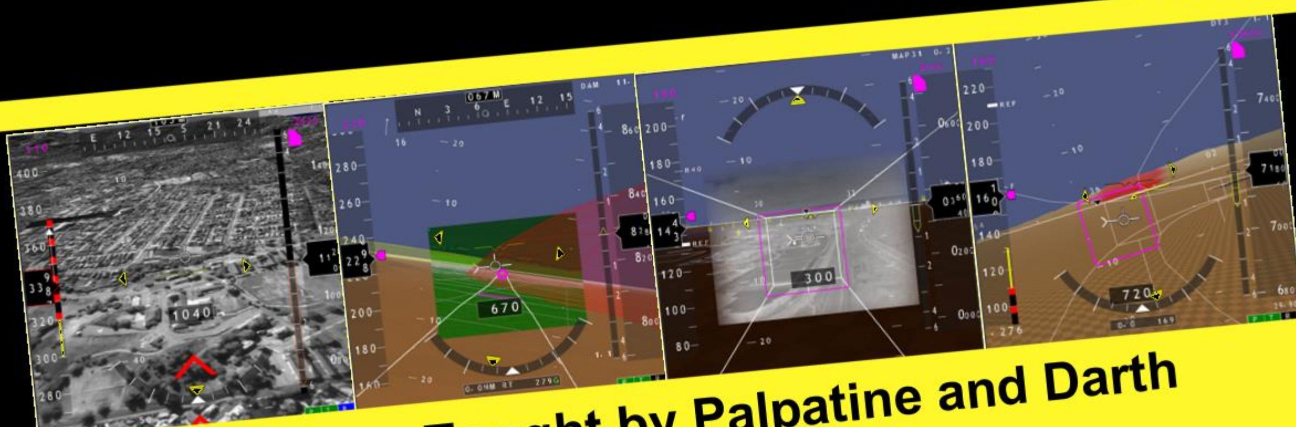
Your nuts-and-bolts guide to the power of synthetic vision

Synthetic Vision FOR DUMMIES®

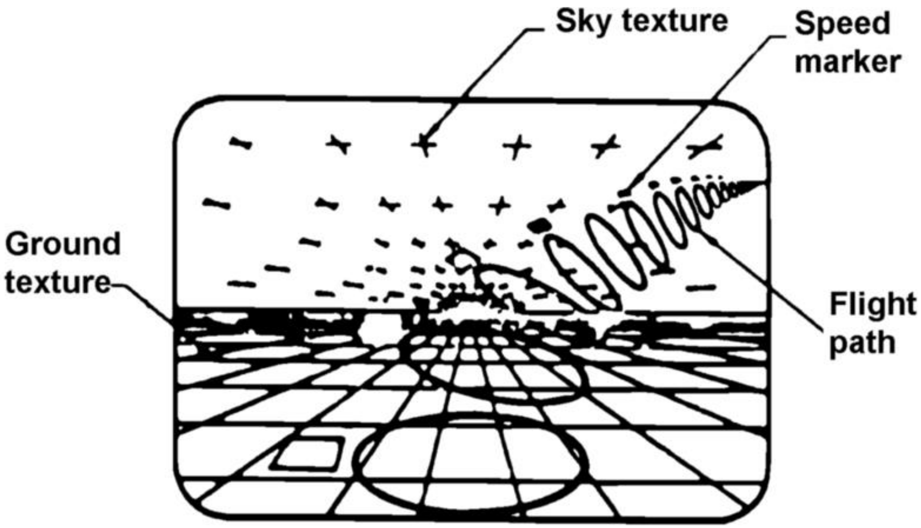


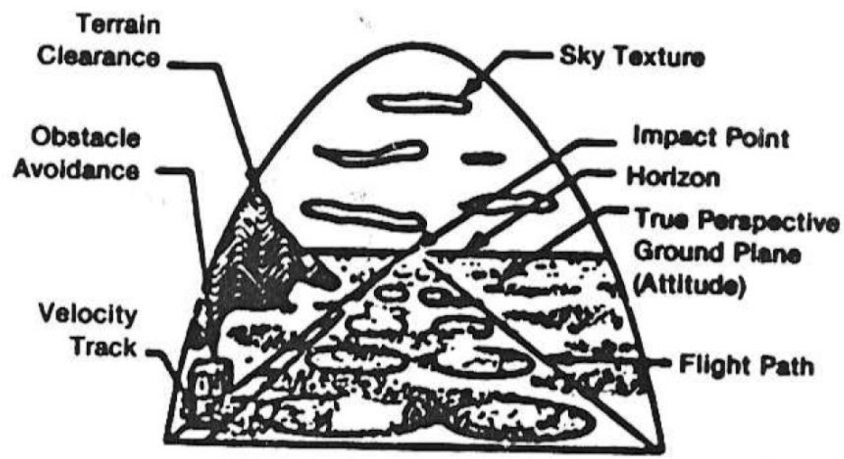
Tought by Palpatine and Darth

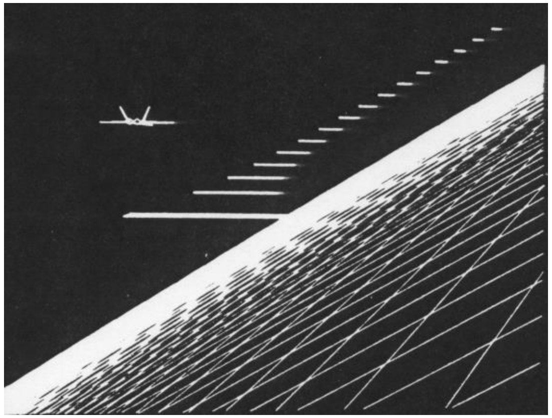
Topics

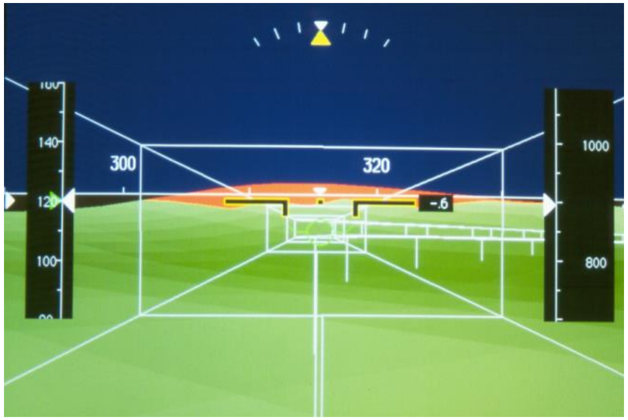
- What is SVS
  – Examples from 50’s & 60’s contact analog to SV products today
  – Reasons to pursue SV
- Design questions
  – Content (terrain, constraints, hazards, guidance)
  – Representation (geometry, color, textures)
  – Mapping to the display (projection)
  – Integration of sensor images
- From design to implementation
  – Data requirements
  – Hardware and software

