

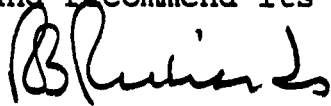
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C. Fredrick Watts,
Major Professor

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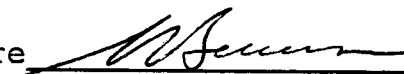
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AIRBORNE NAVIGATION SYSTEMS TESTING:
A TECHNICAL HANDBOOK FOR PERFORMANCE ANALYSIS
OF AIRBORNE NAVIGATION SYSTEMS IN NAVAL AIRCRAFT

A Thesis
Presented for the
Master of Science
Degree
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Philip C. Brennan

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ABSTRACT

Since man has first wandered out of sight of familiar surroundings, he has needed a means of returning from whence he came. The degree of accuracy required during the evolutionary processes of mankind and his desire for travel has varied widely. The purpose of this thesis is to develop a standardized method for testing and evaluating navigation sources that are common in military aircraft, present and future. The emphasis will be on the tactical aspects of navigation sources that affect the accuracy of the primary mission of the tactical aircraft, that is, delivery of weapons on the target.

This thesis will examine the following sources of enroute position fixing: Inertial navigation (INS), OMEGA Navigation System, Doppler Navigation, Long Range Navigation (LORAN C) and the TRANSIT Satellite navigation system, and will also examine the fields of Laser-ring gyroscopic Inertial Navigation Systems and satellite navigation using the Global Positioning System (GPS). The thesis will then present methods for functional testing and evaluation of the accuracy and tactical utility in the operational mission. It is assumed that each system described is a generic navigation system designed to meet the applicable military design specifications for a generic military multi-mission tactical aircraft.

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INTRODUCTION

The concept of navigating through the air mass involves a process of directing and monitoring the progress of the aircraft between selected geographic points from the time it takes off, attains operating altitude and reaches its destination. This introduces the need for accurate guidance and navigation in three dimensions. Prior to certification of an air navigation system as safe for use by both the military and civilian aviator, the system must be validated against known geographic and atmospheric truth data by reputable agencies of the Federal government who maintain a depth of experience in the test and evaluation of airborne navigation systems. Once the system is certified, then the individual user equipment that is integrated into the cockpit must be checked to ensure that the navigation system is fully integrated into the flight logic of the aircraft. This involves independent verification above and beyond the efforts provided by the contractor to ensure that the equipment is integrated into the airframe properly, that proper compromises have been made between optimum positioning for conflicting mission critical avionics and that the provided positioning system meets the performance specifications contracted against it. This thesis assumes that the proposed navigation systems under test and evaluation is optimally integrated into the aircraft weapon

system and that it meets or exceeds the design/contract specifications. It will focus only on the method for verification of the accuracy and performance of the system when compared to geographic and atmospheric truth data.

CHAPTER 1

NAVIGATION SYSTEMS AND MODELS

GENERAL

It is possible to classify airborne navigation systems into two broad categories, classical and self-contained. In a classical system, a transmitter radiates energy which travels through the airmass over one or more paths to a receiver. The derived navigational parameter is the time delay between transmission and reception of the signal. All classical systems assume that the transmitted wavefront is rectilinear and that the speed of propagation is a constant value. Classical navigation systems can be further sub-divided into single path and multiple path systems. The single path systems measure absolute transmission time and calculates lines of position. Position location is achieved through intersecting lines of position received from at least two (preferably three) different transmitting sources. The multiple path systems measure differences in the transmission times from each source. These systems calculate hyperbolic lines of position since the locus of points having a constant time difference from two other points is a hyperbola. Position location is achieved through intersecting hyperbolic lines of position from at least two (preferably three) transmitting stations. An essential error common to classical navigation systems is the error associated with Geometric Dilution of Precision (GDOP). GDOP

occurs when hyperbolic lines of position transmitted by separate navigation stations fail to intersect. GDOP is at a minimum value when the hyperbolic lines cross orthogonally and is at a maximum when they share a single point of tangency. The user must be aware of the effects of GDOP on the accuracy of the classical system.

There are three types of self-contained navigation systems. This is a misnomer as they all rely on observations made on external occurrences as a basis for their measurements. From these observations, the navigation parameters of course and speed are calculated and used to project an advanced position based on a known point in space. These systems include atmospheric pressure measuring devices such as an Air Data Computer, Doppler measurement of the apparent change in frequency due to the Doppler effect and inertial systems which measure forces applied to a stable platform in inertial space.

THE EARTH MODEL

Prior to evaluating the components of an aircraft navigation system, it is necessary to describe the model to be used as truth data. The Earth is best described as an oblate spheroid of revolution that rotates about its minor axis which joins the North and South poles. The degree of ellipticity (length of the major axis minus the length of the minor axis divided by the length of the major axis) can

be calculated and is currently valued at 0.003353. For purposes of evaluating airborne navigation systems, the Earth can be assumed to be a perfect sphere (degree of ellipticity is equal to zero). The Earth sphere has an equatorial circumference of 21,600 nautical miles (nmi) and rotates about its minor axis at a periodic rate of 1 revolution every 23 hours and 56 minutes. This gives a calculated equatorial speed of revolution of 902.5 nautical miles per hour (nmi/hr).

The Earth sphere is divided for position data by a series of intersecting lines. Those lines that are oriented North and South are labeled meridians or lines of longitude. Those lines that parallel a line proscribed at the equatorial position and are oriented orthogonal to the meridians are labeled as parallels of latitude. Several navigationally significant datum points are associated with these lines of latitude and longitude. The Prime Meridian (0 degrees longitude) directly bisects the pre-WW II position of the Royal Observatory in Greenwich, England. Longitudinal measurements are considered East progressing east of Greenwich and West proceeding west. The Equator (0 degrees latitude) is the reference datum for parallels of latitude. Parallels of latitude are considered north in the Northern hemisphere and south in the Southern hemisphere. Navigationally significant parallels of latitude in addition to the Equator include those located at 22.5 degrees North

(Tropic of Cancer) and 22.5 degrees South latitude (Tropic of Capricorn).

Complicating the Earth model are the existence of two distinct polar datum points for each minor axis. The true polar position is that which exists at the extremities of the minor axes of rotation. These are referred to as True North/South and are the reference datum against which navigation parameters are measured. In addition to the true poles, there are polar positions that exist as a direct result of the Earth's magnetic field. These magnetic poles, similiar to the poles on any bar magnet, are connected by magnetic lines of flux that envelope the earth sphere. The geographic position of these magnetic poles, labeled Magnetic North/South, vary with time and the intensity of the lines of magnetic flux. The position difference of Magnetic North from True North is measurable, predictable and is defined as variation.

Additionally, compasses that point the operator to the position of Magnetic North are subject to influences from local large magnetic sources, i.e., large steel ship superstructures, that deflect the compass needle from accurate location of the magnetic pole. This effect, defined as deviation, varies with each host platform, can be measured and is compensated for in navigation calculations. There are other error sources associated with airborne applications of the magnetic compass. These are introduced

by the motion of the aircraft and are defined in Appendix A, table 1.

The simplicity of the magnetic compass earmarks it as the primary backup navigation instrument for aviators. The naturally occurring error sources can be overcome in an emergency. Since the magnetic compass is an auxiliary navigation source in all military aircraft, it will not be discussed further.

TIME, DISTANCE, SPEED AND ALTITUDE

Movement over the surface of the earth sphere in an aircraft requires the definition of the following parameters: Time; distance; speed and altitude. Time is defined by Webster as "a non-spatial continuum in which events occur in apparently irreversible succession from past through the present to the future: , An interval separating two points on the continuum measured essentially by selecting a regularly occurring event." For navigation purposes, by international convention, the units of choice for time measurement are hours, minutes and seconds as defined by the National Cesium Clock maintained by the National Bureau of Standards, Washington D.C. Time is broadcast over high-frequency radios worldwide over stations WWV and WWVH (2.5, 5.0, 15.0, 15.0, 20.0 Megahertz (MHz) Upper Sideband) as Coordinated Universal Time (UTC or GMT). Time coordination is gaining greater importance in

navigation with the implementation of precise space-based positioning systems that require participants to finely synchronize clocks with satellite-borne atomic clocks. Time difference is an important measurement in hyperbolic based navigation systems and is a primary tool for use in Deduced Reckoning (DR).

Distance is defined as the length of a line between two points. The accepted standard unit of measurement for distance is the kilometer based on the Systeme International d'Unites (SI) units. However, navigation is based on a sexagesimal system of measurement (based on the number 60), and the nautical mile (nmi) is still the accepted distance reference. The nautical mile is defined as the length of arc of a great circle subtended by an angle of one minute at the center of the Earth. Therefore in a 1 degree arc projected on the Earth's surface that would contain 60 nautical miles. Small errors occur due to the Earth being an oblate spheroid as the average length of a minute of great circle arc is 6077 feet while the ideal spherical measurement of a minute of great circle arc is 6080 feet. The three foot error is considered negligible and 6080 feet is used by convention as the standard nautical mile measurement.

Speed is defined as the timed rate of change of distance. By convention, air navigation uses the units of nautical miles per hour (nmi/hr) or knots. For higher speed aircraft, those approaching or exceeding the speed of sound,

speed is given in the unit of Mach number. Mach number is defined as the ratio of the speed of the aircraft through the airmass to the speed of sound in the aircraft local vicinity. Aircraft speed will be indicated to the pilot via the Mach number gauge (or the Indicated Airspeed, IAS) in the cockpit. Pitot-static system corrections must be included in the display of Mach number and true airspeed.

The earth sphere is surrounded by a layer of mixed gasses to a thickness of approximately 500 miles. The atmospheric model used by convention is the International Standard Atmosphere as adopted by the International Civil Aviation Organization (ICAO) in 1952. The standard Atmosphere is defined with the following parameters measured at mean sea level; pressure equal to 1013.25 millibars of mercury, a temperature of +15 degrees Centigrade (C), a density of 1225 grams per cubic meter, and possesses an adiabatic lapse rate with a temperature decrease of 1.98 degrees C per thousand feet altitude until reaching 36,090 feet where the temperature thereafter is assumed to be a constant -56.5 degrees C to the extreme limits of the atmosphere. A depiction of the ICAO Standard Atmosphere can be found in Appendix B, figure 1. The standard atmospheric pressure at any altitude under standard conditions can be calculated with the following equation:

$$H = 221.152(T) \log (29.92/P) \quad (1)$$

where H= altitude in feet
 T= mean temp of air column (degrees K)
 P= air pressure at altitude (inches Hg)

Altitude is defined as the vertical distance above a reference datum. True Altitude (TA) is referenced as actual height above mean sea level and is considered by convention to be the reference for barometric altimeter measurements. Pressure inputs for barometric altimeter measurements come from the aircraft pitot-static system and for the purposes of navigation systems testing are considered corrected for inherent errors prior to arrival at the altitude input for the particular user device.

CHAPTER 2

SELF CONTAINED NAVIGATION SYSTEMS

INERTIAL NAVIGATION SYSTEM

General

The ability for self contained navigation for aircraft can directly trace its roots to navigational accuracy requirements for early generation ballistic missiles and host launching platforms. Refinements in both size and cost have lead to both permanently installed and so-called "strap down" inertial navigation devices in military aircraft. Inertial navigation is defined as the technique for determining a host vehicle's position and velocity by measuring its accelerometers in three dimensions (North, East and Up) and integrating those inputs to arrive at a computed position, course and speed. Advantages over other forms of airborne navigation systems include:

- 1). Instantaneous position and velocity are displayed to the pilot after inertial alignment
- 2). Since it relies on no external emissions, it is particularly suited to the covert nature of most military operations.
- 3). Worldwide coverage in all weather conditions

and at all latitudes.

4). Virtually unaffected by aircraft maneuvers in roll, pitch and yaw.

With all of the advantages inertial navigation systems present, there are some detracting factors:

1). Accelerometer based inertial systems are subject to degradation in accuracy over time.

2). Initialization and alignment of the stable platforms are required prior to use. Carrier based systems take longer to align due the motion of the host carrier and can transfer erroneous alignment data if it exist within the carrier inertial navigation system.

3). Navigation alignment at polar latitudes is not impossible but it is difficult to obtain.

A Basic System

Basic inertial systems contain a cluster of gimballed gyroscopic inertial platforms whose reactions to accelerations in three axes are picked off by linear accelerometers and forwarded to a general purpose digital

computer for calculation of an independent solution to the navigation question. A diagram of a basic inertial system is shown in Appendix B, figure 2.

Alignment

When the inertial system is initially powered on, the gyroscope/accelerometer cluster, or stable platform, must be initialized with its current position and orientation relative to the earth. Alignment of most inertial platforms is attained after the solution to five simultaneous differential equations for attitude and longitudinal position are obtained. Up to ten initial conditions must be supplied to the general purpose digital computer in order for initialization to occur. These are:

- 1). Two initial position coordinates: normally supplied as current latitude and longitude.
- 2). Two initial velocity coordinates: normally supplied as horizontal and vertical velocities (nominally zero).
- 3). Three platform orientation coordinates: two to determine true horizontal (platform leveling), and one for azimuth alignment (True North search).

4). Three platform orientation rates: normally transferred to the computer at the instant of switching from "alignment" mode to "navigation" mode.

As the aircraft moves away from its initialized position, the measured accelerations of the three orthogonally oriented accelerometers are integrated together and the actual vector value of the accelerations is attained and the differential equations are solved resulting in precise position information for aircraft use. Most accelerometers used in inertial systems utilize rotating, pendulous masses and detect motion through the use of some induction-type motion sensor. Many incorporate gyroscopic and viscous damping elements for smoothing the output acceleration. Some do not allow the mass to move opting rather for a force balancing transducer to cancel the motion. The output then would be the current or voltage required to counteract the sensed acceleration.

Military aircraft navigation instruments are subjected to sustained operations in roll, pitch and yaw with accelerations as high as nine times the force of gravity (9 g's) and must be capable of an accuracy of at least two nautical miles at mission completion. Accelerometers can sense the presence of vibration transmitted through airframe maneuver to the stable platform. Vibration can cause the

accelerometers to sense erroneous accelerations and forward these errors to the computer. A majority of these vibrations are damped out of the system through the use of gyroscopes that measure the effects of vibrations on the stable platform.

