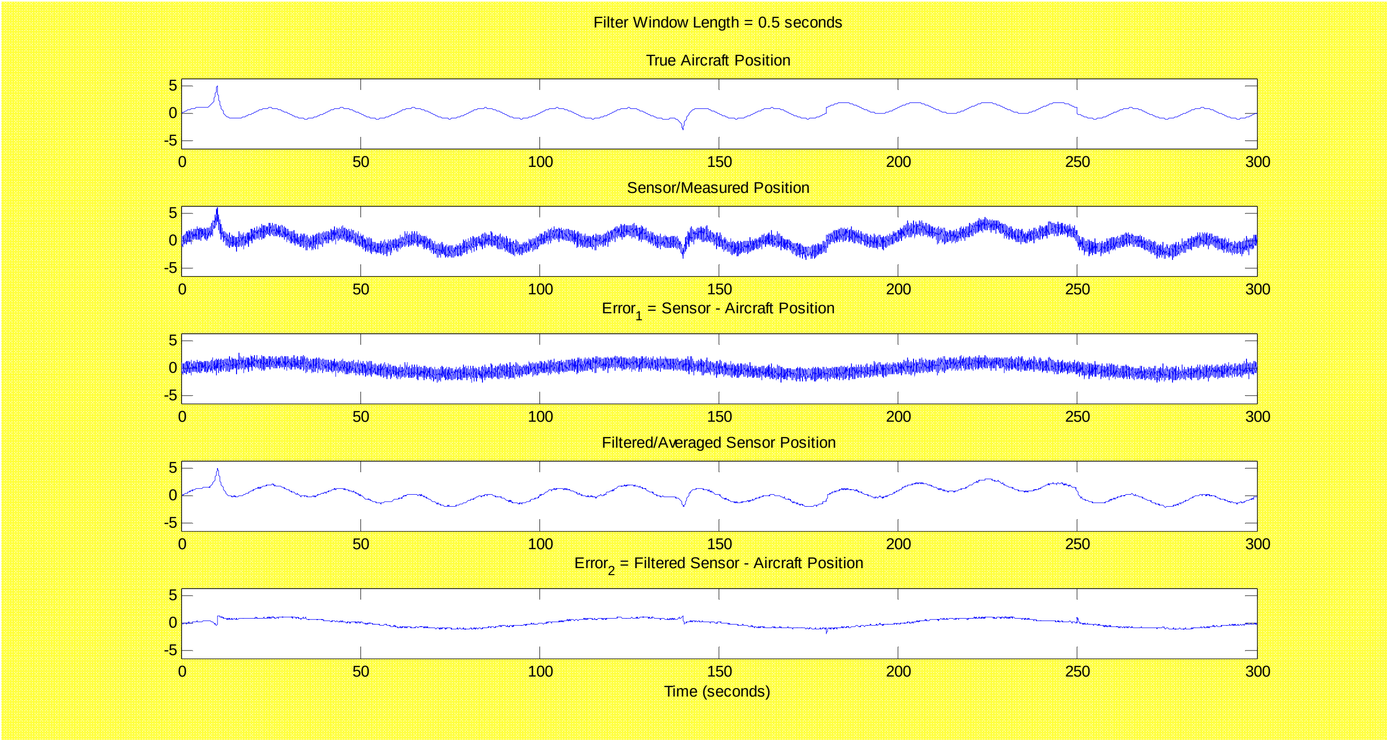

Figure 3. Example of Filtering Effects, 0.5-Second Interval.

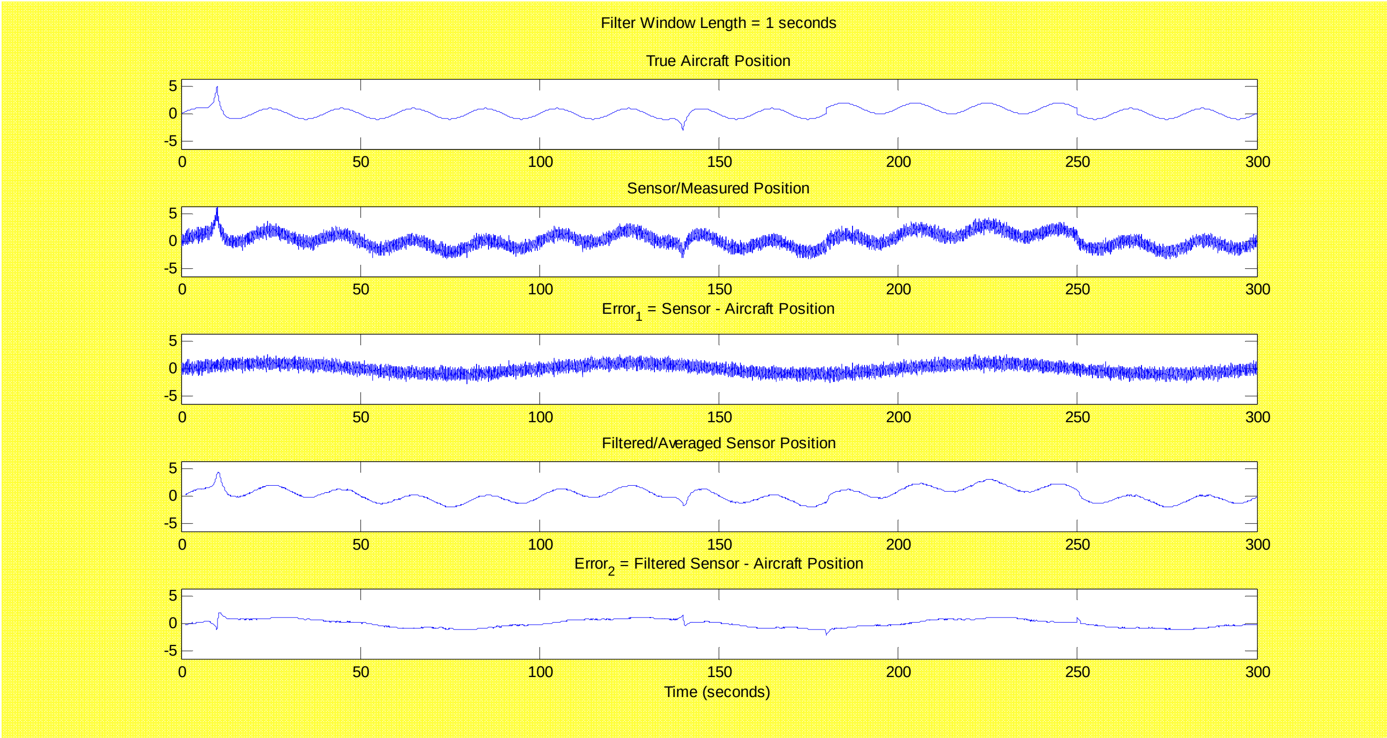

Figure 4. Example of Filtering Effects, 1-Second Interval.

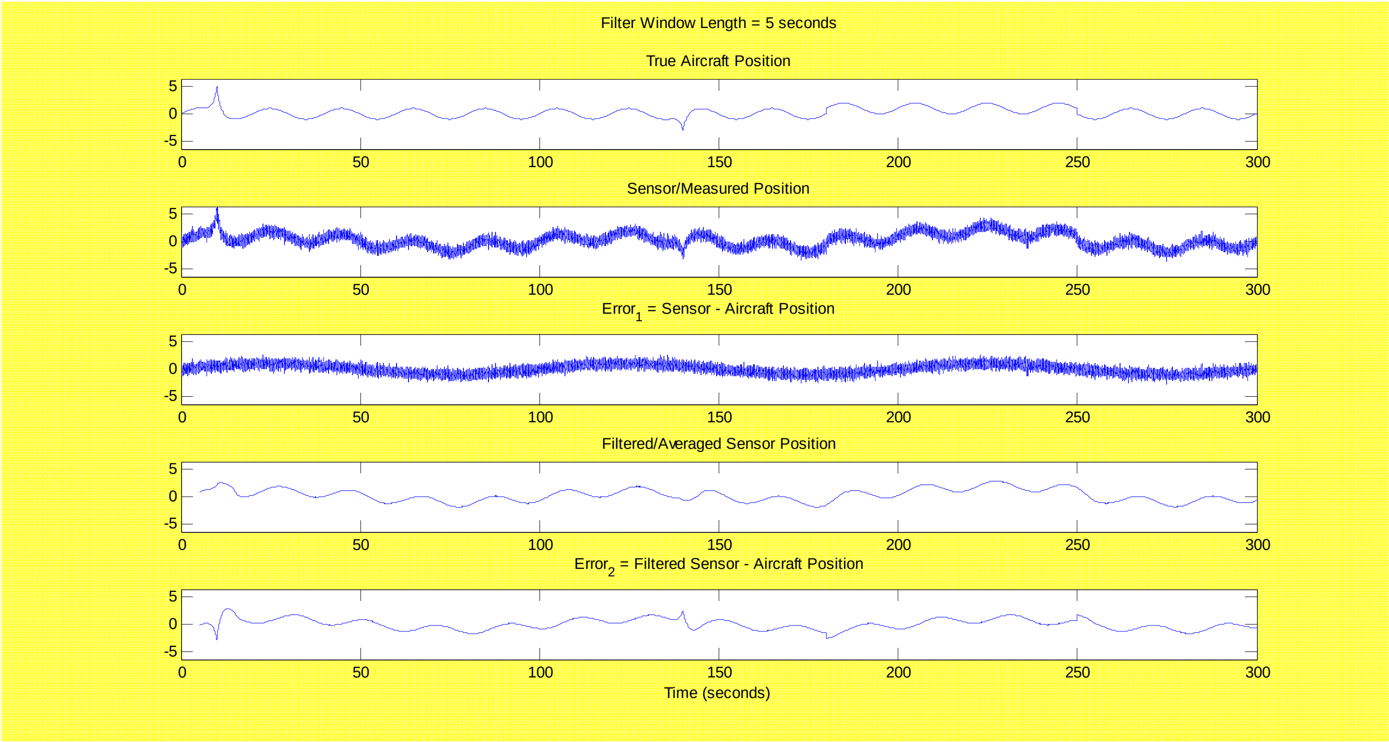

Figure 5. Example of Filtering Effects, 5-Second Interval.

