Information: DGPS Requirements Document April 14, 1997

Gregg G. Fleming DTS-75

DISTRIBUTION

Attached please find Volpe Center Letter Report DTS-75-FA753-LR3, "Requirements for DGPS-Based TSPI Systems used in Aircraft Noise Certification Tests." This document outlines the recommendations and requirements to be followed by FAR Part 36 noise certification applicants using a differential global positioning system (DGPS) for collection of time space position information (TSPI). It provides specific requirements related to DGPS hardware, related software, as well as system installation, verification and use. It also provides a list of suggested DGPS receivers around which a suitable TSPI system may be based.

Any questions regarding this document should be directed to myself at (617) 494-2876, or Michael Geyer or Phil McCarty at (617) 494-2475.

Attachement

Distribution:
K.L. Van Dyke; Volpe Center, DTS-52
C.A. Holclaw; FAA, AEE-110
J.M. Skalecky; FAA, AEE-110
K.E. Jones; FAA, AEE-110
M. Marsan; FAA, AEE-110
T.E. Van de Ven; FAA, ANM-110 (10 Copies)
L. Gant; FAA, ASW-170G
M. Downs; FAA, ACE-111
B. Conze; FAA, ANM-40L
K.A. Wilhelm; Boeing Aircraft
N.L. Haight; Douglas Aircraft
J. Pridgeon; Locheed-Martin Aircraft
E. Jacobs; Sikorsky Helicopter
M. Hardesty; Douglas Helicopter
J.R. Alberti; JREngineering
G. Blankenship; Aviation Acoustics
G. Gorder; Aero Acoustics

J. Mills; AAAI
L. Timmons; AES

C:\zzz\dgpsreqs.wpd

DTS-75-FA753-LR3

REQUIREMENTS FOR DGPS-BASED TSPI SYSTEMS USED IN AIRCRAFT NOISE CERTIFICATION TESTS

John A. Volpe National Transportation Systems Center
Acoustics Facility and Landing Systems Laboratory
Cambridge, MA 02142-1093

Letter Report
April 14, 1997

U.S. Department of Transportation
Federal Aviation Administration

1. INTRODUCTION

1.1 Purpose

The U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in cooperation with the Volpe Center's Landing Systems Laboratory, is supporting the Federal Aviation Administration's (FAA) Office of Environment and Energy (AEE) by developing "Requirements for DGPS-Based TSPI Systems Used in Aircraft Noise Certification Tests."

This letter report addresses that portion of a noise certification applicant's Differential Global Positioning System (DGPS-based), Time Space Position Information (TSPI) system which is to be used as a position reference in place of a laser tracker, microwave system, photoscaling, or other TSPI system. *Section 1* presents background information and the objectives of this report. *Section 2* discusses DGPS system design issues, including configuration, airport survey, DGPS receiver output data and sources of error in DGPS systems. *Section 3* contains specific requirements on material to be provided to the FAA as part of an application for DGPS-based TSPI system approval. *Section 4* gives specific examples of data to be stored for GPS receivers from Ashtech, Inc., Leica, Inc., Novatel Communications, and Trimble Navigation, Ltd. *Appendix A* reproduces an FAA memorandum regarding the use of DGPS for general certification flight testing. This letter report provides recommended further requirements for a DGPS system to be used for aircraft noise certification.

1.2 Background

Several aircraft manufacturers are developing aircraft flight test reference systems — often called TSPI systems — based upon DGPS technology. Requests have been received, and additional requests are expected, for approval of these systems for use during noise certification tests. Typically, the hardware components of these systems are (see Figure 1): GPS receivers and antennae on the ground and in the aircraft; data link transmitter and antenna on the ground and corresponding receiver and antenna in the aircraft; a laptop computer in the aircraft; and batteries and electronic power supplies. Software, running on the laptop computer in the aircraft, provides the user control/display function and performs data logging. A personal computer is generally needed to initialize the GPS receiver on the ground, but

