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FLIGHT INSPECTION OF GNSS PROCEDURES

ABSTRACT

Over the past seven years the Federal Aviation Administration (FAA) has been actively involved in the development of policies, methods, and procedures for the implementation of GPS and related space-based technologies being introduced into the National Airspace System (NAS). Satellite navigation services require new technologies be implemented into the FAA flight inspection fleet. These include passive monitoring, non-precision approach, Wide Area Augmentation System (WAAS), and Local Area Augmentation System (LAAS). This paper describes the methods and policies being employed by the FAA to meet these requirements. System level descriptions of the equipment involved in the commissioning and periodic inspection of GPS-based instrument approach procedures are provided. The current automated Flight Inspection System (FIS) used aboard FAA aircraft is described along with the portable GPS Flight Inspection System (GFIS) unit for use on helicopter or non-FIS fixed wing aircraft.

INTRODUCTION

The Aviation System Standards (AVN) program is a part of the Air Traffic Services (ATS) line-of-business. ATS installs, operates, and maintains the National Airspace System (NAS). The AVN program provides flight procedures development, flight inspection of air navigation facilities and procedures, and maintenance of the flight inspection fleet. Procedures development and flight inspection operations are worldwide in scope and include domestic and overseas Department of Defense facilities.

The AVN organization has three elements: the National Flight Procedures Office, the Flight Inspection Operations Division, and the Flight Inspection Maintenance Division. These offices are located at the Mike Monroney Aeronautical Center in Oklahoma City. In addition, we have four Flight Inspection Offices (FIO) located in Atlanta, GA, Battle Creek, MI, Sacramento, CA, and Oklahoma City, OK, and an International Flight Inspection Office (IFIO) also located in Oklahoma City. The Flight Inspection Operations Division is made up of five branches; Flight Inspection Technical Support, Evaluation and Training, Flight Inspection Policy and Standards, Aircrew Resources, and Flight Inspection Central Operations. The flight inspection mission is accomplished by a fleet of 33 aircraft including eighteen Beechcraft Super King Air 300s, six British Aerospace 125-800s, six Lear 60s and three Challenger CL601s. Each airframe is equipped with an automated Flight Inspection System (FIS) that provides independent, post-processing of flight inspection and aircraft position data. All aircraft operations are conducted under Part 135 of the Federal Aviation Regulations.

GPS REQUIREMENTS

AVN is responsible for the development, review, maintenance, and revision of standard and special instrument approach procedures within the NAS. The NAS currently includes over 9,300 instrument approach procedures predicated on ground-based facilities such as the Non-directional Beacon (NDB), Very High Frequency Omnidirectional range (VOR), Distance Measuring Equipment (DME), Tactical Air Navigation system (TACAN), Microwave Landing System (MLS), and Instrument Landing Systems (ILS). Flight inspection of these facilities and procedures required more than 17,500 flight hours in fiscal year 2001 for the commissioning of new or upgraded facilities and periodic inspections of existing systems and procedures. Over 1,500 of these hours was for Department of Defense facilities in the United States and around the world.

Area Navigation (RNAV)

GPS-based approaches are published as area navigation (RNAV) procedures. RNAV is a method of navigation that allows operation on any desired course within the coverage of ground-based systems, satellite systems, or self-contained systems (inertial navigation). RNAV may use waypoints (latitude/longitude), fixes (azimuth and distance), or offsets from the existing airway/route structure. RNAV instrument approach charts may include several levels of landing minimums based on three-dimensional (GPS/Wide Area Augmentation System [WAAS] or lateral GPS and barometric vertical), and two-dimensional (GPS or inertial lateral) navigation.

Required Navigation Performance (RNP)

The continuing growth of aviation places increasing demands on airspace capacity and emphasizes the need for the best use of the available airspace. These factors, along with the enhanced accuracy of current navigation systems and the requirement for operational efficiency in terms of direct routings and track-keeping accuracy, have resulted in the concept of Required Navigation Performance (RNP).

Rapid changes in technology in the area of navigation performance, including the change from source- to earth-referenced systems, provide the foundation for aviation's global evolution. This progress will be marked by combining all elements of communication, navigation, and surveillance, and air traffic management (ATM) into tomorrow's CNS/ATM based systems. Concepts in CNS/ATM such as RNP provide the path for this transition.

RNP is a statement of the navigation performance accuracy necessary for operation within a defined airspace. The term RNP is also applied as a descriptor for airspace, routes, and procedures (including departures, arrivals, and instrument approach procedures). The descriptor is flexible and can apply to a unique approach procedure or to a large region of airspace. RNP applies to navigation performance within an airspace, and therefore includes the capability of both the available infrastructure (navigation aids) and the aircraft.