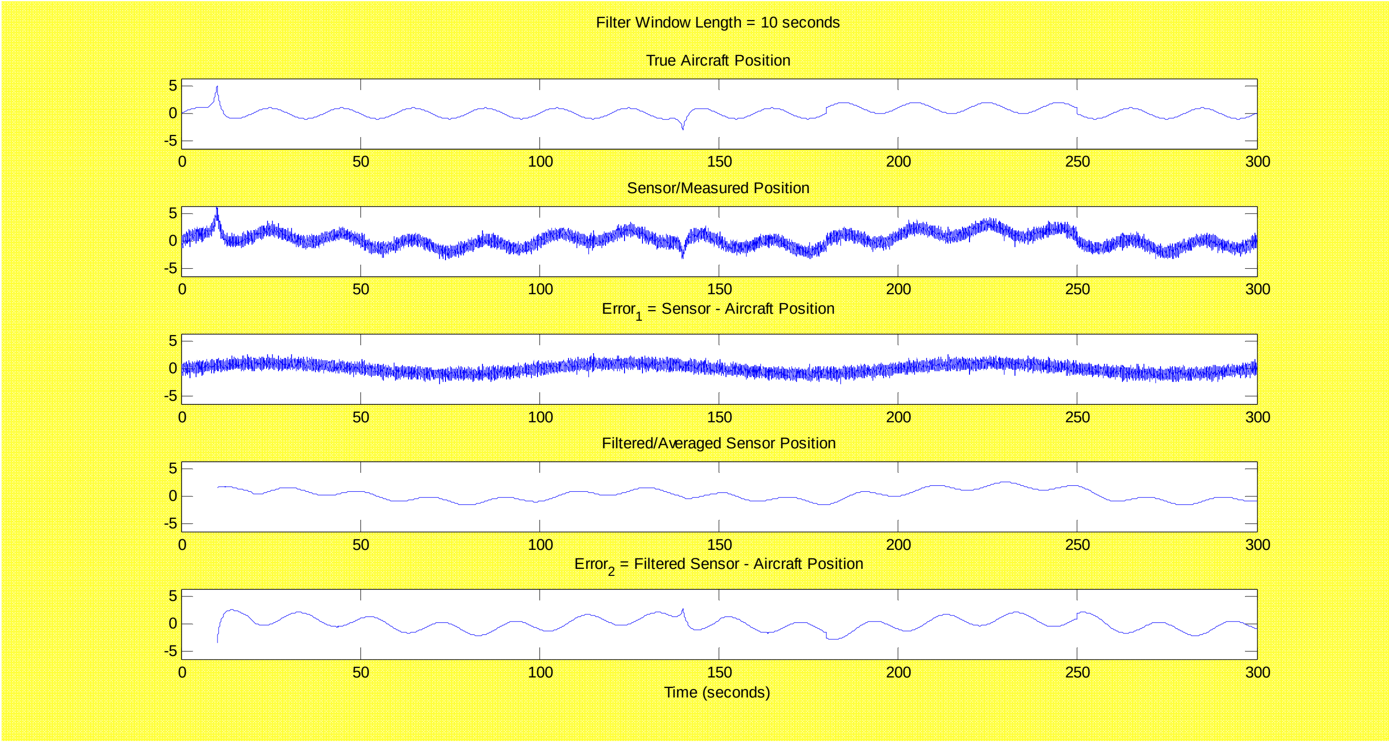

Figure 6. Example of Filtering Effects, 10-Second Interval.

IV. CONCLUSIONS

This report documents the work performed, provides a summary of the ANP tutorial material developed under this study, documents the occurrence of the first tutorial, and presents the results of the assessment performed to determine the suitability of ANP as a truth reference system for flight inspection applications.

The following has been concluded based on the results of this study:

1) Under certain conditions, it is theoretically possible for an ANP-based system to support select flight inspection applications, such as infrastructure and accuracy evaluations;

2) Those conditions are not those that prevail at this writing, particularly meeting the requirement to have sufficient documented characterization of how ANP-based systems perform;

3) If a well characterized ANP-based system existed and its performance was sufficiently documented and shown to meet prevailing flight inspection system requirements (i.e., documented performance beyond that required by RTCA DO-236), it would be a viable candidate for supporting select flight inspection applications; and,

4) In addition to accuracy assessment, the flight inspection of most navigational aids requires the evaluation of other signal-in-space characteristics, such as signal strength, cross-polarization, depth of modulation, accuracy of broadcast data blocks, etc. Thus, the availability of a suitable ANP-based system does not mitigate the need for specially-equipped flight inspection aircraft.

V. ACKNOWLEDGEMENTS

The author thanks fellow engineer Mr. Frank Alder and undergraduate student Mr. Daniel Shapiro for their assistance with the MATLAB simulations and generation of the plots used in this report.

VI. REFERENCES

1 Federal Aviation Administration, “Roadmap for Performance-based Navigation, Evolution for Area Navigation (RNAV) and Required Navigation Performance (RNP) Capabilities 2003-2020,” Version 1.0, July 2003.

2 Task Performance Work Statement, Task Order 0004, Contract DTFAAC-03-A-15686, Dated 26 July 2006.

3 Task Performance Work Statement, Task Order 0004, Modification 0001, Contract DTFAAC-03-A-15686, Dated 12 July 2007.

4 "Two Dimensional Measures of Accuracy in Navigational Systems", (U.S.) Transportation Systems Center, Cambridge, MA; PB87-194569.

5 "RNP Capability of FMC Equipped 737, Generation 3", Boeing Document D6-39067-3, January 14, 2003.

6 "RNP Capability of FANS 1 FMCS Equipped 747-400, Gen 1", Boeing Document D926U050.

7 "777 RNP Navigation Capabilities, Generation 1", Boeing Document D243W018-13, August 28, 2003.

8 "757/767 FMCS RNP Navigation Capabilities, Gen 1", Boeing Document D926T0120-1

9 United States Department of Transportation, Federal Aviation Administration Order VN 8200.8, "Flight Inspection Program Standards", 20 August 2007.

10 United States Department of Transportation, Federal Aviation Administration, Order 8200.1C, "United States Standard Flight Inspection Manual (USSFIM)," October 2005.

11 DiBenedetto, Michael F., and Roger Radcliff, "Effects of Simulated MLS Installations on the Capture Effect Glide Slope and 14-Element Log-Periodic Localizer at Airborne Airpark, Wilmington, Ohio," Technical Memorandum R-1, Avionics Engineering Center, Department of Electrical and Computer Engineering, Ohio University, Athens, Ohio, August 1985.

12 DiBenedetto, Michael F., and Roger Radcliff, "Results for a Study on MLS-ILS Collocation," EER 85-1, Avionics Engineering Center, Department of Electrical and Computer Engineering , Ohio University, Athens, Ohio, August 1987.

13 Edwards, Jamie S. and Michael F. DiBenedetto, "Effects of a Simulated MLS Azimuth Station Constructed of Sheet Metal on the 8-element V-ring Localizer at the Tamiami Airport," Technical Memorandum OU/AEC 17-87TM00006/2-1, Avionics Engineering Center, Department of Electrical and Computer Engineering , Ohio University, Athens, Ohio, Revised December 1987.

14 DiBenedetto, Michael F. and Michael S. Braasch, "Validation Results Obtained to Date on MLS Critical and Sensitive Areas," Technical Memorandum OU/AEC 91-88TM00006/9B/ICAO, Avionics Engineering Center, Department of Electrical and Computer Engineering , Ohio University, Athens, Ohio, August 1988.

15 DiBenedetto, Michael F., Eric R. Maurer and David Dudding, "Final Report on Results Obtained From MLS Critical Area Flight Evaluations Using a Boeing 727," Technical Memorandum OU/AEC 88-88TM86:1088.001/2-1/ICO, Avionics Engineering Center, Department of Electrical and Computer Engineering , Ohio University, Athens, Ohio, February 1988, Revised August 1988.

16 DiBenedetto, Michael F., “Presentation of Flight Data Collected at Standiford Field, Louisville, Kentucky to Measure the Effects of an Interfering Boeing B-747 on the MLS Azimuth and Elevation Signals,” Technical Memorandum OU/AEC 96-88TM00006/9B-3, Avionics Engineering Center, Department of Electrical and Computer Engineering , Ohio University, Athens, Ohio, October 1988.

17 DiBenedetto, Michael F., “Siting Criteria for the Microwave Landing System (MLS): MLS/ILS Collocation and Runway Hump Shadowing,” Master of Science Thesis, College of Engineering and Technology, Ohio University, Athens, Ohio, August 1988.

18 DiBenedetto, Michael F.,” Flight Measurement Results Quantifying the Effect on the Redlich Dual-frequency, Wide-aperture Localizer Array Due to Sitting an MLS Azimuth Antenna in Front of the Array,” Technical Memorandum OU/AEC 09-89TM00006/2B/ICAO, Avionics Engineering Center, Department of Electrical and Computer Engineering , Ohio University, Athens, Ohio, April 1989.

19 DiBenedetto, Michael F. and Michael S. Braasch, “Analysis of Simulation Data and Flight Data Collected At Standiford Field, Louisville, KY, to Investigate the Effects of an Interfering Boeing B-747 on the MLS Azimuth and Elevation Signals,” Technical Memorandum OU/AEC 97-88TM00006/9C-01, Avionics Engineering Center, Department of Electrical and Computer Engineering , Ohio University, Athens, Ohio, October 1988, Revised May 1989.

20 DiBenedetto, Michael F. and Stephen J. Kruger, “DME/P Module Validation: The Comparison of Measured and Modeled Multipath Errors due to Signal Scattering by the DOT/FAA Technical Center Hangar,” Technical Memorandum OU/AEC 92-75TM00006/51-4, Avionics Engineering Center, Department of Electrical and Computer Engineering , Ohio University, Athens, Ohio, August 1993.

21 DiBenedetto, Michael F., “Development of Critical-Area Criteria for Protecting Microwave Landing System Azimuth and Elevation Guidance Signals,” Dissertation, Fritz J. and Dolores H. Russ College of Engineering and Technology, Ohio University, Athens, Ohio, March 1999.

APPENDIX A: Tutorial Slides

Real Time Navigation Performance

Methods of Estimation & Usage
(RNP / ANP / EPU)

Michael R Cramer
Cramer Consulting LLC

"This Tutorial was Developed by Cramer Consulting, LLC, for the Federal Aviation Administration Under Subcontract to Ohio University; it is the Joint Intellectual Property of Cramer Consulting, LLC, the Federal Aviation Administration, and Ohio University."

Syllabus

- **Part I - Evolution of performance based navigation (PBN)**
  - **A brief overview of how the concepts of relative navigation are changed by performance based navigation**
- **Part II - Performance based operations**
  - **Extends the previous section by showing how the navigation performance concepts affect airspace design methodology in relative and PBN systems**

Syllabus

- **Part III - Real-time estimation of ANP**
  - **Qualitatively explain the elements & concepts needed to derive ANP (EPU) from known and assumed information**
  - **Describe the different methods that are used to compute ANP for use in aircraft operations**
- **Part IV - Validation of performance estimates**
  - **Describe how ANP estimation methods are verified during design, and validated from limited sampling during integration & flight test**

Syllabus

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- Part V - Applicability of ANP (EPU) for flight check
  - How and when a particular system's ANP might be used in flight checking
  - How that might (or might not) extend to other implementations and systems
  - Major participant discussion desired / expected
- Part VI - Reference documents
  - Compilation of publicly available documentation
  - Limited compilation of FAA internal documentation

Part I

Evolution of Performance Based Concepts

Relative / Area Navigation

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- Relative Navigation
  - Point to point guidance for pilot
  - Geographic location not available or necessary in the aircraft
  - Depends on ground & airborne equipment pairs
    - VOR station (ground) & VOR receiver (aircraft)
    - NDB (ground) & ADF (aircraft)
- Area Navigation
  - Geographic location computed & known
    - Specific ground track guidance for the pilot
  - Can depend on multiple sources for positioning
    - Database of navigation aids required; e.g. ephemeris

