RNAV (GPS) Total System Error Models for Use in Wake Encounter Risk Analysis of Candidate CSPR Pairs for Inclusion in FAA Order 7110.308

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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/named parallel runways separated by less than 2,500 feet that have ILS guidance to both runways, with Heavy and B757 aircraft excluded from the lead 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 Nautical Mile (NM) minimum radar separation, to Closely Spaced Parallel Runways (CSPR). CSPR are 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 pairs, in lieu of or in addition to ILS guidance.

1.2 Wake Encounter Risk Analysis Methodologies

When analyzing dependent operations to candidate CSPR pairs pursuant to Order 7110.308, separate analysis methodologies, including separate aircraft TSE models, are used to evaluate the wake encounter risk of the trailing aircraft in the following regimes:

- Out of Ground Effect (OGE) regime — taken to begin 2 NM from the threshold of the runway approached by the lead aircraft, and to end at 14 NM from that threshold. The 2NM boundary is based on the fact that Large wake category aircraft, when in the lead (wake-generating) position, are expected to have their vortices completely remain in the OGE regime at this location until their demise
- In Ground Effect (IGE) / Near Ground Effect (NGE) regime — taken to be the region between the touch-down point and 2 NM from the arrival runway threshold for the lead aircraft. In this region, a Large 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 (a) geometry of the CSPR pair (centerline separation and arrival threshold stagger); (b) statistical crosswind profile (which transports the wakes) derived from measurements or data-driven nowcasting models; (c) measured wake descent distribution ; (d) nominal lateral and vertical separation of the aircraft along the approach route; and (e) 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 — see Section 4.3.2.

2. Certified GPS Receiver Families and Associated Approach Procedures

There are three families of GPS receivers certified for use under Instrument Flight Rules (IFR):

'GPS' Receivers — 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 IFR operations. However, they cannot be used as a vertical guidance source under IFR operations. Instead, a Baro-VNAV system (which includes a Flight Management System (FMS)) is employed to achieve an approach capability with vertical guidance. The LNAV/VNAV procedures for which GPS/Baro-VNAV guidance is qualified generally have significantly higher minima than ILS Category I procedures or the LPV procedures for which 'WAAS' receiver guidance is qualified — see example RNAV (GPS) approach plates in Sections 5.1 thru 5.3.

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.*

'WAAS' Receivers — 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. These 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 (Sections 5.1 thru 5.3). When satellite coverage is degraded, 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).

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

The third/last family is not addressed further herein. 'LAAS' receivers are intended to provide the equivalent of ILS Category II and/or III precision approach capabilities (CAT II/III), whereas the focus of Order 7110.308 is CAT I or near CAT I approach capabilities.

* 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.

3. Additional Aircraft Equipage Restrictions for RNAV (GPS) ".308" Operations

3.1 Summary of Recommended Restrictions

For ".308" dependent approaches to CSPR with RNAV (GPS) guidance to one or both runways, it is recommended that two restrictions be placed on the aircraft's equipage and usage, in addition to those required for independent single-runway approach operations:

- A flight director (FD) (which is often accompanied by autopilot (AP) equipage) be required
- Additional temperature limitations be imposed if an LNAV/VNAV procedure is flown using baro-altimeter vertical guidance without temperature compensation when ILS guidance is used for the other runway (see Section 3.3.2).

For ".308" operations, a RNAV (GPS) equipped aircraft must conduct an approach procedure that requires vertical guidance — either LPV or LNAV/VNAV. RNAV (GPS) equipped aircraft engaged in ".308" operations should not be authorized to conduct a LNAV approach.

It is recommended that requirements for these equipage capabilities be stated on the approach plates involved, in the pilot briefing information section near the top of the chart. This section consists of three horizontal rows of boxed procedure-specific information. The middle row contains procedure notes and limitations (as well as other information).

3.2 Flight Director Required

Basic information about Flight Directors (FDs) is presented in Section 5.4. The primary benefit of a FD is that it significantly reduces Flight Technical Error (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. 10). Current Instrument Approach Procedures (IAPs) for simultaneous approaches to parallel runways at several airports require use of a FD (examples are shown in Sections 5.1 thru 5.3).