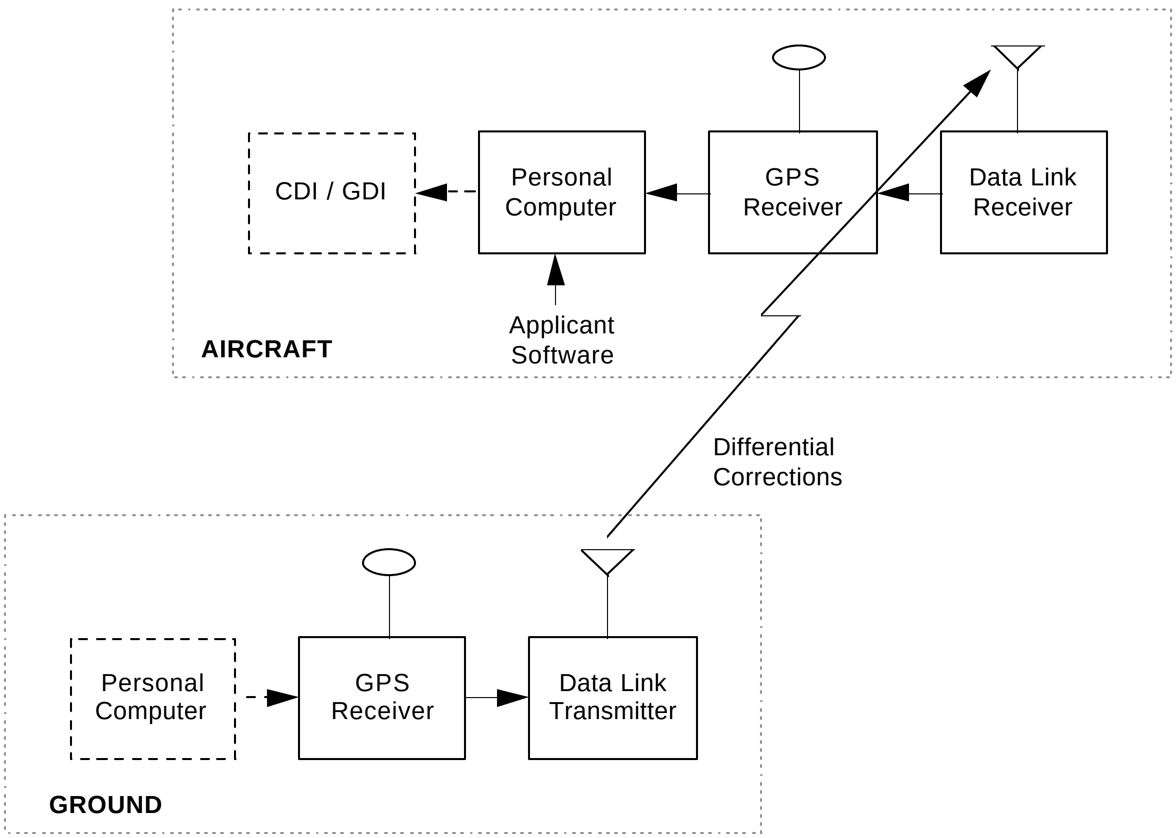

Figure 1: DGPS TSPI System Basic Architecture

is not necessary for continuous operation.

In addition to generating flight reference data for post processing, some applicants' systems provide the pilot with information to navigate the aircraft. Measured aircraft position is compared to a desired reference flight path, and steering commands are sent to a course/glide slope deviation indicator (CDI/GDI) installed specifically for use with the DGPS system. While the real-time navigation portion of the TSPI system is a useful tool that allows tests to be performed more efficiently, it is outside of the scope of this letter report.

Variations on the basic architecture shown in Figure 1 are possible. For example, it is possible to eliminate the data link elements by: (1) collecting and storing data from both GPS receivers during a flight; and (2) post-processing these data in a single computer after the flight is complete. However, without a data link, DGPS data cannot be used for aircraft guidance, nor can an aircraft-based operator obtain "quick-look" information regarding the DGPS solution quality. Another possible variation on the basic architecture in Figure 1 involves uses of a two-way data link; typically, identical transceivers would be used on the ground and in the aircraft. This enables ground tracking of the aircraft during testing.

1.3 Objectives

The objectives of this letter report are as follows:

(1) to provide the noise certification applicant with a defined set of requirements, related to both hardware and software, which must be met for approval of a DGPS-based TSPI system; and

(2) to provide the certificating authority with guidance on issues related to DGPS-based TSPI systems, addressing their use both in field testing and during post-test analysis and processing of data.

2. SYSTEM DESIGN ISSUES

This section discusses DGPS system design issues, including configuration, airport survey, DGPS receiver output data and sources of error in DGPS systems.

2.1 Coordinate Frames and Waypoint Navigation

The native coordinate system for GPS, i.e., the one in which its computations are performed, is the World Geodetic Survey of 1984 (WGS-84). Most GPS receivers provide output position information (latitude, longitude and altitude) in a variety of geodetic coordinate systems by transforming the WGS-84 position data.

Aircraft noise certification tests typically involve use of a rectangular coordinate frame whose definition is based upon an array of microphones or the centerline of an airport runway. Typically, the frame x-axis is established from two points on the ground that are nominally aligned with the runway centerline; the y-axis is orthogonal to the x-axis and also level; and the z-axis is vertical.

Some GPS receivers can furnish data in a rectangular coordinate system based on waypoints (equipment from two of the four manufacturers discussed in Section 4 have this feature). Waypoints are reference points defined to facilitate navigation along a route or in a local area. If a receiver supports waypoint navigation, then two such points (defined in terms of latitude, longitude, and altitude) can be entered into the receiver.[1] The receiver will subsequently provide aircraft position relative to the coordinate frame implicitly defined by the points, i.e., distance from the line connecting the two points and distance to one point.

---

[1] For noise certification testing it is required that the GPS receiver read the waypoints from the submitted data file. Alternatively, the waypoints could be keyed into the receiver and then written to the data file.

If waypoint navigation is to be used for noise testing, then the initial survey performed to determine the position of the two waypoints is critical to the accuracy of the TSPI results (See Section 2.2). If waypoint navigation is not available or is not to be used, then the geodetic position solution, i.e., latitude, longitude and altitude, must be transformed to a local coordinate system through post processing by the applicant prior to noise data processing.

2.2 Airport Survey

A careful survey of the airport and nearby areas where noise testing is to be conducted is critical to the success of a measurement program. The following steps are involved in a survey.

(1) An initial reference location, including numerical values for its latitude, longitude and altitude, is selected and its coordinates are recorded in a permanent file on a computer hard disk. Normally the initial reference location will be a surveyed monument on the airport, upon which latitude/longitude are stamped. (Often the monument will have been derived from a third-order[2] survey, in which case geodetic position errors on the order of hundreds of feet are not uncommon. However, such errors have virtually no effect on the measurement of positions relative to that point or another point derived from it.) The published airport reference altitude can be assigned to the monument. (Although this altitude typically is applicable to the base of the tower, the altitude difference between the monument and tower will not degrade the accuracy of differential measurements relative to the reference location.) Many GPS receivers have a "survey" mode whereby they average position measurements over a user-selected period of time, e.g., 24 hours, to generate a surveyed position estimate. Typical resulting absolute accuracies are 3 to 10 feet, which are more than adequate if the DGPS-based TSPI system measurements will not be related to measurements from another system.