RNP can include both performance and functional requirements, and is indicated by the RNP or RNP RNAV type. [1,2] RNP RNAV environment standards are intended for designers, manufacturers, and installers of avionics equipment, as well as service providers and users of these systems for global operations. The system performance provides guidance for the development of airspace and operational procedures needed to obtain the benefits of improved navigation capability.

RNP or RNP RNAV type is used to specify navigation requirements for the airspace. The required performance is obtained through a combination of aircraft capability and the level of service provided by the corresponding navigation infrastructure. From a broad perspective, the equation to be satisfied for the evolution to RNAV and RNP RNAV is:

aircraft capability + level of service = access.

In this context, aircraft capability refers to the airworthiness, certification, and operational approval elements (including avionics, maintenance, database, human factors, pilot procedures, training, and other issues). The level of service element refers to the airspace system infrastructure (including signal-in-space performance, availability of source, and air traffic management). When considered collectively, these elements result in providing access. Access provides the desired benefit (airspace, procedures, routes of flight, etc.).

Nonprecision Approach

In 1994, the FAA published over 4,000 nonprecision GPS approaches as overlays of existing ground-based procedures. In 1995, AVN began developing stand-alone GPS nonprecision approaches at a rate of 500 per year. Many of these replaced the overlay approaches with equal or better minimums, and others provided airports that never had approaches with new procedures. To date, AVN has developed over 2,600 nonprecision GPS procedures.

FAA policy is to establish a nonprecision and/or precision GPS approach to each Instrument Flight Rules (IFR) qualified end-of-runway in the United States not currently served by GPS in less than three years. This goal will be achieved through continued nonprecision stand-alone GPS procedures and the transition to WAAS procedures development.

Wide Area Augmentation System

WAAS implementation is being accomplished in two phases. Phase 1 (initial operational capability) will provide precision approach capability with an availability of 95 percent. The central United States will have greater than 95 percent service availability and border states less than 95 percent. Phase 1 will include two geostationary satellites and 25 reference stations. This phase will provide en route and terminal navigation along with nonprecision and precision approaches without redundancy. Phase 1 is planned for public use in 2001.

Phase 2 (end-state) will have options for as many as 8 geostationary satellites and 24 additional reference stations and provide primary-means capability. Service availability will increase to 99.9 percent. Phase 2 also includes automatic Notice to Airmen capabilities, predictive service volume modeling, remote maintenance monitoring, international connectivity, and other improvements.

It will take almost nine years to provide a GPS/WAAS precision approach to every IFR end-of-runway currently served by a ground-based facility. A three-dimensional (precision) approach based on WAAS Terminal Instrument Approach (TERPS) criteria will be designed for each runway end currently served by an existing ground-based approach procedure. [3,4,5]

Initial procedure development began in 1999 with a goal of having 50 WAAS-based precision procedures published on the Phase 1 commissioning date. Development will continue at a rate of 500 RNAV approaches per year until the current functional capability of the NAS is matched by WAAS-based procedures. In addition, it is estimated that over 200 new GPS-based helicopter procedures will be required.

Local Area Augmentation System

The LAAS program has been approved as a cooperative venture between government and industry. The program is established in three stages.

In Stage 1, the FAA is working with various manufacturers to develop a Cat I system. This stage incorporates much of the experience industry gained in the Special Category I Differential GPS (SCAT-1) program. There will be no government funding used for Stage 1; only in-kind resources will be provided. These systems will be approved for nonfederal ownership. For Stage 2, the government-industry consortium will develop Cat II/III ground systems, avionics and necessary software. Fees will be awarded in accordance with development milestones. Stage 3 will be the government acquisition program to provide full operational capability in 2006. The government expects to purchase 143 systems (31 Cat 1 and 112 Cat II/III).

The LAAS system includes the differential ground station, a VHF data broadcast (VDB) function, and pseudolites when required for Cat II/III operations. The standard VDB service volume will be 23 nmi. These systems are cost-effective when compared to ground-based landing aids. One LAAS ground facility (LGF) can provide approaches to all runway ends at the host airport. In addition, airports within the VDB service volume may also be provided approaches from the same ground unit [6,7,8].

