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I am submitting herewith a thesis written by James Robert Mires entitled "A Compliance Strategy for Use of GPS for IFR Navigation in the E-2C Hawkeye". I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

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**A Compliance Strategy
for Use of GPS for IFR Navigation
in the E-2C Hawkeye**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

James Robert Mires
May 2007

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DEDICATION

This thesis is dedicated to my loving wife Beth.
Without her patience and support, it would not have been possible.
Your thoughtful encouragement strengthens me daily.

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ABSTRACT

Naval aviation is on the brink of taking advantage of a 12 year old capability. Naval commercial derivative aircraft have had the ability to navigate in instrument meteorological conditions using global positioning technology for nearly as long as civil commercial-for-hire aircraft. However, tactical naval aircraft, like the E-2C Hawkeye, are now only beginning to obtain and install the necessary technology to meet federal aviation regulations for satellite based area navigation.

Worldwide airspace controlling agencies have mandated the use of navigation equipment that meets highly specific performance standards prior to entry in required navigation performance airspace. Aircraft not compliant with these standards are denied flight clearance or experience clearance delays. The Department of Defense has issued policy guidance that allows military aviation organizations to self-certify satellite based navigation technologies to meet required navigation performance standards.

In many ways, military navigation technologies far exceed the performance requirements for civil and international airspace use. These technologies, however, are highly specific in their mission orientation and must demonstrate their compatibility with civil aviation standards.

This study focused on the source and the specifics of navigation performance requirements. Domestic and international regulations and policies were reviewed as they pertain to civil aviation, and then applied to military aviation. Critical technical standards documents

were reviewed to determine the best strategy for complying with civil and international regulations. Lessons learned from previous E-2C navigation system evaluations were also reviewed and incorporated within this compliance strategy. Compliance and self-certification responsibilities belong to aircraft specific program managers within the Navy's acquisition organization.

Sophisticated navigation systems incorporating satellite positioning technology require a tailored approach toward compliance demonstration. Military receivers with precise positioning capability satisfy many of the required availability, accuracy and containment standards. To satisfy civil requirements, correctly keyed, military navigation systems may be evaluated according to standards typically applied to the most highly augmented standard civil systems. This thesis contains a comprehensive list of compliance items selected for their applicability to the E-2C Hawkeye mission.

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ABBREVIATIONS

AC	Advisory Circular
CJCS	Chairman of the Joint Chiefs of Staff
CNS	Communication, Navigation and Surveillance
CWI	Continuous Wave Interference
dBm	Decibel above one milliwatt
DOP	Dilution of Precision
EME	Electromagnetic Environment
EPE	Estimated Position Error
FAA	Federal Aviation Administration
FDE	Fault Detection and Exclusion
FM	Frequency Modulation
FMS	Flight Management System
FOM	Figure of Merit
FRD	Functional Requirements Document
GATM	Global Air Traffic Management
GIC	GPS Integrity Channel
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human Machine Interface
ICAO	International Civil Aeronautic Organization
IFRB	International Frequency Registration Board

IMC	Instrument Meteorological Conditions
ISHP	Indicated Shaft Horsepower
kHz	Kilohertz
MASPS	Minimum Aviation System Performance Standards
MFCDU	Multi Function Control Display Unit
MOPS	Minimum Operational Performance Standards
msec	Milliseconds
NAS	National Air Space
NAVAIR	Naval Air Systems Command
NAVSTAR	
nm	Nautical mile
PNT	Position Navigation and Timing
PPS	Precise Positioning System
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RNAV	Area Navigation
RNP	Required Navigation Performance
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime Services
SA	Selective Availability
SARP	Standards and Recommended Practices
SPS	Standard Positioning Service
STC	Supplemental Type Certificate
SV	Space Vehicle
TC	Type Certificate

TSO	Technical Standard Order
TTA	Time to alert
TTFF	Time to first fix
US	United States
U.S.C.	United States Code
VOR	Very High Frequency Omni-directional Radio Ranging
Wi-fi	Wireless fidelity

CHAPTER 1: EVOLVING AVIATION

Introduction

Despite the lengthy and considerable negative impact to the commercial airline industry following the tragic terrorist attacks on 11 September 2001, the skies are becoming more crowded. Figure 1 is an illustration of the increase in density of both airplanes and electromagnetic emissions in the radio frequency (RF) spectrum over time[2]. The 2006 Federal Aviation Administration (FAA) Aerospace Forecast states that "the number of domestic commercial aircraft is forecast to grow from 7,836 in 2005 to 10,677 in 2017, an average annual growth rate of 2.6

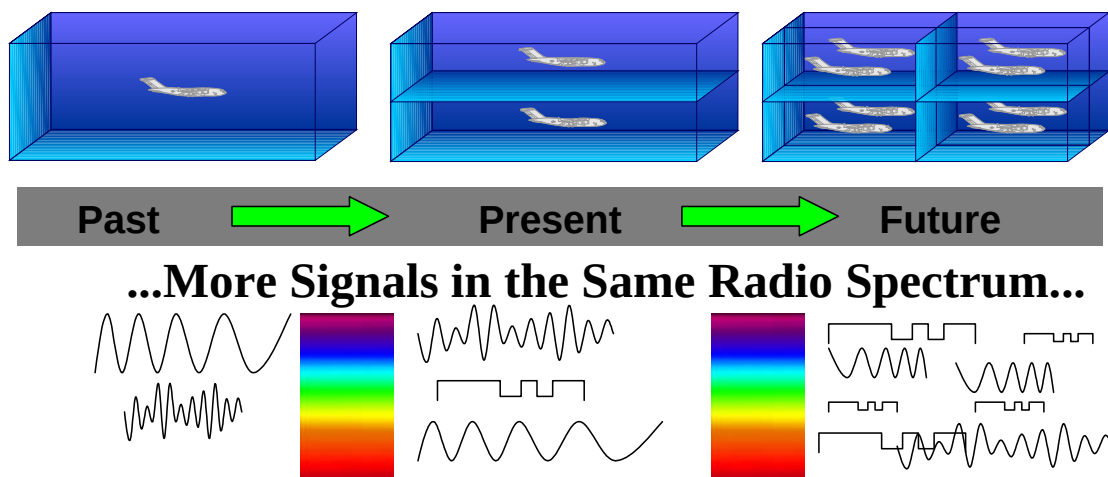


Figure 1
Illustration of Increase in Air Traffic
and Radio Frequency Congestion

Source: <http://pma209.navair.navy.mil/teams/navigation/cnsatm/challenges.asp>
30 Nov 2006

percent or 237 aircraft annually"[3]. Total enplanements are forecast to increase by 68 percent by 2020[4].

Technologies have been developed to accommodate the increase in aircraft and signal density. These technologies must be integrated in Navy aircraft whose capabilities must conform to global requirements, which are increasing as available airspace continues to shrink.

The airwaves are also becoming more congested with RF signals. The aerospace industry must compete with booming industries in technologies such as cellular phones and wi-fi. What was once an allocated and assigned "spectrum", has become a dynamic multifaceted commodity. Ownership of a piece of the spectrum has given way to spread-spectrum technology in which spectrum-sharing and dynamically allocated frequency assignments have become the norm. The sophisticated parceling of RF signals requires a sophisticated response for aviation applications.

Global Positioning Systems (GPS) have demonstrated reliable and consistent receipt of signals use in instrument meteorological conditions (IMC). IMC is a condition in which a pilot of an aircraft does not have external visual reference to the earth's horizon or the airspace around him. Military applications require

reliable and consistent receipt while in foreign, specially tailored or special use airspace. Accurate and reliable navigational systems allow for safe operation of multiple aircraft within a given airspace, without visual contact between them or the ground. It also help keeps aircraft within a tightly bound region.

A Global Approach to Crowded Skies

To address such a complex and dynamic problem, the FAA and the International Civil Aerospace Organization (ICAO) recognized the need to draw upon the expertise of multiple sources within the aerospace industry to recommend viable and affordable solutions. Teamed with the RTCA, formerly the Radio Technical Commission for Aeronautics, recommendations were outlined to develop a performance-based global air traffic management (GATM) system. RTCA is a not-for-profit corporation made up of a widely varied group of avionics and aerospace-industry partners. It was founded to advance the art of aviation and aviation electronic systems for public benefit. It serves as a Federal Advisory Committee to develop consensus-based recommendations concerning contemporary aviation issues[5]. The FAA relies heavily on RTCA recommendations in all of its standard technical requirements. A proposed

performance-based system is composed of measurable safety and security parameters. The ultimate goal is to achieve a verifiable air traffic capacity and navigation performance efficiency, the foundations of a performance-based navigation system.

The underpinning of GATM is the concept of a Global Navigation Satellite System (GNSS). A GNSS provides worldwide positioning and time information in all weather and to an unlimited number of users. It is composed of orbiting satellite constellations, earth-based receivers, and system integrity monitoring stations. GNSS is the foundational solution to accurate and reliable global positioning, navigation and timing (PNT).