Navigation Equipment

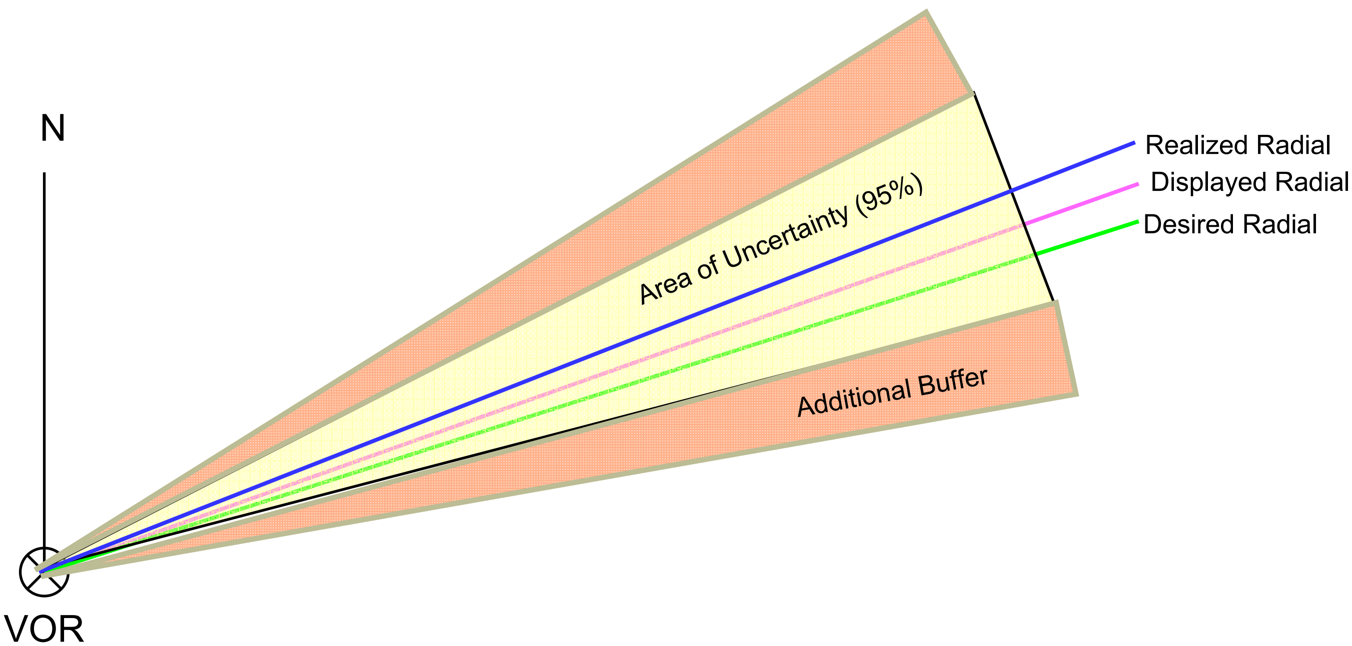
- Relative Navigation
  - Ground station broadcasting or responding
    - Non-directional signal (ADF/NDB)
    - Directional signal (VOR, TACAN)
    - Signal on demand (DME)
  - Airborne receiver interprets relative to station (direction to OR direction to radial OR distance to)
- Area Navigation
  - Combines relative information with database navaid location and barometric altitude
  - Formulates geographic location and track for the aircraft

Federal Aviation Administration

Performance Description Relative Navigation - VOR

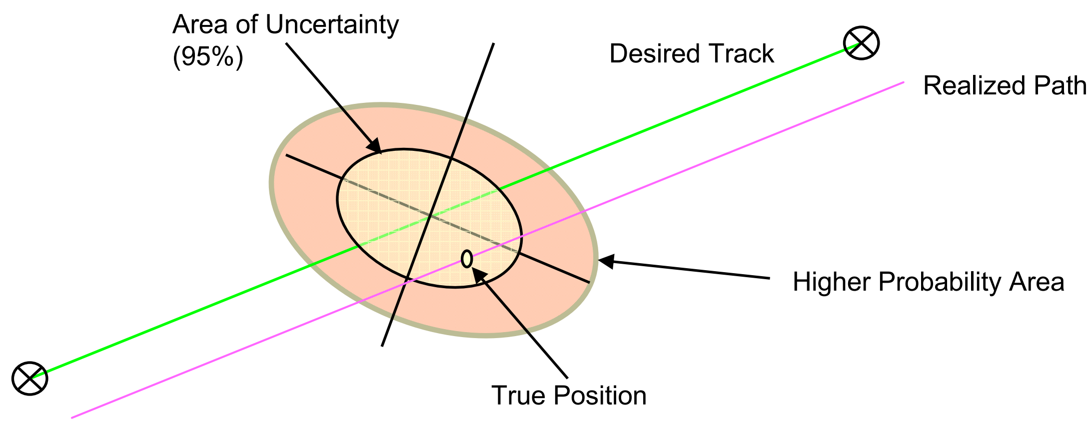
Avionics Engineering Center Ohio University, Athens

- Errors in received radials show an
  - angle bias, display vs. desired (varies with direction to the station)
  - noise component, display vs. realized
- Spatial uncertainty increases with distance along the flown radial since the errors are angles relative to path
  - Fixed orientation relative to path
  - Realized radial is probabilistic, as shown
- Higher probability areas can be defined if necessary for safety or other reasons



Performance Description
Area Navigation - General

- **Area of uncertainty containing true position is centered on estimated position**
  - **No constant orientation relative to track**
  - **Shape a function of the sensor mix and locations of navaids**
  - **Unlikely to be biased due to sensor mixing (zero mean)**
    - **Database errors may introduce a local transient bias if undetected**
  - **Higher probability area can be defined as needed**



Performance Descriptions

- Both relative and area systems have three other performance parameters that affect usage:
  - Continuity = detected failure rate of the system (normal operation, probability of loss of function per hour)
  - Integrity = undetected failure rate of the system (normal operation, probability misleading information per hour)
  - Availability = amount of time the system is useable when called upon (non-airborne infrastructure unavailable)
- These measures are typically assessed independently of the accuracy by other means
  - Safety analysis
  - Failure mode & effects analysis
  - Service history & validation

Airspace Design – Relative Model

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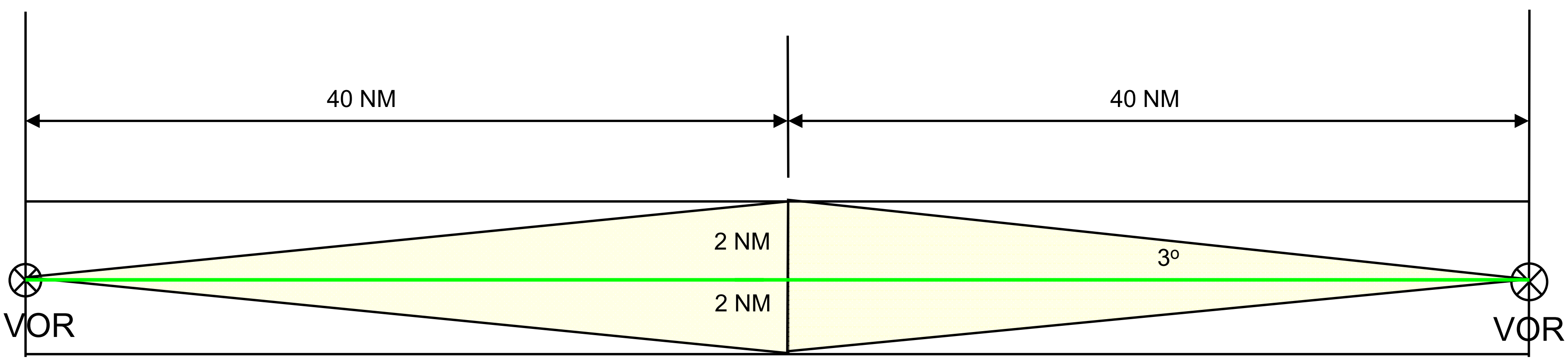
- Design criteria directly model the equipment (air & ground)
- Airway & procedure design boundary models the equipment performance & is not scalable to fit airspace
- Airspace needs / requirements met by navaid placement, i.e., sizes of areas cannot change with desired application
- Assuming VORs have a 95% angle error (with bias) of 3°
  - At 40 NM, the lateral uncertainty is 2 NM, so airways might be 4 NM wide with VORs no more than 80 NM apart



Airspace Design – RNAV Model

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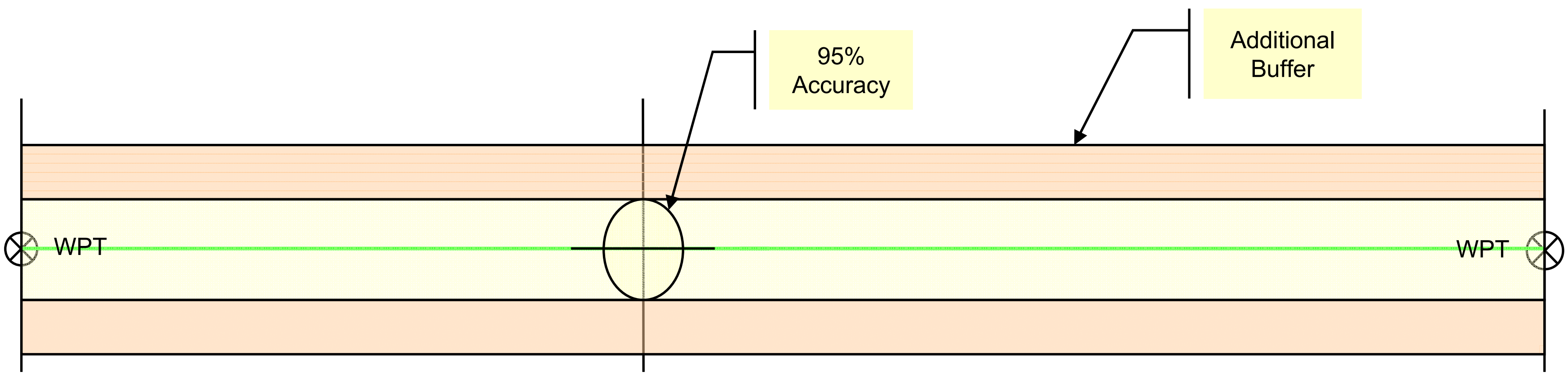
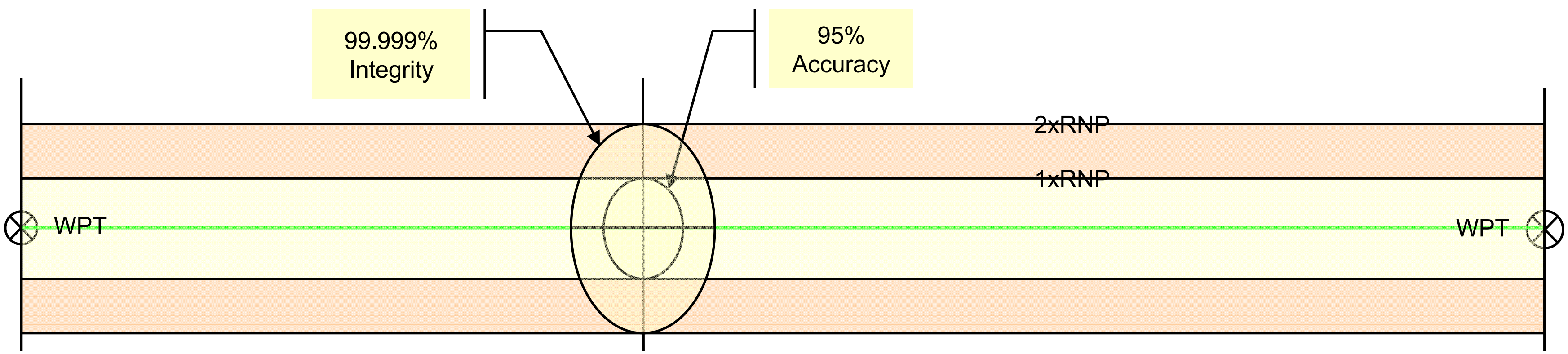
- The model changes from strictly sensor based to one based on <u>assumed sets</u> of sensors (e.g., D/D or D/V, LORAN)
- Assumptions of how signals are combined to do RNAV are made, setting accuracy requirements, size is not scalable
- Sustainable accuracies by flight phase are fixed based on these sets and are related to criteria (e.g., 0.5 NM terminal)
- Path can be fixed to arbitrary geographic points, not necessarily navaids