The Gyroscope

The purpose of the gyroscope in an inertial navigation system is to space stabilize the accelerometers(ref 1, p 292). The gyroscope acts as an error detector that forwards error messages to the general purpose digital computer and provides correction to eliminate the inadvertent rotation of the stable element to a value of zero referenced to its initial aligned position. There are two types of gyroscopes commonly used. Position gyroscopes sense the rotational displacement of the stable element around the input axis from its aligned position. Rate gyroscopes sense the rotational rate of the stable element around the input axis. Gyroscopes operate in accordance with the following physical principal: " A rapidly rotating mass will tend to maintain its orientation in inertial space, in the absence of applied torque. If torque acts on the mass, then it will precess at a constant rate" (ref 1, p 292). Inertial space is defined using a coordinate frame oriented at the center of the Earth that is not rotating with relation to the stars. The precession is used to correct the orientation of the stable

element and return it to the initialized conditions.

INERTIAL NAVIGATION SYSTEM INTEGRATION

The gyroscopic-stabilized cluster of accelerometers, or stable platform, is gimballed to isolate the platform from aircraft motion and to maintain it in a fixed orientation with respect to the center of the earth. Changes in gimbal angle are forwarded to the general purpose digital computer to indicate the aircraft maneuver angles in roll, pitch and yaw and are displayed on cockpit instruments. The primary function of the computer is to calculate the aircraft position and velocity from the outputs of the horizontal accelerometers. A secondary computer function is to calculate gyroscopic precession signals that are used to return the stable platform back to its aligned orientation with respect to true horizontal. The third accelerometer is used to smooth the barometric altimeter or air data computer inputs as aircraft altitude changes. Basic inertial systems also contain servo motors for platform stabilization, a display and control panel for initialization and monitoring system status/aircraft position, and some form of protection from aircraft power transients (i.e., battery, fuse).

Types of Inertial Navigation Systems

Analytic Systems

The system usage for gyroscopes depends on which type of

inertial system is installed in the host aircraft. If the INS is of the Analytic variety, the coordinate axes frame of reference is fixed in inertial space and as the Earth rotates and the aircraft system transits over the Earth's surface, the coordinate system appears to rotate with respect to local vertical and True North. Gyroscopic angular precession is measured to determine the orientation of the aircraft with respect to inertial space and local displacements from the aligned position. The accelerometers sense aircraft accelerations in the three axes relative to inertial space. The host aircraft computer computations resolve the inputs from the gyroscopes and accelerometers to solve a series of five second order differential equations prior to position information being forwarded to the pilot or mission computer navigation program.

Since the analytic inertial navigation system operates in a non-rotating frame of reference, there is no need to correct for the effects of Earth-rate rotation or the effects of the Coriolis force. Since the analytic inertial system requires no gyro torquing due to the fixed nature of the coordinate system, Schuler oscillations (a major source of error) are avoided. However, due to the computations required to navigate in inertial space, gravity (local vertical) components are computed and fed back into the mathematical model and constitute an equivalent Schuler system complete with oscillations. Schuler cycles are

discussed in detail in a paragraph on page 19.

Semi-analytic Systems

If the inertial navigation system is of the semi-analytic variety, gyroscopic inputs are used to orient the stable platform to a position that represents true local vertical and the other two coordinate axes define local horizontal. The semi-analytic system resolves the navigation problem into two dimensions. Gravitational corrections are applied to the stable platform as the host aircraft transits over the surface of the Earth.

A special implementation of the semi-analytic inertial system orients one of the horizontal coordinate axes to always seek the position of True North. This implementation, called a North-seeking semi-analytic inertial navigation system, provides instantaneous measurement of latitude, longitude and altitude displacement from the aligned position.

Another special implementation of the semi-analytic inertial system is the wander azimuth inertial navigation system. In a wander azimuth system, one of the horizontal axes is no longer required to continuously orient itself towards the position of True North. Based on an initialized True North orientation, computer calculations of gyroscopic displacement angles are used to maintain track of the position of True North. The accelerometer outputs are

resolved into North/South and East/West vector components. The disadvantage to this type of system is the amount of computer calculations required to resolve the location of True North and the vector mathematics for the motion through inertial space.

Vertical orientation of some semi-analytic inertial systems are maintained through the use of the vertical tracker. Other semi-analytic systems rely directly on barometric or radar altimeter altitude data for vertical orientation. The vertical tracker can be modeled as an undamped second order system that has a natural period identical to the period of a Schuler pendulum(ref 3, p 2.24). If altitude information is to be provided by the vertical tracker, it must be smoothed through barometric or radar altimeter smoothing as the actual vertical tracker output is basically unstable and its accuracy decays with time(ref 1, p 326). Together, the vertical tracker output with baro/radar altimeter smoothing can maintain an arbitrary orientation relative to the force of gravity. This creates an interesting effect that is the source of predictable periodic error in this type of inertial system.

Schuler Cycle Effects

The Schuler Pendulum

Imagine that the host aircraft is in a plane that is parallel to a tangent to the Earth out at some altitude. If

a cable was stretched from the center of the Earth and was attached to the aircraft at the point of tangency, true vertical could be continuously maintained. However, the aircraft, platform and attached cable act as a dynamic system known as a Schuler pendulum. This system has one periodic cycle of one complete oscillation every 84.4 minutes and a second periodic cycle every 24 hours. The second periodic cycle has little effect on the tactical jet inertial system and for purposes of this testing can be ignored. However, aircraft with long flight times, in excess of 12 hours from alignment to shutdown, must be aware of this second periodic error source and corrections must be applied during the computer calculations for accurate position fixing. The effects of the Schuler pendulum can be mathematically modeled and when used with the known factors of the Earth's rotation rate and aircraft latitude and altitude, the direction of local vertical can be calculated.

Basic Corrections

Additional calculations must be performed to compensate for centrifugal acceleration and the effects of the Coriolis force on moving aircraft. The rotation rate of the Earth input into the vertical calculation must take into account the direction of travel of the host aircraft. If the aircraft is moving in a westerly direction, the value for rotation rate must be decreased due to the effects of

aircraft motion contrary to the direction of rotation. The value for rotation rate must be increased if the aircraft is moving in an easterly direction due to the additive nature of the aircraft motion and the direction of rotation. Since the Earth is not a perfect sphere and is tilted on its minor axis, the distance to the center of rotation changes. The Coriolis force is responsible for an additional easterly acceleration when the aircraft is moving in a northerly direction and a westerly acceleration when the aircraft is moving in a southerly direction. Once these calculations are made, they must be compensated for and canceled out in the mathematical model resident in computer.

THE STRAP DOWN INERTIAL NAVIGATION SYSTEM

As the name implies, the strap down inertial navigation system is directly attached to the host airframe and as such is subjected to angular rates and accelerations that are measured in an entirely nonstabilized frame of reference. The computer calculates aircraft orientation from the outputs of the axial mounted gyroscopes and resolves accelerometer outputs to create local level coordinates which are then processed as if they were provided from a stable platform equipped system. The advantages associated with a strap down inertial navigation system are:

- 1). The system is less mechanically complex because

it is not gimballed. Computer calculations are substituted for hardware that is found in most semi-analytic inertial systems. This in turn makes it cost less.

2). The system requires no gyro-torquing as it calculates local coordinate reference frames continuously.

3). Corrections for Coriolis and centrifugal accelerations are unneeded due continuous computer calculations in the rotating frame of reference.

There are some disadvantages to the strap down inertial system. They are:

1). Gravity components must be calculated for all axes.

2). Complex computer calculations for coordinate transformation are required in real time.

3). There is no motion compensation as would be provided by a stable platform since the system is directly mounted to the movable aircraft.

4). Reduced accuracy due the combination of the above factors.

The strap down inertial system lacks a gimballed stable platform to provides motion isolation. Because of this, the internal motion sensors have a very large dynamic range of motion detection. This greatly reduces the accuracy of the system at low acceleration levels like those encountered during straight and level flying at transport aircraft type speeds. An additional source of error is generated by the continuous need for gravity calculations for all axes of the coordinate frame of reference.

THE LASER RING GYROSCOPE

In an attempt to improve the inertial navigation accuracy and reduce the amount and effect of error sources, navigation systems designers are beginning to use ring laser gyroscopes as a replacement for the mechanical inertial navigation systems.

Actual development of ring laser theory began in 1914 with the work of a French physicist, G. Sagnac. Sagnac's experiment was one square meter in size and consisted of a light source (probably not a laser as they were only theory at this time!) and four highly silvered reflecting mirrors oriented in a square. Sagnac was able to measure rotation rates as fast as 46,000 degrees per minute(ref 6 ,p 215).

The most important contribution to come out of the Sagnac experiment was the discovery that when the ring was rotated slightly, the light formed fringes and those fringes were displaced sideways as the loop was rotated. This resultant shift in light frequency is the basis for the ring laser gyroscope.

The example ring laser gyroscope consists of four helium-neon gas tubes positioned to form a square with Brewster angle windows and four corner reflecting mirrors. With the laser excited, the light beams travel around the circumference of the cavity of the laser so that each oscillates independently of the other three. Oscillation frequency depends on the length of path traveled. When the ring is slightly rotated, one of the light beams has to travel slightly farther thereby decreasing its frequency. The opposite beam length of travel is slightly shorter thereby increasing its frequency. The two beams are combined through a process called optical heterodyning and forwarded to a photodetector. The resultant beat frequency (from heterodyning) is directly proportional to the rotation rate of the ring(ref 6, p216). After further calculations, the final output is angular displacement that has been shown to be as accurate as 0.015 degrees(ref 6, p 217). Maximum sensitivity is obtained when when the axis of rotation of the sensor is perpendicular to the plane of rotation(ref 6, p 217).

The advantages posed by laser ring gyroscopes are obvious. The current generation of inertial navigation systems are subject to mechanical errors, gravitational and acceleration effects. The laser ring gyroscope is free of these effects. It is a motionless, strap down unit that is mechanically simple yet more sensitive to small accelerations and rotational effects from the host aircraft. The output is already digital rather than analog which makes the laser ring gyroscope much more adaptable to instantaneous position readout and no analog to digital conversion errors prior to computer position calculations.

ERROR SOURCES

Each inertial system possess characteristic errors that are propagated through the system that effect the position output. The most common errors associated with analytic and semi analytic systems are listed in Appendix A, table 2.

Some of the system errors are constant, some increase with time, some occur only in a dynamic environment. Errors are of two basic kinds, random and deterministic. Deterministic errors are predictable "biases" that can be compensated for and removed from the ultimate solution. Random errors are both unpredictable and uncorrelated with time.

THE DOPPLER NAVIGATION SYSTEM

General

The Doppler Navigation System (DNS) is a self contained dead reckoning system that obtains the necessary navigation information through the measurement of aircraft velocity using a Doppler radar and independant direction information of North and vertical from other aircraft sources. These components of North, vertical and aircraft velocity are integrated into two components of distance travelled since point of departure. Doppler velocity measurements can be separated into principal components of along-heading velocity, cross-heading (drift) velocity and vertical velocity. The Doppler navigation system outputs groundspeed, drift angle and vertical velocity.

The advantages of the Doppler system are:

- 1). Continuous velocity and position information with respect to the ground.
- 2). Completely self contained, no external source is required.
- 3). Supplies extremely accurate average velocity information.
- 4). Worldwide usage including in the Polar regions

where other systems are less effective.

- 5). All weather capable with no preflight or alignment time required.

It also has the following disadvantages:

- 1). Depends on other sources for azimuth and vertical reference information.
- 2). Military applications are limited due to the external radar emissions that compromise covert military operations.
- 3). Position information degrades with time as distance travelled increases and degrades in accuracy as the aircraft maneuvers.
- 4). Instantaneous velocity information is not as accurate as the average velocity.

A Basic System

A Doppler navigation system has three basic components, the Doppler radar, a heading reference and a digital computer that resolves the inputs into position information for display to the pilot. A diagram of a basic Doppler

navigation system can be found in Appendix B, figure 3. The Doppler radar measures aircraft velocity as a function of Doppler shift detected in the returned signal. The heading reference determines the orientation of the antenna array with respect to True North or ground track and also provides information for computer resolution of north and east velocities. A vertical reference, if employed, provides the aircraft pitch and roll angles to the antenna stabilization system. Not all Doppler systems have an antenna stabilization system, some are attached directly to the aircraft. Direct airframe mounting provides a minor source of error but it can be ignored due to the virtually instantaneous position information provided upon aircraft stabilization on course. The pitch and roll data provided by the vertical reference are combined with sensor velocity data and corrected velocities are used during position computations. In a stabilized antenna system, the antenna maintains local horizontal, thus the radar beams maintain constant orientation with respect to the aircraft velocity vector provided the maneuvers of the aircraft do not exceed the gimbal limits of the stabilization system.

Doppler Theory

The Doppler shift can be described as the apparent change in received frequency when there is relative motion between the transmitter and the receiver(ref 1, p 212). The

shift is directly proportional to the relative speed between the two. It makes no apparent difference if both the transmitter and receiver are moving. The detected Doppler shift in the return signal is converted into velocities using fairly complex calculations. A further technical discussion on Doppler theory can be found in reference 1.

Overland Operations

As the aircraft flies over land, the radar beams are subjected to scatter as they contact the earth surface. This gives rise to two paradoxes concerning overland operations. The smooth earth paradox implies arguments that as the aircraft flies over the smooth earth, the range to the ground does not apparently change, therefore there can be no closure, i.e., no Doppler shift. In fact, transmitted signals are reflected off of irregular shaped objects found on the surface of the earth and are backscattered in the direction of the receiver and eventually if enough signal is received, a Doppler shift can be calculated. The sloping earth paradox implies arguments that as the aircraft flies horizontally above upsloping earth, the range to the ground continually decreases. The closure rate is measured at a finite rate and the Doppler should indicate a closing velocity. The fact is that no error is detected due to the randomness of the Doppler correlation times and there is enough backscatter signal to overcome a rate of closure

measurement.

