ORDER **8260. 50**

UNITED STATES STANDARD
FOR
WIDE AREA AUGMENTATION SYSTEM (WAAS)

L P V

APPROACH PROCEDURE

CONSTRUCTION CRITERIA

September 6, 2002

U. S. DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION

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Initiated By: AFS-420

RECORD OF CHANGES

DIRECTIVE NO. **8260.50**

CHANGE TO BASIC	SUPPLEMENTS			OPTIONAL USE	CHANGE TO BASIC	SUPPLEMENTS			OPTIONAL USE

FOREWORD

The Wide Area Augmentation System (WAAS) is a major step in the evolution of aeronautical satellite navigation. Order 8260.48, Area Navigation (RNAV) Approach Construction Criteria, introduced WAAS precision approach construction criteria based on a VAL value ≤12 meters. This order introduces criteria for construction of approaches based on VAL values >12 meters and ≤50 meters. Approaches constructed under these criteria are termed "LPV." The WAAS system will not support high availability of precision WAAS approaches until later in this decade. In the interim, WAAS LPV procedures can be supported to height above touchdown (HAT) values ≥250 with the increased VAL. As the term LPV infers, the lateral protection area is based on the precision approach trapezoid dimensions, and the vertical surfaces constructed around WAAS vertical performance given the stated VAL parameters.

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Director, Flight Standards
Service

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

Page

CHAPTER 1. GENERAL

1.0 PURPOSE.

This document specifies criteria for the Wide Area Augmentation System (WAAS) approach procedures where the value for the vertical alarm limit (VAL) is >12 meters and ≤50 meters. Approaches constructed under these criteria are termed "**LPV.**" The lateral protection area is based on the precision approach trapezoid dimensions, and the vertical surfaces are structured around WAAS vertical performance given the stated VAL parameters.

1.1 DISTRIBUTION.

This order is distributed in Washington headquarters to the branch level in the Offices of Airport Safety and Standards and Communications, Navigation, and Surveillance Systems; Air Traffic, Airway Facilities, and Flight Standards Services; to the National Flight Procedures Office and the Regulatory Standards Division at the Mike Monroney Aeronautical Center; to branch level in the regional Flight Standards, Airway Facilities, Air Traffic, and Airports Divisions; special mailing list ZVS-827, and to Special Military and Public Addressees.

1.2 BACKGROUND.

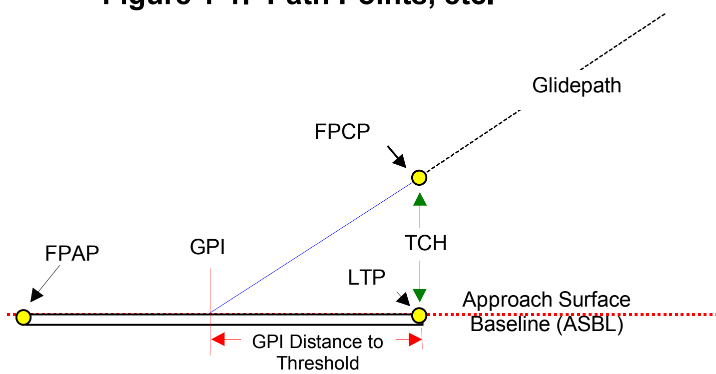
The WAAS is a major step in the evolution of aeronautical satellite navigation. Order 8260.48, Area Navigation (RNAV) Approach Construction Criteria, introduced WAAS precision approach construction criteria based on a VAL value ≤12 meters. This order introduces criteria for construction of approaches based on VAL values >12 meters and ≤50 meters. The WAAS system will not support high availability of precision WAAS approaches until late in this decade. In the interim, WAAS LPV procedures can be supported to HAT values ≥ 250 with the increased VAL.

1.3 DEFINITIONS.

1.3.1 Approach Surface Baseline (ASBL).

The horizontal line tangent to the surface of the earth at the runway threshold (RWT) point, aligned with the final approach course (see figure 1-1).

Figure 1-1. Path Points, etc.



1.3.2 Barometric Altitude.

The barometric altitude above the orthometric Geoid surface; i.e., mean sea level (MSL), is based on atmospheric pressure measured by an aneroid barometer. This is the most common method of determining aircraft altitude.

1.3.3 Decision Altitude (DA).

The DA is a specified barometric altitude at which a missed approach must be initiated if the required visual references to continue the approach have not been established.

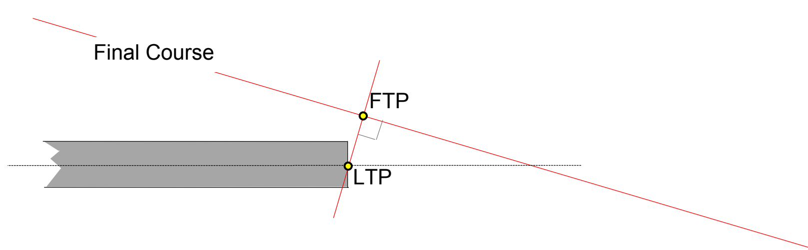
1.3.4 Departure End of Runway (DER).

The DER is the end of the runway that is opposite the landing threshold. It is sometimes referred to as the stop end of runway.

1.3.5 Fictitious Threshold Point (FTP).

The FTP is the equivalent of the landing threshold point (LTP) when the final approach course is offset from runway centerline. It is the intersection of the final course and a line perpendicular to the final course that passes through the LTP. FTP elevation is the same as the LTP (see figure 1-2). For the purposes of this document, where LTP is used, FTP may apply as appropriate.

Figure 1-2. Fictitious Threshold Point



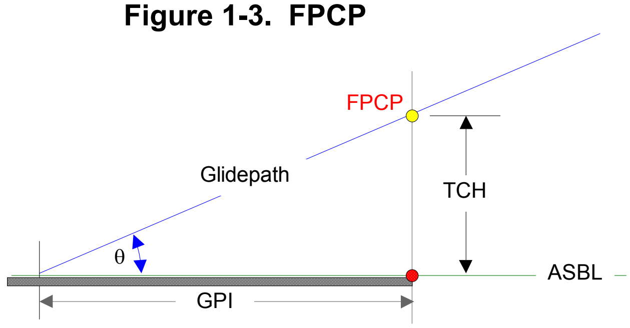
1.3.6 Flight Path Alignment Point (FPAP).

The FPAP is a 3D point defined by World Geodetic System (WGS)-84/ North American Datum (NAD)-83 latitude, longitude, MSL elevation, and WGS-84 geoid height (see figures 1-1 and 1-3). The FPAP is used in conjunction with the LTP and the geometric center of the WGS-84 ellipsoid to define the vertical plane of a precision RNAV final approach course. The course may be offset up to 3° by establishing the FPAP left or right of centerline along an arc centered on the LTP.

1.3.7 Flight Path Control Point (FPCP).

The FPCP is a 3D point defined by the LTP or FTP latitude/longitude position, MSL elevation, and a threshold crossing height (TCH) value. The FPCP is in the vertical plane of the final approach course and is used to relate the glidepath angle of the final approach track to the landing runway. It is sometimes referred to as the TCH point or reference datum point (RDP) (see figure 1-3).

Figure 1-3. FPCP



1.3.8 Geoid Height (GH).

The GH is the height of the geoid (reference surface for orthometric or MSL heights) relative to the WGS-84 ellipsoid. It is a positive value when the geoid is above the WGS-84 ellipsoid and negative when it is below. The value is used to convert an MSL elevation to an ellipsoidal or geodetic height - the height above ellipsoid (HAE).

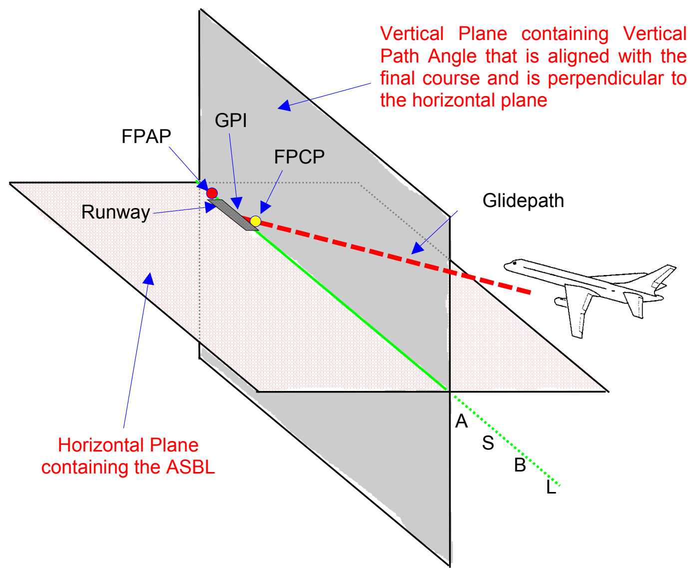
1.3.9 Glidepath Angle (GPA [θ]).

The angular displacement of the vertical guidance path from a horizontal plane that passes through the FPCP. This angle is published on approach charts (e.g., 3.00°, 3.20°, etc.). In this order, the glidepath angle is represented in formulas as the Greek symbol θ.

1.3.10 Ground Point of Intercept (GPI).

The GPI is a point in the vertical plane that contains the glidepath where the glidepath intercepts the ASBL. GPI is expressed as a distance in feet from the runway threshold (see figure 1-4).

Figure 1-4. 3D Path and Course



1.3.11 Height Above Ellipsoid (HAE).

The HAE is a height expressed in feet above the WGS-84 ellipsoid. This value differs from a height expressed in feet above the geoid (essentially MSL) because the reference surfaces (WGS-84 ellipsoid and the geoid) do not coincide. To convert an MSL height to an HAE height, algebraically add the geoid height value to the MSL value. HAE elevations are not used for instrument procedure construction, but are documented for inclusion in airborne receiver databases.

EXAMPLE

Given:	KOUN RWY 35	Runway ID
	N 35 14 31.65	Latitude
	W 97 28 22.84	Longitude
	1177.00	MSL Elevation
	-87.29 feet (-26.606 m)	Geoid Height (GH)

HAE = MSL+GH
HAE = 1,177+(-87.29)
HAE = 1,089.71

1.3.12 Height Above Touchdown (HAT).

The HAT is the height of the DA above touchdown zone elevation (TDZE).

1.3.13 Inner-Approach Obstacle Free Zone (OFZ).

The inner-approach OFZ is the airspace above a surface centered on the extended runway centerline. It applies to runways with an approach lighting system.

1.3.14 Inner-Transitional OFZ.

The inner-transitional OFZ is the airspace above the surfaces located on the outer edges of the runway OFZ and the inner-approach OFZ. It applies to runways with approach visibility minimums less than ¾ statute mile

1.3.15 Landing Threshold Point (LTP).

The LTP is a 3D point at the intersection of the runway centerline and the runway threshold. WGS-84/NAD-83 latitude, longitude, MSL elevation, and geoid height define it (see figure 1-1). It is used in conjunction with the FPAP and the geometric center of the WGS-84 ellipsoid to define the vertical plane of an RNAV final approach course. LTP elevation (LTP_E) applies to the LTP and FTP when the final approach course is offset from runway centerline. For the purposes of this document, where LTP is used, FTP may apply as appropriate.

1.3.16 Lateral Navigation (LNAV).

LNAV is lateral navigation without positive vertical guidance. This type of navigation is associated with nonprecision approach procedures.

1.3.17 LPV.

An LPV approach is classified as an APV procedure based on the lateral OCS dimensions of the precision approach trapezoid, with vertical guidance provided by the WAAS where the VAL is >12 and ≤ 50 meters. These procedures are published on RNAV Global Positioning System (GPS) approach charts as the LPV minima line.

1.3.18 Object Free Area (OFA).

The OFA is an area on the ground centered on a runway, taxiway, or taxilane centerline provided to enhance the safety of aircraft operations by having the area free of objects, except for objects that need to be located in the OFA for air navigation or aircraft ground maneuvering purposes.

1.3.19 Obstacle Clearance Surface (OCS).

The OCS's are inclined surfaces associated with a climbing or descending flight path used for obstacle evaluation. The separation between this surface and the vertical path angle defines the MINIMUM required obstruction clearance at that point.

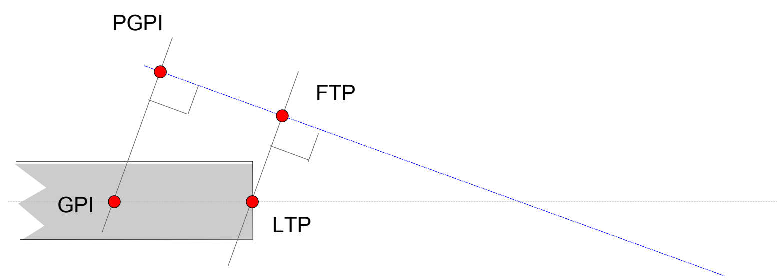
1.3.20 Precision Final Approach Fix (PFAF).

A 2D point located on the final approach course at a distance from LTP where the GPA intercepts the intermediate segment altitude (glidepath intercept altitude). The PFAF marks the outer longitudinal limit of the precision final segment.

1.3.21 Pseudo Ground Point of Intercept (PGPI).

PGPI is a phantom location abeam GPI on an approach course offset from the runway centerline. PGPI elevation is the same as ASBL (see figure 1-5).

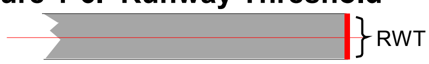
Figure 1-5. PGPI and FTP Locations



1.3.22 Runway Threshold (RWT).

The RWT marks the beginning of the part of the runway that is usable for landing (see figure 1-6). It includes the entire width of the runway.

Figure 1-6. Runway Threshold



1.3.23 Three-Dimensional (3D) Point/Waypoint.

A waypoint defined by WGS-84 latitude and longitude coordinates, MSL elevation, and GH.

1.3.24 Touchdown Zone Elevation (TDZE).

The highest elevation in the first 3,000 feet of the landing surface.

1.3.25 Two-Dimensional (2D) Point/Waypoint.

A waypoint defined by WGS-84 latitude and longitude coordinates.

1.3.26 Wide Area Augmentation System (WAAS).

The WAAS is a method of navigation based on the GPS. Ground correction stations transmit position corrections that enhance system accuracy and add satellite based VNAV features.

1.4 GENERAL.

1.4.1 Drawings.

Drawings in this order are not to scale.

1.4.2 Formulae Used in LPV Criteria.

Where standard values are specified in increments of meters (i.e., VAL = 50 meters), they are incorporated into calculation formulas converted to feet. Explanatory comments are printed in *{ blue italic font inside distinctive brackets. }*. Formulas are numbered for easy reference. All possible construction scenarios cannot be anticipated and addressed in this order; therefore, sound judgment and common sense based on procedure development experience is a requirement for application of these criteria. Appendix 1 contains the formulae used in developing the LPV criteria.

1.4.3 LPV Rationale.

Appendix 2 contains the rationale for developing the criteria and the many formulas in this order.

1.4.4 Validation Summary for LPV Obstacle Clearance Surfaces.

This report (appendix 3) summarizes data collected from flight testing and computer simulations, and the analysis of that data supports and validates the proposed obstacle clearance areas described in this order. This report also contains an Executive Summary for the validation report.

1.5 INFORMATION UPDATE.

For your convenience, FAA Form 1320-19, Directive Feedback Information, is included at the end of this order to note any deficiencies found, clarifications needed, or suggested improvements regarding the contents of this order. When forwarding your comments to the originating office for consideration, please use the "Other Comments" block to provide a complete explanation of why the suggested change is necessary.

CHAPTER 2. GENERAL CRITERIA

2.0 POLICY DIRECTIVES.

The following FAA orders apply unless otherwise specified in this order:

2.0.1 **8260.3,** United States Standard for Terminal Instrument Procedures (TERPS).

2.0.2 **8260.19**, Flight Procedures and Airspace.

2.0.3 **8260.38**, Civil Utilization of Global Positioning System (GPS).

2.0.4 **8260.44,** Civil Utilization of Area Navigation (RNAV) Departure Procedures.

2.0.5 **8260.45**, Terminal Arrival Area (TAA) Design Criteria.

2.0.6 **7130.3**, Holding Pattern Criteria.

The final and missed approach criteria described in this order supersede the other publications listed above, except as noted.

2.1 DATA RESOLUTION.

Perform calculations using at least 0.01 unit of measure accuracy. Use double precision where calculation is accomplished by automated means. The following list specifies the minimum accuracy standard for documenting data expressed numerically. This standard applies to the documentation of final results only; e.g., a calculated adjusted glidepath angle of 3.04178° is documented as 3.04°. The standard does not apply to the use of variable values during calculation. Use the most accurate data available for variable values. Do not round intermediate results. Round only the final result of calculations for documentation purposes.

2.1.1 Documentation accuracy:

a. WGS-84/NAD-83 latitudes and longitudes to the nearest one hundredth (0.01) arc second;

b. LTP MSL elevation to the nearest foot,

c. LTP HAE to the nearest tenth (0.1) meter;

d. Course width at threshold to the nearest quarter (0.25) meter;

e. Glidepath angle to the next higher one-hundredth (0.01) degree;

f. Courses to the nearest one-hundredth (0.01) degree; and

g. Distances to the nearest-hundredth (0.01) unit.

Use the above documented rounded values in paragraphs 2.1.1a through g in calculations.

2.1.2 Mathematics Convention

2.1.2 a. Definition of Mathematical Functions.

$a+b$ indicates addition
$a-b$ indicates subtraction
$a \times b$ or ab indicates multiplication
$\frac{a}{b}$ or a/b or $a \div b$ indicates division
$(a-b)$ indicates the result of the process within the parenthesis
$|a - b|$ indicates absolute value
$\approx$ indicates approximate equality
$\sqrt{a}$ indicates the square root of quantity "a"
a^2 indicates $a \times a$
$\tan(a)$ indicates the tangent of "a" degrees
$\tan^{-1}(a)$ indicates the arc tangent of "a"
$\sin(a)$ indicates the sine of "a" degrees
$\sin^{-1}(a)$ indicates the arc sine of "a"
$\cos(a)$ indicates the cosine of "a" degrees
$\cos^{-1}(a)$ indicates the arc cosine of "a"

2.1.2 b. Operation Precedence (Order of Operations).