Examples


Sky texture
Speed marker
Ground texture
Flight path


Terrain Clearance
Sky Texture
Obstacle Avoidance
Impact Point
Horizon
True Perspective Ground Plane (Attitude)
Velocity Track
Flight Path

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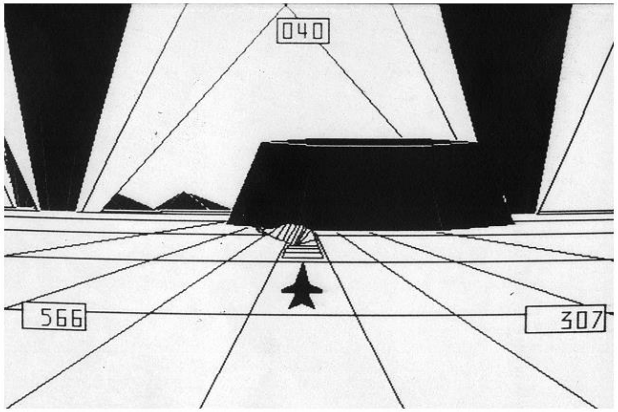
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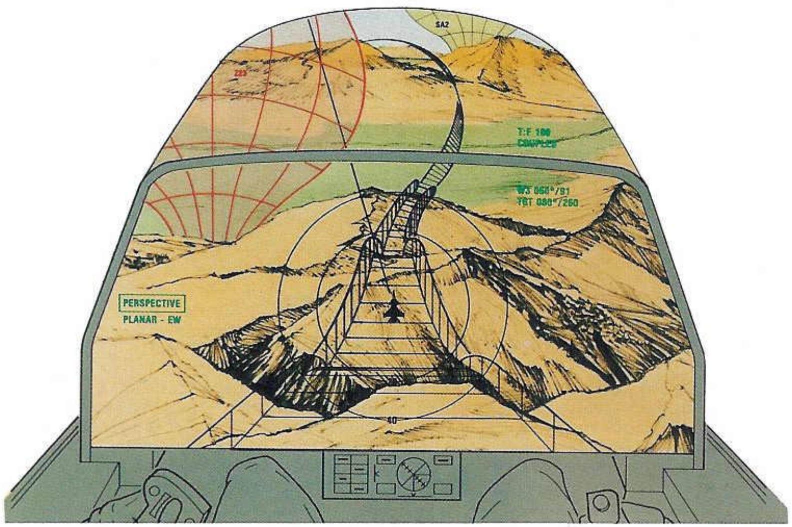
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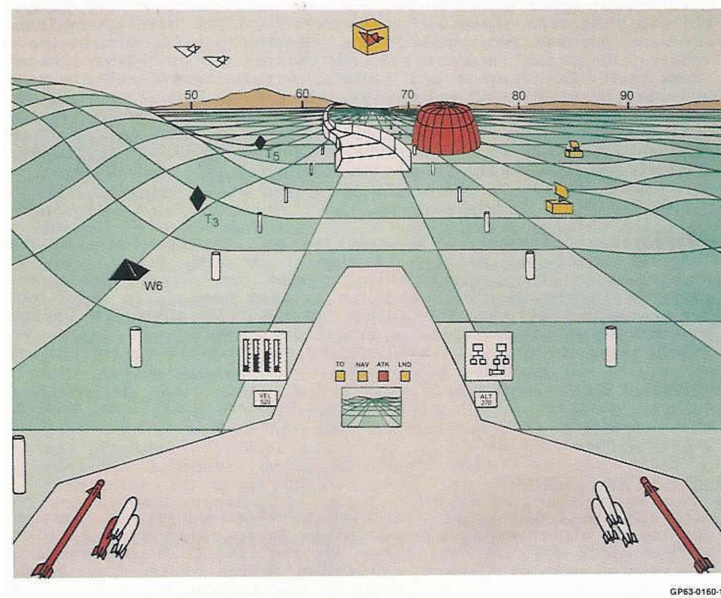
PLANAR - EW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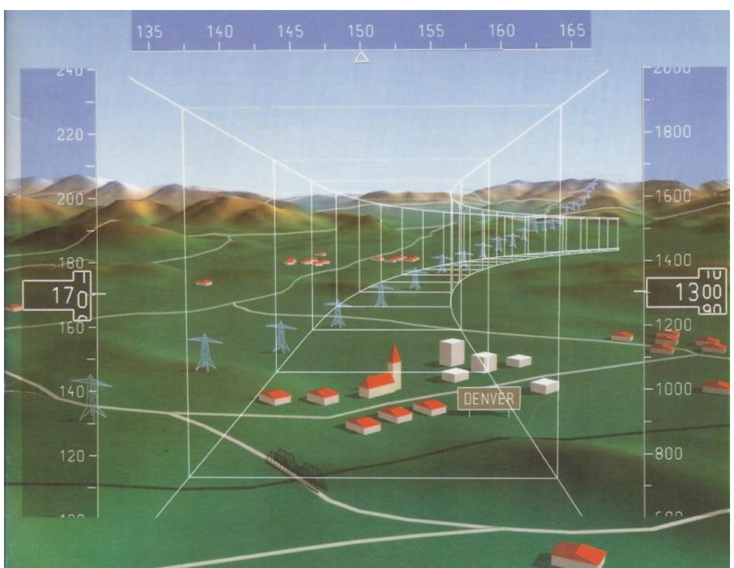
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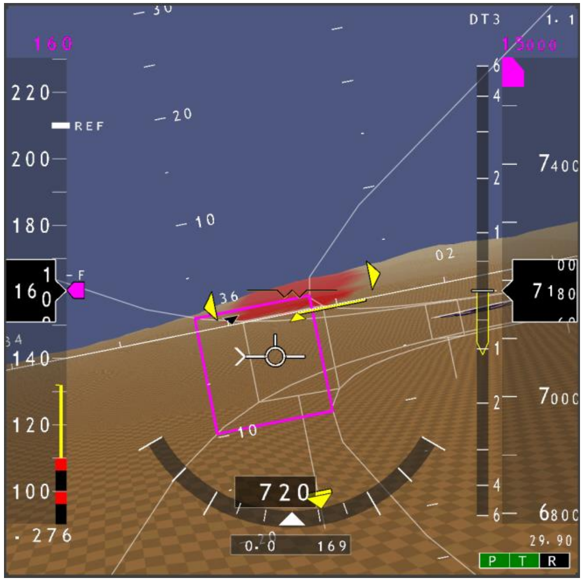
Examples