Airspace Design - RNP Model

- **In this model, a scalable size parameter called the <u>RNP value</u> 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 operational considerations**
  - **Importantly, this choice also sets the required integrity and continuity performance that the airplane must meet**
  - **Airspace <u>design</u> is thus not dependent on sensors**
  - **However, <u>operational approval</u> will have that dependency**



System Operation & Performance

- Relative Systems (Single sensor)
  - Accuracy – implicit, unmonitored by avionics
  - Integrity, Continuity – implicit, evaluated during certification
  - Availability – dependent on reliability of facility
- RNAV & RNP Systems (Multi-sensor)
  - Accuracy – implicit based on sensor sets for RNAV, airborne monitoring for RNP compliance using ANP
  - Integrity / Continuity – same as accuracy
  - Availability – dependent on system analysis of all possible sensor mixes

Part II

Performance Based Operations

Path Definition

- Elements of an RNAV path
  - Minimum but sufficient set (DO-236B RNP/RNAV)
    - Waypoints (fixes) – any latitude / longitude
    - RNP: geodesic track, fixed radius turn, hold pattern
    - Non-RNP: fix to altitude, direct to fix, course to fix
  - Extensions to replicate traditional flying techniques
    - Heading legs, other course types, intercepts
- Limitations of RNAV / RNP Path Elements
  - Turns between track legs:
    - Unspecified ground track
    - Only a worst case boundary is specified

Required Navigation Performance (DO-236B)

- **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**
- **In addition, 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 probability of annunciated loss of RNP capability (for a given RNP type) shall be less than 10^{-4} per flight hour**

Required Navigation Performance - Design Enabler

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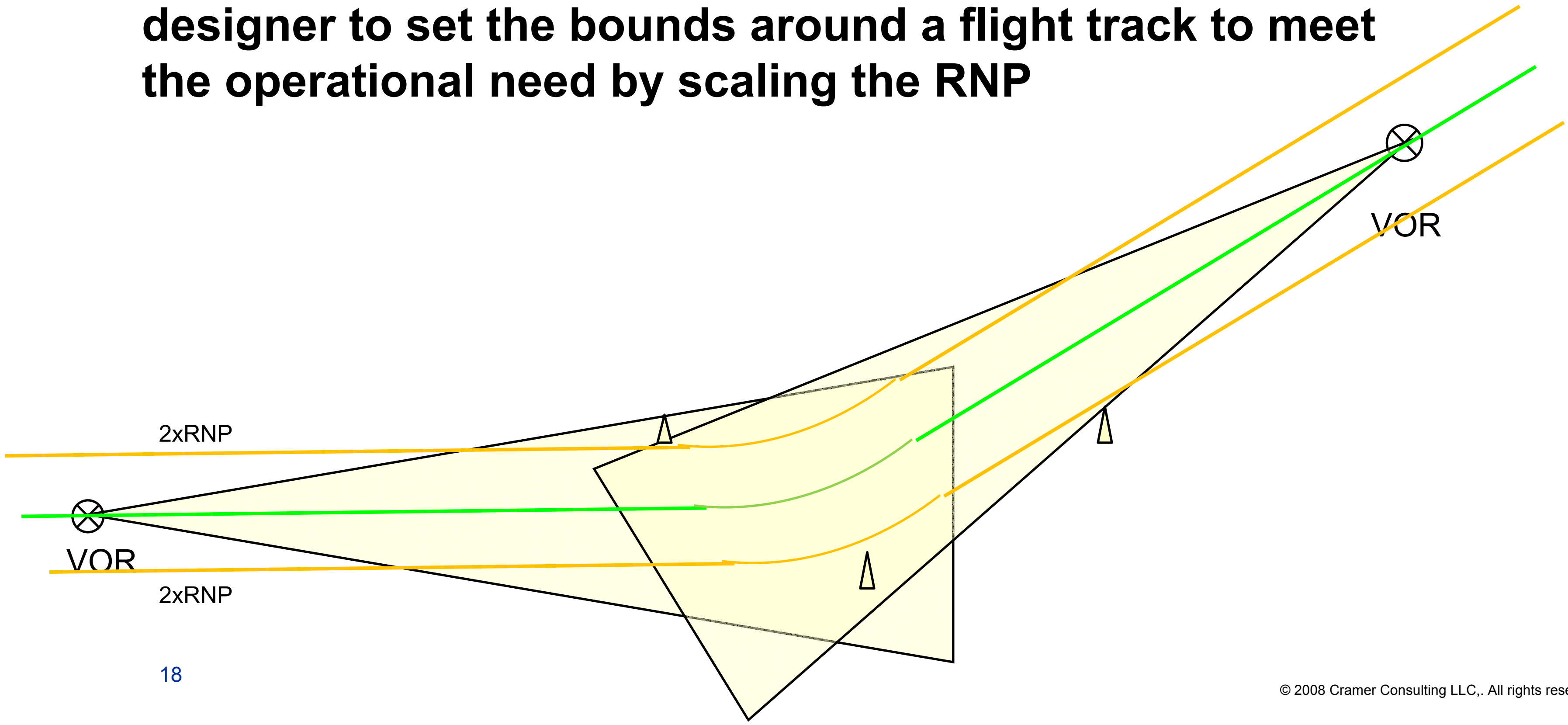
- Sensor based design has limitations on its flexibility, navaids are fixed, safe corridors are unchangeable
- But what if things are in the way?
- RNP provides a means for the airspace or procedure designer to set the bounds around a flight track to meet the operational need by scaling the RNP



Actual Navigation Performance - Compliance Monitor

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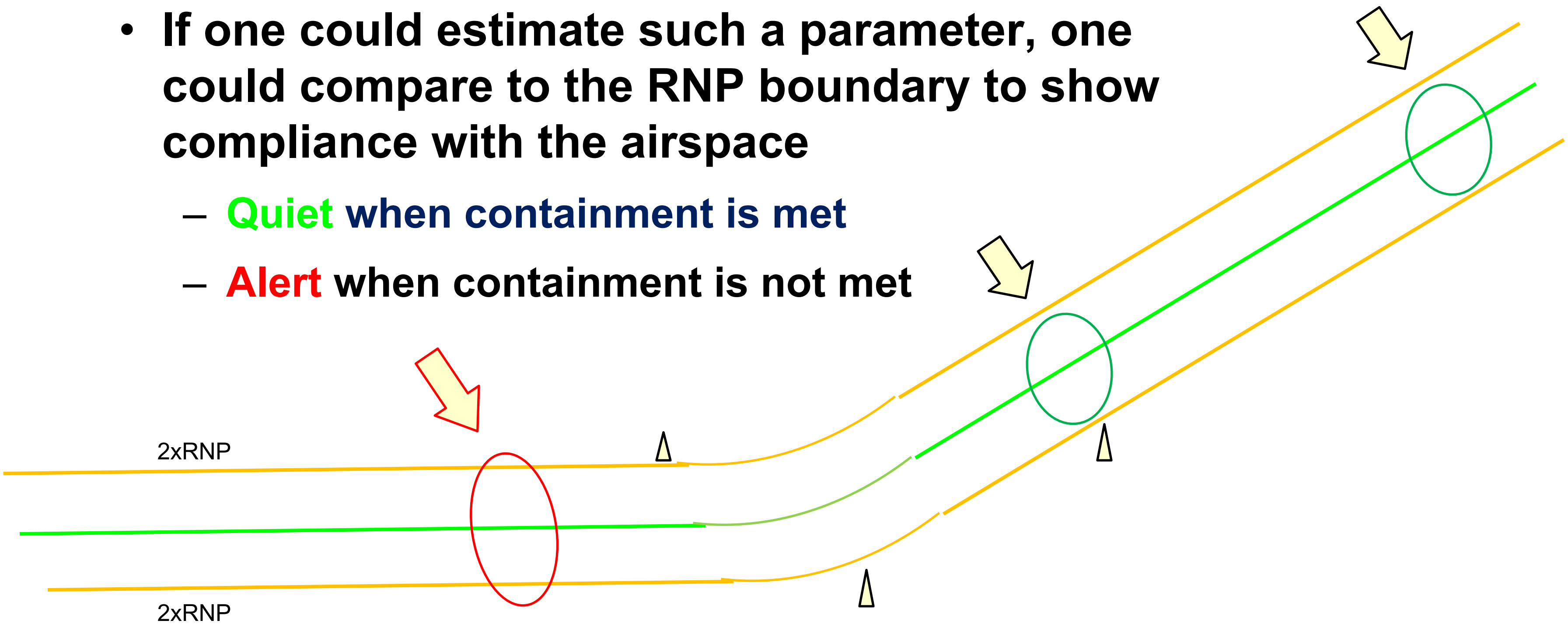
- **Think about an estimate of the achieved containment area, a statistical distribution representing the location of the true aircraft relative to the estimated position**
- **If one could estimate such a parameter, one could compare to the RNP boundary to show compliance with the airspace**
  - **Quiet when containment is met**
  - **Alert when containment is not met**



Actual Navigation Performance – Factors to Consider

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- RNP has made the procedure / airspace design scalable and sensor independent
- The achieved positioning performance depends
  - On navigation sensors and their true performance
  - On the methods used in combining sensor data to produce system position
  - On the assumptions & constraints made in method
- But, this true performance cannot be directly measured, so, it must be estimated (ANP / EPU)
  - This means that however the estimate of the true performance is made, its correctness must be assessed or demonstrated in some manner

Part III

Estimation of Navigation Performance

Overview

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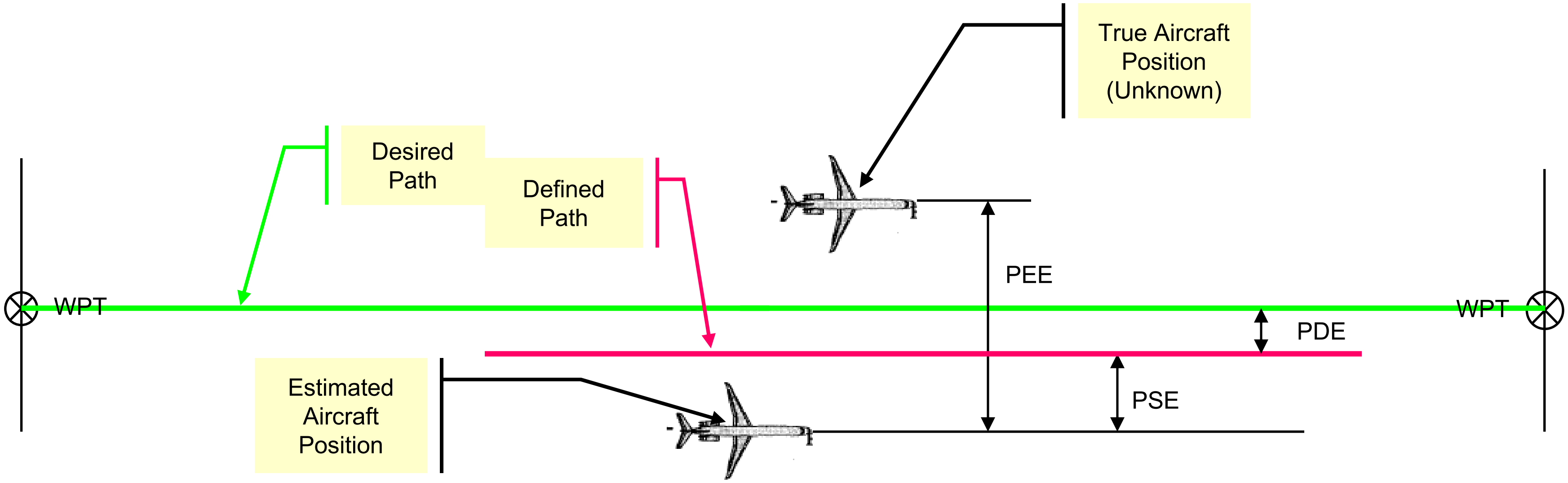
- The purpose of this part of the course is to lead the students to an understanding of how and why ANP estimates differ between systems by:
  - Defining navigation errors and error statistics
  - Reviewing airborne assessment and alerting requirements
  - Presenting the methods of position fixing and area navigation currently available in systems
  - Describing error models for various sensors
  - Explaining different techniques of data screening
  - Showing how the methods of fixing and navigation together with the sensor error models affect ANP