(2) The DGPS-based TSPI system, with the ground-station antenna at the initial reference location, is used to measure the coordinates of the location where the ground-station antenna will be installed for the remainder of the test series. The latitude / longitude / altitude of this

---

[2] Prior to the advent of satellite-based techniques in the 1990s, land surveys were performed using an optical theodolite (to measure angles) and chain (to measure linear distance). Networks of interlocking triangles were surveyed, with measurements collected at each vertex. The accuracy of such a survey was classified by the amount that the sum of the interior angles of a triangle deviated from 180 degrees (after accounting for the earth's curvature). A first-order survey was the most accurate; the vertices were typically 10 to 40 miles apart, and the angular error 1 arc second or less. Also, for a first-order survey, the latitude/longitude of one point was measured by astronomical means (accuracy approximately 50 feet). A second-order survey had vertices 5 to 10 miles apart and maximum angular error of 5 arc minutes. A third-order survey had vertices 1 to 2 miles apart and angular error not exceeding 15 arc minutes.

second location is recorded in a permanent file on computer hard disk. If convenient, the ground-station antenna may be installed at the initial reference location and left there during the test series.
(3) If waypoint navigation is to be used for the measurement program, the DGPS-based TSPI system, with the ground station at the second, i.e., the normal, location, is used to measure the latitude / longitude / altitude of the FROM and TO waypoints which will be used to establish the test program coordinate frame. At least three measurements shall be made to guard against errors. The resulting locations shall be recorded in a permanent file on computer hard disk.

(4) The DGPS-based TSPI system, with the ground station at its normal location, is used to measure the microphone positions. The measured positions are recorded in a permanent file on computer hard disk. If waypoint navigation is to be used for the measurement program, microphone positions should be recorded in test coordinates; otherwise, latitude / longitude / altitude should be used.

(5, Alternative to 4) If it is not feasible to use the DGPS-based TSPI system to survey the microphone locations, and another technique must be used, then direct measurements of at least three common points must be performed in order that the relationship between the two surveys can be determined. For example, if the microphones are surveyed using classical techniques, then a DGPS-based TSPI survey of the two microphones at the ends of a microphone line and one other microphone, as far removed from the first two as possible, will be sufficient. The surveys should agree to within 1 foot at each common point. If they differ by more than 1 foot and the difference can be described by an offset and a rotation, then it may be possible to adjust the results of one survey to agree with the other. Such adjustments must be approved by the FAA prior to testing.

The above tests must be performed as a minimum before and after each measurement program. Post-test data analysis shall include a comparison of the two surveys.

2.3 Receiver Output Data

Three kinds of GPS receiver output data are of interest:

(1) data stored during flight testing, for use during post-test processing of noise data, collected from either the aircraft receiver (when a real-time data link is used) or from both receivers (when a real-time data link is not used);

(2) differential correction data output by the ground-station receiver, transmitted to the aircraft via a real-time data link, and input to the aircraft receiver [these data are not stored, but directly influence the accuracy of the stored data addressed in item (1)]; and

(3) data collected from the ground-station GPS receiver during multipath verification tests prior to flight testing.

This section addresses the GPS receiver messages[3] which support these three purposes. All data are furnished via RS-232 serial port; GPS receivers generally have multiple RS-232 ports. Specific messages available from receivers offered by four manufacturers are discussed in Section 4.

2.3.1 Data Stored During Aircraft Noise Testing (Real-Time Data Link Used)

GPS receivers provide TSPI data in a variety of formats, both industry-standard and proprietary. The National Marine Electronics Association (NMEA) has issued standards (References 1 and 2) which are intended to facilitate user communications with GPS receivers and other navigation devices. Some GPS manufacturers have adopted NMEA standards, some use proprietary formats, and some use both. Those manufacturers that provide NMEA outputs generally only implement a subset of the full set of messages set forth in the standards, and some follow the older Version 1.5 rather than the current Version 2.0. Also, GPS receiver manufacturers have chosen different parameters to indicate the quality or status of the TSPI data.

DGPS-based TSPI systems considered for FAA noise certification tests, using a real-time data link, shall save data from the aircraft GPS receiver in raw, i.e., the receiver's native, format on computer hard disk. Stored data must include time, e.g., Universal Time Code (UTC) or GPS time with or without a local offset, aircraft latitude / longitude / altitude (or equivalently, aircraft position relative to a pre-defined waypoint), and a status or quality flag indicating the "goodness" of the DGPS solution. Typically the applicant will employ post-processing software which will read the raw data, parse and format these data, perform any necessary transformations, and generate a file which will be used for noise data processing. Storage of raw data will allow the FAA to verify the validity of the post-processed results.

[3] Standards organizations and manufacturers employ different terminology for pre-defined groups of data parameters available from receiver output ports. For example, the National Marine Electronics Association (NMEA) uses the term "sentences," the Radio Technical Commission for Maritime Services (RTCM) uses "messages," Novatel Communications uses "logs," and Trimble Navigation Ltd. uses "Cycle Printouts."

2.3.2 Data Stored During Aircraft Noise Testing (Real-Time Data Link Not Used)

DGPS-based TSPI systems considered for noise certification tests which do not use a real-time data link shall save data from both the ground and aircraft GPS receivers in raw, i.e., the receiver's native, format on computer hard disk. Manufacturers' proprietary formats must be used; NMEA standard messages do not support this application. Stored data must include time, e.g., UTC or GPS time with or without a local offset, satellite ephemeris (See Section 2.6.4 for a discussion of satellite ephemeris/clock data), pseudoranges[4], signal-to-noise ratios[5], and carrier phase.[6] Applicants using dual-frequency (L1/L2) receivers will typically also save L2 carrier phase data.[7] Typically, post-processing of the ground-based and airborne GPS data will be performed using manufacturer-supplied software. If this is not the case, then any applicant-developed software must be approved by the FAA.

2.3.3 Real-Time DGPS Messages

GPS receiver manufacturers have implemented both industry-standard and proprietary messages for use on real-time DGPS data links. The Radio Technical Commission for Maritime Services (RTCM), Special Committee 104 (SC-104) has issued a standard (Reference 3) that is followed by most manufacturers. Manufacturers usually implement only a subset of the RTCM/SC-104 messages, and

---

[4]Pseudorange is the receiver's measured distance to a satellite, and is derived from the coarse/acquisition (C/A) code. It includes a receiver clock bias error, and may be quantified in units of time or distance.

[5]Signal-to-noise ratio (also called carrier-to-noise ratio) is derived from the receiver's tracking loop circuits, and is a measure of the received signal strength. It is usually quantified in dB-Hz, and varies from approximately 33 to 50.