Recommended wording for the procedure using RNAV (GPS) guidance would be similar to:

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

Recommended wording for the associated ILS procedure would be similar to:

> **"Simultaneous approach operations authorized with Rwy YY RNAV(GPS). Use of FD or AP required for course and path guidance during simultaneous operations."**

The requirement for a FD will only exclude a small fraction of aircraft which might want to participate in ".308" operations at major airports. Aircraft with un-augmented GPS receivers and a Baro-VNAV system are currently required to have a FD to perform LNAV/VNAV approaches (Ref. 11). 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. 12).

During a ".308" operation, the leading aircraft sheds wake vortices that, in effect, could be "soft obstacles" for the trailing 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 rate or likelihood of wake encounters will be no more than occur with current single-runway in-trail operations that have been demonstrated to be and accepted as safe.

Reduced lateral and vertical TSE for both the leading and trailing aircraft is instrumental to wake avoidance by the trailing aircraft during ".308" operations. The rationale for requiring a FD for an RNAV (GPS) equipped aircraft is, firstly, 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 trailing 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 lead position is similarly important, as the leader's glide path is designed to be lower than trailer's.

The second reason for requiring a FD is to limit the horizontal FTE (and thus TSE) of an aircraft participating in ".308" operations prior to its arriving at the Precision Final Approach Fix (PFAF). Nominally, the PFAF is located 5 NM from the runway threshold, while ".308" 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 1, from Ref.12, Section 1.4). For 'WAAS' receivers, there is another CDI display mode, Vector-To-Final (VTF), which may be used as an alternative but has not been fully vetted in this context. The VTF mode is intended for use when ATC is vectoring aircraft off of a defined route or procedure to intercept the approach course. Implementation of VTF mode is manufacturer dependent and in some cases, certain waypoint information may be lost when it is engaged. This could create complications for ATC in certain situations. Thus use of a FD is preferred.

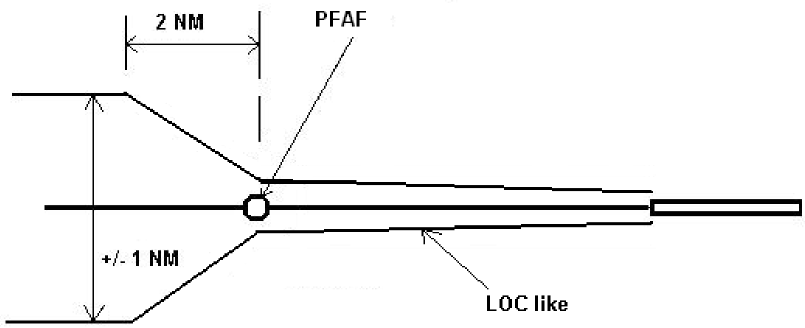


Figure 1 CDI Scaling for TSO-C145b / C146b WAAS Receiver in Non-VTF Mode (Ref. 12)

3.3 Temperature Restrictions on Use of Baro-VNAV Systems

3.3.1 Background on Baro-VNAV Guidance Temperature Sensitivity

The design of aircraft altimeters does not provide a means for compensating for deviations from the standard day sea level temperature of 15 ^{o}C (59 ^{o}F). Ambient temperatures which are less than the standard cause the altimetry system to report a higher altitude (height above sea level) than is true. Conversely, ambient temperatures which are greater than the standard day value cause the altimetry system to report a lower altitude than is true.

Some aircraft are equipped with a Flight Management System (FMS) that can compensate for the effect of non-standard temperature on the output of the barometric altimeter (Ref. 13). Since cold weather is the greater safety concern, a significant fraction of these FMS systems only compensate for temperatures that are less than the standard day value.

Because of the pronounced effect of nonstandard temperature on Baro-VNAV operations, IAPs that have baro-altimeter vertical guidance contain temperature limits below and above which use of the approach is not authorized unless temperature compensation is available. For example, the RNAV (GPS) approach plate shown in Section 5.1 has this statement: “For uncompensated Baro-VNAV systems, LNAV/VNAV NA [Not Available] below -8 ^{o}C (18 ^{o}F) or above 54 ^{o}C (130 ^{o}F)”.

