PBN Airspace Design Workshop

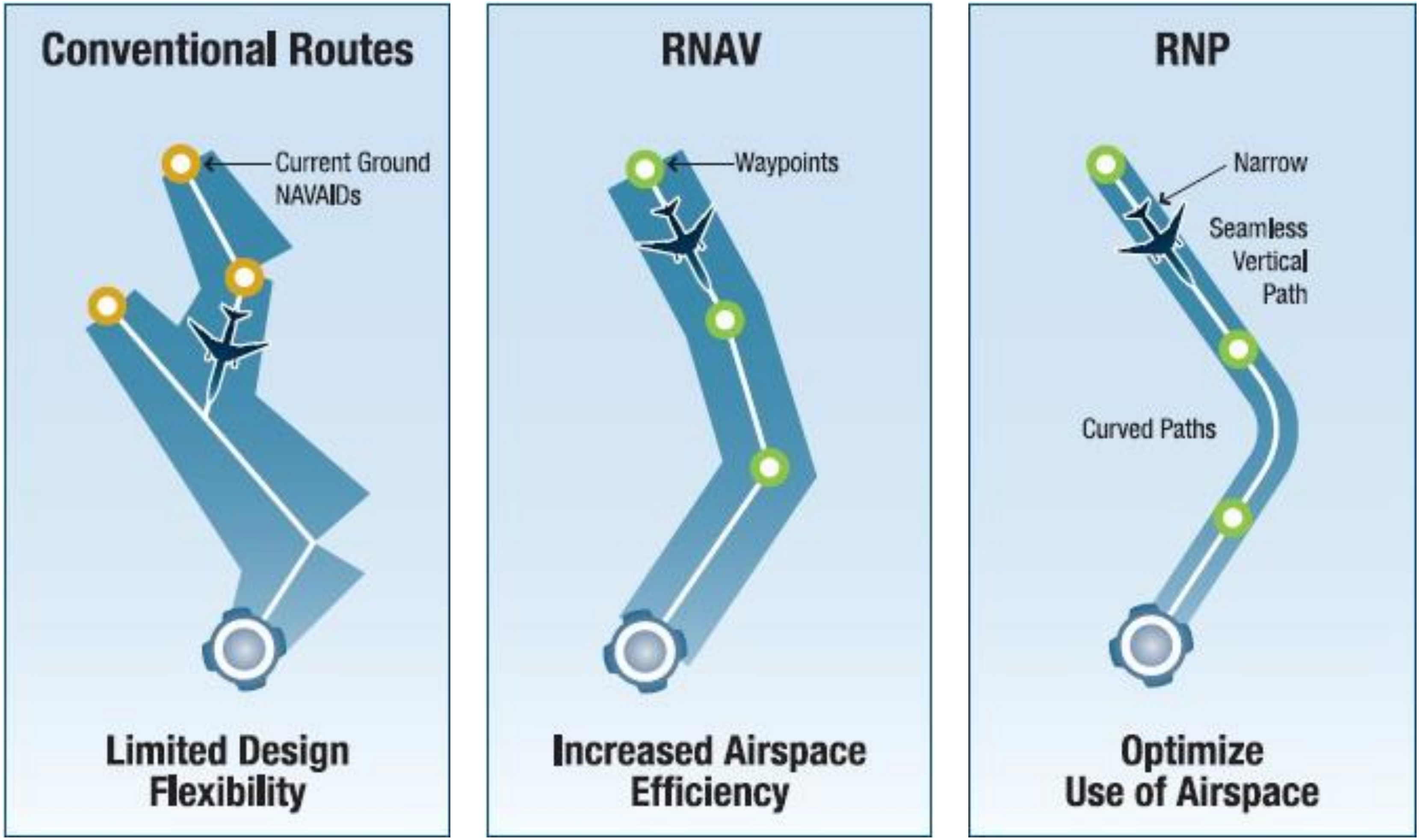
PBN Procedure Design Considerations

Asia and Pacific Regional Sub-Office
Beijing, China

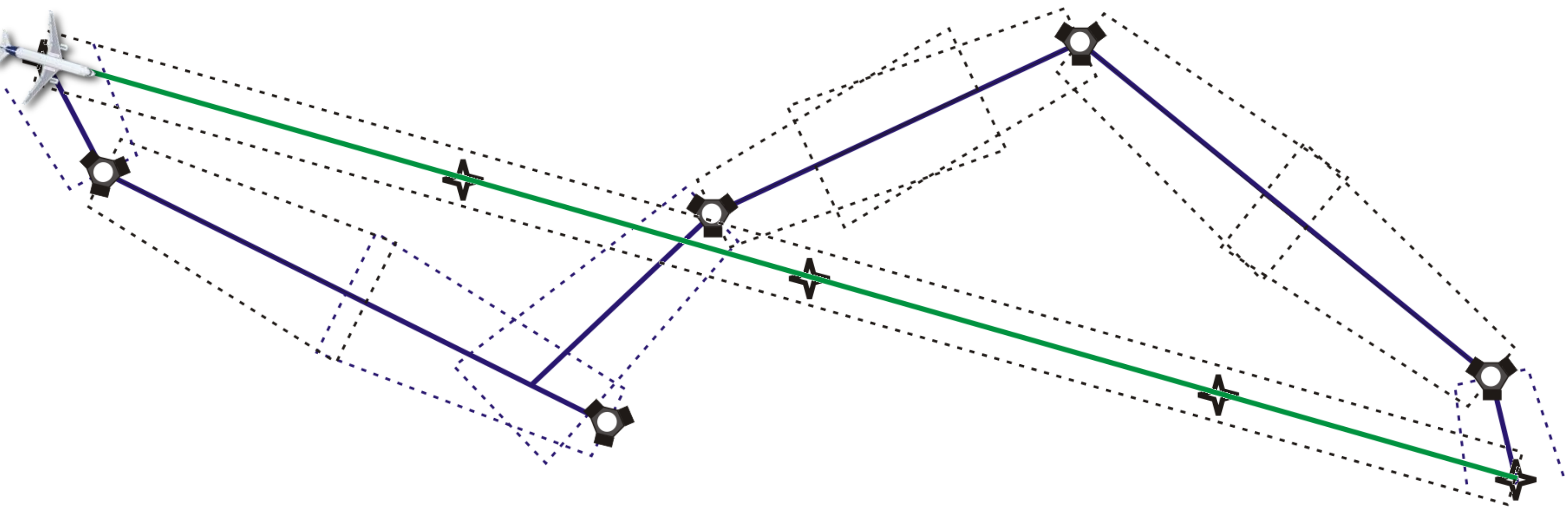
Learning Objectives

- By the end of this presentation, you will :
  - Understand procedure design considerations including:
    - Waypoint Types
    - Path Terminators
    - SIDs & STARs Design
    - Route spacing
    - Approach Procedure Design
  - Understand flight procedure validation
    - Ground Validation
    - Flight Validation
    - Flight Inspection

Why PBN?


Conventional Routes
Current Ground NAVAIDs
Limited Design Flexibility
RNAV
Waypoints
Increased Airspace Efficiency
RNP
Narrow
Seamless Vertical Path
Curved Paths
Optimize Use of Airspace

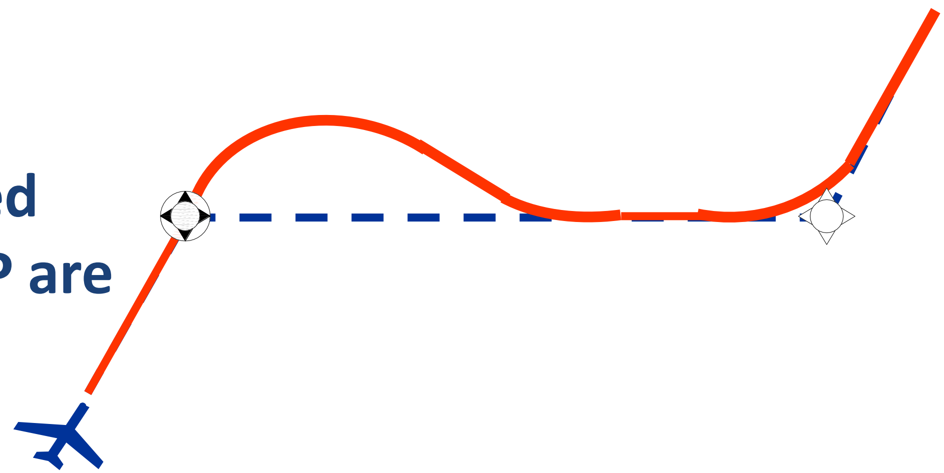
Waypoints



PBN Route Using Waypoints

Waypoints

- A specified geographical location expressed in WGS84 coordinates
- Used to define an area navigation route or flight path of an aircraft employing area navigation
- A flight path is defined by waypoints and/or by specific condition as altitude
  - Fly-over waypoint :
  - Fly-by waypoint :
- Fly-by waypoint is preferred but MAPt, MAHF and HWP are always Fly-over waypoint



Waypoints

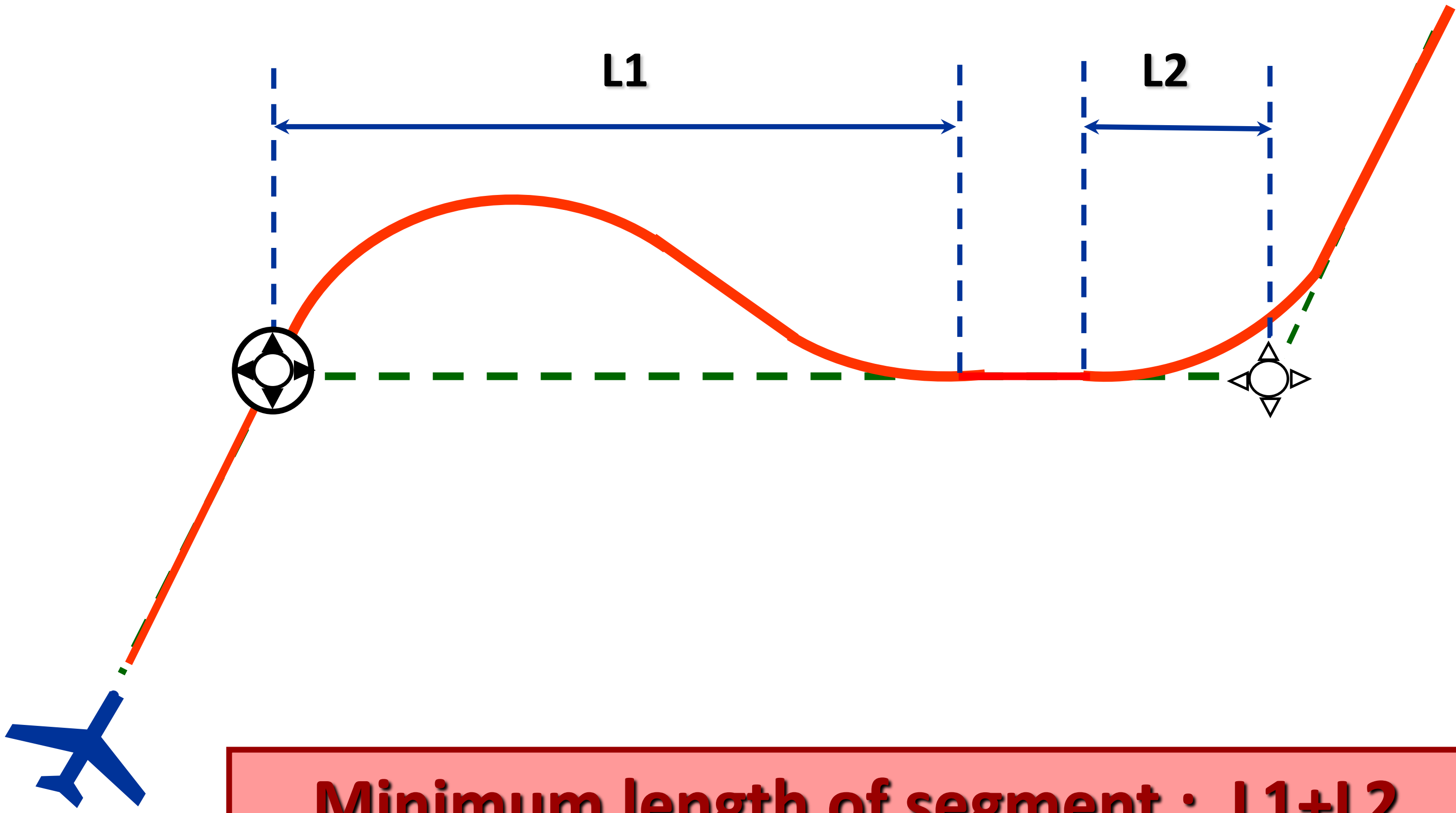
- Waypoints are defined to express
  - Function, e.g. IAF, IF, FAF, MAPT, beginning of a STAR etc.
  - Turning point
  - Speed or altitude constraint
  - Reporting point
- Number of waypoint should be limited to a minimum
  - Within a straight segment, no more than 2 additional waypoints which are fly-by waypoints.
- Navigation system has a function of "turn anticipation" to transition to the next segment upon turning at fly-by waypoint
- Turn anticipation distance prior to fly-by waypoint depends on aircraft speed, bank angle, etc.

Minimum Length

- Segment shall be long enough
  - To allow aircraft to perform turn and stabilization (Turn Stabilization Distance)
  - Where no turn is required, to achieve the constraint at the waypoint
- Minimum Stabilization Distance (MSD)
  - The minimum distance to complete a turn maneuver and after which a new maneuver can be initiated

Minimum Length

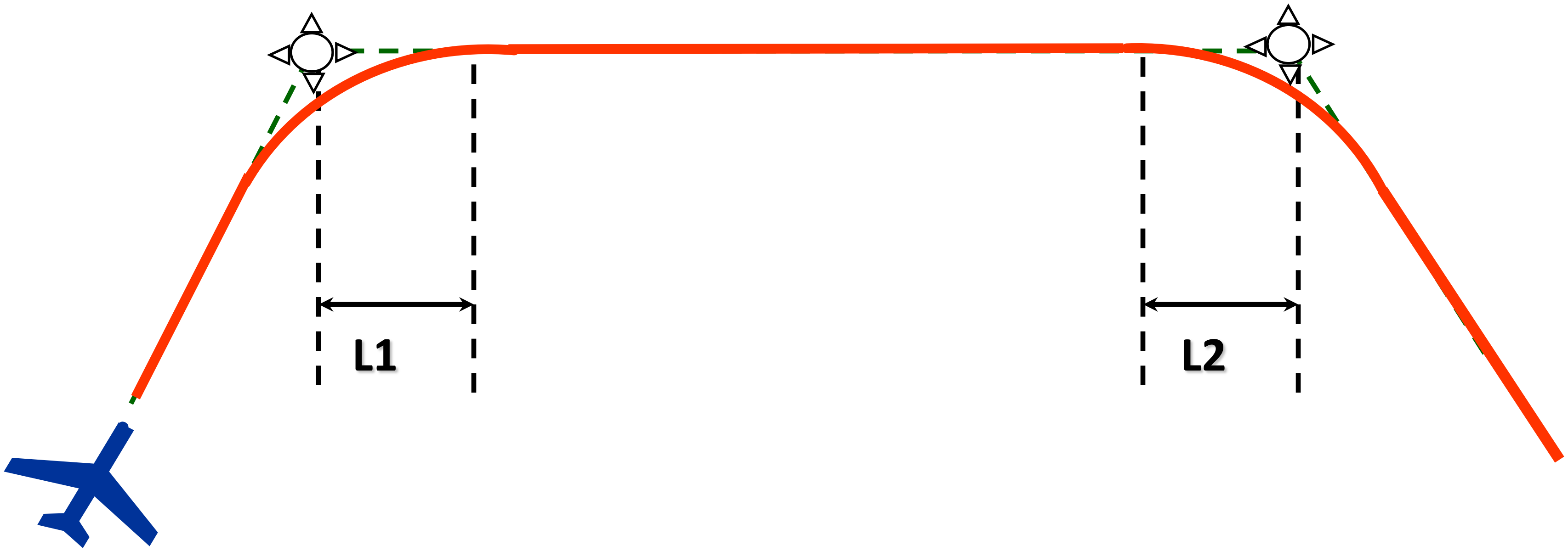
- Case 1 - Fly-over (FO) and Fly-by (FB) Combination



Minimum length of segment : L1+L2

Minimum Length

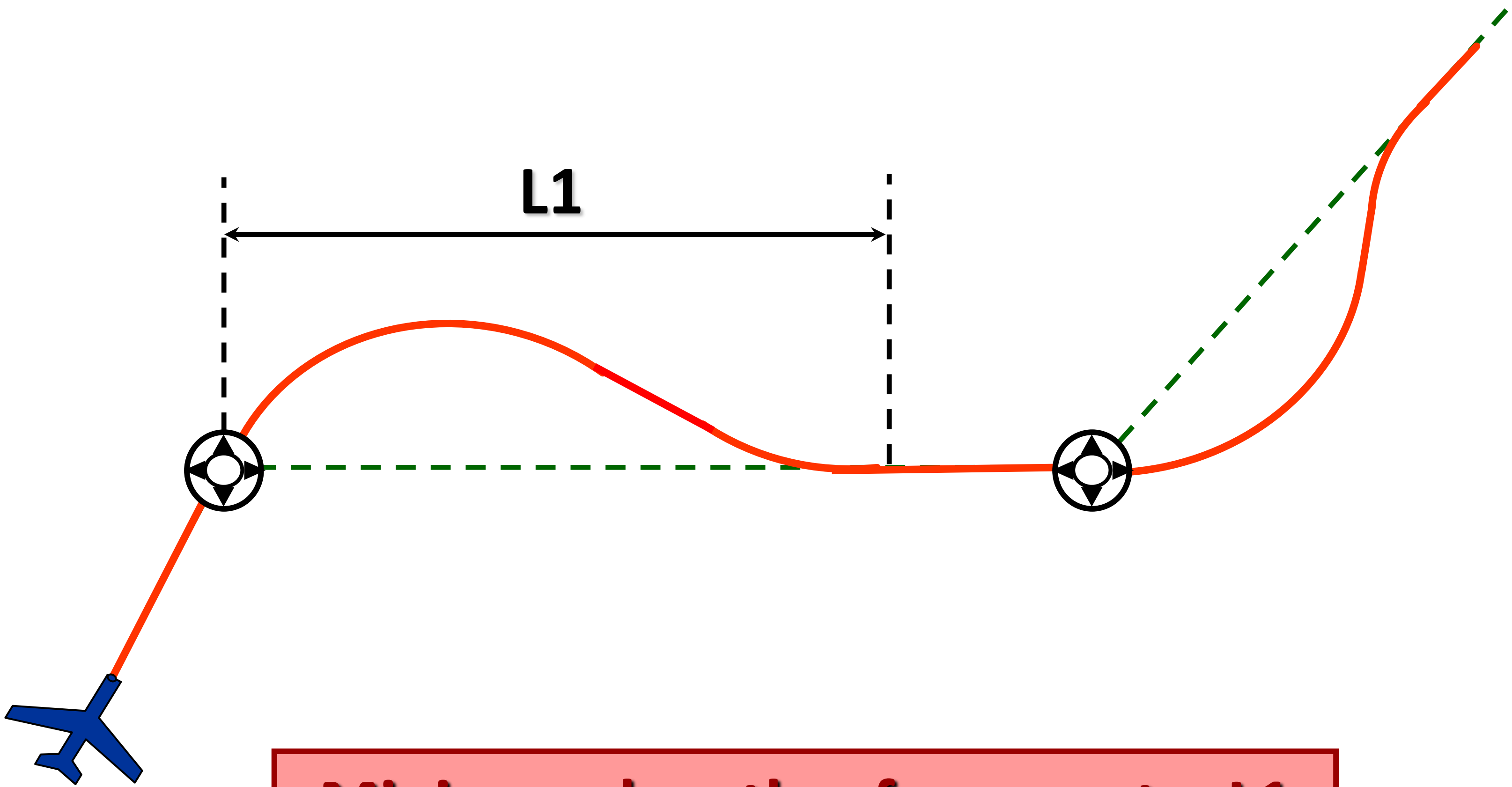
- Case 2 - Fly-by (FB) and Fly-by (FB) Combination



