RNAV (GPS) Total System Error Models for Use in Wake Encounter Risk Analysis of Dependent Paired Approaches to Closely-Spaced Parallel Runways

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ABSTRACT

The purpose of this memorandum is to provide recommended Total System Error (TSE) models for aircraft using RNAV (GPS) guidance when analyzing the wake encounter risk of proposed simultaneous dependent ("paired") approach operations to Closely Spaced Parallel Runways (CSPR, defined as having centerline spacing less than 2,500 feet). RNAV (GPS) is being evaluated as a source of guidance to aircraft approaching one or both runways of specific CSPR pairs, in lieu of or in addition to ILS guidance, for possible inclusion in future changes to FAA Order 7110.308 and/or in future orders authorizing Wake Turbulence Mitigation for Arrivals – Procedure-based (WTMA-P).

This memorandum supersedes Project Memorandum DOT-VNTSC-FAA-13-08, which is now obsolete. The primary differences from DOT-VNTSC-FAA-13-08 are: (1) the lateral NSE and FTE models for LNAV/VNAV operations are changed, and (2) recommended analysis approaches and possible operational restrictions are included for situations when both aircraft employ baro-VNAV vertical guidance.

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1. Introduction

1.1 Purpose

Background:

- FAA Order 7110.65 (Ref. 1), Section 5-9-6, authorizes simultaneous dependent approaches for aircraft pairs with a minimum of 1.5 nautical mile (NM) radar separation to parallel runways whose centerlines are at least 2,500 feet but no more than 4,300 feet apart, with Instrument Landing System (ILS) or Area Navigation (RNAV) Global Positioning System (GPS) guidance permitted for aircraft approaching either runway.
- FAA Order 7110.308 (Ref. 2) authorizes simultaneous dependent approaches for aircraft pairs with a minimum of 1.5 NM radar separation to specific parallel runway pairs separated by less than 2,500 ft that have ILS guidance to both runways, with Heavy and B757 aircraft excluded from the leader position.
- The Wake Turbulence Mitigation for Arrivals – Procedure-based (WTMA-P) project within the FAA Wake Turbulence Research Program is evaluating extending the concept of dual, dependent arrival streams to CSPR pairs with Heavy or 757 category aircraft in the leader position.

The purpose of this memorandum is to provide recommended Total System Error (TSE) models for aircraft using RNAV (GPS) guidance when analyzing the wake encounter risk of proposed simultaneous dependent (“paired”) approaches, with 1.5 NM minimum radar separation, to Closely Spaced Parallel Runways (CSPR, defined as having centerline spacing less than 2,500 feet). RNAV (GPS) is being evaluated as a source of guidance to aircraft approaching one or both runways of specific CSPR pairs, in lieu of or in addition to ILS guidance, for possible inclusion in future changes to Order 7110.308 and/or inclusion in future orders authorizing Wake Turbulence Mitigation for Arrivals – Procedure-based (WTMA-P) to specific runway pairs.

1.2 Wake Encounter Risk during CSPR Approaches

1.2.1 Factors Affecting Aircraft Wake Risk during Approaches

During approaches to a single-runway (SR) or to a CSPR pair, the leader aircraft sheds wakes that are “soft obstacles” for the follower aircraft. Wake vortices are soft obstacles in the sense that some encounters are permitted and acceptable, but a proposed new procedure or operation must demonstrate that, statistically, the likelihood of wake encounters will be no greater than occur with SR in-trail operations with current separation standards, as those have been demonstrated to be and accepted as safe.

During SR approach operations, an aircraft engaged in the operation maintains a minimum required separation from the aircraft immediately ahead on the same approach horizontal course and vertical path. Wake encounters by the subject aircraft are reduced by three mechanisms:

(a) Descent – wakes generated by the preceding aircraft generally descend, and the following aircraft flies above them;

(b) Demise – wakes generated by the preceding aircraft will usually have decreased in strength when the following aircraft reaches the position where the wake was generated; and

(c) Transport – wakes generated by the preceding aircraft will generally transport with the wind away from the course of the following aircraft.

Dependent, paired approaches are illustrated in Figure 1 and Figure 2 (from Ref. 2). During dependent approaches to CSPR, mitigation mechanisms (a), (b) and (c) are also present, but their beneficial effects may be lessened, as the separation between the two aircraft is reduced. To compensate, dependent operations to CSPR generally involve additional mechanisms to reduce the effects of wake encounters by the follower aircraft:

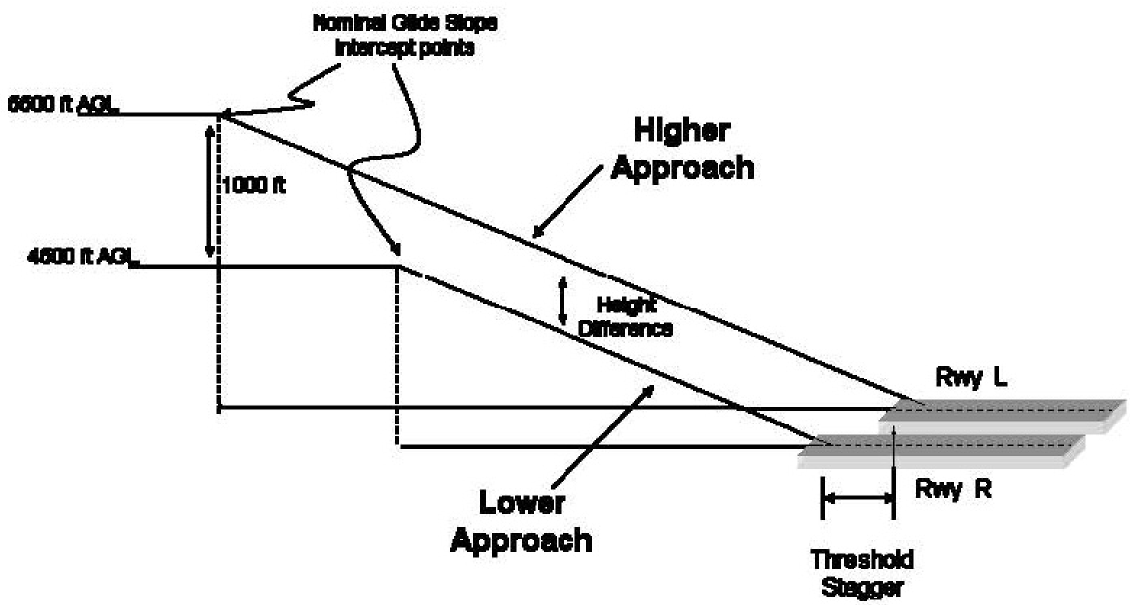


Figure 1 Side View of Example CSPR Approaches

(1) The follower aircraft's defined vertical path is higher than that of the leader aircraft

(2) The aircraft defined horizontal courses are separated by at least the centerline separation between the runways

(3) Approach courses to one or both runways may have small angular offsets to provide increased lateral separation

(4) Vertical guidance is required for both the leader and follower aircraft, and standards more stringent than those for SR operations may be imposed

(5) Horizontal guidance is required for both the leader and follower aircraft, and standards more stringent than those for SR operations may be imposed

(6) The effects of prevailing crosswinds on wake transport are taken into account.

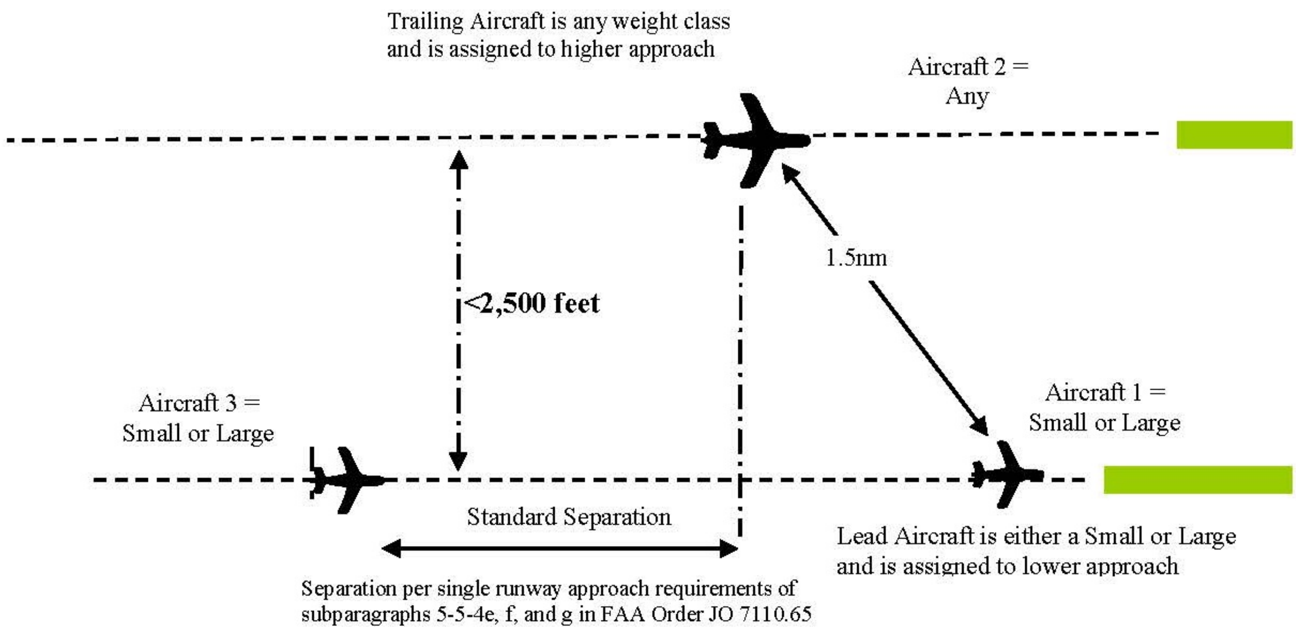


Figure 2 Top-Down View of Dependent Staggered Approach Procedure

Standard in-trail separation is applied to the aircraft following a dependent pair on approach to either runway (Aircraft 3 in Figure 2). Thus the risk of a wake encounter to an aircraft following a dependent pair is the same it is currently under Order 7110.65.