Existing and New Ground-Based Systems

The FAA operates over 900 ILS facilities in the NAS, 121 of which are Cat II/III systems. In addition, the Department of Defense operates approximately 200 ILS facilities in the United States and abroad. There are approximately 1100 VOR, VOR/DME, and VORTAC (collocated VOR and TACAN) facilities and 173 military TACAN systems in the NAS utilized for en route and terminal navigation in the NAS that require flight inspection. There are over 700 FAA, 200 military, and 800 nonfederal NDB transmitters in operation. All of these systems and any associated approach procedures require continuing flight inspection. Other systems, such as primary and secondary radar, minimum safe altitude warning systems, precision approach radar, communications, and lighting aids, add to the flight inspection workload.

New systems are still being added to the NAS and older facilities are being upgraded. Secondary radar systems are being upgraded to Mode-S capability and Precision Runway Monitors are being installed at major airports worldwide. New technologies such as the Transponder Landing System and upgrades to Cat II/III ILS facilities continue to add to the flight inspection mission.

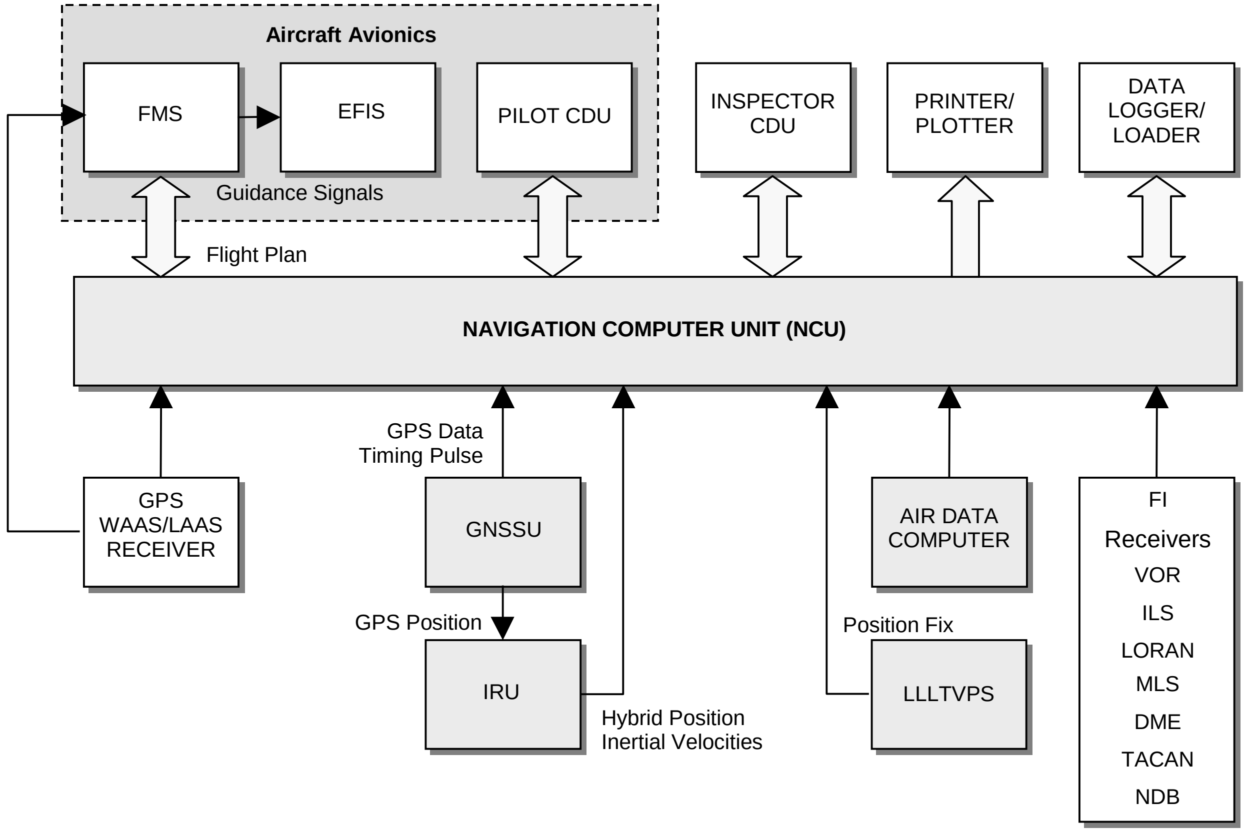

Figure 1. Flight Inspection System (FIS) Functional Diagram

Many existing ground-based navigation systems will be decommissioned after primary means GPS navigation is available in the NAS. The timeline for these actions is published in the Federal Radionavigation Plan [9]. No decommissionings are scheduled until 2005 and are then phased-out over five or more years. The result is a near doubling of the flight inspection workload during the overlap. For this reason, careful analysis of GPS flight inspection methodologies and extensive use of automated flight inspections systems are necessary.