[6]Carrier phase is the amount of carrier cycles (at 1,575.42 MHZ) which have accumulated since logging of this parameter was begun. It may be quantified in radians, degrees, cycles, or feet (to convert to cycles, divide by the wavelength, 0.6247 feet).

[7]The highest accuracy DGPS systems employ the signal carrier (L2=1,575.42 MHZ), rather than the code (L1=1.023 MHZ) which modulates the carrier, as the basic measurement observable. These techniques require that the number of full carrier cycles, i.e., 8 inch wavelengths, between the ground station and aircraft be determined once during a test. After the cycle count is established, the ground-station/aircraft-separation is tracked to fractions of a wavelength, provided that the receiver carrier tracking loops (circuits) maintain phase lock.

some follow the older Version 2.0 rather than the current Version 2.1. Some manufactures have also implemented proprietary DGPS messages; these frequently bear a close resemblance to the RTCM/SC-104 messages.

Applicants implementing a real-time DGPS data link are required to employ RTCM/SC-104 messages for this purpose. Type-1 or Type-9 messages (each of which contains the actual DGPS corrections) must be selected and transmitted at a rate of 0.5 Hz or higher. Other message types, e.g., Type-3 (ground-station location) and Type-5 (satellite health), may be used, but should be sent at a rate of once per minute or slower. There is no requirement for storing real-time DGPS correction data; however, the data status or quality flag (discussed in Section 2.3.1) must provide an indication that the correction data has been properly received and processed by the aircraft.

2.3.4 Messages for Multipath Testing

Applicant's systems using code-based DGPS processing must collect and save data from dedicated multipath tests to be conducted prior to aircraft noise testing (see Section 2.5). Data collected during multipath tests must include individual satellite pseudoranges and signal-to-noise ratios. These parameters are only provided by receiver manufacturers' proprietary messages. Applicants are not required to conduct a dedicated test for systems using carrier-based DGPS processing.

2.4 System Accuracy and Sources of DGPS Error

If only divergence (spherical spreading) of the noise is considered, and atmospheric absorption mechanisms are ignored, then 0.1 dB of change in the noise level corresponds to approximately 1.1% of the distance between the aircraft noise source and the measurement microphone. Thus, for an aircraft altitude of 400 feet (approximate minimum altitude during noise certification tests), 4.4 feet of position error along the line-of-sight vector connecting the microphone and aircraft will introduce 0.1 dB error in the processed noise data. Equivalently, 10 feet of position error along the line-of-sight vector will introduce 0.23 dB error in the processed noise data.

For most DGPS systems, the most important error sources are, in decreasing order of importance: multipath, correction latency, and tropospheric delay. When these error sources are properly controlled, DGPS systems provide accuracies between a few inches and approximately 15 feet for an aircraft in low-dynamics flight regimes. Even the poorest of these accuracies is superior to that achieved by most TSPI systems used for aircraft noise tests today, including microwave and photoscaling. The best accuracies are superior to those for a laser tracker.

DGPS systems under consideration by noise certification TSPI applicants are expected to achieve accuracy of a few inches to five feet. The highest accuracy is achieved using carrier-based techniques and post-flight processing of data collected from both the aircraft and ground-station computers. Code-based solutions which use carrier smoothing, e.g., Novatel RT-20, achieve accuracies of 3 to 5 feet, provided that the error sources discussed in this section are addressed properly. Consequently, it is expected that the DGPS systems used for noise certification tests will introduce less than 0.2 dB error into the noise data, in a worst case scenario, i.e., a noise certification approach operation. Typical errors will be less than 0.1 dB for noise certification take-off and sideline measurements.

In addition to the three error sources cited above, increases in DGPS position errors also occur when the ground station and aircraft do not have the same manufacturer and model GPS receiver, or when the ground station and aircraft receivers use different satellite ephemeris/clock data (specifying the satellite orbital parameters).

Sections 2.5 and 2.6 address all of the above errors, and include methods for minimizing these errors or eliminating them entirely.

2.5 Multipath Errors

2.5.1 Characteristics

Multipath refers to signals from GPS satellites which are reflected from objects, e.g., the ground, buildings, and aircraft structural elements, before reaching the GPS antenna. Multipath signals add (algebraically) to the desired line-of-sight signal, and thereby decrease the accuracy of measurements made with the latter. Multipath occurs independently at the aircraft and ground- station antennae. Thus the differential correction from the ground do not actually correct multipath errors at the aircraft antenna. Rather, the broadcast corrections can contain ground- station multipath errors which, in a statistical sense, add to those in the aircraft.

Measurements have consistently shown that ground-station multipath is significantly more deleterious as compared with aircraft multipath, because ground-station multipath varies slowly (acts like a bias over a test run of a few minutes), while normal motion of the aircraft causes airborne multipath to behave like noise (which can be reduced somewhat by processing techniques such as filtering and averaging) . For code-based processing, the size of the ground- station multipath error is typically between 1 and 10 feet. Under very adverse conditions, e.g., GPS antenna near the side of, and well below the top of, a large building, multipath errors can be several hundred feet. Multipath errors associated with carrier-based processing techniques are significantly less than those for code-based methods, and are usually on the order of centimeters. The size of the multipath error primarily depends on two factors: (1) the capability of the ground- station antenna; and (2) the location of the ground-station antenna relative to reflecting objects such as paved runways, buildings, and parked aircraft. Receiver processing, e.g., use of narrow correlators (available in most Novatel receivers) and/or carrier smoothing (available from several manufacturers), can reduce multipath errors.

2.5.2 Code-Based System Ground Station

To mitigate the effects of multipath on DGPS-based TSPI performance, the applicant's ground- station installation must meet the following requirements:

- C The ground station shall employ a multipath-limiting antenna, such as one with a choke ring or an absorbing-ground plane; and

- C The ground-station antenna shall be mounted on a pole or tower, with unobstructed visibility of the sky. A minimum height of 10 feet above ground level is recommended for the ground-station antenna.