Part III Section A

Definitions of Performance Parameters

Lateral Total System Error

- **DO-236B defines lateral TSE as the sum of three parts representing the true position of the aircraft relative to the desired position on the path; TSE = PDE + PSE + PEE**
  - **PDE = distance from desired path to defined (computed) path**
  - **PSE = distance from estimated position to defined path**
  - **PEE = distance from true position to estimated position**



Estimate of Position Uncertainty (EPU)

- **DO-236B requires that an RNP system provide an estimate of navigation performance, called EPU**
  - **Note that in the requirement text, there is no specified statistical level associated with EPU**
    - EPU is a measure based on a defined scale, in nautical miles, which conveys the current position estimation performance
  - **There is a requirement that such a measure be available continuously in flight**
    - 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.

"Actual" Navigation Performance (ANP)

- **The initial (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**
  - **Comparison of the two values (RNP to ANP) provided an indirect measure of compliance**

ANP Defined as R_{95}

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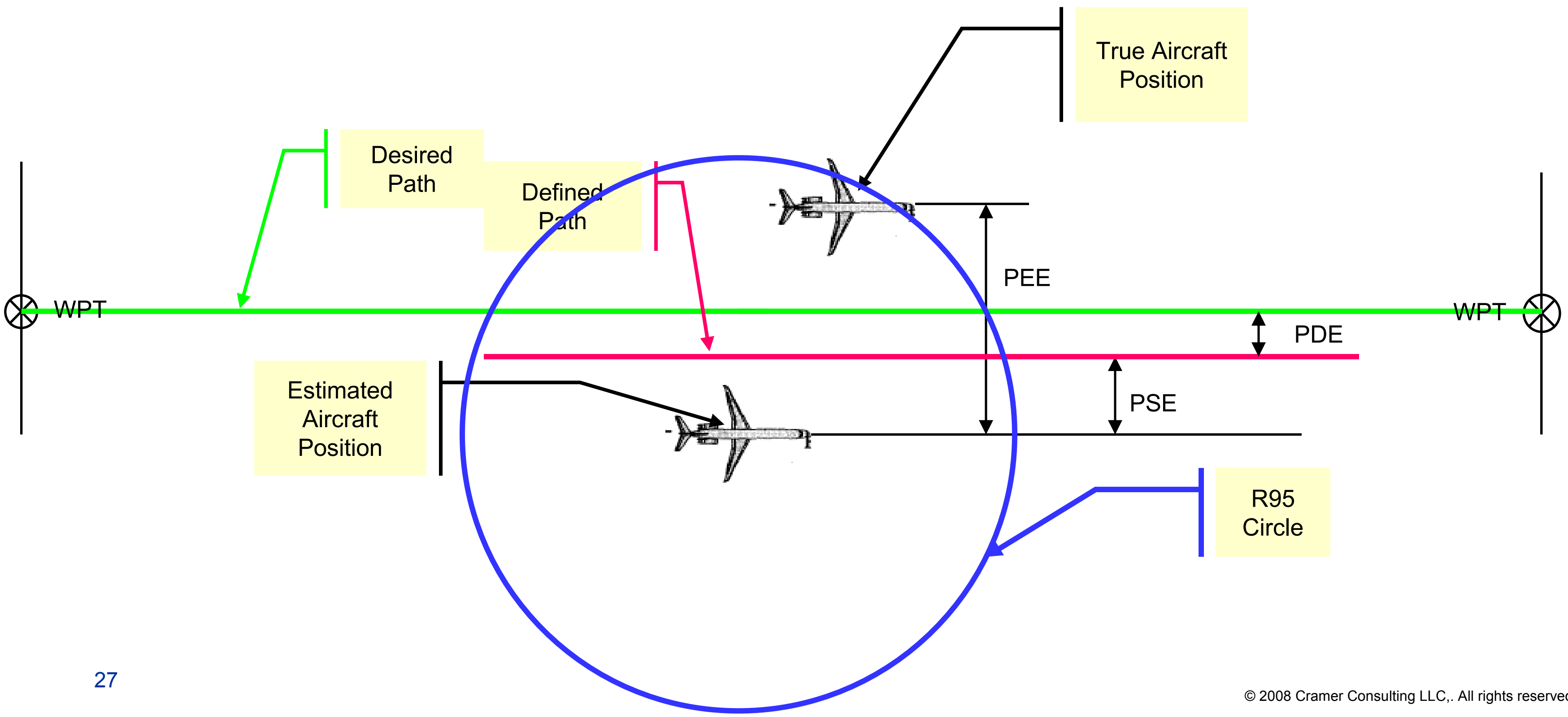
- **Provides a statistical bound for unknown PEE**
- **A real-time estimate of a 2-D boundary**
- **Probability of true being inside the circle is 95%**



Monitoring Compliance

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- The requirements on total system error (TSE) in DO-236() are stated relative to the RNP value
  - 95% accuracy (along and cross track) < RNP value
  - 99.999% integrity (cross track) < 2xRNP value
- The significance of this is that both ANP and EPU as designed as statistical bounds on position estimation error, not total system error
  - ANP (EPU) do 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

Part III
Section B

Navigation & Position Estimation Methods

Inertial Systems

- Directly sense accelerations, both linear and rotationally induced (angular rate)
  - Three axis set of accelerometers measure linear
  - Three axis set of gyroscopic (laser or mechanical) sense rotation rate
  - Redundant axes sometimes provided for reliability
- Given linear acceleration and rotational rates, equations of motion can provide velocity, spatial orientation and position of the computational coordinate system
  - Position initialization and coordinate axis alignment are crucial
- The computational coordinate system is related to the body axes of the aircraft, providing
  - Pitch, yaw and roll
  - North / east / down velocity
  - Latitude / longitude / inertial altitude

2D Position Fixing

- There are four primary methods of estimating position (latitude / longitude) using geometric measures relative to a known location:
  - Range / bearing from a single known location
  - Range / range from two known locations
  - Multi-ranges from three or more known locations
  - Bearing / bearing from two known locations
- Examples in use today are:
  - VOR/DME or TACAN
  - DME/DME, multi-DME or multi-satellite (GPS)
  - VOR/VOR (only in some military systems)

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Range / Bearing Method

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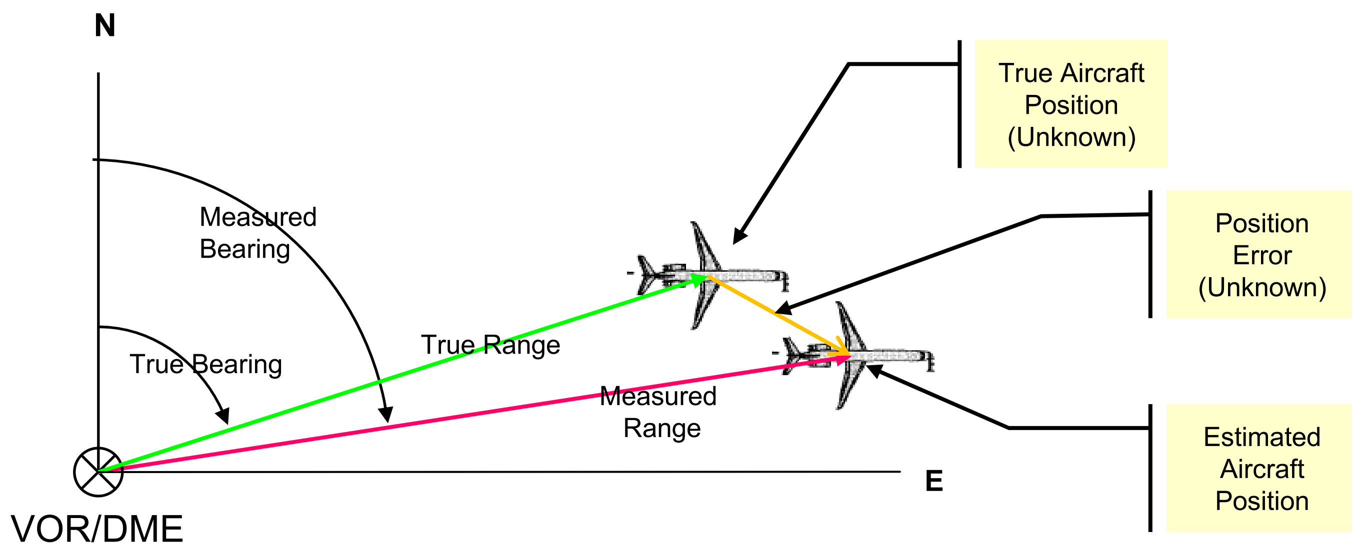
- **Diagram illustrates simplified method (flat earth)**
  - **True aircraft position has range and bearing shown**
  - **Position relative to VOR depends on measured values, which have errors**
  - **Measured range and bearing converted to a relative location (N,E) as shown**
  - **Estimated position is derived by combining location of station with the N,E offset**
  - **Position error, which is unknown, is the result of measurement errors which must be quantified to estimate navigation performance**
  - **ANP will be based on characterizing the position error statistically**