Two satellite systems have obtained certification from the International Frequency Registration Board (IFRB): NAVSTAR GPS, developed by the United States (US), and Global Orbiting Navigation Satellite System (GLONASS), currently operated by Russia[6]. Also, the European Union and European Space Agency have announced plans to launch a space-based PNT system called Galileo.

The US NAVSTAR system consists of three major elements, referred to as segments: the space segment, the control segment and the user segment. The space segment is



Figure 2
GPS Constellation

Source: National Spaced Based PNT, Executive Committee Website

currently a constellation of 30 satellites, depicted in figure 2. They are grouped in 6 orbital planes at near-stationary orbit 11,000 miles above the earth. These satellites transmit complex signals to a receiving system, the "user segment". The receiving system performs computations to determine the receiver's position relative to an accepted, world-wide coordinate system, currently the World Geodetic System 1984. The user segment consists of antennas, receivers and signal processors to provide position, velocity, and precise timing for a particular user's applications. Finally, the control element consists of monitoring stations, ground antennas, a master control station and a backup master control station to sample and evaluate the health of each satellite[7].

From the beginning, NAVSTAR was designed for dual use. US government agencies have access to the most accurate service, known as Precise Positioning Service (PPS), while the general public may receive the potentially less accurate Standard Positioning Service (SPS). The difference in the services can be errors intentionally introduced through a process called Selective Availability (SA). Intentional degradation of the SPS was discontinued on May 1, 2000 by presidential order[8].

Since the discontinuation of selective availability, highly accurate GPS signals have been available to the entire general public. Today, exceptionally capable GPS receivers are available at a reasonable cost. These affordable, highly accurate navigation systems have accuracies of a few feet and are available for automobile, marine and aviation applications.

Over the past 13 years, GPS has matured into a robust critical aid to navigation as it was envisioned in the 1960s. Today, most IMC certified aircraft include at least one GPS receiver. Advanced navigation systems integrate one or more receiver into a flight management system for primary navigation.

The most common aviation use of GPS is for area navigation or RNAV. RNAV is airspace navigation in which the pilot of an aircraft may choose any course within a network of navigation beacons or waypoints. RNAV is possible with equipment that calculates position relative to ground-based beacons or GPS satellites. Using RNAV methods, an aircraft is not limited to navigating directly to and from beacons or waypoints. Instead the aircraft can fly an off-set course or even a course defined by user generated waypoints. This conserves flight distance, reduces congestion, and permits instrument flight plans into airports without beacons. The concept of RNAV was developed in the 1960s and has continued in popularity because of its efficiency. Performance enhancements throughout global airspace systems directly target the additional benefits of improving RNAV.

Despite the quickly evolving capabilities of GPS systems, the concepts of navigation integrity and containment are still in the deployment phase. Most naval tactical aircraft do not have compatible equipment that meets the requirements of a performance-based system.

Performance-based Systems

A performance-based air traffic management system centers on the desire for reliable and consistent navigational solutions. The focus shifts from specific equipment type to equipment independent capability. Aircraft, regardless of type of equipment installed, should have the capability to reliably remain within a specified volume of airspace for a majority of the time.

For civil aircraft equipment in the US, the minimum navigation performance-based standards can be found in FAA Technical Standard Orders (TSO). A TSO is often a list of minimum performance standards issued by the FAA for specific civil aviation materials, parts, processes, and appliances. For international civil aviation, ICAO issues standards and recommended practices (SARP).

The concept of required navigation performance (RNP) applies to the airspace and the systems designed to operate within a performance-based system. The airspace or equipment is given a value based on the performance accuracy or capability required to fly within a specific airspace. Aircraft operation within or access to a defined airspace may be limited by a lack of performance capability.

In order for a performance-based navigation system to demonstrate performance capability, the minimum operational performance standards (MOPS) must be defined. The FAA has relied on RTCA for gathering input from members of the aviation industry to recommend MOPS for various systems. The MOPS for airborne supplemental navigation equipment using GPS are located in RTCA document 208 (DO-208). TSO-C129a, which is the TSO for airborne supplemental use of GPS, incorporates the MOPS listed in DO-208. Standards for receivers with ground station based signal augmentation can be found in RTCA document 229C, Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment.

Military combat and combat support aircraft have PNT capabilities designed to operate in combat and otherwise stressed environments where civil PNT services are likely to be jammed or severely limited. As a result, current military PNT systems exceed the RNP requirement for navigational accuracy. However, these systems do not conform to the RNP requirements designed for civil operations such as commercial air carriers.

Components of a Performance-based System

The critical concepts intrinsic to RNP systems are availability, accuracy, and containment [9]. Containment refers to a combination of system integrity and continuity. Most navigation systems in use in naval aviation today lack a suitable level of assurance in availability, containment integrity and continuity. Each concept must be precisely understood to define appropriate requirements for future PNT solutions.

A navigation system's availability addresses the need for assurance of safe operation within unpredictable environments, of which Naval Aviators often find themselves. Aviators must have confidence in the PNT system's capability to reliably perform its required function with every initiation of an intended operation. Regardless of whether the changes in the environment are natural or man-made, the system has to be available when needed.

Containment integrity is the idea that the region around an aircraft's desired path can be defined, and that the probability that the aircraft does not remain in that region can be bounded [9]. A depiction of lateral cross-track containment parameters is shown in figure 3. This

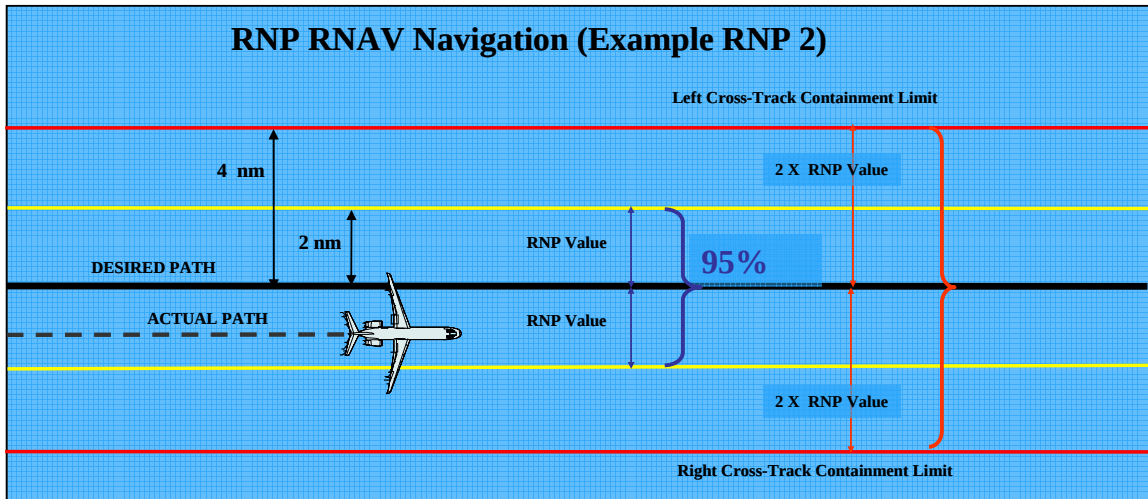


Figure 3
Illustration of Lateral Cross-Track Containment Parameters

Source: http://pma209.navair.navy.mil/teams/navigation/cnsatm/rnp_rnav.asp
 30 Nov 2006

illustration depicts a RNP 2 containment region. An aircraft would be required to remain within 2 nautical miles of the desired path, 95 percent of the total flight time along that path. The probability that the total system error would exceed the specified cross track containment limit, 4 nm in the above case, without annunciation must be less than 10^{-5} per flight hour [9].

Containment continuity is based on the capability of the aircraft's navigation system to self-monitor and evaluate the validity of its own navigation solution. Errors in the navigation solution are detected by an algorithm. The result of which must be a timely warning sent to the operator indicating that the system is not

useable for navigation. Two common methods of monitoring the "goodness" of GPS navigation solutions are: GPS Integrity Channel (GIC) and Receiver Autonomous Integrity Monitoring (RAIM).

GIC is a ground-based monitoring system. Ground stations monitor the signals from all satellites in view. The ground station's positions are known precisely and easily validate position calculations from satellites. This has the distinct advantage over a self-contained monitoring systems, in that satellite redundancy is not required to detect pseudorange errors or other satellite failures. Once detected, the ground stations transmit the pseudorange errors or go-no-go signals to the user [10].

RAIM, as its name states, is self-contained and autonomous. Traditional RAIM uses five satellites to detect a fault in its position solution. Reception of six satellites is required for the GPS receiver to detect a fault in one satellite and exclude it from its position solution. A RAIM equipped GPS receiver can also determine if sufficient satellite coverage will be available at a specific time, allowing the operator to select and plan an approach before reaching the terminal area environment.