1.2.2 Wake Encounter Risk Analysis Methodology

When analyzing dependent operations to candidate CSPR pairs, separate methodologies, including separate aircraft TSE models, are used to evaluate the wake encounter risk of the follower aircraft in two distinct regimes:

- Out of Ground Effect (OGE) regime — The OGE regime is taken to begin 2 NM ("308" analysis) or 3 NM (WTMA-P analysis) from the threshold of the runway approached by the lead aircraft, and to end at 14 NM from that threshold. The 2-NM or 3-NM (respectively) boundary is based on the fact that Large or Heavy/757 category aircraft, when in the lead (wake-generating) position, are expected to have their vortices completely remain in the OGE regime until their demise
- In Ground Effect (IGE) / Near Ground Effect (NGE) regime — The IGE/NGE regime is taken to be the region between the touch-down point and 2 NM or 3 NM (respectively) from the arrival runway threshold for the lead aircraft. In this region, a Large or Heavy/757 category aircraft could have portions of the wake it generates affected by the influence of the ground.

In the OGE regime, a simulation is used to predict wake encounter risk as a function of the (i) geometry of the CSPR pair (centerline separation and arrival threshold stagger); (ii) statistical crosswind profile (which transports the wakes) derived from measurements or data-driven nowcasting models; (iii) measured wake descent distribution ; (iv) defined lateral and vertical flight paths of the aircraft along the approach route; and (v) lateral and vertical total system errors (TSEs) of both aircraft.

In the IGE/NGE regime, a data-driven wake encounter analysis methodology that has been used to analyze CSPR approaches with ILS guidance (e.g., for the initial approval of Ref. 2) is used, without modification, for analyses involving RNAV (GPS) guidance.

1.3 TSE Taxonomy

Figure 3 illustrates an accepted taxonomy of an aircraft's inability to fly a desired flight trajectory. Although the figure depicts lateral errors, a similar figure applies to vertical errors. TSE is shown as the sum of three components:

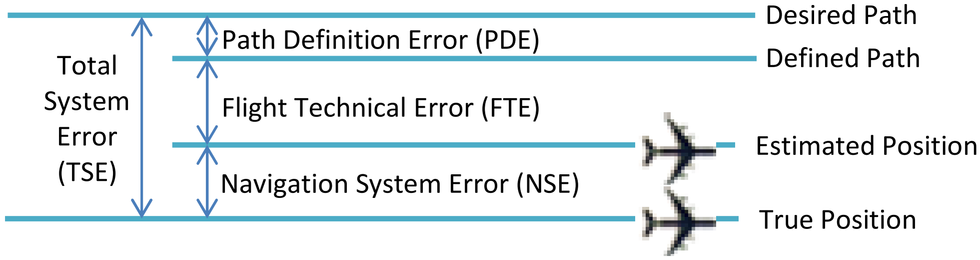


Figure 3 Components of Aircraft Total System Error

- Path Definition Error (PDE) — Difference between the desired flight path (e.g., a perfectly straight line coincident laterally with the extended centerline of the destination runway that makes a 3.00 deg vertical angle with a plane parallel to the local horizon at the threshold) and the defined path presented to the pilot/aircraft navigation and control instrumentation.
- Flight Technical Error (FTE) — Difference between the aircraft location indicated by the navigation system and the defined flight path. FTE is a function of the aircraft "steering system" (pilot, flight director or autopilot), the weather conditions (e.g., wind, particularly buffeting) and the operation involved (e.g., straight-and-level versus turning and descending trajectories). An alternate term for this component is Path Steering Error; however, the traditional FTE term is used herein.
- Navigation System Error (NSE) — Difference between the true aircraft location and the aircraft location indicated by the navigation system. The NSE is largely independent of the aircraft on which the navigation system is installed.

These components address functionally distinct equipment and activities, which are often performed by different organizations.

1.4 Memorandum Outline

Chapter 2 summarizes the characteristics of the GPS receivers and baro-VNAV systems used for RNAV (GPS) approaches.

To achieve PDEs, FTEs and NSEs that are comparable to those needed for conducting dependent paired approaches, restrictions must be placed on aircraft operations and equipage. These restrictions are addressed in Chapter 3 and (for baro-VNAV systems) Chapter 4.

With one exception, in this memorandum the PDE is taken to be zero. It is usually assumed that the process of defining the course/path to be flown — involving accounting for physical phenomena, conducting geodetic surveys, database integrity assurance measures and aircraft flight checks — is performed sufficiently well that the resulting residual errors are negligible.

The exception is the difference between the desired and defined vertical flight paths for LNAV/VNAV procedures. These may differ due to the temperature sensitivity of baro-altimeter systems that do not have temperature compensation. Such a PDE is a known quantity and is analyzed as a deterministic error in Chapter 4.

The sources of NSE and FTE considered herein to be random, so that statistical characterizations are appropriate. Models for lateral and vertical NSEs and FTEs are the subject of Chapter 5.

Chapter 6 summarizes the error models described herein.

This memorandum concludes with: an appendix containing additional, detailed information (Chapter 7); a list of acronyms and abbreviations (Chapter 8); and a list of sources referenced (Chapter 9).

2. RNAV GPS and Baro-Altimeters Sensors and Associated Procedures

2.1 GPS Receiver Families

All GPS receivers provide latitude, longitude and altitude information. They differ in the performance (accuracy, integrity, availability, etc.) of this information. The primary source of such differences is the augmentation signals that are processed in conjunction with the signals from the GPS satellites. On this basis, three families of GPS receivers are certified for use in the National Airspace System (NAS) under Instrument Flight Rules (IFR). Approach procedures have been developed based on the capabilities of each family.

2.1.1 'GPS' Receivers and LNAV or LNAV/VNAV Procedures

Receivers that do not utilize augmentation signals from outside the aircraft are informally called 'GPS' receivers. These receivers can be used as a source of horizontal guidance during operations under Instrument Flight Rules (IFR). However, they cannot be used as a vertical guidance source under IFR operations. RNAV (GPS) procedures which utilize a 'GPS' receiver for lateral guidance and lack vertical guidance are termed LNAV (for Lateral Navigation) procedures, and are classified as nonprecision approaches. LNAV procedures are functionally similar to VOR (VHF Omnidirectional Ranging) procedures but usually have better guidance accuracy and thus may have lower minima.

A Barometric-Vertical Navigation (Baro-VNAV) system, which includes a Flight Management System (FMS), is often employed in conjunction with a 'GPS' receiver to achieve an approach capability with vertical guidance. The Lateral Navigation / Vertical Navigation (LNAV/VNAV) procedures for which 'GPS' and Baro-VNAV guidance is qualified generally have significantly higher ceiling and visibility minima than ILS Category I procedures or the Localizer Performance with Vertical guidance (LPV) procedures[*] for which 'WAAS' receiver guidance is qualified — see example approach plates in Sections 7.1 thru 7.3.

Originally, to be certified for IFR, FAA required that 'GPS' receivers comply with Technical Standard Order (TSO) C129 (Ref. 3), which relies heavily on RTCA Document DO-208 (Ref. 4). Subsequently, after over a decade of operational experience and lessons learned, new standards addressing the same topics — TSO C196 (Ref. 5) and DO-316 (Ref. 6) — were issued and TSO C129 was cancelled.[†]

* Technically, an LPV approach is usually not a procedure, but are one of multiple options for an RNAV (GPS) procedure. However, this semantic distinction is not observed herein.

† A "cancelled TSO" means that the FAA will no longer issue authorizations for new/revised avionics designs against that TSO. However, any equipment authorization issued prior to the cancellation of the TSO remains valid and may continue to be manufactured and marked in accordance with that authorization. Also, operational use in the National Airspace System (NAS) of aircraft equipment previously authorized under a now-cancelled TSO continues to be authorized.

2.1.2 'WAAS' Receivers and LPV Procedures

Receivers that utilize Satellite-Based Augmentation System (SBAS) signals are informally called 'WAAS' receivers. In the U.S., SBAS signals are provided by the FAA's Wide Area Augmentation System (WAAS) satellites. 'WAAS' receivers can provide both horizontal and vertical guidance that (when the satellites within view meet certain criteria) is comparable to that from ILS Category I installations. The associated approach procedures are called LPV procedures, and, when satellite coverage permits, generally have minima comparable to those for ILS Category I procedures (see examples in Sections 7.1 thru 7.3). When satellite coverage is degraded (which is rare), 'WAAS' receivers may meet the requirements for LNAV/VNAV approaches while providing more accurate guidance than 'GPS'/Baro-VNAV equipage.

WAAS receivers conform to either TSO C145 (Ref. 7) or TSO C146 (Ref. 8), both of which rely heavily on RTCA DO-229 (Ref. 9). TSO C145 applies to receivers that are integrated with an aircraft's FMS, while C146 applies stand-alone receivers (which generally have some FMS functionality built in).

2.1.3 'LAAS' Receivers and GLS Procedures

Receivers that utilize Ground-Based Augmentation System (GBAS) signals are informally called Local Area Augmentation System (LAAS) receivers, the name of the FAA program addressing this topic.

The 'LAAS' receiver family is not addressed further herein. 'LAAS' receivers are intended to be used for GLS procedures which are the equivalent of ILS Category II and/or III precision approach capabilities, whereas the focus of Order 7110.308 is CAT I or near CAT I approach capabilities.