$$N_{EST} = R_m \cos\varphi_m$$
$$E_{EST} = R_m \sin\varphi_m$$

Range / Range Method

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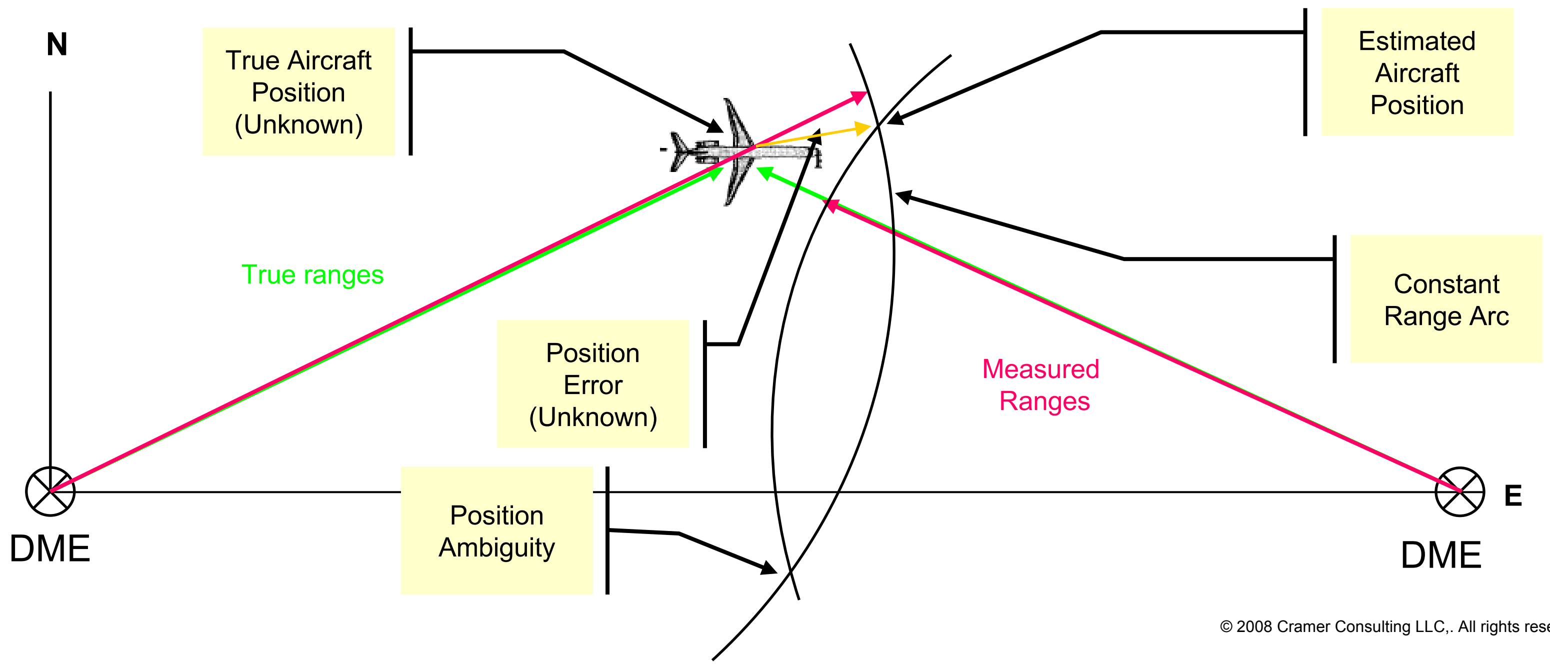
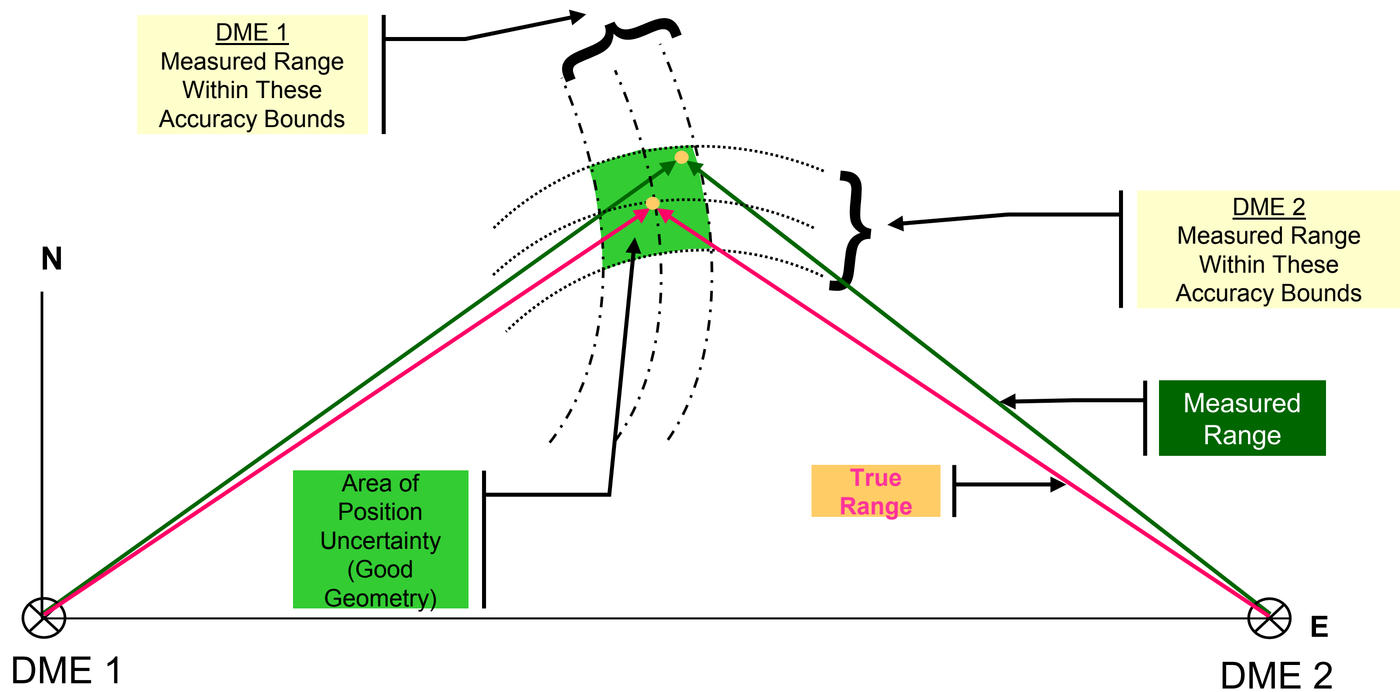
- **Diagram illustrates simplified method (flat earth)**
  - **True aircraft position has ranges whose circles are tangent (1 point)**
  - **Estimate of position depends on <u>measured</u> values, which have error**
  - **Measured ranges converted to intersecting arcs as shown, estimated position is at the intersection of the arcs**
  - **Position error, which is unknown, is the result of measurement errors which must be quantified**
  - **Note that this example shows a second possible estimate of position off the bottom where the arcs intersect again**



Range / Range Method

- **This diagram illustrates one way of looking at uncertainty**
  - **Each measured range has a statistical uncertainty associated with it**
  - **Applying the range uncertainty to measured range generates two more arcs associated with each measurement**
  - **The area of intersection is a region around the estimated position with a definable probability of containing the true position**

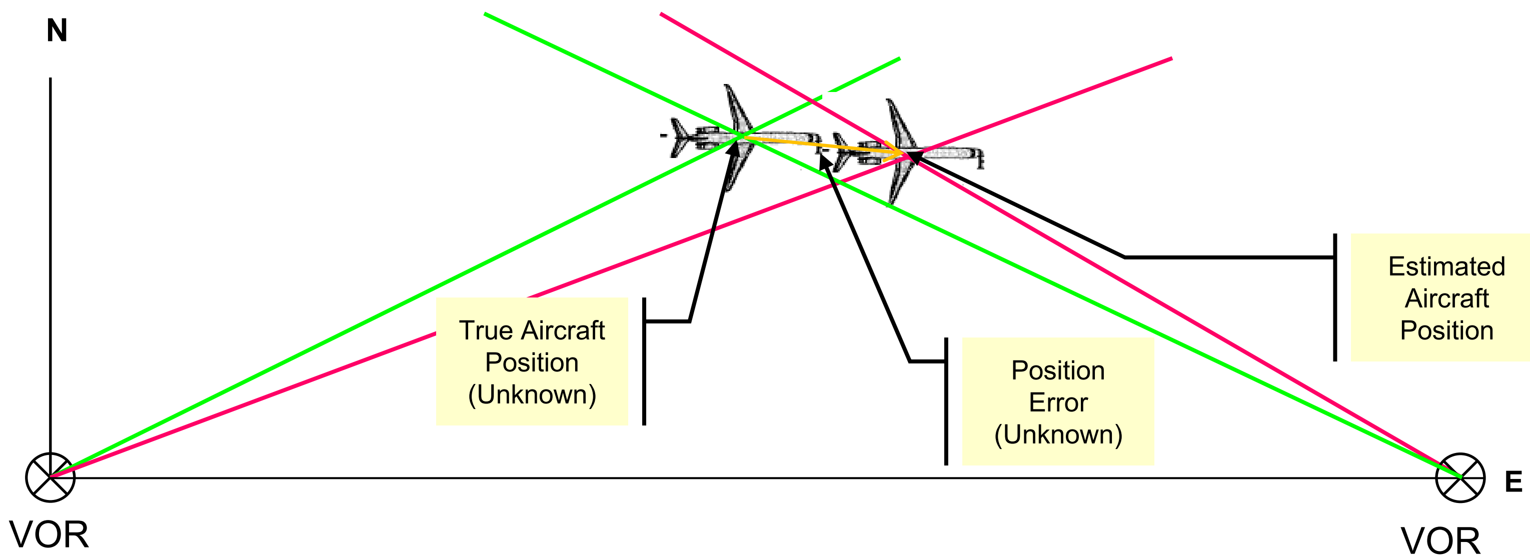


Multi-Range Method

- **This is an extension of range / range method**
- **Where the range / range method has either zero or two solutions, multi-range has more dimensions which affords an over determined solution**
- **A least squares method of minimizing residuals from the last known position can be applied to resolve the ambiguity**
- **Typically this method provides a better estimate of position due to the extra data being considered**
  - **Statistically it will have smaller variance**

Bearing / Bearing Method

- **Diagram illustrates simplified method (flat earth)**
  - **True bearing lines to the aircraft intersect at the aircraft true position**
  - **Estimated position depends on <u>measured</u> values, which have errors**
  - **Estimated position is derived by finding the intersection of the measured bearing lines**
  - **Position error, which is unknown, is the result of measurement errors which must be quantified to estimate navigation performance**



One Dimensional Methods

- It is possible to gain some information on position using single measurements
  - A single range or bearing when combined with estimated position and a dynamic model can be used to correct error in one direction
  - Simplest version of this technique is to assume no error in the orthogonal direction
    - For range measurement, assume estimated bearing is correct and adjust estimated range
    - For bearing measurement, assume estimated range is correct and adjust estimated bearing
  - If one has a dynamic model for the aircraft motion, those estimates can be used to compute a correlation between the orthogonal directions and improve the estimate

Sensor Use Limitations

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- **There are four main areas from which limitations on sensor usage must be derived:**
  - **Physical; sensor error characteristics & geometric relationships (these limits are a priori)**
    - **E.g., "crossing angle limits" for range / range**
  - **Comparative; redundant comparison of independent sources (this happens in flight)**
    - **E.g., "RAIM" method for multi-range (GPS or DME)**
  - **Procedural; flight rules, NOTAMs, etc**
    - **E.g., using the procedure navaid for a VOR approach**
  - **Experience; map shifts, in-flight navigation errors**
    - **E.g., particular sorts of database errors**

Navigation Methods - 1

- Primary function of an area navigation system is to provide an estimate of vehicle position (latitude & longitude) and velocity (north & east)
- Position fixing methods previously described can be used singly or together to provide navigation
- The two basic methods can be categorized as
  - Mode based (using one type of fixing at a time)
  - Measurement based (blending position fixing types)
- Both types require a mathematical model of the expected vehicle dynamics to smooth data

Navigation Methods - 2

- Mode based systems will navigate in only one position fixing mode at a time; they will contain
  - A model of vehicle motion providing an estimate of current state (p, v)
  - A computation of position based on the fixing method e.g., range / bearing
  - A method of updating the state model based on each position fix
  - A method of estimating navigation uncertainty based on sensor models and the state model
  - As the position fixing mode changes, so do all the above computations, requiring reinitialization

Navigation Methods - 3

- **Measurement based methods are typically in Kalman filter form, two types exist:**
  - **"Whole state" filter (direct estimation of position, velocity)**
  - **"Error state" filter (estimation of navigation errors which are then applied to correct a reference)**
- **Kalman filtering optimizes the statistical performance of the navigation estimates**
  - **Provides a direct output of state error statistics**
  - **Provides a method of statistical data screening that combines the a priori sensor model with current state model**

Dual Navigation Methods

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- Navigation systems are often installed in pairs; the method in which they operate affects position estimation error which in turn affects ANP
- Systems can be totally independent of one another; navigation error will be a function of the system in use only
- Systems can trade information at some level; navigation error will be a function of the method and extent of the combination of data
- Much more on this during discussion of the computation of ANP

Part III
Section C

Sensor Characteristics

Why are Error Models Important?