The temperature restrictions on approach plates were developed for *independent* operations to a single runway. In some cases, for a 3.0 degree charted Baro-VNAV glide path angle, the temperature limits correspond to 2.5 degree and 3.5 degree actual glide path angles at the extremes. The low-temperature restriction ensures that the actual vertical path flown is obstacle-free. The high-temperature restriction reduces the likelihood that, at Decision Height, the aircraft will be above the minimum ceiling and/or have to execute a significant vertical flight correction.

IAP temperature restrictions were not developed to protect the trailing aircraft during dependent approaches to CSPR involving an ILS procedure on one runway and LNAV/VNAV with baro-altimeter guidance on the other. ILS procedures are not temperature sensitive, while LNAV/VNAV procedures flown with baro-altimeter vertical guidance are temperature sensitive. Requiring the runway for the trailing aircraft to have a higher glide path than the leading aircraft is instrumental for reducing the trailing aircraft’s wake encounters. However, if the ILS runway glide path angle is fixed with respect to temperature while the LNAV/VNAV glide path angle varies with temperature, the relationship between the two glide paths cannot be assured without additional temperature restrictions or use of temperature compensation.

3.3.2 Recommendations for Baro-VNAV Temperature Limitations for “.308” Operations

ILS Lead / RNAV Trail — If the lead aircraft utilizes ILS lateral/vertical guidance while the trail aircraft utilizes GPS/Baro-VNAV guidance, then, without temperature compensation, temperatures less than the standard day value will increase the incidence of wake encounters, while temperatures greater than the standard day value will decrease it. For this combination, it is recommended that the approach plate contain a statement similar to

> “**For uncompensated Baro-VNAV systems, LNAV/VNAV NA for simultaneous dependent operations below 15 ^{o}C (59 ^{o}F)**”.

RNAV Lead / ILS Trail — If the lead aircraft is utilizes GPS/Baro-VNAV lateral/vertical guidance while the trail aircraft utilizes ILS guidance, then without temperature compensation, temperatures less than the standard day value will decrease the rate of incidence of wake encounters, while temperatures greater than the standard day value will increase it. For this combination, it is recommended that the approach plate contain a statement similar to

> **“For uncompensated Baro-VNAV systems, LNAV/VNAV NA for simultaneous dependent operations above 15 ^{o}C (59 ^{o}F)”.**

Because a significant fraction of FMS temperature compensation system only compensate for temperatures less than the standard day value, when mixed guidance systems (ILS and GPS (RNAV)) are used for CSPR ".308" operations and there is an option as to which system will guide the lead or trail aircraft, a greater number of users can be served by requiring that the lead aircraft utilize ILS guidance and the trail aircraft utilize RNAV (GPS) guidance.

4. Recommended Error Models for Evaluating Candidate ".308" CSPR

4.1 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 the required nor typical values are available, values are used for a similar, but lower-performing, system.

4.2 TSE Model for OGE: 'WAAS' Receiver – LPV Approach

WAAS NSE — The WAAS Navigation System Error (NSE) is so small that it can generally be ignored when formulating a TSE model for LPV approaches. For over a decade the FAA has measured WAAS NSE 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 feet (e.g., Ref. 14). 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.

A second justification for the statement that WAAS NSE can be neglected when considering WAAS TSE is Ref. 15, 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 very likely to be representative of what a WAAS receiver will provide to an aircraft.

This effort has not identified a currently applicable, published requirement for the TSE of WAAS-guided LPV approaches that aircraft manufacturers and operators must satisfy. The closest approximation to such a requirement is shown in Figure 1.[*]

Recommended LPV TSE Model for OGE Regime — 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 TSE model is largely based on the model that the Volpe Center has developed and previously used (with the FAA) for the analysis of ILS Category I approaches.

[*] When a FD is required, as recommended herein, the CDI is not the primary source of information for positioning the aircraft.

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.

For aircraft between 2 NM and 14 NM from Threshold:

- Lateral TSE (95%): ±24 feet/NM x Distance from the threshold in NM (increases linearly from ±48 feet @ 2 NM to ±336 feet @ 14 NM)
- Vertical TSE (95%)
  - Within 4.5 NM of the threshold: Same as Lateral (increases linearly from ±48 feet @ 2 NM to ±108 feet @ 4.5 NM)
  - 4.5 NM or more from the threshold: ±108 feet

The lateral model was derived from aircraft position measurements by Airport Surface Detection Equipment, Model X, (ASDE-X) systems at multiple major U.S. airports (Ref. 16) — 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.