2.2 Baro-Altimeters and VNAV Systems

An aircraft's VNAV system, which includes a baro-altimeter and an FMS module, can provide vertical guidance during an approach (LNAV/VNAV procedure). However, VNAV guidance is not a direct/complete substitute for ILS glide slope guidance, as baro-altimeters have two physical behavior mechanisms that are not present in ILS glide slope guidance:

- Defined vertical path is curved
- Defined vertical path is sensitive to temperature

2.2.1 Defined Vertical Path Is Curved

Figure 4, from Ref. 10 volume 6, depicts the vertical paths defined for ILS glide slope and baro-VNAV guidance systems. The paths are different geometrically — the ILS glide slope path is straight, while the VNAV path is concave downward logarithmic spiral. (Vertical paths defined by 'WAAS' receivers for LPV approaches are also straight.) If the published angles for the ILS and VNAV paths are the same for a given runway end (as preferred by Refs. 10 and 11), then the

VNAV-defined path will be lower than the glide slope path over the entire final approach. If the end points of the two paths are the same at the runway and at the Precision Final Approach Fix (PFAF), then the VNAV trajectory will be above the glide slope over the entire final approach. For the latter situation, the published ILS and VNAV angles would be different. This is not preferred, but may be done when there is a need for the RNAV (GPS) procedure to use the PFAF previously established for an ILS approach.

Equations for the altitude above a spherical earth for ILS/LPV and VNAV approaches are given in Section 7.5. For the same vertical angle at the runway threshold, the VNAV path bends downward from the straight-line ILS glide slope (toward the horizon) at a constant rate that is approximately equal to that of the earth's curvature, 1 arcmin/NM. Thus the separation between the two paths increases approximately as the square of the distance from the threshold in accordance with Equation 1.

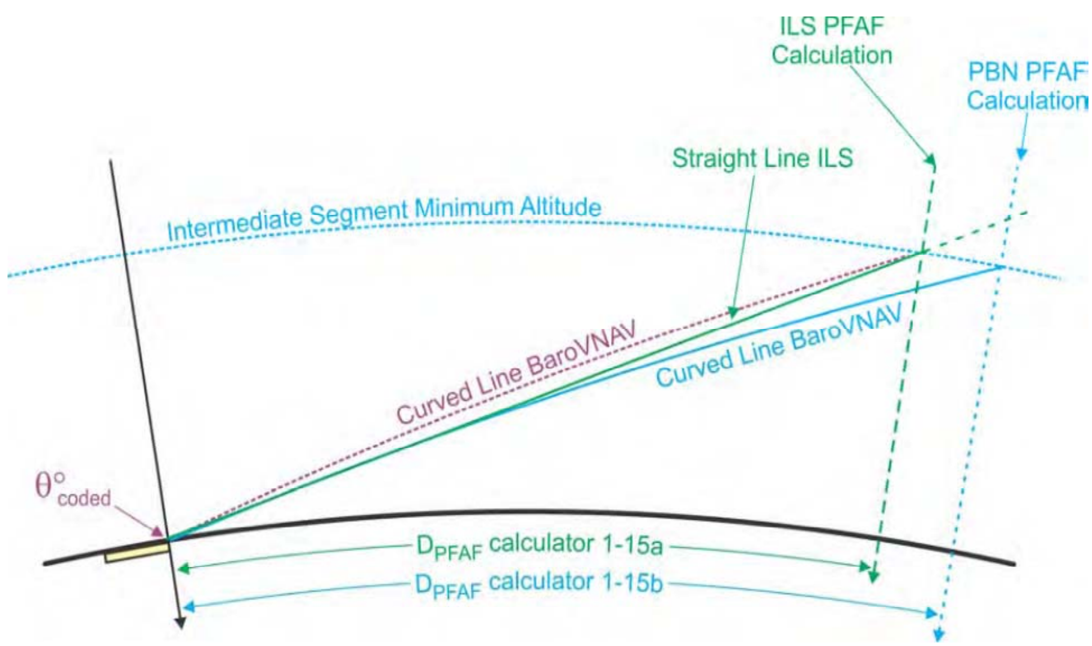


Figure 4 Defined Vertical Paths for ILS Glide Slope and Baro-VNAV Guidance

Equation 1 Approximate Difference between ILS and VNAV Vertical Paths

$$\Delta h = kD^2$$

where

- ***Δh:*** Difference between defined altitudes for ILS/LPV and VNAV guidance (feet)
- ***k:*** Proportionality factor, 0.8837
- ***D:*** Distance along the curved surface of the earth from the threshold (NM)

The difference between straight and curved vertical paths is not a concern when independent approaches are conducted to a single runway with standard longitudinal separation. However, during “308” or WTMA-P operations to CSPR, when the longitudinal separation is reduced and the relative positions of the vertical paths may be a more significant element in the wake mitigation strategy, these differences may be important. Wake encounter simulations should model the VNAV trajectory using the equation in Section 7.5.

2.2.2 Defined Vertical Path Is Sensitive to Temperature

When the static pressure at the aircraft and the pressure at sea level are known, and the outside air temperature is known as well, then the aircraft’s altitude can, under most circumstances (e.g., absence of temperature inversions), be calculated accurately. However, the basic design of aircraft barometric altimeters employs a “standard day” model for temperature rather than a measurement, and does not provide a means for compensating for deviations from the assumed sea level temperature of 15 °C (59 °F). A deviation results in an uncompensated altitude PDE, as the path defined by the aircraft VNAV system differs from the desired path. This PDE: (a) is the same for all aircraft at the same altitude, and (b) does not fluctuate. Thus a deterministic, rather than random, characterization is appropriate.

Sea level temperatures that are less than the standard 15 °C cause the altimetry system to report a higher altitude than is true. Conversely, temperatures that are greater than the standard value cause the altimetry system to report a lower altitude than is true. The International Civil Aviation Organization (ICAO) has estimated the impact of temperature on VNAV approaches, and published the following table in the Procedures for Air Navigation Services, Aircraft Operations (PANS-OPS, Ref. 12, paragraph II.1.4.3) for changes in Glide Path Angle (GPA):

Table 1 Effect of Uncompensated Airport Temperature on Baro-VNAV Glide Path Angle

Airport* Temperature	Defined† GPA
+30 °C (+86 °F)	3.2 deg
+15 °C (+59 °F) *Standard Day Value*	3.0 deg
0 °C (+32 °F)	2.8 deg
-15 °C (+5 °F)	2.7 deg
-31 °C (-24 °F)	2.5 deg

*For airport at MSL and a charted 3 deg glide path angle
†Implicit in the guidance presented to the pilot by the aircraft VNAV system

Figure 5 depicts the vertical path defined by an ILS glide slope subsystem (or a ‘WAAS’ receiver LPV vertical guidance) and the path defined by a baro-VNAV system. The published/charted GPA is assumed to be 3.00 deg for both systems, and the effects of ±15 °C (±59 °F) temperature deviations from the standard day value are also depicted. It is clear that both VNAV phenomena, curved path and uncompensated temperature deviations, can result in significantly different vertical paths than occur with ILS guidance.

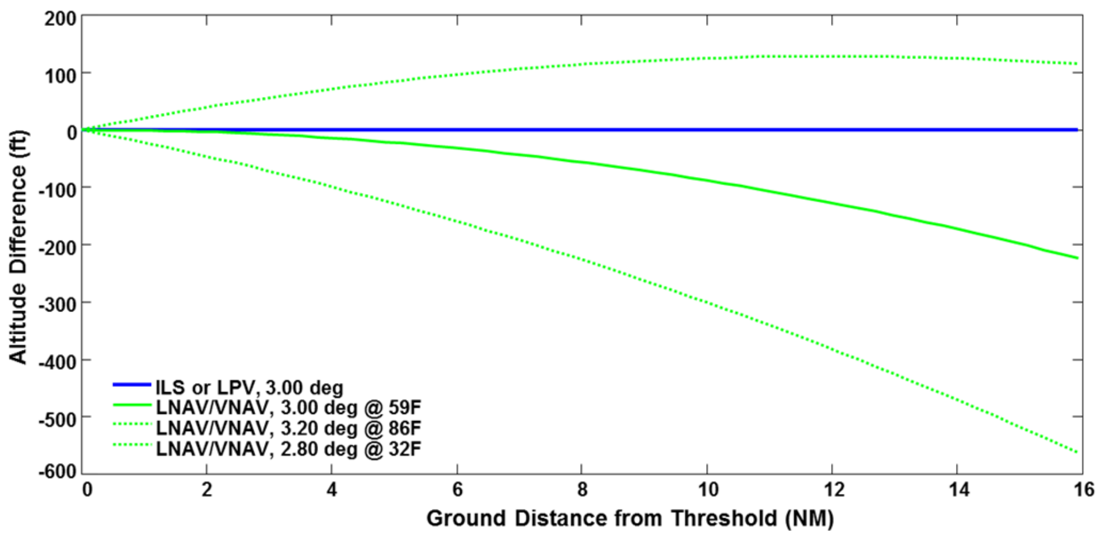


Figure 5 Difference in Defined Vertical Paths for ILS/LPV and Baro-VNAV Guidance

Temperature compensation of the barometric altimeter is available on many full-sized transport aircraft and some smaller aircraft. For aircraft with full temperature compensation (i.e., for temperatures both colder and warmer than the standard day value), this PDE mechanism is not present.