First: Grouping Symbols: parentheses, brackets, braces, fraction bars, etc.
Second: Functions: Tangent, sine, cosine, arcsine and other defined functions
Third: Exponentiations: Powers and roots
Fourth: Multiplication and Division: Products and quotients
Fifth: Addition and subtraction: Sums and differences
e.g,
$5-3\times 2=-1$ because multiplication takes precedence over subtraction
$(5-3)\times 2=4$ because parentheses take precedence over multiplication
$\frac{6^2}{3}=12$ because exponentiation takes precedence over division
$\sqrt{9+16}=5$ because the square root sign is a grouping symbol
$\sqrt{9}+\sqrt{16}=7$ because roots take precedence over addition
$\frac{\sin(30°)}{0.5}=1$ because functions take precedence over division
$\sin\left(30°/0.5\right)=0.8660254$ because parentheses take precedence over functions

{ Notes on calculator usage:

1. Most calculators are programmed with these rules of precedence.
2. When possible, let the calculator maintain all of the available digits of a number in memory rather than re-entering a rounded number. For highest accuracy from a calculator, any rounding that is necessary should be done at the latest opportunity. }

2.1.3 ROUNDING

Paragraph 2.1 details the minimum accuracy standard for documenting data expressed numerically. This standard is for documentation of final results only; e.g., the calculated adjusted glidepath angle of 3.04178° is documented as 3.04°. The standard does not apply to use of variable values during calculation. Use the most accurate data available for variable values. Do not round intermediate results. Round only the final result of calculations for documentation purposes.

2.2 PROCEDURE IDENTIFICATION.

These criteria support a minima line titled LPV published on an RNAV instrument approach procedure chart. Title an RNAV approach procedure RNAV (GPS) RWY (Runway number). Examples: **RNAV (GPS) RWY 13, RNAV (GPS) RWY 34R.** A typical RNAV approach chart normally depicts minima for LPV, LNAV/VNAV, LNAV, and circling.

2.3 EN ROUTE, INITIAL, AND INTERMEDIATE SEGMENTS.

Apply Order 8260.38, paragraphs 8-12, for construction of the en route, initial, and intermediate segments except as noted.

2.3.1 **Initial Segment.** Apply Order 8260.45, paragraph 5, if a terminal arrival area (TAA) is desired.

2.3.2 **Intermediate Segment.** The intermediate segment primary and secondary boundary lines connect at the plotted position of the FAF/PFAF at the appropriate primary and secondary final segment beginning widths. Turns at the FAF are not permitted for LPV procedures.

2.4 MAXIMUM AUTHORIZED GLIDEPATH ANGLES (GPAs).

These tables list the MAXIMUM allowable GPA (θ) and MINIMUM visibility by aircraft category, and MAXIMUM TCH values for allowing light credit (see tables 2-1A, 2-1B, and 2-1C). Angles less than 3° or greater than 3.1° require Flight Standards or appropriate military authority approval.

Table 2-1A. Maximum GPAs

Category	θ
A (80 knots or less)	6.4
A (81-90 knots)	5.7
B	4.2
C	3.6
D&E	3.1

Table 2-1B. Standard Precision Landing Minimums

<table>
<tr><th rowspan="3" colspan="2">GLIDEPATH ANGLE
(WITH APPROACH LIGHT CONFIGURATION)</th><th rowspan="3">MINIMUM HAT</th><th colspan="4">AIRCRAFT CATEGORY</th></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D & E</th></tr>
<tr><th colspan="4">MINIMUM VISIBILITY</th></tr>
<tr><td rowspan="3">3.00° — 3.10°</td><td>★</td><td>250</td><td colspan="4">¾ 4000</td></tr>
<tr><td>#</td><td>250</td><td colspan="4">½ 2400</td></tr>
<tr><td>$</td><td>250</td><td colspan="4">½ 2400</td></tr>
<tr><td rowspan="3">3.11°-3.30°</td><td>★</td><td>250</td><td colspan="2">¾ 4000</td><td>1 5000</td><td>NA</td></tr>
<tr><td>#</td><td>250</td><td colspan="2">½ 2400</td><td>¾ 4000</td><td>NA</td></tr>
<tr><td>$</td><td>250</td><td colspan="2">½ 2400</td><td>½ 2400</td><td>NA</td></tr>
<tr><td rowspan="6">3.31° — 3.60°</td><td>★</td><td>250</td><td colspan="2">¾ 4000</td><td colspan="2">NA</td></tr>
<tr><td>★</td><td>270</td><td colspan="2">¾ 4000</td><td>1 5000</td><td>NA</td></tr>
<tr><td>#</td><td>250</td><td colspan="2">½ 2400</td><td colspan="2">NA</td></tr>
<tr><td>#</td><td>270</td><td colspan="2">½ 2400</td><td>¾ 4000</td><td>NA</td></tr>
<tr><td>$</td><td>250</td><td colspan="2">2000</td><td colspan="2">NA</td></tr>
<tr><td>$</td><td>270</td><td colspan="2">2000</td><td>½ 2600</td><td>NA</td></tr>
<tr><td rowspan="2">3.61° — 3.80°</td><td>★</td><td>250</td><td colspan="2">¾ 4000</td><td colspan="2">NA</td></tr>
<tr><td>#</td><td>250</td><td colspan="2">1/2 2400</td><td colspan="2">NA</td></tr>
<tr><td rowspan="2">3.81° — 4.20°</td><td>★</td><td>250</td><td>¾ 4000</td><td>1 5000</td><td colspan="2">NA</td></tr>
<tr><td>#</td><td>250</td><td>½ 2400</td><td>¾ 4000</td><td colspan="2">NA</td></tr>
<tr><td rowspan="2">4.21° — 5.00°</td><td>★</td><td>250</td><td>¾ 4000</td><td colspan="3">NA</td></tr>
<tr><td>#</td><td>250</td><td>½ 2400</td><td colspan="3">NA</td></tr>
<tr><td rowspan="2">5.01° — 5.70°</td><td>★</td><td>300</td><td>1 5000</td><td colspan="3">NA</td></tr>
<tr><td>#</td><td>300</td><td>¾ 4000</td><td colspan="3">NA</td></tr>
<tr><td rowspan="2">5.71° — 6.40°
AIRSPEED NTE 80 KNOTS</td><td>★</td><td>350</td><td>1 ¼</td><td colspan="3">NA</td></tr>
<tr><td>#</td><td>350</td><td>1 5000</td><td colspan="3">NA</td></tr>
</table>

★= No Lights $ = # Plus TDZ/CL Lights

= MALSR, SSALR, ALSF NA = Not authorized

NOTE: For a HAT higher than the minimum, the visibility (prior to applying credit for lights) must equal the distance MAP to threshold, or (a) 3/4 mile up to 5.00°, or (b) 1 mile 5.01° through 5.70°, or (c) 1 1/4 miles 5.71° through 6.40°, whichever is the greater.

Table 2-1C. Threshold Crossing Height Upper Limits For Allowing Visibility Credit For Lights

HAT	Angle	TCH
250	3.00-4.10	75
	4.11-4.20	71
	4.21-4.30	67
	4.31-4.40	62
	4.41-4.50	58
	4.51-4.60	54
	4.61-4.70	50
	4.71-4.80	45
	4.81-4.90	41
	4.91-5.00	37
270	3.00-4.40	75
	4.41-4.50	73
	4.51-4.60	68
	4.61-4.70	64
	4.71-4.80	59
	4.81-4.90	55
	4.91-5.00	51
300	3.00-4.90	75
	4.91-5.00	71
	5.01-5.10	66
	5.11-5.20	61
	5.21-5.30	56
	5.31-5.40	52
	5.41-5.50	48
	5.51-5.60	43
	5.61-5.70	39
350	3.00-5.60	75
	5.61-5.70	70
	5.71-5.80	65
	5.81-5.90	60
	5.91-6.00	55
	6.01-6.10	50
	6.11-6.20	45
	6.21-6.30	40
	6.31-6.40	35

2.5 THRESHOLD CROSSING HEIGHT (TCH).

Select the appropriate TCH from table 2-2. Publish a note indicating visual glide slope indicator (VGSI) not coincident with the procedure GPA when the VGSI angle is more than 0.2 degrees from the LPV GPA, or when the VGSI TCH is more than 3 feet from the LPV TCH.

Table 2-2. TCH Requirements

Representative Aircraft Type	**Approximate Glidepath-to-Wheel Height**	**Recommended TCH ± 5 Feet**	**Remarks**
HEIGHT GROUP 1 General aviation, Small commuters, Corporate turbojets, T-37, T-38, C-12, C-20, C-21, T-1, Fighter Jets	10 Feet or less	40 Feet	Many runways less than 6,000 feet long with reduced widths and/or restricted weight bearing which would normally prohibit landings by larger aircraft.
HEIGHT GROUP 2 F-28, CV-340/440/580, B-737, C-9, DC-9, C-130, T-43, B-2, S-3	15 Feet	45 Feet	Regional airport with limited air carrier service.
HEIGHT GROUP 3 B-727/707/720/757, B-52, C-135, C-141, C-17, E-3, P-3, E-8	20 Feet	50 Feet	Primary runways not normally used by aircraft with ILS glidepath-to-wheel heights exceeding 20 feet.
HEIGHT GROUP 4 B-747/767/777, L-1011, DC-10, A-300, B-1, KC-10, E-4, C-5, VC-25	25 Feet	55 Feet	Most primary runways at major airports.

Note 1: To determine the minimum allowable TCH, add 20 feet to the glidepath-to-wheel height.

Note 2: To determine the maximum allowable TCH, add 50 feet to the glidepath-to-wheel height (precision approaches not to exceed 60 ft.).

2.6 GROUND POINT OF INTERCEPT (GPI).

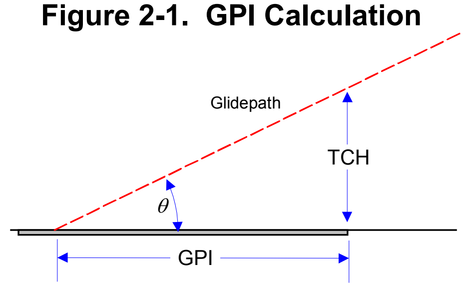
Calculate GPI distance using the following formula:

Formula 2.1

$$GPI = \frac{TCH}{\tan(\theta)}$$

Where θ = glidepath angle

Figure 2-1. GPI Calculation



2.7 DETERMINING FPAP COORDINATES.

The positional relationship between the LTP and the FPAP determines the final approach ground track. Geodetically calculate the latitude and longitude of the FPAP using the LTP as a starting point, the desired final approach course (OPTIMUM course is the runway bearing) as a forward azimuth value, and an appropriate distance. If an ILS or MLS serves the runway, the appropriate distance in feet is the distance between the LTP and the localizer antenna minus 1,000, or the distance between the LTP and the DER, whichever is greater. Apply table 2-3 to determine the appropriate distance for runways not served by an ILS or MLS.

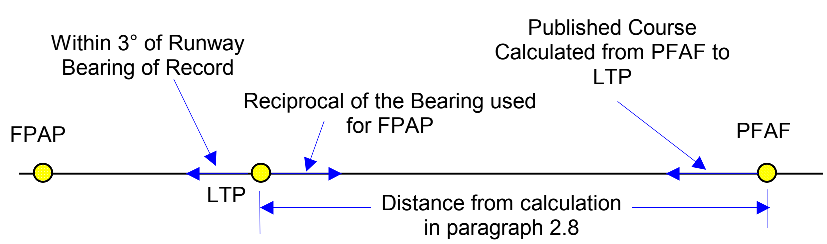
Table 2-3. Runways not Served by an ILS or MLS

Runway Length	FPAP Distance from LTP	Splay	± Width
≤ 9,023'	9,023'	2.0°	350' (106.68 m)
> 9,023' and ≤ 12,366'	to DER	Formula 2.2 $\tan^{-1}\left(\frac{350}{\text{RWY length}+1000}\right)$	350' (106.68 m)
> 12,366 and ≤ 16,185'	to DER	1.5°	Formula 2.3 $\frac{\tan(1.5)\times(\text{RWY length}+1{,}000)}{3.2808}$ m
> 16,185' (AFS or Appropriate Military Agency Approval)	to DER or as specified by approving agency	1.5°	Formula 2.4 $\frac{\tan(1.5)\times(\text{RWY length}+1{,}000)}{3.2808}$ m*

* Round result to the nearest 0.25 meter.

2.8 DETERMINING PFAF/FAF COORDINATES. See figure 2-2.

Figure 2-2. Determining PFAF Location



Geodetically calculate the latitude and longitude of the PFAF using the horizontal distance (D-GPI) from the LTP to the point the glidepath intercepts the intermediate segment altitude. Determine D using the following formulas: {step 2 formula includes earth curvature}

Step 1: Formula: Formula 2.5

$$Z = A - F$$

Where: A = FAF Altitude in feet (example 2,100)
F = LTP elevation in feet (example 562.30)
θ = Glidepath angle (example 3.00°)

Example: 1537.70=2,100-562.30

Step 2: Formula 2.6

$$D = 364{,}609\left[90 - \theta - \sin^{-1}\left(\frac{\sin(90+\theta)20{,}890{,}537}{z + 20{,}890{,}537}\right)\right]$$

Example: $$D = 364{,}609\left[90 - 3 - \sin^{-1}\left(\frac{\sin(90+3)20{,}890{,}537}{1537.7 + 20{,}890{,}537}\right)\right]$$

$$D = 364{,}609\left[87 - \sin^{-1}\left(\frac{20{,}861{,}907.2451}{20{,}892{,}074.70}\right)\right]$$

$$D = 364{,}609(0.0794166528)$$

$$D = 28{,}956.03$$

Determine the PFAF coordinates with the direct geodetic function, using the specified bearing and distance D. If the procedure will provide LNAV minima, locate the FAF coincident with the PFAF. LNAV is not authorized when the PFAF is more than 10 NM from RWT. LNAV FAF coordinates may require recalculation when an LPV approach is added to an existing RNAV procedure depicting LNAV and circling minimums only.

2.9 COMMON WAYPOINTS.

Design all procedures published on the same chart to use the same sequence of charted waypoints.

2.10 CLEAR AREAS AND OBSTACLE FREE ZONES (OFZ).

Airports division is responsible for maintaining obstruction requirements in AC 150/5300-13, Airport Design. Appropriate military directives apply at military installations. For the purpose of this order, there are two OFZs that apply: the runway OFZ and the inner approach OFZ. The runway OFZ parallels the length of the runway and extends 200 feet beyond the runway threshold. The inner OFZ overlies the approach light system from a point 200 feet from the threshold to a point 200 feet beyond the last approach light. If approach lights are not installed or not planned, the inner approach OFZ does not apply. When obstacles penetrate either the runway or approach OFZ, visibility credit for lights is not authorized, and the lowest authorized HAT and visibility values are (USAF/USN NA):

- For GPA $\leq$ 4.2°: 300-¾
- For GPA $>$ 4.2°: 400-1

2.11 GLIDEPATH QUALIFICATION SURFACE (GQS).

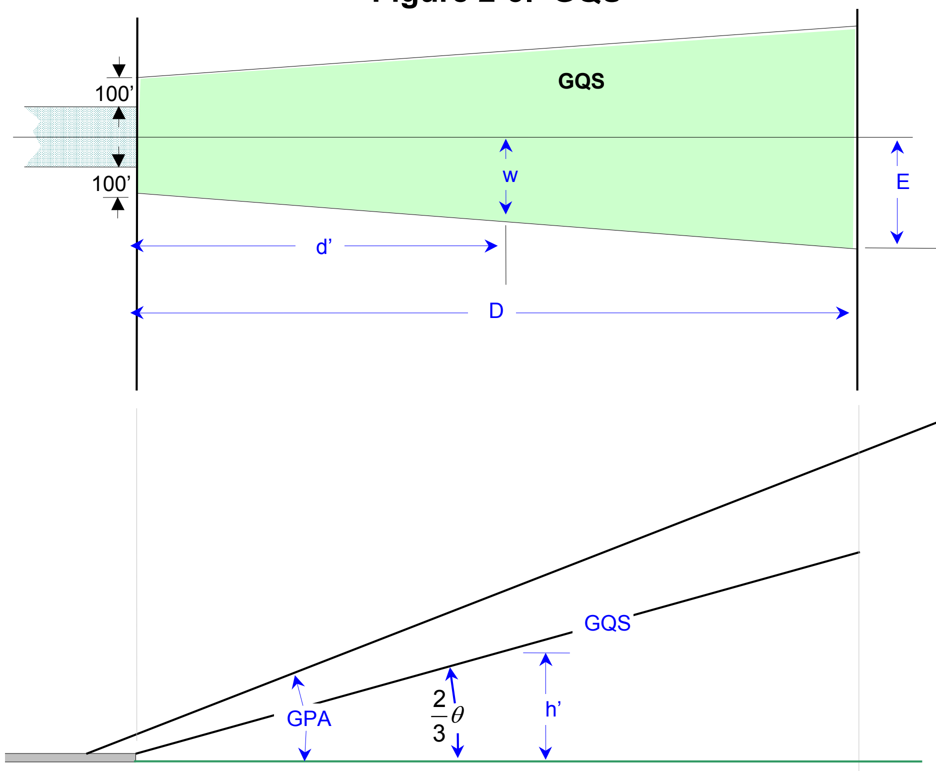
The GQS extends from the runway threshold along the runway centerline extended to the DA point. It limits the height of obstructions between DA and RWT. When obstructions exceed the height of the GQS, an approach procedure with positive vertical guidance (ILS, MLS, TLS, GLS, VNAV, LPV, etc.) is not authorized (see figures 2-3 and 2-4).

2.11.1 Area.

2.11.1 a. **Length**. The GQS extends from the runway threshold to the DA point.

2.11.1 b. **Width**. The GQS originates 100 feet from the runway edge at RWT.