AIRCRAFT CONFIGURATIONS

All flight inspection aircraft are equipped with dual electronic flight instrumentation (EFIS) and all required avionics to navigate and evaluate NAS procedures. The newer aircraft are also equipped with dual flight management systems (FMS). The FIS uses separate receivers that have been modified to provide the necessary outputs for signal analysis.

The heart of the FIS is the navigation computer unit. The NCU utilizes multiple 32-bit processors to deal with the control and analysis of the inspection data. This unit contains the data processing algorithms, a database of all facility and runway parameters, and the interfaces to the flight inspection and aircraft avionics. Navigation signals are sampled 8 times per second. Peripherals include a printer, removable hard disk data logger, spectrum analyzer and oscilloscope. Guidance for many of the required flight inspection profiles are generated by the FIS and coupled to the autopilot or flight director system. The truth source for the system is a ring laser inertial reference unit (IRU) that utilizes a 12-channel GPS sensor (GNSSU) and a low-light level television positioning system (LLLTVPS) for position updates. The FIS uses the inertial data combined with a position fix from the LLLTVPS to correct for any drift of the system throughout the flight inspection mission. The FIS functions independently of the aircraft systems under the control of the flight inspection technician through the inspector Control Display Unit (CDU). In addition, a pilot CDU provides flight planning and information exchange. A typical flight inspection configuration is presented in Figure 1.