3. Equipage and Operational Restrictions

3.1 Need for Restrictions

The example RNAV (GPS) approach plates in Sections 7.1 thru 7.3 have up to four lines of minima – i.e., for LPV, LNAV/VNAV, LNAV and Circling approaches. Standard air traffic control practice is to clear an aircraft for the “RNAV approach to runway XX”. The term *GPS* is not stated, and the qualifier *to runway XX* may be omitted if there is no ambiguity. Important for the analysis of candidate dependent approaches is that a line of minima is not stated as part of the clearance, and may be selected by the pilot, subject to the aircraft’s equipage and restrictions stated on the approach plate.

Consequently, analysis of dependent operations must (a) address approach types which support the operation, and (b) recommend appropriate restrictions on aircraft equipage and the conditions when the approach may be flown. Any limitations for dependent operations to CSPR would in addition to those for SR operations.

For conducting dependent approaches to CSPR with RNAV (GPS) guidance to one or both runways, one operational and one equipage restriction are recommended:

- Participating aircraft not be authorized to conduct a LNAV or Circling approach (Section 3.2).
- Use of a flight director (FD) or autopilot (AP) be required (Section 3.2)

It is recommended that these restrictions be stated on approach plates, in the pilot briefing information section near the top of the chart.

In addition, as a means of limiting PDE, ambient temperature and/or aircraft equipage restrictions be imposed on use of LNAV/VNAV procedures using baro-altimeter vertical guidance. This topic is addressed in Chapter 4.

3.2 LNAV and Circling Approaches Not Available

As noted in Subsection 1.2.1, in item (3) of the numbered list of mitigations, vertical guidance is required for both leader and follower aircraft that participate in dependent, paired CSPR operations. As LNAV and Circling approaches lack vertical guidance, they cannot be used.

Suggested wording for the procedure using RNAV (GPS) guidance is:

> “**Simultaneous approach operations authorized with Rwy XX ILS. LNAV procedures NA during simultaneous operations.**”

Similar wording is used on many IAPs, including the examples in Sections 7.1 and 7.3.

3.3 Flight Director Required

3.3.1 Recommendation

The primary benefit of a FD is that it significantly reduces the lateral and vertical FTE, in some cases to less than one-third the FTE achieved by "hand flying" the aircraft using basic Course Deviation Indicator (CDI) and Vertical Deviation Indicator (VDI) displays (Ref. 13). Current Instrument Approach Procedures (IAPs) for simultaneous approaches to parallel runways at several airports require use of a FD (examples are shown in Sections 7.1 thru 7.3).

Suggested wording for the procedure using RNAV (GPS) guidance is:

> "**Simultaneous approach operations authorized with Rwy XX ILS. Use of FD or AP required for course and path guidance during simultaneous operations.**"

3.3.2 Background/Rationale

Basic information about Flight Directors (FDs) is presented in Section 7.4. The requirement for a FD will only exclude a small fraction of aircraft which might want to participate in dependent, paired operations at major airports. Aircraft with un-augmented 'GPS' receivers and a Baro-VNAV system are required to have a FD to perform LNAV/VNAV approaches (Ref. 14). Also, aircraft with 'WAAS' receivers conforming to TSO C145 (Ref. 7, addressing navigation sensors that must be integrated with an aircraft's FMS) usually have a FD as well. The primary aircraft group that might be excluded is those with panel-mounted WAAS receivers conforming to TSO C146 (Ref. 8). These aircraft generally have basic CDI and VDI displays and fly at slower approach speeds than most aircraft with a FD (Ref. 15).

Reduced lateral and vertical TSE for both the leader and follower aircraft is instrumental to wake avoidance by the follower aircraft during dependent, paired operations. The rationale for requiring a FD for an RNAV (GPS) equipped aircraft is, first, to reduce the vertical FTE so that the TSE is in the range ±100 to ±125 feet (95%). Modeling, simulations and analyses have shown this TSE range to be effective in limiting the wake encounter rate for an aircraft in the follower position. Without a FD, the VDI display full-scale deflection will be ±500 feet for a significant portion of the operation, making it difficult to attain the target TSE level (Ref. 9). Limiting the vertical TSE of the aircraft in the leader position is similarly important, as the leader's glide path is designed to be lower than follower's.

The second reason for requiring a FD is to limit the horizontal FTE (and thus TSE) of an aircraft participating in dependent, paired operations prior to its arriving at the Precision Final Approach Fix (PFAF). Nominally, the PFAF is located 5 NM from the runway threshold, while dependent approaches operations can extend to 12-14 NM from the threshold. In the region outside the PFAF, the CDI display can have full-scale deflections of ±1 NM (see Figure 6, from Ref.15, Section 1.4).

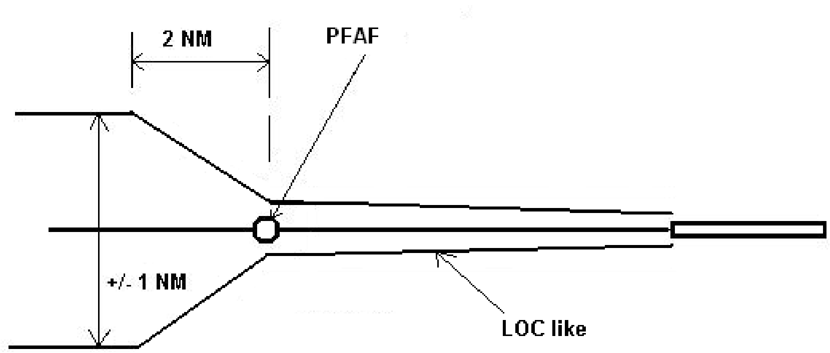


Figure 6 CDI Scaling for TSO-C145b / C146b WAAS Receivers

4. PDE Models for Baro-VNAV Systems

4.1 Baro-VNAV Temperature Sensitivity

4.1.1 Temperature Sensitivity Effect on SR and Paired CSPR Approaches

As noted in Subsection 2.2.2, the vertical path presented to the pilot/aircraft by a baro-VNAV system that lacks temperature compensation will be higher or lower than the path corresponding to the charted GPA approximately in proportion to the temperature deviation from the "standard day" value of 15 ^{o}C (59 ^{o}F). Current RNAV (GPS) IAPs that include an LNAV/VNAV line of minima contain temperature limits below and above which use of the approach is not authorized ("NA") without temperature compensation. For example, the RNAV (GPS) approach plate shown in Section 7.1 has this statement: "For uncompensated Baro-VNAV systems, LNAV/VNAV NA below -8 ^{o}C (18 ^{o}F) or above 54 ^{o}C (130 ^{o}F)".

The temperature restrictions on current approach plates were developed for SR operations. In some cases, the temperature limits correspond to 2.5 deg and 3.5 deg GPAs defined by the aircraft VNAV system at the time the approach is conducted, which are the minimum and maximum GPAs stated in Ref. 10. In other cases, the limits are more restrictive. The low-temperature limit ensures that the actual vertical path flown is obstacle-free. The high-temperature limit reduces the likelihood that, at Decision Altitude, the aircraft will be above the minimum ceiling and/or have to execute a significant vertical flight correction.

IAP temperature limits were not developed to protect the follower aircraft during dependent paired approaches to CSPR involving baro-VNAV guidance on one or both runways. Requiring the runway for the follower aircraft to have a higher glide path than the runway for the leader aircraft is often a significant element in the strategy for reducing the follower aircraft's wake encounters. ILS, LPV and temperature-compensated VNAV guidance are not temperature sensitive. When dependent paired operations are conducted, if the GPA actually flown to one runway is insensitive to temperature changes while the LNAV/VNAV GPA actually flown to the other runway varies with temperature, the relationship between the two vertical paths cannot be assured.

Evaluating a proposed CSPR pair for dependent paired approaches involving RNAV guidance is a two-step process, each employing wake encounter risk simulation analysis (Subsection 1.2.2):

(1) Step 1: <u>The published GPAs for the two runways are established for the worst-case combination of applicable vertical guidance options</u> to achieve a wake encounter risk at the standard day temperature that is no greater than the encounter risk for current SR operations. When RNAV (GPS) guidance is involved, both LPV and VNAV guidance must both be considered for the applicable runway(s).

(2) Step 2: <u>The impact of temperature on wake encounter risk with baro-VNAV guidance is evaluated to establish temperature limits</u> for dependent paired approaches to CSPR.

The combination of vertical guidance systems governing the establishment of GPAs and temperature limits during these two steps may be different.

4.1.2 Methods for Reducing the Probability of Wake Encounters

Utilizing RNAV (GPS) guidance, in lieu of ILS guidance, to one runway of a CSPR pair often increases the risk of a wake encounter for a given pair of GPAs, due to the temperature sensitivity and/or curved nature of VNAV vertical paths. Utilizing RNAV (GPS) approaches to both runways usually increases the encounter risk to a greater extent. The following options, separately or in combination, can be used to reduce the risk associated with the follower aircraft encountering wakes shed by the leader:

- Decrease the GPA for the leader aircraft
- Increase the GPA for the follower aircraft
- Increase the follower aircraft runway's threshold stagger
- Define an angled offset approach course for the leader aircraft
- Define an angled offset approach course for the follower aircraft
- Require use of LPV guidance
- Prohibit use of baro-VNAV guidance without temperature compensation
- Assign aircraft using baro-VNAV guidance to approaches having published GPAs based on the current temperature at MSL (Table 2 is an example).

Table 2 Example of Multiple GPAs Associated with Temperature Ranges for Baro-VNAV

Published GPA	Temperature Range	Range of GPAs Flown
2.80 deg	86 °F to 113 °F	3.00 to 3.20 deg
3.00 deg	59 °F to 86 °F	3.00 to 3.20 deg
3.20 deg	32 °F to 59 °F	3.00 to 3.20 deg
3.40 deg	5 °F to 32 °F	3.00 to 3.20 deg

4.2 Temperature Limits for CSPR Having ILS and RNAV (GPS) Approaches

4.2.1 Temperature Limitations for ILS Leader / RNAV Follower

If the leader aircraft utilizes ILS guidance while the follower may utilize either WAAS-LPV or GPS-LNAV/Baro-VNAV guidance, then during Step 1 (when establishing the leader and follower GPAs) both RNAV (GPS) options must be considered. If maintaining the follower's vertical path above that of the leader is necessary for wake mitigation, the downward curving nature of the vertical path for baro-VNAV guidance will usually cause baro-VNAV to govern establishment of the GPA.