Overwater Operations

The Doppler navigation system is affected many ways during overwater operations. Due to the difference in reflecting medium for the Doppler signal, the returned signal strength is appreciably reduced primarily due to specular reflection(ref 1. p 217). As a result of received signal reduction or total loss, the Doppler system reverts to "memory operations" or a dead reckoning mode that uses the last known reliable value for aircraft velocity and uses it to dead reckon its position information. The effect is primarily noted in areas of very calm sea states and antenna depression angles that combine to give angles of incidence where the beam is scattered away from the receiver or absorbed by the water.

Another method to alleviate the effects of signal loss over water is to switch to fixed value of average velocity and use it as an input to the navigation computer. This form of compensation is a source of a great deal of error since it in no way reflects actual aircraft velocity performance in the environment. Another way to decrease the signal loss overwater is to beam shape the transmitted beam. This decreases the probability of error due to water attenuation at higher frequencies and increases the possibility of an increased signal to noise ratio of the received signal. This

is normally used in conjunction with other velocity bias corrections.

One of the most effective methods for increasing the reliability of Doppler systems over water is through the use of beam switching. The use of beam switching involves alternately switching between different Doppler radar beams. This technique alternates the antenna depression angles and changes the angles of incidence with the surface of the water. This produces two overlapping returns that the computer can use to calculate velocities. This technique is the most effective and the most complex method of reducing velocity bias errors overwater.

Other over water conditions affect the reliability of the Doppler system. One is the velocity error caused by flowing water which tends to shift the Doppler return an amount equal to the velocity of the flowing water. Another velocity error is caused by windblown water droplets and wind induced surface currents both of which require the operator to be knowledgeable of the current weather observations and compensate for them.

Doppler System Error Sources

Doppler navigation system errors can be broadly classified into two general categories, random and bias errors. Random errors are defined as those errors that vary during a flight or flight leg. Systematic or bias errors are

those errors that are constant, although unknown for the duration of the flight.(ref 1, p 255). These errors are listed in Appendix A, table 3.

Typical Doppler performance after a 10 nautical mile leg of flight contained errors of +0.5 knots velocity and 0.25 degrees of drift angle(ref 1, p 255).

CHAPTER 3

RADIO NAVIGATION SYSTEMS

GENERAL

Radio navigation is defined as the practice of determining position by means of externally generated radio-frequency electromagnetic waves(ref 5, p 2.55). Position is determined by the measurement of signal time of arrival, direction of arrival or received frequency. Position is fixed relative to the geographic position of the transmitting station.

Current radio-navigation systems can be broken down into enroute systems, and those found only in the terminal phase of flight. Only the enroute systems of OMEGA and LORAN-C will be discussed here. In general, these systems are primarily intended for position fixing in one or two dimensions due to the fact that in comparison to the distance from the transmitting station, aircraft altitude is negligible. The primary advantage to systems such as these is that the cost of the aircraft equipment is small and complexity is minimal.

Two factors that effect the performance of radio navigation systems are electromagnetic wave propagation (signal attenuation, multi-path, and velocity of propagation variations) and externally generated noise. Signal attenuation and externally generated noise are inversely related to each other. Signal attenuation increases with

increasing carrier frequencies while externally generated noise increases with decreasing frequencies. Multi-path affects direction or arrival of the transmitted signal. Speed of propagation variations affect internal time to distance conversions.

OMEGA WORLDWIDE NAVIGATION SYSTEM

General

The OMEGA navigation system, developed and implemented by the US Navy and the US Coast Guard, provides worldwide, all-weather radio navigation capability for airborne and surface users. The OMEGA system establishes a hyperbolic line of position (LOP) by measuring the phase difference between two continuous wave (CW) signals transmitted by two known stations. The user is required to observe the radiated signal characteristic from a minimum of two of stations. These provide intersecting LOP's which is also known as a position fix. The phase of the transmitted signal is a function of range from the transmitting station. The phase measurement can be compared to the measurement of signal time of arrival that is used by other radio navigation sources such as LORAN-C.

Specific

The OMEGA system uses CW phase comparison collected from pairs of stations which transmit time shared signals on four

distinct frequencies. The frequencies in order of use are 10.2 Kilohertz (kHz), 11.33 kHz, 13.6 kHz, and 11.05 kHz. Each station also uses a unique frequency to assist the operator in station identification. The OMEGA station locations are listed in Appendix A, table 4. OMEGA performance characteristics are summarized in Appendix A, table 5.

Propagation Characteristics

OMEGA depends on the electromagnetic propagation of precisely timed and sequenced radiofrequency (RF) signals that are transmitted in an expanding circular wave pattern. The received signal alternates between positive and negative values at a rate which depends on the transmitted signal frequency. The signal closely resembles and has many of the same physical characteristics of a basic sinusoidal wave. The frequency of 10.2 kHz completes one sinusoidal transmit cycle every 98 microseconds. If a receiver was co-located with the transmitter, the received signal would be phase-matched. As the receiver is moved away from the transmitter site, the additional time required for signal arrival creates time delay. As the receiver is moved farther away, more time delay and associated phased shift is encountered. When the receiver is equal in distance to one wavelength of the transmitted signal, (at 10.2 kHz the distance is 16 nmi) the phase is again synchronized. Beyond

the distance of one wavelength of the transmitted frequency, it is possible to find position but there are ambiguities that are sources of position error. For example, beyond 16 nmi at a transmit frequency of 10.2 kHz, phase shift of 1/8th of a cycle can be calculated to be a distance of 2 nmi. The phase measurement continues indefinitely. From this example, it is apparent that the measurement of the apparent phase shift between the original transmitted signal and the signal as received at the receiver is essentially insufficient as it does not disclose the specific whole number of wavelengths away from the transmitting station. Only the fractional phase shift from wavelength to wavelength is provided.

Lane Ambiguity Resolution

Any radio navigation signal that uses the observation of the relative phase of the CW signals for position determination will encounter the ambiguity discussed previously. Because of this ambiguity, the OMEGA receiver must be preset to a known preflight location. The accuracy of that location must be known to be within the lane width that the receiver is capable of generating (i.e., within 4 nmi for a single lane receiver or about 144 nmi for a four frequency receiver). Once it is set to a known location, the receiver counts the number of lanes it crosses during the course of the flight. In the event of a loss of power to the

OMEGA receiver, changes in the propagation conditions near sunset or sunrise, or environmental interference, it is necessary that the host platform have onboard another navigational source such as an INS with sufficient accuracy to resolve the position ambiguity to be used in conjunction with OMEGA to provide the necessary "memory" to resolve the ambiguity as the host platform moves from lane to lane.

Signal Propagation

Long range communication and navigation systems depend on the existence of the ionosphere which is located in the upper atmosphere between 40 and 150 nmi. The ionosphere is a region of electrically charged particles created and maintained by the influence of solar and cosmic radiation. At frequencies less than 50 MHz, the ionosphere functions as a mirror that reflects and refracts radio-frequency waves back towards the surface of the Earth. Transmitted frequency affects where in the ionosphere the signal is reflected. For VLF signals, such as OMEGA, the redirection occurs at the bottom of the ionosphere. The actual height of the ionosphere migrates between 50 +/- 7 nmi depending on time of day. At night, the reflection occurs at 55 nmi and during the daylight hours, it occurs at 43 nmi. Transition between day or night generates a minor source of error.

When the transmitter site and the receiver site are co-located in a daylight hemisphere, the signal path phase

shift accuracy is ± 5 lanes of zero phase difference ($2\frac{1}{2}$ wavelengths, 40 nmi at 10.2 kHz). For signal paths where both transmitter and receiver are in night conditions, the accuracy is reduced to ± 10 lanes of zero phase difference (5 wavelengths, ± 80 nmi at 10.2 kHz). For signal paths where a sunset or a sunrise line is between the transmitter and receiver, accuracy is further reduced due to the dynamic ionospheric transition. These propagation anomalies are predictable and occur on a regular basis. Corrections are applied through Propagation Correction Tables. For most airborne applications these corrections are programmed in the receiver and automatically accounted for during the position calculations.

Unpredictable Interference Sources

The dynamic nature of our solar system presents opportunities where interference with the normal signal propagation is observed. The results have a wide ranging effect on signal propagation and are usually unpredictable. Three such disturbances affect OMEGA performance: Sudden Ionospheric Disturbance (SID), Polar Cap Anomalies (PCA) and Modal Interference.

A SID is associated with additional ionizing solar radiation affecting the activity of the ionosphere. The additional ionization lowers the effective height of the ionospheric layer over daylight areas. This lowering forms

in a matter of minutes after a solar flare and can last anywhere from 45 minutes to three hours. SIDs may cause errors of 4 nmi or more depending on the observed transmit frequency.

A PCA is particularly noticeable at high latitudes and is caused by emission of high energy protons from the sun. These protons are concentrated around the high latitudes due to the orientation of the Earth's magnetic fields. The resultant effect is a reduction of ionospheric height which in turn affects OMEGA signal propagation when using stations with trans-polar transmission paths. PCA is evident normally within a few hours after a solar flare and can last from 1 to 3 days depending on flare strength. The nominal position error associated with PCA can be up to 8 nmi depending on the observed transmit frequency.

Modal interference is experienced when competing modes affect the predictable propagation characteristics of the transmitted signal. Three conditions can occur that will effect the accuracy of the transmitted signal. The first condition exists when a mode small in relative magnitude is competing with a dominant mode signal. The resultant signal is that the dominant will establish a near regular phase pattern. The second condition exists when the modes are of equal magnitude. The third and most common occurs when the modal dominance is altered. This occurs during periods of sunset and sunrise transition where one mode is dominant

during daylight conditions and a second mode is dominant at night. LOP errors can be a minimum of 8 nmi or more at 10.2 kHz. The areas and times of modal interference are generally predictable. The degree of error induced is unpredictable.

Airborne Employment

OMEGA transmission formats extend over a period of 10 seconds, therefore position information is updated every 10 seconds. At modern tactical aircraft speeds, a position update every 10 seconds is unsatisfactory for accurate navigation inputs into weapons delivery system computers. This problem is handled differently in each type of OMEGA receiver.

Common to most receiver systems is the use of the technique of rate-aiding. This technique artificially advances each phase so that it appears to have been received simultaneously. Aircraft heading and velocity are automatically entered into the OMEGA receiver to assist in rate-aiding the host platform. This projects changes on the basis aircraft heading and velocity to assist the receiver in holding on to its lane identification.

Corrections for propagation anomalies discussed earlier can be programmed directly into the OMEGA receiver. These are automatically applied to the calculated position. In the case of modal interference, the receiver can be programmed to automatically deselect the particular station responsible

for transmitting the particular signal. Receiver initialization with the initial start point is usually the only required entry. Continuous monitoring and comparison with other onboard navigation sources is also required in the event of the OMEGA system losing lane identification. The airborne OMEGA receiver is optimized for overwater flight and flight in unimproved areas. The development associated with large cities can distort the signal propagation flow.

LONG RANGE NAVIGATION (LORAN-C)

General

The LORAN-C navigation system is a hyperbolic radiofrequency navigation system that uses the transmit time of arrival difference from a known set of stations to determine a position fix. The system does not provide worldwide coverage but does cover most free world land masses with coverage extended to coastal areas. The system uses a station relationship known as "master/slave". The timing of transmissions between master and slaves is the critical factor in LORAN-C operations. The master station transmits its signal, then after receiving the signal from the master, the slave or slaves (depending on particular system architecture) transmit their respective signals. The LORAN-C receiver measures the time difference between the reception of the master and slave signals. Using information stored within the receiver, the receiver can

calculate the position on the hyperbolic line of position. Normally, two sets of master/slave station received signal combinations are necessary for accurate position fixing. In some times, it is possible that some degree of ambiguity can affect system accuracy. It is then required to sample a third set of signals to resolve the system ambiguity.

Specific

LORAN-C operates at a fixed frequency of 100 kHz and by convention must confine 90% of the radiated energy within the 90 to 110 kHz band(ref 1, p 193). Each pulse is radiated in such a way as to rapidly build up and decay slowly. A graphic representation of a typical LORAN-C transmitted signal is presented in figure 1.

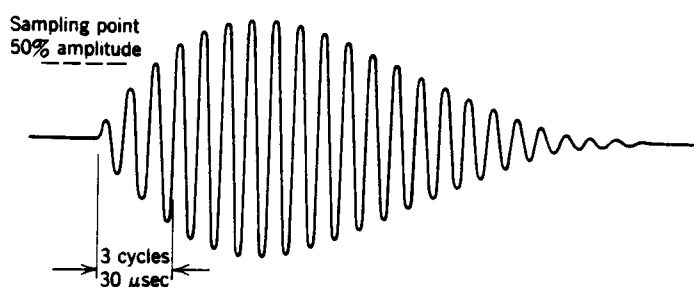


FIGURE 1
TYPICAL LORAN-C SIGNAL

The system is based on the measurement of the difference in the time of arrival of these pulses radiated by a chain of synchronized transmitter sites that are separated by hundreds of miles. The transmitter produces both ground and skywave signals. The receiver measures the time difference by comparing the zero crossing of a specified RF cycle within the pulse transmitted by master and slave stations within a chain. Making the comparison early in the transmit cycle assures that the receiver will use the ground wave based signal and ignore the slower skywave when it arrives. The skywave can be used but the user can encounter a considerable decrease in accuracy.

The LORAN-C transmitter generates the signal at a peak power of 4 megawatts. The waveform is generated pulses in groups of nine at a rate of 10-25 groups per second. Systemwide, there are 5 basic pulse rates, each with eight sub-groups of specific pulse rates. Pulse group spacing is 1000 microseconds(ref 1, p 194). Later, by an amount of time equal to one way transmission time from master to slave plus an additional 2000 microseconds for skywave dissolution, the slave transmits its eight pulse grouping also spaced 1000 microseconds apart(ref 1, p 195). Within a designated time the remainder of the slaves, if there are other slave stations associated with the chain, transmit their own signals. Each pulse within a grouping may be 180 degrees out of phase. This phase coding assists in identification of

particular station pairs and reduces skywave interference. This pulsing integration system allows the signal-to-noise ratio of the received signal to be greatly improved. The master station transmits nine pulses, the slaves eight. This allows for master station identification. LORAN-C signal transmission format is shown in figure 2.