The overall ability of a system, as a whole, to perform its intended function is the concept of continuity. As it applies to an aircraft's capability of remaining within a specified volume of space, containment continuity is the probability that the navigational system will provide the information required to continuously remain within a specified volume of airspace.

As airspace becomes more congested and technology solutions increase, safety of flight considerations will require all participants to meet a minimum standard of navigation capability. The individual military services assume the burden of ensuring compliance with civil requirements in all aircraft. Countries implementing specific navigation performance mandates may deny airspace entry to non-compliant aircraft. This will certainly apply to the E-2C Hawkeye.

CHAPTER 2: NAVAL AVIATION EVOLUTION

The E-2C Hawkeye

The E-2C Hawkeye was designed as an airborne early warning, combat command and control aircraft. A complete description is located in the E-2C NATOPS Flight Manual [11]. A profile of the aircraft is shown in figure 4. The Hawkeye was built by Grumman Aerospace Corporation as a high-wing, twin engine, turboprop. The aircraft has several unmistakably identifiable features, one of which is the 24-foot diameter, combination radar rotodome antenna. It also has four vertical tails on the empennage and twin 8-bladed propellers.



Figure 4
E-2C Hawkeye

Source: <http://www.fas.org/man/dod-101/sys/ac/e-2.htm>, 30 Nov 2006

The two unique, eight-bladed Hamilton Sundstrand propellers are attached to two Rolls-Royce T56-A-427 engines rated at 5,100 indicated shaft horsepower (ISHP). The combination of each engine makes the E-2C one of the most powerful, twin-engine turboprops in the world.

The mission of the Hawkeye is to provide airborne early warning, detection and combat command and control in the context of complete battle space management. Designed to be launched from the flight deck of an aircraft carrier, the E-2 is suited for missions around the globe.

E-2C Navigation Systems

The E-2C rolled off the assembly line in the early 1970s with a navigation system that, at the time, was top-of-the-line. Those system components are listed in table 1. [12]

Table 1: Initial E-2C Navigation Components

System Designation	Long Name	Short Name
AN/ASN-92 (V)	Carrier Inertial Navigation System	CAINS
CP-10851AS	Air Data Computer	ADC
AN/APN-153 (V)	Doppler Radar Navigation Set	
AN/ASN-50	Heading & Attitude Reference System	HARS
AN/ARN-52 (V)	Tactical Air Navigation System	TACAN
AN/ARA-50	UHF Automatic Direction Finder	UHF ADF

The original inertial navigation system, CAINS, is still in use in some E-2Cs operating today. CAINS, although capable, is highly susceptible to position drift and tumbling gyros following catapult launches. It also has a poor user interface. The combination of these shortfalls illustrates the lack of RNP availability assurance.

Since 1997, significant changes have been made to the aircraft's navigation system. Some of those changes are still underway today. The Doppler navigation system was the first system to be removed. The air data computer has been updated to a standard central air data computer by incorporating more solid state components. The TACAN receiver was upgraded to the AN/ARN-118(v). The integration of these more reliable systems has been a vast improvement. However, the availability of newer, more capable systems has far out-paced the E-2's system upgrade rate.

Current E-2C Navigation Systems

With the exception of a recent commercial, off-the-shelf navigation system, the E-2's navigation system does not meet most navigation performance standards. The

Table 2: Current E-2C Navigation Components

System Designation	Long Name	Short Name
AN/ARN-151(V)	GPS Receiver	GPS
GNS-530	Garmin GNS-530	NA
AN/ASN-139	Strap down Ring Laser Gyro Carrier Inertial Navigation System	CAINS II
AN/ARN-118(V)	Tactical Air Navigation System	TACAN
CPU 140/A	Standard Central Air Data Computer	SCADC

Hawkeye's current navigation components are listed in table 2.

The current integrated GPS, the AN/ARN-151(V), was a vast improvement to the navigation suite. The ARN-151(V) has a five channel receiver, four of which are used at any one time to calculate position for use in determining navigation solutions. The fifth channel tracks one extra satellite for use in the event of a satellite drop-out in one of the first four channels. The system's functions are controlled through one of two Multi-function Control Display Units (MFCDU).

The ARN-151(V) is a PPS receiver which achieves position accuracies within a few meters. However, the ARN-151 is susceptible to frequent satellite reception drop-outs, resulting in degraded reliability. The drop-outs are

usually due to aircraft attitude or to antenna masking by part of the aircraft's structure. The aircraft's position solution can be aided by the inertial navigation system.

Aside from the GPS receiver and MFCDU, the aircraft's navigation capability also includes two strapped-down ring laser gyroscopes and a TACAN receiver. Both components should remain as part of the aircraft's standard configuration for the foreseeable future.

A recent upgrade to the E-2 navigation system was the Garmin GNS-530. The GNS-530 is a commercial off-the-shelf GPS system that has FAA TSO-C129a, class A1 certification for area navigation to 0.3 nautical miles (nm). Additionally, the GNS-530 offers very high frequency (VHF), omni-directional radio range (VOR) navigation, frequency modulation (FM) immune instrument landing system (ILS) precision approach capability, a color moving map display, and an national air space (NAS) waypoint and instrument approach procedures navigation database. Finally, the GNS-530 has a 10-watt embedded VHF radio that is capable of both 8.33 kHz and 25 kHz channel spacing.

The Navy completed testing of the GNS-530 in January 2004 with a total cost of approximately \$360,000. The test program consisted of 11 flights, five days of lab testing

and 23 days of ground testing. A majority of the tests focused on electromagnetic compatibility, human machine interface (HMI) characteristics and shipboard compatibility.

The GNS-530 is, however, a very short-term solution to the E-2C navigation RNP shortfall. The GNS-530 is not integrated into the E-2's navigation data bus, which negates all of its desirable characteristics with regard to weapon system augmentation. Additionally, the GNS-530 is only a standard precision receiver. It is not suitable for GPS jammed environments or for combat operations where selective availability could once again introduce significant navigational errors.

Future proposed components of the E-2C navigation system must be fully integrated with the aircraft's weapon systems. To meet the requirements of RNP, the next generation GPS receiver should be an all-in-view receiver with integrity monitoring capability. An all-in-view GPS receiver has the ability to receive signals from all satellites above the horizon, usually 8 to 10 satellites, to determination position. These requirements must be clearly stated within the functional requirements documents

(FRD) during the requirements determination phase of the acquisition process.

CHAPTER 3: APPLICABILITY OF AVIATION REGULATIONS

Instrument Flight Rules and GPS

Federal regulations are specific about the use of GPS in IMC conditions. The GPS must be approved by the FAA according to the standards, or some equivalence, outlined in TSO-129a. Depending on configuration, the installation must be completed in accordance with Advisory Circular AC20-138, AC20-130A or an equivalent. The aircraft must also have an alternate means of navigation, should the GPS system fail. Future E-2 navigation equipment should be acquired with these requirements in mind.

Applicability to State Aircraft

The aforementioned requirements pertain only to civil aircraft. The E-2, however, is a public aircraft or more specifically, it is a state aircraft.

The definition of a public aircraft is located in Title 49 United States Code (U.S.C.) § 40102(a)(37). The Convention on International Civil Aviation, the organization credited for forming ICAO, defines any aircraft engaged in customs, police and military services as a "state" aircraft. State aircraft status is not granted by organization, nor is the US government required to make a declaration in writing of any such status. There

is no requirement to carry proof of this status.

Correspondingly, the FAA does not certify or attest to the airworthiness of state aircraft[13]. As such, the E-2C has never been required to obtain a type certificate (TC) or a Supplemental Type Certificate (STC) for newly installed equipment, like the GNS-530.

Compliance Now Applies to State Aircraft

To prevent violation of civil air traffic clearances, and to ensure safe separation of military and civil air traffic, the Chairman of the Joint Chiefs of Staff (CJCS) has issued policy stating that military aircraft must conform with civil airspace PNT requirements. This policy which defines the acquisition, operation and sustainment of PNT systems is found in the 2003 CJCS, Master Positioning, Navigation and Timing Plan [1].

In short, all military aircraft must have appropriate instruments and navigation equipment that are compatible to the airspace in which they are to be flown. Historically, as with all state aircraft, the E-2 was not required to conform to civil aviation system standards. However, now that non-compliance may compromise safety and access, the Navy assumes the burden of complying with federal and international regulations.

Certification Process

In the United States, certification of civil aircraft or aircraft systems falls under the purview of the FAA. The process details how to design, build, test and operate an aircraft. One of the instructions governing the process is "Airworthiness Certification of Aircraft and Related Products", Order 8130.2F [14]. FAA certification standards rely heavily on work by the RTCA. The basis of GPS certification standards, as set for by TSO-C129a and others, refers predominantly to RTCA minimum operational performance specifications (MOPS) for technical validity.