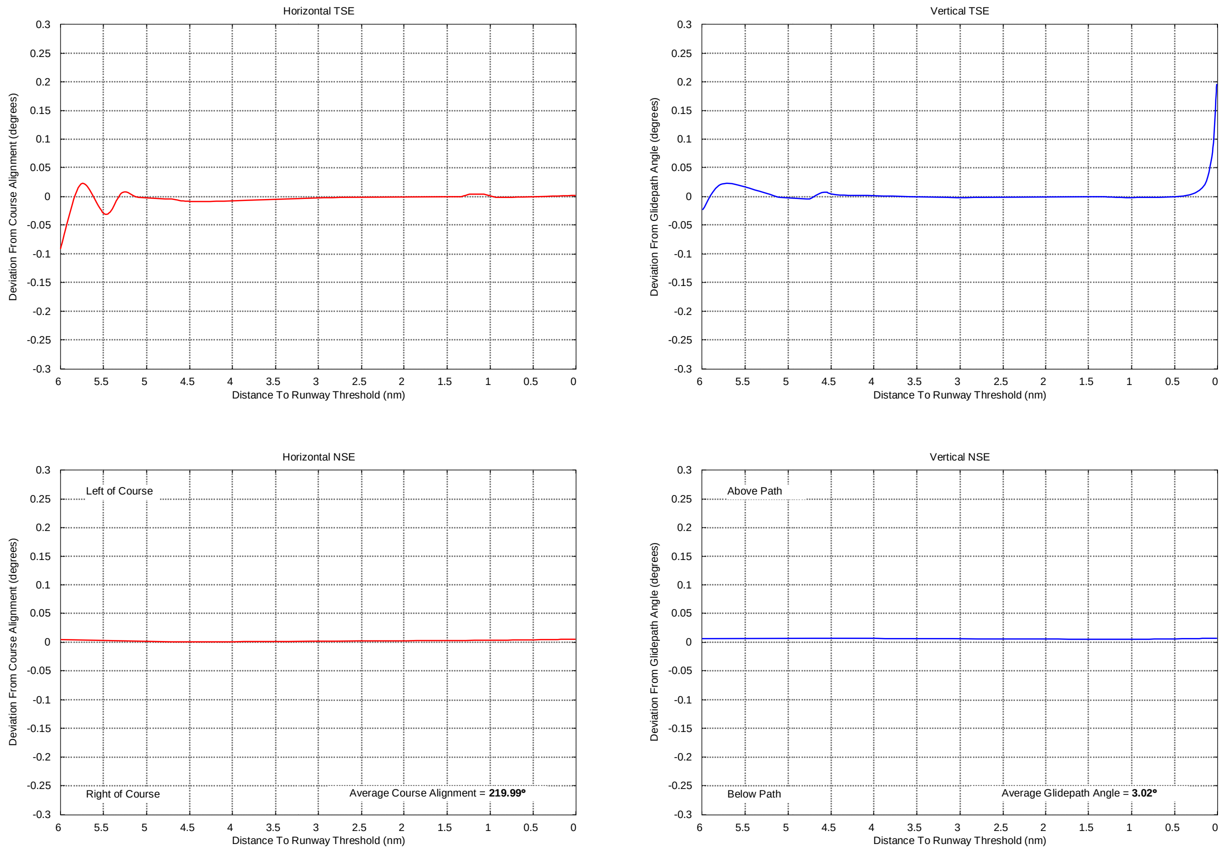

Figure 2. Horizontal and Vertical plots for a typical Category I ground-based differential GPS approach. (TSE plots indicate actual aircraft position errors. Note that the aircraft arrived below glidepath and to the right of course, made corrections and continued to the approach decision altitude. NSE plots are the actual system performance with FTE removed by back processing from the truth system.)

The IRU is cast free (unaided) at the start of a flight inspection profile and updated at the runway threshold and stop-end as the aircraft flies along the centerline, utilizing the LLLTVPS. This video system captures images of the runway threshold and stop-end. This requires the aircraft to make a low pass approximately 50 feet above the full length of the runway. The images are correlated to the geodetic coordinates of the centerline threshold and stop-end, then processed for cross-track and along-track displacement. The IRU position samples are then back-corrected to provide an accurate NSE. The update produces post-processed results with a computed accuracy of one-foot lateral, four-foot along-track, and one-foot vertical when used in conjunction with a laser or radio altimeter system. The system is completely independent of the GPS computed position and velocity because the IRU is decoupled from the GPS position. Figure 2 is an example of TSE and NSE plots for a DGPS approach. The FIS is integrated into the aircraft avionics with direct connections to the Flight Management System (FMS) or GPS navigation equipment, which allows the transfer of approach procedures and position data required for inspections. [10]

GNSS Flight Inspection Systems

Figure 3 is a system level block diagram of the non-precision flight inspection avionics used in the BE-300 airframe. This aircraft is not FMS-equipped; rather it utilizes a TSO-129 GPS receiver for navigation. The FIS receives procedure waypoints and present position from the receiver via an ARINC 429 bus. The waypoint data is loaded into the FIS memory and is compared with the receiver position. The FIS computes system position based on data received from the GNSSU sensor. A hybrid position is maintained in the FIS computer. Satellite specific data (PRN, SNR, etc.) are received from the GNSSU sensor. This information is correlated in time with the GPS timing pulse from the sensor. Raw data from the aircraft sensors, GNSSU, IRU, and FIS are recorded in the FIS. The raw position data may be back-corrected from the video position fix and recorded. All inspection data is stored on magnetic media (FIS Data Logger) for use in report generation, data archives and playback.

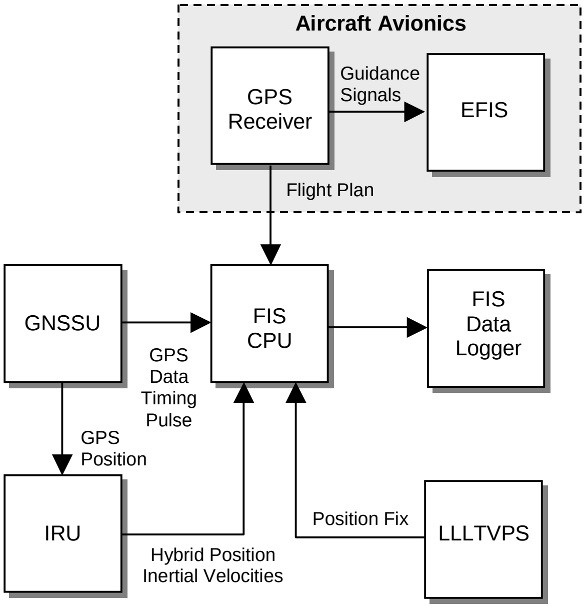

Figure 3. BE-300 GPS FIS

The Lear, Hawker and Challenger utilize dual FMS navigation (Figure 4). The FMS receives GPS data from the MMR and inertial position from the IRUs. The FMS uses the published GPS approach from its internal database or the crew can manually input the approach. The flight plan is transferred to the FIS and the inspection procedure is flown as described above. The FMS provides for the selection of specific sensors, which allows exclusive use of GPS data during the approach.