Figure 2-3. GQS



Calculate the half-width of the GQS (E) from the runway centerline extended at the DA point using the following formula:

Formula 2.7

$$E = 0.036(D - 200) + 400$$

Where: D = the distance (ft) measured along RCL extended from RWT to the DA point
E = GQS half-width (ft) at DA

Calculate the half-width of the GQS at any distance “d” from RWT using the following formula:

Formula 2.8

$$w = \left(\frac{E-k}{D}d\right) + k$$

Where: D = distance (ft) from RWT to the DA point
d = desired distance (ft) from RWT
w = GQS half-width at distance d

$$k = \frac{\text{RWT width}}{2} + 100$$

2.11.1 c. **If the course is offset** from the runway centerline (3° MAXIMUM), expand the GQS area on the side of the offset as follows referring to figure 2-3:

<u>STEP 1</u>. Construct line **<u>BC</u>**. Locate point "**B**" on the runway centerline extended perpendicular to course at the DA point. Calculate the half width (E) of the GQS for the distance from point "**B**" to the RWT. Locate point "**C**" perpendicular to the course distance "E" from the course line. Connect points "**B**" and "**C.**"

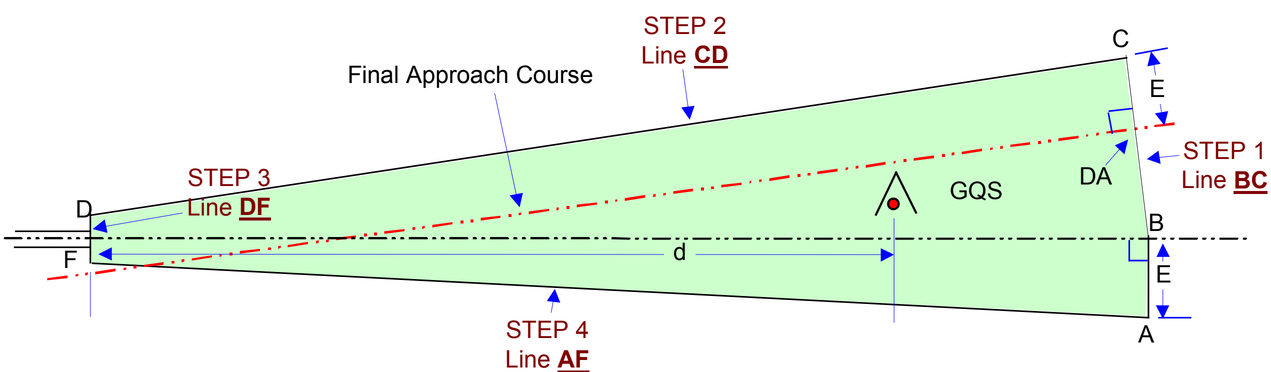
<u>STEP 2</u>. Construct line CD. Locate point "D" 100 feet from the edge of the runway perpendicular to the LTP. Draw a line connecting point "C" to point "D."

<u>STEP 3</u>. Construct line DF. Locate point "F" 100 feet from the edge of the runway perpendicular to the LTP. Draw a line connecting point "D" to point "F."

<u>STEP 4</u>. Construct line AF. Locate point "A" distance "E" from point "B" perpendicular to the runway centerline extended. Connect point "A" to point "F."

<u>STEP 5</u>. Construct line AB. Connect point "A" to point "B."

Figure 2-4. Final Approach Course Offset >3°



2.11.1 **d. OCS**. Obstructions must not penetrate the GQS. Calculate the height of the GQS above ASBL at any distance "d" measured from RWT along RCL extended to a point abeam the obstruction (see figure 2-4) using the following formula:

Formula 2.9

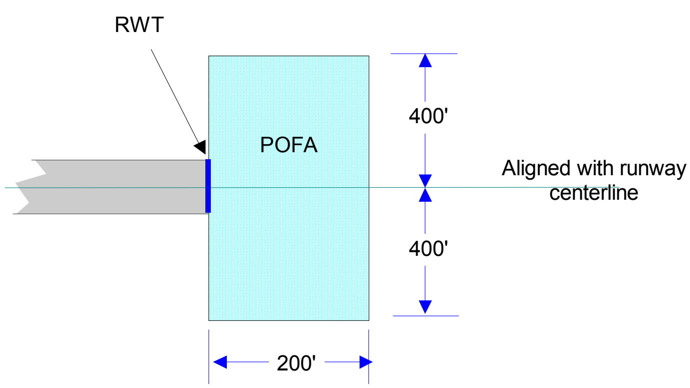
$$h = \tan\left(\frac{2\theta}{3}\right)d$$

Where d = distance from RWT (ft)
θ = glidepath angle

2.12 PRECISION OBJECT FREE AREA (POFA).

An area centered on the runway centerline extended, beginning at the RWT, 200 feet long, and ± 400 feet wide. The airport sponsor is responsible for maintaining POFA obstruction requirements in AC 150/5300-13 (see figure 2-5).

Figure 2-5. POFA

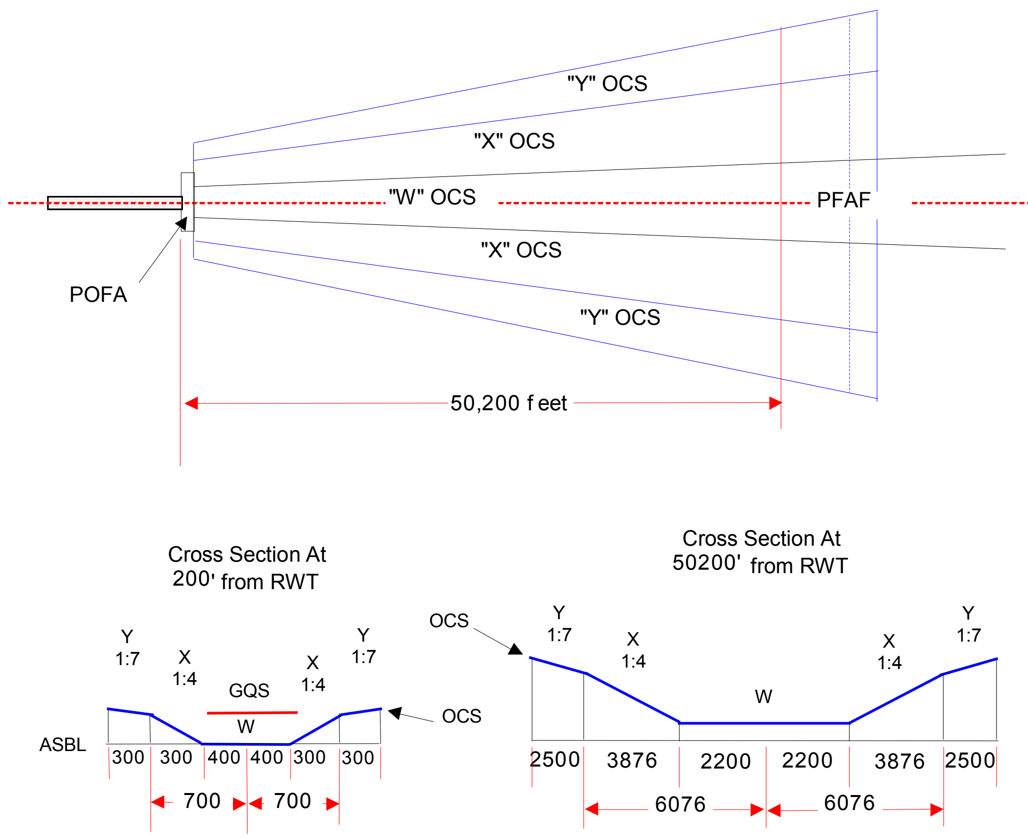


CHAPTER 3. LPV FINAL APPROACH SEGMENT (FAS) EVALUATION

3.0 FINAL SEGMENT.

The FAS originates 200 feet from LTP and ends at the PFAF (see figure 3-1). The primary area consists of the "W" and "X" obstacle clearance surface (OCS), and the secondary area is the "Y" OCS.

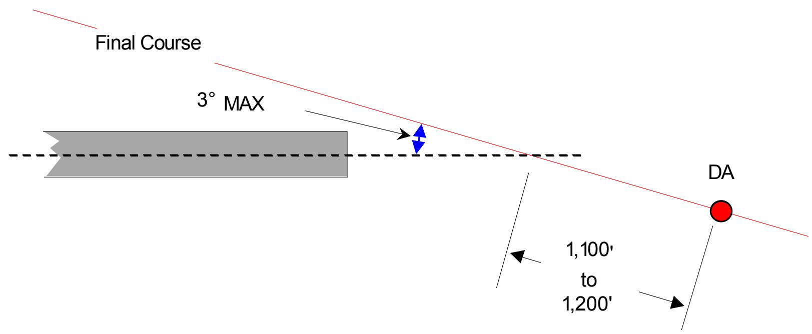
Figure 3-1. Obstacle Clearance Areas



3.1 ALIGNMENT.

The final course is normally aligned with the runway centerline extended (± 0.03°) through the LTP (± 5 feet). Where a unique operational requirement indicates a need for an offset course, it may be approved provided the offset does not exceed 3°. Where the course is not aligned with the RCL, the MINIMUM height above touchdown (HAT) is 300 feet, and MINIMUM runway visual range (RVR) is 4,000 feet/prevailing visibility ¾ SM. Additionally, the course must intersect the runway centerline at a point 1,100 to 1,200 feet toward the LTP from the DA point (see figure 3-2).

Figure 3-2. Offset Final



3.2 OCS SLOPE(S).

In this document, slopes are expressed as run over rise; e.g., 34:1. The OCS is comprised of three longitudinal sections of differing slopes. For a 3° glidepath angle, the three sections are: Zero slope (elevation equal to ASBL), 27.03:1 slope, and 34:1 slope (see figure 3-3). Determine the OCS slope associated with a specific GPA using the following formula:

Determine distance "D"

Formula 3.1

$$D = 200$$

or if $\frac{TCH}{\tan(\theta)} < 954$

$$D = 200 + \left(954 - \frac{TCH}{\tan(\theta)}\right)$$

Section 1 Slope: No Slope, level with ASBL

Section 2 Slope (S_2):

Formula 3.2

$$S_2 = \frac{\tan(\theta) 940{,}474.476}{\theta\left((12{,}753.277 - D)\tan(\theta) - TCH\right)}$$

Where θ = GPA

Section 3 Slope (S_3):

Formula 3.3

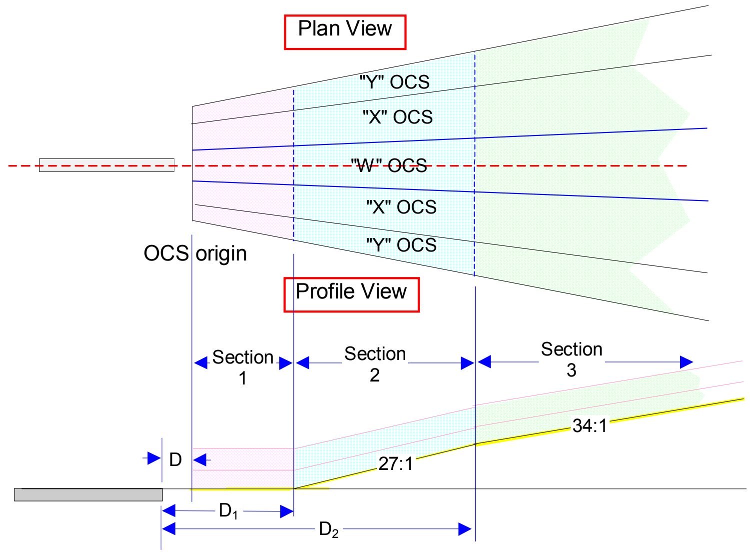
$$S_3 = \frac{102}{\theta}$$

Where θ = GPA

3.2.1 OCS Origin.

The OCS begins 200 feet from LTP, measured along course centerline, and extended to the PFAF.

Figure 3-3. Distance from LTP to Beginning of Slope Rise



Formula 3.4

$$D_1 = D + 3{,}332.939' - \frac{TCH}{\tan(\theta)}$$

Formula 3.5

$$D_2 = D + 12{,}553.277' - \frac{TCH}{\tan(\theta)}$$

3.3 DETERMINING SURFACE WIDTHS.

In order to determine which surface (W, X, or Y) to use to evaluate an obstacle at a known perpendicular distance (d_y) from the final approach course, the width of the surfaces at the obstacle distance from RWT (d_x) must be determined. Calculate the perpendicular distance from the course centerline to the edge of the surface using the following formulae:

"W" Surface: Formula 3.6

$$0.036(d_x - 200) + 400$$

"X" Surface: Formula 3.7

$$0.10752(d_x - 200) + 700$$

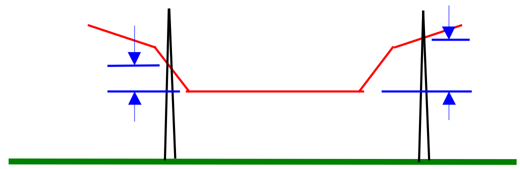
"Y" Surface: Formula 3.8

$$0.15152(d_x - 200) + 1000$$

3.4 OCS PENETRATIONS.

Evaluate obstacles at the longitudinal slope of the "W" surface. If obstacles penetrate the "X" or "Y" surfaces, calculate their "effective height" ($h_{effective}$) relative to the "W" surface and evaluate the obstacle as if it penetrated the "W" surface (see figure 3-4). To determine $h_{effective}$, use the following formula:

Figure 3-4. Calculating Obstacle Effective Height



Formula 3.9

$$h_{effective} = h - (x + y)$$

where h = height of obstacle
x = rise of "X" surface
y = rise of "Y" surface (may be zero)

Example: 1049' obstacle is located 4,600' from RWT.

Distance to edge of "W" Surface $= 0.036(4{,}600\text{-}200) + 400 = 558.40\cdot\cdot'$

Distance to edge of "X" Surface $= 0.10752(4{,}600\text{-}200) + 700 = 1{,}173.09\cdot\cdot'$

Distance to edge of "Y" Surface $= 0.15152(4{,}600\text{-}200) + 1000 = 1{,}666.69\cdot\cdot'$

CASE 1: Obstacle is in "X" surface, 1,000' from course centerline. It is $(1{,}000 - 558.40\cdot\cdot = 441.6\cdot\cdot')$ from edge of "W" surface.

$$h_{effective} = 1{,}049 - \left(\frac{441.6\cdot\cdot}{4} + 0\right) = 938.60\cdot\cdot'$$

CASE 2: Obstacle is in "Y" surface, 1,250' from course centerline. It is $(1{,}250 - 1{,}173.09\cdot\cdot = 76.91\cdot\cdot')$ from edge of "X" surface.

$$h_{effective} = 1{,}049 - \left(\frac{1{,}173.09\cdot\cdot - 558.40\cdot\cdot}{4} + \frac{76.91\cdot\cdot}{7}\right) = 884.34\cdot\cdot'$$

3.4.1 LOWEST ELEVATION EVALUATED.

Determine the lowest obstruction MSL elevation (or effective elevation) to be considered in the OCS evaluation using the following formula:

{ The minimum HAT value attainable is 250 feet. The elevation derived from formula 3.10 represents the obstruction elevation that results in a 250-foot HAT value. Therefore, obstructions lower than this value need not be considered. The GQS and the visual segment evaluation surface evaluate these obstructions. }

Formula 3.10

$$LE = LTP_E + \frac{\dfrac{(250 + (TDZE - LTP_E)) - TCH}{\tan(\theta)} - D_1}{S_2}$$

Where LTP_E = LTP Elevation
TDZE = Touchdown Zone Elevation

Example

$$313+\frac{\frac{(250+(315-313))-50}{tan(3)}-2{,}578.87\cdot\cdot}{27.027\cdot\cdot}=360.19\cdot\cdot$$

3.5 SECTION 1 OCS EVALUATION.

The section 1 OCS is a longitudinally level surface at LTP (ASBL) elevation. Actions relating to eliminating section 1 OCS penetrations do not include raising the glidepath angle. Proposed obstacles must not penetrate the OCS. Where EXISTING obstacles (elevation greater than the value from formula 3.10) penetrate the section 1 OCS's, take one of the following actions in the listed order of precedence:

First - remove obstacle.
Second - reduce obstacle height to eliminate penetration.
Last - determine the minimum DA using the following formula:

3.5.1 DA ADJUSTMENT OPTION (see figures 3-5A and 35B).

STEP 1: Determine the end of section 2 MSL elevation (Z_{MSL}):

Formula 3.11

$$Z_{MSL}=LTP_E+\frac{D_2-D}{S_3}$$

Example: $$313+\frac{11{,}799.33\cdot\cdot-200}{34}=654.16\cdot\cdot$$

STEP 2: Determine the adjusted DA for section 1 penetrations using the following formula:

Where h_{MSL} = Obstacle MSL elevation ($h_{effective}$)
d = distance (ft) measured along course from LTP to a point abeam the obstacle
θ = Glidepath angle

---------- CASE 1: $h_{MSL} < Z_{MSL}$ ----------

Formula 3.12

$$DA=LTP_E+tan(\theta)\left(\frac{TCH}{tan(\theta)}+D_1+S_2(h_{MSL}-LTP_E)\right)$$

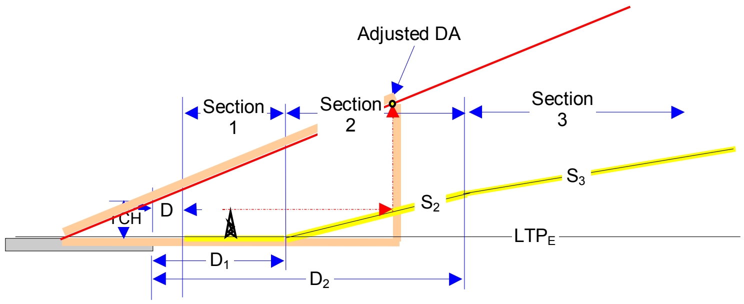
Example

$$313+tan(3)\left(\frac{50}{tan(3)}+2{,}578.88\cdot\cdot+27.02\cdot\cdot(379-313)\right)=600^{*}\quad(591.65\cdot\cdot)$$

600-313=287 HAT

*{ * The actual result is 591.65 feet. Round the result to the next higher 10-foot increment }*

Figure 3-5A. Section 1 DA Adjustment
Based on Section 2 OCS



---------- CASE 2: $h_{MSL} \geq Z_{MSL}$ ----------

Formula 3.13

$$DA = LTP_E + \tan(\theta)\left(\frac{TCH}{\tan(\theta)} + D + S_3\left(h_{MSL} - LTP_E\right)\right)$$

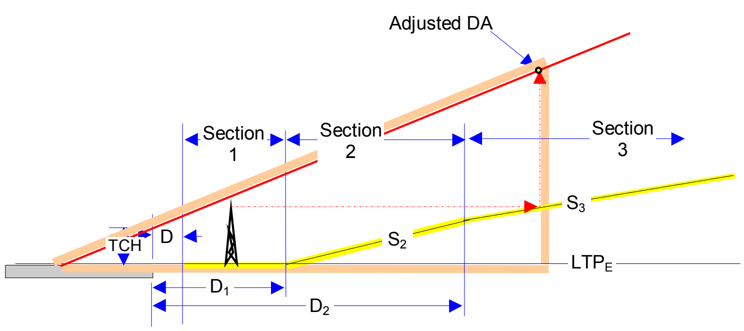
Example

$$313 + \tan(3)\left(\frac{50}{\tan(3)} + 200 + 34(699 - 313)\right) = 1{,}070\,^{*} \quad (1{,}061.28\cdots)$$

1070-313=757 HAT

{ *The actual result is 1,061.28 feet. Round the result to the next higher 10-foot increment }

Figure 3-5B. Section 1 DA Adjustment
Based on Section 3 OCS



3.6 SECTION 2.

The section 2 OCS is a longitudinally sloping surface. The slope is determined by the formula:

Formula 3.14

$$S_2 = \frac{\tan(\theta)940{,}474.476}{\theta((12{,}753.277 - D)\tan(\theta) - TCH)}$$

where θ=glidepath angle

Example

$$\frac{\tan(3)940{,}474.476}{3((12{,}753.277\text{-}200)\tan(3)\text{-}50)} = 27.02\cdot\cdot$$

S_2 for the nominal 3° glidepath angle is 27.03:1. Calculate the MSL elevation (Z_W) of the OCS at any distance (d) from LTP using the following formula:

Formula 3.15

$$Z_W = \frac{d\text{-}D_1}{S_2} + LTP_E$$

Proposed obstacles must not penetrate the OCS. Where EXISTING obstacles penetrate the section 2 OCS, take one of the following actions in the listed order of precedence:

First - remove obstacle.
Second - reduce obstacle height to eliminate penetration.
Third - raise glidepath angle (see paragraph 3.6.1).
Fourth - Adjust DA (see paragraph 3.6.2).