The Cost of Certification

When discussing the cost of a new system, the fact that every component of a system must be certified, as well as the entire system of navigation components, is often overlooked. The cost associated with installing a new component, such as a GPS receiver, includes developing and testing the new component along with its integration with currently installed systems.

The process of introducing new operational capabilities has become more costly for civil aviation industries, in terms of both time and money. According to the "Executive Summary of the Final Report of RTCA Task

Force 4 Certification"[15], the dynamic growth and globalization of aviation technology has outpaced the government's certification policies and regulatory oversight. The cost required to keep pace with improving technologies has inhibited the introduction of additional safety enhancements. Therefore, an acquisition strategy that capitalizes on previously certified technology increases the likelihood of economically fielding the system.

CHAPTER 4: HAWKEYE NAVIGATION, THE ROAD AHEAD

Foundations of Future Compliance

To acquire capable navigation systems that are cost effective and suitable for the E-2 mission, the Navy should leave the development and integration of all components to the contractor or manufacturer. The Navy should only evaluate the system for the mission and environment in which it would be operated. Naval aviation's acquisition burden would then be to evaluate the system beyond the certification requirements. The scope of developmental and operational test would be greatly reduced. To obtain the right solution the first time, the requirements documents must clearly capture the appropriate civil document standards. A simplified acquisition flow diagram is located in Figure A-1.

NAVAIR, with the aid of various contractors, plans to bring an integrated GPS RNP RNAV system into the Hawkeye's cockpit. Those plans include both the E-2C and follow-on E-2D models. The exact type of GPS navigation system solution should result from balancing capability with available funding. Lessons learned from previous GPS evaluations must be applied to these future systems.

Any future GPS based RNP RNAV solution should take advantage of industry obtainable FAA certifications. The remainder of the self-certification process would include only highly focused, targeted evaluations with the intent to answer requirements in the areas of availability, integrity and containment.

Scope of Previous GPS Testing

The GNS-530 underwent a minimal, yet focused evaluation period. Since the GNS-530 is TSO certified, many of the tests performed on the GNS-530 were unrelated to RNP RNAV or IMC flight. A majority of the GNS-530's test results that are reviewed below.

The evaluation concentrated on installation, human machine interface (HMI) and carrier suitability. In addition, the performance of the GNS-530 was evaluated for its ability to provide accurate position information and guidance during en route, terminal, and non-precision approaches. Position accuracy was adequate, and waypoint sequencing provided the aircrew with proper and timely visual indications of navigation information and course guidance.

Bench testing was limited to the communications system since the GNS-530 has TSO GPS certification. The

receiver and transmitter characteristics were evaluated to verify the manufacturer's specifications. Baseline testing required the construction of a break out box specifically tailored to isolate the GNS-530 from the aircraft ICS and to interconnect with our testing equipment. Test equipment included, but was not limited to, the use of the IFR 2947, 1840-A Audio Power Meter, as well as the HP54600A oscilloscope.

Ground testing verified the power on self tests, and static position satellite reception. Ground testing also evaluated the systems compatibility, susceptibility and vulnerability in various electromagnetic environments.

The in-flight evaluation focused on the GNS-530's compatibility with the E-2C Hawkeye's mission. One of the primary compatibility areas of interest was the E-2's electromagnetic environment. It is unique to the aircraft when airborne. The aircraft's structures, specifically the rotodome antenna, propellers and vertical tails were also potentially system degraders. Once it was determined that there were no problems with signal reception due to airframe masking, antenna patterns were not recorded. Lastly, the flight evaluation targeted the operational suitability of using the communication and navigation

functions in terminal environments. A summary of GNS-530 test points are located in Table B-1 and Table B-2.

Lessons Learned from the GNS-530 Evaluation

The GNS-530 was evaluated for SPS L1 GPS signal reception during static ground test and in-flight dynamic maneuvering. The GNS-530 demonstrated excellent signal reception while its antenna was in full view of orbiting Space Vehicles (SV). Dynamic maneuver testing including 360-deg right and left turns at bank angles of 15, 30 and 45 degrees. Test data revealed that at bank angles of 30 degrees, one or two signal levels were significantly reduced or lost due to masking by the aircraft's vertical tails, rotodome, and legacy GPS antenna fairing. However, signal reception remained adequate for accurate navigation solution.

The GNS-530 receiver was evaluated for electromagnetic susceptibility and compatibility other onboard E-2C during all phases of testing. The GNS-530 satellite status was observed while each of the ARC-182 UHF/VHF transceivers were tuned to specific frequencies and transmitted on for 20 seconds. The frequencies were tested in accordance with the test as listed in Table B-1 and Table B-2. No adverse effects to GPS signal strengths, navigation indications,

GNS-530 display quality, alerts and warnings, or satellite DOP were observed. Transmissions from the E-2 radar and other avionics systems also indicated no adverse effects or interference to GPS signal strengths, ADI and BDHI indications, GNS-530 display quality, alerts and warnings, or receiver DOP.

Within the cockpit, the distance from a pilot's or copilot's outstretched arm to the GNS-530 controls was approximately 2 feet. The placement required the operator to lean forward against the seat straps, pulling with 20 to 30 pounds of force. Also, while manipulating the controls, the operator must look away from all aircraft attitude and performance reference displays to focus on the manipulations required to operate the control interface knobs and buttons. Entering or modifying a flight plan required several minutes to perform, distracting the pilot or copilot from flight duties for an excessive time frame and increasing pilot fatigue. The in-flight operation of the GNS-530 should be delegated to the copilot.

Position data was compared to AN/ARN-151 position data during all regimes of normal aircraft maneuvering. During ground testing and prior to each flight, the Dilution of Precision (DOP) and Estimated Position Error (EPE) values

were observed on the GNS-530. DOP values were less than 1.4 and EPE values were less than 19 feet. During ground evaluation, the position difference between the GNS-530 and the AN/ARN-151 was 18.52 meters. The maximum in-flight position difference between the GNS-530 and the AN/ARN-151 was indeterminate. There were insufficient numbers of data points collected during test flights to precisely evaluate the accuracy of the GNS-530's GPS position. All data were hand recorded and resulted in excessive time between successive data points. The figure of merit (FOM) of the AN/ARN-151 drifted from 1, most accurate to 5, significantly less accurate. Use of the AN/ARN-151 receiver was not a good "truth data" source since the FOM was known to vary.

Overall, the performance of the GNS-530 was able to provide accurate position information and guidance during en route, terminal, and nonprecision approaches. Position accuracy was adequate, and waypoint sequencing provided the aircrew with proper and timely visual indications of navigation information and course guidance. The performance of the GNS-530, as installed, satisfied FAA criteria for supplemental navigation use in conjunction with a sole means navigation system. The GNS-530

installation in the E-2C Hawkeye should have been approved for immediate use as a supplemental means of navigation under visual and instrument flight rules within oceanic en route, domestic en route and terminal areas.

Future GPS System Evaluations

Specific mission suitability evaluation of GPS receivers or integrated GPS navigation systems with capabilities designed for specific military requirements, such as highly dynamic maneuvering, anti-spoofing and anti-jamming should be evaluated prior to fielding future satellite based navigation systems in hostile environments. Integrated GPS receivers would have to satisfy many more requirements than the GNS-530 evaluation. For purposes of demonstrating RNP RNAV compliance, a PPS receiver should be evaluated as a SPS receiver with proposed performance equivalent to a differential GPS.

To date, there has been no formal requirement for an improved flight control system in the E-2. With the exception of heading, attitude and altitude hold, the E-2's automated flight control system does not receive steering cues from the navigation system. The GNS-530 does not supply any navigation information to the flight controls. However, if in future configurations the navigation system

and flight control system are coupled, an extensive evaluation would be required.

Just as SPS receivers are required to receive the L1 signal and C/A code, optimum PPS GPS receiver based navigation solutions should be capability of receiving and exploiting all available civil GNSS signals. This would include the L2 and L5 signals. In addition, the receiver should also use signals from the GLONASS and Galileo satellite navigation systems. Global operation would imply selectively choosing optimal signal source.

RNAV evaluation of future satellite-based navigation systems would, therefore, focus on the following areas: path estimation, path definition, user interface and system features and capabilities. A comprehensive list of tests, as they apply to these areas, is listed in appendix B. Table B-3 is a proposed bench test matrix. Table B-4 is a proposed ground test matrix and Table B-5 has proposed test items for a flight evaluation. Compliance items are listed in the first column. The second column contains a description of the compliance item. The third column contains limits for bench test and space for assessment comments for the ground and flight tests. A HMI checklist is contained in Table B-6.