Minimum length of segment : L1 + L2

Minimum Length

❖ Case 3 - Fly-over (FO) and Fly-over (FO) Combination



Minimum length of segment : L1

Minimum Length

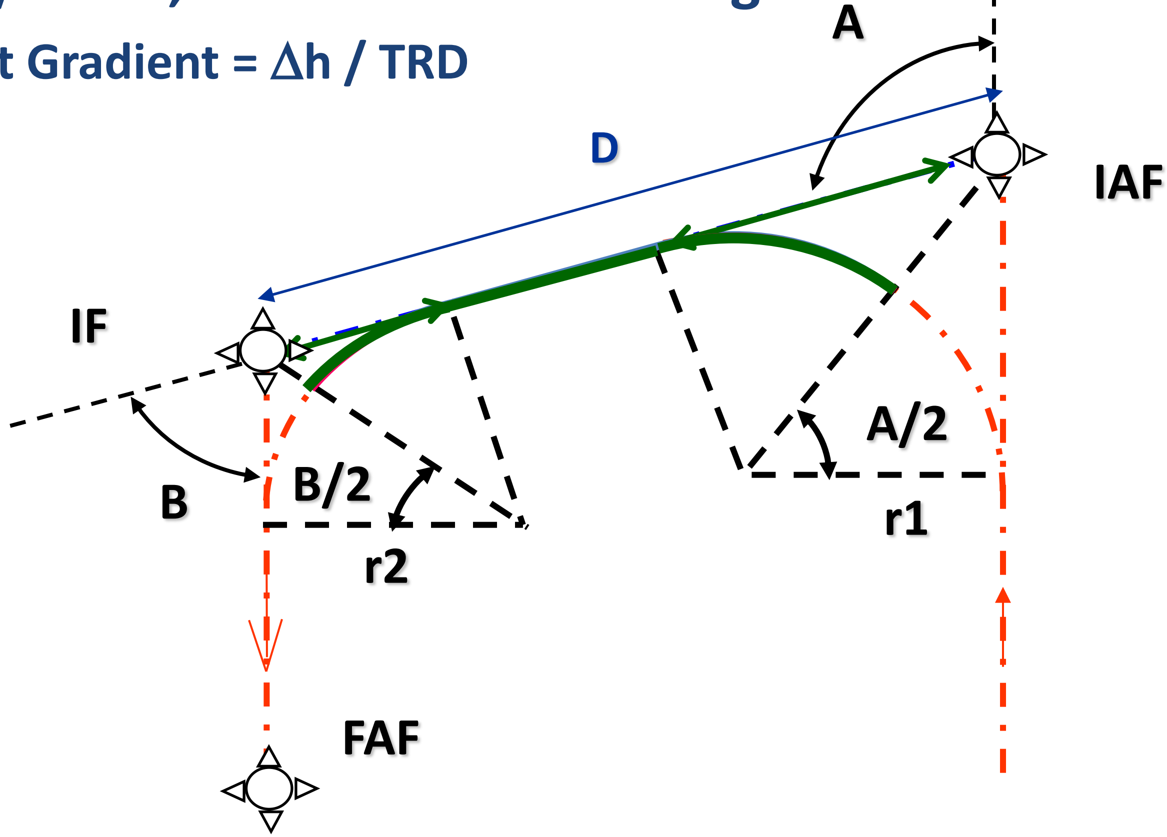
❖ Minimum length of RNAV Segment limited by at least one waypoint which is not a turning waypoint

Phase of Flight	D: Minimum distance to waypoint*
Enroute More than 30NM from departure or destination ARP	5.0 NM
STARs, Initial within 30NM of the ARP	3.0 NM
SID within 15NM ARP an d final approach	1.5 NM
Missed App and SID within 30NM of the ARP	3.0NM

* When the stabilization distance is greater than D, minimum distance is equal to the stabilization distance.

Track Resultant Distance (TRD)

- For fly-by turns, aircraft is descending ABEAM the waypoint
  - Descent Gradient = Δh / TRD



$$TRD = D - (r_1 \times \tan A/2) - (r_2 \times \tan B/2) + (r_1 \times \pi/180 \times A/2) + (r_2 \times \pi/180 \times B/2)$$

A and B are expressed in degrees

Path Terminators

- **What is Path Terminators?**
  - Transform procedures into coded flight path
  - Set of two alphabetic characters that define the flight path along the leg, and the terminator or end-point of the leg
  - Instruct to navigate from a stating point to a specific point of terminating condition
  - Only ONE Path Terminator associated with a WP, but additional constraints (altitude or speed) are possible

- **Why do we need t know about ARINC 424?**
  - Because not all systems can use all leg types
  - Operators need to understand the limitations
  - Special crew procedures may be needed
  - Fight path dependent on functionality/crew input

➡ ALL AREA NAV SYSTEMS ARE NOT EQUAL

Path Terminators

- Some Path Terminator considerations
  - TF/TF – “flyby” turn, no track guidance
  - DF – direct to fix – flight path depends on point of sequencing
  - CA Course to altitude – termination variable, manual sequencing may be required, subsequent flight path variable
  - RF radius to fix – fixed radius, limited by bank angle/groundspeed
  - VA, VM, VI, FM terminations
- A certain NavSpec requires specific path terminators, for example:
  - Advanced RNP requires RF and FRT is optional
  - RNP AR APCH requires RF
  - RNP 0.3 requires CA together with VNAV system

Path Terminators

Paths

Terminators	Fix to	Track from fix to	Course to	Heading to	Direct to	Racetrack	DME Arc to	Radius from fix
Fix	IF	TF	CF		DF	HF	AF	RF
Altitude		FA	CA	VA		HA		
Manual Termination		FM		VM		HM		
Distance		FC						
DME Distance		FD	CD	VD				
Intercept			CI	VI				
Radial			CR	VR				
Procedure Turn	PI							

Each leg type has a two letter name based on the path and terminator combination

Path-Terminator

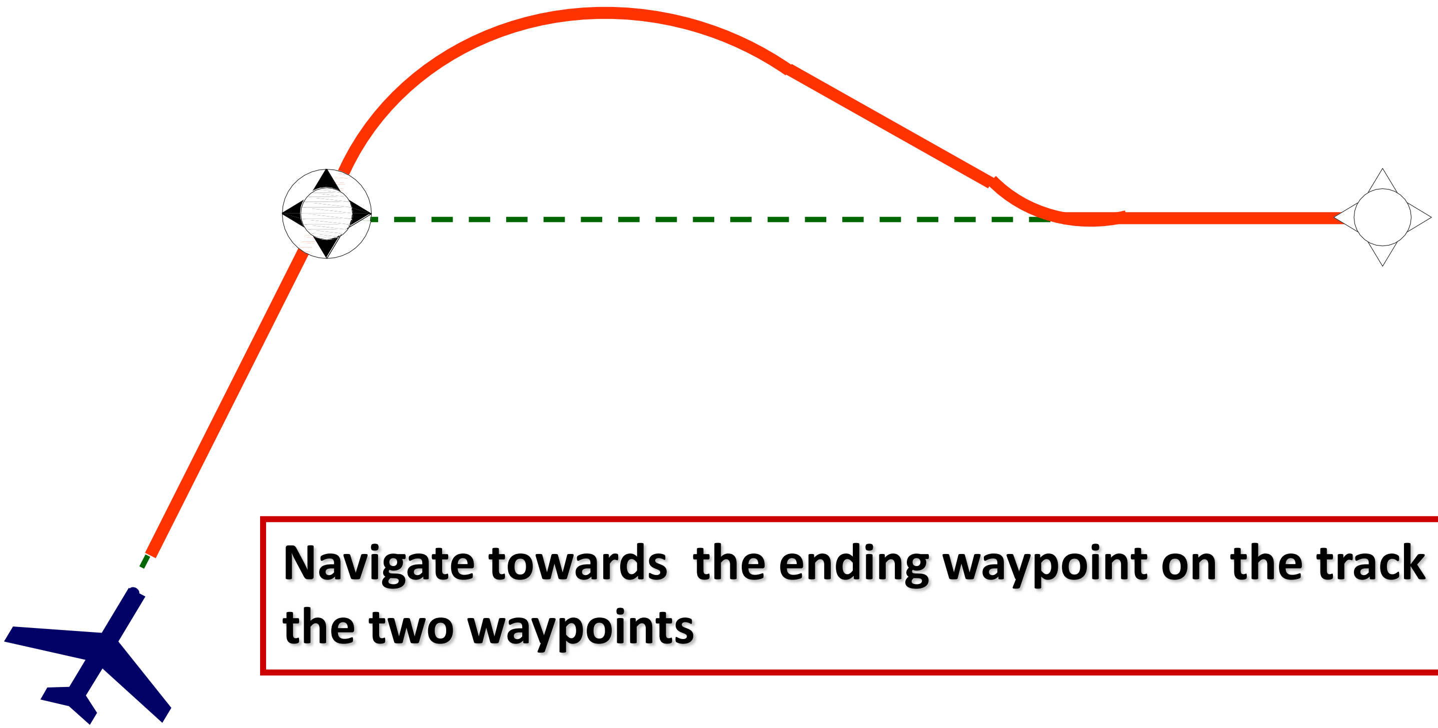
❖ ARINC 424 Path Terminator

IF	Initial Fix
TF	Track between Fixes
RF	Radius to Fix
DF	Direct to Fix
CF	Course to Fix
CA	Course to Altitude
FA	Fix to Altitude
VA	Heading to Altitude
VI	Heading to Intercept
FM	Vectors from Fix
HM	Hold for clearance
VM	Heading to Vectors

HF	Hold to Fix
HA	Hold to Altitude
PI	Procedure turn to intercept
CI	Course to intercept
CD	Course to DME Arc
CR	Course to VOR radial
FC	Course from Fix
FD	Fix to DME Arc
AF	DME Arc to Fix
VD	Heading to DME ARC
VR	Heading to VOR Radial

Path Terminators

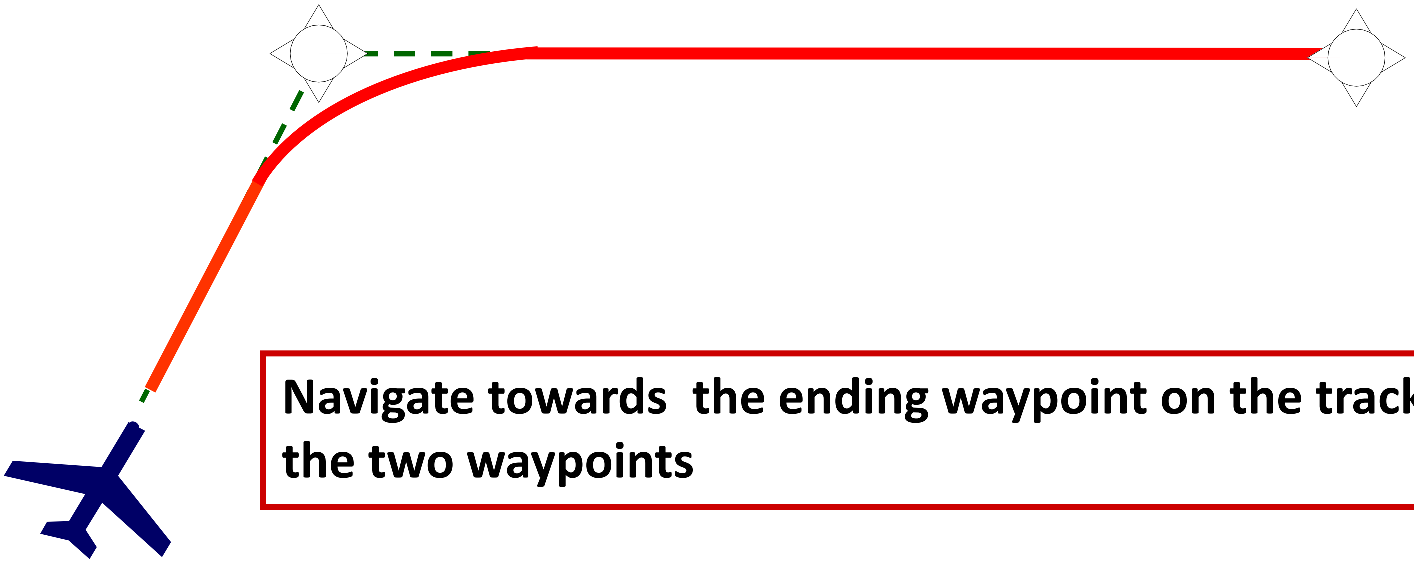
- TF : Track between Fixes (Fly-Over)



Navigate towards the ending waypoint on the track between the two waypoints

Path Terminators

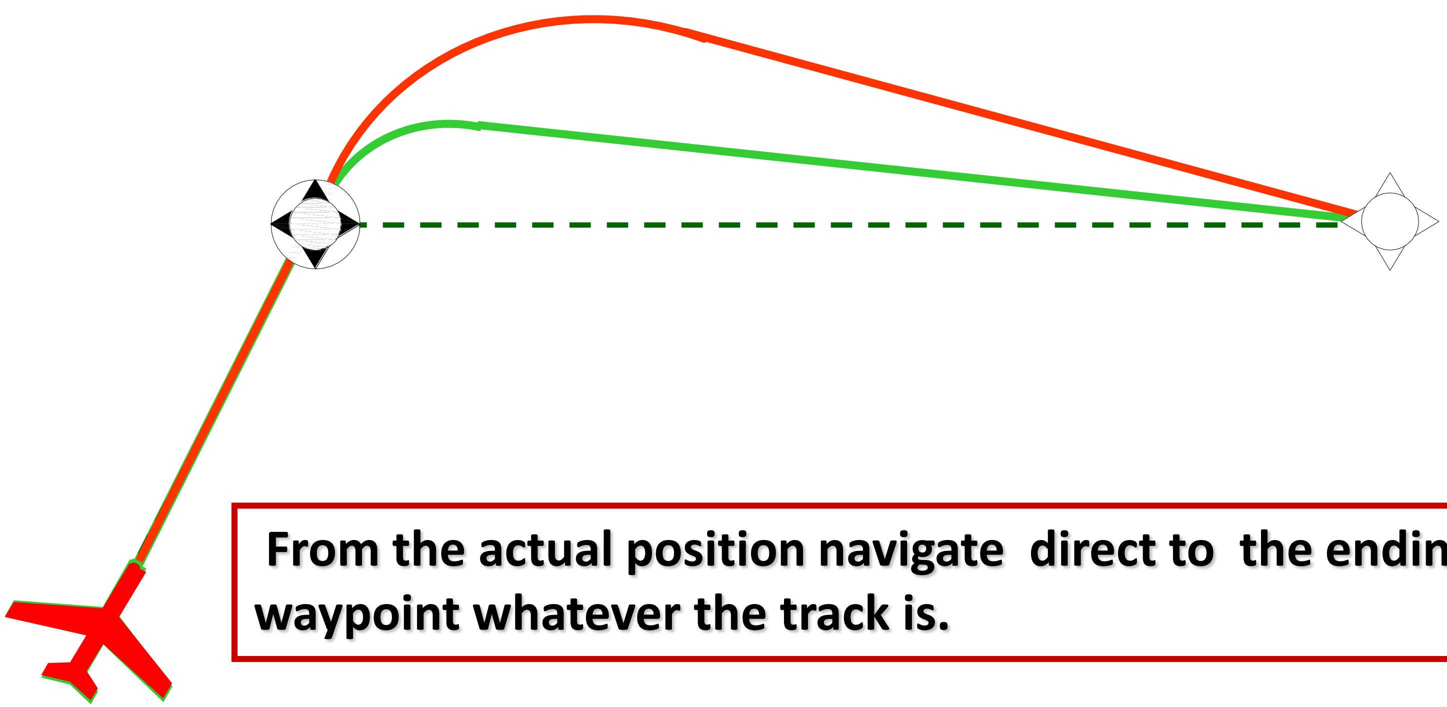
- TF : Track between Fixes (Fly-By)



Navigate towards the ending waypoint on the track between the two waypoints

Path Terminators

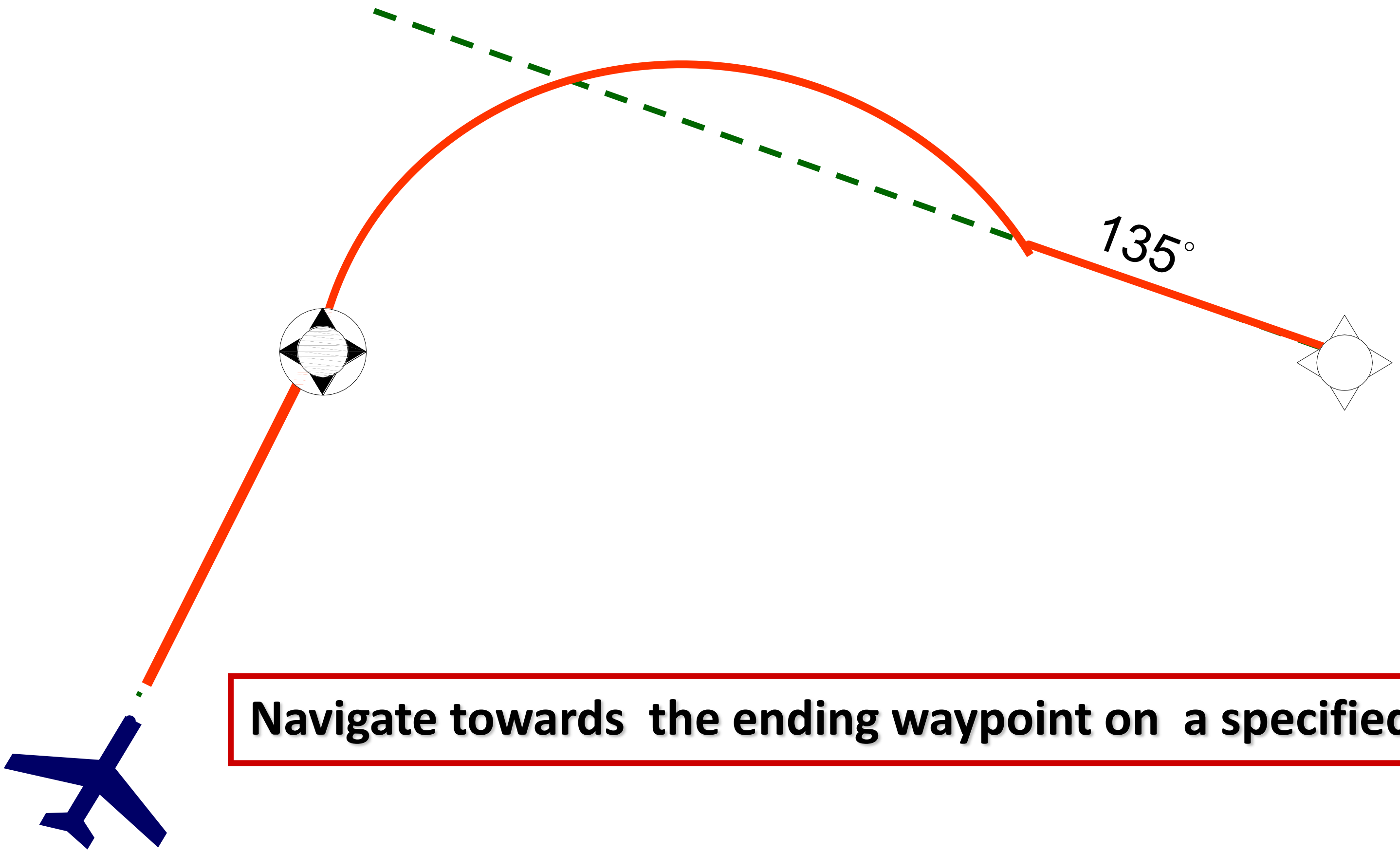
- DF : Direct to Fix



From the actual position navigate direct to the ending waypoint whatever the track is.