Within 4.5 NM of the threshold, the vertical TSE model is selected to be the same as the lateral model.* This is a conservative selection, as ILS 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 Decision Height Above Threshold (DHAT) for the LPV approach will be considerably lower than the DHAT for the LNAV/VNAV approach.

4.3 TSE Models for OGE: 'GPS' Receiver and Baro-Altimeter – LNAV/VNAV Approach

The error model when a 'GPS' receiver is used for LNAV and a baro-altimeter is used for VNAV has two components — a generally larger random (unpredictable) component, analogous to that for 'WAAS' guidance, and a smaller deterministic bias (predictable but uncompensated) error that does not have an analog for 'WAAS' guidance.

4.3.1 Random Error Model

The recommended random error model for LNAV/VNAV approaches is:

For aircraft between 2 NM and 14 NM from Threshold:

- Lateral TSE (95%): ±0.3 NM = ±1,823 feet
- Vertical TSE (95%): ±108 feet

An LNAV lateral error requirement of ±0.3 NM (95%) dates to the introduction of GPS for IFR operations in the early 1990s (Refs. 3 and 4). Currently, AC 90-105 (Ref. 11), Appendix 1, addresses GPS LNAV requirements, and states that the aircraft Total System Error (TSE), in the lateral and longitudinal

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

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

directions (separately) must be within ±0.3 NM [±1,823 feet] for at least 95 percent of the total flight time.

The lateral TSE requirement is considered to be conservative, as there is evidence that the typical lateral TSE for U.S. wake category Small and Large aircraft utilizing GPS receiver and FD guidance is smaller. For example, Ref. 10 states that B737-300 and later B737 series with GPS and FD equipage achieve RNPs of approximately ±0.1 NM. Similarly, Ref. 17 states: "Only Global Positioning System (GPS) equipped RNAV aircraft were considered. Although these aircraft are typically classified as RNP 0.3, all performance data collected to date indicate that RNP 0.2 containment or better is routinely achieved."

The recommended vertical TSE is taken from AC 20-138C (Ref. 18), §10.2, and its associated RTCA document DO-236B (Ref. **Error! Bookmark not defined.**), §2.1.2. This requirement applies to baro-altimeter system designs approved after January 1, 1997; these are required to be consistent with Reduced Vertical Separation Minima (RVSM) standards.

4.3.2 Bias Error Model

Unlike an ILS or LPV guidance, baro-VNAV guidance does not does not provide a constant glide path angle (GPA) to the pilot or flight instruments. Instead, baro-VNAV guidance presents a slightly curved vertical path. The equation to be used for analyzing baro-VNAV approaches is specified in Ref. 19 (volume 3, chapter 4):

Equation 1 Aircraft Elevation versus Ground Range for Baro-VNAV Guidance

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

In the above equation:

- $\boldsymbol{AC_{elev}}$: 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, ft
- **α** : Glide path angle defined ("charted") for the procedure

The following figure is a plot of aircraft elevation above MSL versus distance along the ground from the runway threshold for (a) baro-VNAV guidance with a defined angle of 3.00 deg, (b) ILS guidance with a defined glide path angle of 3.00 deg, and (c) ILS guidance with a defined glide path angle of 2.90 deg. At approximately 5-7 NM from the threshold, the baro-VNAV curve is about halfway between the two curves for ILS guidance; at 14 NM, the baro-VNAV and ILS 2.90 deg curves over lay each other.

Thus, when mixed (ILS and RNAV(GPS)) guidance sources are involved, to take account of the curvature of baro-VNAV guidance, either Equation 1 should be used for the aircraft's vertical profile or an ILS glide path profile can be used, as follows:

- If the lead aircraft has baro-VNAV guidance, its glide path can be model by ILS guidance at the charted glide path angle

- If the trail aircraft has baro-VNAV guidance, its glide path can be model by ILS guidance with a glide path angle of 0.10 degree less than the charted angle.

It may be confusing to term the baro-VNAV vertical profile an error, as it is a matter of well-known physics. It is, however, different than the more familiar ILS glide slope profile and thus must be accounted for or an error is incurred.