3.6.1 GLIDEPATH ANGLE ADJUSTMENT OPTION.

Determine the adjusted glidepath angle to accommodate an OCS penetration using the following formula:

Formula 3.16

$$\theta_{adjusted} = \frac{940{,}474.476(h - LTP_E)}{(D_2 - D)(d - D_1)}$$

Example: $$\frac{940{,}474.476(1{,}049\text{-}981.37)}{(11{,}799.33\cdots - 200)(4{,}310 - 2{,}578.79\cdot\cdot)} = 3.17°^* \quad (3.167\cdot\cdot)$$

*{ *Actual answer is 3.167·· °. Always round to the next higher hundredth (0.01) degree. This prevents rounding errors in the amount of penetration causing miniscule penetration values using the revised angle. }*

Where d = obstacle distance (ft) from LTP
h = $h_{effective}$ MSL height
$\theta_{adjusted}$= adjusted glidepath angle
E = LTP elevation

3.6.2 DA ADJUSTMENT OPTION.

DA may be increased to occur at a height that forces the penetrating obstacle to be encountered in the visual segment of the approach. To adjust DA, use the following formulae:

Variables: LTP_E = LTP elevation
θ = Glidepath Angle
h_{MSL} = effective height of obstacle (MSL)

STEP 1: Determine the end of section 2 MSL elevation (Z_{MSL}):

Formula 3.17

$$Z_{MSL} = LTP_E + \frac{D_2 - D}{S_3}$$

$$\text{Example: } 313 + \frac{11{,}799.33 - 200}{34} = 654.16$$

STEP 2: Determine the adjusted LTP to DA distance:

CASE 1 - Penetrating obstacle MSL elevation ≥ than Z_{MSL}:

Calculate Adjusted LTP to DA distance:

Formula 3.18

$$D_{adjusted} = D_2 + \frac{102(h_{MSL} - Z_{MSL})}{\theta}$$

$$\text{Example: } 11{,}799.33 + \frac{102(699-654.16)}{3} = 13{,}323.89$$

CASE 2 - Penetrating obstacle MSL elevation < Z_{MSL}:

Calculate Adjusted LTP to DA distance:

Formula 3.19

$$D_{adjusted} = D_1 + S_2(h_{MSL} - LTP_E)$$

$$\text{Example: } 2{,}578.79 + 27.02(399-313) = 4{,}900.79$$

STEP:3: Calculate the adjusted DA (MSL) value using the following formula**:**

Formula 3.20

$$DA_{adjusted} = LTP_E + tan(\theta)\left(D_{adjusted} + \frac{TCH}{tan(\theta)}\right)$$

Round to next higher 10-foot increment

Example

$$313 + tan(3)\left(4{,}900.79 + \frac{50}{tan(3)}\right) = 619.84 \quad \text{round to } 620$$

STEP 4: Initiate action to mark and light obstruction(s) that would require DA adjustment.

3.7 SECTION 3.

The section 3 OCS is a longitudinally sloping surface. The slope is determined by the formula:

Formula 3.21

$$S_3 = \frac{102}{\theta}$$

S_3 for the nominal 3° glidepath angle is 34:1. Calculate the MSL elevation (Z_W) of the OCS at any distance (d) from LTP using the following formula:

Formula 3.22

$$Z_W = \frac{d-D}{S_3} + LTP_E$$

Proposed obstacles must not penetrate the OCS. Where EXISTING obstacles penetrate the section 3 OCS's take one of the following actions in the listed order of precedence:

First - remove obstacle.
Second - reduce obstacle height to eliminate penetration.
Third - adjust glidepath angle (see paragraph 3.7.1).
Fourth - adjust TCH (see paragraph 3.7.2).
Fifth - adjust DA (see paragraph 3.7.3).

3.7.1 To determine the adjusted glidepath angle, use the following formula:

Formula 3.23

$$\theta_{adjusted} = \frac{102(h - LTP_E)}{d - D}$$

Example

$$\frac{102(719\text{-}313)}{12{,}500\text{-}200} = 3.37°* \quad (3.367\cdot\cdot)$$

*{ *Actual answer is 3.367°. Always round to the next higher hundredth (0.01) degree. This prevents rounding errors in the amount of penetration causing miniscule penetration values using the revised angle. }*

3.7.2 ADJUSTING TCH.

Calculate the TCH (within limits of tables 2-1C and 2-2) adjustment required to eliminate an OCS penetration using the following formula:

Formula 3.24

$$TCH_{adjustment} = \tan(\theta)PS$$

Example

$$\tan(3)(4.5)(27) = 6.37\cdot\cdot$$

where P = amount of penetration (ft)
S = slope ratio of penetrated surface
θ = glidepath angle

3.7.3 TO DETERMINE THE ADJUSTED DA.

DA may be increased to occur at a height that forces the penetrating obstacle to encounter the visual segment of the approach. To adjust DA, take the following steps:

STEP 1: Determine the adjusted LTP to DA distance:

Formula 3.25

$$D_{adjusted} = D + S_3(h_{MSL} - LTP_E)$$

Example

$$200+34(799\text{-}313) = 16{,}724$$

STEP 2: Calculate the adjusted DA (MSL) value**:**

Adjusted DA:

Formula 3.26

$$DA_{adjusted} = LTP_E + \tan(\theta)\left(D_{adjusted} + \frac{TCH}{\tan(\theta)}\right)$$

Round to next higher 10-foot increment

Example

$$313 + \tan(3)\left(16{,}724 + \frac{50}{\tan(3)}\right) = 1{,}239.47\cdot\cdot \quad \text{round to } 1{,}240$$

STEP 3: Initiate action to mark and light obstruction(s) that would require DA adjustment.

3.8 DA AND HAT.

The DA value may be derived from the HAT. The MINIMUM HAT is 250 feet (300 or 400 feet if paragraph 2.10 applies). Calculate the DA using the formula:

Formula 3.27

$$DA = HAT + TDZE$$

Round to the next higher 10-foot increment

If DA was adjusted for obstacle penetrations, publish the higher of minimum DA or adjusted DA.

3.8.1 Calculate the HAT:

STEP 1:

Formula 3.28

$$HAT = DA - (LTP_E + (TDZE - LTP_E))$$

Where TDZE = touchdown zone elevation

STEP 2:

Minimum HAT is 250 or
300 or 400 if paragraph 2.10 is applied

STEP 3: Compare HAT and Minimum HAT. Publish the higher of the two values.

Example

$$HAT = 600 - (313 + (313 - 313)) = 287$$

$$\text{Min HAT} = 300 \qquad 287 \langle 300$$

$$DA = 313 + 300 = 613 \text{ round to } 620$$

CHAPTER 4. MISSED APPROACH

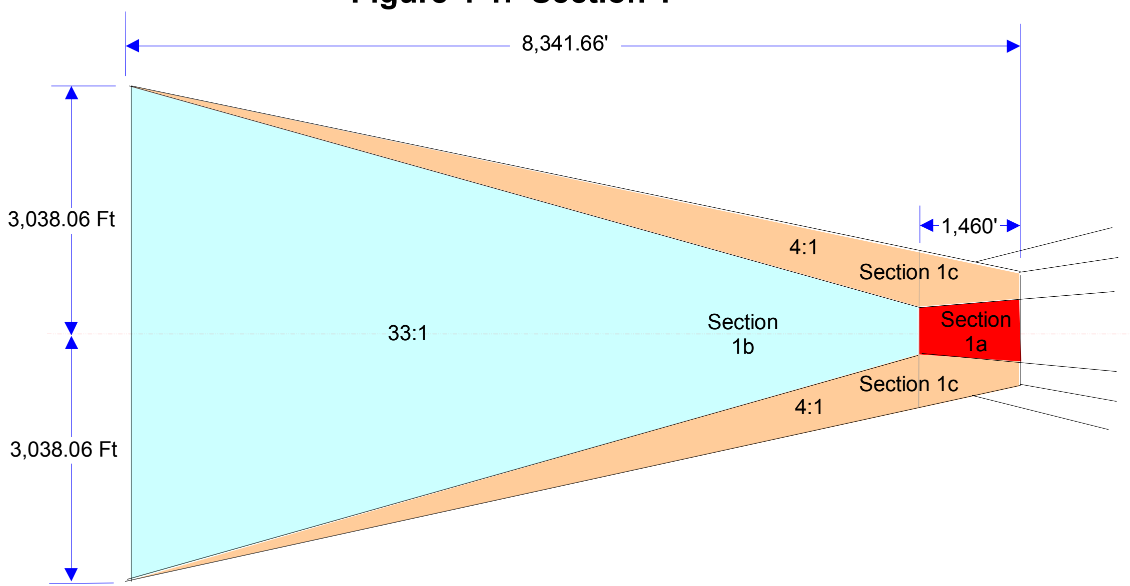
4.0 MISSED APPROACH SEGMENT.

The missed approach segment begins at the DA and ends at the clearance limit. It is comprised of section 1 (initial climb) and section 2 (from end of section 1 to the clearance limit). Section 2 is constructed under criteria contained in Order 8260.44 for RNAV departure procedures. Section 2 beginning width is ± 0.5 NM. The 40:1 OCS begins at the elevation of section 1b at centerline. The MA procedure is limited to two turn fixes (see figure 4-1).

4.1 SECTION 1.

Section 1 is aligned with the final approach course. It is comprised of three subsections, beginning at the DA and extending 8,341.66 feet.

Figure 4-1. Section 1

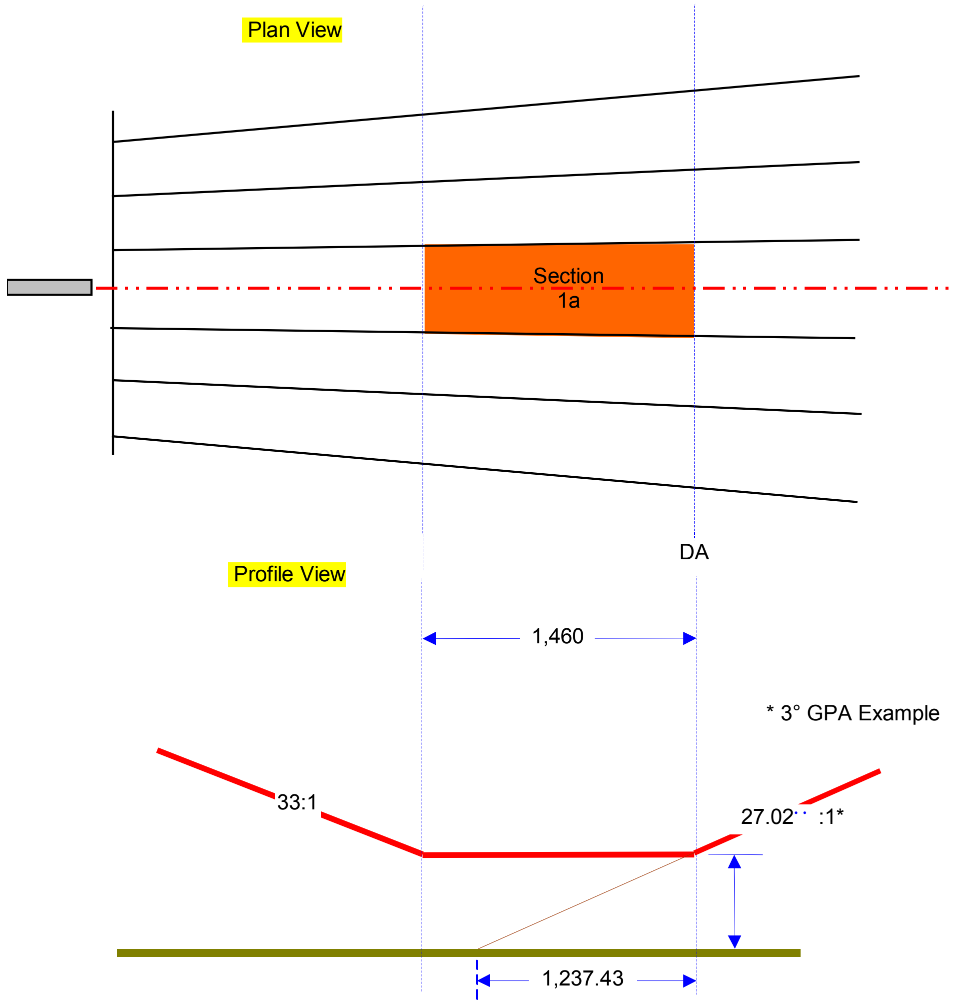


4.1.1 Section 1a.

4.1.1 **a. Area.** Section 1a begins at the DA point and overlies the final approach "W" OCS, extending 1,460 feet in the direction of the missed approach. This section is always aligned with the final approach course (see figure 4-2).

4.1.1 **b. OCS.** The height of section 1a surface is equal to the underlying "W" surface at DA. If this section is penetrated, apply paragraph 3.6.2.

Figure 4-2. Section 1a

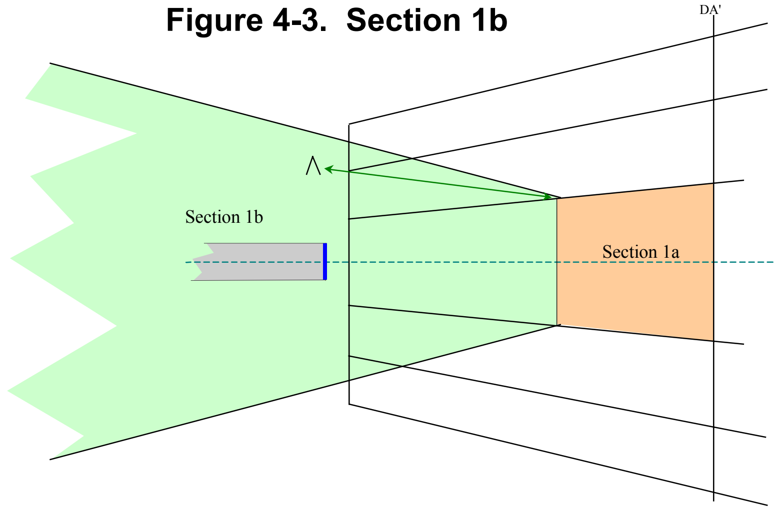


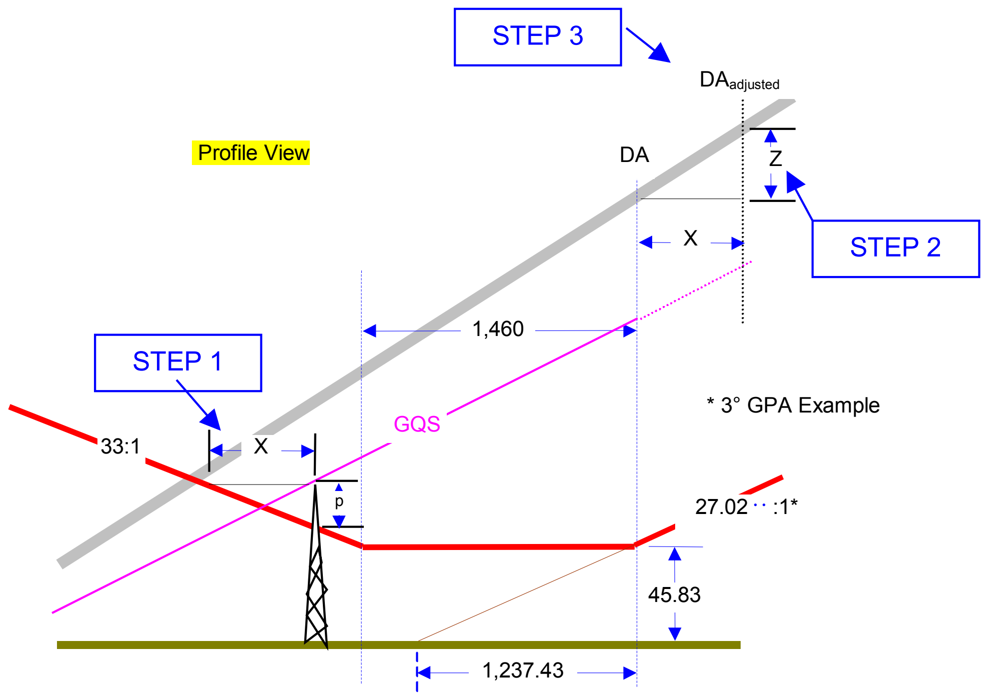
4.1.2 **Section 1b.**

4.1.2 **a. Area.** Section 1b begins at the end of section 1a, extends to a point 8,341.66 feet from DA, and splays along the extended final course to a total width of 1 NM. This section is always aligned with the final approach course (see figures 4-1, 4-3).