Path Terminators

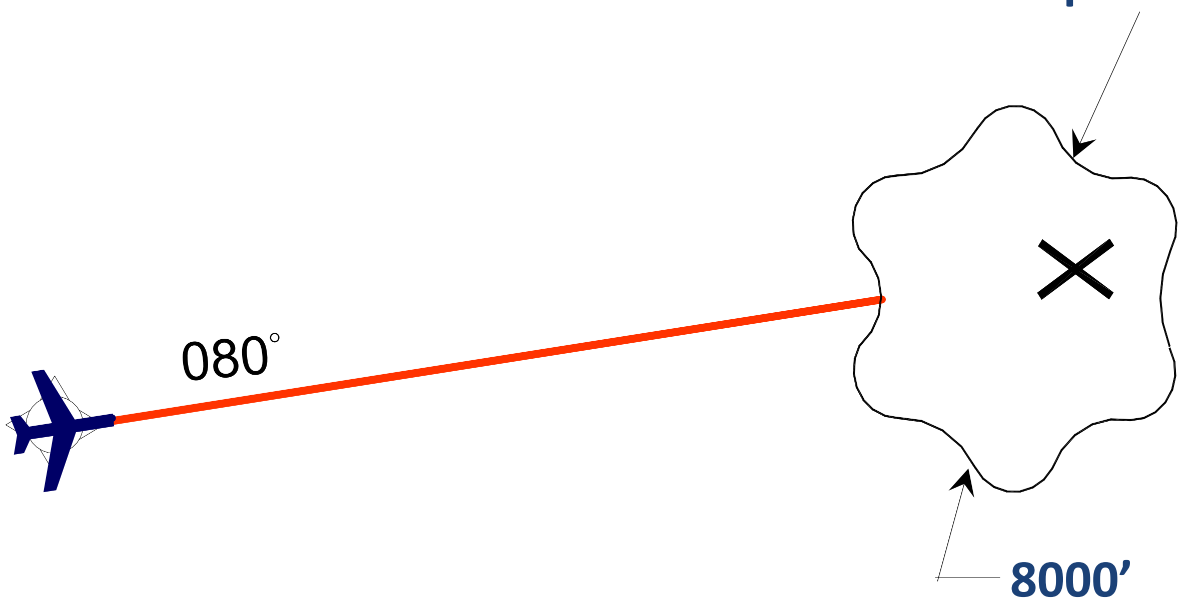
❖ CF : Course to Fix



Navigate towards the ending waypoint on a specified track.

Path Terminators

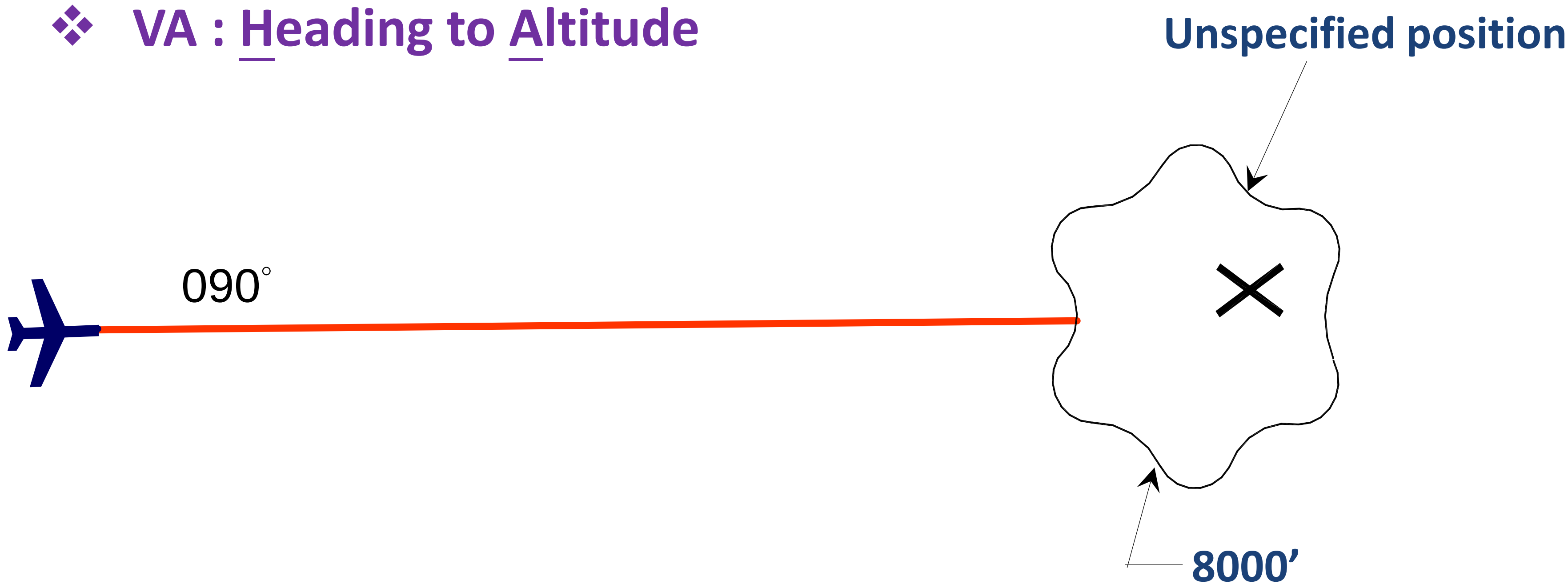
- FA : Fix to Altitude



Navigate towards assigned altitude on a specified track.

Path Terminators

- CA : Course to Altitude
- VA : Heading to Altitude

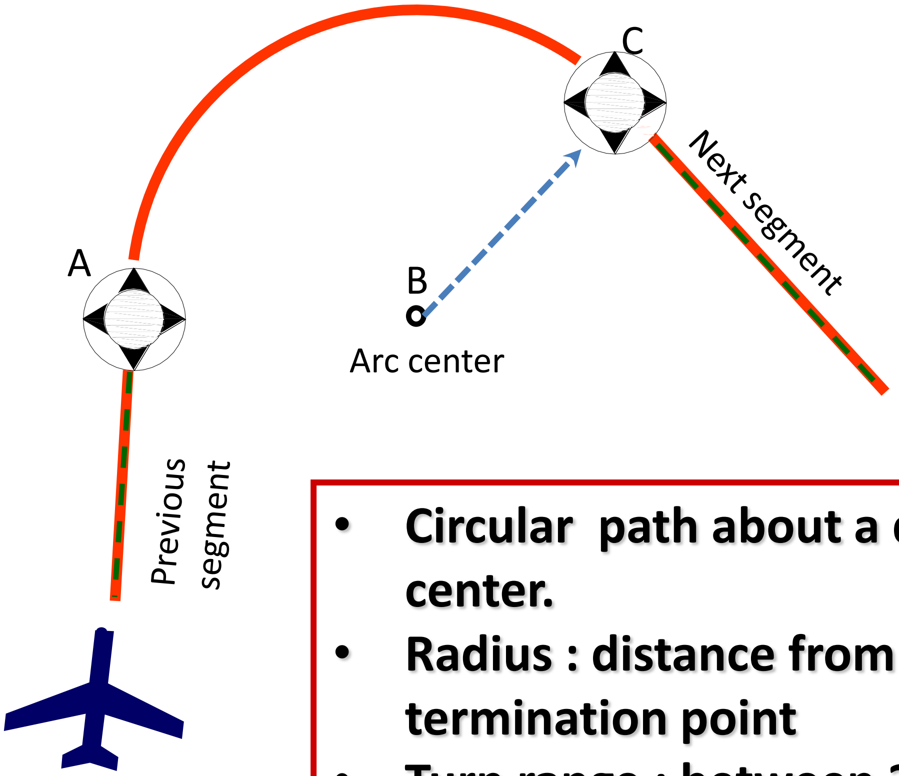


Navigate towards assigned altitude on a specified course

Navigate towards assigned altitude on an assigned heading

Path Terminators

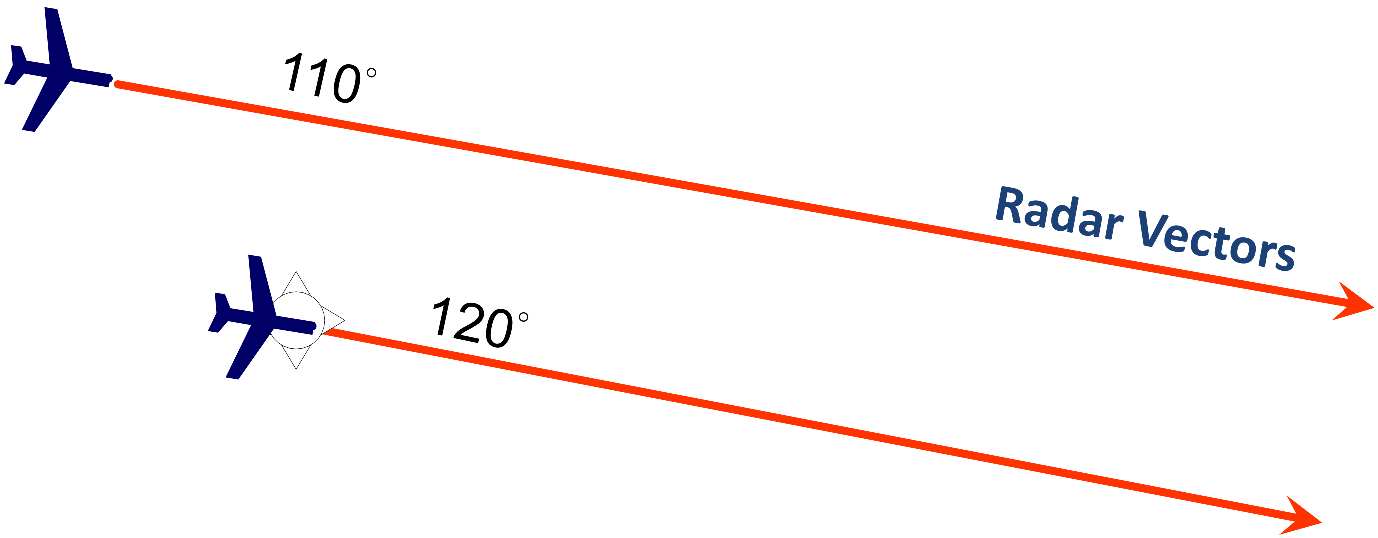
- RF : constant Radius arc to a Fix



- Circular path about a defined turn center.
- Radius : distance from turn center to termination point
- Turn range : between 2˚ and 300 ˚

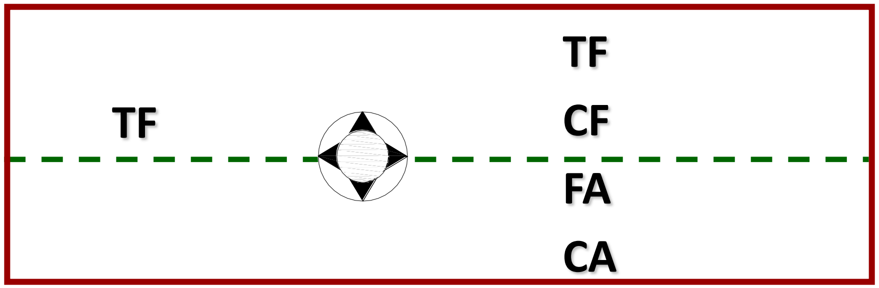
Path Terminators

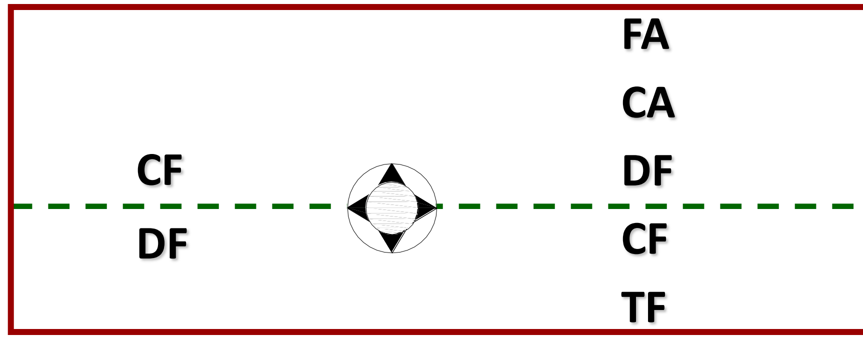
- VM : Heading to Manual Termination
- FM : Fix to Manual Termination

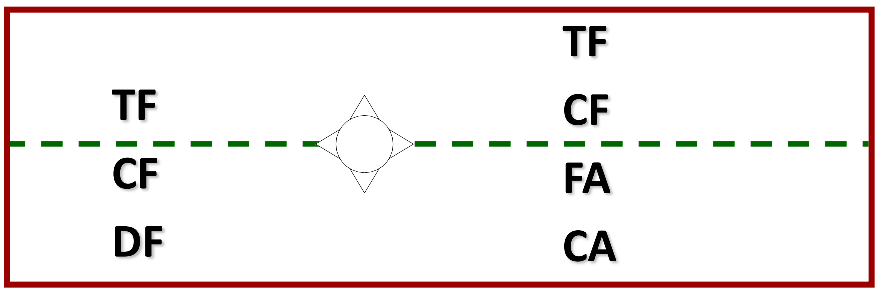


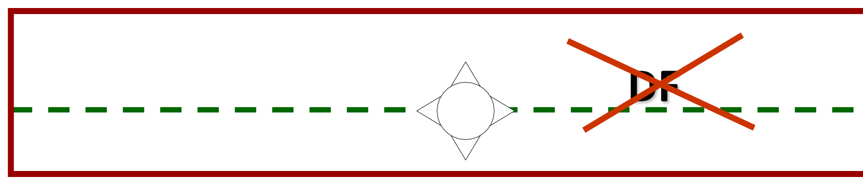
Path Terminators

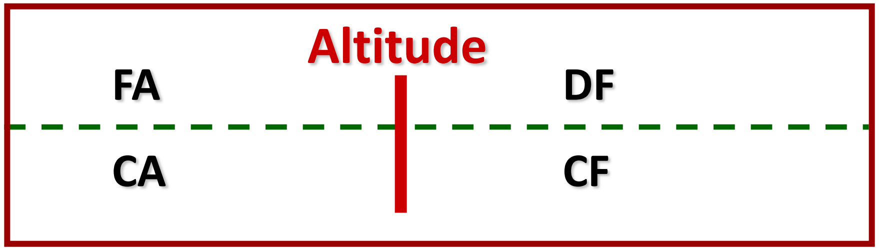
❖ Path Terminator Combination











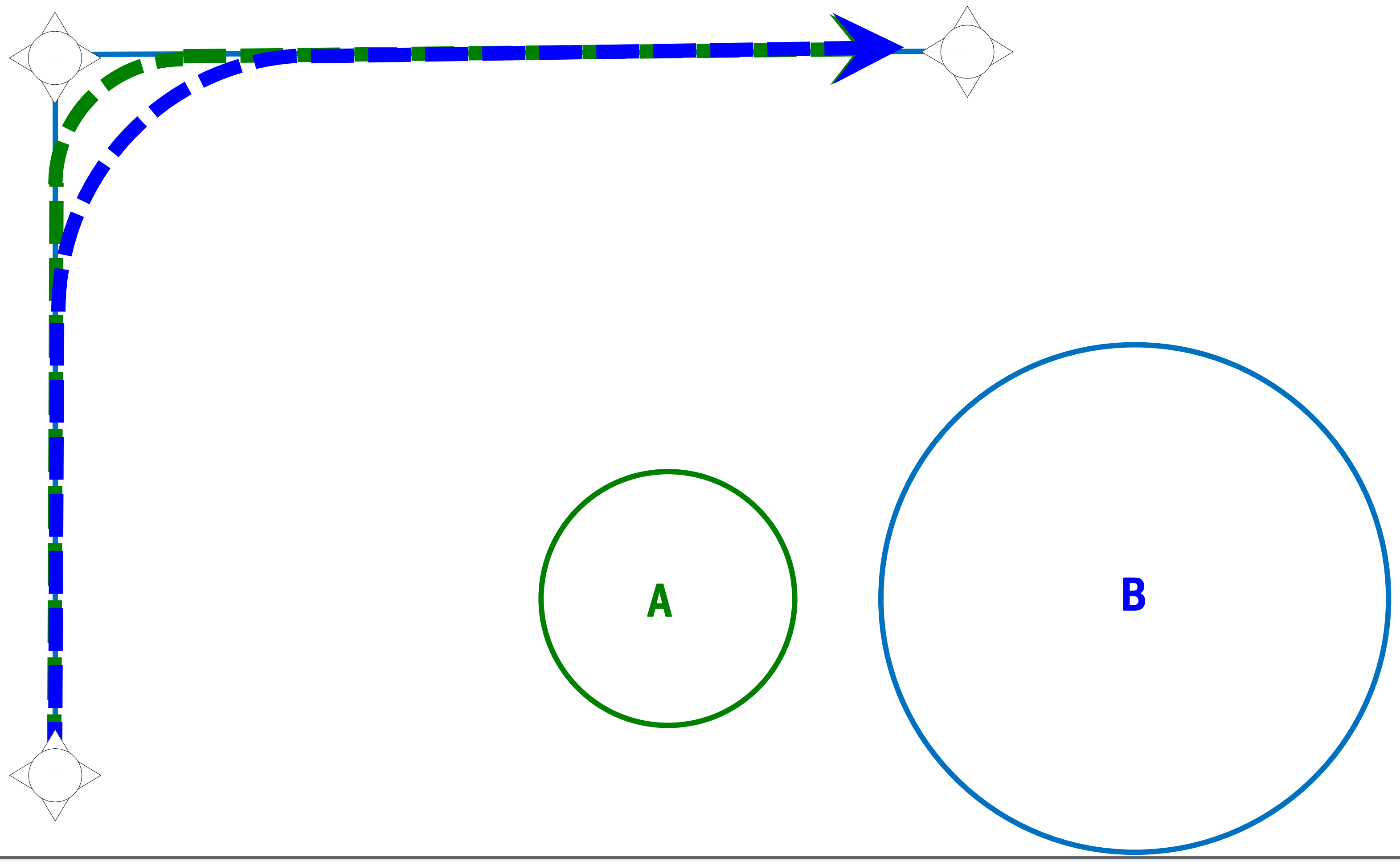
TF : Track between fixes
CF : course to fix
DF : Direct to fix
FA : Fix to an altitude
CA : Course to an altitude

Impact of Turn Performance

- Speed affects turn radius
- Bank angel affects turn Radius

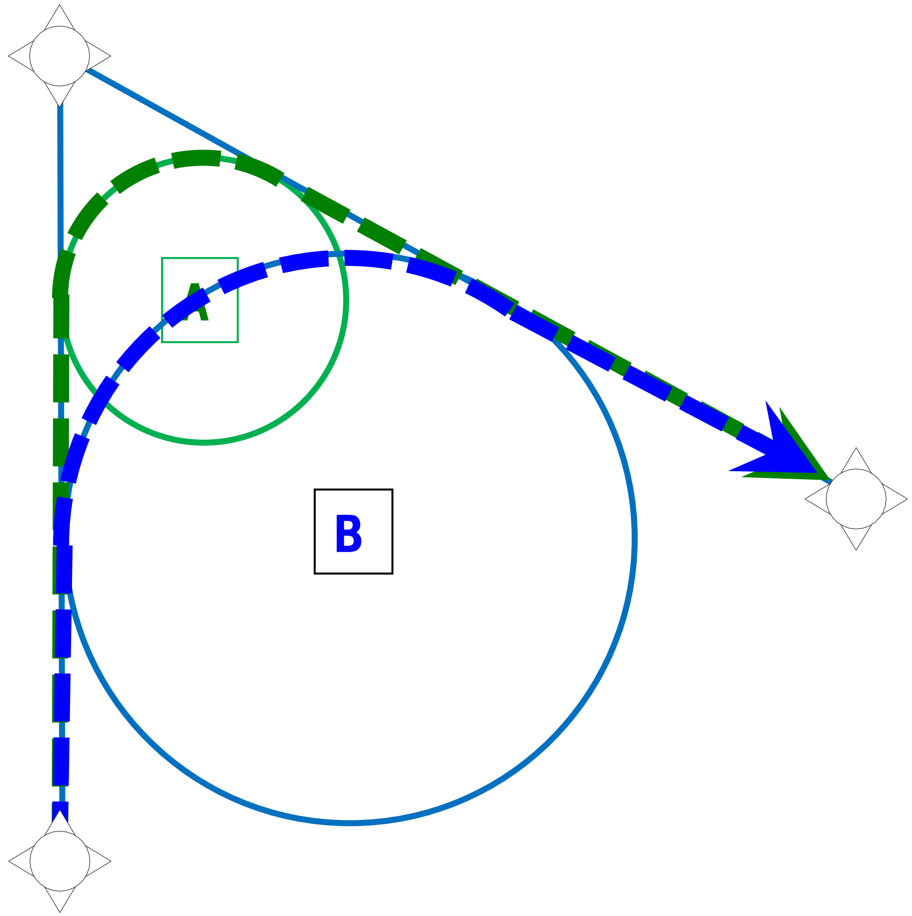
Impact of Turn Performance

- Turn angle (= 90˚)