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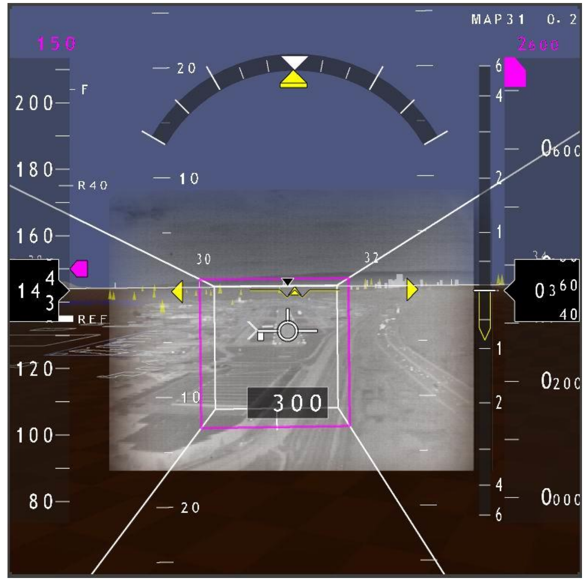

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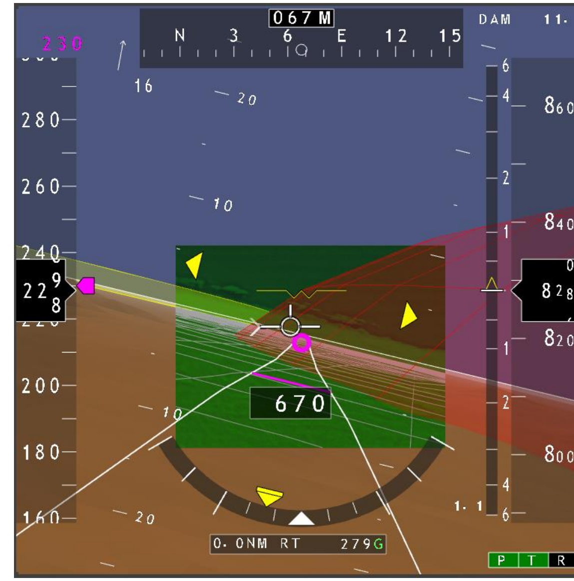

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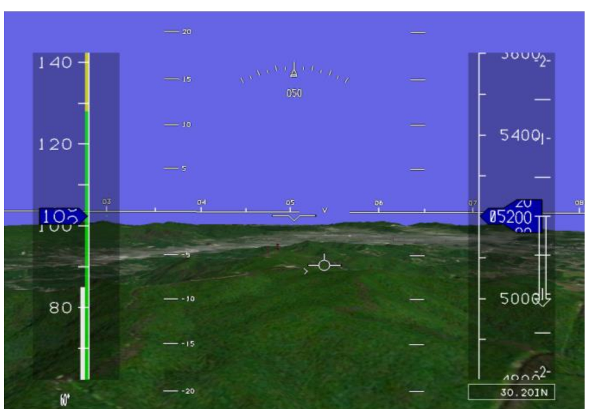

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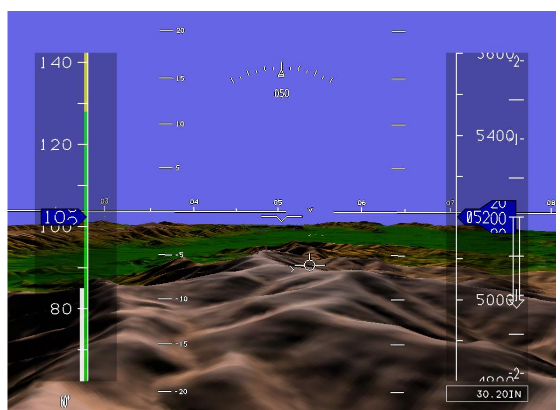

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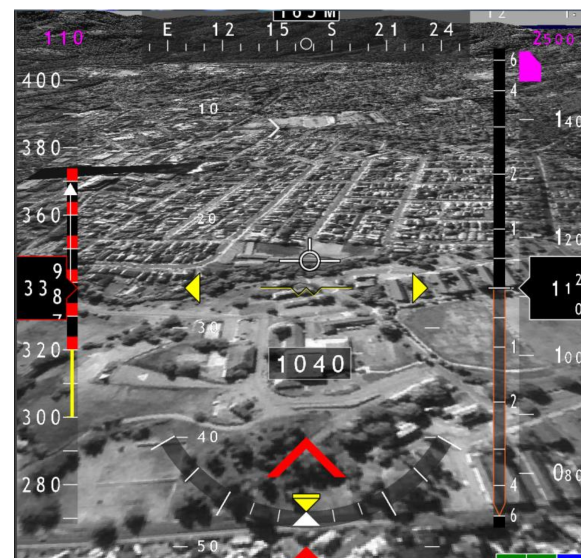