During Step 2, the analysis must take into consideration the possibility of the follower utilizing VNAV guidance without temperature compensation, due to its shift downward with decreasing temperature. Upward shifts in the follower's vertical path reduce wake encounter risk. Consequently, a high-temperature limit is not imposed by an ILS leader / RNAV follower combination (other than the SR limit for the follower).

If uncompensated baro-VNAV systems are permitted, then simulations should be used to determine the lowest temperature for which the probability of a wake encounter is no worse than for SR operations. Based on that finding, the approach plate for the follower should contain a statement similar to

> "**For uncompensated Baro-VNAV systems, LNAV/VNAV NA for simultaneous dependent operations below XX ^{0}C (YY ^{0}F)**".

An alternative to a temperature limitation is to restrict use of dependent paired operations to follower aircraft with LPV or temperature compensated VNAV systems. The latter can be accomplished by including a statement similar to the following on the follower's approach:

> "**LNAV/VNAV NA for simultaneous dependent operations using uncompensated Baro-VNAV systems**".

Because a some temperature compensation system only compensate for temperatures that are lower (colder) than the standard day value, when ILS and GPS (RNAV) are used for CSPR "308" operations and there is an option as to which system will guide the leader aircraft and which will guide the follower, a greater number of users can be served by requiring that the leader utilize ILS guidance and the follower utilize RNAV (GPS) guidance.

4.2.2 Temperature Limitations for RNAV Leader / ILS Follower

If the leader aircraft may utilize either WAAS-LPV or GPS-LNAV/Baro-VNAV guidance while the follower utilizes ILS guidance, then during Step 1 (when establishing the leader and follower GPAs) both RNAV (GPS) options must be considered. If maintaining the follower's vertical path above that of the leader is necessary for wake mitigation, the straight-line nature of the vertical path for LPV guidance will usually result in LPV guidance governing establishment of the GPAs.

During Step 2, the analysis must take into consideration the possibility of the leader utilizing VNAV guidance without temperature compensation, due to its shift upward with increasing temperature. Downward shifts in the leader's vertical path reduce wake encounter risk. Consequently, a low-temperature limit is not imposed by RNAV leader / ILS follower combination (other than the SR limit for the leader).

If uncompensated baro-VNAV systems are permitted, then simulations should be used to determine the highest temperature for which the probability of a wake encounter is no worse than for SR operations. Based on that finding, the approach plate for the leader should contain a statement similar to

> **"For uncompensated Baro-VNAV systems, LNAV/VNAV NA for simultaneous dependent operations above XX ^{0}C (YY ^{0}F)".**

An alternative to a temperature limitation is to restrict dependent paired arrivals to leader aircraft utilizing LPV or temperature compensated baro-VNAV vertical guidance. This can be accomplished by including a statement similar to the following on the approach plate for the leader aircraft:

> "**LNAV/VNAV NA for simultaneous dependent operations using uncompensated Baro-VNAV systems**".

4.3 Temperature Limits for CSPR Both Having RNAV (GPS) Approaches

4.3.1 Establishing Leader and Follower Published GPAs

If the leader and follower aircraft both utilize either WAAS-LPV or GPS-LNAV/Baro-VNAV guidance, then during Step 1 (Subsection 4.1.1) all four combinations of leader/follower vertical guidance must be considered (LPV/LPV, LPV/VNAV, VNAV/LPV and VNAV/VNAV). When maintaining the follower's vertical path above that of the leader is necessary for wake mitigation, the analysis will often result in the LPV/VNAV combination governing establishment of the published GPAs.

4.3.2 Establishing Temperature Limitations

When RNAV (GPS) guidance is used for both runways, nine combinations of vertical guidance systems are possible (Table 3). These combinations involve aircraft that utilize vertical guidance from a LPV system, a baro-VNAV system with temperature compensation or a baro-VNAV system without temperature compensation. Fewer combinations are possible if restrictions are placed on aircraft equipment permitted to participate in dependent paired arrival operations. For example, if the leader cannot have an uncompensated baro-VNAV system, then only six combinations are possible (the top two non-header rows in Table 3).

Table 3 Leader/Follower Combinations for RNAV (GPS) Approaches to Both Runways

Leader \ Follower	LPV	VNAV with Temp Comp	VNAV without Temp Comp
LPV	LPV / LPV	LPV / $VNAV_{TC}$	LPV / $VNAV_{NC}$
VNAV with Temp Comp	$VNAV_{TC}$ / LPV	$VNAV_{TC}$ / $VNAV_{TC}$	$VNAV_{TC}$ / $VNAV_{NC}$
VNAV without Temp Comp	$VNAV_{NC}$ / LPV	$VNAV_{NC}$ / $VNAV_{TC}$	$VNAV_{NC}$ / $VNAV_{NC}$

Shaded cells do not require temperature sensitivity analysis (Step 2).

In Table 3, the equipment combinations in shaded cells do not impose temperature limits on dependent paired arrivals. Thus only four combinations need to be analyzed during Step 2: an uncompensated baro-VNAV system in either the leader or follower position combined with either an LPV or compensated baro-VNAV system in the other position.

These analyses are similar to those addressed in Subsections 4.2.1 and 4.2.2, except for the substitution of LPV or baro-VNAV NSE and TSE errors for the corresponding ILS errors. In every case, the aircraft approaching one runway is not sensitive to temperature (ILS, LPV or compensated VNAV vertical guidance) and the aircraft approach the other runway employs uncompensated VNAV vertical guidance. The high temperature limit is found when the leader employs uncompensated VNAV, while the low temperature limit is found when the follower employs uncompensated VNAV.

5. NSE and FTE Models

5.1 Model Selection and Applicability

5.1.1 Distinction between Required and Typical Error Values

Generally, navigation (and other) systems are developed to satisfy one or more *requirements*. Subsequently, after the system is developed, test results become available which characterize the system's *typical* performance. Often, the typical performance is significantly better than the original requirement. Thus, for analysis purposes, one must decide which value to use. The approach taken herein is, first, to use documented typical values that are the result of extensive testing/measurements. When typical performance information consistent with these conditions is not available, the system requirement is used. If neither required nor typical values are available, values are used for a similar, but lower-performing, system.

5.1.2 Boundary between OGE and IGE/NGE Regimes

As stated in Chapter 1, the models described herein are used for two projects within the FAA Wake Turbulence Research Program: FAA Order 7110.308, which authorizes dual steams to specific CSPR pairs when the lead aircraft is limited to the Large or Small weight class; and Wake Turbulence Mitigation for Arrivals – Procedure-based (WTMA-P), which is investigating dual steams to specific CSPR pairs when the lead aircraft is permitted to be a 757 or Heavy class. Because the weight classes of the leader aircraft are different for these projects, the boundary between the OGE and IGE/NGE wake behavior regimes are different. For Order 7110.308, the boundary is 2 NM; for WTMA-P, the boundary is 3 NM.

5.2 OGE Model for LPV Approaches

5.2.1 LPV Lateral and Vertical NSEs

The WAAS lateral and vertical Navigation System Error (NSE) components are so small that they can generally be ignored when formulating a TSE model for LPV approaches. For over a decade the FAA has measured WAAS NSEs at the WAAS Reference Station (WRS) sites. These measurements have consistently found the WAAS NSE 95% horizontal and vertical errors to be less than 6 ft (e.g., Ref. 16). While the WRS measurement scenario is nearly optimal for performance — e.g., stationary receivers, well-placed antennas, external interference monitoring, and oversight by a skilled technical staff — even if the error statistics were multiplied by ten, the resulting hypothetical NSE would be less than the expected LPV FTE.

OGE LPV Lateral and Vertical NSE Model (95%)

For aircraft between 2 or 3 NM and 14 NM from the runway threshold:
Negligible

A second justification for the statement that WAAS NSE can be neglected when considering WAAS TSE is Ref. 17, Table 3.3-1, which states that the WAAS Signal-In-Space (SIS) 95% accuracy, separately for horizontal and vertical, is 5.3 feet. While a SIS specification does not include the effects of receiver implementation errors, it is likely to be representative of what a WAAS receiver will provide to an aircraft.

5.2.2 LPV Lateral TSE Model

Given (1) the limited amount of published information available concerning required and typical TSE values during LPV approaches, (2) that LPV approaches are designed as WAAS equivalents to ILS Category I approaches, and (3) that WAAS NSE are negligible relative to FTE, the recommended LPV lateral TSE model is based on the model that the Volpe Center has developed and previously used (with the FAA) for the analysis of ILS Category I approaches. Random errors are assumed to normally distributed, and, as is common in the aircraft navigation field, are quantified by their two-sided 95% error bounds rather than their standard deviations.

OGE LPV Lateral TSE Model (95%)

For aircraft between 2 or 3 NM and 14 NM from the runway threshold:
(±24 feet/NM) x (Distance from the threshold in NM)

The above model was derived from aircraft position measurements by Airport Surface Detection Equipment, Model X, (ASDE-X) systems at three major U.S. airports (Ref. 18): Detroit Metropolitan Wayne County (DTW), Lambert – St. Louis International (STL) and John F. Kennedy International (JFK). The majority of traffic at these airports is presumed to be air carrier aircraft equipped with a FD and AP. This presumption is supported by the fact that the 95% error rate of growth, ±24 feet/NM, is equivalent to ±0.23 degrees, or less than 10% of full-scale deflection on a CDI.