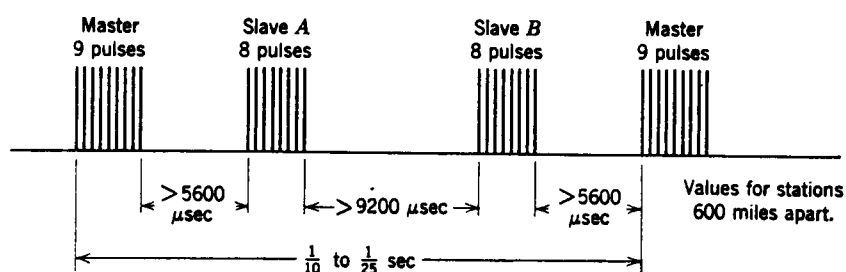


FIGURE 2

LORAN-C SIGNAL TRANSMISSION FORMAT

LORAN-C PERFORMANCE CHARACTERISTICS

The performance characteristics of the LORAN-C navigation system are summarized in Appendix A, table 6. The LORAN-C receivers are available at a relatively low cost and can achieve a great degree of accuracy in position fixing. The receiver is basically a 100 kHz scanner that uses a search and track operation scheme to search for and identify the signal emanating from the master station. The receiver identifies the master through its repetition rate

and phase coding. It then locks on a local reference oscillator for time reference. When the slave signals are received, the difference in times of arrival are calculated. By using this measured time delay, the receiver generates a position on a particular hyperbolic line of position. By comparing two such positions from different pairs of stations, a position fix can be plotted or displayed to the user.

Modern LORAN-C receivers are low weight (<25 lb.), have a low power consumption (<200 watts) and can automatically calculate a position fix and present it to the operator in latitude/longitude format. Some aircraft types use LORAN-C positions to smooth INS drift during Schuler divergences thereby increasing the accuracy of the other navigation systems onboard the aircraft.

CHAPTER 4

SATELLITE NAVIGATION SYSTEMS

GENERAL

Navigation by the means of a series of artificial satellites is a modern extension of a form of celestial navigation. With this follow-on, the user is no longer limited to line of sight angle measurements produced by sighting the celestial bodies but is supplied with a variety of measurements from which he can accurately calculate a position fix. By using satellites, the user is supplied with angular measurements as well as data in satellite position, range and range rates.

From the satellite, the user could receive the following data: satellite ephemeris and orbital corrections, ranging signals, time of day in Coordinated Universal Time (GMT) and downlinked signal propagation factors. From the supplied data, the user can compute the velocity and relative position of the satellite, range, range rate and orbital corrections that had been uplinked to the satellite by the controlling ground station. By combining this with data generated by the host platform's altitude, attitude and velocity, the satellite receiver can generate a circular line of position (LOP). When two or more circular LOP's are calculated, position fixing information can be presented to the operator. The position fix is normally generated in two dimensions (latitude and longitude) until the Global

Positioning System (GPS) is operational. GPS will also generate altitude for airborne platform applications. Some major advantages to satellite navigation are:

- 1). All weather service: Satellite RF signal propagation is less affected by atmospheric disturbances and absorption than are optical frequencies used for celestial observations.
- 2). Worldwide coverage: The satellite orbits are high enough in altitude to provide essentially worldwide navigation coverage. With some systems, coverage continuity is periodic and is dependent on the latitude of the user.
- 3). Extreme degree of accuracy: Direct path signals and lack of atmospheric contamination of the down-linked signals provide accuracies of +/- 50 feet of position error in three dimensions for some systems.
- 4). Secure operations: Military use of these systems can require signals to be encrypted and due to the covert nature of some military operations require receivers to remain passive only.

Some major disadvantages of the satellite systems are:

- 1). High cost: The complexity and expense of a satellite and associated ground control stations are costly to operate, maintain and replace when faulty.
- 2). Complex support equipment: Satellites must be tracked continuously and may require corrections applied to maintain the proper orbital parameters.
- 3). Satellite vulnerability: The advantages afforded to military users of the satellite generated navigation data make it a primary target for ground, air or space based anti-satellite weapons.

Orbital Error Sources

If the Earth were a perfect sphere, the orbit of a satellite would be inertially fixed and would be planar. Since neither a perfect sphere or perfect orbit are attainable, there are forces which act on the orbit of the satellite which affect the system performance.

The first of these error sources, or orbital perturbations, is caused by spherically assymetrical components of the earthly gravitational field. These errors are induced as the result of oscillations in the satellite orbit caused by varying lines of gravitational flux that the orbit must interface with(ref 9, p 37). The degree of effect depends on the orbital path as the satellites in

geosynchronous Equatorial orbit are relatively unaffected while non-polar (planar and elliptical) orbits that tend to cross all of the lines of flux receive the greatest effect. The remaining sources; luni-solar perturbations, air drag and magnetic/static electrical forces are dynamic type errors that are unpredictable error sources, and like gravity perturbations, can only be corrected for by the satellite ground controllers. If unable to correct the orbit, the mean life and the accuracy of the satellite data could severely decrease due to premature orbit decay or restrictions in the area of coverage.

Major Error Sources

Major error sources for satellite navigation systems are listed below:

- a). Signal Propagation Anomalies
- b). Multi-path Effects
- c). Satellite Ephemeris Errors
- d). Altitude Errors
- e). Velocity Errors
- f). Timing Errors
- g). Atmospheric Noise

For the TRANSIT and the Global Positioning System (GPS), which will be discussed later, these errors are common and vary in effect with each system.

THE NAVY NAVIGATION SATELLITE SYSTEM

General

The Navy Navigation Satellite System (NNSS) or more commonly referred to as the TRANSIT navigation system is a space-based navigation system which provides accurate two-dimensional position information to most submarines, surface ships, and for some specially equipped aircraft. The system is most widely used by many foreign, commercial and military surface vessels. The system consists of a minimum of four satellites in low altitude polar orbits, ground stations to track the orbital characteristics of the particular satellites and control facilities that inject updated orbital parameters every 12 hours.

Specific

The satellite network that comprises the TRANSIT network are designed to provide periodic position fixing information to a mixture of military/commercial users. The TRANSIT satellite is in a low altitude polar orbit of approximately 600 nautical miles in height above the surface of the Earth. The satellite system, comprised of at least four satellites, continuously broadcast ephemeris information on 150MHz and 400MHz. The user is required to only copy one of the transmitted frequencies however accuracy is greatly increased if both transmitted frequencies are used to obtain position data. The receiver measures the apparent Doppler

shift of the transmitted CW signal during the satellite approach and calculates a circular line of position based on known position of the satellite that is transmitted every two minutes. In addition to the Doppler signal, the satellite also transmits its orbital parameters and GMT time. The host vehicle must input ownship altitude and velocity. Accuracy in inputting the ownship data is imperative as an input error of 1 knot in velocity can result in approximately 0.2 nmi fix error(ref 4, p A-34).

TRANSIT navigation system performance characteristics are shown in Appendix A, table 6.

THE GLOBAL POSITIONING SYSTEM

General

The Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS) is a space-based navigation system that, when fully operational, will provide worldwide satellite position and velocity information in three dimensions to both civil and military users. The system, when fully deployed, will consist of 18 primary satellites with three orbiting spare vehicles. They will be placed equally spaced in circular orbits at an altitude of 10,898 nmi above the earth's surface. The arrangement of orbits and planar separation will give the satellites a periodic orbit of 12 hours. The orbital planes are inclined 55 degrees and spaced every 60 degrees apart as depicted in figure 3.

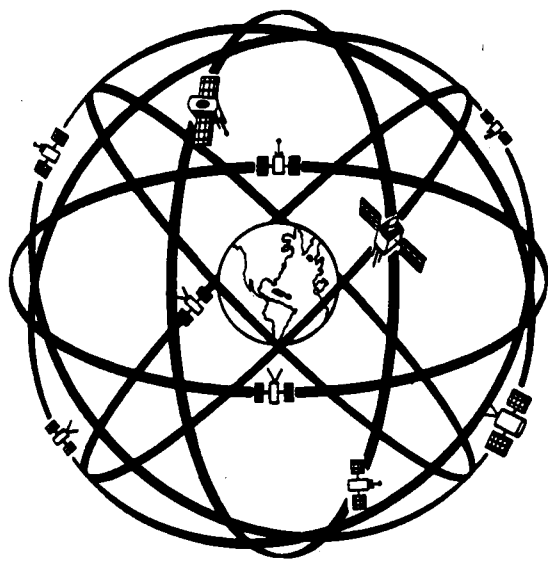


FIGURE 3

GPS SATELLITE ORBIT ORIENTATION

The GPS system is comprised of three distinct segments. The satellite vehicle, the ground-based control segment and the user segment. The satellite vehicle will be discussed further in a later paragraph. The function of the ground-based segment is to track the satellites, determine signal propagation error corrections based on transmitted signal monitoring and monitoring system timing errors. The ground-based control stations are also responsible for uplinking corrections to the satellite orbital parameters. Satellite orbits are monitored by several ground sites and deviations that are detected are flagged as errors. Orbital corrections are uplinked to the satellite as necessary to

maintain proper orbits. Satellite ephemeris data is corrected onboard the vehicle and corrected information is transmitted. In the event that the accuracy of a satellite or series of satellites has degraded, the ground station is also responsible for originating worldwide notification of the inaccuracies associated with the satellites in question. For the military user, this notification comes in the form of a Notice to Airmen (NOTAM) or a GPS Validity report.

The user segment has the most to benefit from the expected capabilities of the GPS system when fully deployed. Depending on the parameters and the complexity of the GPS user's equipment (UE), GPS presents very precise position information in latitude, longitude and altitude for a relatively low cost with worldwide coverage in all weather conditions. Military applications also include encrypted position data to greater degree of accuracy than that afforded to the civil user with the added benefits of being totally passive and jam resistant. The user will have access to extremely accurate time standards as each satellite contains 2 cesium and 2 rubidium atomic clocks that provide time accuracy in excess of that available to the users of current satellite navigation systems.

Military applications for GPS include but are not limited to the following:

- a). Search and Rescue
- b). Mine Placement

- c). Pre/post Mission Rendezvous
- d). Command & Control
- e). Low-level Navigation
- f). En-route Navigation
- g). Terminal Approaches (VFR/IFR)
- h). Precision Geodetic Survey
- i). Strategic Targeting

Each of these mission areas historically have suffered from imprecise position location information. Civil applications for GPS include but are not limited to the following:

- a). Enroute Navigation (surface/air)
- b). Terminal Navigation
- c). Oceanic/Coastal Navigation
- d). Hydrographic Surveying
- e). Aids to Navigation Placement
- f). Space Operations (landing, re-entry)
- g). Coordinated Search and Rescue
- h). Collision/Hazard Avoidance

Once the 18 satellite constellation is in place (currently estimated to be the middle of 1992), several forms of navigation will be replaced by functions embedded in GPS. For aircraft, GPS will present accurate enroute navigation information thereby negating the need for TACAN and will present precise enough position information that military aviators will be able to use GPS for instrument approaches into IFR airfields. Also for military pilots, GPS

will negate the need to actively radiate sensors to maintain location information on the aircraft carrier and will provide precise position information to strike pilots for low-level ingress and egress to a hostile target.

Specific

The GPS satellite system is similiar in function to the TRANSIT system but is more complex. Since there are more satellites available transmitting position information, coverage is continuous with the provision that at any one time at least four satellites will be visible to the user. Accuracy for the military user is estimated to be 50 feet spherical error probable (SEP). For civil users, the accuracy will be no less than 300 feet circular error probable (CEP)(ref 4, p A-31).

GPS is designed around the concept that precise position data for the user can be derived from accurate and continuous knowledge of the spatial position of the satellite in the constellation with respect to time and distance from a transmitting satellite to the user. Each satellite transmits unique ephemeris data thereby identifying itself. Each satellite continuously transmits a composite spread spectrum signal at 1227.6 and 1575.42 MHz that is composed of a precise navigation signal, a coarse navigation signal, satellite ephemeris data, atmospheric propagation correction data and atomic clock bias

information(ref 9, p 37). The two carrier frequencies are bi-phase modulated by psuedorandom sequences thereby providing spread spectrum signals. The 1575.42 MHz carrier signal, L(1), is modulated by a precision (P) signal at a chipping rate of 10.23 MHz (a chip is defined as the time interval of either a zero or a one in the pulse train) with a code long enough ensure a random signal. The signal repeats itself approximately every 280 days. The second psuedorandom sequence is a coarse acquisition (C/A) signal which is used either for initial acquisition of the P signal or as a less accurate navigation signal. The C/A code operates at a chipping rate of 1.023 MHz and repeats itself every 1 millisecond. The 1227.6 MHz signal, or L(2), is also bi-phase modulated but only with the P signal or as a ground station option, the C/A signal(ref 9, p 36).

By measuring the difference between the transmission and reception times of the satellite signal and multiplying those values by the speed of light, the apparent range to the satellite can be calculated. By measuring the frequency difference between the satellite clock and the user's clock, the line of sight velocity (range rate) between the two can be calculated. Due to the biases in time and frequency in the user clock, the measured range and range rate contain bias errors. They are therefore referred to as psuedorange and psuedorange rate(ref 9, p 25).

GPS USER EQUIPMENT

A generic GPS receiver for a tactical aircraft could be categorized as a high dynamic (HD) set. The HD set characteristics cover a broad range of performance requirements, environmental and dynamic conditions and operational scenarios. A generic HD receiver is shown in figure 4.