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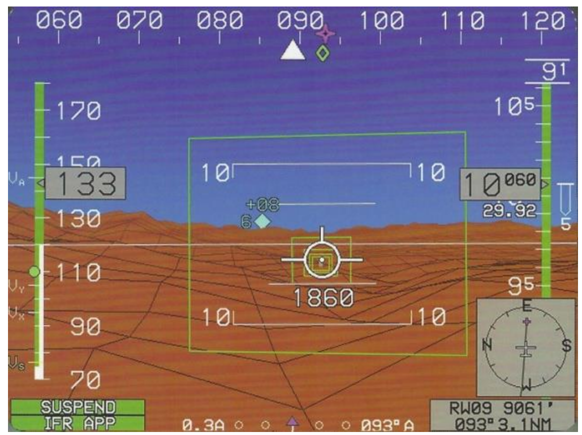
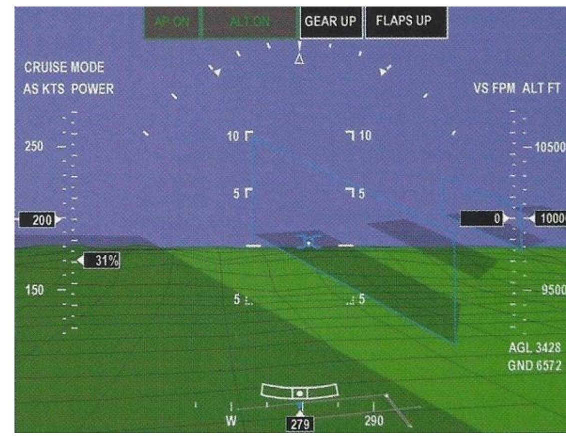
Examples


IFR APP
FMG 10000'
063° 6.0NM


SUSPEND
IFR APP
RW09 9061'
093° 3.1NM


GEAR UP
FLAPS UP
CRUISE MODE
AS KTS POWER
VS FPM ALT FT
AGL 3428
GND 6572


SMARTDECK

Summary

- Synthetic vision systems incorporate ideas that were first explored almost 60 years ago but never made it into a product until recently
- Some of the research projects that addressed SV:
  - Army Navy Instrumentation Program (ANIP) in the 1952-1963 period
  - Joint Army-Navy Aircraft Instrumentation Research (JANAIR)
  - NASA Aviation Safety Program

Summary

- SV is more than a computer generator depiction of the environment
- SV coined in the Nineties
- Many of the concepts include guidance information presented by means of a pathway
- Few of today's SV products include pathway guidance

Why Pursue SV?

- Often quoted reasons:
  - Compensate for the lack of direct visibility
  - Provide better visibility than is possible with the out-of-the-window view
  - Intuitively depict non-physical constraints and threats
- Expected results:
  - Improved terrain awareness
  - Improved conflict/threat awareness
  - Increase in safety and operational capabilities

- SV is seen as an enabler in various CONOPS, both civil and military
  - Functional requirements differ between CONOPS
  - The requirements drive the design!

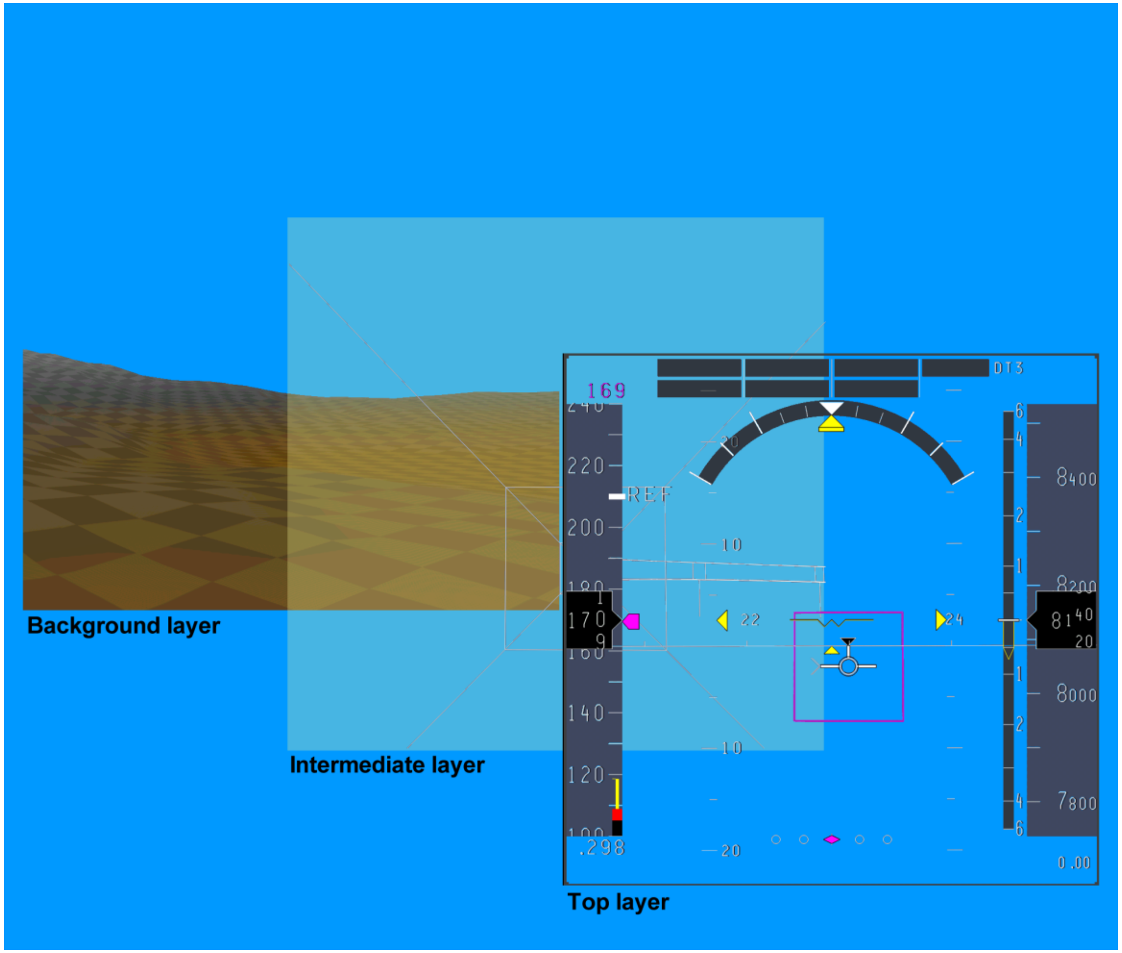
This tutorial

- SV is more than using CGI to replicate the visual environment, it can be regarded as an instrument that converts data into a presentation from which the required information can be obtained
- Like every other instrument, the design requires the consideration of the question how to represent the data in such a way that the information can be obtained:
  - With the required accuracy, timeliness and bandwidth,
  - while minimizing the mental effort required for perception, translation, integration and extrapolation
- This tutorial:
  - Addresses the main design questions that must be answered
  - Provides guidance for selecting between options and associated limitations
  - Provides an overview of the aspects involved when going from design to prototype implementation