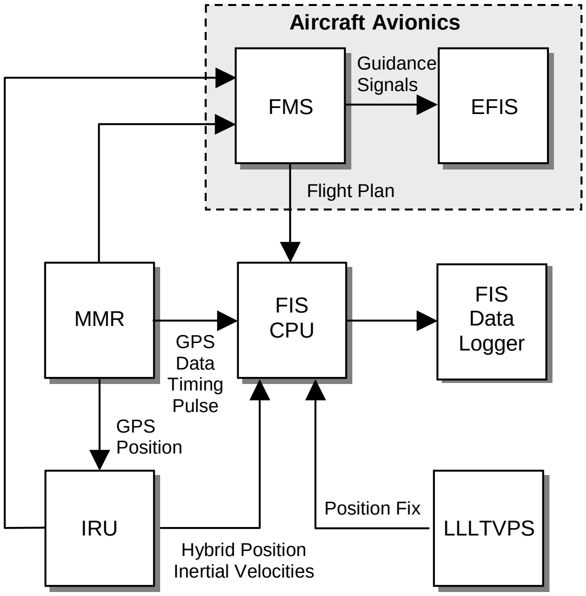

Figure 4. Lear, Hawker and Challenger GPS FIS

GPS Flight Inspection System (GFIS)

This system is a portable self-contained package that requires no connection to the aircraft receiver or FMS (Figure 5). Primary use of the GFIS is for helicopter nonprecision point-in-space procedure inspections. The inspections are accomplished with the user or leased aircraft. The aircraft must be equipped with a TSO-129 compliant GPS receiver. The GFIS has also been used on fixed-wing aircraft at locations that cannot support the AVN fleet.

The system uses an independent differential ground reference unit as the truth system. The ground unit and airborne package communicate via UHF data link, which allows control of the ground unit from the aircraft.

The procedure data is directly entered into the laptop computer or loaded from a file generated off-line. The GFIS processes and records all data required to meet nonprecision criteria. The system relies on a real-time differential system requiring no fix updates after initial positioning of the ground reference unit.

WAAS Flight Inspection

The WAAS flight inspection system was developed utilizing a WAAS Verification Receiver (WVR) provided to AVN by the Naval Air Warfare Center Aircraft Division. However, the WVR will not be used due to marketing decisions by the manufacturer. The final system architecture employed in the Lear 60, Challenger and Hawker aircraft (Figure 6) will be based on a Multi-Mode Receiver (MMR) along with upgraded FIS and FMS hardware and software. The result will be an integrated WAAS (/LAAS) system for IFR operations and flight inspection.