4.1.2 **b. OCS.** Section 1b OCS is a 33:1 inclined plane rising in the direction of the missed approach. The height of the beginning of section 1b is equal to the height of the "W" OCS at the end of section 1a. Evaluate obstructions using the shortest distance of the obstruction from the end of section 1a (see figure 4-3). Adjust DA to mediate penetrations in this section.

Figure 4-3. Section 1b





STEP 1: Calculate the along track DA adjustment (X):

Formula 4.2

$$X = \frac{P \times S_2 \times 33}{S_2 + 33}$$

STEP 2: Calculate the vertical DA adjustment (Z):

Formula 4.3

$$Z = \tan(\theta)X$$

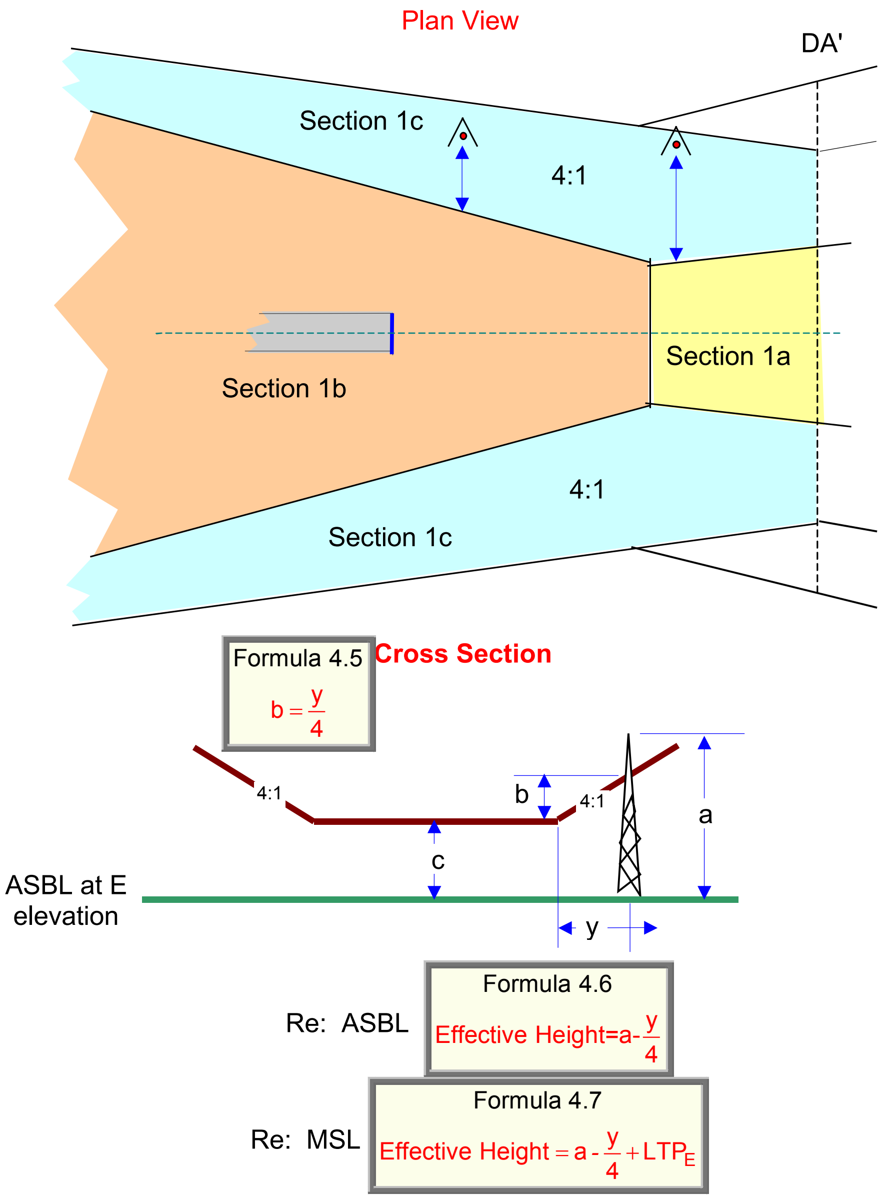
STEP 3: Calculate the adjusted DA value (MSL):

Formula 4.4

$$DA_{adjusted} = DA + Z$$

4.1.3 **Section 1C** (see figure 4-4)

Figure 4-4. Section 1c



4.1.3 **a. Area.** These are 4:1 secondary areas that begin at the DA point. These sections splay to a point on the edge and at the end of section 1b.

4.1.3 **b. OCS.** An inclined plane starting at the DA point and sloping 4:1. Obstacles in section 1c are evaluated with a 4:1 slope measured perpendicular to the MA course from the elevation of the outer boundaries of section 1a or 1b surface as appropriate. The inner and outer boundaries of section 1c converge at the end of section 1b (8,341.656 feet from the DA point). Reduce the obstruction height by the amount of 4:1 surface rise (b) from the edge of section 1a or 1b (measured perpendicular to section 1 course). Then evaluate the obstruction as if it were in section 1a or 1b.

4.1.4 **Section 2**. Apply Order 8260.44, level 1 criteria in this section. Instead of the departure trapezoid originating at DER altitude at the DER, it originates at the elevation of the end of section 1b OCS at centerline, with a width of ± 0.5 NM (along the ab line). It ends at the plotted position of the clearance limit. The primary and secondary widths must be the appropriate width from the distance flown. Secondary areas begin abeam the first following section 1 where positive course guidance commences. Direct to fix (DF), course to fix (CF), track to fix (TF), and heading to altitude (VA) leg types are allowed. TF legs are preferred. If the first leg is a turn using the DF leg-type, the tie-back point is the turn side edge of section 1c abeam the DA point. Establish a fix on the continuation of the final approach course at least 0.5 NM from the end of section 1 (ab line). If the fix is a fly-by turning waypoint, locate the fix at least DTA+0.5 NM from the ab line (see figures 4-5, 4-6, and 4-7). Use table 4-1 airspeeds to determine turn radii from Order 8260.44, table 3. Establish the outer boundary radius of a turning procedure based on the highest category aircraft authorized to use the approach.

Table 4-1

Category	***MA Altitude < 10,000' MSL***	***MA Altitude ≥ 10,000' MSL***
A, B	200 KIAS	200 KIAS
C, D, E	250 KIAS	310 KIAS

Figure 4-5. Turning Missed Approach with Turning Fix at Minimum Required Distance

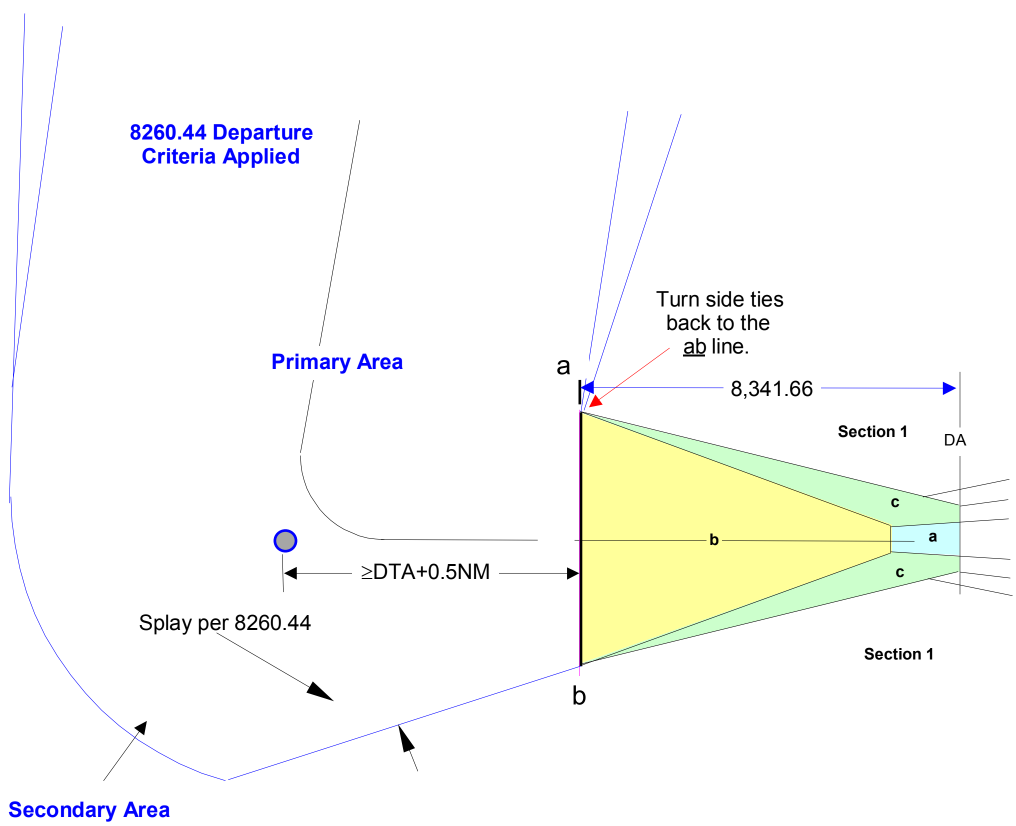


Figure 4-6. Turning Missed Approach with Turn Fix at Greater Than Minimum Distance

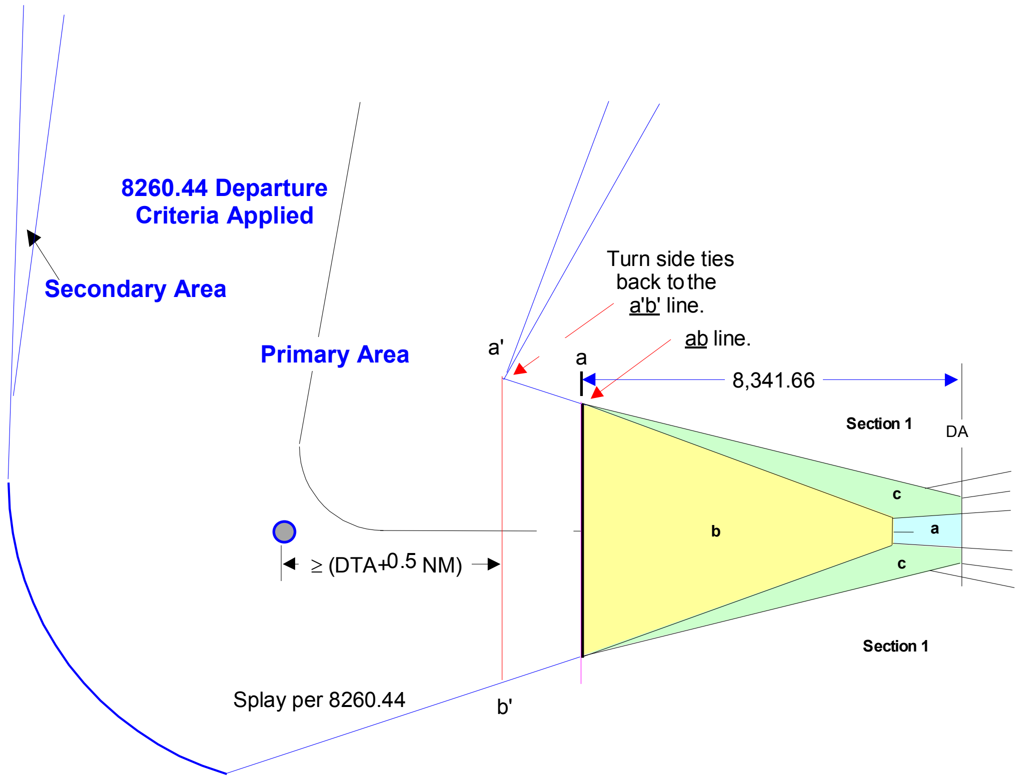
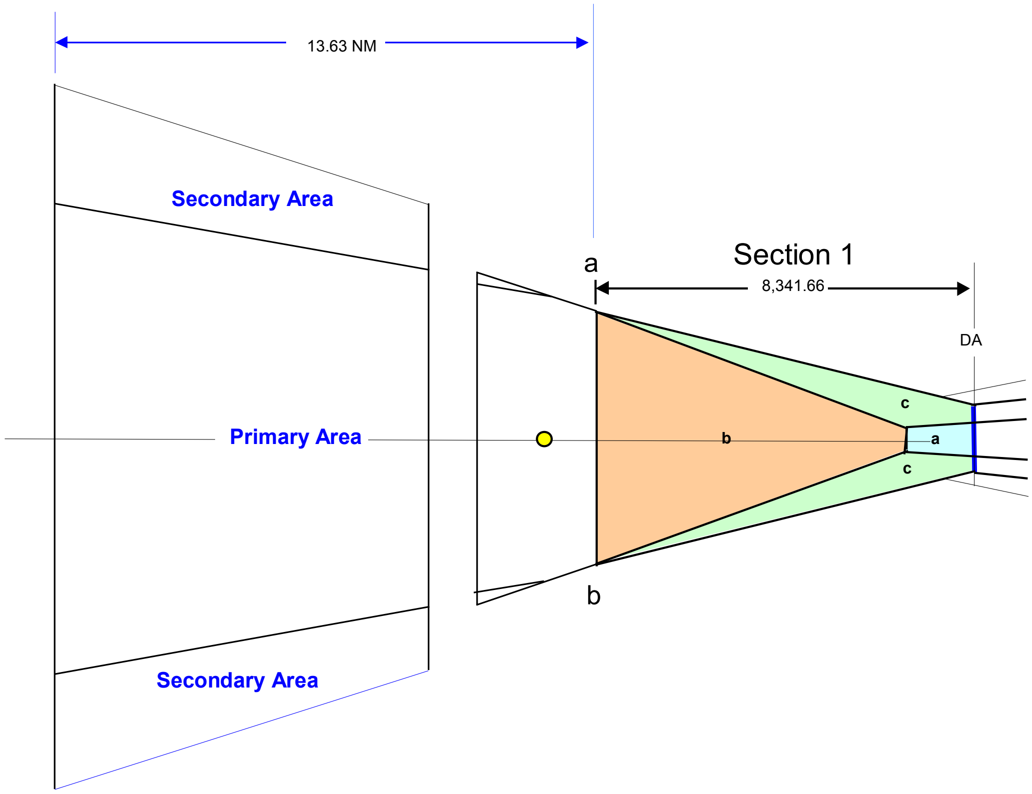


Figure 4-7. Straight Missed Approach



4.2 MISSED APPROACH CLIMB GRADIENT (DOD ONLY).

Where the 40:1 OCS is penetrated and the lowest HAT is required, a mandatory missed approach climb gradient may be specified to provide ROC over the penetrating obstruction. Use the following formula to calculate the climb gradient (CG) in feet per NM.

Formula 4.8

$$CG = \frac{h - \left(DA - \tan(\theta)1{,}460\right)}{0.76d}$$

Where h = MSL height of obstruction
d = Shortest distance (NM) from end of section 1a to obstruction

$$\text{Example:}\quad \frac{1849\text{-}\left(610\text{-}\tan(3)1{,}460\right)}{0.76(5.26)} = 329.07\cdot\cdot \approx 330$$

Formulae Used in LPV Criteria

Chapter 1. NONE

Chapter 2.

- **Paragraph 2.6.** Calculation of GPI value.

Formula 2.1

$$GPI = \frac{TCH}{tan(\theta)}$$

- **Paragraph 2.7.** Determining FPAP, signal splay value for runways >9,023' and ≤ 12,366'.

Formula 2.2

$$tan^{-1}\left(\frac{350}{\text{RWY length} + 1000}\right)$$

- **Paragraph 2.7.** Determining FPAP, ± signal width at DER (meters) for runways >12,366' and ≤ 16,185'.

Formula 2.3

$$\frac{tan(1.5) \times (\text{RWY length} + 1{,}000)}{3.2808}$$

- **Paragraph 2.7.** Determining FPAP, ± signal width at DER (meters) for runways >16,185'.

Formula 2.4

$$\frac{tan(1.5) \times (\text{RWY length} + 1{,}000)}{3.2808}$$

- **Paragraph 2.8.** Determining PFAF coordinates: Calculates height above ASBL.

Formula 2.5

$$Z = A - F$$

- **Paragraph 2.8.** Determining PFAF coordinates: Calculated distance from runway threshold to PFAF.

Formula 2.6

$$D = 364{,}609\left[90 - \theta - sin^{-1}\left(\frac{sin(90+\theta)20{,}890{,}537}{z + 20{,}890{,}537}\right)\right]$$

- **Paragraph 2.11.1b**. GQS Width. Calculates half width of GQS at DA.

  Formula 2.7

  $$E = 0.036(D - 200) + 400$$

- **Paragraph 2.11.1b.** GQS Width. Calculates half width of GQS at any distance from runway threshold.

  Formula 2.8

  $$w = \left(\frac{E - k}{D} d\right) + k$$

- **Paragraph 2.11.1d.** Calculates GQS height above ASBL at any distance "d" from runway threshold.

  Formula 2.9

  $$h = \tan\left(\frac{2\theta}{3}\right) d$$

Chapter 3.

- **Paragraph 3.2**. OCS Slope(s). Calculates the OCS origin distance from runway threshold.