Design questions

- Which data needs to be presented?
  - Terrain, obstacles, constraints, trajectory, primary flight information, guidance augmentation
- How should the data be represented?
  - 3D static and dynamic objects, matrices, 2D objects
  - Colors, textures
- How to map the representation onto the display?
  - Transformations, projections, clipping

Classification using 3 layers



- Top layer: Primary Flight Information
- Intermediate layer: Guidance preview
- Background layer: Awareness (terrain, obstacles, threats, conflicts)

Design guidance

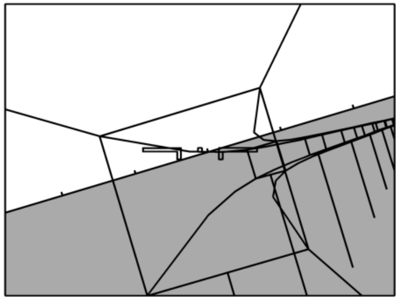
- The design of the SVS top layer with the Primary Flight Information relies on the same guidance as other Primary Flight Displays:
  - AC 25-11A Transport Category Airplane Electronic Display Systems
  - ARP 5364 Human Factor Considerations in the Design of Multifunction Display Systems for Civil Aircraft
  - ARP 4102/7 Electronic Displays

Design guidance

- For the intermediate layer (flightpath-based guidance), much information is available in published research
- The design options for the guidance layer and the environment layer are the topic of this tutorial
- Other guidance:
  - SAE ARP5589 Human Engineering Considerations for Design and Implementation of Perspective Flight Guidance Displays (2005)
  - SAE ARP5677 Human Engineering Considerations for Cockpit Integration of Enhanced/Synthetic Vision Systems (status: Work in Progress)
  - RTCA SC-213 DO-315B (3.3 SVS for Lower than Standard Minima)

Overview

- Terrain, obstacles and other hazards/ constraints
  - Awareness
  - Conflict detection
- The guidance layer
  - Temporal range information
  - Emergent features
- Mapping the data to a viewport
- Guidance augmentation
- From design to implementation



Terrain, obstacles and other hazards/constraints

Source data and 3-D models

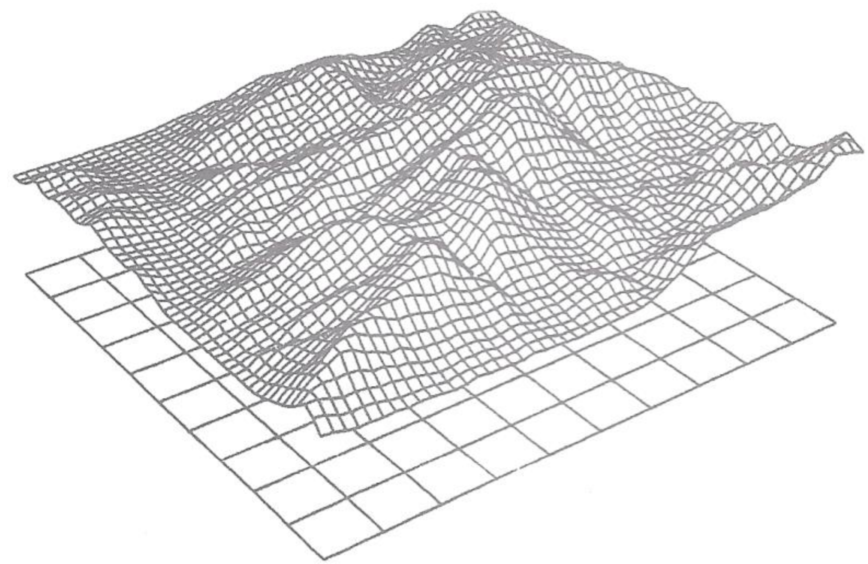
- Digital Terrain Elevation Data
- Obstacle data
- Digital Feature Analysis Data
- Special Use Airspace
- Trajectory data
- Traffic data

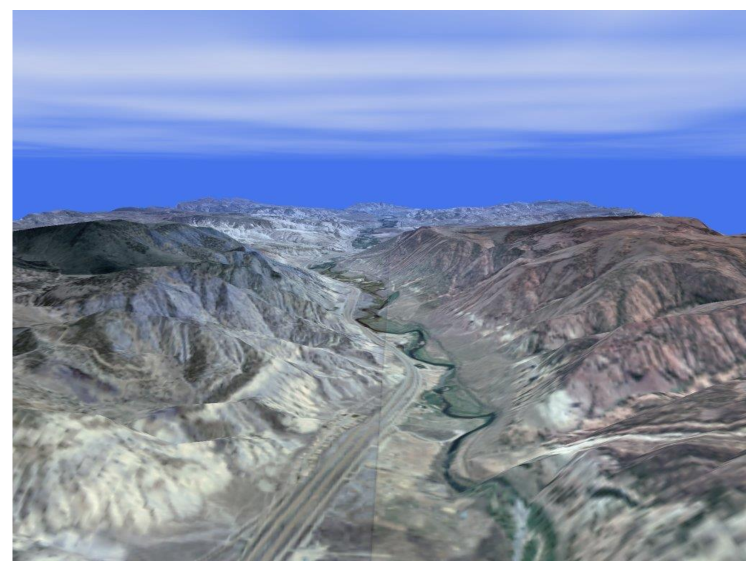
From data to representation

- The terrain data that is used to generate the synthetic terrain presentation can be divided into:
  - Data that describes the shape of the terrain (elevation data) and
  - Attributes that provide information on other terrain features
    - Color coding for absolute or relative terrain altitude
    - Lighting and textures to emphasize terrain features
- The representation of terrain can vary from an abstract set of dots indicating the elevation points, to a photo-realistic image based on textures derived from pictures of the actual terrain

Terrain object

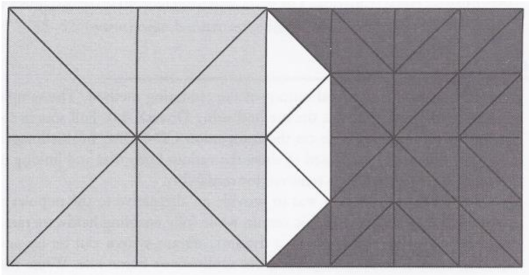
- The shape of the synthetic terrain is determined by the elevation points in a grid that when connected form a terrain "mesh"
- The accuracy with which the terrain mesh matches the shape of the real terrain is dependent on the accuracy and resolution of the available terrain elevation data
- The fidelity/realism of the representation can be increased by draping a textured terrain skin that resembles the real terrain over the mesh