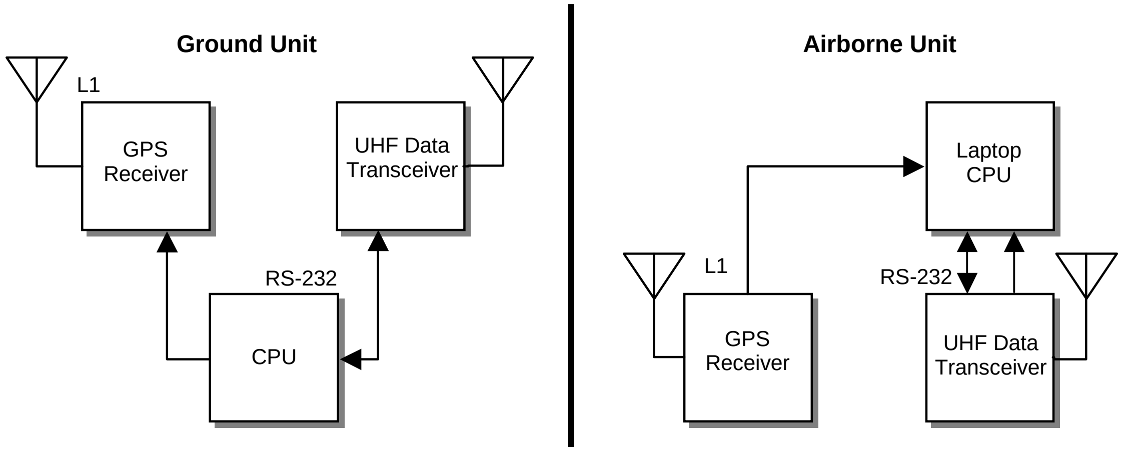

Figure 5. GFIS Nonprecision Approach System

Table 1. Captured GPS WAAS Parameters

Parameter	Source of Information
PRN	GPS, WAAS and WAAS Healthy Satellites (WM #1277)*
Pseudoranges	Each Satellite (WM #1277)
Carrier Phase	Each Satellite (WM #1278)
Satellite Coordinates	(WM #2422)
Signal-to-Noise Ratio (SNR)	Each Satellite (WM #4)
WAAS Operating Mode	(WM #4)
Horizontal Dilution of Precision (HDOP)	MMR (ARINC 429)
Vertical Dilution of Precision (VDOP)	MMR (ARINC 429)
Horizontal Protection Limit (HPL)	MMR (ARINC 429)
Vertical Protection Limit (VPL)	MMR (ARINC 429)
WAAS Latitude	MMR (ARINC 429)
WAAS Longitude	MMR (ARINC 429)
WAAS Altitude	MMR (ARINC 429)
WAAS East Velocity	MMR (ARINC 429)
WAAS North Velocity	MMR (ARINC 429)
WAAS Up Velocity	MMR (ARINC 429)
WAAS Heading	MMR (ARINC 429)
WAAS Ground Speed	MMR (ARINC 429)
Horizontal Figure of Merit (HFOM)	MMR (ARINC 429)
Vertical Figure of Merit (VFOM)	MMR (ARINC 429)
Alerts	WAAS Satellite Not Visible, WM #4
WAAS Downlink (raw data)	WM #6100 Words 1 - 30
Real-time Navigation Data	Position Samples, Unaided IRU Position, LLLTVPS Fix
Summary Data	Errors Cross-Track, Along-Track TSE, NSE (min, max, avg.)

*WM – WAAS Message [4, 12]

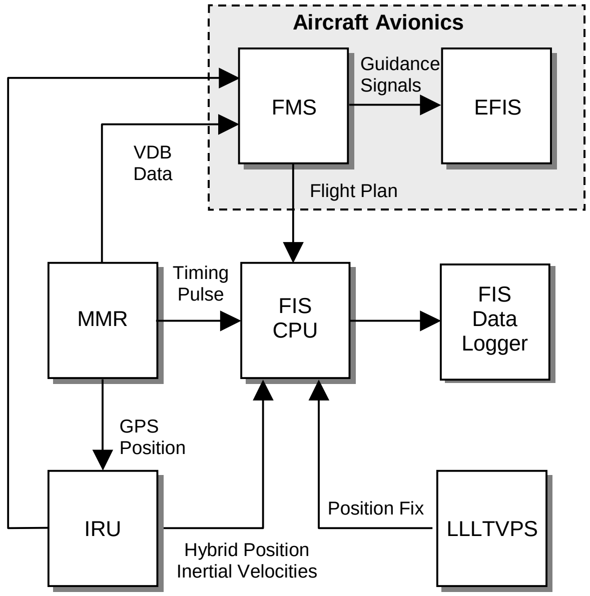

Figure 6. Lear, Hawker and Challenger LAAS FIS

The MMR will provide WAAS position data to the aircraft FMS and the FIS. Additional data will be available from an RS-429 port on the MMR. This output will contain data packets made up of WAAS messages, raw WAAS downlink data, carrier-phase and pseudorange measurement data.

The data will be used by the FIS as part of the flight inspection process (Table 1). In addition, the passive monitoring function, discussed later, will be expanded to include WAAS parameters.

Integration of WAAS capability into the BE-300 airframes will require upgrades to the navigation, display, and flight control systems. Upgrades to the GFIS equipment and software are also being considered, such as incorporating a WAAS receiver and increasing the performance of the truth system to include dual-frequency receivers. These upgrades will facilitate use of the GFIS for precision approach applications.

LAAS Flight Inspection

Development of the LAAS will require AVN to equip the entire fleet with LAAS capable receivers and sensors. This process will be similar to the WAAS conversion and will begin with a prototype Multi-Mode Receiver (MMR).

The MMR will be part of the aircraft navigation system and will provide guidance during approach with additional connections to the FIS. The MMR provides VDB reception through the VOR/ILS module. The installation will also include the ability to measure both horizontal and elliptical polarized VDB transmissions.

GPS Passive Monitoring

The initial use of GPS for enroute navigation and nonprecision approaches in the NAS generated several reports of loss-of-function and interference to the approved receivers. Many flight hours were spent attempting to locate these “wormholes” and investigate the cause. In the end, these reports were directly related to unreported GPS ground testing (antenna characterization, jamming tests, etc.). However, the vulnerability of the GPS signal-in-space was brought to the forefront. In order to monitor the NAS for these anomalies, AVN aircraft are equipped with a passive monitoring capability. This allows monitoring during all flight inspection missions. When a user reported anomaly occurs, the passive monitoring is used to locate and describe affected area.

Passive monitoring uses the aircraft GPS sensor and the FIS with dedicated software. The monitoring function is active as long as the flight inspection system is powered up and airborne. The system is disabled on the ground to prevent data recording while the aircraft is near (or in) hangers and other airport structures. The operation of the monitoring function is transparent to the flight crew until an anomaly is detected.