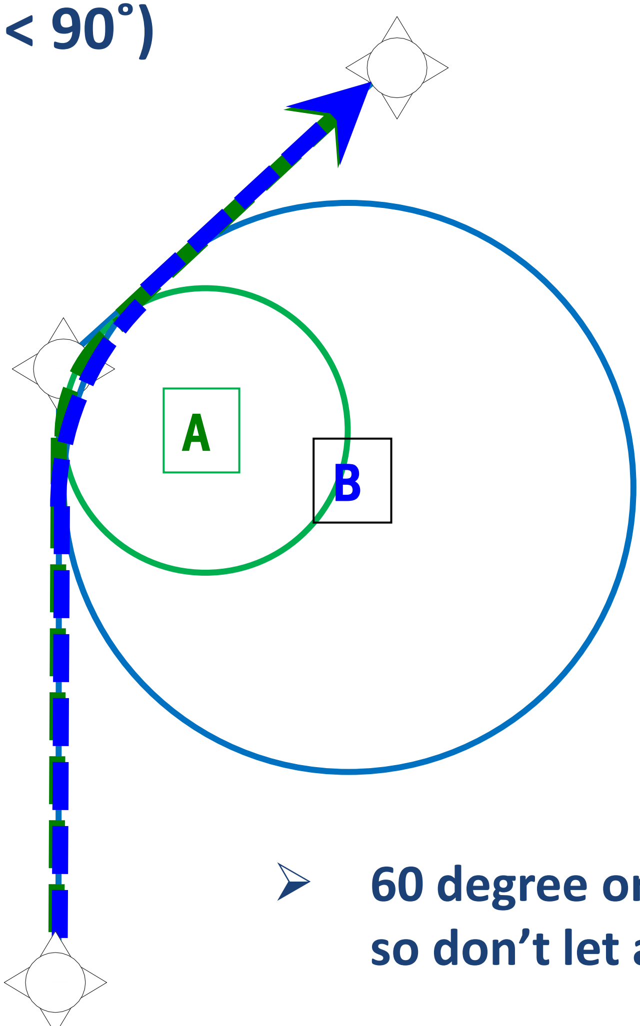
Impact of Turn Performance

- Turn angle (> 90˚)



Impact of Turn Performance

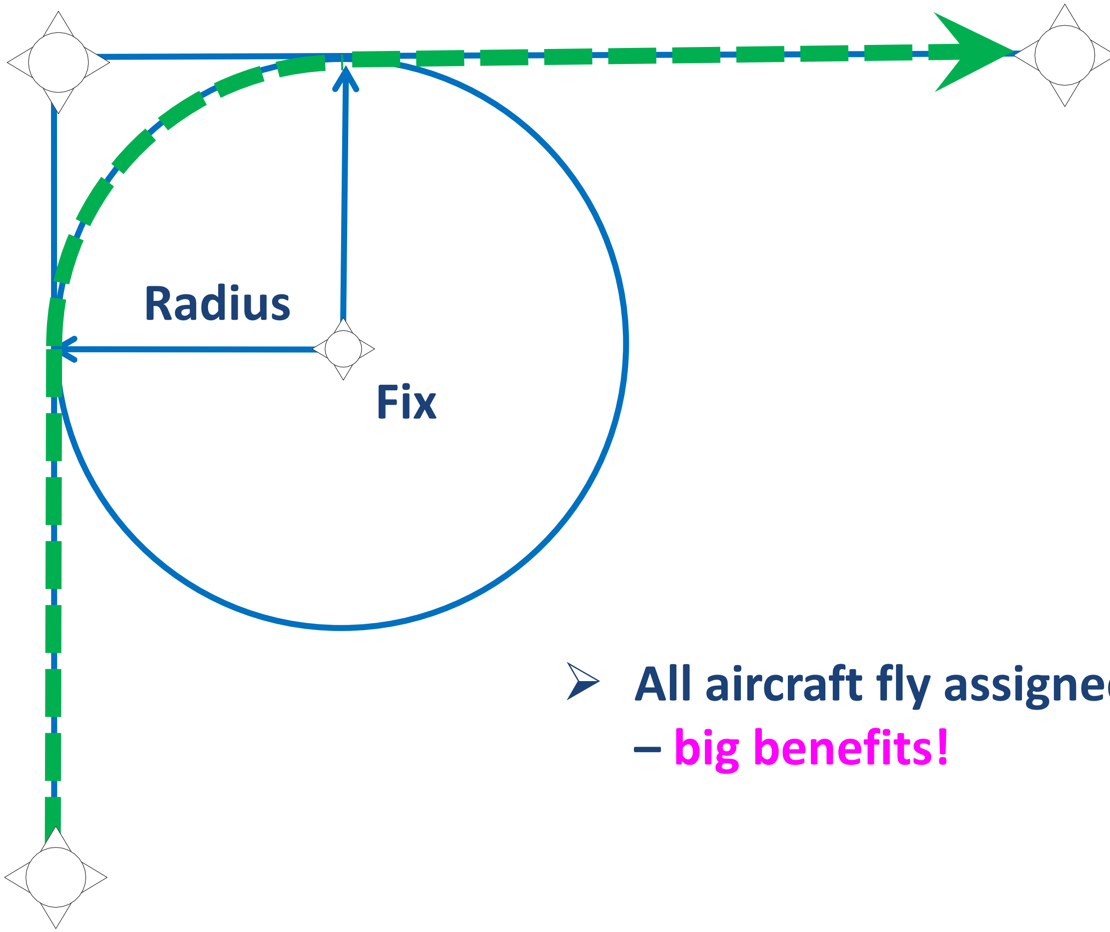
- Turn angle (< 90˚)



- 60 degree or less will be the same track, so don't let a/c turn steep turn angle

Impact of Turn Performance

❖ RF Turns / FRT



➢ **All aircraft fly assigned radius – big benefits!**

ATC Design Considerations

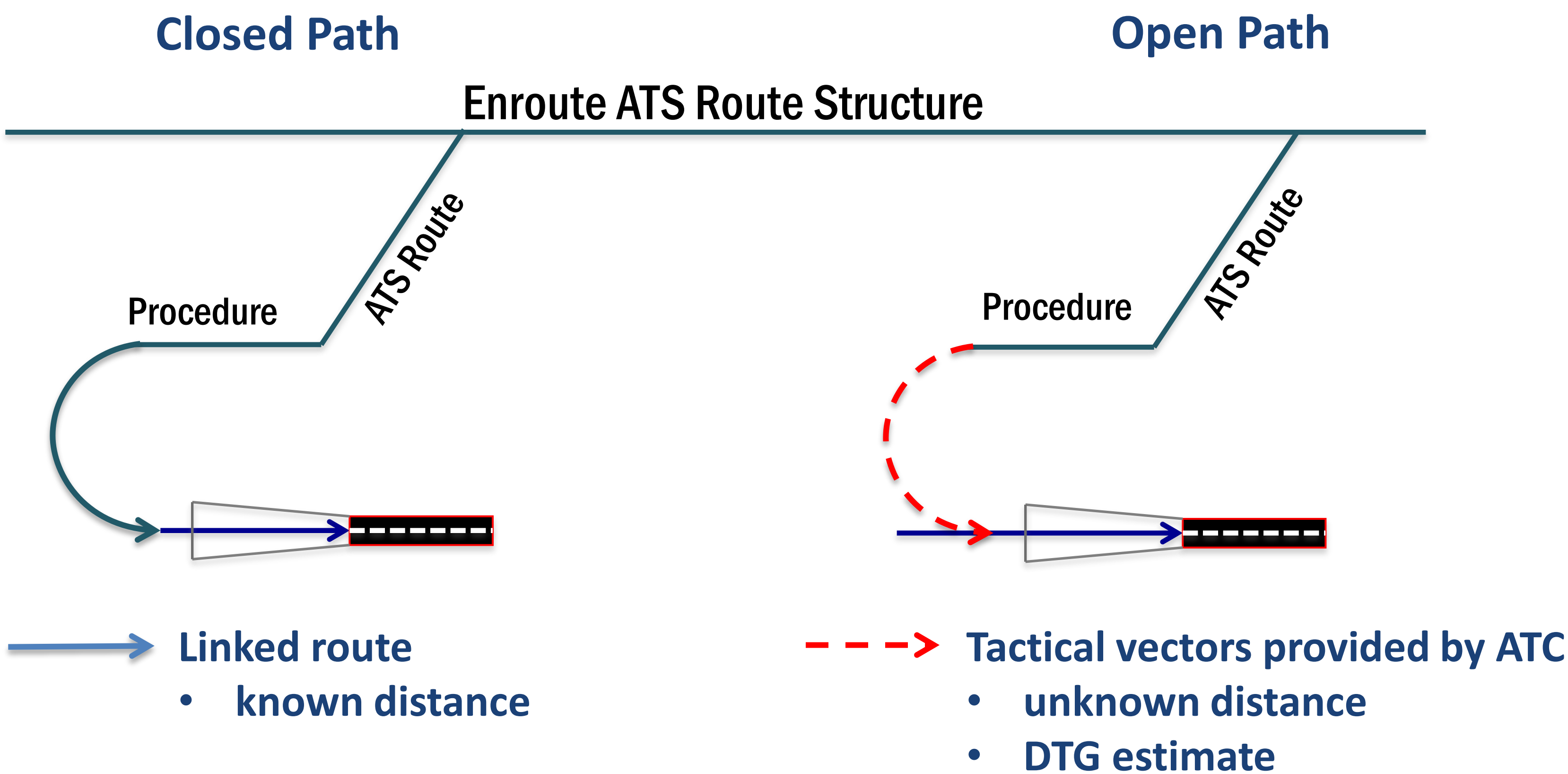
- Turns of more than 90 degrees may result in significant track variation
- Turns of 60 to 90 degrees create more manageable track variations
- Turns of 60 or less result in little track variation
- RF turns result in little track variation
- Speed and altitude constraints
  - Speed constraints allow tighter turns and can assist ATC function.
  - Altitude constraints can provide separation from obstacles and other aircraft

SIDs and STARs Design

- SID (Standard Instrument Departure)
  - Lead aircraft to en-route phase including radar departure
  - Minimize the effect from arrival courses
  - Altitude or speed restriction may be assigned
  - Continuous Climbing is necessary to enhance efficiency, economy and environmental benefits
- STAR (Standard Instrument Arrival)
  - Connects en-route phase to approach phase
  - Separate arrival course from departure course
  - When arrival and departure courses are crossing each other, altitude restriction is assigned, e.g. at, at or above/below, level window
  - May apply CDO (Continuous Descent Operations)

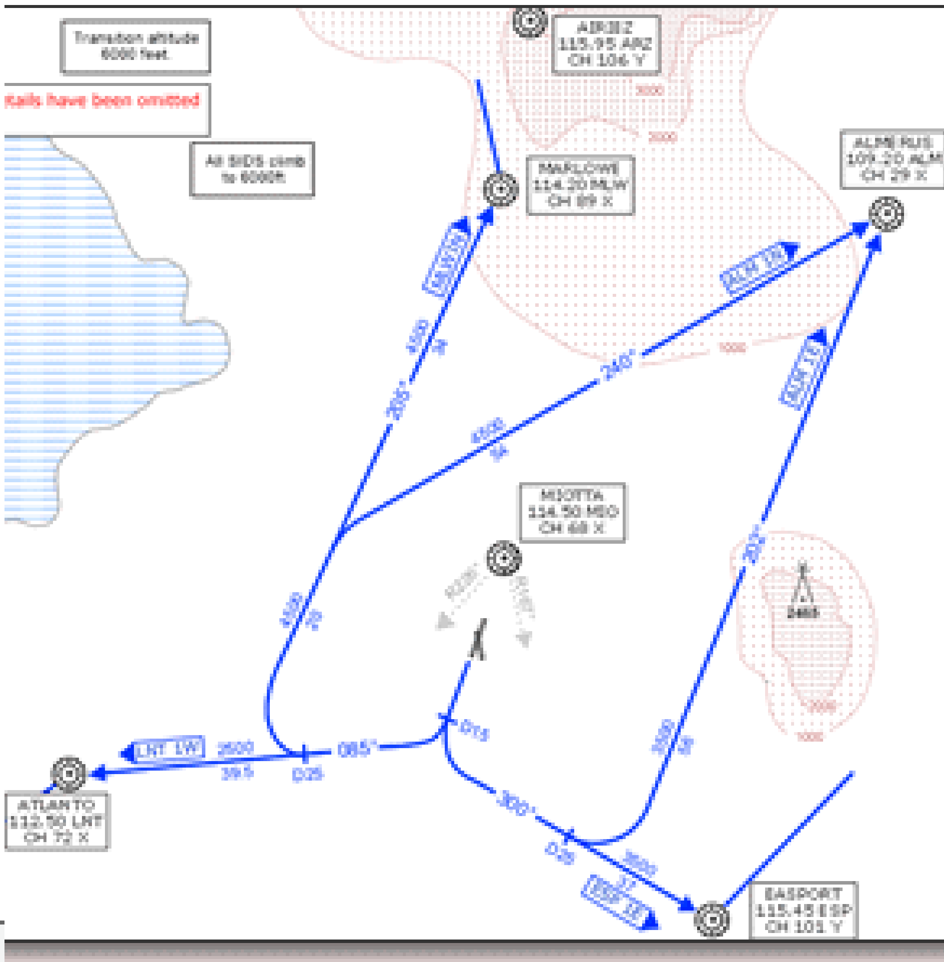
SIDs and STARs Design

❖ Different Types of Arrivals



SIDs and STARs Design

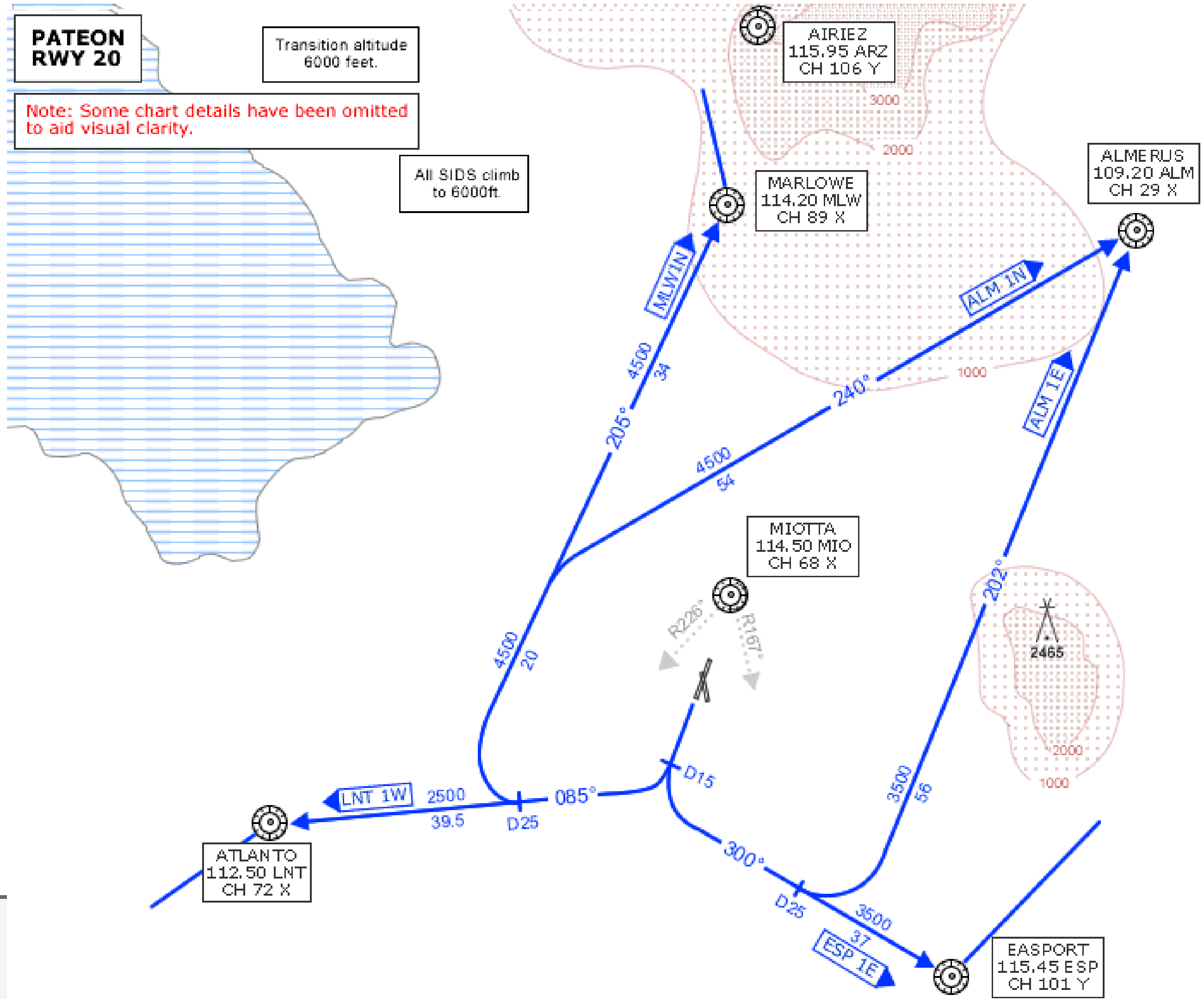
❖ Conventional SID Design



- **Limitations:**
  - **Inflexible SID/STAR design – a constraint to airspace optimization**
  - **Inconsistent track-keeping performance**
  - **Requires use of VOR/DME and/or DME**
- **Advantages**
  - **All aircraft operating under IFR are suitably equipped**

SIDs and STARs Design

❖ The Benefits of RNAV



STANDARD INSTRUMENT DEPARTURES

MSA ARP 25 NM

2000' 4500' 3500'

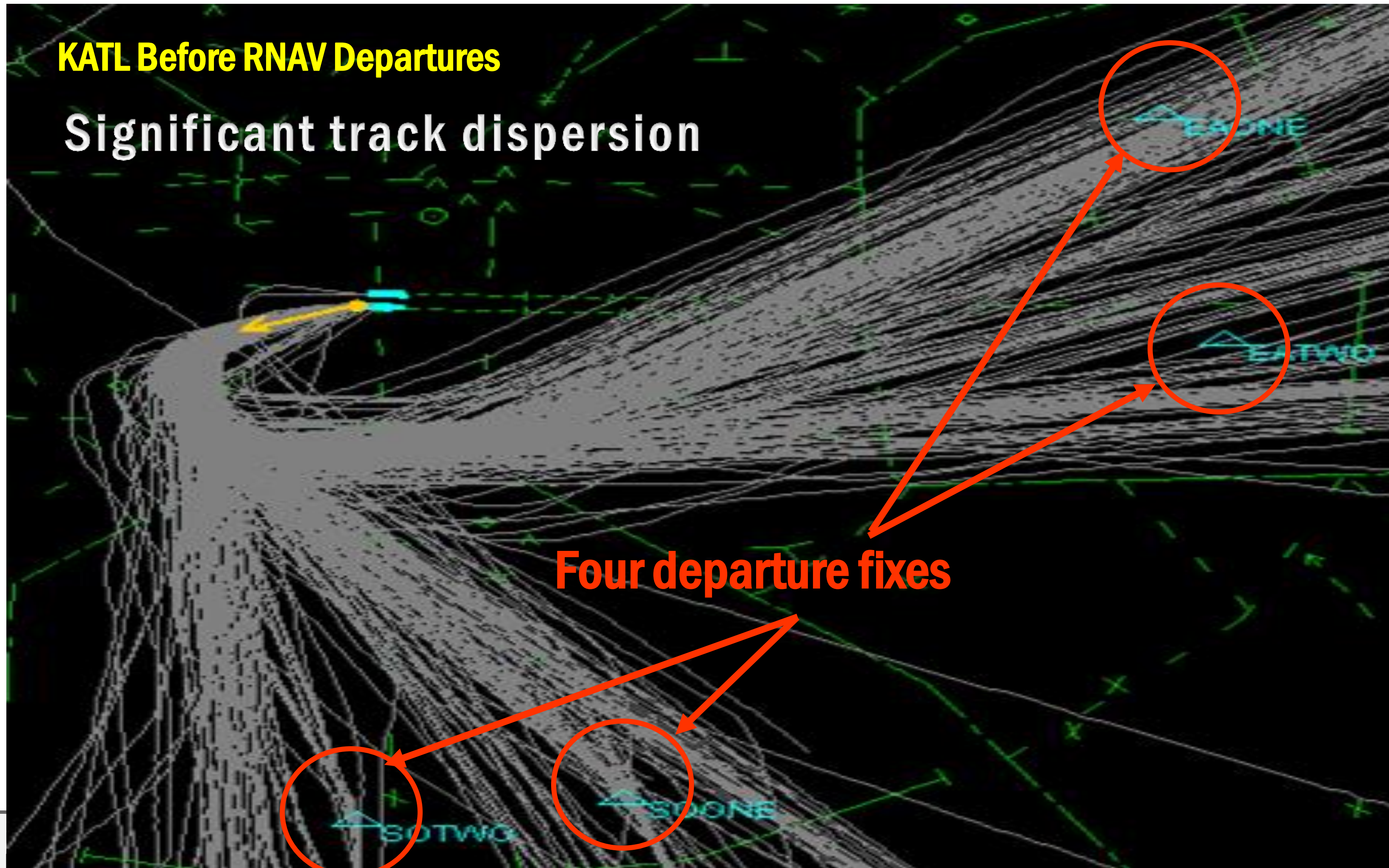
Bearings and tracks are magnetic. Tracks in brackets are true. Altitudes in feet AMSL.