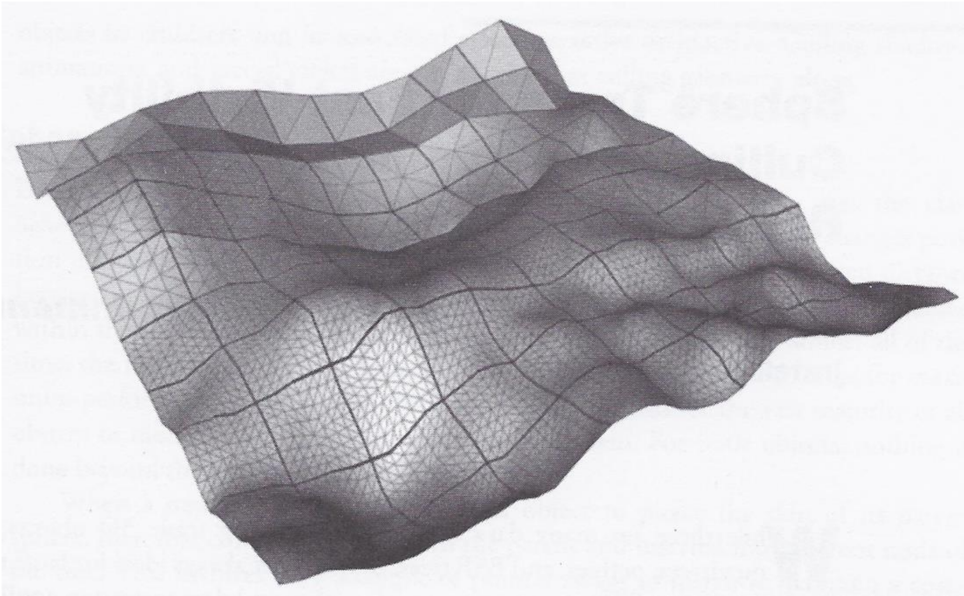




Terrain object

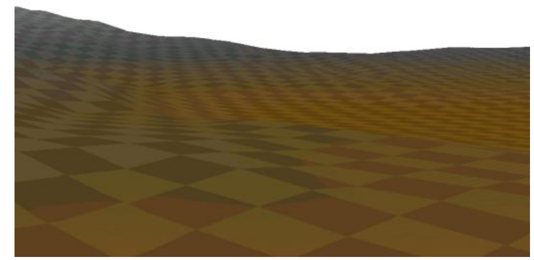
- When a perspective projection is used, the visible resolution is inversely proportional to the viewing distance
- The resolution of terrain elevation data is typically defined as the distance between two elevation samples expressed in arc-seconds. One arc-second resolution corresponds to a distance of approximately 30 meters latitude.
- To limit the number of required transformations, multiple levels of detail are typically used in the terrain object





Terrain skin representations

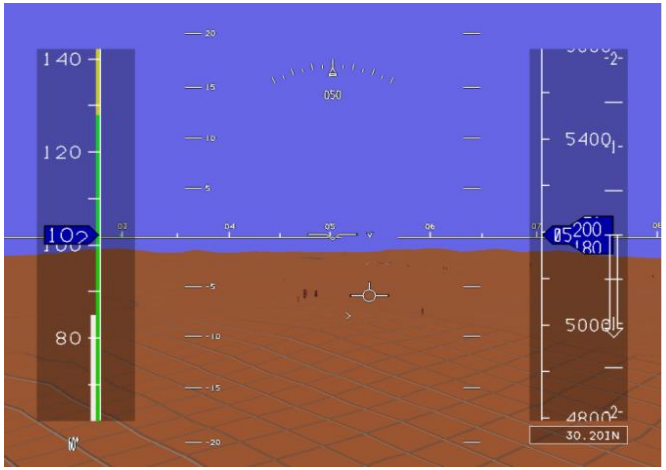
- Terrain textures can be classified into:
  - Geometric patterns
  - Rule-based patterns / textures
  - Photographic textures

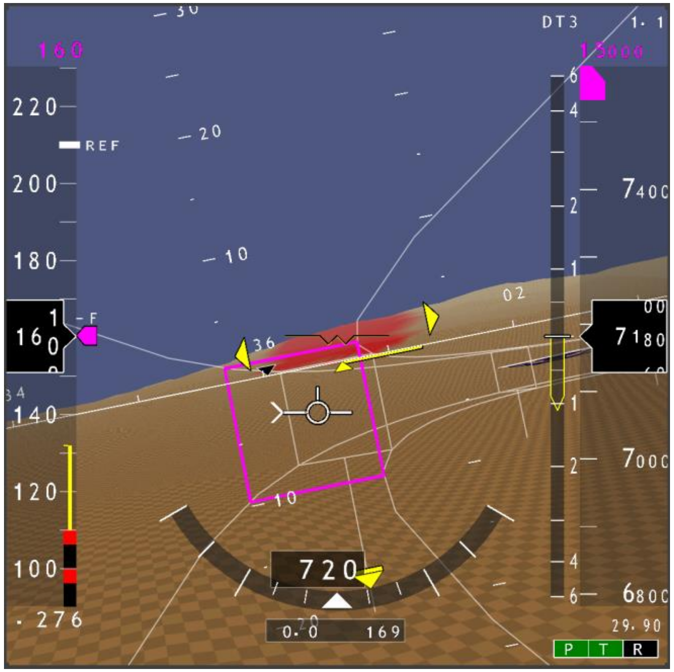


- Reasons to choose a particular texture comprise:
  - Increase the conveyed realism
  - Integrate navigational information
  - Control the spatial frequency
  - Emphasize geometric features