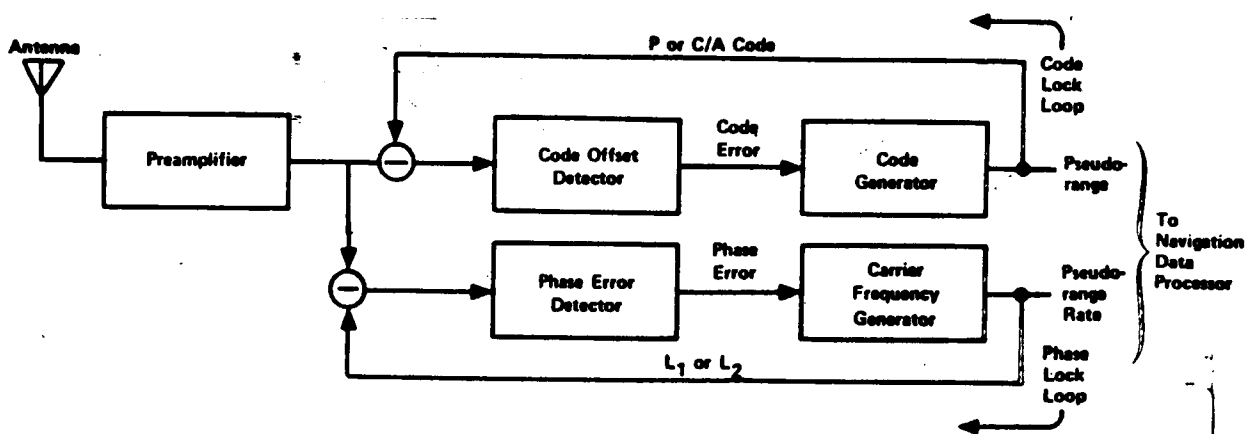


FIGURE 4

GENERIC GPS HIGH DYNAMIC RECEIVER

The performance of any GPS User Equipment (UE) such as the receiver is affected by a number of interrelated factors. Some of these are predictable, some have confidence level boundaries and others can only be estimated based on the mission of the host aircraft. These factors are:

- 1). Host vehicle dynamics including velocity,

acceleration, angular velocity and angular acceleration.

- 2). Ionospheric and Tropospheric effects
- 3). Multipath effects.
- 4). Uncompensated clock errors.
- 5) Ephemeris prediction uncertainties
- 6). Receiver noise and resolution.
- 7). Extreme environmental conditions.
- 8). Jamming, spoofing, nuclear events such as
Electromagnetic Pulse (EMP) effects.
- 9). Constellation geometry relative to UE.

Each of these affect the performance of the GPS receiver in a variety of ways.

The UE set data inputs and outputs will vary with the host vehicle type. A list of inputs and outputs for a generic HD receiver is presented below:

INPUTS	OUTPUTS
a). Satellite signals	a). Position, velocity, time
b). Position, velocity altitude, acceleration attitude	b). Altitude c). Steering data d). Time/Distance to waypoint
c). Waypoints	e). Groundspeed/groundtrack
d). Nav system mode	f). True heading/Mag heading g). Calendar/time of day h). Test and Status data i). Figure of merit

The received satellite signal near the earth is less than the background noise. To obtain the navigation signal, a generic receiver uses a phase lock loop to capture the carrier frequency while a code locked loop is used to track the coded signal. The receiver uses the difference between the phase lock loop signal and the satellite signal to calculate the Doppler shift of the satellite signal. The code locked loop is used to calculate the time delay between the receiver and the satellite signal.

CHAPTER 5

NAVIGATION SYSTEMS TEST AND EVALUATION PROCEDURES

GENERAL

Effective evaluation of the capabilities of airborne navigation systems cannot be complete without determining whether or not the system under test will suffice for the mission of the aircraft. At the same time, it is imperative that the evaluator be cognizant of the intended mission areas that the aircraft will be operating in. If the test system is intended solely for operations that require that the host platform be straight and level to obtain accurate position information it probably will not suit the navigation needs of a fighter aircraft. Intended mission knowledge is also critical for development of realistic test scenarios and flight test durations that are relatable to the duration and expected operational scenarios that the host aircraft will encounter.

Aircraft maneuvers that can be expected in actual operations must be performed in an effort to evaluate the test system limitations and any limitations it sets on the test aircraft. For example, if the gimbal limits of the Doppler navigation system only allow 20 degrees of pitch and 20 degrees of roll prior to complete system degradation into a dead reckoning mode, then perhaps it is not suited for an all weather attack aircraft that must erratically

maneuver (jink) to prevent fire control radar lock on and still deliver weapons accurately on the target. If the navigation suite onboard the aircraft contains multiple independent navigation systems, it is important that the evaluator judge the relative placement of the systems on the airframe. This will prevent degraded systems performance due to any antenna masking, casual interference or error coupling from system proximity.

A certain amount of the test effort will be pure number gathering for later comparison with the test system performance specifications. There is a part that is purely qualitative in nature that relies on the experience of the evaluator in the field and prior mission experiences in like aircraft. Without this experience base, evaluators must do extensive research into the mission areas of intended use, cockpit environment, controls and displays effect on pilot workload, mission relatable test scenarios and realistic accuracy and reliability/maintainability tests.

NAVIGATION SYSTEM ERGONOMICS

The design of the navigation system must be such that it becomes a help to the pilot not a source of more work. The man/machine interface in the cockpit must be designed in such a way that emphasis on the human factor be primary. Human factors engineers should be included in a test team to determine if the system design and layout is in accordance

with accepted ergonomic principals. Evaluation of the system for human factors compliance should be accomplished with a test subject (human or dummy) with suitable anthropometric measurements dressed in actual flight equipment (helmet, flight gloves, harness, personal survival equipment and flight suit) seated at the Designed Eye Position (DEP) for the aircraft. Controls should be tested for accessibility and function with flight gloves on. Displays should be tested both under daylight and night flying conditions for readability and contrast control. Data entry should be attempted in both static and dynamic environments to ensure that entry does not interfere with the safe operation of the aircraft in flight. If the test system is accurate to the millionth of a foot but cannot be used in the air safely then it is unsuitable for any aircraft.

NAVIGATION SYSTEM TRUTH DATA

Since the aim of testing navigation systems is to accurately determine position, it is obvious that the system performance must be judged against actual position data. The most accurate method of determining position is to conduct the test effort in an instrumented test range that can give instantaneous readout of space positioning data to the inch. The Chesapeake Test Range at the Naval Air Test Center, Patuxent River, MD is one such range. Three dimensional space positioning to the inch probably exceeds the accuracy

required for most navigation systems with the exception of the instrument approach capability that is advertised as a part of the Global Positioning System (GPS). The major drawback to using an instrumented test range is cost.

An alternate source of position truth data is available in the form of surveyed geographic points found on most charts or maps. By moving the test aircraft to a surveyed point on an airfield, the source of static truth data is available for static position accuracy testing. Dynamic testing requires the use of a series of geographic points along some route of flight. This method, called the flyover method, is an accurate way to judge the dynamic accuracy of the test system. The two most important factors to a successful flyover test are comprehensive preflight planning and flying the route prior to a data taking evolution to familiarize the pilot with the route of flight, enroute hazards and local area flying rules.

Comprehensive preflight planning can make a test flight successful. It involves members of the test team choosing a route of flight that contains a number of surveyed landmarks that can be easily discerned from an altitude of 200 to 1000 feet above ground level (AGL). Target selection can be tall towers, river junctions, railroad crossings, small towns, power plants or bridges. The only requirements for target selection are that the target be visible from the air at the specified altitudes and that the surveyed position from the

chart be current. Route of flight selection should be such that large, populated areas, restricted areas and airport traffic areas be avoided.

Flying the route prior to data collection can validate the choice of truth data both as visible and still there. Although for some aircraft the pre-data familiarization flight might be too long (12 to 15 hours in some cases), in most cases it has proved to be beneficial. The flyover technique involves target acquisition either visually or with radar/TACAN, flying directly over the point and recording the time and system position while "on top" of the point. If unable to fly directly over the top, data collectors must make every effort to determine the closest point of approach (CPA) and attempt to record any bearing and slant range to the target for post-flight error analysis. In an initial phase of the flight, it is advisable for the pilot to calibrate his eyeball using some form of visual reference and truth data for distance. This will reduce estimation error during a CPA flyover data point. This technique is flown for dynamic testing of all types of enroute navigation systems.

NAVIGATION SYSTEMS TESTS

Evaluation of a navigation system involves both static and dynamic testing. Ground testing of an installed navigation system gives the evaluator some qualitative data

on how the system will perform airborne. It also gives a quantitative data base of accuracy, performance, reliability/maintainability, system integration and human factors compliance with the design specifications against which the system performance is held accountable. Dynamic testing validates data discovered during ground testing and together with qualitative data from the pilot on system performance airborne can completely evaluate the navigation system under test.

The following tests are considered the minimum required for a complete evaluation of a particular navigation system. Not all apply to every system as some position fixing systems are nothing more than a series of independent events.

STATIC	DYNAMIC
A). Preflight	A). Static test A-E
B). Built-in Test (BIT)	B). Non-maneuvering Accuracy
C). Controls	C). Maneuvering Accuracy
D). Displays	D). Stabilization
E). Alignment	E). Ambiguity Resolution
F). Position Accuracy	
G). System Integration	

PREFLIGHT AND BUILT IN TEST

Purpose

The purpose of these tests is to determine the utility of the navigation system for warm-up time, time to determine the status of the system using the BIT equipment, depth and thoroughness of the preflight checklist and time for pre-flight insertion of data.

Procedure

With the aircraft on ground power or internal power, perform a normal navigation system preflight in accordance with the published preflight checklist noting the time of beginning and the time of completion. The operator should pay particular attention to logical order of turn on sequence, amount of data entry required, and whether or not other mission systems must be initialized prior to preflight of the navigation system. Perform a system BIT check in accordance with the published procedures noting time of beginning, time of completion and indications of system detected BIT failures. Correlate identified BIT failures with actual system performance to determine BIT accuracy in identifying faults. Comments as to cockpit placement, ease of operation and other qualitative comments should be recorded on supplied data cards.

Data Analysis

The mission relation for the preflight phase of the system turn-on must take into account the military requirements for rapid turn around of essential aircraft and the amount of operator workload required prior to launch. The evaluator must take into account the amount of other aircraft systems that require preflight initialization, and whether they can be accomplished concurrently or must be accomplished sequentially after the navigation system is operational. The amount of operator interface during preflight and running BIT should be analyzed in the context of other pilot tasks prior to launch and can it be accomplished at night and in adverse weather operations. Lengthy preflight and consistently erroneous BIT indications indicate an increased probability of late or missed launches when in an alert condition. Poor cockpit placement or other human factors violations will lead to increased pilot compensation and added workload that is unneeded in an already stressful environment.

Instrumentation Requirements

A clock is essential for this test. A handheld voice recorder for qualitative comments is optional.

Data Cards

Sample data cards are presented in figures 5 and 6.

DATA CARD _____

_____ NAVIGATION SYSTEM PREFLIGHT

BEGIN TIME _____

CHECKLIST

CLARITY OF INSTRUCTIONS:

LOGICAL SEQUENCE:

SYSTEM COVERAGE:

BIT

START TIME _____

END TIME _____

DIAGNOSTICS/PROBLEM ISOLATION:

ISOLATION TO THE SRA LEVEL: YES _____ NO _____

PREFLIGHT END TIME _____

QUALITATIVE COMMENTS:(continue on reverse as necessary)

FIGURE 5

NAVIGATION SYSTEM PREFLIGHT/BUILT-IN TEST

DATA CARD _____

NAVIGATION SYSTEM BUILT IN TEST

TIME OF START: _____

BIT INITIATION PROCEDURES:

BIT FAULT ISOLATION DISPLAY: CODES _____

BIT ACCURACY: ACTUAL FAULTS:

DISPLAYED BIT FAULTS:

EFFECTS OF BIT RUNNING DURING PREFLIGHT:

QUALITATIVE COMMENTS: (continue on reverse as required)

FIGURE 6

NAVIGATION SYSTEM BUILT-IN TEST

CONTROLS AND DISPLAYS

Purpose

The purpose of these tests is to evaluate the utility and suitability and man-machine interface of the navigation system controls and displays for the assigned missions of the aircraft in all environments. An additional purpose is to evaluate the controls for compliance with accepted human factors engineering practice and compliance with contracted human factors specifications (i.e., MILSTD 1472A, Human Factors Specification for Human Factors Utilization in Government Aircraft).

Test Procedures

General

Without the capability for the pilot to interact with the navigation system and receive accurate, readable data in a tactically significant format, the navigation system, however accurate, is without use in a tactical military aircraft. The push for human factors engineering has brought to the forefront the need for the system to be tactically usable by the flightcrew as well as accurate, easy to operate by 98 percent of all persons who make up flight crew and possess controls that can be operated in all conditions. The controls and displays must be operable in all flight regimes, day or night, fair or foul weather, peacetime or combat.

Specific

The aircraft should be on ground or internal power, navigation system on and aligned, and the evaluator in proper flight clothing (including flight gloves). The controls should be easily accessible while seated comfortably in the seat. The controls should be operable with a good degree of tactile differentiation to the major controls (ON/OFF, RESET, OPERATING MODE SELECT, BRIGHT/DIM). The differentiation should also extend to other systems in proximity to the navigation system controls. This will prevent inadvertant turning off the attack radar instead of switching modes of the navigation system. The controls should possess detents with definite tactile feedback to the operator that he has in fact made the proper selection. Controls that are expected to be used during other than straight and level flight should be accessable from the DEP (an aircraft design point for controls and displays). Controls must possess the correct operative sense, clockwise for ON/OFF, increasing intensity, etc. Controls should be logically grouped to eliminate searching for a particular control amidst a panel of small buttons. This also serves to reduce the pilot scan of the cockpit during normal periods. Controls should be integrated into the total cockpit layout and evaluated with the thought that the pilot must access multiple systems at the same time while airborne.

The displays should be clearly visible to the pilot in all

ambient light conditions (day, night, direct sunlight and direct glare into the display) from the DEP. The display should have a range of display intensities to cover all lighting conditions, for example, to prevent too much display light from blinding the pilot at night. Navigation information should be displayed in a clear and concise format in alphanumeric characters that cannot be confused with other symbology. Integrated displays (i.e., Heads-Up Display, tactical plot) should have navigation information displayed in such manner as to not interfere with other tactically significant data (i.e., cursors, target symbology, other graphics). The mechanization of the display should be such that it provides smooth, non-flickering symbologies, concise coded fault messages. The display should be capable of transitioning from different usages without too much residual display cluttering up the new display and it should be placed in a mission significant area of the cockpit. A display of navigation data located on the left side of the cockpit behind the throttles would make it difficult to update during a low level ingress to a target.