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- Navigation estimates of position and velocity are based on the methods shown earlier
  - These methods each depend on a set of measurements from navigation sensors, sensor errors result in position errors
  - Sensor errors and the resulting position errors are UNKNOWN to the navigation system
- For us to compute a real time bound on these errors (ANP), we need models of the sensors
  - These models are <u>assumed</u> in the navigation
  - They are based on real world tests and are statistical
  - They are combined based on the position fixing method
- A priori assumed values will be surveyed in the ANP part

Inertial Systems

- Error modeling for inertial systems ranges from the very simple to very complex
  - An IRS drift model simply says that a velocity error exists and that it is constant, resulting in a position error over time
  - An IRS sensor based model may model up to 40 acceleration and rotation rate sensor errors
  - The navigation error model is typically a discrete time state space model
    - $x_n = \Phi x_{n-1}$
    - For the simple drift model for instance
      - $x = \{\Delta N, \Delta E, \Delta V_N, \Delta V_E\}$

$$\Phi = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Inertial Systems – cont'd

- For the more complex models, a standard in use is a 7-state error model
  - States are two position errors, two velocity errors and three misalignment errors
  - This model can generate the Schuler and the 24 hour cyclical behavior in the IRS errors, as opposed to the "drift" of the simple model
  - Sensor errors (gyro and accelerometer errors) are handled by added uncertainty of process noise

Ranging Measurements

- **GPS satellites and DME stations (with their respective receivers) provide ranges which can be used in position fixing**
- **DME range error models typically have:**
  - **A Gaussian component with zero mean - $N(0,\sigma_r)$**
  - **An unknown correlated noise or a range dependent bias**
  - **There are standard models in RTCA docs**
- **GPS range error models are typically handled in the receivers resulting in both position estimates & related 2D (or 3D) uncertainty estimates**
  - **These combine satellite geometry and range errors**
  - **HFOM and HIL are ANP-like 2D statistics related to probability of position error exceeding them**

Bearing Measurements (VOR)

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- VORs and TACANs with their airborne receivers provide a bearing relative to the station
- The errors in the received signal are typically modeled as having
  - A "noise" component on the true bearing, usually a zero mean Gaussian error – $N(0,\sigma_B)$
  - A correlated noise component representing the uncertainty caused by "scalloping" of the signal as one orbits the station
  - Values have been assumed in various RTCA and FAA documents, experimental data supports others as well

Localizer Deviation

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- Some navigation systems will utilize localizer deviation received from a localizer associated with the approach being flown
- Generally, the deviation is mathematically converted to and used like a VOR bearing measurement
- Error model is typically a white noise on the bearing, Gaussian zero mean with a priori standard deviation based on localizer DDMs

Part III
Section D

Data Rejection / Screening

Relationship to ANP

- Data screening is essential to meeting navigation performance requirements
- The assumed error models for sensors provide both a way to screen data and a way to estimate performance, i.e., ANP
- There are two main ways to prevent corrupted navigation results due to “bad” data:
  - Statistical tests on individual measurements, so called “reasonableness” tests
  - Statistical tests using many measurements
    - Comparison of redundant similar data, e.g., ranges
    - Comparison of redundant dissimilar data, e.g., IRS and GPS

Reasonableness Tests

- This type of screening is used on individual measurements, such as a range or a bearing
- The sensor error model statistics are used with a prediction of the measurement value to test
- A common limit is two standard deviations
- For instance, the DME range error model says that the range error is a $N(0,\sigma_R)$ random variable
- A "reasonableness" test would:
  - Compute a predicted range for the time sample
  - Compare predicted to measured range by differencing
  - If the difference is > 2 σ_R reject the measured range

Comparison Tests – Redundant Data

- When one has more measurements than necessary to solve for all unknowns, one has redundant data
- Use of an over-determined set of data is exemplified by the RAIM technique used in GPS (also applied to multiple DME ranges in B737 FMS)
  - With redundant data, subsets can be used to estimate position
  - The range error models can be used to estimate uncertainty in each subset position
  - The subset positions are compared to each other by computing differences
  - The differences are compared to the statistical predictions
    - If the differences are statistically “close”, it is inferred that no “bad” data are included
    - If one subset results in a position statistically “far” from the rest, it is inferred that it eliminated a “bad” range

Comparison Tests – Different Sensors

- When a aircraft is equipped with multiple means of navigation, integrated or not, comparisons can be made among them to provide detection
- IRS, GPS and FMS all produce navigation position and velocity in geographic coordinates
  - FMS can produce geographic location based on raw radio data (range/range or range/bearing)
  - Cross comparison of these positions vs airspace rules (RNP) gives an indication of nav error
  - Velocity comparisons can capture IRS drifts as well as erroneous shifts (steps) in GPS
- The primary purpose is to deselect systems when a fault is detected

Part III
Section E

Recovery from Corrupted Estimates

Navigation Integrity

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- To provide integrity, i.e., a low level of undetected error, multi-sensor cross checks are essential
- These checks, combined with either automatic or pilot controlled selection / deselection of systems, help bound probable error
- Assurance of navigation integrity is what provides reliable ANP with its usefulness for warnings of non-compliant navigation
- The next two charts summarize two of these techniques used in one advanced system

Example Crew Overrides

- Warnings can be provided by multiple sensor comparisons:
  - IRS to IRS
  - IRS to FMS
  - FMS to GPS
  - FMS to radio
  - FMS to FMS (dual system)
- Data provided on MAP and CDU showing relative locations of each position used for compares
- Crew can select or deselect individual navaids or updating sources (GPS, VOR, DME) (some systems)
- Crew can re-initialize by controlling single / dual

Automatic Overrides

- **Velocity comparisons between IRSs and FMS can allow deselection of a drifting IRS or re-initialize the FMS navigation**
- **Velocity comparison between IRS and GPS can detect "steps" in GPS and automatically drop it**
- **DME RAIM can detect corrupted navigation as well as bad ranges and re-initialize navigation**
  - **standard reasonableness tests cannot do this**

Part III
Section F

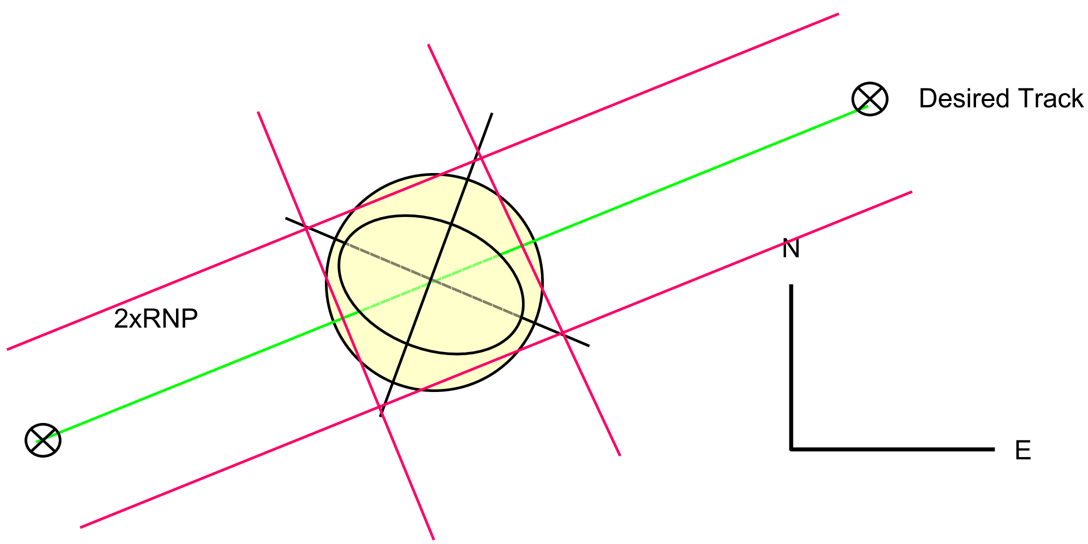
Computation of ANP (EPU)

ANP (EPU)

- Referring back to the “open” definition in DO-236()
  - Must be based on a “defined” scale
  - Must convey current position estimation performance
  - No further specification is made
- The “open” definition above leaves much to the choices made during implementation of various systems
- The next few slides will
  - Examine differing 2-D accuracy measures, then
  - Examine difference in the computational characteristics between navigation mode based and blended measurement methods
- Important to note is that for most navigation systems, the performance statistics are Gaussian (normal)

General 2-D Problem

- **The methods of position estimation presented result in generally elliptical error distributions whose principal axes are not aligned with either track or N-E coordinate frame**
- **The DO-236 requirements are individually applied to the along track and cross track errors**
- **This leads to the use of circular regions of constant probability (ANPs or EPUs) for comparison to RNP values**



Simple Performance Measures

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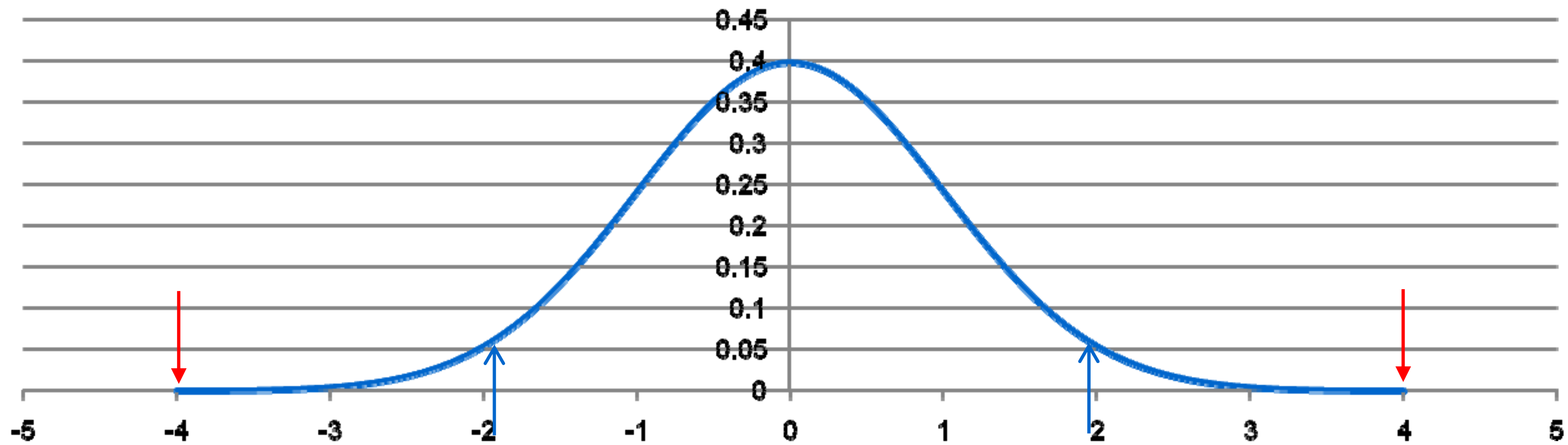
- **Most accuracy measures of statistical parameters are expressed as 95% probability numbers**
  - **For any type of distribution, the parameter can be related to the probability level**
- **For a 1-D Gaussian distribution, there is a 95% probability that the parameter value will be bounded by plus/minus 1.96 standard deviations**
  - **The graphic below has a standard deviation of 1 to illustrate the concept**
  - **Probability is 95% between +/- 1.96σ**
  - **Probability is 99.9% between +/- 4σ**