Geometric pattern textures

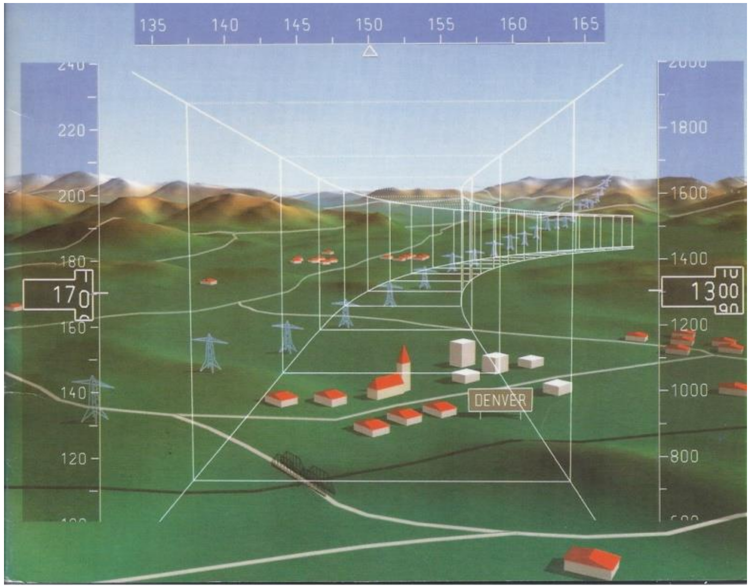
- Wireframe or checkerboard
  - Adds a perspective gradient and optical compression cues
  - Combines well with color coding
  - Emphasizes terrain shape
  - Provides consistent optic flow cues
  - Designer has full control over spatial frequency





Rule-based / generic textures

- A limited set of different textures can be used to suggest a high degree of visual realism, e.g.
  - Rock-type textures for steep slopes
  - Grass-type textures for flat areas
- Consistency and hence predictability
- Some, but limited possibility to combine with color coding



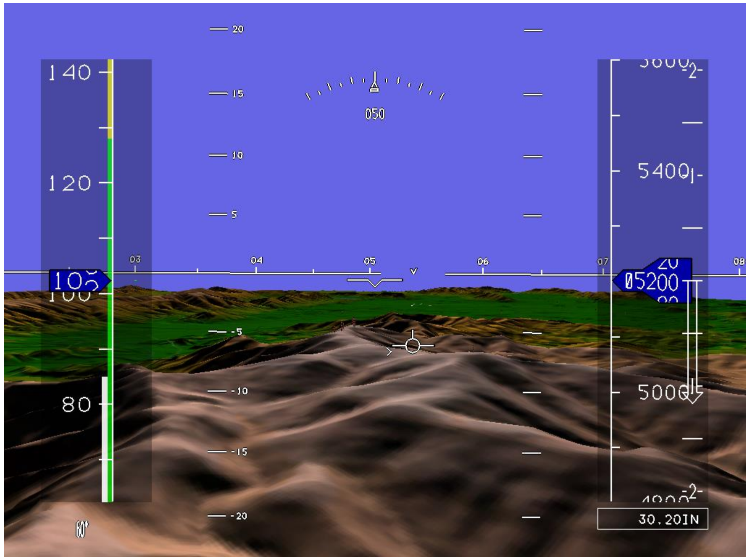
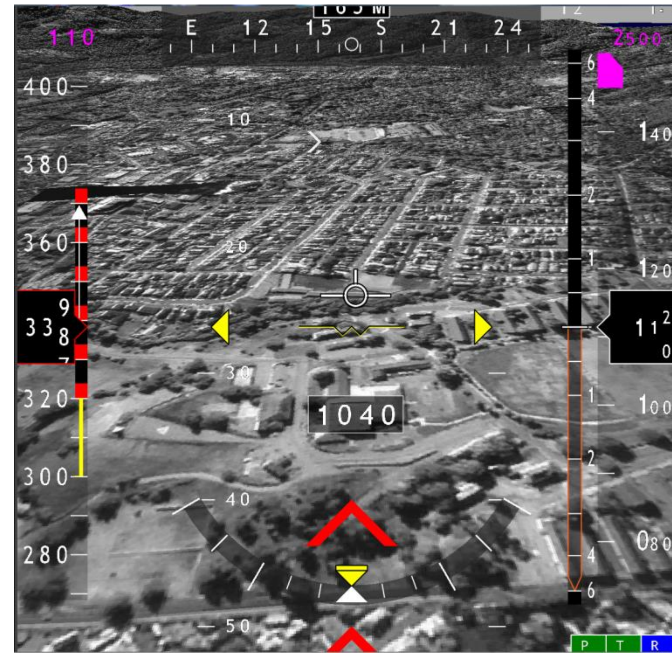
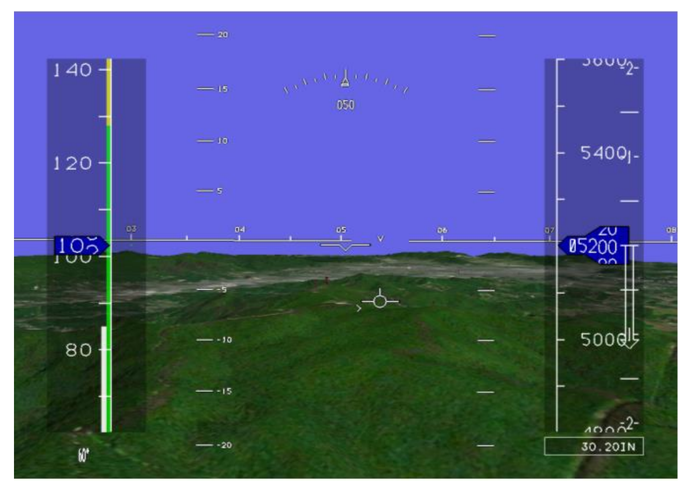


Photo-textures

- Sources
  - Aerial photography
- Very realistic synthetic environment
- Issues:
  - Never the real thing, e.g. due to seasonal effects
  - May weaken terrain shape cues as compared to regular patterns
  - Uncontrolled cue type and strength