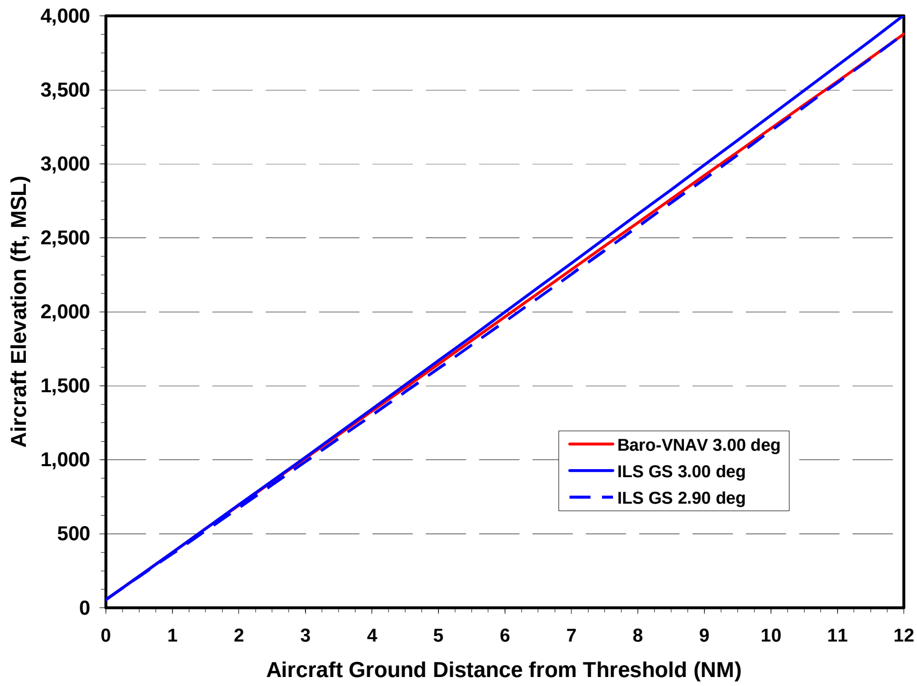


Figure 2 Aircraft Elevation vs. Distance along Ground, for Three Vertical Guidance Sources

4.4 TSE Model for IGE/NGE – LPV or LNAV/VNAV Approach

In the IGE/NGE regime — the region between the touch down point for the lead aircraft and 2 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 taken to be

- Lateral TSE (95%): ±50 feet
- Vertical TSE (95%): ±24 feet

The vertical TSE model is based on measurements with a laser range finder at Lambert – St. Louis International Airport (STL) and Denver International Airport (DEN).

While not equal to the models for aircraft TSEs for the OGE regime at the 2-NM boundary between the regimes, the IGE/NGE model is reasonably consistent with the OGE model in three of four cases. The exception is the LNAV/VNAV error model in the lateral dimension (±1,823 feet); it is generally recognized this model significantly overstates the errors incurred in practice, particularly close to the threshold.

4.5 Summary of TSE Models for ".308" Wake Encounter Risk Analysis

The TSE error models described in Sections 4.2 to 4.3.2 are summarized in Table 1 below