VOR/DME	Latitude	Longitude
AIRIEZ	N54º 01'	E003º 03.1'
ALMERUS	N53º 48.9'	E003º 25.1'
ATLANTO	N53º 14.3'	E002º 34.8'
EASPORT	N53º 05.2'	E003º 14.2'
MARLOWE	N53º 50.5'	E003º 01.2'
MIOTTA	N53º 27.7'	E003º 01.6'

DEPARTURES	ROUTEING
ALM 1E	Climb on track 203, at 15D MIO turn left to intercept ESP R300. At 25D MIO turn left to intercept ALM R202 to ALM.
ALM 1N	Climb on track 203, at 15D MIO turn right to intercept LNT R085. At 25D MIO turn right to intercept MLW R205. Intercept ALM R240 to ALM.
ESP 1E	Climb on track 203, at 15D MIO turn left to intercept ESP R300 to ESP.
LNT 1W	Climb on track 203, at 15D MIO turn right to intercept LNT R085 to LNT.
MLW 1N	Climb on track 203, at 15D MIO turn right to intercept LNT R085. At 25D MIO turn right to intercept MLW R205 to MLW.

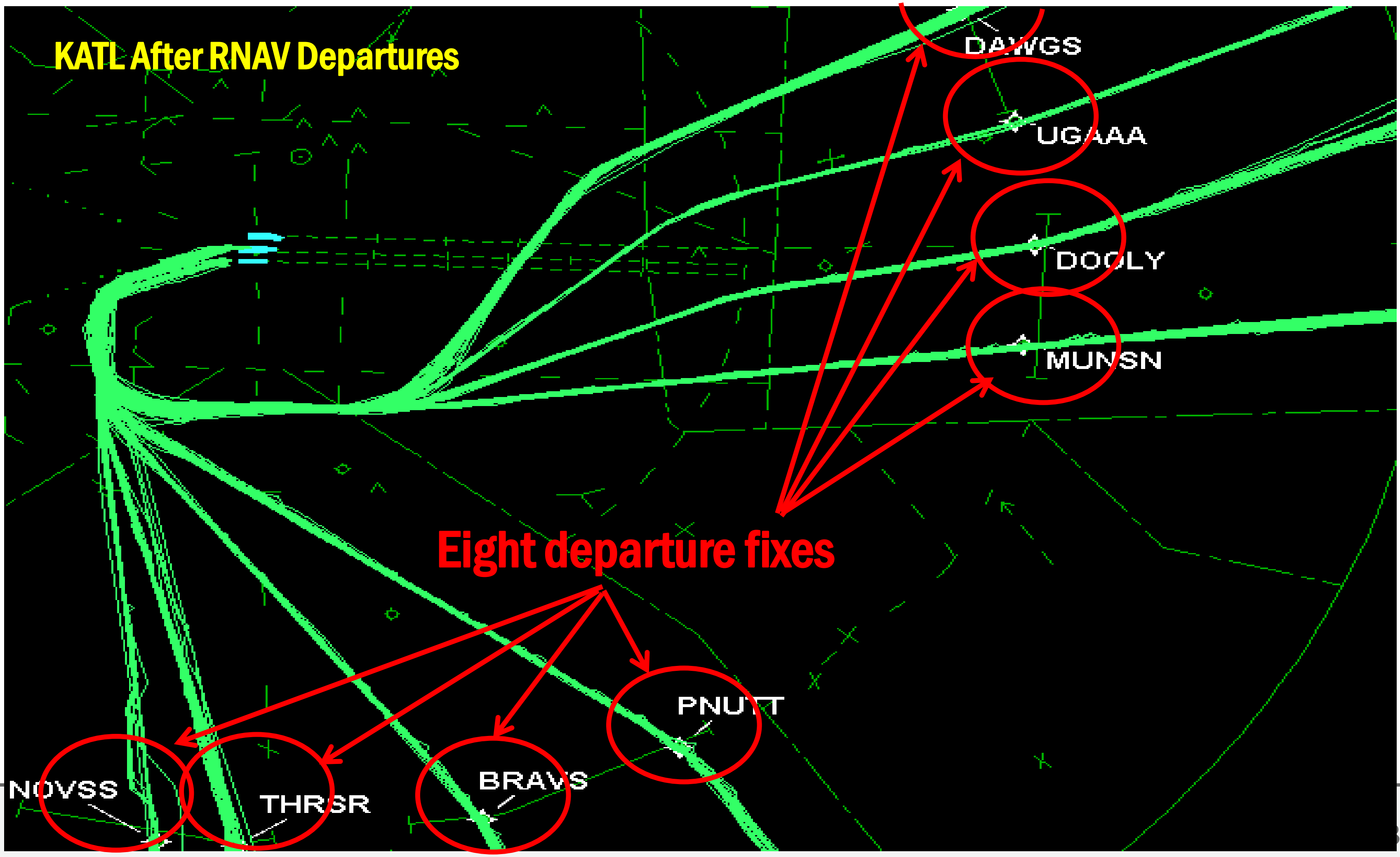
SIDs and STARs Design

❖ RNAV Departures at Atlanta USA

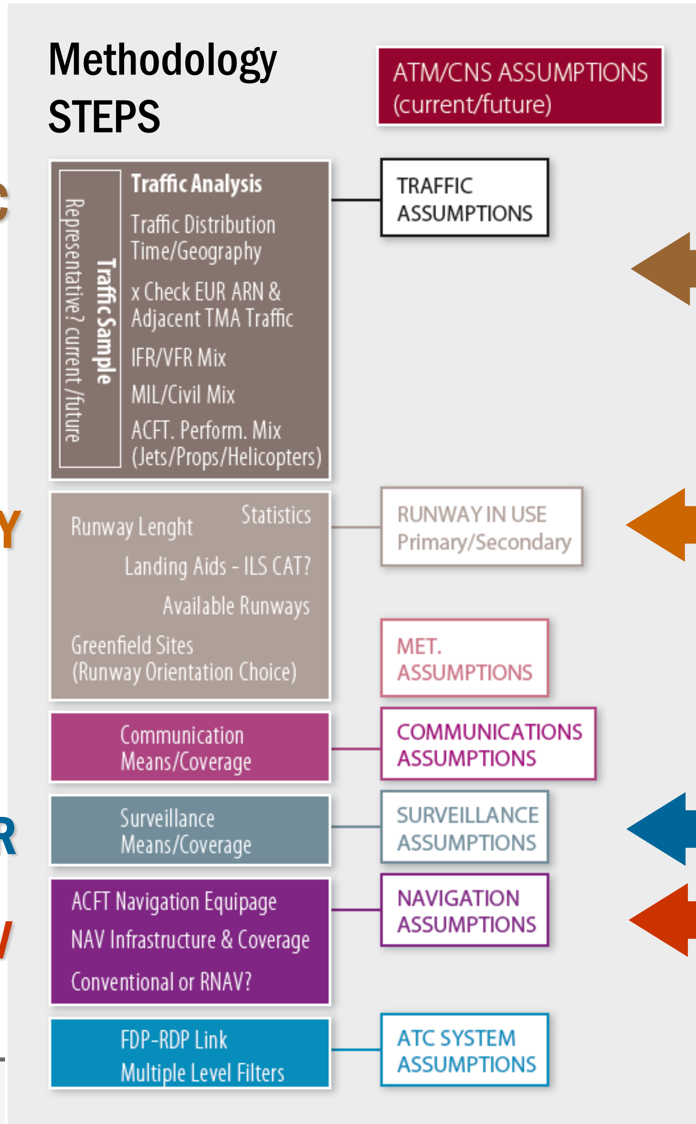


SIDs and STARs Design

❖ RNAV Departures at Atlanta USA



Design in Context



TFC

RWY

SUR

NAV

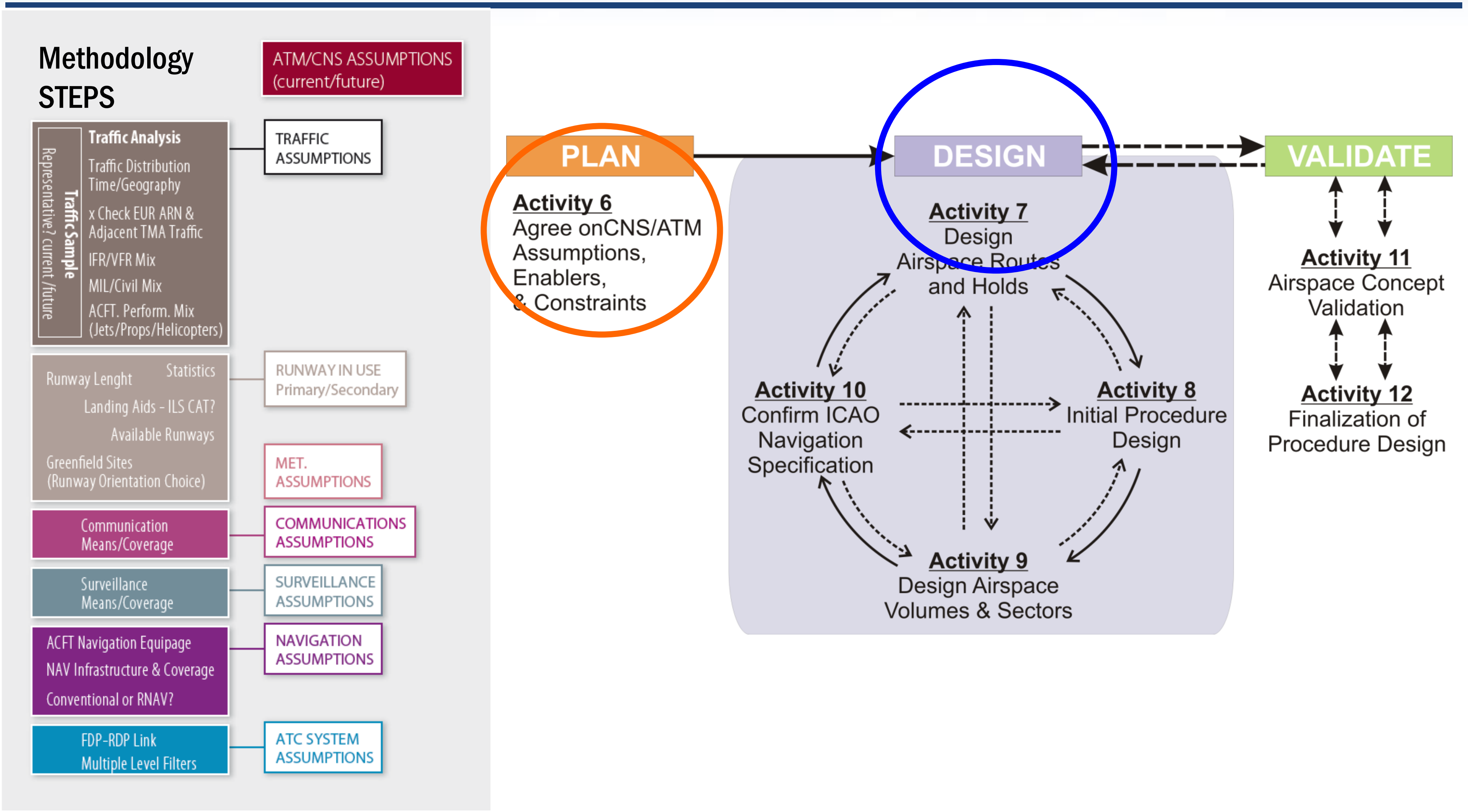
Where does the traffic come from?
And when?

Which Runway(s)?

Is there Radar?

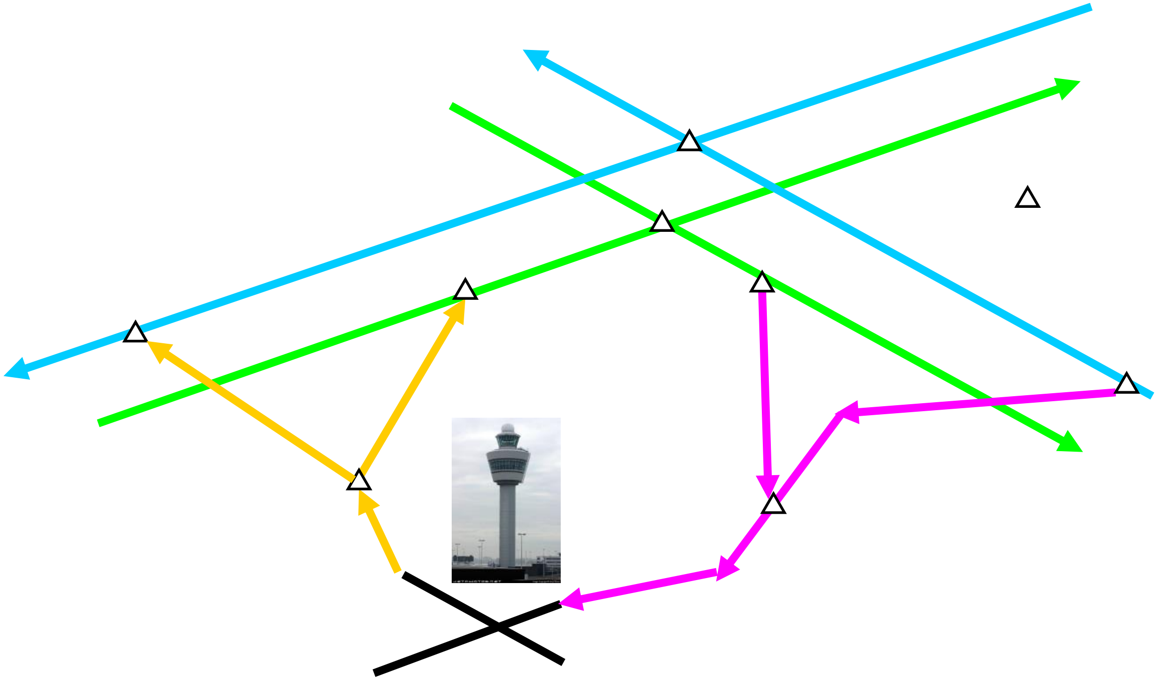
Which equipage?
How many aircraft ?

Design in Context



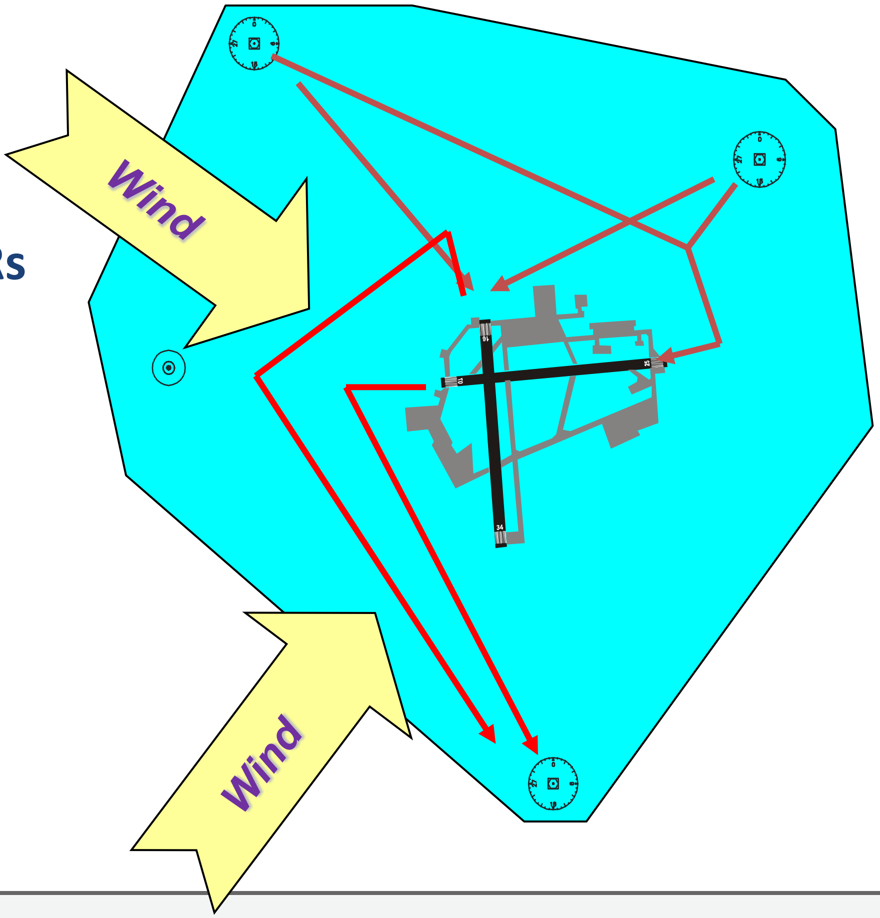
Terminal Routes

- Routes in Terminal Airspace link…
  - Changing demand
  - Runway in use
  - ATS Routes



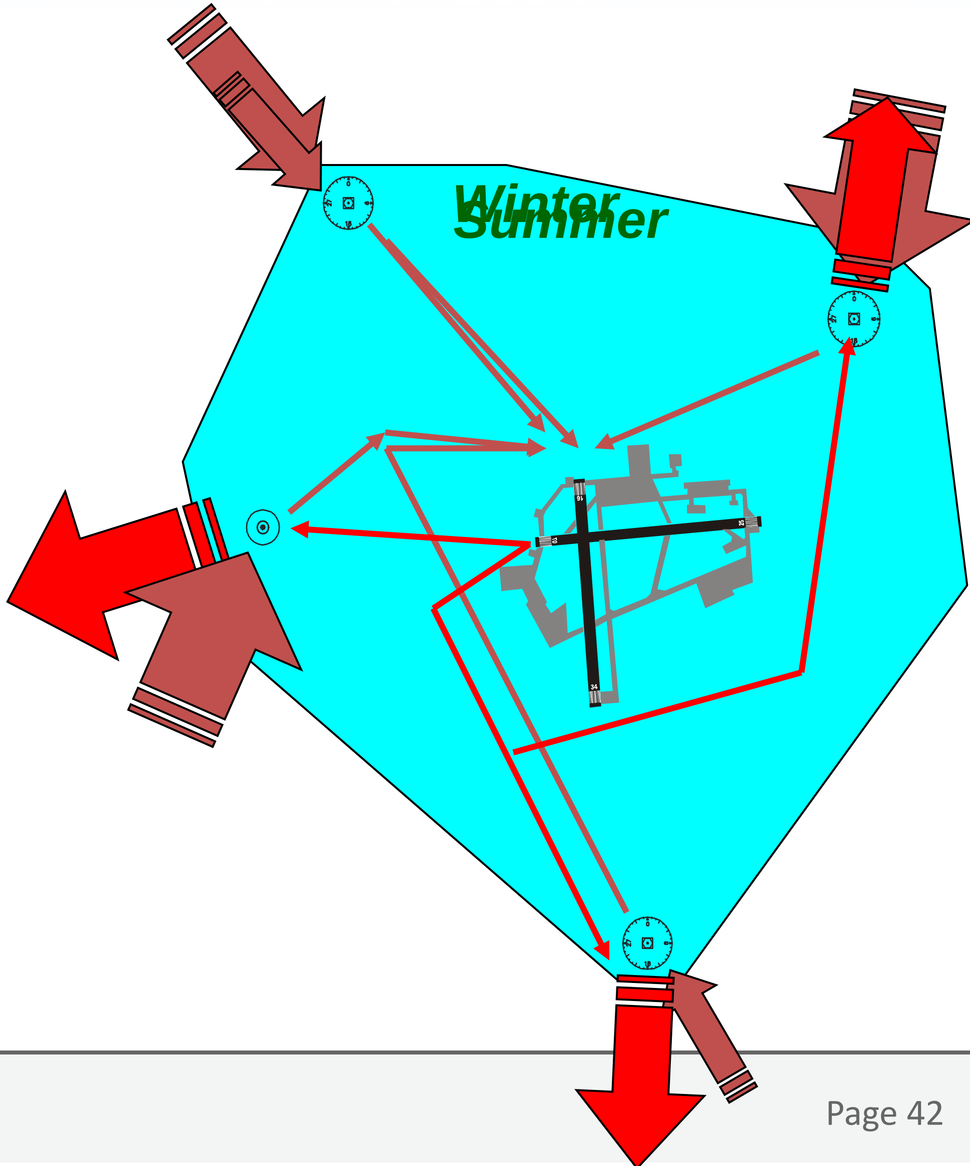
Terminal Routes

- ❖ Dependence on RWY
  - ➢ RWY orientation is given
  - ➢ Direction of RWY in use depends on wind
  - ➢ Different set of SIDs and STARs for different runway in use