Lessons learned from previous evaluations illustrate that; above all else, the pilot and copilot have a clear and unobstructed view of all displayed data when in the seated position. Also, the displays used for maneuver anticipation and for failure annunciation must be located within the pilot's primary field of view. The brilliance of any display must be adjustable to levels suitable for data interpretation under all cockpit ambient light conditions ranging from total darkness to reflected sunlight. The approach mode annunciation and distance to waypoint in the approach mode must be clearly visible to the pilot with the least practicable deviation from his normal position and from his line of vision when he is looking forward along the fight path.

Conclusions and Recommendations

Every acquisition strategy places the mission capability of a system as the first priority. For the mission of global navigation, naval aircraft must have the capability to meet the applicable civil requirements. Based on previous system evaluations and current regulatory recommendations, the following recommendations apply to all future navigation system programs.

All future navigation solutions should state within their respective specification documents, the highest level civil certification attained. The test and evaluation process should honor the level of certification and not retest to that level.

For systems lacking certification, the author recommends using the compliance items listed in Table B-3 through Table B-5. Compliance with these items, in addition to those required for mission suitability, would ensure a reliable navigation capability in all environments.

When accuracy validation is required, a highly reliable "truth data" source is imperative. Only the most sensitive test ranges for fly-over data or an independent, onboard installation with precise calibration would be suitable.

Future navigation solutions should be hybrid navigation systems capable of exploiting all available satellite systems and all satellites in view. This would include having the capability to exploit differential GPS technology with integrity monitoring when the service is available. When not available, the systems should be able to switch to military precision service with augmentation

where needed. Satellite based augmentation is not required for PPS, however there may be a need such for capability near military landing facilities. For navigational purposes, correctly coded PPS receivers have the performance equivalence of highly augmented civil, commercial of the shelf receivers.

Reuse of technology and components is always desired; however, the question remains whether or not a current system can, with modification, fulfill future emergent environmental or mission requirements. The ultimate goal is compliance using current or new technology without duplicating cost and effort through developmental and operational test.

Future acquisition strategies should acquire new GPS navigation technologies that meet or exceed the minimum civil requirements. Military PPS receivers should have the same integrity monitoring, alerting and assurances technology SPS receivers possess now. In the interim, current technologies, such as the GNS-530, should be quickly self-certified and put into operational use. The E-2C Hawkeye will then be assured of having accurate, self-contained, all-weather access to any foreign environment, with safe separation from all aircraft.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. United States Joint Chiefs, "2003 CJCS MASTER POSITIONING, NAVIGATION, AND TIMING PLAN". 31 March 2003. § 6130.01C. Enclosure A, Pg. A-2.
2. PMA-209 INTERnet. <http://pma209.navair.navy.mil/teams/navigation/cnsatm/challenges.asp> (accessed 26 Oct 2006).
3. US DOT/FAA/Office of Policy and Plans, FAA Aerospace Forecast Fiscal Years 2006-2017, 2006, Pg 37.
4. Federal Aviation Administration. Roadmap to Performance-Based Navigation, Ver. 1.0, July 2003, Pg. 1.
5. Guidelines for Communication, Navigation, Surveillance, and Air Traffic Management (CNS/ATM) Systems Software Integrity Assurance, RTCA, INC. MARCH 5, 2002.
6. Federal Aviation Administration. Advisory Circular (AC) 90-94, "Guidelines For Using Global Positioning System Equipment For IFR En Route And Terminal Operations And For Non-precision Instrument Approaches In The US National Airspace System", 14 Dec 1994. Pg 1.
7. Assistant Secretary Of Defense for Command, Control, Communications, And Intelligence. "Global Positioning System Standard Positioning Service Performance Standard", October 2001, Pg 2.

8. Office of Science and Technology Policy. Presidential statement to stop degrading GPS, May 1, 2000.
9. RTCA Document 236B. "Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation", October 28, 2003.
10. RTCA Document 208, "Minimum Operational Performance Standards For Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)", 12 July 1991.
11. United States Navy. NAVAIR 01-E2AAB-1. "E-2C NATOPS Flight Manual Navy Model E-2C Plus Aircraft", 30 JUN 2004.
12. United States Navy. NAVAIR 00-110AW2-2. "Standard Aircraft Characteristics Navy Model E-2c Aircraft", Mar 1975.
13. United States, Code of Federal Regulations. "Qualifications for public aircraft status", 49USC40125, GPO 24 Jan 2002.
14. Federal Aviation Administration. "Airworthiness Certification of Aircraft and Related Products", Order 8130.2F, November 5, 2004.

15. RTCA Document, "Executive Summary of the Final Report of RTCA Task Force 4 Certification", February 26, 1999, Pg 3.
16. Federal Aviation Administration, Advisory Circular (AC) 20-138B, "Airworthiness Approval of Global Positioning System (GPS) Navigation Equipment for Use as a VFR and IFR Supplemental Navigation System", 14 Dec 1994, Pg 1.
17. RTCA Document 178B, "Software Considerations in Airborne Systems and Equipment Certification", 1 Dec 1992, Pg 1.
18. Naval Air Warfare Center Aircraft Division, "Evaluation Of the Garmin Navigation System (GNS-530) As Installed In The E-2C Hawkeye Aircraft". Winkel and Guoan.
19. RTCA Document 229C, "Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment", 28 November 2001.
20. RTCA Document 283A, "Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation", 28 October 2003.