Additionally, to ensure that significant, undetected multipath-errors do not corrupt the TSPI data collected during aircraft-noise testing, the applicant's ground-station installation shall be tested for adequate multipath performance prior to commencing with the test by: (1) collecting GPS receiver data during the time-of-day when the system will be used for noise tests, plus additional 1 hour buffers on either side of this period; and (2) examining the data on a per-satellite (rather than navigation solution) basis, including at least pseudoranges and signal-to-noise ratios, for multipath signatures. Reference 4 (beginning on Page 560) gives a procedure for examining GPS data for multipath.

If multiple periods of significant (several feet) multipath error are found when examining the data, then a new location for the ground-station antenna must be selected and tested. If only one or two isolated, brief multipath incidents are found, then antenna location can be retained but aircraft testing shall not be conducted during these periods. (The satellite-user geometry repeats with a period of approximately 23 hr 56 min. Thus if a ground-station multipath incident is observed one day, a similar incident is expected to occur 4 min earlier the following day.) These procedures are similar to those utilized by the U.S. Coast Guard in checking out a marine DGPS station installation (References 5 and 3)[8]. After

[8] Coast Guard DGPS ground stations employ two GPS receiver/antenna pairs. The "additional" receiver/ antenna pair (termed the integrity monitor) provide a real-time continuous check on the validity of the differential

establishing a ground-station antenna site/configuration that satisfies the multipath criterion, the ground-station antenna shall not be moved without performing another multipath test. The ground-station GPS receiver and any computer used in conjunction with the receiver may be removed and re-installed without repeating the multipath test. The multipath, verification-test data shall be saved as part of the permanent test-series data archive, and shall be available for FAA inspection.

2.5.3 Carrier-Based System Ground Station

To mitigate the effects of multipath on DGPS-based TSPI performance, the applicant's ground- station installation must meet the following requirements:

- The ground station shall employ a multipath-limiting antenna, such as one with a choke ring or an absorbing ground plane; and
- The ground-station antenna shall be mounted on a pole or tower, with unobstructed visibility of the sky. A minimum height of 10 feet above ground level is recommended for the ground-station antenna.

There is no requirement for collecting data to assess multipath errors when carrier-based processing is employed.

2.5.4 Aircraft Installation

It is expected that aircraft manufacturers will select a location on each aircraft model that minimizes multipath effects; this document does not impose a requirement. For most smaller aircraft, e.g., 10 seats or fewer, it has been found the roof area directly behind the windshield is most advantageous. Manufacturers of larger aircraft have found forward positions on the roof to be desirable, but others have mounted the GPS antenna on the tail structure. Selecting a location for the GPS antenna on a helicopter is more challenging, since the rotor will momentarily obscure most areas on the airframe.

---

corrections generated by the "basic" receiver/antenna pair (termed the reference station). DGPS ground-station architectures being investigated for the FAA Local Area Augmentation System (LAAS) program employ between 2 and 4 receiver/antenna pairs to verify the corrections sent to the aircraft. No requirement for redundant ground-station equipment is recommended for DGPS-based TSPI systems used in noise certification tests.

Mounting the GPS antenna on the top of the rotor shaft is the recommended location on a helicopter.

2.6 Other Sources of DGPS Error

2.6.1 Correction Latency

Correction latency, also called staleness, refers to the delay between the time of validity of a differential correction at the ground station and the time that the correction is applied in the aircraft. Delays in processing at both ends of the ground-to-air data link, combined with the effect of Selective Availability[9] (which causes GPS errors to change at a much more rapid rate than they would as a result of natural effects such as ionospheric or tropospheric delays) can cause stale corrections to introduce unacceptably large errors.

A second form of latency, solution latency, refers to the delay between the time a GPS receiver's measurement is valid and the time it is available at the output of the receiver. Solution delays are inherently smaller than correction delays and, in this context, are only of concern for aircraft guidance.

For a system with a real-time data link which employs code-based DGPS solutions, it is required that ground-to-aircraft messages conform to the RTCM/SC-104 standards used by the Coast Guard DGPS system.[10] These messages contain pseudorange rates-of-change (as well as the correction at an identified time), to allow the user to correct for most of the latency-induced error. (All of the receiver

---

[9]Selective Availability is intentional degradation of the GPS broadcast signal in order to reduce the navigation accuracy of a non-differential user.

[10] The U.S. Coast Guard DGPS system's (as well as marine systems of other nations) broadcast messages include the rate-of-change of each pseudorange error, in addition to the pseudorange error at a reference time. The user's receiver is required to apply an adjusted correction consisting of the broadcast pseudorange error, plus its rate-of-change multiplied by the time elapsed between the time the adjusted correction is applied, and the validity time for the pseudorange correction.

models discussed in Section 4 support RTCM/SC-104 messages.) It is also required that the corrections be computed and transmitted at least at a 0.5 Hz rate.

2.6.2 Tropospheric Delay

The troposphere is that portion of the earth's atmosphere between the surface and an altitude of approximately 20 miles. Differences in temperature and humidity between ground station and aircraft can cause dissimilar changes in the propagation times of signals from a satellite to these two locations; the effect is most pronounced for low-elevation-angle satellites. Since these changes are not common to the two locations, they are not removed by differential corrections.

Experiments performed for the FAA LAAS program have found tropospheric differences to introduce DGPS errors between 1.5 and 3 feet when the aircraft was at 3,000 feet altitude, but only an inch or two when the receiver antennae were at the same altitude. To reduce the effects of tropospheric errors on DGPS-based TSPI systems used in noise certification tests, it is required that their usage be limited to aircraft within 20 nmi (lateral) and 5,000 feet (altitude) of the ground station.