Formula 3.1

$$D = 200$$

or if $\frac{TCH}{\tan(\theta)} < 954$

$$D = 200 + \left(954 - \frac{TCH}{\tan(\theta)}\right)$$

- **Paragraph 3.2**. OCS Slope(s). Calculates OCS section 2 slope.

Formula 3.2

$$S_2 = \frac{\tan(\theta)940{,}474.476}{\theta\left((12{,}753.277 - D)\tan(\theta) - TCH\right)}$$

- Formula 3.3 $S_3 = \frac{102}{\theta}$ **Paragraph 3.2**. OCS Slope(s). Calculates OCS section 3 slope.

- **Paragraph 3.2.1**. Calculates OCS section 2 origin distance from runway threshold.

Formula 3.4

$$D_1 = D + 3{,}332.939' - \frac{TCH}{\tan(\theta)}$$

- **Paragraph 3.2.1**. Calculates OCS section 2 end, section 3 beginning distance from runway threshold.

Formula 3.5

$$D_2 = D + 12{,}553.277' - \frac{TCH}{\tan(\theta)}$$

- **Paragraph 3.3.** Determining Surface Widths. Calculates the half width of the "W" surface at any distance "d_x".

Formula 3.6

$$0.036(d_x - 200) + 400$$

- **Paragraph 3.3**. Determining Surface Widths. Calculates the half width of the "X" surface at any distance "d_x".

Formula 3.7

$$0.10752(d_x - 200) + 700$$

- **Paragraph 3.3.** Determining Surface Widths. Calculates the half width of the "Y" surface at any distance "d_x".

Formula 3.8

$$0.15152(d_x - 200) + 1000$$

- **Paragraph 3.4**. OCS Penetrations. Calculates the "effective" height of an obstacle penetrating the "X" or "Y" surface. The effective height is the obstruction height reduced by the amount of "X" and/or "Y" surfaces rise, allowing it to then be evaluated against the height of the "W" surface.

Formula 3.9

$$h_{effective} = h - (x + y)$$

- **Paragraph 3.4.1**. Lowest Elevation Evaluated. Calculates the MSL height of the section 2 OCS at the point DA reaches 250' above TDZE.

Formula 3.10

$$LE = LTP_E + \frac{\frac{(250 + (TDZE - LTP_E)) - TCH}{\tan(\theta)} - D_1}{S_2}$$

- **Paragraph 3.5.1.** DA Adjustment. Step 1. Calculates the height of the end of section 2 OCS above MSL.

Formula 3.11

$$Z_{MSL} = LTP_E + \frac{D_2 - D}{S_3}$$

- **Paragraph 3.5.1.** DA Adjustment. Step 2, Case 1 (obstacle height less than end of section 2 OCS). Calculates the MSL DA value at the point that the OCS height equals the penetrating obstacle height.

Formula 3.12

$$DA = LTP_E + \tan(\theta)\left(\frac{TCH}{\tan(\theta)} + D_1 + S_2(h_{MSL} - LTP_E)\right)$$

- **Paragraph 3.5.1.** DA Adjustment. Step 2, Case 2 (obstacle higher than end of section 2 OCS). Calculates the MSL DA value at the point that the OCS height equals the penetrating obstacle height.

Formula 3.13

$$DA = LTP_E + tan(\theta)\left(\frac{TCH}{tan(\theta)} + D + S_3(h_{MSL} - LTP_E)\right)$$

- **Paragraph 3.6.** Section 2. Calculates the slope of the section 2 OCS depending on glidepath angle (θ) , TCH, and OCS origin distance from LTP.

Formula 3.14

$$S_2 = \frac{tan(\theta)940{,}474.476}{\theta((12{,}753.277 - D)tan(\theta) - TCH)}$$

- **Paragraph 3.6.** Section 2. Calculates the MSL elevation of the section 2 OCS at any distance (d) from LTP.

Formula 3.15

$$Z_W = \frac{d - D_1}{S_2} + LTP_E$$

- **Paragraph 3.6.1.** Glidepath Angle Adjustment Option. Calculates the adjusted glidepath given the penetrating obstacle MSL elevation.

Formula 3.16

$$\theta_{adjusted} = \frac{940{,}474.476(h - LTP_E)}{(D_2 - D)(d - D_1)}$$

- **Paragraph 3.6.2**. DA Adjustment Option. Step 1. Calculates the OCS MSL elevation at the end of section 2.

Formula 3.17

$$Z_{MSL} = LTP_E + \frac{D_2 - D}{S_3}$$

- **Paragraph 3.6.2.** DA Adjustment Option. Step 2. CASE 1 (Obstacle MSL elevation $\geq$ end of section 2 OCS). Calculates the adjusted LTP to DA distance.

Formula 3.18

$$D_{adjusted} = D_2 + \frac{102(h_{MSL} - Z_{MSL})}{\theta}$$

- **Paragraph 3.6.2.** DA Adjustment Option. Step 2. CASE 2 (Obstacle MSL elevation< end of section 2 OCS). Calculates the adjusted LTP to DA distance.

Formula 3.19

$$D_{adjusted} = D_1 + S_2\left(h_{MSL} - LTP_E\right)$$

- **Paragraph 3.6.2.** DA Adjustment Option. Step 3. Calculates the adjusted DA MSL value given LTP to DA distance.

Formula 3.20

$$DA_{adjusted} = LTP_E + tan(\theta)\left(D_{adjusted} + \frac{TCH}{tan(\theta)}\right)$$

- **Paragraph 3.7.** Section 3. Calculates the slope ratio.

Formula 3.21

$$S_3 = \frac{102}{\theta}$$

- **Paragraph 3.7.** Section 3. Calculates the MSL elevation of the OCS at any distance (d) from LTP.

Formula 3.22

$$Z_W = \frac{d\text{-}D}{S_3} + LTP_E$$

- **Paragraph 3.7.** Determine adjusted glidepath angle. Calculated adjusted angle.

Formula 3.23

$$\theta_{adjusted} = \frac{102\left(h - LTP_E\right)}{d - D}$$

Paragraph 3.7.2. Adjusting TCH. Calculate revised TCH value to eliminate penetration.

Formula 3.24

$$TCH_{adjustment} = tan(\theta)PS$$

- **Paragraph 3.7.3.** To Determine the Adjusted DA. Step 1. Calculate adjusted LTP to DA distance.

Formula 3.25

$$D_{adjusted} = D + S_3\left(h_{MSL} - LTP_E\right)$$

- **Paragraph 3.7.3.** To Determine the Adjusted DA. Step 2. Calculate the adjusted MSL DA value.

Formula 3.26

$$DA_{adjusted} = LTP_E + tan(\theta)\left(D_{adjusted} + \frac{TCH}{tan(\theta)}\right)$$

- **Paragraph 3.9.** DA and HAT. Calculates DA given HAT and TDZE.

Formula 3.27

$$DA = HAT + TDZE$$

- **Paragraph 3.9.1.** Calculate the HAT Step 1. Calculated HAT value.

Formula 3.28

$$HAT{=}DA{-}\left(LTP_E{+}\left(TDZE{-}LTP_E\right)\right)$$

Chapter 4.

Paragraph 4.1.1. Section 1a. Calculates the adjusted DA for a section 1a penetration.

Formula 4.1

$$DA_{adjusted} = \tan(\theta)\left[D + 3{,}332.939 + S_2\left(h - LTP_E\right)\right] + LTP_E$$

Paragraph 4.1.2b. OCS.

Step 1. Calculates along track DA adjustment.

Formula 4.2

$$X = \frac{P \times S_2 \times 33}{S_2 + 33}$$

Step 2. Calculates the vertical DA adjustment.

Formula 4.3

$$Z = \tan(\theta)X$$

Step 3. Calculates the adjusted DA value (MSL).

Formula 4.4

$$DA_{adjusted} = DA + Z$$

Paragraph 4.1.3. Section 1C. Calculates 4:1 surface rise.

Formula 4.5

$$b = \frac{y}{4}$$

Calculates obstruction effective height referenced to ASBL.

Formula 4.6

$$\text{Effective Height}=a-\frac{y}{4}$$

Calculates obstruction effective height referenced to MSL.

Formula 4.7

$$\text{Effective Height} = a - \frac{y}{4} + LTP_E$$

Paragraph 4.2. Missed Approach Climb Gradient (DoD Only).

Formula 4.8

$$CG = \frac{h - \left(DA - \tan(\theta)1{,}460\right)}{0.76d}$$

LPV RATIONALE

Paragraph 2.8 - DETERMINING PFAF/FAF COORDINATE.

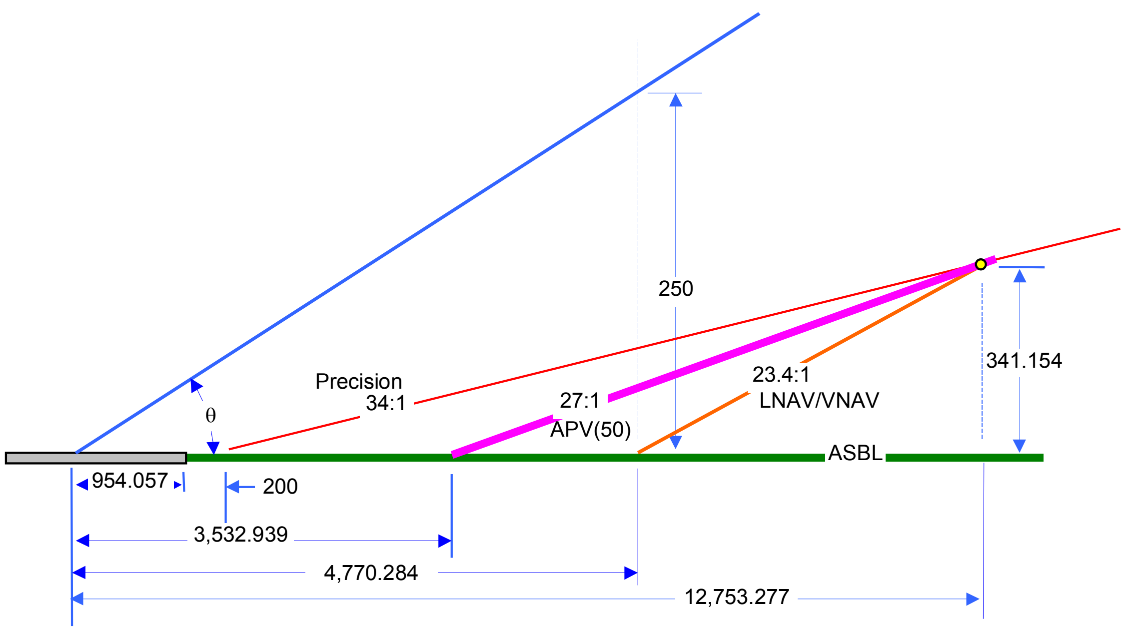
Step 1: Formula: $\boxed{Z = A - F}$

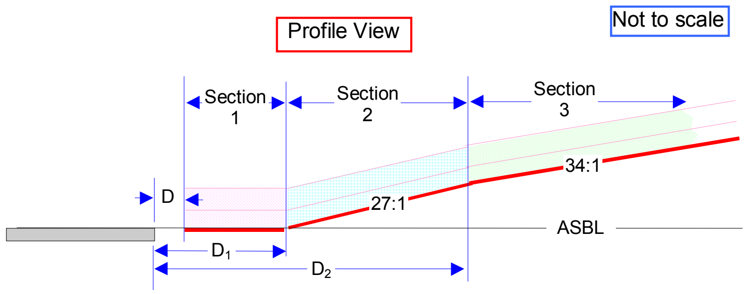
Step 2: Formula: $$\boxed{D = 364{,}609\left[90 - \theta - \sin^{-1}\left(\frac{\sin(90+\theta)20{,}890{,}537}{z + 20{,}890{,}537}\right)\right]}$$

Where: A = FAF Altitude in feet
F = LTP elevation in feet
θ = Glidepath angle

Rationale for formula. The formula is based upon a spherical model of the earth with a radius equal to the geometric mean of the semi-major and semi-minor axes of the WGS-84 ellipsoid (20,890,537 feet). The leading coefficient $(364{,}609)$ of the formula is the same radius multiplied by the degree-to-radian conversion factor $\left(\frac{\pi}{180} \times 20{,}890{,}537 = 364{,}609\right)$. Using this spherical model formula instead of a much more complex ellipsoidal solution which is both altitude and heading dependent results in errors less than one part in ten thousand over nominal glidepath lengths.

Paragraph 3.2 - OCS SLOPE(S).





Section 1:

ILS 5.33σ value for VAL is 12 meters

LPV with 5.33σ value for VAL is 50 meters

$\frac{50-12}{0.3048} = 124.672'$ additional possible vertical bias error

$\frac{124.672}{tan(3°)} = 2{,}378.883'$ Vertical bias error converted to longitudinal displacement

$\frac{50}{tan(3°)} + 200 = 1{,}154.057'$ ILS GPI to OCS (34:1) origin minimum distance [50' TCH, 3°θ]

If GPI<954, then the 200-foot value must be increased by the amount GPI is short of 954

Let $D = 200$ if $GPI \geq 954$

Let $D = 200 + \left(954 - \frac{TCH}{tan(\theta)}\right)$ if GPI < 954'

$\frac{250}{tan(3°)} = 4{,}770.284$ GPI to LNAV/VNAV OCS [23.4:1] origin

1,154.057+2,378.883=3,532.939 GPI to LPV OCS [34:1] where GPI ≥ 954'

$\boxed{D_1 = D + 3{,}332.939' - \frac{TCH}{tan(\theta)}}$ RWT to LPV OCS origin

Section 2:

$$\frac{\left(\frac{250-50}{tan(3)} \times 34\right) - (200 \times 23.4)}{34 - 23.4} + \frac{50}{tan(3)} = 12{,}753.277$$ GPI to S_W/S_V crossover point

$\boxed{D_2 = D + 12{,}553.277' - \frac{TCH}{tan(\theta)}}$ RWT to S_W/S_V crossover point

Slope is expressed as RUN/RISE in TERPS

RUN: 12,753.277-3,532.939=9,220.338

RISE:
$$\frac{12{,}753.277-\left(\dfrac{TCH}{\tan(\theta)}+D\right)}{\dfrac{102}{\theta}}=\frac{\theta\left(12{,}753.277-\left(\dfrac{TCH}{\tan(\theta)}+D\right)\right)}{102}=$$

$$\frac{\left(12{,}753.277-D-\dfrac{TCH}{\tan(\theta)}\right)\theta}{102}=\frac{\left(\left(12{,}753.277-D\right)\tan(\theta)-TCH\right)\theta}{102\tan(\theta)}$$

Slope (RUN/RISE):
$$\frac{9{,}220.338}{\dfrac{\left(\left(12{,}753.277-D\right)\tan(\theta)-TCH\right)\theta}{102\tan(\theta)}}=\boxed{\frac{\tan(\theta)940{,}474.476}{\theta\left(\left(12{,}753.277-D\right)\tan(\theta)-TCH\right)}}$$

$$\frac{\tan(3)940{,}474.476}{3\left(\left(12{,}753.277-200\right)\tan(3)-50\right)}=27.027$$ Slope of LPV OCS from origin to SW/SV crossover point

Section 3:

$$\boxed{\frac{102}{\theta}}$$ Slope of Section 3

PARAGRAPH 3.3 DETERMINING SURFACE WIDTHS.

The widths of the final approach trapezoid are identical to the United States Standard for precision approaches stated in Order 8260.3B, United States Standard for Terminal Instrument Procedures (TERPS), Volume 3, Precision Approach (PA) and Barometric Vertical Navigation (Baro VNAV) Approach Procedure Construction.

PARAGRAPH 3.5 - SECTION 1.