5.2.3 LPV Vertical TSE Model

Within 4.5 NM of the threshold, the vertical TSE model is selected to be the same as the lateral TSE model.[*] This is a conservative selection, as ILS guidance is inherently more accurate in the vertical dimension than in the lateral dimension.[†]

At more than 4.5 NM from the threshold, the vertical TSE model, ±108 feet (95%), is the same as the TSE requirement for Baro-VNAV approaches using a FD (discussed in the following section). This is also a conservative selection, as WAAS vertical guidance is significantly better than Baro-VNAV guidance — e.g., when both approaches are provided at the same runway, the

* ASDE-X vertical measurements are not sufficiently accurate to evaluate aircraft vertical TSE.

† For example, for a 6,000-ft runway and a 3.0 deg glide path angle, the full-scale deflection for the CDI is ±2.8 deg, while the full-scale deflection for the VDI is ±0.75 deg (approximately a 3.8:1 ratio).

Decision Height (DH) above the threshold for the LPV approach will be considerably lower than the DH for the LNAV/VNAV approach.

OGE LPV Vertical TSE Model (95%)

For aircraft between 2 or 3 NM and 4.5 NM of the runway threshold:
(±24 feet/NM) x (Distance from the threshold in NM)

For aircraft at 4.5 NM or more from the runway threshold:
±108 ft

5.3 OGE Model for LNAV/VNAV Approach

5.3.1 Lateral NSE Model

It is assumed herein that the aircraft has a 'GPS' receiver conforming to either the Technical Standard Order (TSO) C129 family (Ref. 3, originally released in the early 1990s) or the TSO C196 family (Ref. 5, first released in 2011).* These two series of TSOs are the only TSOs issued for GPS receivers having only aircraft-based augmentations.

TSO C129 required, for use during non-precision approach operations (the most demanding operation addressed), that the receiver provide "GPS RNAV 2D Accuracy (95% confidence)" of 0.056 NM, which is equivalent to 340.3 ft. The same specification was subsequently contained in AC 20-130A (Ref. 19). The LNAV/VNAV lateral NSE model is based on these documents.

OGE LNAV/VNAV Lateral NSE Model (95%)

For aircraft between 2 or 3 NM and 14 NM from the runway threshold:
±340 ft

For several reasons, the above lateral NSE value selected is quite conservative, including:

- Reference 3 was first released when GPS Selective Availability (SA) was a concern, and took account of an assumed SA level. SA ceased to be an issue with an announcement by the President in May 2000 that "The United States has no intent to ever use Selective Availability again".
- While the intended full GPS constellation has 24 satellites, when Ref. 3 was released the Air Force commitment was only to provide for 21 working satellites on orbit. However, for many years there has generally been more than a "full constellation" of satellites on orbit — e.g., on Jan. 8, 2014, there were 32 working GPS satellites on orbit.
- Several generations of civil GPS receivers have been developed since Ref. 3 was released. These receivers are widely deployed and regularly used on transport passenger aircraft.

* TSO C129 was cancelled upon the release of C196 but equipment designs approved under C129 remained in service.

- Reference 3 contains a two-dimensional (two axes) accuracy standard while the application addressed herein is one dimensional, and logically could be smaller.

Reference 20 states that "Actual GPS navigation errors are typically around 15 to 20 meters [50 to 66 ft] 99% of the time, so this represents a very conservative estimate".

5.3.2 Lateral FTE Model

Authoritative FTE models are less readily available than those for NSE, for several reasons:

- More variables are involved — including aircraft control and display systems, prevailing weather conditions, and the flight operation being performed
- Measurements are more difficult and costly to obtain.

Available information (e.g., Ref. 13) indicates that a hand flown aircraft using a course deviation indicator (CDI) for guidance will not have a sufficiently small FTE for simultaneous approaches to be flown during dependent paired approaches to CSPR. Thus this analysis assumes that a flight director or autopilot is employed. This assumption does not limit the use of dependent paired approaches to any significant extent, as the expected aircraft participants in such operations (turbojet aircraft with takeoff weights over 60,000 pounds) virtually always have a flight director.

Reference 20 addresses an operation very similar to (but requiring smaller navigation errors than) simultaneous dependent approaches — simultaneous independent and dependent approaches to parallel runways, primarily by turbojet aircraft, with at least one aircraft employing RNAV (GPS). As a result of the analysis documented in Ref. 20, simultaneous approaches to dual and triple parallel runways spaced more than 4300 feet apart utilizing RNAV (GPS) guidance were approved (Ref. 1). The FTE model adopted in Ref. 20 —80 m (95%) — is also used herein.

OGE LNAV/VNAV Lateral FTE Model (95%)

For aircraft between 2 or 3 NM and 14 NM from the runway threshold:
±262 ft

The rationale presented in Ref. 20 is:

> "Historical flight test data were consulted to determine representative FTE values for flight director guided precision approaches. The standard deviations reported from these tests were up to 8 meters at Decision Height (DH) and no larger than 40 meters at 7 miles out from threshold. Data collected on RNAV approaches flown with GPS and flight director produced standard deviations of less than 20 meters. Using a standard deviation (σ) of 40 meters should represent a very conservative estimate. This gives a 2σ, approximately 95%, value of 80 meters."

In terms of aircraft type, the study document in Ref. 20 addressed "Boeing 747, 767, and 777 models, Airbus A310, A330, A340, and some A300 models, and a handful of older types".

5.3.3 Lateral TSE Model

Combining the NSE and FTE components by the root-sum-square method yields a TSE of 430 ft (95%).

OGE LNAV/VNAV Lateral TSE Model (95%)
For aircraft between 2 or 3 NM and 14 NM from the runway threshold: ±430 ft = ±0.07 NM

5.3.4 Vertical TSE Model

The vertical TSE due to random sources onboard the aircraft is taken from AC 20-138C (Ref. 21), §10.2, and its associated RTCA document DO-236B (Ref. 22), §2.1.2. This requirement, that the TSE during flight along a specified vertical profile be 160 ft (99.7%) is equivalent to 108 ft (95%). This requirement applies to baro-altimeter system designs approved after January 1, 1997; and is consistent with Reduced Vertical Separation Minima (RVSM) standards. The referenced documents require that a flight director be utilized for VNAV operations.

OGE LNAV/VNAV Vertical TSE Model (95%)
For aircraft between 2 or 3 NM and 14 NM from the runway threshold: ±108 ft

5.4 IGE/NGE TSE Model for LPV or LNAV/VNAV Approaches

In the IGE/NGE regime — the region between the touch down point for the lead aircraft and 2 or 3 NM from the lead aircraft's arrival threshold — the wake encounter risk analysis methodology utilizes measured wake locations and strengths as a function of the time since their generation, rather than predictions of wake locations/strengths based on prevailing winds. For both LNAV/VNAV and LPV approach procedures, aircraft TSE in the IGE/NGE regime is shown below.

IGE/NGE LPV & LNAV/VNAV TSE Model (95%)
For aircraft between 0 NM and 2 or 3 NM from the runway threshold: Lateral: ±50 ft Vertical: ±24 ft

The IGE/NGE lateral TSE model for the final 2 or 3 NM of an approach is essentially equal to the LPV OGE lateral model at 2 NM from the threshold. The IGE/NGE vertical TSE model is based on measurements with a laser range finder at Lambert – St. Louis International Airport (STL) and Denver International Airport (DEN). It is one-half of the LPV OGE lateral model at 2 NM from the threshold, illustrating the conservative nature of the LPV model.

6. Summary of Random and Deterministic Errors

6.1 Models for Random TSEs

Table 4 Summary of TSE Random Components (95%)

Approach Procedure / Guidance Source — Regime / Distance to Runway	LNAV/VNAV		LPV	
	Lateral 'GPS' Guidance	**Vertical** Baro-Altimeter Guidance	**Lateral** 'WAAS' Guidance	**Vertical** 'WAAS' Guidance
IGE/NGE Random (95%) Touch down to 2 or 3 NM from Threshold	±50 ft	±24 ft	±50 ft	±24 ft
OGE Random (95%) 2 or 3 NM to 14 NM from Threshold	±430 ft	±108 ft	Table 5	Table 5
Restrictions Pilot briefing section of approach plate	"Simultaneous approach operations authorized with Rwy XX." "LNAV procedures NA during simultaneous operations." "Use of FD or AP providing course and path guidance required during simultaneous operations."			