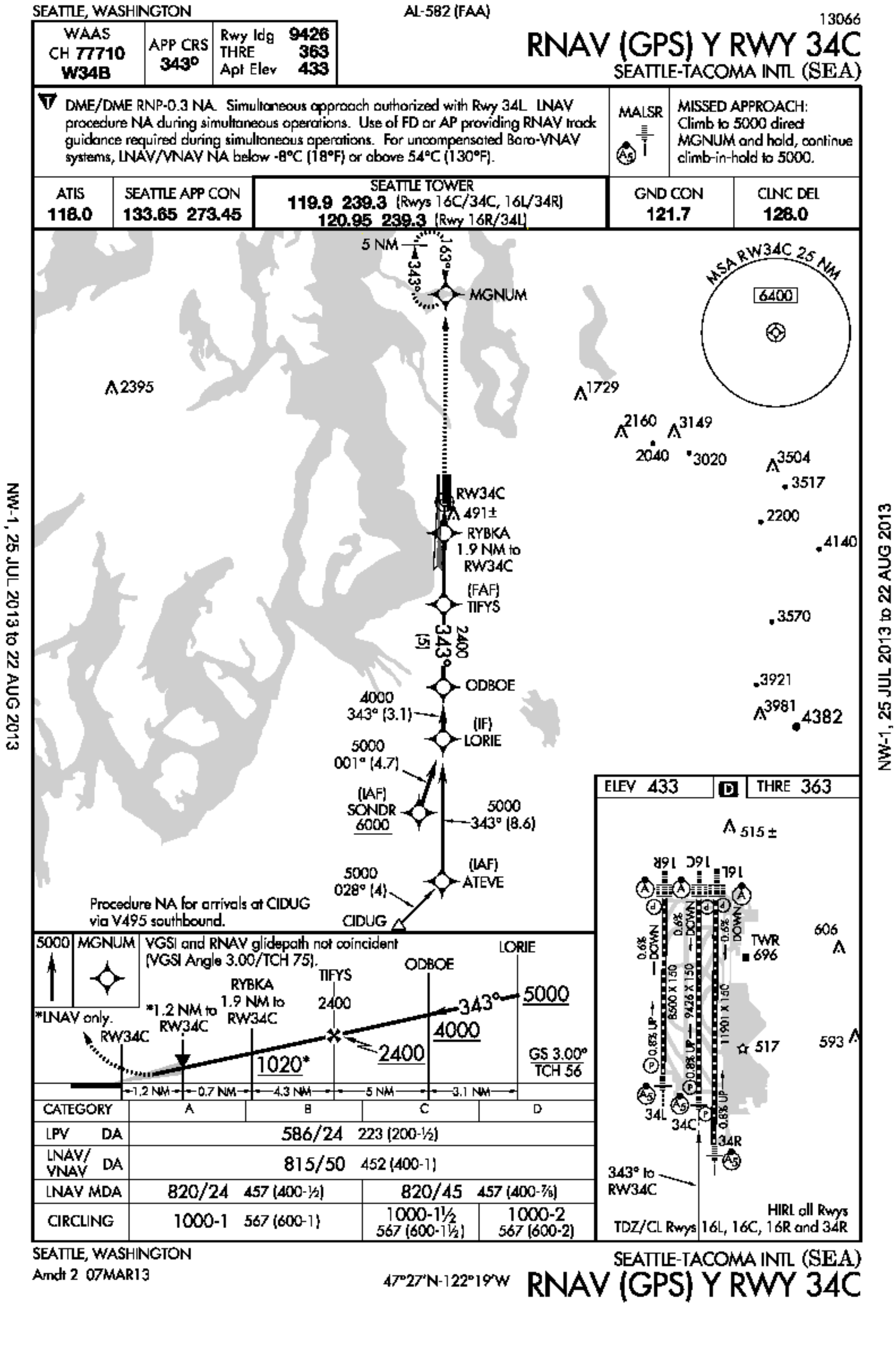
Table 1 Summary of TSE Models for ".308" Wake Encounter Risk Analysis

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 NM from Threshold	±50 ft	±24 ft	±50 ft	±24 ft
OGE Random (95%) 2 NM to 14 NM from Threshold	±1,823 ft	±108 ft	±24 ft/NM x Distance (NM) from Threshold	For 2 to 4.5 NM from Threshold: ±24 ft/NM x Distance (NM) from Threshold For 4.5 to 14 NM from Threshold: ±108 ft
OGE Bias 2 NM to 14 NM from Threshold	N/A	Vertical profile per Eq. 1, or use ILS profile but for trail A/C: reduce GPA from charted value by 0.10 deg	N/A	N/A
Restrictions Pilot briefing section of approach plate	"Use of FD or AP providing course and path guidance required during simultaneous dependent operations." Runway for lead AC: "For Uncompensated Baro-VNAV systems, LNAV/VNAV NA for simultaneous dependent operations above 15 ^{o}C (59 ^{o}F)." Runway for trail AC: "For uncompensated Baro-VNAV systems, LNAV/VNAV NA for simultaneous dependent operations below 15 ^{o}C (59 ^{o}F)."		"Use of FD or AP providing course and path guidance required during simultaneous dependent operations."	