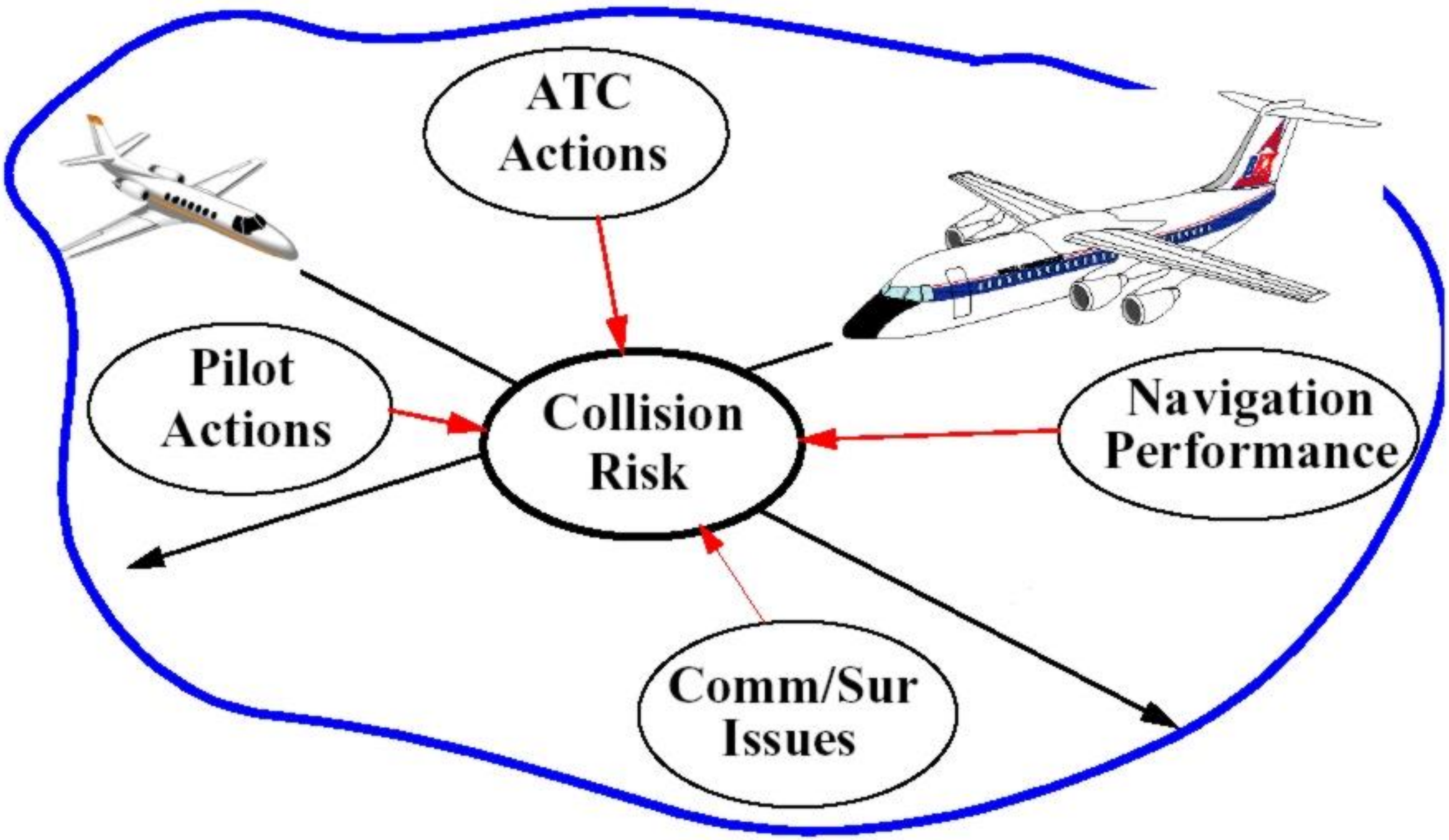


Terminal Routes

- **Seasonal Effect**
  - **Demand and route placement can vary for different seasons**
  - **Different set of SIDs and STARs per season**



Route Spacing



Route Spacing

❖ The spacing between ATS routes may be determined, in part, by the navigation performance of the aircraft that are expected to use them, by anticipated aircraft density, and by the communication and ATS surveillance services that are available to those aircraft.

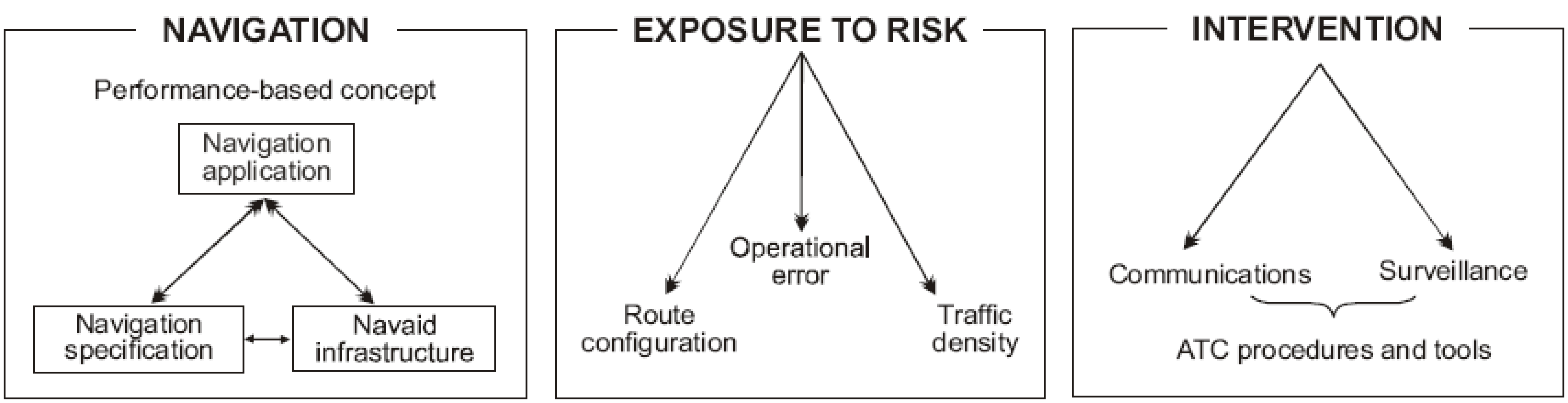
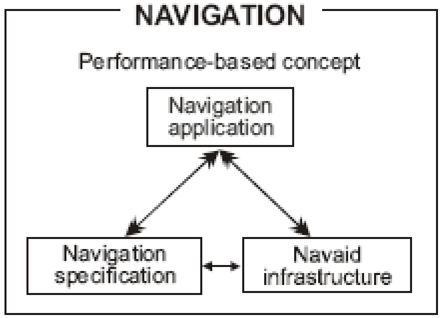
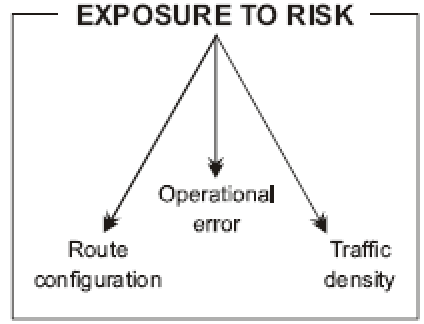
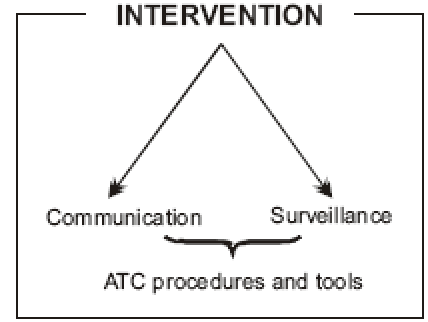


Figure I-A-3-2 Generic model used to determine separation and ATS Route spacing

Route Spacing

PBN	NAVIGATION 	EXPOSURE TO RISK 	INTERVENTION 
Determination of **separation minima** *(1)* for tactical use *without* ATC surveillance	✓	✓ (2)	✗
Determination of **separation minima** *(1)* for tactical use *with* ATC surveillance	✗	✗ (2) and (3)	✓
Determination of **route spacing** *without* ATC surveillance	✓	✓	✗
Determination of **route spacing** *with* ATC surveillance	✓	✓	✓

*✓ Relevant; ✗ Largely irrelevant; **(1)** In context, separation minima based on navaid or navigation sensor or PBN; **(2)** traffic density = single aircraft pair; **(3)** separation minima determined as a function of performance of ATC surveillance system.*

Figure I-A-3-3Factors affecting the determination of separation and Route spacing

Route Spacing

- ICAO PANS-ATM, Doc 4444

5.4.1.2.1.3 By use of different navigation aids or methods. Lateral separation between aircraft using different navigation aids, or when one aircraft is using RNAV equipment, shall be established by ensuring that the derived protected airspaces for the navigation aid(s) or RNP do not overlap.

Route Spacing

❖ ICAO PANS-ATM, Doc 4444 (Cont')

5.4.1.2.1.4 Lateral separation of aircraft on published adjacent instrument flight procedures for arrivals and Departures

5.4.1.2.1.4.1 Lateral separation of departing and/or arriving aircraft, using instrument flight procedures, will exist:

a) where the distance between any combination of RNAV 1 with RNAV 1, RNP 1, RNP APCH or RNP AR APCH tracks is not less than 13 km (7 NM); or

b) Where distance between any combination of RNP1, RNP APCH or RNP AR APCH tracks us not less than 9.3 km (5NM); or

c) where the protected areas of tracks designed using obstacle clearance criteria do not overlap and provided operational error is considered.

Route Spacing

❖ **ICAO PANS-ATM, Doc 4444 (Cont')**

5.4.1.2.1.6 Lateral separation of aircraft on parallel or non-intersecting tracks or ATS routes. Lateral separation between aircraft operating on parallel or non-intersecting tracks or ATS routes shall be established in accordance with the following:

a) **Between RNAV 10 (RNP 10), RNP 4 or RNP 2 tracks : minimum 93 km (50 NM) :**

b) **Between RNP 4 or RNP 2 tracks : minimum 55.5 km (30 NM);**

c) **Between RNP 2 or a GNSS equipage aircraft while maintaining VHF DCPC : minimum 27.8 km (15 NM) ;**

d) **While one aircraft climbs/descends through the level of another aircraft, between RNP 2 or a GNSS equipage aircraft while maintaining VHF DCPC : minimum 13 km (7 NM), ; and**

e) **While one aircraft climbs/descends through the level of another aircraft, between RNP2 or a GNSS equipage aircraft with different communication environment from d) : minimum 37 km (20 NM)**

Route Spacing

- **RNP Lateral Separation**
  - PANS OPS Doc 8168, Vol II, Part III, Section 7.5
    - ✓ RNP area semi-width is determined by the formula: 1.5(XTT) + BV
    - ✓ Where: BV = buffer value (see Table III-1-1-3, except RNP AR)
  - The calculation for a RNP 1 arrival (ARP<30NM) is shown below:

XTT = 1.00 NM; BV= 1.0 NM

area semi-width = 1.5(1.00) + 1.0 = 2.50 NM

Phase of flight	*BV for CAT A–E*	*BV for CAT H*
En-route, SIDs and STARs (greater than or equal to 56 km (30 NM) from departure or destination ARP)	3 704 m (2.0 NM)	1 852 m (1.0 NM)
Terminal (STARs, initial and intermediate approaches less than 56 km (30 NM) of the ARP; and SIDs and missed approaches less than 56 km (30 NM) of the ARP but more than 28 km (15 NM) from the ARP)	1 852 m (1.0 NM)	1 296 m (0.7 NM)
Final approach	926 m (0.5 NM)	648 m (0.35 NM)
Missed approaches and SIDs up to 28 km (15 NM) from the ARP	926 m (0.5 NM)	648 m (0.35 NM)

Approach Procedure Design

❖ RNP APCH

- Designated RNAV (GNSS) (From 1 Dec 2022, RNP)
- Only GNSS sensor used
- RNP navigation specification $\Rightarrow$ OPMA REQUIRED
- RNP1 (or RNAV1) for initial, intermediate and missed approach
- RNP 0.3 for final
- NO specific AUTHORIZATION REQUIRED unlike RNP AR
- Identified as LNAV in the minima box, descend to MDA/H

Approach Procedure Design

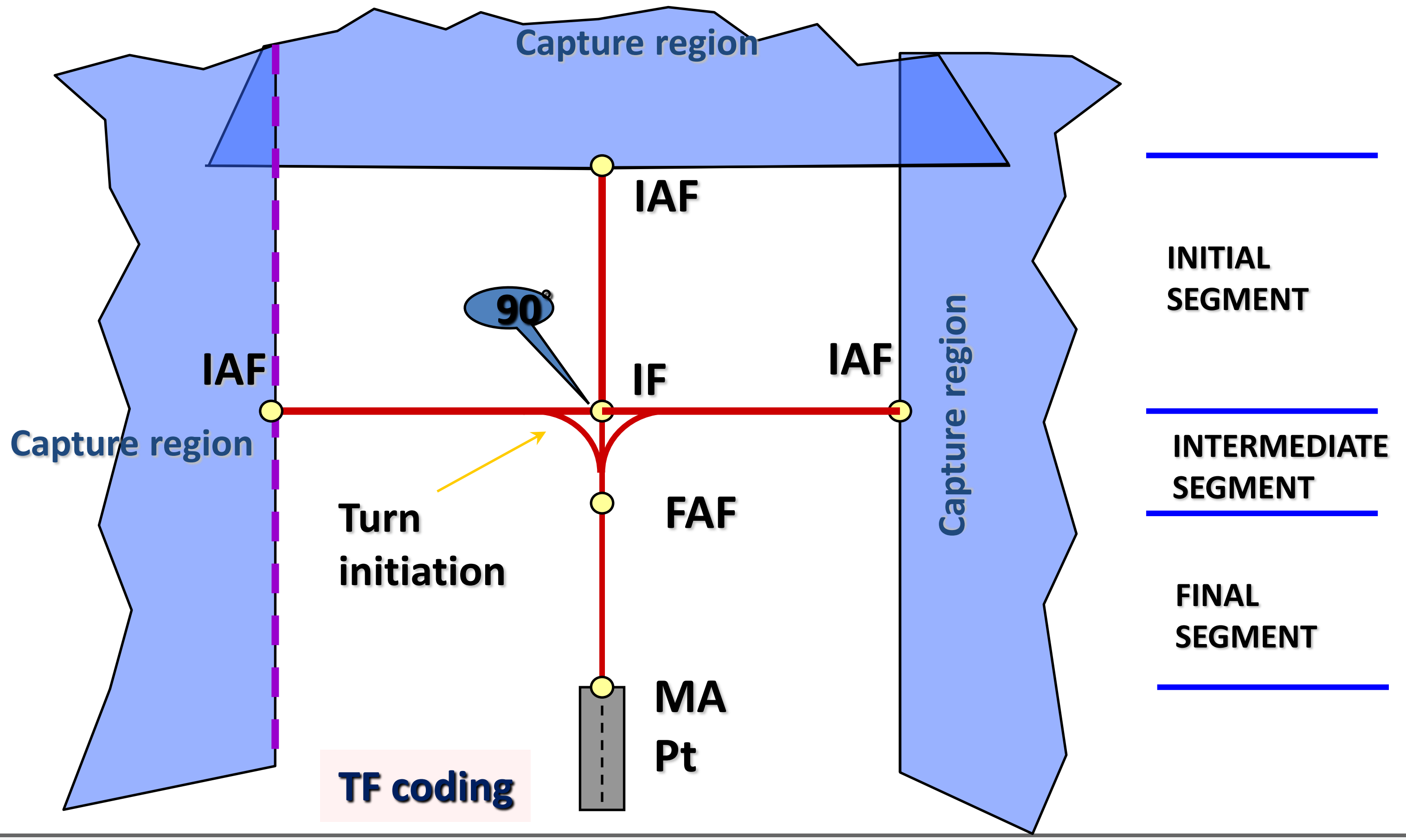
- T or Y-bar Procedures
  - T- or Y-bar arrangement is based on
    - a runway aligned final segment
    - preceded by an intermediate segment and
    - up to three initial segments
      - ✓ arranged either side of and along the final approach track to
      - ✓ form a T or a Y.
  - It permits direct entry to the procedure
    - from any direction,
    - provided entry is made from within the capture region associated with an IAF
  - This arrangement ensures that entry from within a capture region requires a change of course at the IAF no greater than 110°.

Approach Procedure Design

- **T or Y-bar Procedures (Cont')**
  - **Terminal Arrival Altitudes (TAAs) may be provided to**
    - **facilitate descent and**
    - **entry to the procedure.**
  - **The IAF, IF and FAF are defined by fly-by waypoints.**
  - **The missed approach segment**
    - **starts with a flyover waypoint (MAPt) and**
    - **ends at a missed approach holding fix (MAHF).**
  - **For turning missed approaches**
    - **a missed approach turning fix (MATF) may also be established to define the turn point.**