Probably the most critical portion of the controls and displays evaluation is the requirement that there must be a compromise for position of the controls and displays. The real estate in the cockpit of tactical aircraft is at a premium. Therefore the evaluator needs to qualitatively evaluate whether or not the compromise in control and

display placement is at an optimum for the aircraft mission.

Data Analysis

For reference purposes, the evaluator must include the anthropometric data and the calculated DEP used for the evaluation. Qualitative comments concerning the controls and displays could be corroborated with pictures, videotape or the actual control/display taken for analysis in a lab. Quantitative data such as controls with improper operative sense, no tactile differentiation, improper sensitivity, or displays with illegible symbologies, improper contrast and those that are too bright/too dim should be noted on the data cards. Mission relation for these anomalies involve a great increase in pilot workload, excessive operator compensation, or cluttering of the tactical display with illegible symbology that could mask a hostile target. Controls evaluation should contain a section for blind testing of tactile differentiation. Displays evaluations should be conducted in all lighting conditions.

Instrumentation Requirements

The evaluator should have the data cards and a tape measure for DEP calculation. A voice recorder, video recorder or camera would be optional for recording qualitative comments, control and display anomalies and for further analysis for specification compliance.

Data Cards

Sample data cards are presented in figures 7 and 8.

NAVIGATION SYSTEM ALIGNMENT

Purpose

The purpose of this test is to evaluate the capabilities of the navigation system under test to achieve a full system navigation capability in a minimal amount of time and a minimum of operator actions and begin providing accurate position information prior to launch of the aircraft. This is a generic test for all of the systems described in this manual.

Test Procedures

General

Navigation system alignment involves the process of initialization of the system coordinate frame of reference. This could include just simple actions such as turning it on and letting it calculate its position to very repetitive data entries that tell the system where it is, how it is oriented with relation to horizontal and vertical, where it is relation to True North or some other reference point. The time it takes and the number of data entries required to initialize the navigation system are critical data points in evaluating the system. Where the initialization and alignment fit in to the preflight setup of the aircraft is

DATA CARD _____

NAVIGATION SYSTEM CONTROLS

DEP POSITION _____ INCHES

TACTILE FEEDBACK:

NAVIGATION SYSTEM:

NAV SYSTEM COMPARED WITH OTHER SYSTEMS:

CONTROL ACCESSIBILITY:

LOGICAL GROUPING:

CONTROL SENSITIVITY:

CORRECT OPERATIVE SENSE:

MAJOR CONTROLS:

DATA ENTRY CONTROLS:

DISPLAY CONTROLS:

COCKPIT INTEGRATION:

QUALITATIVE COMMENTS:(continue on reverse as required)

FIGURE 7

NAVIGATION CONTROLS EVALUATION

DATA CARD _____

NAVIGATION SYSTEM DISPLAYS

DISPLAY INTENSITY:

LIGHTING CONDITION:

CONTROL SETTING:

UTILITY:

SYMBOLOLOGY LEGIBILITY:

CONTRAST/BRIGHTNESS/GAIN:

EFFECTIVENESS:

RANGE OF CONTROL:

DISPLAY REFRESH RATE:

DISPLAY RESIDUE UPON CHANGING DISPLAY SCREENS:

INTEGRATION WITH TACTICAL DISPLAY:

COCKPIT PLACEMENT/DISPLAY UTILITY:

QUALITATIVE COMMENTS: (continue on reverse as required)

FIGURE 8

NAVIGATION SYSTEM DISPLAY EVALUATION

critical also as other systems could rely on a rapid source of position information. The pilot has other systems to bring on the line as well so the amount of time spent initializing the navigation source can delay indications of mission readiness or alert launch against hostile aircraft .

Specific

The aircraft must be in a surveyed position thereby giving it a source of truth data. The surveyed position should also have a source of accurate heading data for another source of truth data. The aircraft should be on a source of stable power (external or internal) with the preflight for the navigation system complete. The evaluator should be in appropriate flight gear. Local navigation parameters such as local magnetic variation should be provided for input in the event no heading truth data is available. The system should be at local ambient temperature to avoid any thermal effects on some of the sensitive components. The evaluator should follow the initialization checklist and perform the required data entries. The time that data entry is started and completed should be recorded. Qualitative comments about the degree of difficulty encountered during data entry should also be recorded.

Once the data has been entered, begin the alignment by whatever method is suggested in the checklist. Record the time alignment is commenced. The evaluator should closely

monitor the progress of the alignment and look for any indications of alignment progress or malfunctions. When the alignment is complete, record the time of completion. The evaluator should then check the aligned position against the truth data and record any deviations, malfunction codes or any aircraft motion that occurred during the alignment. If the aircraft was moved during the alignment, record the time and duration of the interrupt and any effects on the alignment or position calculation.

Data Analysis

The data gathered during the alignment should be recorded on data cards. The degree of difficulty in entering initialization data, the time required to enter the data and the amount of data required to initialize the system are critical parameters. Other critical parameters include the time required for alignment of the system and accuracy of the aligned position are a measure of tactical utility. The evaluator should relate the time required to initialize the system to the need for rapid turnaround of tactical aircraft in a alert launch scenario. The evaluator should also comment on any indications observed during the alignment as to the status of the system or where in the alignment process the system is. The degree of accuracy of the aligned position is the primary data point to be gathered. If the position drifts with time or puts your aircraft in the other

hemisphere, the evaluator can relate this to the need for rapid, accurate initialized position data for aircraft in an alert launch.

Instrumentation Requirements

The evaluator will need a stopwatch, truth data position entries, local magnetic variation (if required) and data cards. A voice recorder for recording qualitative comments is recommended.

Data Cards

Sample data cards are presented in figures 9 and 10.

NAVIGATION SYSTEM STATIC POSITION ACCURACY

Purpose

The purpose of this test is to evaluate the position accuracy calculations in a static environment with known truth data for comparison and isolate significant errors that are not caused by a flight (dynamic) environment. An additional purpose of this test is to confirm the presence and effects of known physical phenomenon (Schuler cycle for inertial navigation systems, near and far modal effects for hyperbolic navigation systems, system drift with time, etc) on the static position accuracy of the navigation system.

DATA CARD _____

NAVIGATION SYSTEM ALIGNMENT

NAVIGATION TRUTH DATA:

LATITUDE: _____

LONGITUDE: _____

HEADING: _____

MAG VAR: _____

OUTSIDE AIR TEMPERATURE:

INITIALIZATION START TIME: _____

QUALITATIVE COMMENTS ON EASE OF ENTRY:

QUALITATIVE COMMENTS ON ANCILLARY SYSTEM EFFECTS:

QUALITATIVE COMMENTS ON CHECKLIST ENTRIES:

INITIALIZATION STOP TIME: _____

ALIGNMENT START TIME: _____

QUALITATIVE COMMENTS ON ALIGNMENT PROGRESS:

FIGURE 9

NAVIGATION SYSTEM ALIGNMENT EVALUATION

DATA CARD _____

NAVIGATION SYSTEM ALIGNMENT

IF AIRCRAFT IS MOVED NOTE TIME:

TIME ALIGNMENT SUSPENDED: _____

TIME ALIGNMENT RESTARTED: _____

ENTER NEW TRUTH DATA:

LATITUDE: _____

LONGITUDE: _____

HEADING: _____

MAG VAR: _____

NOTE TIME THAT ALIGNMENT IS COMPLETE:

TIME OF COMPLETION: _____

ALIGNED POSITION DATA:

DISPLAYED LATITUDE: _____

DISPLAYED LONGITUDE: _____

DISPLAYED HEADING: _____ MAG

DISPLAYED HEADING: _____ TRUE

DISPLAYED MAG VAR: _____

QUALITATIVE COMMENTS: (continued on reverse as required)

FIGURE 10

NAVIGATION SYSTEM ALIGNMENT EVALUATION (cont)

Test Procedures

General

Static position accuracy testing should be of long enough duration to see the effects of the physical phenomenon during a mission relatable time period. Static testing defines the performance baseline for the navigation system under test as all of the effects of flight dynamics are removed. Errors defined during this phase of testing will be magnified during any follow-on dynamic flight testing as total system error will increase.

Specific

Prior to beginning static testing it is necessary for the aircraft to be in a surveyed position for truth data. The position should be in a relatively open area clear of overhangs that might mask reception of transmitted navigation signals, if any. The system should be initialized and aligned in accordance with the initialization checklist. As the system is placed in the operate or navigate mode, record the time, initialized position and the true position. Observations of navigation system position fixing should be taken every minute for hyperbolic navigation systems and every five minutes for inertial systems for the duration of the test period. Record any system fault indications along with the time of occurrence. Upon completion of the test period, record the

final position and the time of the last observation.

Data Analysis

The difference between the truth data position and the observed position fix determined through the navigation system under evaluation is the static position error. Plot the data as distance error in nautical miles versus elapsed time of the evaluation. For inertial systems, this plot should be analyzed closely looking for the relative amount of position error caused by a pronounced Schuler cycle over the period of the cycle. For Hyperbolic navigation systems, each fixed position is considered an independent random event, therefore, the data should be plotted as an elliptical error probable centered on the truth data position. Scatter is of interest as it degrades the overall system accuracy by artificially enlarging the axes of the ellipse. Note any system faults that might have occurred during the test period and attempt to determine system implications, if the faults were valid and judge the reliability of the system performance monitor for percentage of operating time that invalid faults were displayed to the operator. Mission relation for static accuracy could involve the need for the aircraft to be turned on, warmed up and standing by for an alert launch as short as a five minute scramble. The system needs to have an accurate position prior to launch. With a poor static position accuracy over

time, the error could be gross enough to require a navigation re-initialization thereby negating the tactical advantage gained by strip alert aircraft.

Instrumentation Requirements

The evaluator will require a stopwatch, the data cards and truth data for the test. A handheld voice recorder for recording qualitative comments is optional.

Data Cards

Sample data cards are presented in figures 11 and 12.

SYSTEMS INTEGRATION

Purpose

The purpose of this test is to qualitatively evaluate the integration of the navigation system into the aircraft avionics and the cockpit. The major impact of this test will be to evaluate how the navigation system interfaces with systems that will use its position data and whether or not the system will suit the mission for which the aircraft was designed with this system installed.

Procedure

The aircraft must be on ground or internal power with the system on, aligned and statically navigating. This will provide navigation inputs to ancillary systems. The

DATA CARD _____

_____ NAVIGATION SYSTEM STATIC POSITION ACCURACY

TRUTH DATA POSITION:

LATITUDE _____

LONGITUDE _____

HEADING _____

MAG VAR _____

TIME COMMENCED _____

TIME	LAT	LONG	TIME	LAT	LONG
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____

FIGURE 11

NAVIGATION SYSTEM STATIC POSITION ACCURACY

DATA CARD _____

_____ NAVIGATION SYSTEM STATIC POSITION ACCURACY

TIME	LAT	LONG	TIME	LAT	LONG
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____

FAULT CODES DISCOVERED:

QUALITATIVE COMMENTS: (continued on reverse as required)

FIGURE 12
NAVIGATION SYSTEM STATIC POSITION ACCURACY (cont)

evaluator will then proceed with a basic cockpit evaluation. The cockpit evaluation should consist basically of determining how the system interacts when placed in mission relatable scenarios. This could be as easy as whether or not the display can be read while the evaluator is straining under simulated "g" forces to how many display screens must be cycled through prior to returning to the main navigation display. This is particularly important for "glass cockpits" that only contain multi-function display screen. An example could be to determine if the only screen available for updating the navigation position with a radar significant geographic point requires the operator to leave the radar display to activate the function or enter the coordinates for the update. The depth of this test relies on the mission relatability of the evaluator and the particular installation of the navigation suite.

Data Analysis

For analysis purposes, the deficiency data should be presented in relation to a specific mission. How a navigation system operates by itself will fulfill the requirements for testing specification compliance. How a navigation system is integrated into the total weapons system determines the complete viability of the aircraft. Qualitative comments as to the system integration should encompass ergonomic aspects as well as technical ones. If

the ON/OFF switch has to be turned on without a glove on then it probably is unsuitable for the mission of a tactical fighter. In general, the data gathered during this portion of the evaluation could overlap with previous tests conducted. This test is designed to evaluate a qualitative "How well does it all fit together?". The data should be analyzed with this in mind.

Instrumentation Requirements

The evaluator will need the data cards only. A voice recorder or video recorder would be optional for recording observed deficiencies as they happen or recording qualitative comments during this evaluation.

Data Cards

A sample data card is presented in figure 13.

DYNAMIC NON-MANEUVERING POSITION ACCURACY

Purpose

The purpose of this test is to evaluate the effects of dynamic flight on the accuracy of the navigation system, to also measure the non-maneuvering accuracy and evaluate the utility of the system for inflight use.

DATA CARD _____

_____ NAVIGATION SYSTEM INTEGRATION

CONTROLS:

DISPLAYS:

SOFTWARE:

SYMBOLOLOGY:

PHYSICAL LOCATION:

WITHIN FIELD OF VIEW:

ADEQUACY FOR MISSION :

QUALITATIVE COMMENTS:(continue on reverse as required)

FIGURE 13

NAVIGATION SYSTEM INTEGRATION

Procedure

General

The effects of the flight regime on aircraft systems is by no means predictable to 100 percent accuracy. However, the science of flight simulation and emulation can be a statistical source of system performance. If a three dimensional flight simulator is available, these tests could first be flown against the simulation scenario to determine effects of the accuracy on the system. This can prove to be "good headwork" if the system under test is being integrated into a new aircraft whose performance airborne is at best guess not 100 percent predictable. Fly-by-wire and fly-by-light aircraft systems do not yet have a wide statistical data base for predicting inflight performance, therefore, a simulator might be the first place to test the effects of a major subsystem such as a navigation system.

Static testing generated a performance baseline for the aircraft. Dynamic testing involves flying the aircraft over routes of flight containing known surveyed positions (truth data) in a straight and level attitude at the aircraft's best maximum endurance speed to minimize the effects of accelerations on the navigation system. The routes of flight for this testing should emphasize testing for the effects of the Schuler cycle, Coriolis, Earth rate rotation anomalies, wide variances in magnetic variation, high latitude effects and overland and overwater performance and any physical

effects peculiar to the particular navigation system under test.