2-D Performance Measures

- For 2-D distribution, complexities arise even if the distribution is Gaussian in both directions
- Common circular measures of performance are:
  - 2-drms – twice the "distance root-mean-squared"
  - R_{95} - radius of a circle equal to 95% probability
  - CEP – radius of a circle equal to 50% probability

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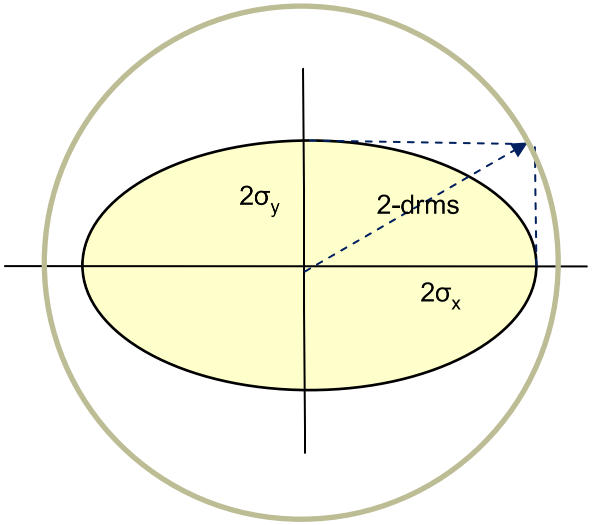
Distance Root-mean-squared

- Begins with the basic 2σ error ellipse (P = 0.86)
- Simply calculated as the RMS value for the two axes of the ellipse: $2drms = [(2\sigma_x)^2 + (2\sigma_y)^2]^{1/2}$
- Probability value in the circle depends on the ratio σ_y/σ_x as shown in the table
- This is the basis for "DOPs" used in GPS systems

σ_y/σ_x	P
0	0.954
0.5	0.969
1.0	0.982



95% Probability Circle (R_{95})

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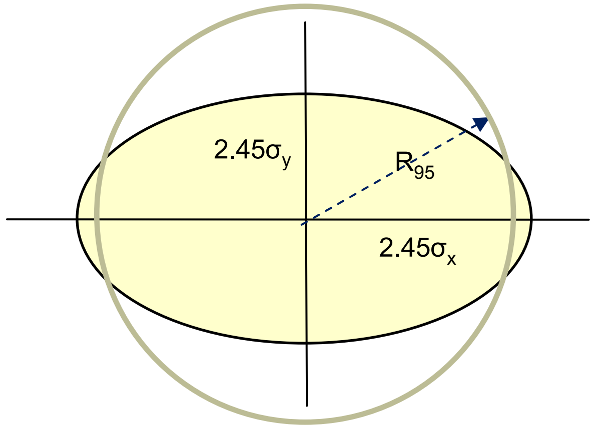
- Again, begins with the basic error ellipse (shown for comparison is the 95% ellipse)
- Complex calculations result in the radii shown based on ratio of σ_y/σ_x
- For all σ_y/σ_x the probability in the circle is 95%
- For low values of the ratio, parts of the 95% ellipse can be outside the circle

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



Comparing R_{95} to 2-drms

- From the tables, it can be seen that 2-drms is always larger than R_{95}
  - The 2-drms circle ranges from 95.4% to 98.2% probability of containing the true position
  - R_{95} is always equivalent to 95% probability
- At the limiting cases we have the following:
  - For $\sigma_y/\sigma_x = 0$, the distribution is linear
    - 2-drms = $2\ \sigma_x$ & $R_{95} = 1.96\ \sigma_x$
  - For $\sigma_y/\sigma_x = 1$, the distribution is circular
    - 2-drms = $2\sqrt{2}\ \sigma$ & $R_{95} = 2.45\ \sigma$
- These are the two most commonly used

Mode Based Systems

- Systems that navigate in unique "modes" will calculate ANP based on that mode
  - Modes are reflective of sensors in use at the time
  - GPS, DME/DME, DME/VOR, DME/ILS are examples
- When the system "switches" modes, the ANP calculations and value will change
  - ANP may be allowed to "step" to the new value
  - Assumptions may be made for a rate of change and the value will move "smoothly" to the new value
    - Measurement sample rate effect
    - Position "slewing" restrictions

Blended Measurement Systems

- Blended systems, whether whole state or error state, have a dynamic “model” of the navigation state which is a function of time
  - Measurements are used to “update” the model
  - The model carries the state forward in time in the absence of measurements
  - The state covariance matrix carries estimates of the navigation accuracy along with the state model
  - Changing sensors in the mix does not change the method of computing performance

2-D Statistics

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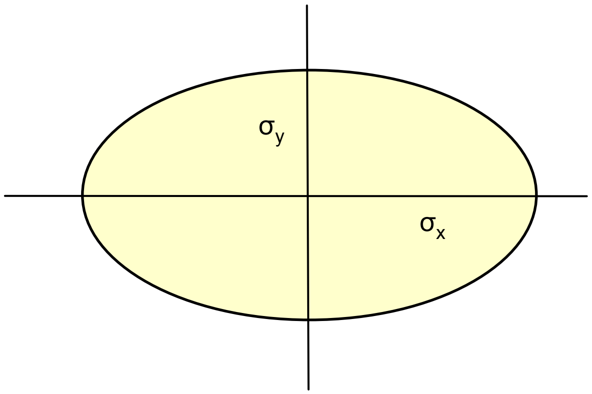
- **The performance estimate (ANP) will depend on the covariance matrix of the position errors**
- **The covariance matrix contains the dimensions of the error ellipse shown in previous discussion**
- **ANP = 2.45σ_x in one major system, since this applies to a circular distribution ($\sigma_y/\sigma_x = 1$) it is conservative for all lower ratios**
- **The conservatism provides margin for PSE**

$$P = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{yx} & \sigma_y^2 \end{bmatrix}$$



Part IV

Validation of ANP / EPU Estimates

Airborne System Models

- **Estimation of performance requires mathematical modeling of the errors inherent in a system**
- **The airborne version of the error model is an approximation of the real system errors**
- **For example, IRS error state models can be written that account for up to 40 or 50 separate errors that combine to cause observed behavior**
  - **Airborne approximations usually have many fewer states, so their performance must be assessed**
- **Remember, state space models contain estimates of errors AND their estimated statistical property**

Assessments of Performance

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- To verify that the models are performing as needed involves multiple steps, typically:
  - Simulation and analysis (computer based)
  - Laboratory testing (partial hardware based)
  - In-flight testing (flight hardware & data collection)
- Each of these methods requires some type of “truth reference” to allow assessing the performance level of the proposed system model
- For navigation, “truth” is defined as the true state of the aircraft (position, speed, etc)
- In the first two methods, truth is modeled, in the last method, it is independently measured

Simulation & Analysis

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- There are two methods commonly used to assess the validity of estimates for errors and statistics
  - Covariance analysis
  - Monte Carlo analysis
- Both methods rely on "truth" models that are more precise than the aircraft system model
- Covariance analysis directly compares the proposed aircraft model to the truth model to assess performance along a single trajectory
- Monte Carlo analysis repeats a trajectory many times with random inputs, computing ensemble statistics at each time point to assess ANP

Laboratory Tests

- Combines flight systems with computer modeled systems, is not statistical in nature
- Truth models contain the environment (wind, temp, etc.), the aircraft dynamics (engines, aero), and avionics models (sensors, non-hardware interfacing systems)
- This type of testing does not really assess the navigation system performance statistically
- It does allow one to compare navigation system performance reflected in ANP to the error between the navigation solution and the truth to check that the error is bounded by ANP

Flight Validation Testing

- Truth in the case of a flight test is more difficult
  - External, independent way of measuring aircraft state, e.g., laser tracking, radar
  - On-board system of higher fidelity than the navigation system, e.g., GPS to assess DME
    - For example, before GPS, we recorded data from all navaids in view and post processed it to provide a "truth" state, comparing to navigation system outputs
    - The comparison resulted in time based statistics, i.e., the percent of flying time the navigation error was less than some threshold
    - This allowed validation of the ANP algorithms for DME

Part V

Applicability of EPU for Flight Checking

Potential ANP Support

- Infrastructure Evaluation
  - Validate availability of signal in space by mode
    - DME/DME geometry and signal strength / blocking
    - DME/DME "gaps"
    - GPS interference
  - Validate minimum supported RNP for route design
    - ANP as a function of location along track
    - Evaluate per sensor combination (navigation mode)
    - Assess loss of facilities (ground infrastructure)
- Cross platform extrapolation
  - Use of one system requires extension to others

Infrastructure Evaluation

- **Availability evaluation**
  - **Requires assessment of system ANP relative to the RNP values used for the design**
- **Estimation of the minimum supportable RNP**
  - **Requires assessment of system ANP relative to expected variations in signal over time**
  - **Requires measuring and accounting for PSE in various steering modes (RNP requires that TSE meet RNP value 95% of flight time)**
- **Each of these depends heavily on the a priori assumptions made in the system**

Cross Platform Extrapolation

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- Once an infrastructure evaluation is made using a particular system, how does it apply to others?
  - Are the sensor error models compatible?
  - Are the data rejection techniques compatible?
    - Reasonableness tests (averages, statistics)
    - Geometric tests (DOP, x-ing angle, distance, horizon)
  - Are the operational modes compatible?
  - Is the ANP value's meaning similar or the same?
- To extend the observed performance of one system to another, the answers must be "yes"
- To date, that is not the case in the population

Flight Check Conclusions

- Given different implementations & differences in ANP / EPU conservatism, results from one system are not directly applicable to another
- For the same reasons, using one system's ANP performance to assess minimum supportable RNP across all systems probably is not valid
- Availability of infrastructure to support the procedure might be assessed, e.g., critical facilities, signal reception, etc.

Part VI

Reference Compilation

Reference Documents

Federal Aviation
Administration

Avionics Engineering Center
Ohio University, Athens

- "Two Dimensional Measures of Accuracy in Navigational Systems", (U.S.) Transportation Systems Center, Cambridge, MA; PB87-194569
- "RNP Capability of FMC Equipped 737, Generation 3", Boeing Document D6-39067-3, January 14, 2003
- "RNP Capability of FANS 1 FMCS Equipped 747-400, Gen 1", Boeing Document D926U050
- "777 RNP Navigation Capabilities, Generation 1", Boeing Document D243W018-13, August 28, 2003
- "757/767 FMCS RNP Navigation Capabilities, Gen 1", Boeing Document D926T0120-1
- No other publicly available documents are known