APPENDICES

APPENDIX A FIGURES

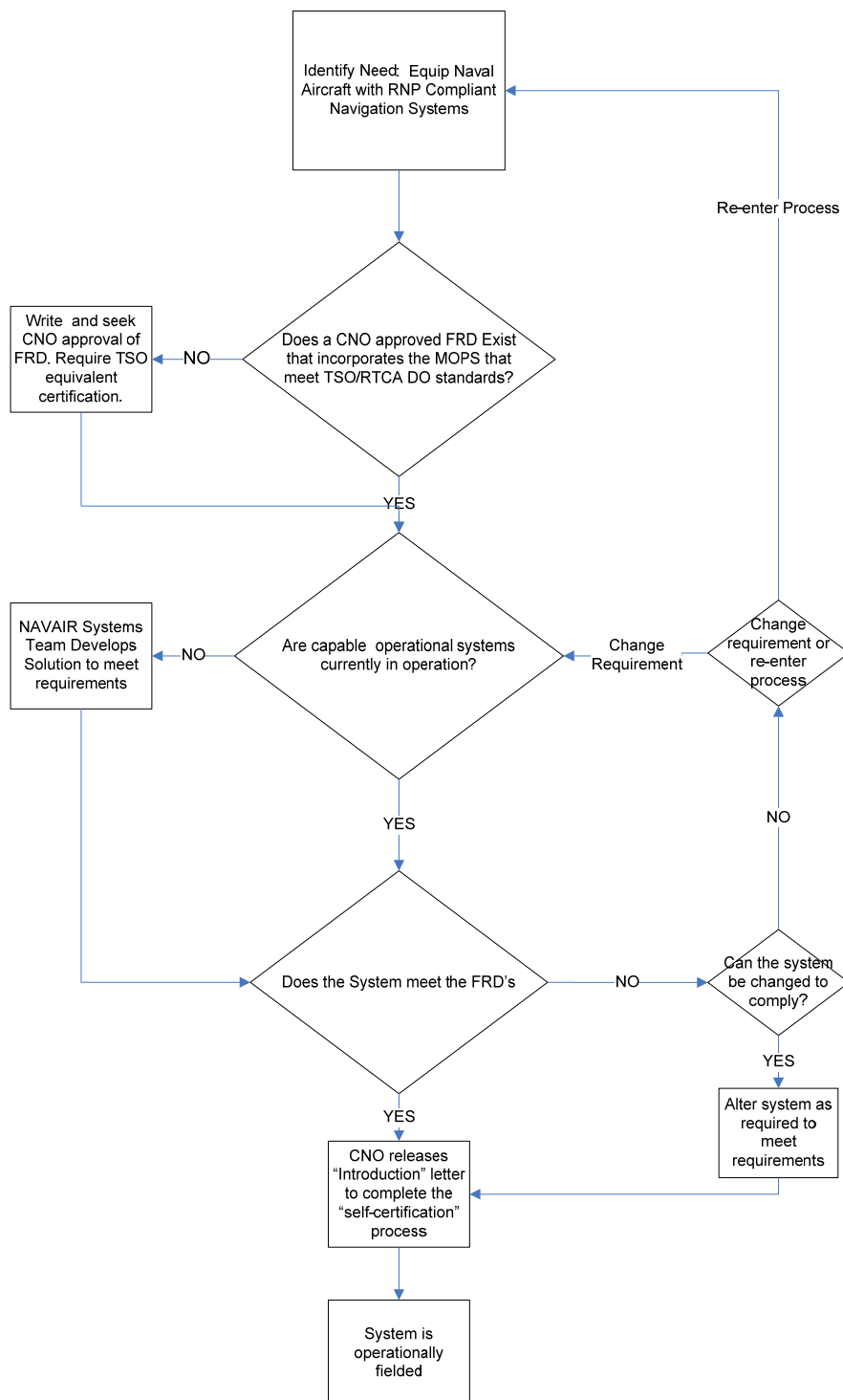


**Figure A-1:
Flow Diagram of Compliance Strategy**

APPENDIX B

TABLES

Table B-1: Garmin Ground Test Summary

Test	Remarks	Pass-Fail Criteria
Verify Jeppesen data base currency	Check database currency following power on.	Jeppesen database is loaded and currency is within 28 days.
Crosscheck instrument panel self-test on the Garmin.	Crosscheck ADI CDI and BDHI with test page.	Record ADI and BDHI indications during self-test. No warning flag displayed.
GPS signal reception and integrity check.	Verify no. of satellites acquired on satellite page.	Verify a sufficient no. of satellites are acquired to provide GPS 3D navigation. Integrity light remains extinguished.
Verify accuracy of GPS position data.	Crosscheck Garmin derived GPS position with ARN-151 position.	Garmin GPS position data should agree with current aircraft position data.
EMC compatibility & Susceptibility of GPS with all VHF radios.	Conduct VHF Comm. on 121.15, 121.175, 121.200, 131.250, 131.275 and 131.300 MHz. Note affects on satellite page.	GPS satellite reception is not affected by VHF transmissions.
Loss of power/signal to GPS receiver and external displays.	Simulate a loss of signal to the GPS and loss of power to the associated displays.	Annunciator indications provide proper warnings for unreliable GPS signal and warning flags are displayed on external displays.

Table B-2: Garmin Flight Test Summary

Test	Remarks	Pass-Fail Criteria
EMC compatibility & Susceptibility of GPS with all VHF radios (Comm 1/2/5), E-2C Radar, & other avionics systems.	Conduct VHF Comm. on 121.15, 121.175, 121.200, 131.250, 131.275 and 131.300 MHz. Operate the E-2C Radar.	GPS satellite reception is not affected by VHF, RADAR, or other Avionics transmissions.
Verify accuracy of GPS position data.	Cross check Garmin derived GPS position against ARN-151 position.	During level and maneuvering flight the Garmin GPS position data should agree with aircraft derived position.
Evaluate GNS-530 capability to create, activate, and modify an existing GPS flight plan. Functionality.	Create a flight plan and activate. Modify flight plan, and perform direct-to function. HMI. Workload.	Operator was able to modify existing plan and perform a direct to function from an active flight plan.
Verify nav data during normal aircraft maneuvers and 360 turns at AOB = 15, 30, & 45 deg	Airframe masking: GPS nav mode selected, monitor integrity indicator and satellite data for uninterrupted coverage.	GPS integrity is not affected. Satisfactory satellite coverage during holding pattern, 360 deg turns both right/left at 15, 30, & 45 deg AOB.
GPS non-precision approaches	Fly multiple approaches and transitions from enroute to terminal to approach using the nav data base. Monitor display sensitivities, annunciations, waypoint sequencing. VMC only.	Cross check GPS guidance against TACAN approach information. GPS provided correct guidance to execute satisfactory approaches to perform a normal landing at airfield.

Table B-3: Proposed Non-certified GPS Bench Test

Compliance Item	Remarks	Limits/Requirements
Satellite visibility, selection and atmospheric compensation	Note signals from which the receiver is able to derive positions and RNAV information under interference conditions. GPS-provided iono correction model Tropospheric corrections are applied. Data decoded continuously. Clock and ephemeris parameters used after they have been successfully collected twice Iono data is used after is has been successfully collected twice. Satellite clock corrections, include relativistic corrections, are applied to pseudorange after smoothing (if applicable) GPS satellites are not mistaken due to cross-correlation during acquisition or reacquisition DO-229C 2.5.1 Table 2-19	IF or RF receiver capable of receiving L1, L2, or L5. Potential reception of GLONASS and Galileo. System selects and uses iono models. System correctly applies Tropo corrections. Downlink data is decoded continuously System validates ephemeris before use. System validates iono data before use. System correctly applies satellite clock info System protects against cross-correlation.
Initial Acquisition Time	System acquires satellites and determines position without initialization information. DO-229C 2.5.1 Table 2-19	TTF $\leq$ 5 minutes, given; initialization of LAT/LONG within 60 nm., TIME/DATE within 1 minute, valid almanac, and unobstructed satellite visibility; under the specified interference conditions
GPS Satellite Acquisition Time	During steady state operation satellites are acquired and incorporated into position solution DO-229C 2.5.1 Table 2-19	Incorporated within 80 seconds

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
Satellite Reacquisition Time	Reacquires satellite and computes pseudo-range within 10 seconds when the remaining satellites provide a GDOP of 6 or less (from point when signal is available after a loss interval up to 30 seconds) DO-229C 2.5.1 Table 2-19	Reacquire and use in position solution within 10 seconds.
Satellite Tracking	System capable of tracking a minimum of 8 satellites	Shown to track 8 satellites simultaneously.
Dynamic Tracking	Equipment maintains accuracy during representative en route and terminal area maneuvering	System maintains accuracy during normal dynamics under the specified signal power and interference conditions. Abnormal maneuvers do not cause misleading information. Re-acquisitions are performed, as specified, when the abnormal maneuvers complete. Proper indication of loss of navigation and loss of integrity is shown during abnormal maneuvers.
Sensitivity and Dynamic Range	System interoperable with a standard antenna or Manufacturer-provided-antenna satisfies performance of RTCA/DO-228. DO-229C 2.5.1 Table 2-19	Tracks satellites at -136 dBm
Equipment Burnout Protection	System withstands in-band CWI @ +20 dBm at the antenna without damage	No damage in-band CWI @ +20 dBm

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
	DO-229C 2.5.1 Table 2-19	
Navigation Alert	Notification is indicated of loss of navigation indication within 1 second following: a) Loss of power b) System malfunctions c) If for 5 seconds insufficient number of satellites for position solution. DO-229C 2.5.1 Table 2-19	Alert visible given during given circumstances within 1 second
En Route and Terminal Navigation Requirements		
Accuracy	Requirement met under the minimum signal conditions defined in DO-229C 2.1.1.10 and interference conditions defined in Appendix C.	Horizontal radial position fixing error ≤ 100 m, 95th percentile, when HDOP is normalized to 1.5.
Integrity	The hardware and software shall be designed such that the output of misleading information, considered to be a major failure condition, shall be improbable. Conduct a safety assessment to evaluate the system's implementation against known failure conditions.	Hardware: show that failures of the equipment that result in misleading information are not more probable than 10^{-5}/flight hour. Software: See AC 20-115B, which references RTCA/DO-178B
Satellite Tracking	Track a minimum of 8 satellites	

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
Dynamic Tracking	Meet en route accuracy requirements during maneuvering flight. During maneuvers, equipment shall not output misleading information. When the aircraft returns to normal maneuvers from abnormal maneuvers, the equipment shall meet the steady-state reacquisition requirements of: DO-229C Section 2.1.1.9.	Ground Speed: 500 kts Horizontal Accel: +2.7, -0.6g Vertical Accel: +3.2, -1.0g
Position Output	Position shall represent the WGS-84 position of the aircraft antenna (or center of navigation) at the time of applicability. The equipment shall provide an electronic data interface capable of transmitting digital data containing position, velocity, integrity and other pertinent data. DO-229C 2.1.2.6	Output based on WGS-84 model
Position Output Update Rate	Minimum update rate of position outputs used for navigation	Position outputs once per second
Position Output Latency	The interval between the time of the measurement and the time of applicability of the position	Latency $\leq$ 500 msec

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
En Route and Terminal Integrity Monitoring		
FDE - Provided Integrity Monitoring	System has autonomous FDE capability: FDE uses URA broadcast to modify modes DO-229C 2.5.1 Table 2-19	FDE algorithm sets: (1)SA mode, if any satellite URA's are greater than 16 meters (2)SA off mode, if the URA for every satellite being used is less than or equal to 16 meters
Time to Alert	Time to alert 8 seconds DO-229C 2.5.1 Table 2-19	System displays alert within TTA
Missed Alert Probability	Analysis validates documentation and tests prove systems missed alert probability ≤ 0.001 .	Probability of missed alert ≤ 0.001
False Alert Probability	Probability of false alert $\leq 10^{-5}$ /hour. Average duration and probability of a false alert will be $< 3.33 \times 10^{-7}$.	Probability of false alert $\leq 10^{-5}$ /hour. Average duration and probability of a false alert will be $< 3.33 \times 10^{-7}$
Failed Exclusion Probability	Validate documentation. Test proves system's failed exclusion probability $\leq 10^{-3}$ /hour.	Probability of failed exclusion $\leq 10^{-3}$ /hour
Availability	Analysis validation proves availability of detection $\geq 99.9\%$ and availability of exclusion $\geq 98.0\%$	Availability of detection $\geq 99.9\%$ Availability of exclusion $\geq 98.0\%$