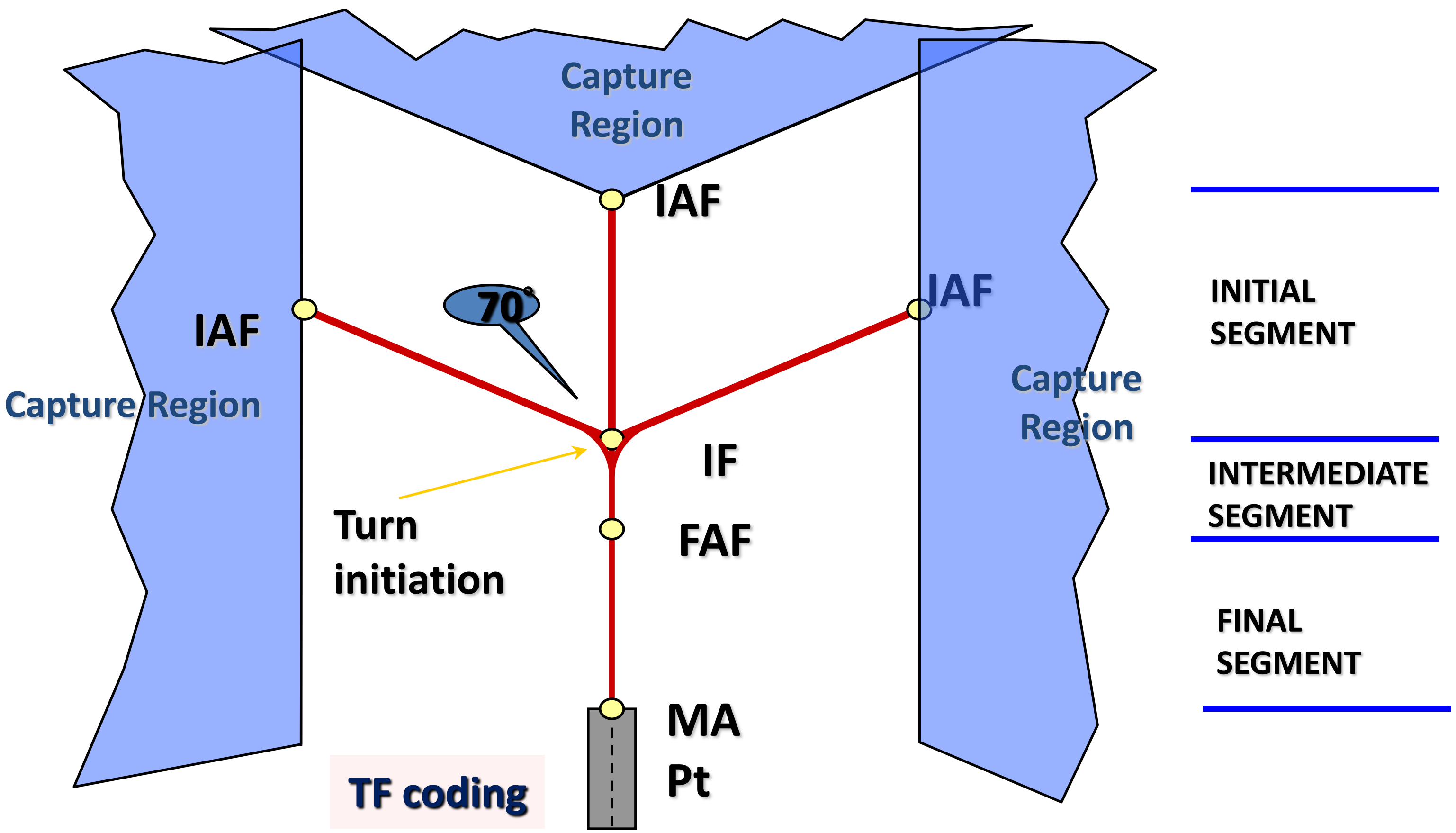
Approach Procedure Design

- T Bar Design Concept



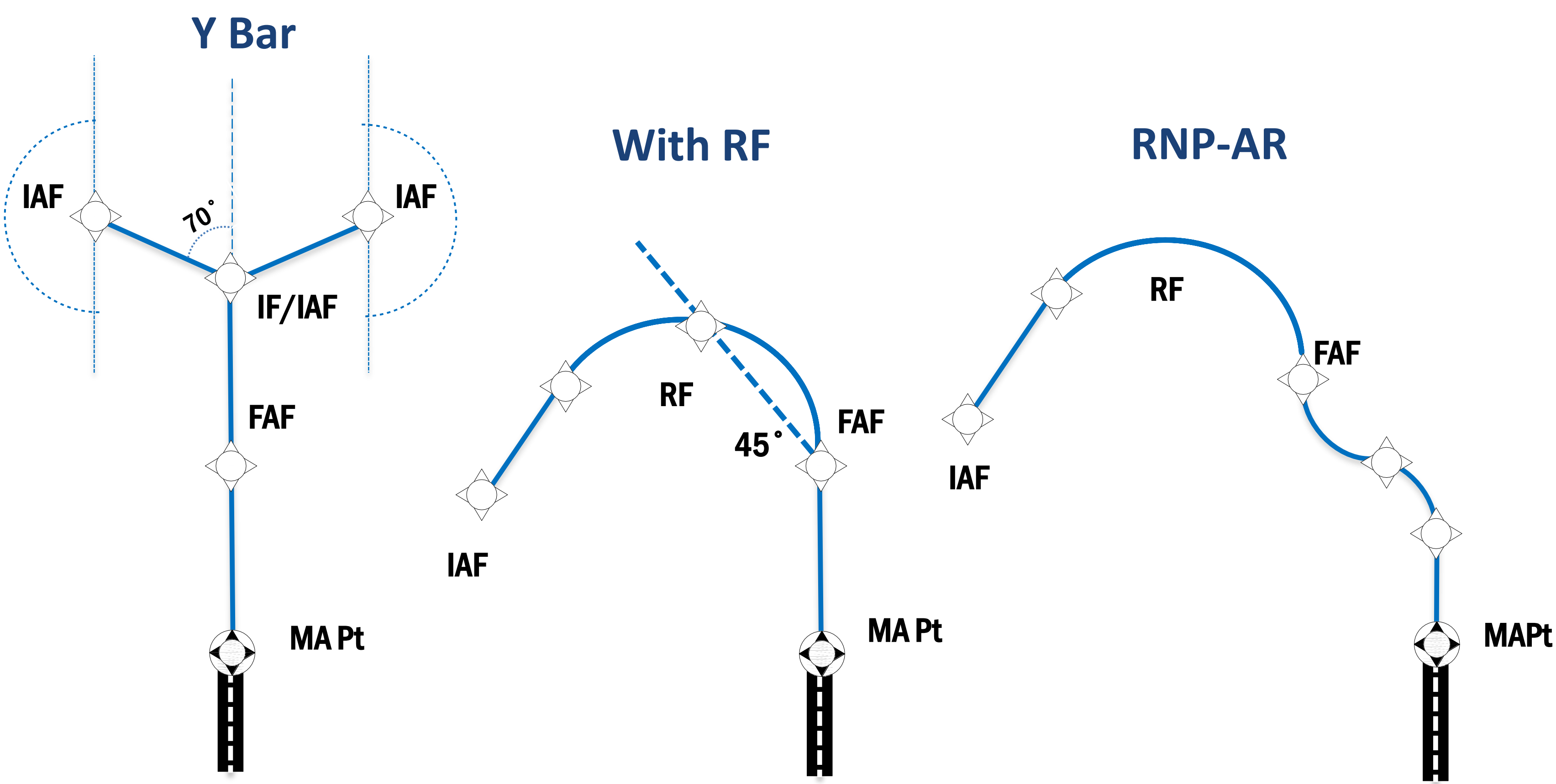
Approach Procedure Design

❖ Y Bar Design Concept



Approach Procedure Design

❖ Other Design Concept



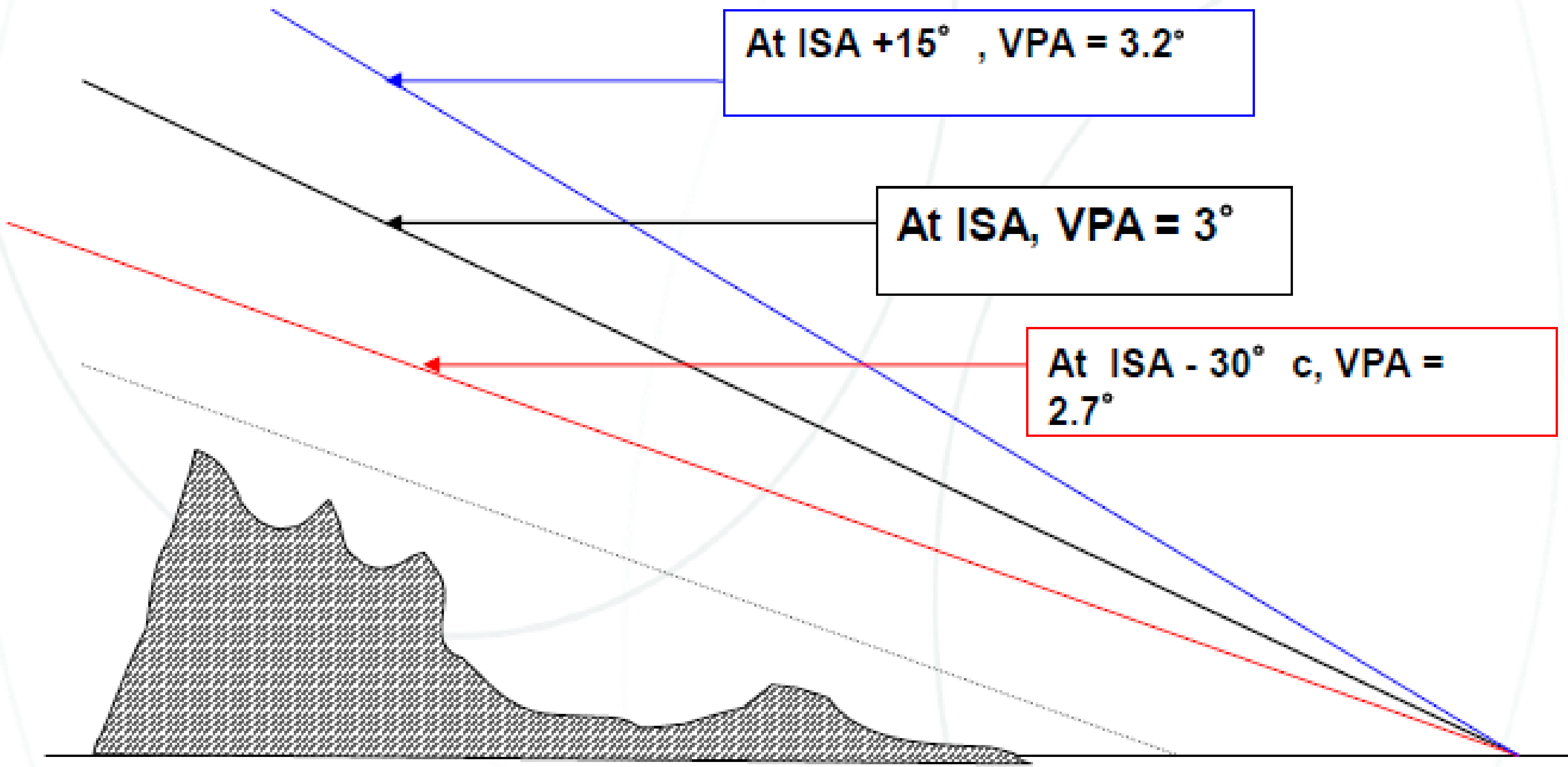
Approach Procedure Design

- Baro VNAV
  - APV (Approach Procedures with Vertical Guidance)
  - DA/H, not MDA/H
  - No FAF and MAPt
  - The LNAV-only FAF and MAPt are used to define the areas but are not part of the VNAV procedure.
  - GNSS lateral navigation required
  - 3˚ Vertical Path Angle defined from FAP to THR above 50ft
  - Considers cold temperature correction while designing procedures
  - Publishes a minimum promulgated temperature
  - Must not be used below the promulgated minimum temperature
  - Cannot be used with remote altimeter setting
  - Identified in the minimum box by “LNAV/VNAV”

Approach Procedure Design

❖ Baro VNAV (Cont')

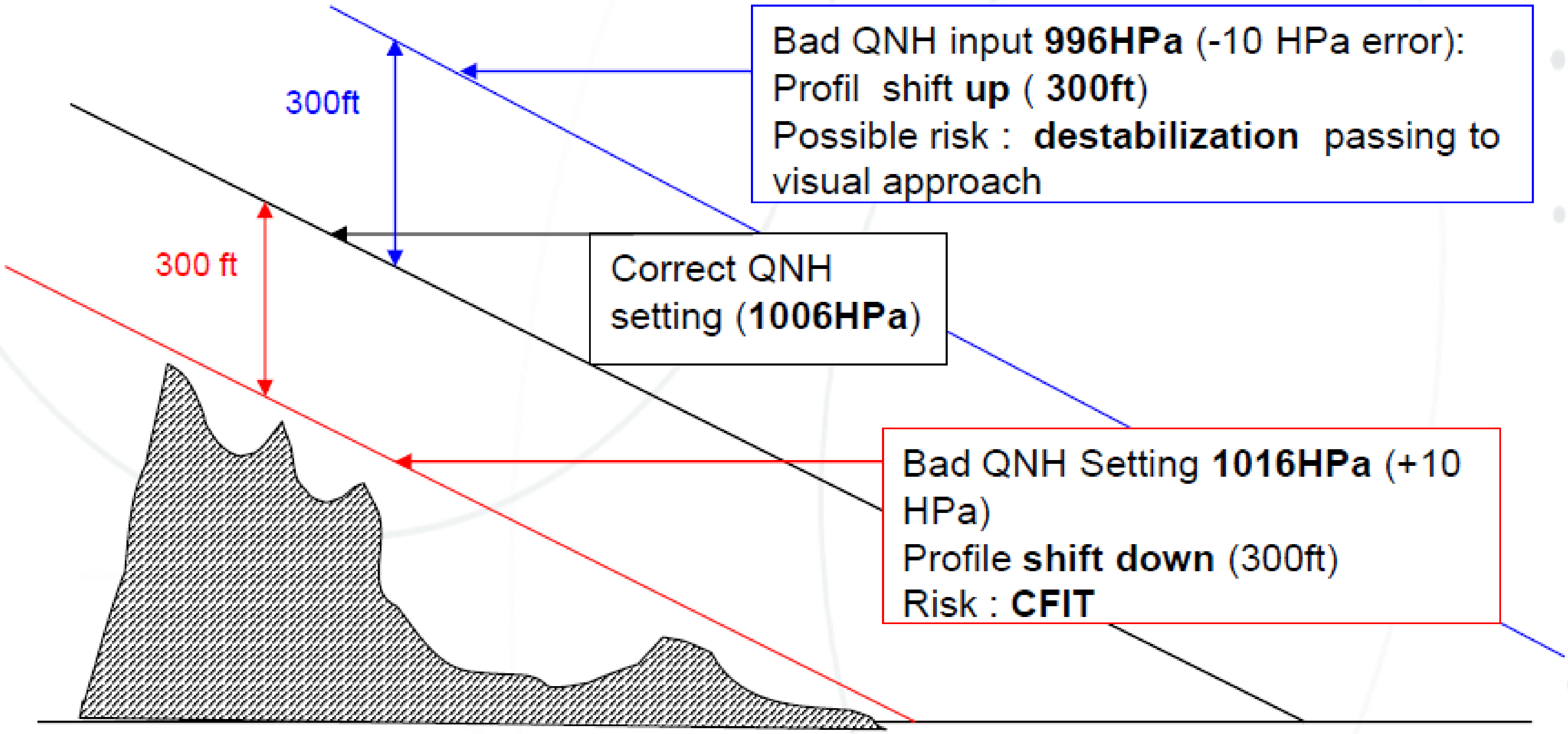
➢ Temperature effect on final approach profile



- Baro VNAV (Cont')
  - QNH and altimeter setting
    - ✓ Pilots must know that vertical path based on Baro VNAV information is influenced by altimeter setting errors.
    - ✓ These errors cannot be detected through cross-check between altimeter indication and values shown on approach chart (altitude – distance check).
    - ✓ APV BaroVNAV (LNAV/VNAV minima) approaches are not authorized in the absence of local altimeter setting (local QNH).
    - ✓ It is also important that the pilot has a recent altimeter setting information. Thus, the crew may request the confirmation of altimeter setting before passing the FAF.

❖ Baro VNAV (Cont')

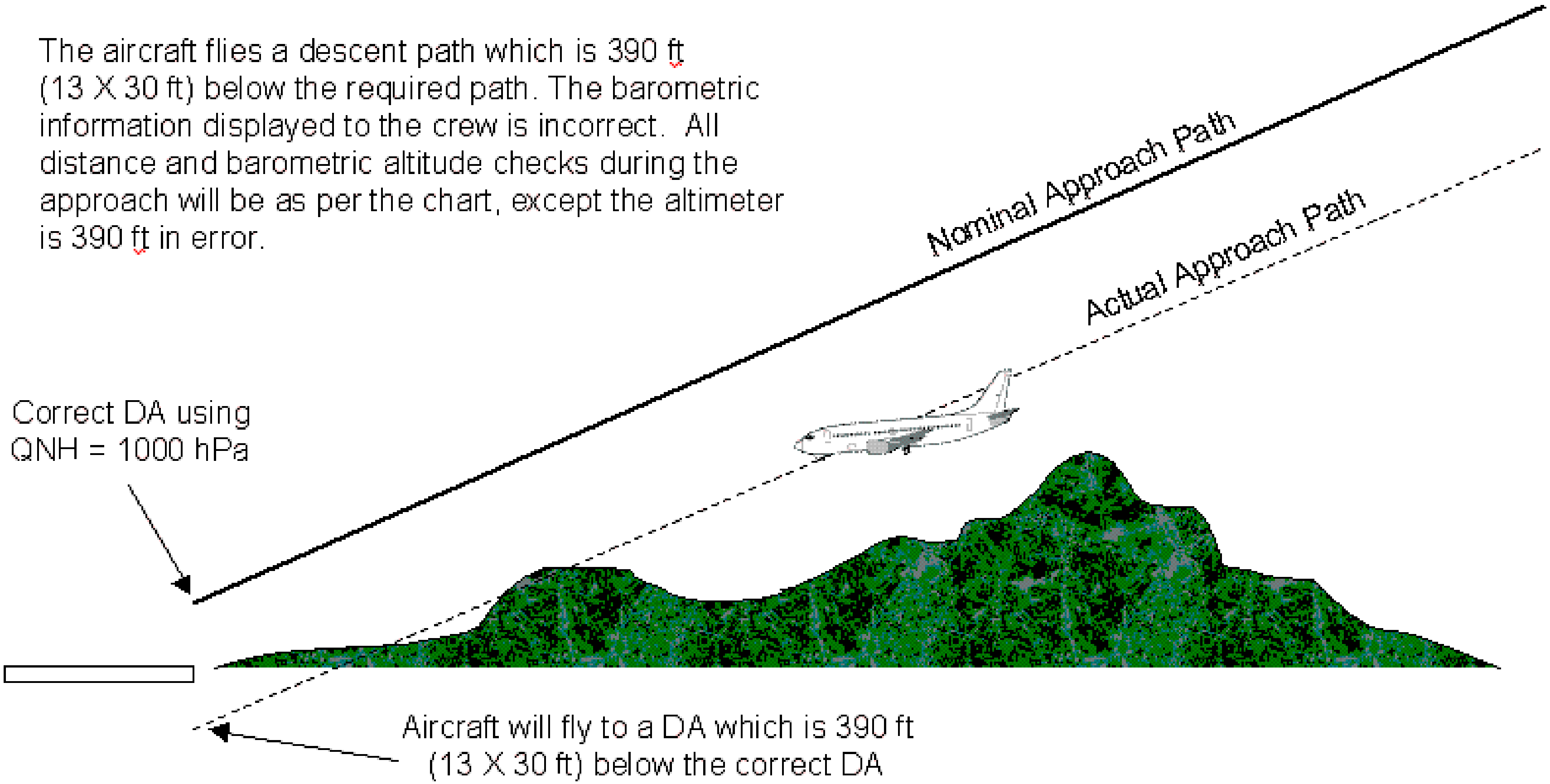
➢ Altimeter Setting Error



❖ Baro VNAV (Cont')

➢ Altimeter Setting Error

The aircraft flies a descent path which is 390 ft (13 X 30 ft) below the required path. The barometric information displayed to the crew is incorrect. All distance and barometric altitude checks during the approach will be as per the chart, except the altimeter is 390 ft in error.



Procedure Validation

- Ground Validation
  - Obstacle clearance
  - Charting
  - Coding
  - Flyability
- Flight Validation
  - Data verification
  - Obstacle verification (optional)
  - Flyability (workload, charting, manoeuvring)
  - Infrastructure
- Database Validation

Procedure Validation

- Ground Validation
  - Obstacle clearance
    - Independent review by procedure designer
  - Charting
    - Independent review
  - Coding
    - Software tool
    - Expert review
  - Flyability – software tools (from PC-based to full flight simulator)
    - Not necessarily an issue with standard procedures (e.g. 'T' approaches), but critical for some aircraft types
    - Range of aircraft and meteorological conditions

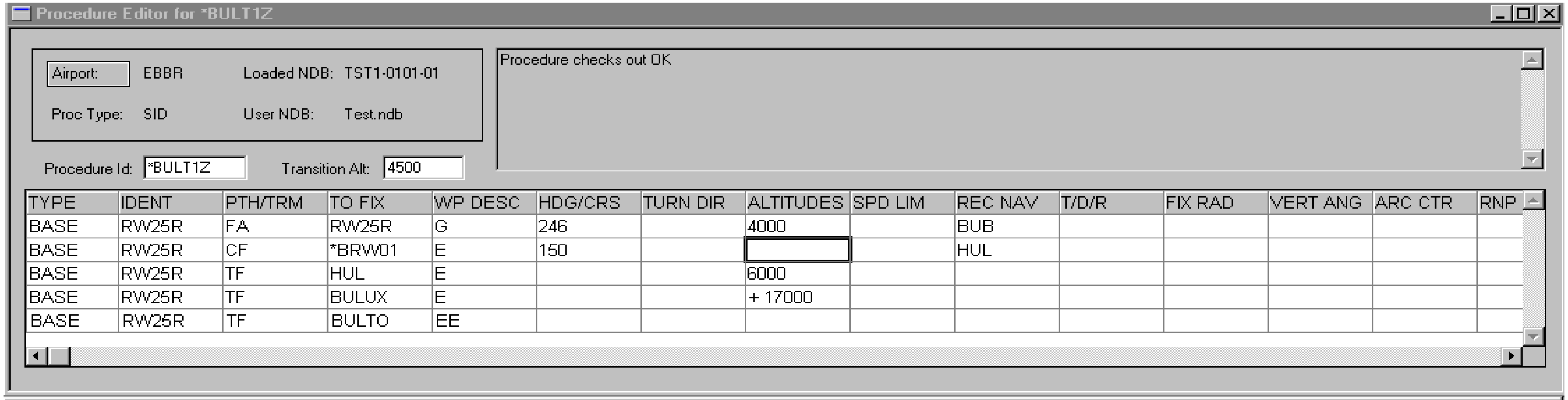
Independent review – can be part of same organization

Procedure Validation

- **Flyability**
  - Independent assessment
  - Use of validation tools
  - Use of aircraft simulators
    - more than one type
  - Flight checks
  - Initial operational checks