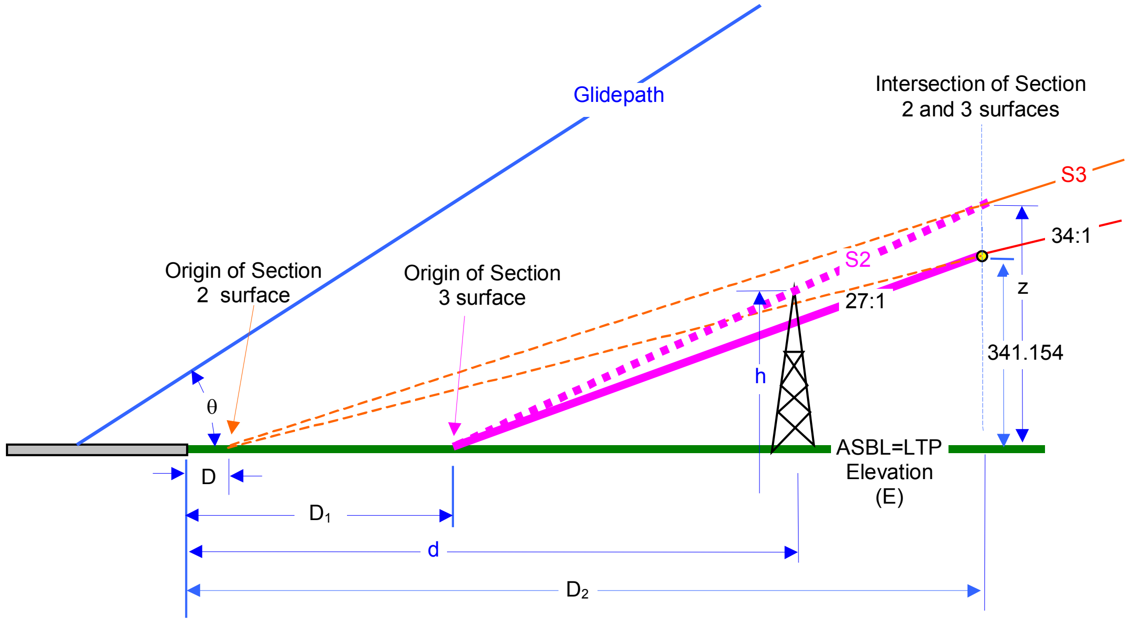
Section 1 is the application of the precision surface with a zero longitudinal slope. Penetrations of the "W", "X", or "Y" surfaces do not affect glidepath angle. Instead, the minimum DA is determined by adding the ROC value (vertical distance between the glidepath and ASBL at the obstacle) to the MSL height of the effective height of the obstacle.

$$\boxed{\begin{array}{l} ROC=\tan(\theta)\left(d+\dfrac{TCH}{\tan(\theta)}\right) \\ \text{Min DA} = h_{MSL}+ROC \end{array}}$$

h_{MSL} = height above mean sea level

PARAGRAPH 3.6.1 - To determine the adjusted glidepath angle,…

Any adjustment in the slope of section 2 will affect the slope of section 3 because the sections share a common height at a point 12,753.277 feet from GPI.



$$S_2 = \frac{d - D_1}{h - E} \quad z = \frac{D_2 - D_1}{S_2} \quad S_3 = \frac{D_2 - D}{z} \quad \theta = \frac{102}{S_3}$$

then by substitution:

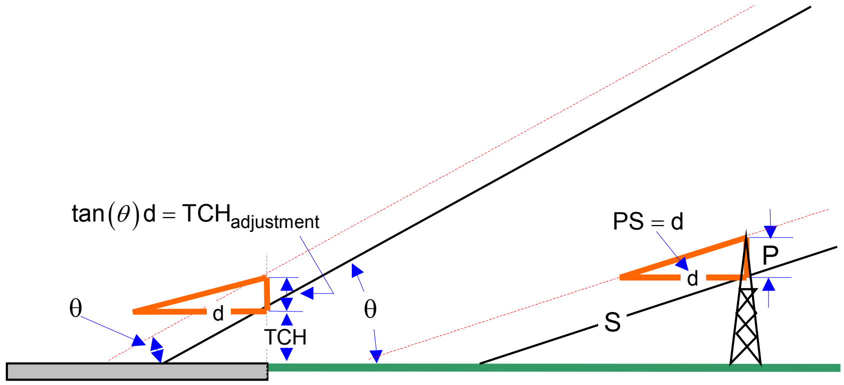
$$\frac{102}{\frac{D_2 - D}{D_2 - D_1 \Big/ \frac{d - D_1}{h - E}}} = \frac{102}{\frac{D_2 - D}{\frac{(D_2 - D_1)(h - E)}{d - D_1}}} = \frac{102}{\frac{(D_2 - D)(d - D_1)}{(D_2 - D_1)(h - E)}} = \frac{102(D_2 - D_1)(h - E)}{(D_2 - D)(d - D_1)}$$

Since D_2-D_1 is always 9,220.338:

$$\boxed{\theta = \frac{940{,}474.476(h - E)}{(D_2 - D)(d - D_1)}}$$

<u>Paragraph 3.8 - ADJUSTING TCH</u>.

Adjusting TCH in LPV criteria is the equivalent to relocating the glide slope antenna in ILS criteria. The goal is to move the origin of the OCS toward the runway sufficiently to cause the OCS at the obstacle location to raise to a point on top of the obstacle.



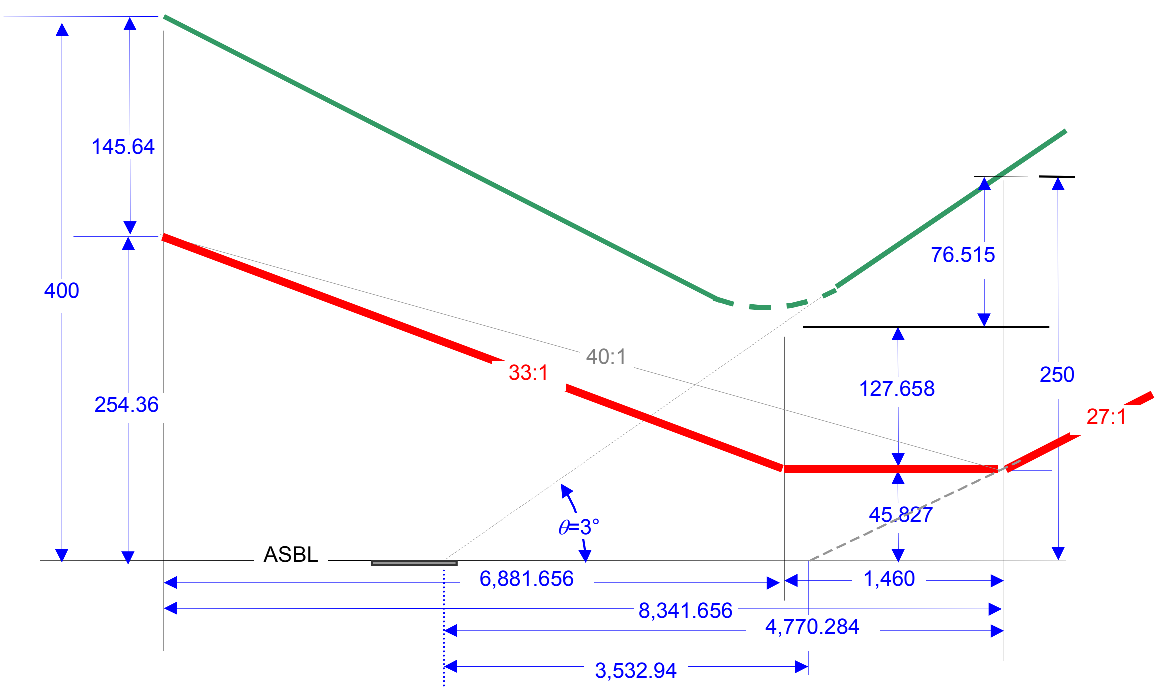
$$\boxed{TCH_{adjustment} = tan(\theta)PS}$$

where P = amount of penetration (ft)
S = slope ratio of penetrated surface
θ = glidepath angle

Example: $\tan(3)(4.5)(27) = 6.37$

Paragraph 4.1 - SECTION 1.

The dimensions of the missed approach segment are based on a standard glidepath angle of 3 degrees, TCH of 50 feet, 250-foot HAT, assumed height loss during 1,460 of horizontal flight descending on the glidepath, recovery of height loss and climb to 400 feet above ASBL. The following diagram depicts the derivation of stated values:



Height Loss: $1460 \times \tan(3) = 76.515$

Required Climb to 400: $400-(250-76.515)=226.515$

Distance required to regain 400: $\frac{226.515}{200}6{,}076.11548=6{,}881.656$

Total length of section 1: $6{,}881.656+1{,}460=8{,}341.656$

Start of Section 2 from GPI: $\frac{(50-12)}{tan(3)\times 0.3048}+\frac{50}{tan(3)}+200=3532.939$

Start of Section 3 from GPI: $\frac{\left(\frac{250-50}{tan(3)}\times 34\right)-(200\times 23.4)}{34-23.4}+\frac{50}{tan(3)}=12{,}753.277$

Elevation of OCS at DA re: ASBL: $\frac{4{,}770.284\text{-}3{,}532.94}{27}=45.827$

Height re: ASBL of surface at end of section 1b if a 40:1 surface starts at DA: $45.827+\left(\frac{8{,}341.656}{40}\right)=254.368$

Slope ratio to reach 254.368 from end of section 1a: $\frac{6{,}881.656}{254.368-45.827}=32.999\approx 33$

EXECUTIVE SUMMARY

AND

VALIDATION SUMMARY

FOR

LPV OBSTACLE CLEARANCE SURFACES

EXECUTIVE SUMMARY

The WAAS system will not support an acceptable availability of precision WAAS approaches until late in this decade when several new system augmentations are brought online. In the interim, a new approach methodology has been developed called LPV that allows for approaches based on vertical alarm limits greater than 12 meters but less than or equal to 50 meters with the same 40-meter horizontal limit. WAAS LPV procedures can be supported to Decision Heights (DHs) as low as 250 feet with the increased VAL. Approach construction criteria for LPV approaches have been developed in FAA Order 8260.50, Wide Area Augmentation System (WAAS) LPV Approach Procedure Construction Criteria.

This report summarizes data collected from flight testing and computer simulations, and analysis of that data that supports and validates the proposed obstacle clearance areas described in Order 8260.50. This is done via two approaches - detailed statistical analysis of flight test data collected at the Federal Aviation Administration William J. Hughes Flight Technical Center (FAATC) in Atlantic City, New Jersey, the University of Oklahoma's Westheimer Field in Norman, Oklahoma, and a computer simulation using high fidelity models of aircraft in Categories A through D. These studies provide sufficient validation of the proposed LPV surfaces.

The detailed statistical analysis is performed in a separate technical paper, DOT-FAA-AFS-420-91, "Analysis of LPV Approach Flight Test Data for Categories A, B, and C Aircraft." The computer simulation is covered in detail in DOT-FAA-AFS-420-9x, "Computer Simulation of WAAS Approaches for Categories A, B, C, and D Aircraft." The results of the two technical reports are summarized here.

WAAS precision approach flight tests were conducted at the FAATC in Atlantic City, New Jersey, with a Category C aircraft, and at the University of Oklahoma, Westheimer Airport in Norman, Oklahoma, for Categories A and B. A statistical analysis of the flight test data was conducted. While the test sample size did not allow any conclusions about 10^{-7} obstacle protection surface containment, neither did it reveal any problems. The analysis found that navigation system errors appear to be independent of along-track position for each aircraft type, as expected in a satellite based navigation system. There was no detectable correlation between horizontal and vertical navigation system errors.

Computer simulations of aircraft in Categories A through D executing a precision approach using WAAS navigation were developed. The simulation uses the Flight Technical Error (FTE) data generated from the statistical analysis to drive the pilot models for the various aircraft models. The simulated aircraft were then exposed to significant turbulence and wind effects and the pilot models guided the high fidelity aircraft models, which reflect the physical properties and responsiveness of the actual aircraft. The computer simulation, using a number of conservative assumptions, nonetheless generated probabilities of exiting the protected areas of less than 10^{-7} in both the lateral and vertical. These two studies provide strong support and validation for the LPV obstacle clearance surfaces as defined in the Order 8260.50.

VALIDATION SUMMARY FOR LPV OBSTACLE CLEARANCE SURFACES

1.0 INTRODUCTION.

The Wide Area Augmentation System (WAAS) is a major step in the evolution of aeronautical satellite navigation. Order 8260.48, Area Navigation (RNAV) Approach Construction Criteria, introduced WAAS precision approach construction criteria based on a Vertical Alarm Limit (VAL) value of 12 meters and a Horizontal Alarm Limit (HAL) of 40 meters. WAAS receivers do a continuous calculation of the Vertical Protection Limit (VPL) and Horizontal Protection Limit (HPL) which is a measure of the current position solution integrity. The VPL and HPL calculations are based on satellite geometry, ionospheric and tropospheric delays, correction residuals, and airborne receiver errors. If the VPL (HPL) exceeds the VAL (HAL) required for the operation, then the approach is not authorized. After the VPL algorithms were fully developed, it became apparent that the availability of a WAAS precision approach service would be severely limited because the VAL could not be achieved a significant portion of the time at a large percentage of the Nation's airports. The WAAS system will not support high availability of precision WAAS approaches until late in this decade when several new system augmentations are brought online.

In the interim, a new approach methodology has been developed called LPV that allows for approaches based on vertical alarm limits greater than 12 meters but less than or equal to 50 meters with the same 40-meter horizontal limit. WAAS LPV procedures can be supported to Decision Heights (DHs) as low as 250 feet with the increased VAL. Approach construction criteria for LPV approaches have been developed in FAA Order 8260.50, Wide Area Augmentation System (WAAS) LPV Approach Procedure Construction Criteria.

This report will summarize data collected from flight testing and computer simulations, and analysis of that data that supports and validates the proposed obstacle clearance areas described in Order 8260.LPV. This is done via two approaches - a detailed statistical analysis of flight test data collected at the William J. Hughes Federal Aviation Administration Flight Technical Center (FAATC) in Atlantic City, New Jersey, and the University of Oklahoma's Westheimer Field in Norman, Oklahoma, and a computer simulation using high fidelity models of aircraft in Categories A through D. These studies provide sufficient validation of the proposed LPV surfaces.

The detailed statistical analysis is performed in a separate technical paper, DOT-FAA-AFS-420-91, "Analysis of LPV Approach Flight Test Data for Categories A, B, and C Aircraft." The computer simulation is covered in detail in DOT-FAA-AFS-420-9x, Computer Simulation of WAAS Approaches for Categories A, B, C, and D Aircraft. The results of the two technical reports are summarized here.

2.0 ANALYSIS PROCEDURE.

In both the analysis work and the simulation exercise, the variable of interest is the Flight Technical Error (FTE) or pilot induced error in the aircraft track. This error will then be statistically combined with the navigation system error (NSE) allowed under the worst case VAL or HAL and compared to the protection offered by the LPV obstacle clearance surfaces. A successful result will show that even for an FTE value that has a likelihood of less than 10^{-7} and a navigation system error of similar probability, the aircraft is still contained in the obstacle clearance areas for the duration of the approach.

A further indicator of the extremely conservative nature of this evaluation is seen in the comparison of the predicted worst-case NSE (based on the VPL/HPL calculation) versus the observed NSE, which is determined by differencing the onboard WAAS position solution with a post-processed truth system calculation. Actual NSE very rarely exceeds 3 or 4 meters, whereas VPL values are consistently in the mid-teens to low twenties and frequently higher. Because of ground station geometry considerations and delays in providing data on "rising" satellites, the VPL/HPL values tend to be significantly worse on the East coast than in the central United States. West coast facilities should experience values somewhere in between as they have the same ground station geometry problems as the East coast but don't have to deal with new satellites coming over the horizon with no data available.

While NSE’s approaching the VPL/HPL predictions are not generally observed, it is assumed that if such large errors ever did occur, they would have the same general properties as the more commonly observed deviations. The largest component is generally of a very low frequency, which translates into a bias for periods appropriate to an approach operation. Higher frequency components are present but appear to be limited in magnitude. By treating the large errors as a bias, predicting the effects upon aircraft becomes relatively straightforward. The exercise is to calculate the statistical motion of the aircraft due solely to the pilot (flight technical error) and then add in the worst-case VPL/HPL predicted navigation system error (50 meters in the vertical case, 40 meters in the lateral).

The critical step is determining a probability distribution function for the flight technical error that will be reasonable at the 10^{-7} level and beyond to some degree of confidence. FTE has been shown to be non-normal in a large number of tests. It generally features thicker tails than a normal distribution and some skewness in the vertical. The significance of these variations from normality is small near the glidepath but can be substantial at the extreme values we are interested in protecting.

2.1 Statistical Analysis of LPV Approach Data for Categories A, B, and C Aircraft.

The Total System Error (TSE), Flight Technical Error (FTE), and Navigation System Error (NSE) for category A, B, and C precision test approaches of aircraft by means of the Global Positioning System/Wide Area Augmentation System (GPS/WAAS) are analyzed. Category C calculations are based upon test flight data collected at the William J. Hughes FAATC in Atlantic City, New Jersey. Categories A and B results are based on data collected by the University of Oklahoma at Westheimer Airport in Norman, Oklahoma.

The TSE and FTE statistics (where TSE = NSE + FTE) are found to be nearly equal because NSE is relatively small. The test statistics are observed to be graphically similar to those predicted by the Collision Risk Model (CRM) for Instrument Landing System (ILS) approaches near (i.e. within about three standard deviations of) the glide slope. A great number more test flights would be necessary; however, in order to validate or invalidate the CRM as a flight error model far from the glidepath. Tabulated FTE statistics are presented over the approach.

Along-Track Position (m)	*Category A Components (m)*		*Category B Components (m)*		*Category C Components (m)*	
	Lateral	*Vertical*	*Lateral*	*Vertical*	*Lateral*	*Vertical*
7800	19	-5	15	0	46	6
4200	8	0	23	-5	20	6
1200	4	10	17	5	4	5

Mean Values for Lateral and Vertical Components of Total System Error

Along-Track Position (m)	*Category A Components (m)*		*Category B Components (m)*		*Category C Components (m)*	
	Lateral	*Vertical*	*Lateral*	*Vertical*	*Lateral*	*Vertical*
7800	82	27	44	26	55	14
4200	53	10	34	17	36	9
1200	25	7	21	6	9	5

Standard Deviations in Lateral and Vertical Components of Total System Error

Navigation system errors appear to be independent of along-track position in each set of tests (as expected), and are slightly different for each category of aircraft. These differences are not significant for the validation exercise.

Location	*Mean Cross-Track NSE (m)*	*Std. Dev. Cross-Track NSE (m)*	*Mean Vertical NSE (m)*	*Std. Dev. Vertical NSE (m)*
Atlantic City, NJ	-.7	1.2	.4	1.7
Norman, OK (Cat. B)	-.1	.8	.5	1.0
Norman, OK (Cat. A)	-.1	1.0	-.7	1.9

Navigation System Error Mean and Standard Deviation Values

The Atlantic City NSE is tested and found to contain short- and long-term components. Short-term NSE statistics (computed from approaches performed within a single flight of approximately two and a half hours) and long-term NSE statistics (computed from the flight various averages of flights that contain five or more approaches) are presented in tables and graphs. It is observed that the root-sum-squares of short- and long-term NSE component standard deviations approximately match the overall Atlantic City component standard deviations.

Short-Term Standard Deviation (m)		*Long-Term Standard Deviation (m)*	
Lateral	*Vertical*	*Lateral*	*Vertical*
.6	1.1	1.0	1.2

Atlantic City Navigation System Error Short- and Long-Term Standard Deviations

No correlation is evident between the vertical and lateral component errors, for any of the three error types.