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
Nonprecision Approach Requirements		
Accuracy	Requirement met under the minimum signal conditions defined in DO-229C 2.1.1.10 and interference conditions defined in Appendix C.	Horizontal radial position fixing error ≤ 100 m, 95th percentile, when HDOP is normalized to 1.5
Integrity	The hardware and software shall be designed such that the output of misleading information, considered to be a major failure condition, shall be improbable. Conduct a safety assessment to evaluate the system's implementation against known failure conditions	Hardware: show that failures of the equipment that result in misleading information are not more probable than 10^{-5} /flight hour. Software: See AC 20-115B, which references RTCA/DO-178B
Satellite Tracking	Track all satellites in view, with mask angle greater than 5 degrees	Track a minimum of 8 satellites
Dynamic Tracking	Meet en route accuracy requirements during maneuvering flight. During maneuvers, equipment shall not output misleading information. When the aircraft returns to normal maneuvers from abnormal maneuvers, the equipment shall meet the steady-state reacquisition requirements of: DO-229C Section 2.1.1.9	Ground Speed: 500 kts Horizontal Accel: +2.7, -0.6g Vertical Accel: +3.2, -1.0g
Position Output	Position shall represent the WGS-84 position of the aircraft antenna (or center of navigation) at the time of applicability. The equipment shall provide an electronic data interface capable of transmitting digital data containing position, velocity, integrity and other	Output based on WGS-84 model

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
	pertinent data. DO-229C 2.1.2.6	
Position Output Update Rate	Minimum update rate of position outputs used for navigation	Position outputs once per second
Position Output Latency	The interval between the time of the measurement and the time of applicability of the position	Latency $\leq$ 500 msec
Nonprecision Approach Integrity Monitoring		
FDE - Provided Integrity Monitoring	System has autonomous FDE capability: FDE uses URA broadcast to modify modes DO-229C 2.5.1 Table 2-19	FDE algorithm sets: (1)SA mode, if any satellite URA's are greater than 16 meters (2)SA off mode, if the URA for every satellite being used is less than or equal to 16 meters
Time to Alert	Time to alert 8 seconds DO-229C 2.5.1 Table 2-19	System displays alert within TTA
Missed Alert Probability	Analysis validates documentation and tests prove systems missed alert probability $\leq$ 0.001.	Probability of missed alert $\leq$ 0.001
False Alert Probability	Probability of false alert $\leq$ 10^{-5} /hour. Average duration and probability of a false alert will be $< 3.33 \times 10^{-7}$.	Probability of false alert $\leq$ 10^{-5} /hour. Average duration and probability of a false alert will be $< 3.33 \times 10^{-7}$
Failed Exclusion Probability	Validate documentation. Test proves system's failed exclusion probability $\leq$ 10^{-3} /hour.	Probability of failed exclusion $\leq$ 10^{-3} /hour

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
Availability	Analysis validation proves availability of detection $\geq 99.9\%$ and availability of exclusion $\geq 98.0\%$	Availability of detection $\geq 99.9\%$ Availability of exclusion $\geq 98.0\%$
Position Estimation		
Present Position	Assess alphanumeric latitude and longitude display of aircrafts present position DO-283 2.2.1.1	Display resolution of 0.1 minutes or better
Estimate of Position Uncertainty	Assess display of Estimated Position Uncertainty. Note system notifications if integrity limit is exceeded DO-283 2.2.1.2	Display resolution of 0.1 nm or better
Containment Radius	Verify true position falls within estimated position containment radius DO-283 2.2.1.3	Probability of true position falling outside containment radius shall be less than 10^{-5} /hour
Position Initialization	If manual system initialization is available, verify resolution DO-283 2.2.1.4	Position entry resolution of 0.1 minute or better
Navigation Aid Selection	If the system has the option to choose between GPS and INS, navigation operations should not be affected during the transfer DO-283 2.2.1.5	Note alerts and annunciations during or following changes in navigation emitter source
Path Definition		
Leg Types	Verify system provision of the following leg types: Course-to-Fix(CF), Direct-to-	Leg types present

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
	Fix(DF), Initial Fix(IF), Radius-to-Fix(RF), Track-to-Fix (TF) DO-283 2.2.2.1	
Flight Planning	Assess the capability to insert, delete waypoints into active and inactive flight plans. Assess ease of entering/activating a flight plan. Assess the ease of appending or removing SID/STAR/Approach procedure DO-283 2.2.2.2	Comment on ease and intuitiveness of each operation
Cross-Track Deviation Display	Verify the display and electrical output of cross track deviation while varying RNP Type, aircraft position, desired track, fix geometry and leg type DO-283 2.2.4.1	Great circle distance from the present position to the closest point on the active leg of the course. ± 20 nm. Minimum resolution of 0.01 nm for distances less than 1 nm. 0.1 for distances less than 9.9 nm and 1.0 nm beyond.
Waypoint Distance Display	Verify distance display to active fix, next fix or destination has the resolution of 0.1 nm or better. The distance display should accommodate a distance display of at least 9999 nm. DO-283 2.2.4.2	Resolution ≤ 0.1 nm Distance displayed ≥ 9999 nm
TO-FROM Indication	Verify TO-FROM indication is continuously displayed whenever a waypoint is selected. DO-283 2.2.4.3	Presence of TO-FROM indication. Matches actual position relative to waypoint
Waypoint Entry	Feedback shall be supplied during data entry, with confirmation of input action prior to activation based upon that input. Any equipment prompts must be easily understood.	Confirmation of input supplied. Assess the ease of waypoint entry.

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
	DO-229C 3.3.1.2.2	
Waypoint or Leg Sequencing	Equipment shall automatically sequence waypoints in the active flight plan. If automatic sequencing is suspended for any reason, the equipment shall retain the active flight plan for later selection. If the equipment provides the capability to suspend and unsuspend automatic sequencing as a discrete action (SUSP), the equipment shall continuously annunciate when waypoint sequencing has been suspended. If the pilot deselects SUSP mode, automatic sequencing of waypoints shall resume upon reaching the current waypoint if the current waypoint is in the flight plan. DO-229C 2.2.1.2.4	Waypoint within active flight plan sequence automatically as aircraft progresses along flight planned path. Pilot is able to suspend and unsuspend waypoint sequencing.
Position Display	Display all positions of latitude and longitude with a minimum resolution of 0.01 min or better. DO-283 2.2.4.6	Position resolution ≤ 0.01 min
Failure/Status Indication	Failures or loss of signal shall be output/displayed within one second of the onset of any of the following conditions: a. Loss of power (loss of function is an acceptable indicator); b. Equipment malfunction or failure c. A condition lasting five seconds or more where there are an inadequate number of satellites to compute a position solution; d. Fault detection detects a position failure, which cannot be excluded within the time-to-alert.	Fault indication: ≤ 1 second Time-to-Alert Oceanic/Remote: 1 minute En Route: 30 seconds Terminal: 10 seconds

Table B-3: Continued

Compliance Item	Remarks	Limits/Requirements
	DO-229C 2.2.2.6.3	
Equipment Computational Response Time	Measure display latency, display update rates, and time to provide flight guidance during nominal and heavy processing conditions. The test objective is to verify that response times are met under both normal and high usage conditions. DO-229C 2.5.11.1.3	Display latency: ≤ 1 second Display update rate: en route ≤ 1 Hz terminal mode ≤ 1 Hz Course guidance: 5 seconds Time between accepting changes to active flight plan and outputting navigation guidance: ≤ 5 seconds

Table B-4: Proposed Non-certified GPS Ground Test

Compliance Item	Remarks	Assessment
Equipment Operation Limitations	Equipment operation limitations that consider sensor availability and navigational aid coverage should be contained in the aircraft flight manual and clearly identified in the aircraft cockpit by means of placards.	
Conformity Inspection	Visually inspect the installed equipment to determine the use of acceptable workmanship and engineering practices. Ref. DO-229 3.1.4.1.1	
Antenna Installation	GPS antenna should be separated as far as possible from other antennas (e.g., UHF/VHF, SATCOM, and HF) and the windscreen (to prevent case-to antenna coupling) Ref. DO-229 3.1.1.2	
Cockpit Layout of Installed Equipment	Evaluate the cockpit layout of the installed equipment with emphasis on equipment controls, applicable circuit breakers (labels and accessibility), power switching arrangement, and related indicators, displays, annunciators, etc. Ref. DO-229 3.3.1.3.1.1	
Accessibility	Accessing controls do not contribute to discomfort or fatigue. Controls installed for in-flight operation shall be readily accessible from the pilot's seated position. Only single-hand operation should be required, the controls should be readily identifiable. Use of the controls	