Specific

Preflight planning for this test is the most important phase of this test! Prior to the flight, plan a low-level route of flight that contains navigationally significant points that have been recently surveyed for use as truth data. The time enroute should be such that at least one full Schuler cycle is observed, or at least one significant event such as observing the diurnal effect or polar cap absorption when testing OMEGA is observed. The time should also be relatable for the mission of the aircraft. Altitude selection should be such as to allow the pilot to observe the navigation point but should be have a floor no lower than 200 feet and recommended ceiling of no higher than 1000 feet.

Along the route, the pilot should record any maneuvers that exceed 1.0 "g", 10 degrees angle of bank, +/- 5 degree change in pitch or any yaw (crab angle) that exists on the aircraft or airspeed changes greater than 5 knots (indicated). The pilot should also record any system faults observed during the event for corellation during data reduction. Data points should be overflown as directly as possible, marking the point with a "Mark on top". The pilot should record the navigation system position displayed, aircraft course and speed, time on top and any faults noted.

If the test aircraft is off course arriving at the time of the turn point, the pilot should evaluate the system cues that alert the operator to the position of the turn point. Estimates of bearing and range to the point should be recorded and will result in scatter when the data is reduced.

Significant daily events that might effect the accuracy of the system should be researched and recorded at the appropriate times. Examples of these times could include, time of sunset near a particular OMEGA station, proximity to a station, any known sunspot activity and its anticipated effect, availability of VLF augment for OMEGA and environmental effects that could effect any skywave transmissions.

Once the aircraft has recovered, the navigation system should be respotted at the truth data point and the navigation system should be retested for static position error. This test measures the "forced" position error caused by the navigation system thinking it is still airborne. The system should be retested for at least one Schuler cycle (84.4 minutes) to observe any system degradation or faults induced by system anomalies.

Data Analysis

Once the data has been gathered, it is important to convert the latitude and longitude differences between truth

data and observed position into radial position error measured in nautical miles. This should be plotted in graph form depicting radial position error versus time (for inertial and other DR type systems) and elliptical error probable for other systems. Occurrences of error, such as fault lights or physical phenomenon should be annotated.

The mission relation for this test could involve the operational requirement for an attack aircraft to be able to navigate low-level while ingressing towards a target that would then require an accurate targeting solution from the navigation system prior to weapons delivery. If the error contained at the end of the ingress would prevent computing an accurate targeting solution, then the system is probably unsatisfactory for the attack mission.

Instrumentation Requirements

The evaluator will require a stop watch, low-level route chart properly indicating truth data points selected, and data cards. A voice recorder, video recorder or a data bus recorder for the navigation bus (if installed) are optional. for recording qualitative comments, recording the mission or recording the navigation inputs to the mission computer (if equipped).

Data Cards

Sample data cards are presented in figures 14 and 15.

DATA CARD _____

_____ NAV SYSTEM DYNAMIC NON-MANEUVERING ACCURACY

EVENT NUMBER _____

TIME _____

OBSERVED LATITUDE _____

OBSERVED LONGITUDE _____

COMMENTS:

EVENT NUMBER _____

TIME _____

OBSERVED LATITUDE _____

OBSERVED LONGITUDE _____

COMMENTS:

EVENT NUMBER _____

TIME _____

OBSERVED LATITUDE _____

OBSERVED LONGITUDE _____

COMMENTS:

FIGURE 14

NAV SYSTEM DYNAMIC NON-MANEUVERING POSITION ACCURACY

DATA CARD _____

_____ NAV SYSTEM DYNAMIC NON-MANEUVERING

EVENT NUMBER _____

TIME _____

OBSERVED LATITUDE _____

OBSERVED LONGITUDE _____

COMMENTS:

EVENT NUMBER _____

TIME _____

OBSERVED LATITUDE _____

OBSERVED LONGITUDE _____

COMMENTS:

EVENT NUMBER _____

TIME _____

OBSERVED LATITUDE _____

OBSERVED LONGITUDE _____

COMMENTS:

(data cards should be continued for the duration of the flight)

FIGURE 15

NAV SYSTEM DYNAMIC NON-MANEUVERING POSITION ACCURACY (cont)

DYNAMIC MANEUVERING POSITION ACCURACY

Purpose

The purpose of this test is to evaluate the dynamic maneuvering position accuracy of the navigation system under evaluation. An additional purpose is to determine the utility of the installed system while in a dynamic maneuvering scenario.

Procedure

General

The success of this test relies heavily on the preflight planning done for the non-dynamic maneuvering flight test. Once the dynamic baseline operation of the navigation system in straight and level flight has been determined, the next step is to determine the position accuracy that can be maintained during maneuvering under controlled conditions. Determining the maneuver limits of the aircraft with the installed navigation system can directly determine some of the tactical limits of the aircraft. A 9 "g" fighter aircraft cannot afford to have an inertial navigator that becomes unusable at less than 3 "g's" caused by a benign maneuver.

The test requires a build-up phase from very benign roll, pitch and yaw rates at medium airspeeds to final maneuvers that could be expected in a mission relatable scenario. A racetrack is flown over a series of two surveyed

geographic positions (truth data). The test aircraft flies the racetrack in orbits in both directions at increasing maneuver rates up to airframe limits if required. The evaluator must be aware of the subtle degradations in accuracy as well as the data point at which the position accuracy is beyond acceptable limits.

Specific

During the preflight planning portion of the test, select two surveyed waypoints that are sequentially placed along the route of flight. These will act as the truth data for the navigation system. It is very beneficial if the waypoints selected are within military controlled airspace (ie, Restricted Area, Military Operating Area (MOA)) or are totally contained in uncontrolled airspace. This will allow the pilot to be able to maneuver the aircraft as required by the test without placing his aircraft or others in risk of midair collision, or having to clear maneuver requests with a civilian controlling agency . A low altitude is optimum for visual observation of the waypoint.

The maneuvers required depend on the platform testing the system. For a tactical aircraft, the following maneuvers might apply:

- A). Minimum to maximum rate of climb
- B). Minimum to maximum rate of descent

- C). Minimum to maximum rate of turn
- D). Minimum to maximum turn radius
- E). Minimum to maximum maneuvers in roll, pitch and yaw
- F). Minimum to maximum level acceleration

These maneuvers should cover the minimum flight envelope of a tactical aircraft and should be accomplished in a build-up phase proceeding from the relatively low risk data points to the high-risk data points for each test.

The pilot should attempt to fly directly over the truth data point. If unable, record the bearing and range to the data point and actual position at the "mark on top" call. The pilot should record any degradations in system performance that is caused by the maneuver as well as any discrete failures and steering cues to the waypoints. Multiple passes around the race track might be necessary to gather enough data to judge system position accuracy.

Data Analysis

Dynamic position error should be plotted as a function of position error (latitude, longitude and radial) versus elapsed time. Maneuvers should be time correlated with the plot and significant maneuvers should be annotated where scatter in the plot is noted. The effects of dynamic maneuvering should be compared against the effects of non-maneuvering and related to a mission for a tactical

aircraft. An example of mission relation could be that the aircraft maintains non-maneuvering position accuracy within 0.5 nautical miles (radial) but when subjected to a series of 3 "g" turns position accuracy degrades to greater than 5 nautical miles (radial).

For hyperbolic systems, error should be plotted as North/South versus East/West error. This is done because each position is an independent event and should not be time correlated. This yields an elliptical error probable region of position accuracy. Significant maneuvers that affected the data scatter should be annotated on the plot.

During the maneuver test, the pilot should conduct an evaluation of the controls and displays during periods of "g" onset. The pilot should further comment on the quality and accuracy of the steering cues received during the overflights.

Instrumentation Requirements

The evaluator will require a stopwatch, data cards and visual acquisition of the truth data . A voice recorder, video recorder or any airframe instrument instrumentation to record airframe stresses during maneuver (i.e., an instrumented "g" meter in the cockpit) are optional.

Data Cards

Sample data cards are presented in figures 16, and 17.

DATA CARD _____

_____ NAV SYSTEM DYNAMIC MANEUVER POSITION ACCURACY

WAYPOINT TRUTH DATA:

LATITUDE _____/_____

LONGITUDE _____/_____

HEADING _____/_____

MAG VAR _____

ALIGNMENT POSITION:

LATITUDE _____

LONGITUDE _____

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

FIGURE 16

NAV SYSTEM DYNAMIC MANEUVERING POSITION ACCURACY

DATA CARD _____

_____ NAV SYSTEM DYNAMIC MANEUVER POSITION ACCURACY

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANUEVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

FIGURE 17

NAV SYSTEM DYNAMIC MANEUVERING POSITION ACCURACY (cont)

NAVIGATION SYSTEM STABILIZATION

Purpose

The purpose of this test is to determine the stabilization limits at which the navigation system performance begins to degrade and also the limits at which the system can no longer provide position data. The maneuvers to test the system stabilization will be to the limits of the airframe only.

Procedure

This test will validate contractor performance data for the stabilization of the navigation system. The initial determination requires that a ground test be accomplished to determine that the aircraft and the navigation system are aligned to a reference datum. This insures that the zero point for stabilization exists at a known point prior to dynamic testing. For example, if the aircraft normally flies at 16 units of angle of attack, the zero reference datum should reflect that this is the normal aircraft orientation.

Flight testing should be accomplished over known truth data points. The navigation system should be aligned and operating normally . The baseline performance for dynamic maneuvering has already been determined previously. Therefore, the pilot should know how the effects of "g" forces affect the system. The pilot should make every effort to maintain positive control of the stabilization testing to

insure that the maneuvers are performed in such a way as to not exceed maneuver limits in roll, pitch, yaw.

The test should be accomplished in a racetrack fashion with maneuvers planned to occur over the truth data points. This test should be accomplished in an area where the same airspace is available for the dynamic maneuvering testing. This test will use the same data point maneuvers as outlined in the dynamic maneuvering test and should be accomplished in a build-up phase method progressing from low to high risk data point. This test is similiar in fashion to the dynamic maneuver test except, in this test the evaluator is concerned with the airframe limits where initial degradation occurs. For example, the evaluator testing a stabilized Doppler navigation system should plan to determine at which pitch rate the groundspeed and drift angle become unusable. For the tactical fighter pilot, at which roll rate does the OMEGA derived position become unusable.

If the system has no inherent stabilization system, the data derived from this test can be gathered during the dynamic maneuvering evaluation.

Data Analysis

The data gathered from this test should be plotted as a function of position error (latitude, longitude and radial) distance versus time of flight. The evaluator should annotate the plot with time of each event and the type of event

performed. The plot should yield a snapshot of long-term system performance with minimum maneuvers performed to the limit of degradation. The evaluator should plot in tabular form the maneuver performed and the effect that the maneuver had on the system. If error lights illuminated or the navigation system automatically switched into a DR mode when a maneuver was detected, the performance table should be annotated to reflect that.

Mission relation for this test could include the need for a stabilized navigation system that can perform in an environment where the host aircraft must erratically maneuver (jink) during ingress to a weapons delivery point and need accurate navigation data for the weapons delivery solution upon arrival at the drop point.

Instrumentation Requirements

The evaluator will require a stopwatch for elapsed time, data cards and visual acquisition of the truth data points. The evaluator will need sufficient test equipment to validate the zero point for stabilization during the ground test. A portable voice recorder, an instrumented "g" meter and a source of pitch, roll, yaw and rate data (perhaps an instrumented data bus) are considered optional.

Data Cards

Sample data cards are presented in Figures 18 and 19.

DATA CARD _____

_____ NAVIGATION SYSTEM STABILIZATION

WAYPOINT TRUTH DATA:

LATITUDE _____ / _____

LONGITUDE _____ / _____

HEADING _____ / _____

MAGVAR _____

ALIGNMENT POSITION

LATITUDE _____

LONGITUDE _____

EVENT TIME _____

AIRSPEED _____

ALITIUDE _____

MANUEVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

FIGURE 18

NAVIGATION SYSTEM STABILIZATION

DATA CARD _____

_____ NAVIGATION SYSTEM STABILIZATION

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

EVENT TIME _____

AIRSPEED _____

ALTITUDE _____

MANEUVER _____

EVENT POSITION:

LATITUDE _____

LONGITUDE _____

BEARING _____

RANGE _____

COMMENTS:

FIGURE 19

NAVIGATION SYSTEM STABILIZATION(cont)

AMBIGUITY RESOLUTION

Purpose

The purpose of this test is to evaluate the capabilities of a hyperbolic navigation system to alert the operator to erroneous position entries during position updates.

Procedure

In pre-flight planning, the evaluator must select the geographic areas for the test conduct where there is little traffic found. The basic idea is to evaluate how the navigation system responds to incorrect entries for updates latitude and longitude position. Manual entry of an incorrect updated position forces the system into a phase of geographic position resolution conflict: the navigation system is calculating one position based on its measurements of time difference and signal frequencies but is manually overridden with false position data. The data points desired are to determine the time involved in resolving the false position data and the amount of false position entry in latitude and longitude that can be added to the system before the system blindly accepts the false position.

Position truth data for this test can be the inertial navigation system or the geographic test position. The amount of introduced error should be a gradual build up starting at 5 miles of error in latitude and be increased in increments of five nmi until the error exceeds 150 miles in

latitude and longitude. For each false position entry, the time of entry and the time of position error resolution should be recorded. Truth data position should be recorded to determine the accuracy of the ambiguity resolution.

Data Analysis

Data collected should be the incremental amount of error applied, the cumulative amount of error present, the difference in the resolved position with the truth data position and the time elapsed from error entry into the control to the resolution of the introduced ambiguity. It is only necessary to introduce an error of not more than 144 nmi to the lane phase repetition. The position error should be plotted as a function of time to resolve the ambiguity. An example for mission relation for this test is attempting to re-initialize the OMEGA or LORAN-C following a loss of power to the navigation equipment.

Instrumentation Requirements

The operator should record the data on handheld data cards. An accurate clock is essential for this test. A portable voice recorder is optional for recording qualitative comments.

Data Cards

A sample data card is presented in figure 20.