Flight Technical Error was evaluated along the approach from the Final Approach Fix five nautical miles from the runway threshold to a 200-foot DH point approximately 870 meters from threshold. The statistics at 500-meter intervals are shown below for the three aircraft categories with extra points included for the three ranges commonly used for comparison to the International Civil Aviation Organization (ICAO) Collision Risk Model data (1,200, 4,200, and 7,800 meters)

Range Along-Track (m)	*Mean FTE Cross-Track (m)*	*Std. Dev. FTE Cross-Track (m)*	*Mean FTE Vertical (m)*	*Std. Dev. FTE Vertical (m)*
8000	15.90	87.60	-5.18	30.38
7800	18.81	82.10	-4.54	28.07
7500	19.78	73.50	-3.42	26.01
7000	15.44	61.43	-4.24	22.40
6500	8.93	61.26	-4.51	19.27
6000	8.58	50.24	-3.66	18.24
5500	14.03	54.82	-3.30	15.94
5000	14.65	58.83	-3.06	12.47
4500	11.88	56.38	-0.48	12.05
4200	8.30	53.77	0.41	10.17
4000	4.88	49.31	1.09	9.97
3500	2.05	41.43	3.05	10.83
3000	-2.09	34.81	4.38	8.78
2500	-1.06	38.20	5.81	7.46
2000	0.50	39.94	7.14	6.55
1500	3.18	31.84	8.49	5.60
1200	4.37	25.58	10.87	4.79
1000	5.45	25.40	10.59	5.56
870	5.72	26.11	10.18	5.50

CATEGORY A FLIGHT TECHNICAL ERROR STATISTICS
FOR GPS/WAAS TEST APPROACHES

Range Along-Track (m)	*Mean FTE Cross-Track (m)*	*Std. Dev. FTE Cross-Track (m)*	*Mean FTE Vertical (m)*	*Std. Dev. FTE Vertical (m)*
8000	13.02	45.52	0.07	26.47
7800	15.54	43.72	-0.56	26.03
7500	15.88	38.13	-1.56	26.25
7000	15.16	34.30	-3.27	24.91
6500	13.52	35.17	-5.05	22.81
6000	13.32	31.90	-6.13	21.76
5500	13.77	32.79	-6.95	20.39
5000	18.57	36.61	-7.17	19.68
4500	21.27	35.30	-6.94	17.95
4200	23.05	34.36	-5.31	16.84
4000	22.77	34.59	-4.78	15.86
3500	19.83	41.14	-1.74	13.87
3000	19.16	41.86	-1.15	10.54
2500	22.65	37.08	-1.16	8.20
2000	24.58	32.52	2.15	5.95
1500	19.99	24.36	4.05	5.70
1200	16.73	21.09	4.68	5.95
1000	15.57	21.68	3.94	6.30
870	14.12	22.41	3.49	5.60

CATEGORY B FLIGHT TECHNICAL ERROR STATISTICS
FOR GPS/WAAS TEST APPROACHES

Range Along-Track (m)	*Mean FTE Cross-Track (m)*	*Std. Dev. FTE Cross-Track (m)*	*Mean FTE Vertical (m)*	*Std. Dev. FTE Vertical (m)*
8000	47.2	56.35	4.9	14.6
7800	46.57	55.12	5.14	13.99
7500	41	58.1	5.1	14.05
7000	38.6	52.15	5.21	14.95
6500	33.1	45.2	4.61	14.55
6000	28.9	37.15	5.81	15.45
5500	26.5	38.2	4.52	14.35
5000	23.8	38	4.12	12.2
4500	21.3	37.5	5.32	9.8
4200	21.08	35.88	5.57	8.65
4000	21	34.4	5.13	8.45
3500	19.9	30.95	6.83	7.65
3000	15.7	25.95	6.74	8.35
2500	9.5	20.3	5.44	7.35
2000	5.3	15.85	5.84	7.7
1500	5.4	10.5	5.05	5.4
1200	4.67	9.38	4.94	5.16
1000	3.7	8.85	4.55	5.15
872	3.4	8.1	4.24	5.05

CATEGORY C FLIGHT TECHNICAL ERROR STATISTICS
FOR GPS/WAAS TEST APPROACHES

While the data presented is insufficient to calculate statistically significant limits for containment, it provides important input for the development of the pilot models in the computer simulation and does not provide any indication of problems with the proposed surfaces.

2.2 Computer Simulation of Categories A through D LPV Approaches.

Computer simulations of aircraft in Categories A through D executing a precision approach using WAAS navigation were developed. The simulation uses the FTE data generated from the statistical analysis to drive the pilot models for the various aircraft models. The simulated aircraft were then exposed to significant turbulence and wind effects and the pilot models guided the high fidelity aircraft models, which reflect the physical properties and responsiveness of the actual aircraft. While navigation system error is factored out of the resultant analysis, the pilot responses to navigation errors typical of WAAS receivers is left as part of the flight technical error, i.e. the higher frequency components of the WAAS signal are not neglected.

The size of the aircraft is factored into the calculation via offsets to the obstacle clearance areas. For Categories C and D, a 6-meter vertical offset is included to reflect the distance from the "antenna" to the lowest part of the airframe as it descends on the glide slope. The "antenna" location here has no necessary relation to the position of the GPS antenna on the aircraft but is adjustable to represent the offset to the normal position of an ILS antenna. A 3-meter vertical offset was used for Categories A and B. The lateral offsets were 30 meters for C and D and 10 meters for A and B.

Aircraft models were selected that were considered representative of the desired category. The selections are shown in the table below.

Category	Aircraft
A	Cessna C-172
B	Beechcraft B99
C	Boeing 727-200
D	Boeing 747-100

AIRCRAFT FLIGHT DYNAMICS MODELS.

Two types of 6-degree freedom flight dynamics models were utilized in the simulation. Linear models using stability and control derivatives from the classic, well-accepted aircraft design textbook "Airplane Design Part VI" by Roskam, were used to simulate the flight dynamics of the smaller aircraft, the Beechcraft B99 and the Cessna C-172. The larger aircraft (Boeing B727-200 and B747-100) flight dynamics models use full non-linear aerodynamic data tables obtained from the manufacturer. The 747 model has been matched against the Boeing Aircraft Company's engineering simulation and accepted by Boeing as equivalent. The 727 model has been matched against the FAA's 727 simulator.

PILOT MODEL

The aircraft models are "piloted" by a pilot model. The pilot model consists of two control loops, one for lateral guidance and one for vertical. These control loops are governed by control laws that command pilot flight control inputs based upon tracking error (proportional control loop) and tracking error rate (rate control loop). For the purposes of this simulation, a combination of no integrators in conjunction with "dead zones" has been used to model the effects of lateral and vertical residual errors and biases typical of hand flown aircraft. (A "dead zone" is a region around the course centerline in which the pilot model will not attempt to make any course corrections.) Figure 1 describes the block diagram of the localizer tracking control law. The distance from threshold is a necessary input to schedule all of the gains in both axes (cross track and altitude control).

The control laws were tailored for this simulation to reflect the observed Flight Technical Error shown during the flight tests for the various aircraft categories. In the absence of any Category D flight test data, Category C data was used for the Category D pilot model. The tailoring consisted primarily of scaling the dead zones to match the "central" part of the FTE distributions observed during the flight tests - approximately the 95% values, or 2 standard deviations, with no turbulence active in the model. Since the flight tests were conducted in conditions that frequently included mild turbulence, this should be another conservative factor.

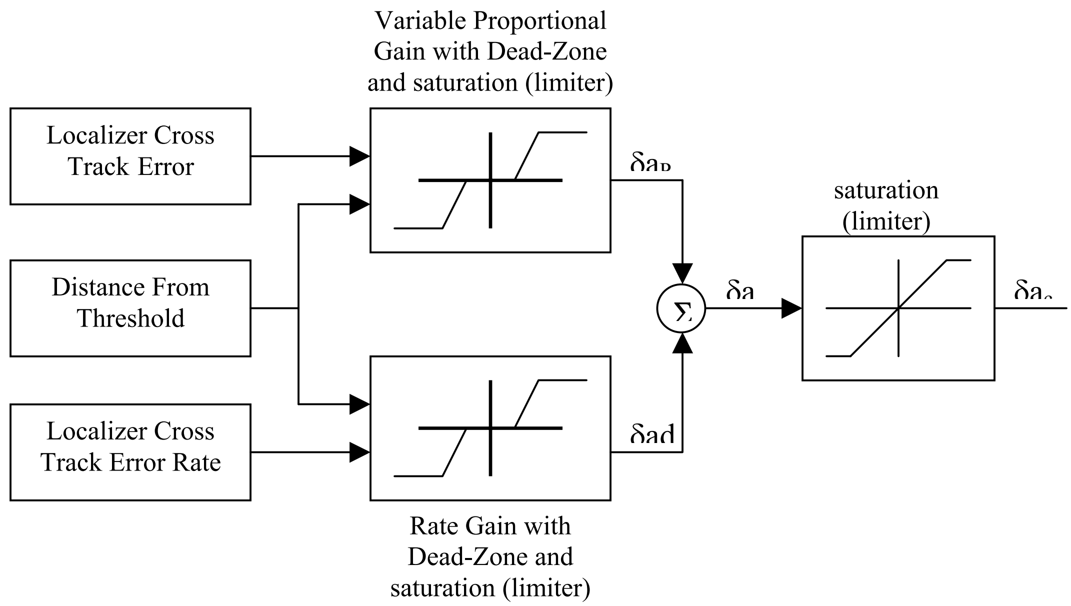


Figure 1. Pilot model - localizer tracking laws

Where:

δa_P: Proportional aileron deflection
δa_d: Rate (derivative) aileron deflection
δa: $\delta a_P + \delta a_d$ prior to final limiter.
δa_c: Commanded aileron deflection.

TURBULENCE/WIND MODELS.

A wide spectrum turbulence model inducing wind velocities in all three aircraft body axes was used. The critical parameters that were varied consisted of gust amplitude, gust period and the interval between gusts. By selecting a relatively wide range of variation for the last two parameters (gust period and between gusts interval) the model was applied using a wide range of mixing lengths. This allowed the model to be used in all aircraft categories without customizing it to a specific combination of aircraft dimensions and air speed. Directional magnitudes were varied between aircraft categories, with mild to moderate turbulence applied to the smaller airframes and moderate to severe turbulence applied to the larger ones.

The mean of each one of the turbulence components was zero (no constant wind was applied within the turbulence model). Wind was incorporated as a separate component with variations in magnitude and velocity based on altitude. Shear was not specifically incorporated but the longer period turbulence models will produce shear-like effects.

SIMULATION.

The model was run from 10,000 to 100,000 times for each aircraft category at a variety of wind and turbulence settings. (This is after a large number of runs were done to tune the pilot models to reflect the FTE observed during the flight testing.)

Tracks were initialized at along track ranges such that the aircraft model was guaranteed to be stabilized before entering the window of interest. The window of interest is the track from the minimum DH point for the operation under study (250 feet above threshold or about 1,163 meters along track from threshold) to the point where the LPV surface becomes equivalent to the Baro-VNAV surface (at 800 feet above threshold or about 4,362 meters along track). The along track range of the initial position was uniformly distributed from 7,000 to 11,000 meters. The large range assured that there would not be any fixed position nodal points driven by the aircraft's longitudinal dynamics (phugoid) or directional/lateral dynamics (dutch roll).

The initial lateral and vertical positions were extrapolated from the flight test data and were somewhat larger than the ICAO Collision Risk Model distributions. This was done in order to increase the likelihood of requiring the pilot model to take some action and generally ensured that there were some pilot induced dynamics coming down the approach path. Track heading was also initialized within the range of +/- 5 degrees which further excited the pilot actions based on both.

Initial Indicated Air Speed (IAS) was fixed per category according to the following table.

Category	IAS (knots)
A	85
B	110
C	145
D	165

The aircraft was released and subjected to the effects of turbulence and wind and the minor perturbations in guidance from WAAS data and the flight dynamics of the airframe as it responded to the pilot commands. The navigation guidance was based on recorded WAAS data that was considered typical. As mentioned earlier, the navigation system error was removed from the analysis but the pilot latencies and responses to it are valid parts of the flight technical error.

Aircraft state information was recorded at particular locations along the track corresponding to heights above threshold of 800, 700, 600, 500, 400, 300, and 250 feet. This information includes the lateral and vertical deviation from the desired track, the lateral and vertical components of the NSE, and the lateral and vertical FTE.

ANALYSIS.

The purpose of the simulation exercise was to show that, to a high degree of confidence, the tracks generated have less than one chance in ten million (10^{-7}) of penetrating the obstacle clearance areas defined in the LPV order during the course of an approach. While the simulation runs at many times real-time, it is still not practical to perform enough runs to statistically validate a 10^{-7} number so a certain amount of extrapolation is necessary. As mentioned earlier, sample sizes for the various simulations ranged from 10,000 to 100,000 runs.

If the data were normally distributed, the analysis exercise would be rather straightforward. Normal distributions are well understood and determining a standard deviation to a desired confidence level is a known process. However, aviation track data has historically tended to have thicker tails than a standard Gaussian distribution and some skewness in the vertical and the flight test data collected for WAAS approaches show the same tendencies. Spearman-rho tests were performed on a number of the FTE distributions and the hypothesis that the distribution was normal could not be accepted, but in most cases, the differences were quite small.

Various mechanisms have been developed to account for the non-normalcy. One method that has been frequently used with some success involves fitting a Johnson distribution to the observed data. Johnson distributions are a family of functions that can be mapped to normal distributions and therefore allow application of many of the techniques associated with handling normal data. The ICAO Collision Risk Model uses Johnson distributions for determining the risk values in the missed approach segment. This method has been used in several GPS associated criteria evaluations.

Conceptually, the analysis should determine a probability distribution function (pdf) for each of a series of vertical planes along the approach path. These pdf's calculate the probability of being a certain distance from the desired track, both laterally (cross-track) and vertically. The spacing of these planes should be sufficient to assure independence of the pdf for each plane. The pdf can then be evaluated at the appropriate obstacle clearance surface, i.e. determine the probability of the aircraft being as far away from the desired track as the surface. The sum of the probabilities is then the risk value for the approach.

Historical data from the ILS Collision Risk Model development and the MLS testing that was done in the 1980's have indicated that a spacing between planes of approximately 100 meters was sufficient to assure independence. For a 5-mile final to a 250-foot decision height with a 3-degree glide slope (the standard conditions that were used in all the simulations), this translates to 82 planes or "tiles", starting at 9,260 meters from threshold and ending at 1,160 meters from threshold. One of the assumptions going into the development of the LPV criteria was that the baro/VNAV surface that accommodates VAL values greater than 50 meters was safe. That surface starts at approximately 4,360 meters from the threshold. The LPV 27:1 surface, therefore, includes only 33 of the 82 tiles. Because the inner 33 tiles are smaller than the outer tiles, where the lower surface has a 34:1 slope and the sides continue to expand at the same rate, the percentage of risk allocated to the inner tiles should be greater than 33/82nd's, probably significantly greater. The highest risk portion of the approach should be the last few tiles where the obstacle clearance surfaces are closest to the desired track. So long as the total risk is less than 10^{-7}, the approach is acceptable.

Johnson distributions were developed for the flight technical error distributions generated by the simulations in the lateral and vertical axes at each of the seven locations defined in the previous section (HATs of 250, 300,…, 800 feet). The Johnson functions were used to generate the 10^{-7} distances at each plane in both directions. Values for tiles in between the seven points were interpolated. The resultant 10^{-7} FTE value was root-sum-squared with the worst case VAL or HAL (50 meters or 40 meters).

According to the central limit theorem, convolving enough non-normal distributions will eventually produce a normal distribution. As we are assuming that the alarm limits are from a normal distribution, the root-sum-square of the alarm limit with the FTE distribution should be even closer to the normal than the original FTE. It should be a reasonably good approximation to treat the 10^{-7} TSE (total system error) point as 5.327 standard deviations and then determine the ratio of that value to the available distance between the desired track and the obstacle clearance surface. Applying the inverse normal transformation to that value will give an estimate of the probability of being at the obstacle clearance surface. Summing these values over the 33 tiles gives the total probability of exiting the LPV containment surface between the decision height and the start of the baro/VNAV like surface. A typical set of results is summarized below.

Category	Lateral Risk Figure – W Surface	Lateral Risk Figure – X Surface	Vertical Risk Figure
A	2.4E-08	<10E-15	4.95E-08
B	3.26E-07	<10E-15	6.78E-08
C	6.3E-06	<10E-15	4.31E-09
D	4.7E-08	<10E-15	7.65E-08

The categories B through D vertical risks were calculated against a 55-foot threshold crossing height (TCH) and the category A against a 50-foot TCH. As mentioned earlier, a 6-meter offset was included in the vertical calculation for categories C and D aircraft and a 3-meter offset for the A and B aircraft. The risk figures for categories A, B, and D all represent more than 33/82nd's of the allowable risk but considering the likely risk contribution of the outer surface, this is not expected to be a problem. The Technical Report will evaluate the total risk including the outer surface and will also examine complete iso-probability contours for the various tiles. Adding a foot or two to the threshold crossing height will resolve the problem.

The A and D aircraft were contained within the W surface but all four were too far inside the X surface. The A and B aircraft used 10 meter semi-spans and the C and D, 30 meter. Turbulence levels were set to moderate to severe levels for categories C and D aircraft and mild to moderate for the A and B. The A turbulence was less than the B setting which may explain the differences in the lateral risk. The lighter and less responsive 727 airframe was apparently moved around significantly more by the severe turbulence than the 747. In any case the lateral protection is clearly adequate.

3.0 CONCLUSION.

A detailed statistical analysis of flight test data was conducted. While the test sample size did not allow any conclusions about 10^{-7} obstacle protection surface containment, neither did it show any problems. The computer simulation, using a number of conservative assumptions, nonetheless generated probabilities of exiting the protected areas of less than 10^{-7} in both the lateral and vertical. These two studies provide strong support and validation for the LPV obstacle clearance surfaces as defined in the Order 8260.50.

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Please submit any written comments or recommendations for improving this directive, or suggest new items or subjects to be added to it. Also, if you find an error, please tell us about it.

Subject: Order 8260.50, United States Standard for Wide Area Augmentation (WAAS) LPV Approach Procedure Construction Criteria

To: DOT/FAA
Flight Procedure Standards Branch, AFS-420
P.O. Box 25082
Oklahoma City, OK 73125

(Please check all appropriate line items)

☐ An error (procedural or typographical) has been noted in paragraph _______ on page ______.

☐ Recommend paragraph ______ on page ______ be changed as follows:
(*attach separate sheet if necessary*)

☐ In a future change to this directive, please include coverage on the following subject:
(*briefly describe what you want added*):

☐ Other comments:

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