2.6.3 Mismatched GPS Receivers

Experiments have shown that DGPS errors are increased when the GPS receivers at the ground station and in the aircraft are not "matched" in terms of manufacturer and model. With mismatched receivers, errors are increased moderately, e.g., 1.5 to 3 times those when the receivers are matched, when the satellites are operating normally. When a rare soft satellite-failure (signal degradation) occurs, errors of several thousand feet have been observed[11]. It is required that applicant's systems have the same manufacturer/model GPS receiver on the ground and in the aircraft.

---

[11] Beginning on or before October 21, 1993, some differential users with mismatched ground and aircraft receivers experienced position errors of thousands of feet. The DoD's GPS Joint Program Office (JPO) attributed the cause to a "deficiency" in the C/A code broadcast by satellite SVN19. It announced that the problem was corrected on January 10, 1994. Official statements are found in Notice Advisory to NAVSTAR User (NANU) 343-93294, 396-93337, and 006-94010.

2.6.4 Mismatched Satellite Ephemeris/Clock Data

GPS satellite broadcasts include a navigation message, in the form of 50 bit/sec modulation superimposed on the pseudorandom codes used for ranging. Within the navigation message are data sets that describe the satellite orbit (ephemeris information) and clock; these data sets are transmitted every 30 seconds. The GPS Control Segment[12] uploads multiple ephemeris and clock data sets to the satellites, typically once per day. Satellites typically change their broadcast ephemeris and clock message every four hours. The ephemeris/clock data sets are used by a receiver to compute its own position and, in the case of a reference station differential corrections for use by other receivers.

For a DGPS system to achieve full accuracy, both the ground station and aircraft receiver must use the same ephemeris and clock data sets. Internal receiver logic ensures that the ephemeris and clock data sets used by a given receiver are consistent for each satellite. However, occasionally the ground and aircraft receivers may use different ephemeris/clock data sets, unless measures are taken by the user to ensure that the sets match. Mismatched ephemeris/clock data sets can occur for several reasons, e.g., a receiver is too busy performing other tasks when the data sets change, or a receiver encounters an error while decoding new data and continues to use an old data set.

The RTCM/SC-104 messages used by the Coast Guard DGPS system guard against mismatched ephemeris/clock data sets by including the Issue of Data (IOD) — an eight-bit data set label broadcast by each satellite — in the broadcast messages (References 3 and 5). User receivers which conform to the RTCM/SC-104 standards will not apply differential corrections unless the IOD from the satellite and the DGPS correction message agree. (All of the receiver models discussed in Section 4 support RTCM/SC-104 messages.)

---

[12]The Control Segment is the ground-based portion of the total GPS system. It includes: the Operational Control facility in Colorado Springs where the satellite ephemeris and clock data are calculated; five worldwide sites which collect satellite broadcast signals and provide data to the Operational Control facility; and three locations from which new ephemeris/clock data are uploaded to the satellites.

The applicant must ensure that the ground station and aircraft use the same ephemeris and clock data sets during testing. One way is to purchase GPS receivers and select DGPS messages which cause this check to be performed automatically, as is the case with the receivers listed in Section 4. Another way to ensure agreement between the ground and aircraft ephemeris/clock data sets is to: (1) store, on computer hard disk at a rate of once each 30 seconds, the IOD used by each receiver; and (2) compare the IODs during post-test processing.

3. SYSTEM APPROVAL REQUIREMENTS

This section summarizes approval requirements for DGPS-based TSPI systems proposed for use during FAA noise certification tests.

3.1 Design Issues

Each applicant's TSPI system design must address the issues identified in Table 1. Firm requirements are not imposed on the design, but the applicant's documentation (Section 3.3) must address each item in the table.

Table 1: TSPI System Design/Development Issues

Number	Issue	Report Location	Major Considerations
1	Selection of processing method (real-time vs. post-test)	Sections 1 and 2	Need for aircraft guidance; ability to check test run quality.
2	Selection of solution method (carrier vs. code)	Section 2	Accuracy (favors carrier); robustness (favors code); cost (favors code).
3	Use of geodetic or waypoint coordinates	Section 2.1	Waypoints can simplify post-processing but not available for all receivers.
4	Selection of GPS receiver and antenna	Section 2	Items 1, 2, 3, and others (antenna multipath control; data messages; solution latency; matched air/ground receivers; and IOD capability).
5	Selection of data link equipment (if real-time system)	Section 2	Assigned frequency; data rate; error detection/correction; flexible interface.

3.2 Data Storage (Logging) During Noise Testing

3.2.1 System with Real-Time Data Link

For applicants employing a real-time data link, the ground-station GPS receiver shall output RTCM/SC-104 Type-1 messages at a rate of 0.5 Hz or greater, which shall be transmitted to, and used by the aircraft GPS receiver.

The applicant's aircraft computer shall collect data from the aircraft GPS receiver and generate permanent data files containing:

(a) three-dimensional aircraft position copied directly from the receiver's data port, i.e., in raw/native form, and not processed;

(b) the waypoints (latitude, longitude, and altitude) used to define the local coordinate frame (if waypoint navigation is used);

(c) time, e.g., UTC or GPS time with or without a local offset, associated with each sample of position data copied directly from the receiver's data port; and

(d) data quality/validity indication associated with each sample of position data.

If waypoints are used (b above), they should be included in the header of each data file. New waypoints should not be able to overwrite existing waypoints. If new waypoints are defined, then a new data file should be created.

For consistency with the noise-data collected during a certification test, it is recommended that (a), (c), and (d) above, be saved in the GPS receiver's raw/native format at a rate greater or equal to 2 Hz, the rate associated with the noise data. However, if hardware limitations preclude following this recommendation, a sampling rate of 0.5 Hz or greater is acceptable.

3.2.2 System Not Using Real-Time Data Link

TSPI systems which do not use a real-time data link shall save data from both the ground-and-aircraft GPS receivers in raw/native format on computer hard disk. Manufacturers' proprietary formats must be used; NMEA standard messages do not support this application. Stored data must include: time, e.g., UTC or GPS time with or without a local offset, satellite ephemeris, pseudorange, signal-to-noise ratio, and carrier phase. It is recommended that applicants using dual-frequency (L1/L2) receivers also save L2 carrier phase data. Typically, post-processing of the ground-based and airborne GPS data will be performed using manufacturer-supplied software. If this is not the case, then any applicant-developed software must be approved by the FAA.