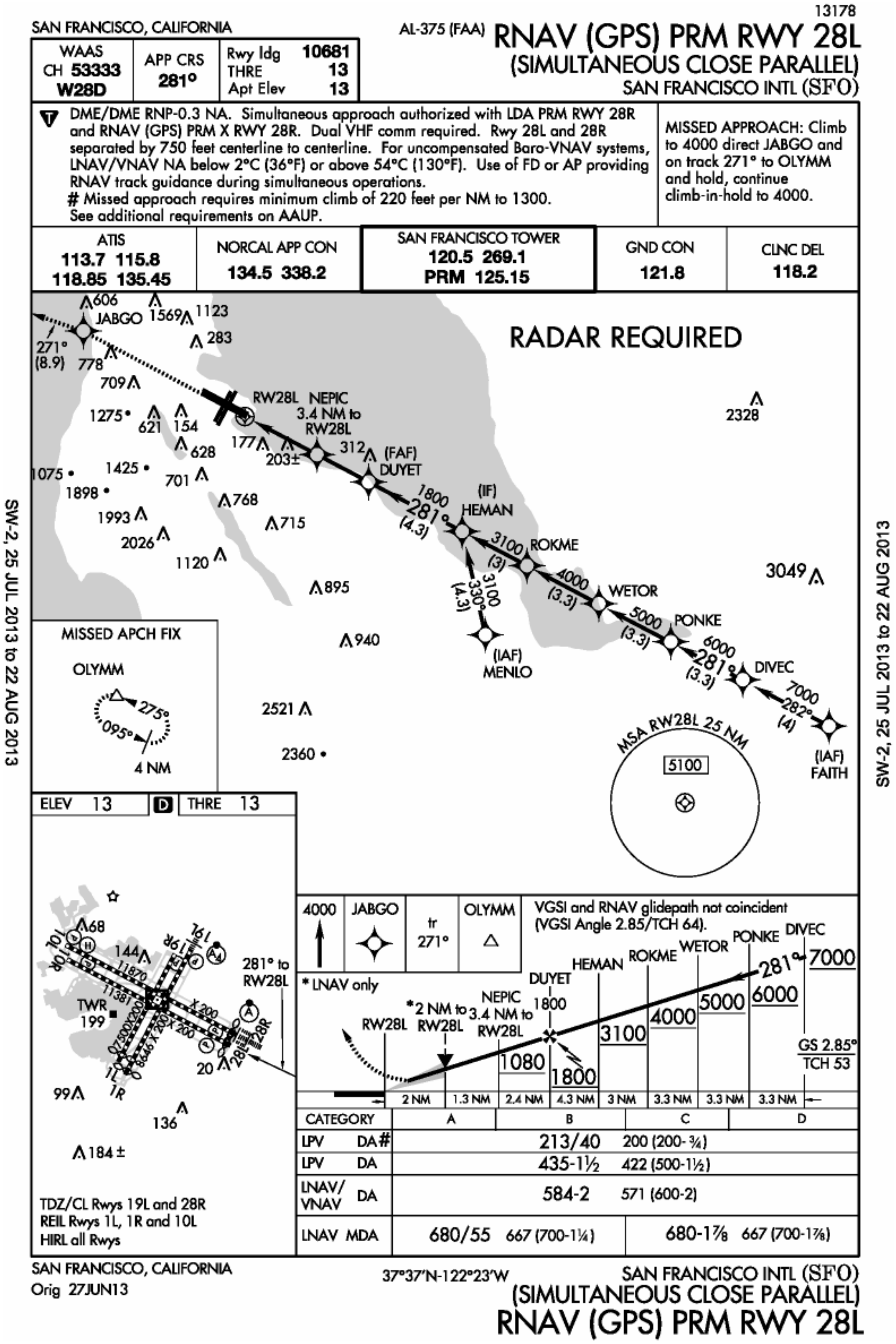
Wake encounter risk analysis is not performed for LNAV/VNAV approaches flown with WAAS horizontal and vertical guidance; thus a TSE model is not needed. The accuracy of WAAS guidance when used for an LNAV/VNAV procedure (because the satellite constellation does not meet the requirement for a LPV procedure) will be (a) more accurate than that of 'GPS' receiver/baro-altimeter guidance for the same procedure but (b) less accurate than that of a 'WAAS' receiver used for an LPV procedure. The wake encounter risk analysis methodology requires that, for approval, both the GPS-Baro/LNAV/VNAV and the WAAS/LPV equipage/procedure combinations be predicted to have no greater wake risk than the current single-runway in-trail operation. When this is the case, the intermediate accuracy WAAS/LNAV/VNAV combination will have no greater wake risk than the current single-runway operation as well.