Table 5 LPV TSE Values for OGE (ft, 95%)

Distance / *Axis*	*2 NM*	*3 NM*	*4 NM*	*5 NM*	*6 NM*	*7 NM*	*8 NM*	*9 NM*	*10 NM*	*11NM*	*12 NM*	*13 NM*	*14 NM*
Lateral	±48	±72	±96	±120	±144	±168	±192	±216	±240	±264	±288	±312	±336
Vertical	±48	±72	±96	±108	±108	±108	±108	±108	±108	±108	±108	±108	±108

6.2 Effects of Deterministic Baro-VNAV Errors

Evaluating a proposed CSPR pair for dependent paired approaches involving baro-VNAV vertical guidance is a two-step process, each involving wake encounter risk simulation analysis:

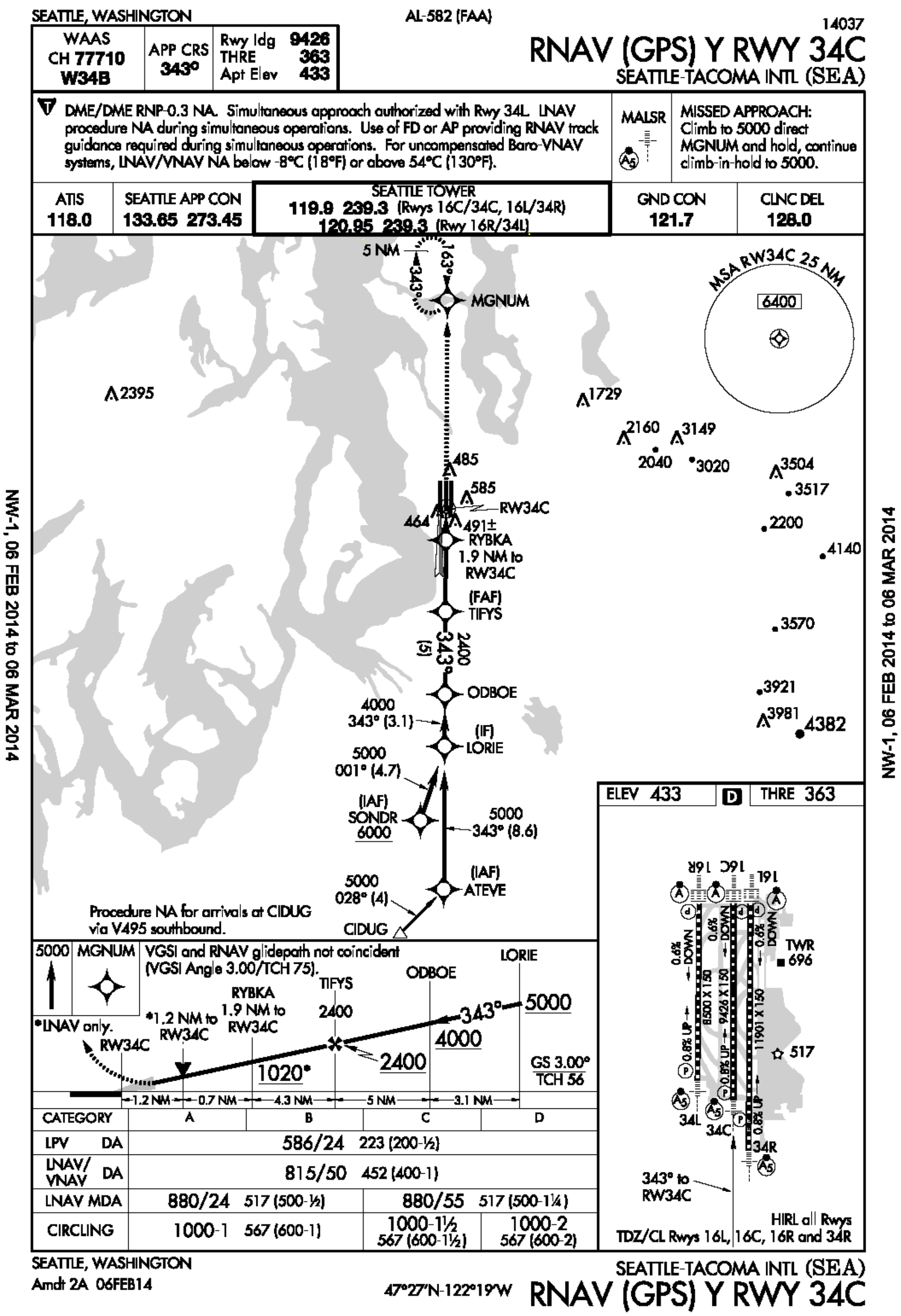
(1) Published GPAs for the runways are determined based on the worst-case combination of applicable vertical guidance options

(2) The effect of temperature on wake encounter risk with uncompensated baro-VNAV guidance is evaluated to establish temperature limits.

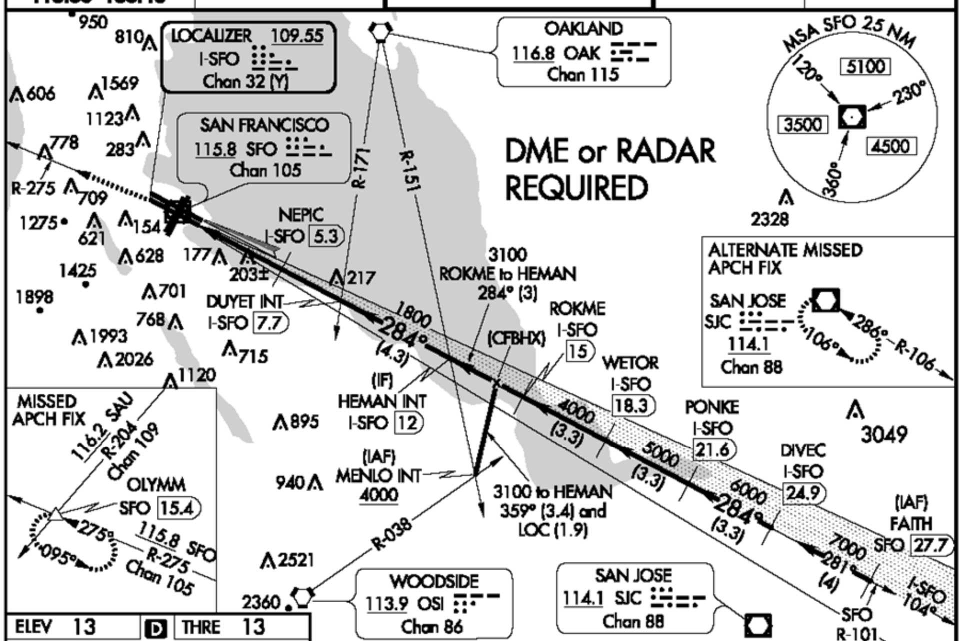
The combinations to be analyzed during Step 2 are: an uncompensated baro-VNAV system in either the leader or follower position, in combination with (as applicable) an ILS, LPV and/or compensated baro-VNAV system in the other position. The high temperature limit is found when the leader employs uncompensated baro-VNAV guidance; the low temperature limit is found when the follower employs uncompensated baro-VNAV guidance. Based on these findings, the pilot briefing section of the approach plate should contain a statement of the form: “For uncompensated Baro-VNAV systems, LNAV/VNAV NA for simultaneous dependent operations below UU ºC (VV ºF) or above XX ºC (YY ºF)”.

7. Appendices

7.1 KSEA Runway 34C RNAV (GPS) Approach Plate



7.2 KSFO Runway 28L RNAV (GPS) Approach Plate



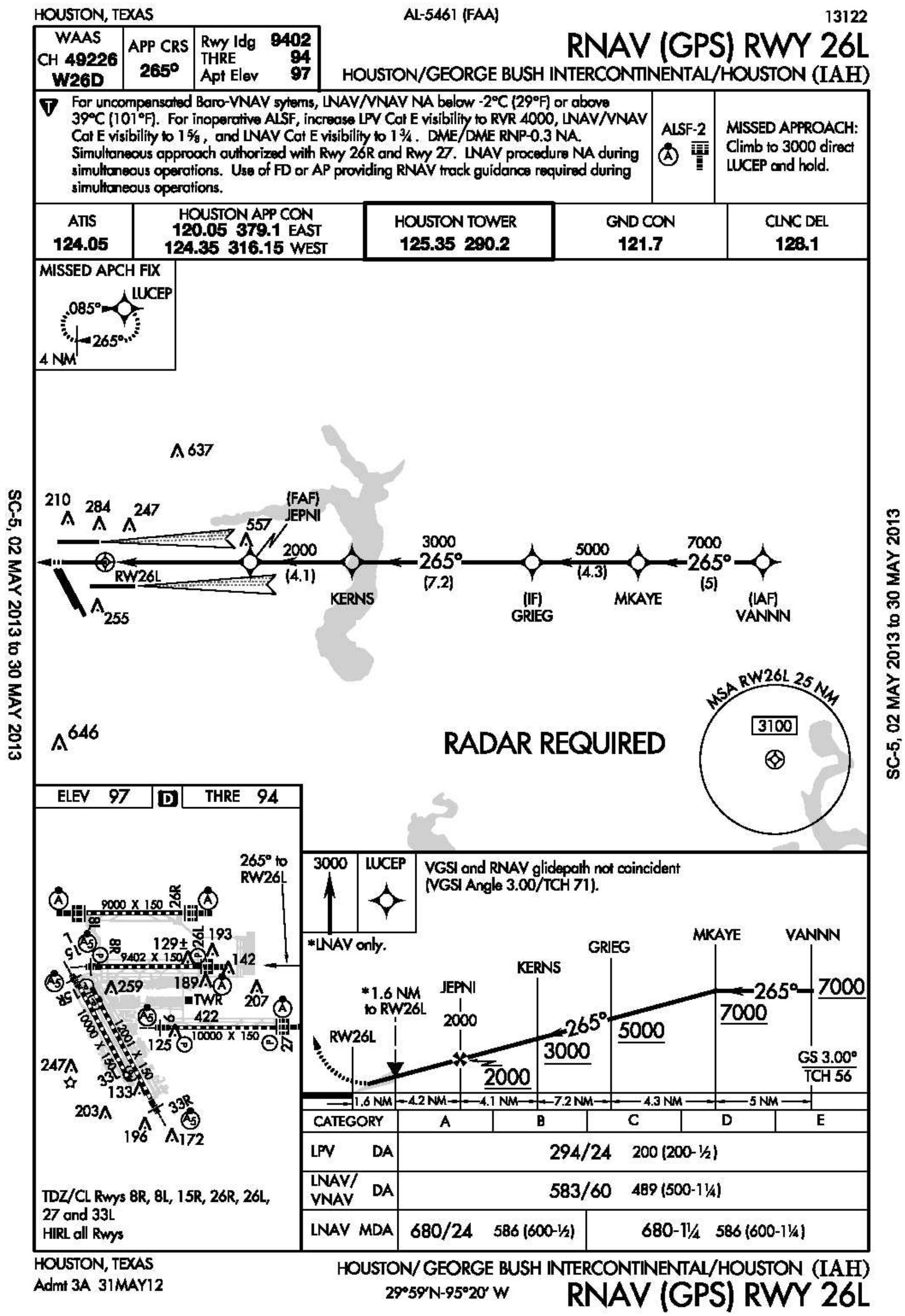
CATEGORY	A	B	C	D
S-ILS 28L †#	213/24 200 (200-½)			
S-ILS 28L	789-2½ 776 (800-2½)			
S-LOC 28L#	460/24 447 (500-½)		460/45 447 (500-⅞)	
S-LOC 28L	760/24 747 (800-½)	760/40 747 (800-¾)	760-1¾ 747 (800-1¾)	
CIRCLING	800-1 787 (800-1)	1000-1½ 987 (1000-1½)	1560-3 1547 (1600-3)	NA