3.3 Documentation

The applicant shall prepare and submit documentation which includes:

(a) System Description: Identifies, at a minimum, the issues in Table 1.

(b) Hardware Description: Model and version number of all system components, including DGPS receivers, antennae, transceivers, and computer;

(c) Software Description: Software functionality and capabilities, data file formats, hardware required, and operating system;

(d) System Setup and Operation: Ground and aircraft installation of the system (including antennae), operating procedures, site survey procedures, power requirements, and system limitations; and

(e) Technique for Validating Installation: For example, an aircraft is parked in a known surveyed location and its position is read from the DGPS system and verified. This can be performed at the test site or at another location, e.g., aircraft home base. As a minimum, this process must be performed at the start and end of each measurement program, and preferably at the beginning and end of each measurement day.

3.4 Accuracy Verification Test

The applicant shall perform a one-time verification of the system accuracy, based on a minimum of six aircraft flight test runs which encompass the conditions, i.e., speed, altitude, range and maneuvers, for which the system will be later used as a reference. The accuracy-verification test shall involve comparison of the DGPS-based TSPI system's position data with those from an accepted reference, such as a laser tracker or another approved DGPS system. This test must be performed on the complete DGPS-based TSPI system developed by the applicant. It is not adequate for an applicant seeking system approval to simply cite prior approval of another applicant's system which was designed around the same GPS receiver.

3.5 Software Verification

Prior to using the system during a noise-measurement program, any applicant-developed software (data logging and post processing) used to obtain data listed herein shall be approved by the FAA. The approved software will be placed under version management.

3.6 Ground-Station Multipath Mitigation and Verification

3.6.1 All Systems

The ground-station GPS receiver antenna shall have a choke ring, absorbing ground plane, or other multipath-reducing technique. The antenna must be positioned on a pole or tower at a minimum height of 10 feet above ground level.

3.6.2 Code-Based Systems

Prior to each measurement program, applicants using code-based DGPS systems must perform a multipath investigation using the ground-station receiver and antenna, as described in Section 2.5.2. The results of the investigation must be saved as part of the permanent test-series data archive, and be available for FAA inspection.

3.7 Airport Survey

Additional information on survey requirements may be found in Section 2.2. Prior to, and after completion of, each measurement program, the applicant must use the DGPS-based TSPI system to survey the locations of either: (1) if no other method of survey is used, all microphones and waypoints (if used); or (2) if another method of survey is used, at least three points in common with the other method. Survey data shall be stored as part of the measurement-program permanent archive. If two survey methods are used, the common points must be reconciled to an accuracy of 1 foot and the adjustment procedure submitted to the FAA for approval.

4. EXAMPLE DATA LOGGING FOR SPECIFIC GPS RECEIVERS

This section provides examples of data to be stored for GPS receivers from Ashtech, Inc., Leica, Inc., Novatel Communications, and Trimble Navigation, Ltd. Data other than those provided as examples may also satisfy the requirements presented in Section 3. In addition, other GPS receivers can be used, provided that the requirements of Section 3 are met. Applicants must ensure, through scrutiny of receiver documentation and discussion with vendors, that the necessary data are available from the selected model. Also provided in Section 4 is a list of technical contacts for the receivers discussed herein.

4.1 Ashtech

4.1.1 Data Stored During Aircraft-Noise Testing

The Ashtech model Z-12 can be used to generate either code-based or carrier-based DGPS solutions. For applicants electing to use a code-based solution, the Z-12 can provide output data sentences conforming to a subset of NMEA-0183 Version 1.5 on serial Ports A and B (Reference 6). The NMEA-0183 GGA sentence contains the receiver's global position (latitude, longitude and altitude), UTC time and status byte. The solution status byte can be used as the quality/validity indication. The status byte can be "0" (fix not available or invalid), "1" (GPS fix) or "2" (Differential GPS fix). A value of "2" is required for the data to be used for processing of noise data.

Applicants using a carrier-based solution will generally store data from both the ground-and-aircraft GPS receivers and process data from both receivers post-flight, using software obtained from Ashtech. The proprietary MBEN sentence should be collected from both receivers and stored.

4.1.2 Real-Time DGPS Data

For applicants employing a real-time data link, the Ashtech Z-12 can provide (at the ground station) and receive (at the aircraft) DGPS messages conforming to a subset of RTCM/SC-104 Version 2.0, on serial Ports A, B, C, and D (Reference 6). A typical scenario would be to transmit Type-1 messages at a rate of 0.5 Hz or faster,[13] and Types 2 and 3 messages at lower rates. For example, Type-2 and Type-3 messages could be alternated, each being transmitted once every other minute.

4.1.3 Data Stored During Multipath Testing

For applicants electing to use a code-based solution, the Ashtech Z-12 receiver can provide the data required for multipath testing via the proprietary MBEN sentence.

4.2 Leica

4.2.1 Data Stored During Aircraft Noise Testing

The Leica model 9400N supplies NMEA-0183 Version 2.0 data sentences on its serial ports (Reference 8). The NMEA-0183 GGA sentence contains the receiver's global position (latitude, longitude and altitude), UTC time and status byte. The solution status byte can be used as the quality/validity indication. The status byte can be "0" (fix not available or invalid), "1" (GPS fix) or "2" (Differential GPS fix). A value of "2" is required for the data to be used for processing of noise data.

[13] The Z-12 Operating Manual (Reference 6) states that ground-station receiver can output Type-1 messages "continuously," but does not provide quantitative information regarding the meaning of this statement.

4.2.2 Real-Time DGPS Data

For applicants employing a real-time data link, the Leica 9400N can provide RTCM messages on its serial ports. A typical scenario would be to transmit Type-1 messages at a rate of 0.5 Hz or faster, and Types 2 and 3 messages at lower rates. For example, Type-2 and Type-3 messages could be alternated, each being transmitted once every other minute.