5. Appendices

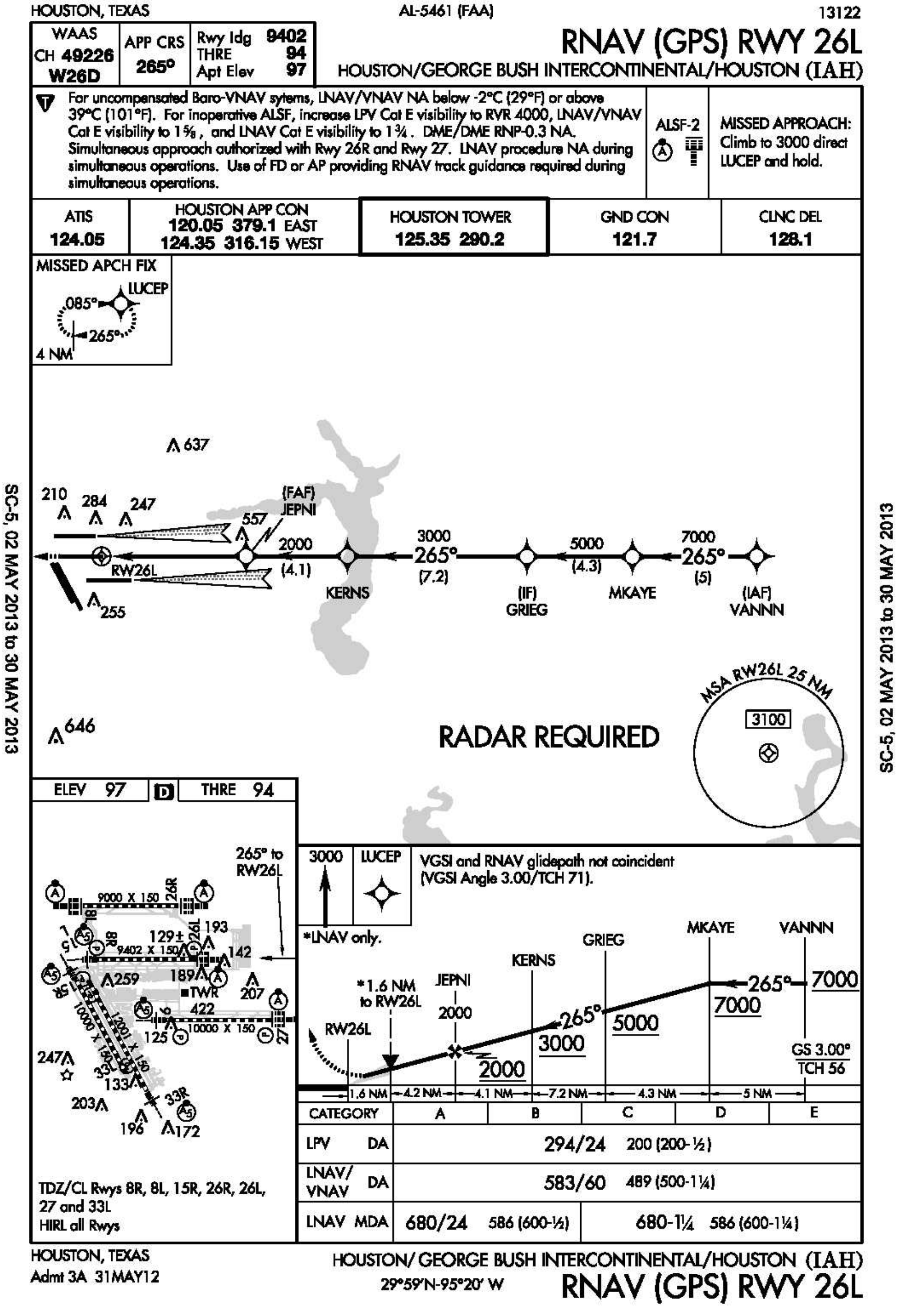
5.1 KSEA Runway 34C RNAV (GPS) Approach Plate



5.2 KSFO Runway 28L RNAV (GPS) Approach Plate



5.3 KIAH Runway 26L RNAV (GPS) Approach Plate



5.4 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 10 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).

6. References

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