DATA CARD_____

_____ NAVIGATION SYSTEM AMBIGUITY RESOLUTION

EVENT TIME_____

DELTA IS THE DIFFERENCE BETWEEN TRUTH DATA POSITION AND
RESOLUTION POSITION.

TRUTH DATA POSITION_____

SOURCE_____ (INS/GPS/TACAN/etc)

LATITUDE_____

LONGITUDE_____

ALIGNED/FIXED POSITION_____

<u>ERROR AMOUNT</u>	<u>LATITUDE</u>	<u>LONGITUDE</u>	<u>TIME</u>	<u>DELTA</u>
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____

QUALITATIVE COMMENTS:

FIGURE 20

NAV SYSTEM AMBIGUITY RESOLUTION

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BIBLIOGRAPHY

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APPENDIX A

TABLE 1
MAGNETIC COMPASS ERROR SOURCES

Error	Source
1. Northerly Turning Error	- The compass card deflection caused by banked turns while airborne. Virtually eliminated by using a gyrocompass.
2. Speed Error	- The compass card deflection caused by horizontal speed changes while the aircraft is transiting on East/West courses.
3. Heeling Error	- Induced while flying straight course but at a banked attitude.
4. Swirl Error	- May occur when the fluid inside a wet compass is set in rotation during a turn.

TABLE 2
INERTIAL SYSTEM ERROR SOURCES

Errors	
General	Specific
Gyroscopic error	Output Drift Rate Torquing Error Scale Factor Acceleration Induced Non-linearity Misalignment
Accelerometer	Output Bias Scale Factor Cross Acceleration Non-linearity Misalignment
Stable Platform	Acceleration Induced Structural Misalignment Mass Imbalance Poor Motion Isolation
Computer Error	Gravity Model Error Sensor Compensation

TABLE 2 (CONT)
INERTIAL SYSTEM ERROR SOURCES

ERROR	
General	Specific
	Analog/Digital Conversion
	Round Off Error
	Computer Approximation
Initialization, Update	Position and Velocity
Gyro and Damping Errors	update error
	Platform Alignment

TABLE 3
DOPPLER NAVIGATION SYSTEM ERROR SOURCES

RANDOM ERRORS	BIAS ERRORS
A). Doppler fluctuation errors	A). Beam Direction
B). Beam direction	B). Frequency Tracker Error
C). Transmission frequency error	C). Low Terrain
D). Altitude Hole error	D). Overwater Calibration
E). Sea Current error	E). Installation error
F). Surface Wind Water Motion	F). Calibration error
G). Attitude Stabilization error	G). Readout error

TABLE 4
WORLDWIDE OMEGA STATION LOCATION

STATION	DESIGNATION	COORDINATES
NORWAY	A	N66 25.62 W013 08 12.12
LIBERIA	B	N06 18 19.11 W010 39 52.4
USA: OAHU, HA	C	N21 24 16.78 W157 49 51.51
USA: N. DAKOTA	D	N46 21 57.29 W098 20 08.77
LA REUNION (Fr)	E	S20. 58 27.03 E055 17 23.07
ARGENTINA	F	S43 03 12.89 W065 11 27.36
AUSTRALIA	G	S38 28 52.53 E146 56 06.51
JAPAN	H	N34 36 52.93 E129 27 12.57

TABLE 5
OMEGA SIGNAL PERFORMANCE CHARACTERISTICS

CHARACTERISTIC	EXPECTED PERFORMANCE
ACCURACY	2-4 nmi
AVAILABILITY	99+%
RELIABILITY	97%
FIX RATE	1 fix every 10 sec
FIX DIMENSION	2 dimension
USER CAPACITY	Unlimited

TABLE 6

LORAN-C PERFORMANCE CHARACTERISTICS

CHARACTERISTIC	EXPECTED PERFORMANCE
ACCURACY	60-300 feet
AVAILABILITY	99+%
RELIABILITY	99.7%
FIX RATE	10-20 fixes/minute
FIX DIMENSION	2 dimension
USER CAPACITY	Unlimited

TABLE 7
TRANSIT NAVIGATION SYSTEM PERFORMANCE

CHARACTERISTIC	EXPECTED PERFORMANCE
ACCURACY	45-150 feet
AVAILABILITY	99%
RELIABILITY	99%
FIX RATE	2 per minute
FIX DIMENSION	2 dimension
USER CAPACITY	Unlimited

APPENDIX B

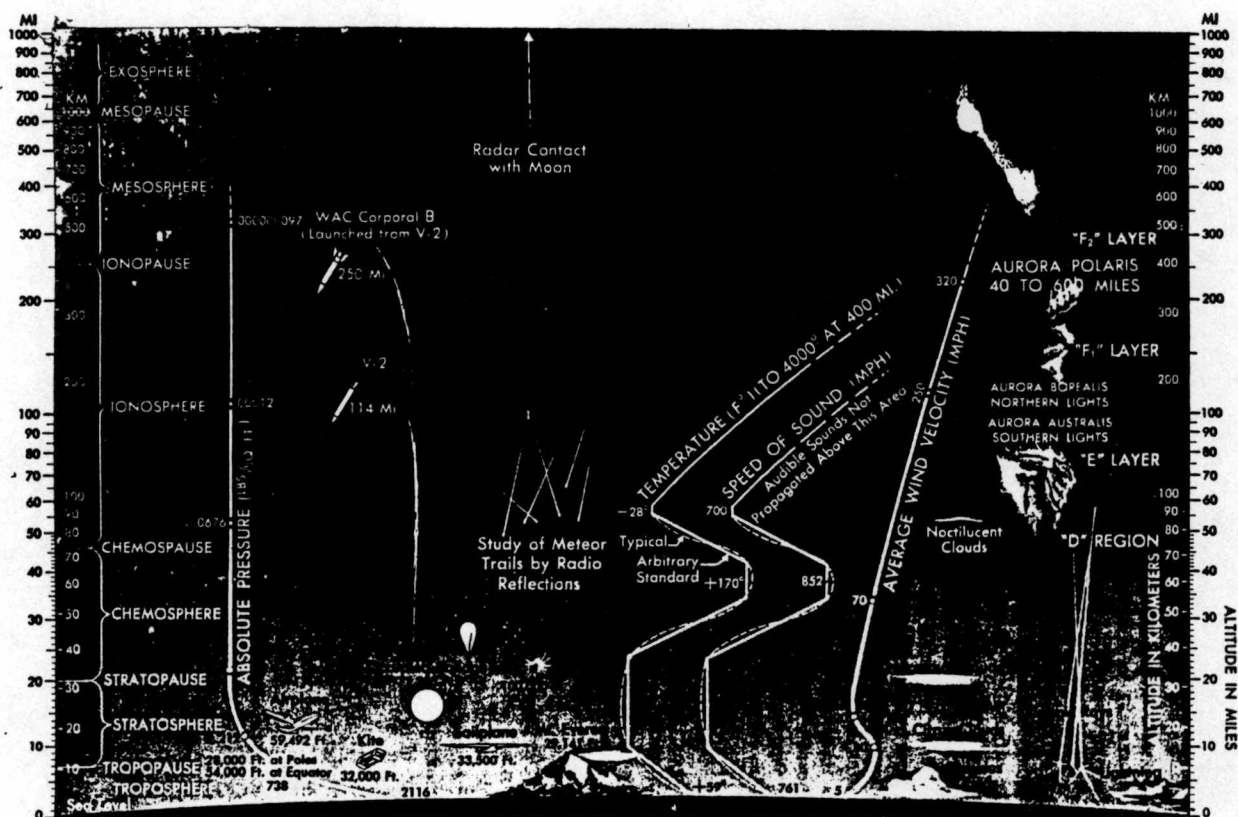


FIGURE B-1

ICAO STANDARD ATMOSPHERE

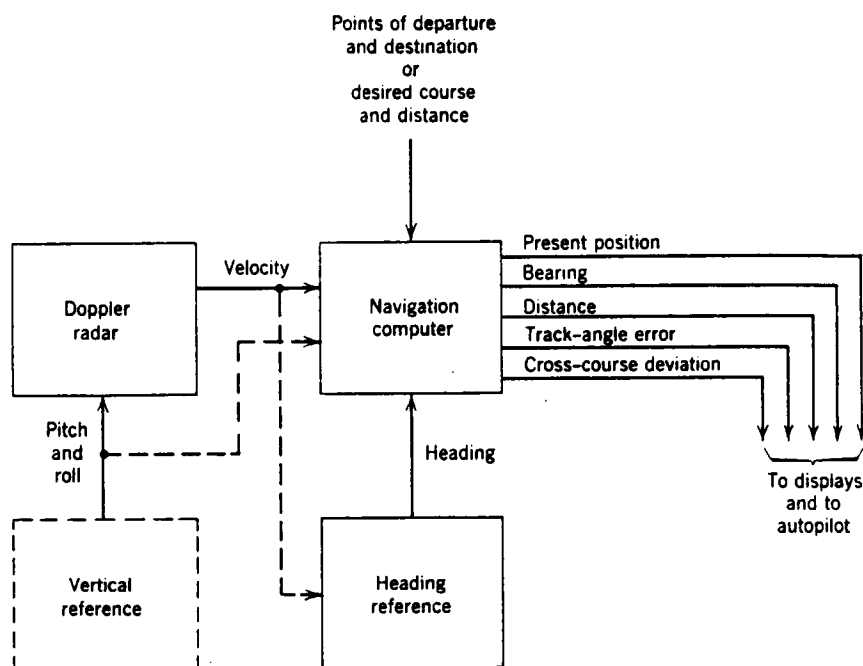


FIGURE B-2
BASIC INERTIAL NAVIGATION SYSTEM

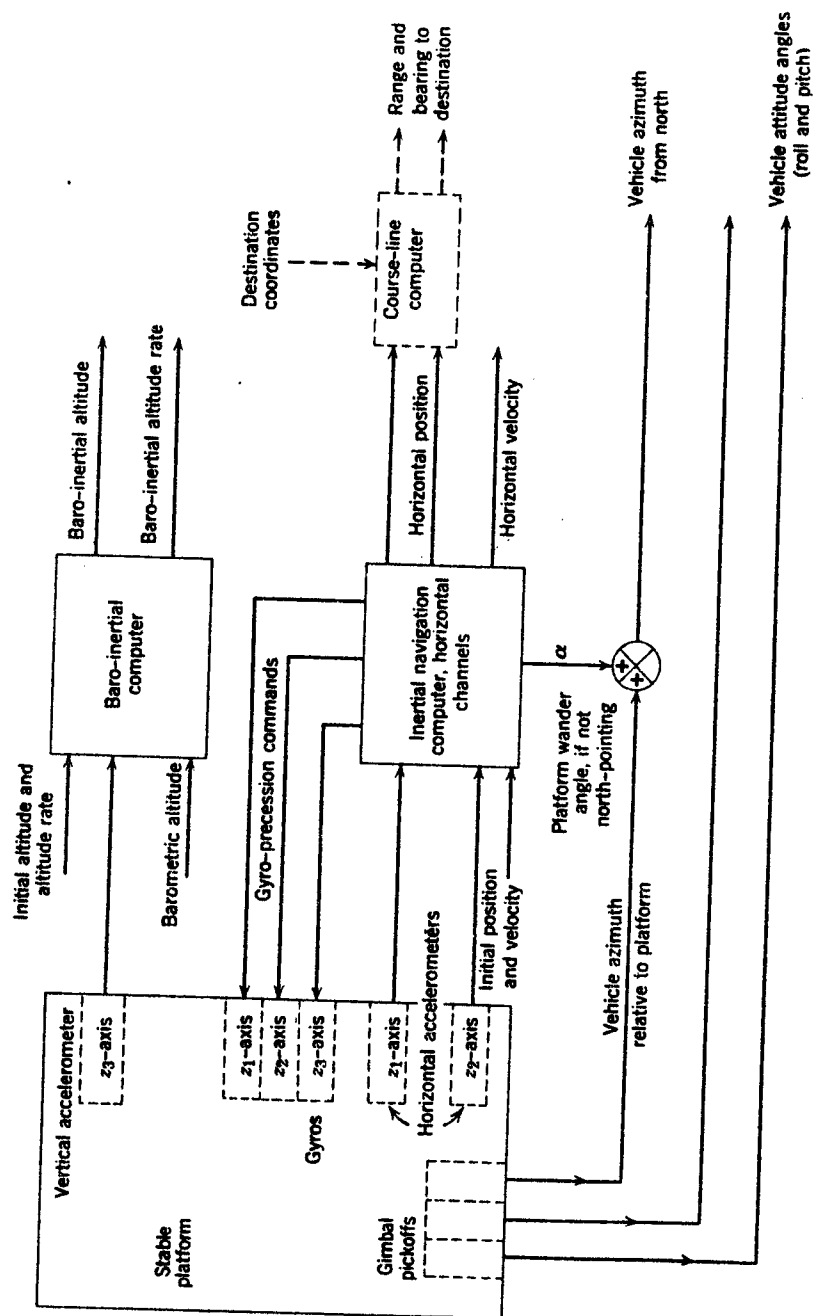


FIGURE B-3

BASIC DOPPLER NAVIGATION SYSTEM

VITA

Philip Clark Brennan was born in Portland, Oregon on June 30, 1954. He attended various elementary schools in the city and was graduated from Central Catholic High School in June of 1972. He enlisted in the U. S. Navy that summer and was voluntarily assigned to the submarine force serving on two different submarines; one diesel/electric and one nuclear powered. In the summer of 1974, he was appointed to the U.S. Naval Academy, Class of 1978, by the Secretary of the Navy. He graduated in June of 1978 and was assigned as Communications Officer on the USS Truxtun (CGN-35). He was awarded his Surface Warfare Officer qualification and subsequently was reassigned to flight school. Mr Brennan was awarded his Naval Flight Officer wings in October of 1982. He served in an E-2C squadron in various billets before being selected for the U.S. Naval Test Pilot School, located at the Naval Air Test Center, Patuxent River, MD. After successfully graduating, he was assigned as a test pilot at NATC where he was responsible for major programs in the area of updating the avionics in the E-2C.

The author is a life member of the Naval Academy Alumni Association and will remain on active duty in the Navy upon graduation.