4.2.3 Data Stored During Multipath Testing

The Leica 9400N can be used to generate either code-based or carrier-based DGPS solutions. For applicants electing to use a code-based solution, the Leica 9400N receiver can provide the data required for multipath testing via the proprietary data from the Instrumentation/Raw Data Port.

4.3 Novatel

4.3.1 Data Stored During Aircraft-Noise Testing

The Novatel models 3951R, RT-20, and RT-2 supply NMEA 0183 Version 2.0 data sentences and numerous proprietary data sentences (referred to by Novatel as logs) on their serial ports. The proprietary log PRTK ("Computed Position – Best Available ") contains the receiver's global position (latitude, longitude and altitude), UTC time and position status flag. The position status flag can be used as the quality/validity indication. A value of "0" or "1" is required for the data to be used during processing of noise data.

The Novatel receivers support waypoint navigation (see Section 2.1). With this feature, a position solution in the same coordinate system as is used for the noise tests can be provided. From the proprietary log NAV ("Navigation") one can obtain the UTC time and position in the horizontal plane (in the local coordinate system used for waypoint navigation).

4.3.2 Real-Time DGPS Data

For applicants employing a real-time data link, the Novatel receivers can provide (at the ground station) and receive (at the aircraft) DGPS messages conforming to a subset of RTCM/SC-104 Version 2.0 (Reference 7). A typical scenario would be to transmit Type-1 messages (log RTCM) at a rate of 0.5 Hz or faster, and Type-3 messages (log RTCM3) at a rate of once per minute.

4.3.3 Data Stored During Multipath Testing

The Novatel RT-2 can be used to generate either code-based or carrier-based DGPS solutions. The other Novatel receivers only generate code-based solutions. For applicants using a code-based solution, the Novatel receivers can provide the data required for multipath testing via the proprietary message RGE.

4.4 Trimble

4.4.1 Data Stored During Aircraft Noise Testing

The Trimble Series 4000 supplies NMEA-0183 Version 2.0 data sentences and numerous proprietary data sentences (referred to by Trimble as Cycle Printouts) on its serial ports. The NMEA-0183 GGA sentence contains the receiver's global position (latitude, longitude and altitude), UTC time and GPS quality indicator. The GPS quality indicator can be used as the quality/validity indication. The quality indicator can be "0" (fix not available or invalid), "1" (GPS fix) or "2" (Differential GPS fix). A value of "2" is required for the data to be used for processing of noise data.

This receiver supports waypoint navigation (see Section 2.1). With this feature, a position solution in the same coordinate system as is used for the noise tests can be provided. From the NMEA-0183 RMB ("Navigation Information") data sentence one can obtain the UTC time and position in the horizontal plane (in the local coordinate system used for waypoint navigation).

4.4.2 Real-Time DGPS Data

For applicants employing a real-time data link, the Trimble Series 4000 can provide RTCM messages on its serial ports. A typical scenario would be to transmit Type-1 messages at a rate of 0.5 Hz or faster, and Type-3 messages at a rate of once per minute.

4.4.3 Data Stored During Multipath Testing

The Trimble Series 4000 can be used to generate either code-based or carrier-based DGPS solutions. For applicants electing to use a code-based solution, the Trimble Series 4000 receiver can provide the data required for multipath testing via the proprietary Raw Measurements Cycle Printout.

4.5 Points of Contact

Information on the receivers mentioned in this section can be obtained from the sources in Table 2.

Table 2: Points of Contact

Company	Contact	Telephone/FAX/Email
Ashtech, Inc. 1170 Kifer Road Sunnyvale, CA 94086	James Murphy, Aviation Marketing Manager	(408) 524-1400 (408) 524-1500 (FAX) james@ashtech.com
Leica, Inc. 23868 Hawthorne Blvd. Torrance, CA 90505-5908	Satish Mittal, Product Manager	(310) 791-5351 (310) 791-6108 (FAX)
Novatel Communications 6732 8th Street Calgary, Alberta T2E 8M4 Canada	Francis Yuen, Customer Service Department	(403) 295-4650 (403) 295-4901 (FAX) fyuen@novatel.ca
Trimble Navigation, Ltd. 645 North Mary Ave Sunnyvale, CA 94086	Mike Margolis Trimble Navigation, Ltd. 11 Flagg Road West Hartford, CT 06117-2309	(860) 523-8787 (860) 231-1795 (FAX) mike_margolis@trimble. com
RTCM P.O. Box 19087 Washington, DC 20036-9087	Not available	(703) 684-4481 (703) 836-4229 (FAX)

REFERENCES

1. *NMEA 0183, Standards for Interfacing Marine Electronics Devices*, National Marine Electronics Association, Version 1.5, December, 1987.

2. *NMEA 0183, Standards for Interfacing Marine Electronics Devices*, National Marine Electronics Association, Version 2.00, January 1, 1992.

3. *RTCM Recommended Standards for Differential Navstar GPS Service*, Radio Technical Commission for Maritime Services, Paper 194-93/SC104-STD, Version 2.1, January 1994.

4. Parkinson, B.W., and Spilker, J.J., editors, *Global Positioning System: Theory and Applications, Volume 1*, American Institute of Aeronautics and Astronautics, 1996.

5. *Broadcast Standard for the USCG DGPS Navigation Service*, U.S. Coast Guard, COMDTINST M16577.1, April 1993.

6. *Ashtech Z-12 Receiver Operating Manual*, Ashtech Inc., Publication Number 600224, Revision B, May 1994.

7. *GPS Card Command Description Manual*, Novatel Communications Corporation, Publication Number OM-20000008, Revision 2, March 1995.

8. *DGPS 12 Channel Technical Reference Manual*, Leica Navigation and Positioning Division, Publication Number 10139, Revision A, September 1996.

APPENDIX A

FAA INFORMATION MEMORANDUM REGARDING USE OF DGPS FOR CERTIFICATION FLIGHT TESTING