Table B-4: Continued

Compliance Item	Remarks	Assessment
	should not obscure pertinent displays.	
Electromagnetic Compatibility	Particular attention should be given to other "L" band equipment, such as TCAS or SATCOM equipment; VHF transmissions on the frequencies listed below; high frequency (HF) communications systems; and other transmitting equipment (e.g., ACARS, AFIS, Flightfone, etc.). The following VHF frequencies shall be evaluated: 121.150 MHz 131.250 MHz 121.175 MHz 131.275 MHz 121.200 MHz 131.300 MHz DO-229 3.1.4.1.4	
Display Visibility	Assess display visibility of the controls, displays, and annunciators from pilot and copilot design eye point of view DO-229 3.3.1.1.1	
Interference Effects	Shall be no navigation or display degradation from E-2 avionics systems. Equipment shall not be installed in such a manner as to be the source of objectionable conducted or radiated interference.	
Inadvertent Turnoff	Minimum risks of unwanted system turn off.	
Accuracy Test	DO-229 3.3.1.3.1.2	

Table B-4: Continued

Compliance Item	Remarks	Assessment
Crew Workload	Rate workload for performing routine functions such as entering and activating flight plan, SID, STAR, flight plan change, user waypoint definition. Ref. DO-229 3.3.1.3.2.6	
System Operational Integrity	System degradation below the minimum acceptable performance required for phase of flight shall be clearly annunciated in the cockpit, and the visual indication of such degradation shall be prominently displayed within the primary field of view of the pilot.	
Switching and Transfer Functions	System display and navigation solution shall not be degraded by electrical bus switching transients less than 1.6 second in duration. Ref. DO-229 3.3.1.3.2.1	
Failure Modes/Annunciations Readiness	All equipment failure annunciators should be tested during preflight to verify proper operation. Ref. DO-229 3.3.1.3.2.2	

Table B-5: Proposed Non-Certified GPS Flight Test

Compliance Item	Remarks	Assessment
EMC compatibility & Susceptibility of GPS with all VHF radios (Comm 1/2/6), E-2C Radar, & other avionics systems.	Particular attention should be given to other "L" band equipment, such as TCAS or SATCOM equipment; UHF/VHF transmissions on the frequencies listed below; high frequency (HF) communications systems; and especially the E-2 Radar system. The following VHF frequencies shall be evaluated: 121.150 MHz 131.250 MHz 121.175 MHz 131.275 MHz 121.200 MHz 131.300 MHz The following UHF frequencies shall be evaluated: 225.125 MHz 325.125 MHz 269.125 MHz 369.125 MHz 299.125 MHz 390.125 MHz DO-229 3.1.4.1.4	
Switching and Transfer Functions	System display and navigation solution shall not be degraded by electrical bus switching transients less than 1.6 second in duration. Ref. DO-229 3.3.1.3.2.1	
Failure Modes and Annunciations	Review, and verify where appropriate through demonstration, various failure modes and associated annunciations, such as loss of electrical power, loss of signal	

Table B-5: Continued

Compliance Item	Remarks	Assessment
	reception or GPS equipment failure. Verify that a warning associated with loss of navigation is accompanied by a visible indication within the pilot's normal field of view. Verify that audible alarms are sufficiently loud and of appropriate pitch quality, duration, and pattern. Verify that alarms are easily deactivated (but not easily deactivated inadvertently). DO-229C 3.3.1.3.2.2	
Display Visibility	Assess display visibility of the controls, displays, and annunciators from pilot and copilot design eye point of view DO-229 3.3.1.1.1	
Controls and Display Readability	Assess readability in total darkness to bright sunlight (to include indirect, reflected ambient conditions). No distracting cockpit glare or reflections may be introduced by the GPS/WAAS equipment and all controls must be illuminated for identification and ease of use. Colors, small symbols, and small alpha- numerics must be clearly distinguishable, brightness of (non-adjustable) annunciators must be acceptable, and brightness and contrast adjustments must be acceptable. Characters embedded in text must be distinguishable. Night lighting shall be consistent with other cockpit lighting. DO-283 2.1.7.2	
Control/Display Capability	Assess data input/output: Operable with one hand:	

Table B-5: Continued

Compliance Item	Remarks	Assessment
	Assess page labeling: Note page continuation identifiers: DO-229 3.3.1.1.2 DO-283 2.1.7.1	
Controls Accessibility, Usability	Evaluate the accessibility and usability of all controls pertaining to GPS. Verify that data entry procedures are in conformance with the requirements of Sections 2.2.1.2 and 3.3.1.2.2	
Displayed GPS Navigation Parameters	Evaluate displayed GPS navigation parameters on interface cockpit instruments such as HSI, CDI, distance display, electronic flight instruments system (EFIS), moving maps, fuel management systems, etc. Verify that display minimum discernible movement accuracy of the centered display, resolution of the electrical output, linearity of the display and/or electrical output, and display latency are appropriate for the navigation modes supported. DO-229C 3.3.1.3.2.4	
Continuity of Navigation Data	Verify continuity of navigation data during normal aircraft maneuvering for the navigation modes to be validated. RO-229C 3.3.1.3.2.7	
Direct-To Function	Verify that execution of an aircraft heading change to intercept a direct leg does not cause "S" turns. DO-229C 3.3.2.3.2.6	

Table B-5: Continued

Compliance Item	Remarks	Assessment
Fly-By Turn Performance	Conduct several fly-by turns. Verify that the equipment accomplishes the turn as a fly-by waypoint and discourages overshoot. DO-229C 3.3.1.3.2.8	
Cross-Track Deviation Display	For installations where GPS outputs can drive a display that is shared in common with other navigation equipment (e.g., TACAN, VOR/DME, ILS) the annunciation of the system in use shall be clearly indicated. Deviation from the desired track shall be displayed to the range and resolution requirements. Demonstrate minimum discernible movement, accuracy of the centered display, resolution of the electrical output, linearity of the display and/or electrical output, and display latency. DO-229C 3.3.1.2.1	
Evaluate work load requited to create, activate, or modify GPS flight plans.	Rate workload for performing routine functions such as entering and activating flight plan, SID, STAR, flight plan change, user waypoint definition. DO-229C 3.3.1.3.2.6	
Verify nav data during normal aircraft maneuvers and 360 turns at AOB = 15, 30, & 45 deg	Airframe masking: GPS nav mode selected, monitor integrity indicator and satellite data for uninterrupted coverage.	
GPS non-precision approaches	Fly multiple approaches and transitions from enroute to terminal to approach using the nav data base. Monitor display	

Table B-5: Continued

Compliance Item	Remarks	Assessment
	sensitivities, annunciations, waypoint sequencing. VMC only. Cross check GPS guidance against TACAN/VOR or INS information.	

Table B-6: Component Human Machine Interface Checklist

Operator Activity	Assessment (Pass/Fail/Comments)
Quantify force required to activate knobs/buttons.	
Quantify risk of inadvertent activation or deactivation based on control operation feedback	
Verify single-hand operations, controls identifiable, use does not obscure displays.	
Controls logically arranged according to functional groups, sequence of use, and frequency of use.	
Quantify chance of error, easy of error recovery, overall usability.	
Evaluate knob shape/size does not interfere with use, distinguishable, aids in pilots use.	
Evaluate label construction: discernible and readable on equipment.	
Evaluate label placement: display is unobstructed by use.	
Evaluate Terminology: Labels describe function of knob, consistent across equipment, abbreviations conform to aviation usage.	

VITA

James Mires grew up in the rural farming communities of south-central Kentucky. He graduated from Hart County High School in 1989 and enlisted in the United States Navy. His first year in the Navy included four months of Electricians "A" School and six months at the Navy's Nuclear Power School, both in Orlando, Florida. While at power school, he received a four-year ROTC scholarship to Auburn University. From Auburn University he received his Bachelor of Electrical Engineering. Following graduation, he attended primary flight training at VT-3 in Whiting Field, FL. From there, he proceeded through the E-2C/C-2A training pipeline to Kingsville, Texas, where he carrier qualified in the T-45A Goshawk. Having earned his Navy Aviator "Wings of Gold", he entered the E-2C Fleet Replacement Squadron in 1998, flying the E-2C Hawkeye for the first time. His first fleet tour as a "nugget" pilot was for the Seahawks of VAW 126. Following two deployments to the Mediterranean Sea and Arabian Gulf, James spent five months at the FRS as an instructor pilot. In 2002, he was accepted as a student test pilot for class 123 at the US Naval Test Pilot School in Patuxent River, Maryland. After graduating in June 2003, he spent two years as an E-2C/C-2A test pilot with Air Test and Evaluation Squadron 20. He currently is flying E-2Cs operationally in Norfolk, Virginia.