Procedure Validation

❖ Validation tools



Procedure Editor for *BULT1Z

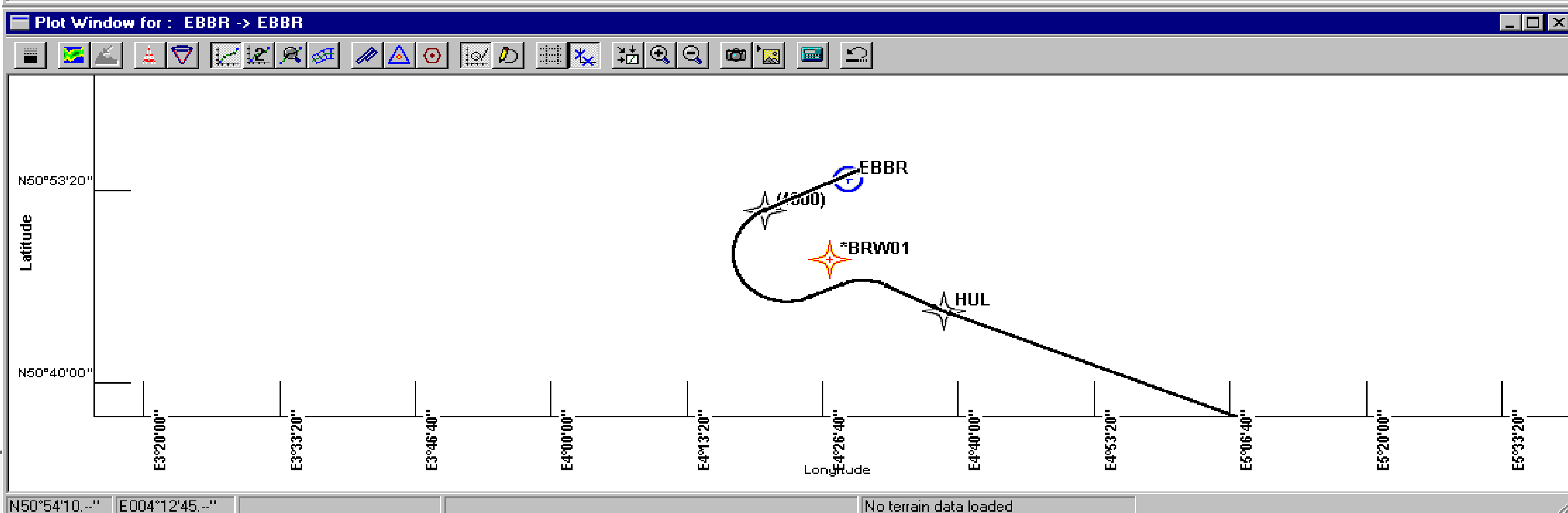
Airport: EBBR Loaded NDB: TST1-0101-01

Proc Type: SID User NDB: Test.ndb

Procedure checks out OK

Procedure Id: *BULT1Z Transition Alt: 4500

TYPE	IDENT	PTH/TRM	TO FIX	WP DESC	HDG/CRS	TURN DIR	ALTITUDES	SPD LIM	REC NAV	T/D/R	FIX RAD	VERT ANG	ARC CTR	RNP
BASE	RW25R	FA	RW25R	G	246		4000		BUB					
BASE	RW25R	CF	*BRW01	E	150				HUL					
BASE	RW25R	TF	HUL	E			6000							
BASE	RW25R	TF	BULUX	E			+ 17000							
BASE	RW25R	TF	BULTO	EE										



Procedure Validation

❖ Validation tools

Procedure Editor for *BULT1Z

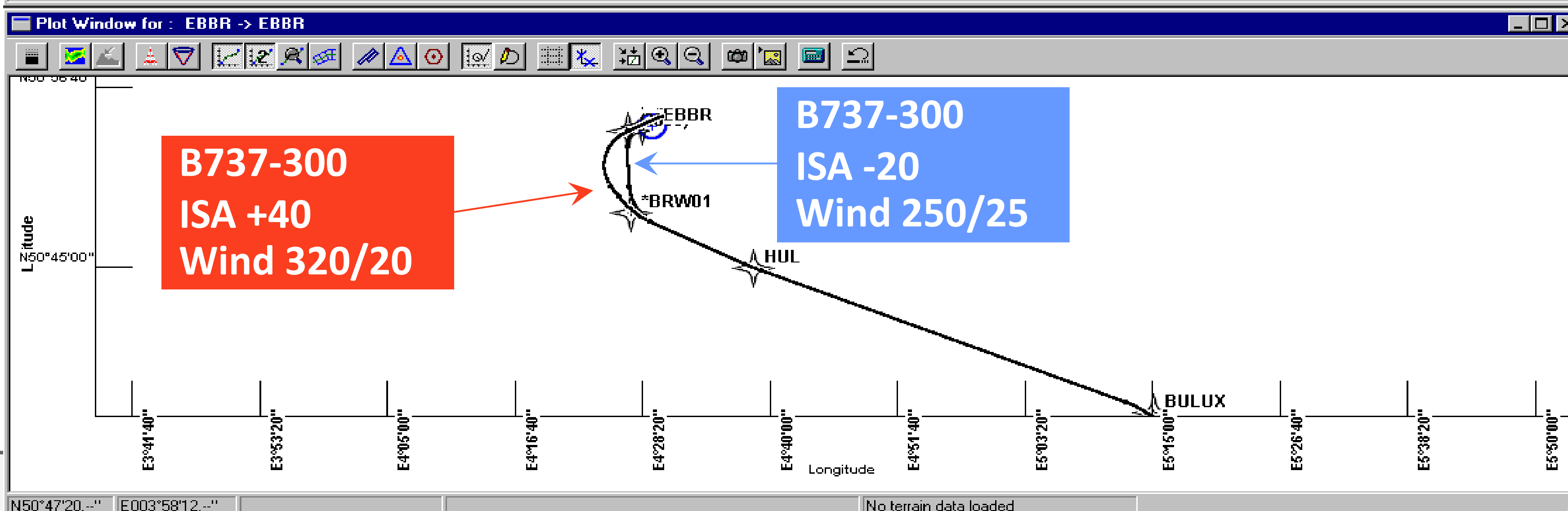
Airport: EBBR   Loaded NDB: TST1-0101-01

Proc Type: SID   User NDB: Test.ndb

Procedure Id: *BULT1Z   Transition Alt: 4500

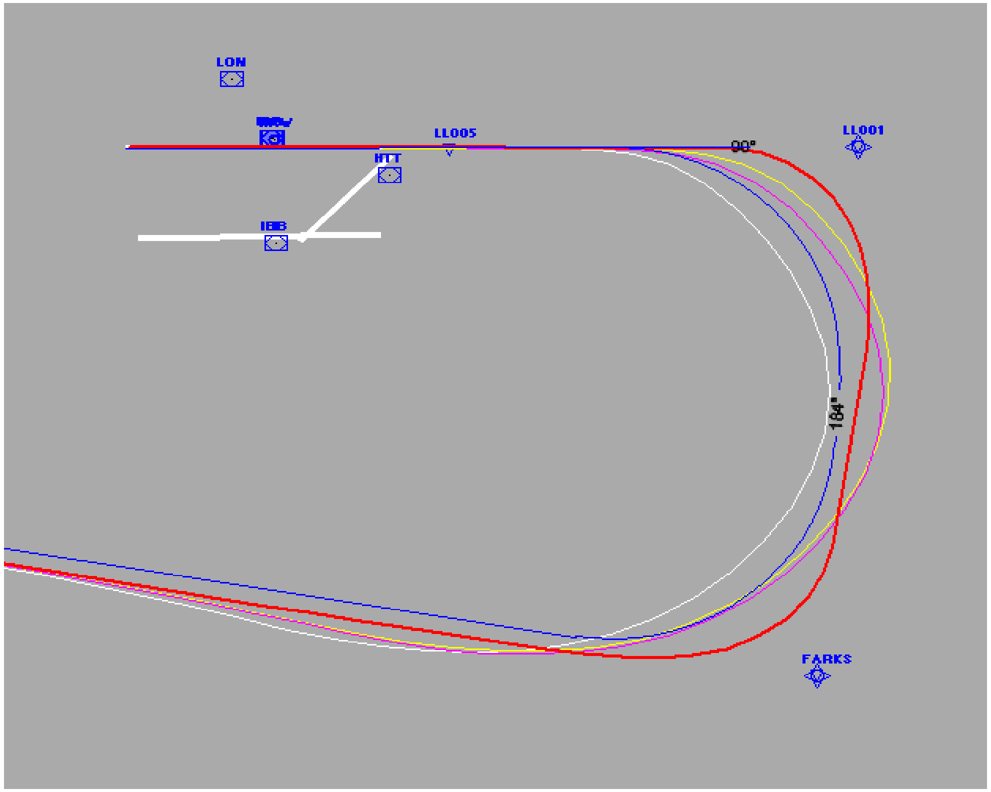
Procedure checks out OK

TYPE	IDENT	PTH/TRM	TO FIX	WP DESC	HDG/CRS	TURN DIR	ALTITUDES	SPD LIM	REC NAV	T/D/R	FIX RAD	VERT ANG	ARC CTR	RNP
BASE	RW25R	FA	RW25R	G	246		2000		BUB					
BASE	RW25R	DF	*BRW01	E										
BASE	RW25R	TF	HUL	E			6000							
BASE	RW25R	TF	BULUX	E			+ 17000							
BASE	RW25R	TF	BULTO	EE										



Procedure Validation

- Different Aircraft and Different Conditions



CA 500ft AGL; DF LL001; TF FARKS; TF…

No wind designed path

A319

B737/400

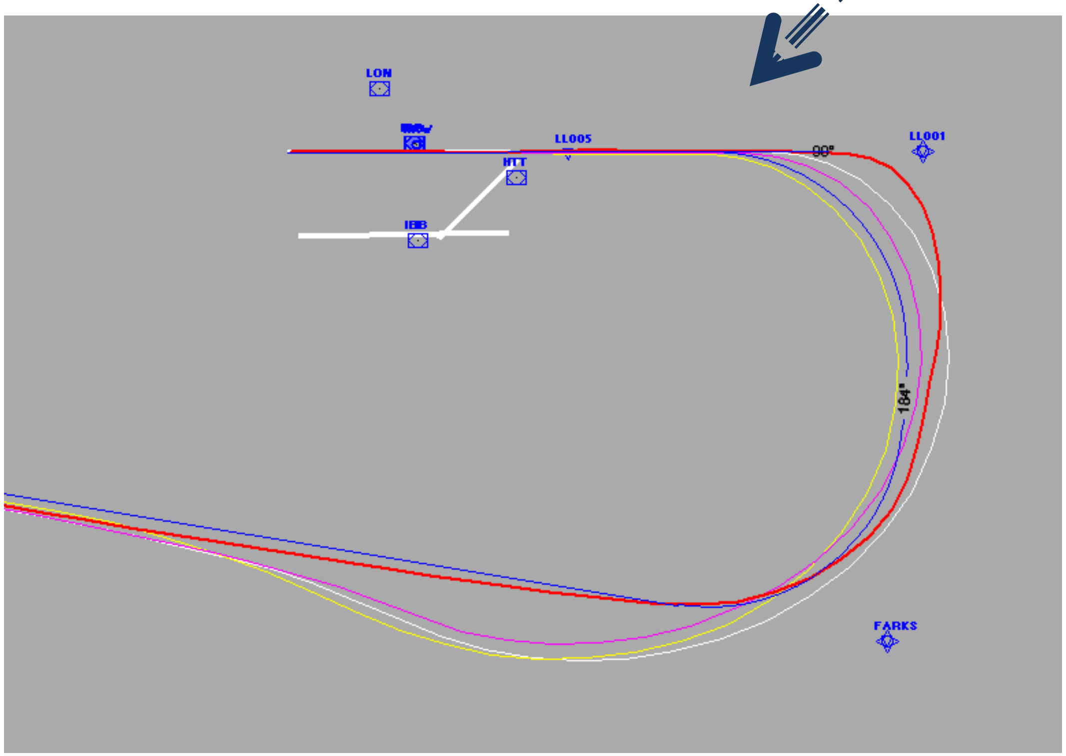
B747/400

A340/300

A320/319

Procedure Validation

- Different Aircraft and Different Conditions
  - Wind Effect



CA 500ft AGL; DF LL001; TF FARKS; TF…

Wind from 045°

A319

B737/400

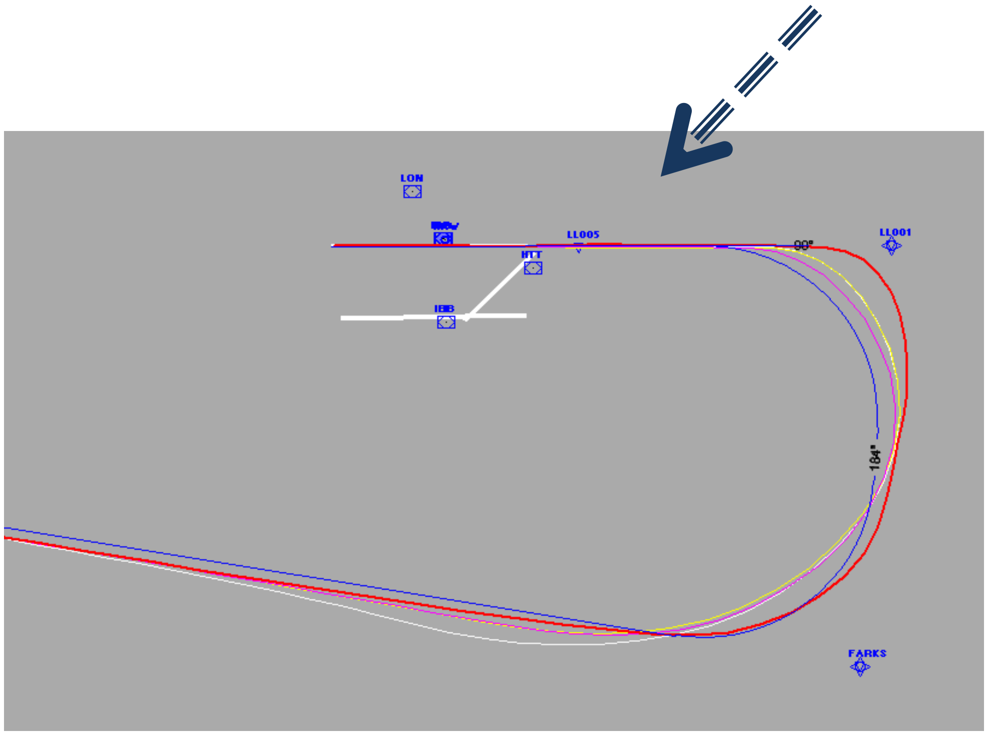
B747/400

A340/300

A320/319

Procedure Validation

- Different Aircraft and Different Conditions
  - Mitigation by speed restrictions



CA 500ft AGL; DF LL001; TF FARKS [*210kts*]; TF…

Wind from 045°

A319

B737/400

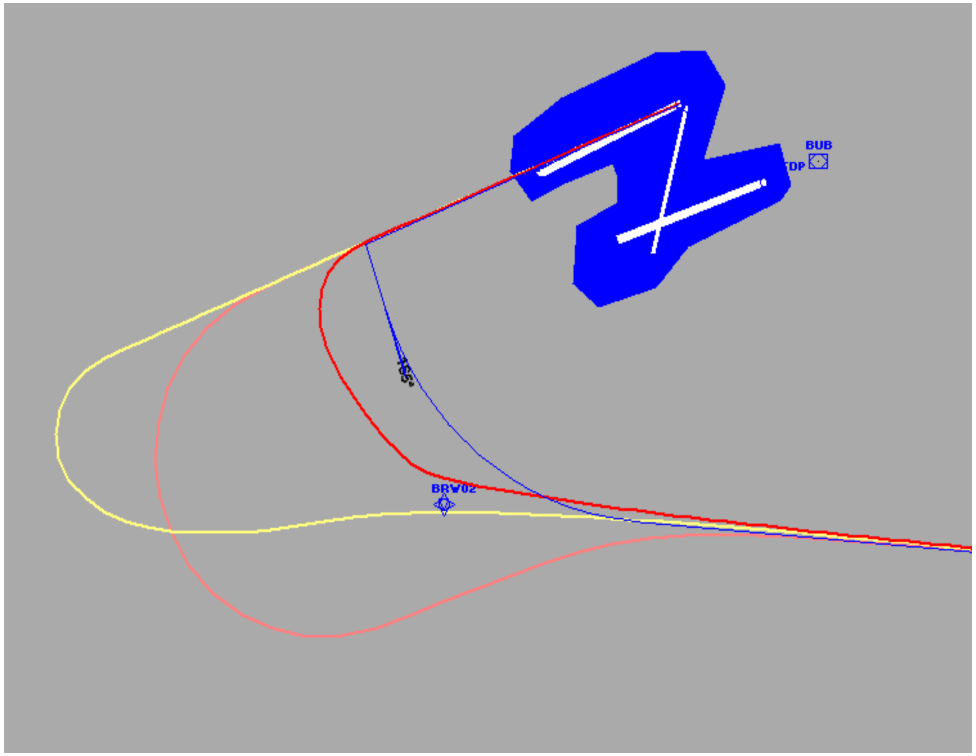
B747/400

A340/300

A320/319

Procedure Validation

- Different Aircraft and Different Conditions
  - Leg length – too short



CA 2000ft AGL; DF BRW02

No wind

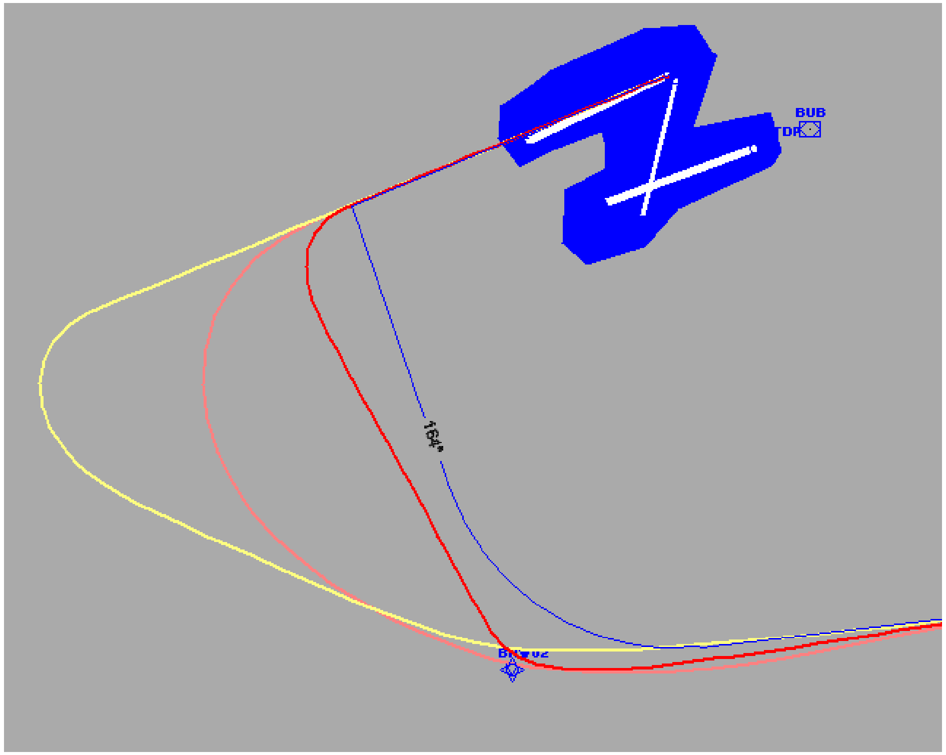
ATR42

B 747-400

A340-300

Procedure Validation

- Different Aircraft and Different Conditions
  - Leg length – Acceptable



CA 2000ft AGL; DF BRW02

No wind

ATR42

B 747-400

A340-300

Procedure Validation

- **Flight Validation**
  - **Obstacle verification**
    - **Has full obstacle survey been completed**
    - **TAWS / GPWS alerts**
  - **Flyability**
    - **Detailed workload and charting assessments**
    - **High level qualitative assessment of manoeuvring via accurate flight simulator**
  - **Infrastructure assessment**
    - **Runway markings, lighting, communications, navigation, etc.**

Procedure Validation

- **Flight Inspection**
  - **Flight Inspection often confused with Validation**
  - **Flight Inspection Addresses:**
    - **Navaid performance and reception for DME/DME**
    - **Unintentional interference for GNSS**
  - **Flight Validation may not fully address NAVAID Infrastructure issues (example: inspect DME/DME reception)**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European and North Atlantic (EUR/NAT) Office Paris
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Eastern and Southern African (ESAF) Office Nairobi
Asia and Pacific (APAC) Office Bangkok
Asia and Pacific Regional Sub-Office Beijing (APAC RSO)

Questions?


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Thank You