FAF to MAP 5.7 NM

Knots	60	90	120	150	180
Min:Sec	5:42	3:48	2:51	2:17	1:54

SAN FRANCISCO, CALIFORNIA
Amdt 24A 17OCT13
37°37'N-122°23'W
SAN FRANCISCO INTL (SFO)
ILS or LOC RWY 28L

7.3 KIAH Runway 26L RNAV (GPS) Approach Plate



CATEGORY		A	B	C	D	E
LPV	DA	294/24 200 (200-½)				
LNAV/VNAV	DA	583/60 489 (500-1¼)				
LNAV	MDA	680/24 586 (600-½)		680-1¼ 586 (600-1¼)		

7.4 What Is a Flight Director?

A flight director (FD) is a specialized aircraft computer that calculates the proper pitch and roll angle commands that will enable the aircraft to follow a selected path. The pilot enters the desired trajectory into the FD, and navigation avionics — e.g., ILS receiver, VOR receiver, GPS receiver and altimeter — provide real-time position information. The FD then displays, usually by placing crossbars on the Attitude Indicator (AI)[*], steering cues for achieving the desired trajectory.

The FD is often used in direct connection with the Autopilot (AP), where the FD commands the AP to put the aircraft in the attitude necessary to follow the desired trajectory. Examples of trajectories that a typical FD can provide command for:

- Fly a selected heading;
- Fly a predetermined pitch attitude;
- Maintain an altitude;
- Intercept a selected VOR or localizer track, and maintain that track;
- Fly an ILS glide slope.

AI without FD

AI with FD

Attitude Indicator (AI) without/with Command Bars from a Flight Director (FD)

When flying an approach without a FD, the pilot must steer the aircraft based on the Course Deviation Indicator (CDI) and Vertical Deviation Indicator (VDI)[†] while monitoring the AI — potentially three separate instruments. The CDI/VDI show the pilot how far the aircraft is off the desired course and glide path, and the AI is used to maintain stable flight. However, none of these instruments provide clues on how much to bank or pitch the aircraft to steer it onto the desired course/path.

By providing steering cues, a FD significantly reduces Flight Technical Error (FTE) — thus Total System Error (TSE) as well as pilot workload — relative to steering based on the CDI/VDI and AI. Reference 13 indicates that with a FD the FTE can be as small as one-third of the FTE without a FD.

* The Attitude Indicator is sometimes called the artificial horizon.

† In jet transport aircraft, the CDI and VDI functions are usually incorporated into a Horizontal Situation Indicator (HSI).

7.5 VNAV and ILS Vertical Path Altitude Equations

This section presents equations for the altitude above mean sea level (MSL), for a spherical model of the earth, as a function of distance along the curved surface of the earth from the runway threshold. Equation 2 is for the path defined by Baro-VNAV guidance, and Equation 3 is for the path defined by ILS or LPV guidance. These equations are from Refs. 10 and 11.

Equation 2 Defined-Path Altitude versus Ground Range for Baro-VNAV Guidance

$$AC_{alt} = -R_e + \left(R_e + TCH_{elev}\right)\exp\left(\frac{GndRng\ \tan(\alpha_V)}{R_e}\right) \qquad \text{(ft)}$$

In the above equation:

- $\boldsymbol{AC_{alt}}$: Aircraft height above Mean Sea Level (MSL), ft
- $\boldsymbol{R_e}$: Earth's radius of curvature; equal to 20,890,537 ft
- $\boldsymbol{TCH_{elev}}$: Threshold crossing height above MSL; typically found as the sum of the threshold landing point elevation, TLP_{elev}, and the aircraft crossing height above the threshold, TCH; ft
- ***GndRng*** : Distance along the curved surface of the earth between the runway threshold and the aircraft's latitude/longitude, ft
- $\boldsymbol{\alpha_V}$: VNAV path angle at the runway for the procedure, optionally adjusted for temperature deviation from the "standard day" value, radians

Equation 3 Defined-Path Altitude versus Ground Range for ILS Glide Slope Guidance

$$AC_{alt} = -R_e + \left(R_e + TCH_{elev}\right)\frac{\cos(\alpha_{GS})}{\cos\left(\frac{GndRng}{R_e} + \alpha_{GS}\right)} \qquad \text{(ft)}$$

In the above equation:

- $\boldsymbol{AC_{alt}}$: Aircraft height above Mean Sea Level (MSL), ft
- $\boldsymbol{R_e}$: Earth's radius of curvature; equal to 20,890,537 ft
- $\boldsymbol{TCH_{elev}}$: Threshold crossing height above MSL; typically found as the sum of the threshold landing point elevation, TLP_{elev}, and the aircraft crossing height above the threshold, TCH; ft
- ***GndRng*** : Distance along the curved surface of the earth between the runway threshold and the aircraft's latitude/longitude, ft
- $\boldsymbol{\alpha_{GS}}$: ILS Glide Slope angle for the procedure, radians

8. List of Acronyms and Abbreviations

AC	Advisory Circular
AGL	Above Ground Level
AI	Attitude Indicator
AP	Autopilot
ASDE-X	Airport Surface Detection Equipment, Model X
CDI	Course Deviation Indicator
CSPR	Closely-Spaced Parallel Runways
DASC	Digital Avionics Systems Conference
deg	degree(s)
DH	Decision Height (above terrain or ground level)
DOT	Department of Transportation
DTW	Detroit Metropolitan Wayne County Airport
FAA	Federal Aviation Administration
FD	Flight Director
FMS	Flight Management System
ft	foot/feet
FTE	Flight Technical Error
GBAS	Ground-Based Augmentation System
GLS	GPS Landing System
GPA	Glide Path Angle
GPS	Global Positioning System
HSI	Horizontal Situation Indicator
IAP	Instrument Approach Plate
IGE	In-Ground Effect
ILS	Instrument Landing System
JFK	John F. Kennedy International Airport
LAAS	Local Area Augmentation System
LNAV	Lateral Navigation
LPV	Localizer Performance with Vertical guidance
m	meter(s)
MSL	Mean Sea Level
NA	Not Authorized
NGE	Near-Ground Effect
NM	Nautical Mile(s)
NSE	Navigation System Error

OGE	Out of Ground Effect
PANS OPS	Procedures for Air Navigation Services, Aircraft Operations
PDE	Path Definition Error
RMS	Root-Mean-Squared
RNAV	Area Navigation
RTCA	RTCA, Inc. (formerly Radio Technical Commission for Aeronautics)
RVSM	Reduced Vertical Separation Minima
SA	Selective Availability
SBAS	Satellite-Based Augmentation System
SIS	Signal-In-Space
SR	Single Runway
STL	Lambert – St. Louis International Airport
TCH	Threshold Crossing Height
TSE	Total System Error
TSO	Technical Standard Order
VDI	Vertical Deviation Indicator
VHF	Very High Frequency
VNAV	Vertical Navigation
VNTSC	Volpe National Transportation Systems Center
VOR	VHF Omnidirectional Range
WAAS	Wide Area Augmentation System
WRS	WAAS Reference Station
WTMA-P	Wake Turbulence Mitigation for Arrivals – Procedure-based

9. References

1. JO 7110.65U with Change 2: *Air Traffic Control*; FAA Order; March 7, 2013.

2. JO 7110.308 with Change 3: *1.5-Nautical Mile Dependent Approaches to Parallel Runways Spaced Less Than 2,500 Feet Apart*; FAA Order; October 30, 2012.

3. TSO C129a: *Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)*; FAA Technical Standard Order; February 20, 1996; CANCELLED.

4. DO-208: *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)*; RTCA; July 1991.

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6. DO-316: *Minimum Operational Performance Standards for Global Positioning System/Aircraft Based Augmentation System Airborne Equipment*; RTCA; April 14, 2009.

7. TSO C145c: *Airborne Navigation Sensors Using the Global Positioning System Augmented by the Satellite-Based Augmentation System*; FAA Technical Standard Order; May 2008.

8. TSO-C146c: *Stand-Alone Airborne Navigation Equipment Using the Global Positioning System Augmented by the Satellite-Based Augmentation System*; FAA Technical Standard Order; May 2008.

9. DO-229d: *Minimum Operational Performance Standards for Global Positioning System (GPS) / Space-Based Augmentation System Airborne Equipment*; RTCA; February 2013.

10. JO 8260.58: *United States Standard for Performance Based Navigation (PBN) Instrument Procedure Design*; FAA Flight Standards Service; September 21, 2012.

11. JO 8260.3B, Change 25: *United States Standard for Terminal Instrument Procedures (TERPS)*; FAA Flight Standards Service Order; March 9, 2012.

12. Doc 8168: *Procedures for Air Navigation Services, Aircraft Operations (PANS OPS) – Vol. 1, Flight Procedures*; International Civil Aviation Organization; Fifth Edition, 2006.

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