A GPS “event” will occur if the sensor loses RAIM or receives a RAIM alert, experiences a position failure, or deterioration of navigation position due to insufficient satellite data. The system maintains a five-minute running log (first-in-first-out) of requisite GPS parameters obtained from the GPS sensor, Flight Management System (FMS), aircraft GPS receiver, and the FIS (Table 2). When detection occurs, these parameters are stored in the FIS Data Storage Unit on removable magnetic media. The period of data recorded will begin five minutes before the anomalous condition and ends five minutes after the condition has cleared. The system alerts the flight crew that a GPS event is occurring. The recorded data will be forwarded to the FAA Spectrum Management Office at the end of the flight inspection mission. AVN and Spectrum Management are developing airborne and ground direction-finding capability to aid in locating sources of GPS interference.

The future FAA flight inspection fleet will primarily utilize leased turbojet aircraft equipped with redundant FMS and IRU systems. Other airframes may include helicopters and short-field turboprops. New flight inspection equipment will be developed based on a modular concept. This system will provide both aircraft and mission flexibility. Installation will require minimal intrusion into the aircraft and avionics systems. Power and antenna connections will the primary interfaces. Weight and power load will be minimized by selectively installing only those modules required for the planned mission.

Table 2. Passive Monitoring Parameters

GPS Sensor (GNSSU)	FMS or GPS Receiver	FIS
UTC (Universal Coordinated Time)	UTC	Heading
GPS Altitude (mean sea level [MSL])	Latitude	Altitude
HDOP	Longitude	Pitch
VDOP	Ground Speed	Roll
GPS Latitude	Altitude (MSL)	Ground Speed
GPS Longitude	HDOP	Latitude
GPS Ground Speed	VDOP	Longitude
Date	Status	
GNSSU Status	RAIM	
Measurement Status		
Autonomous Horizontal Integrity Limit		
Autonomous Integrity Limit		

FLIGHT INSPECTION METHODOLOGY

The approach to flight inspection of GPS procedures requires an entirely new thought process. Inspection of ground-based procedures is predicated on in-depth analysis of the signal-in-space from the terrestrial antenna arrays. Guidance is generated from the modulation schemes recovered from the carrier. Monitoring of the critical parameters is a function of the ground equipment. Maintenance and adjustment of these facilities is controlled by FAA personnel. Most enroute and landing aids operate in the VHF band; therefore, both interference and multipath between the ground antenna and the aircraft are major factors.

GPS approaches, however, are generated within the avionics. The GPS signal-in-space is controlled by the Department of Defense within guaranteed specifications [11]. Any augmentation data must also meet specific criteria, including error checking. The guidance generation process within the avionics incorporates numerous algorithms that control errors caused by outside influences (multipath, ionospheric delay, etc). In other words, monitoring of the critical parameters is now a function of the receiver and/or the augmentation system. Avionics and total system error budgets imposed by FAA for each phase of flight provide various alerts that prevent hazardous or misleading information in the navigation output. Commissioning inspections of GPS-based procedures requires analysis of the approach design. This includes verification of the coordinate data (waypoints) the procedure is based on, obstacle verification throughout the approach procedure, and flyability/human factors (including cockpit workload). The focus of flight inspection will shift from transmitted signal analysis (with the exception of LAAS VDB service) to identification of localized error sources. Should a navigation alert occur, flight inspection will determine the repeatability, location (or area), and cause of the anomaly. This process will require GPS raw and processed data to be recorded and analyzed.

The FIS outputs inspection data in the form of chart recordings and digital files. Current record-keeping regulations require the original commissioning reports/recordings and the three most recent periodic reports/recordings be archived. In addition, copies of reports and recordings (when requested) are provided to facility maintenance. These records provide a baseline for trend analysis of individual ground facilities. All of this requires a significant filing and storage operation.

AVN has begun the transition from paper records to digital files. Flight inspection aircraft are now equipped with digital storage capability. Data files are now being provided to facility maintenance engineering for use in computer analysis of ILS and VOR multipath. GPS data is also stored on magnetic media. Computer analysis tools utilize this data for investigation of anomalies and trends for specific GPS procedures and locations. Paper reports will only be generated upon request.

CONCLUSION

The growth of satellite-based navigation and approach procedures will continue to increase FIS and avionics requirements. Flight inspection aircraft must be among the first equipped with the new navigation systems in order to commission new procedures for public use. The timely addition of new technology to flight inspection aircraft with older avionics will be the largest challenge for us all..

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