Choosing the terrain skin

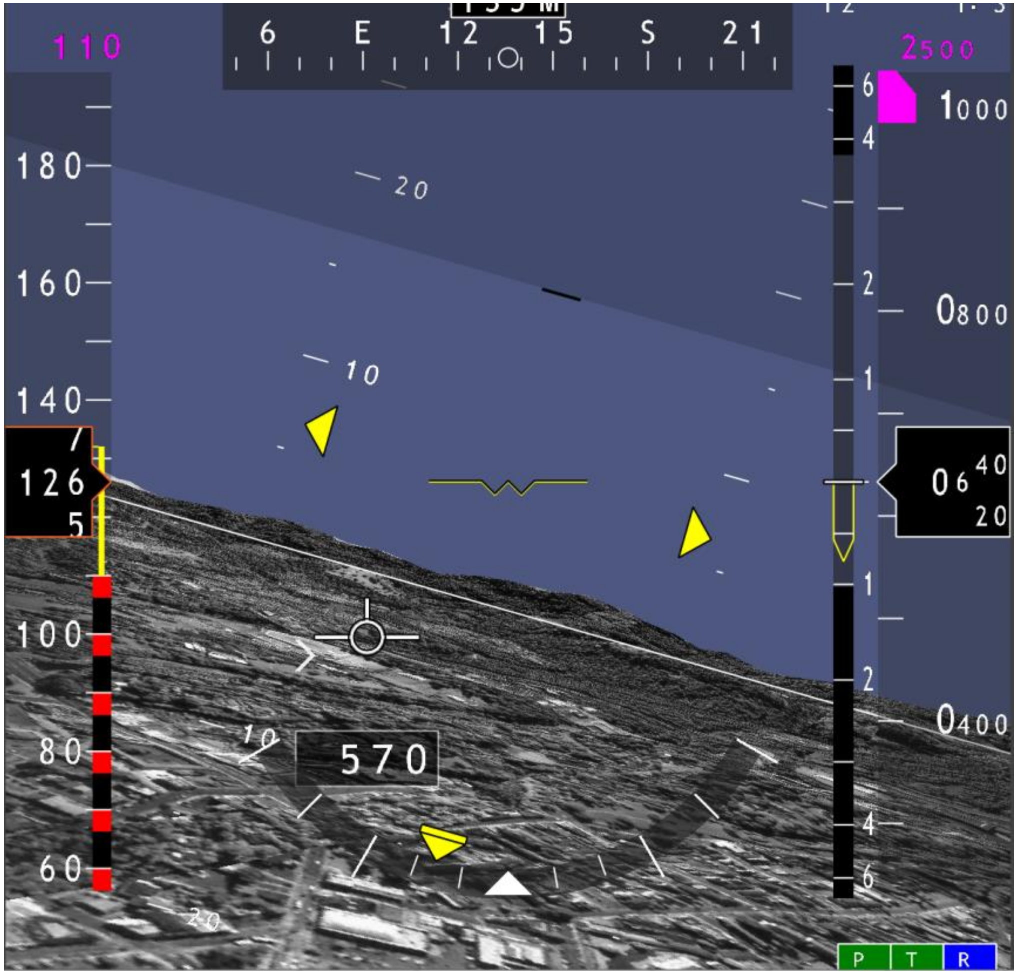
- The way data is presented influences the confidence people have in the correctness of the information they obtain from this data
- The higher the fidelity of the depiction of the terrain data, the likelier it is that pilots will believe it and disregard other information which tells them something is wrong!
- The fidelity of photo-realistic textures is NOT related to the integrity of the terrain elevation data used to construct the 3-D object onto which the texture is mapped

Choosing the terrain skin and color

- An advantage of SVS is that it can be used to emphasize important features in the outside world scene and de-emphasize or eliminate unimportant features
  - Color coding, to convey:
    - Elevation and/or (temporal) range information
    - Shape cues (through lighting)
  - Textures, to control:
    - Visual fidelity / realism
    - Spatial frequency / optic flow rate
    - Terrain shape emphasis

Choosing the terrain skin

- The most realistic presentation of the terrain is not necessarily the best option to convey the desired information

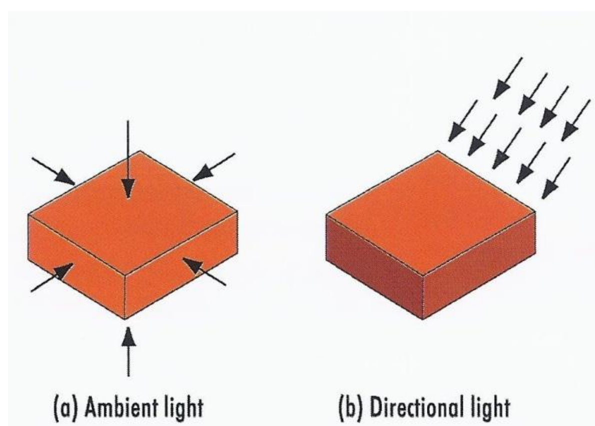


Color coding

- For elevation based color coding, a distinction can be made between:
  - *absolute coding* where color is a function of terrain elevation, and
  - *relative coding* where color is a function of the difference in elevation between a certain reference altitude (e.g., the altitude of ownship) and the terrain elevation.
- Range-based and directional color coding can be used to resolve ambiguities, provide (temporal) range information and/or emphasize relevant terrain for the current direction of flight

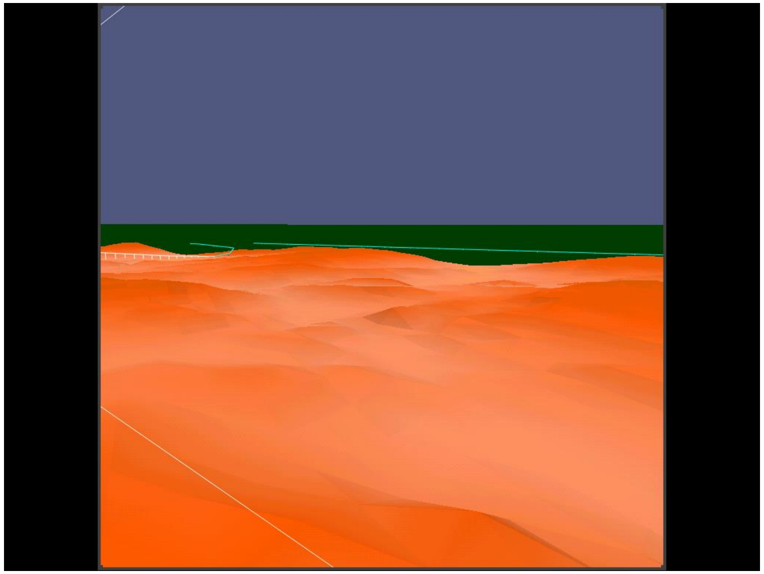
Color coding

- To emphasize terrain shape, the intensity of the color can be made a function of terrain slope, mimicking the concept of lighting. For example, if the intensity is reduced with an increase in slope, this is similar to a situation with a light source illuminating the terrain from above.

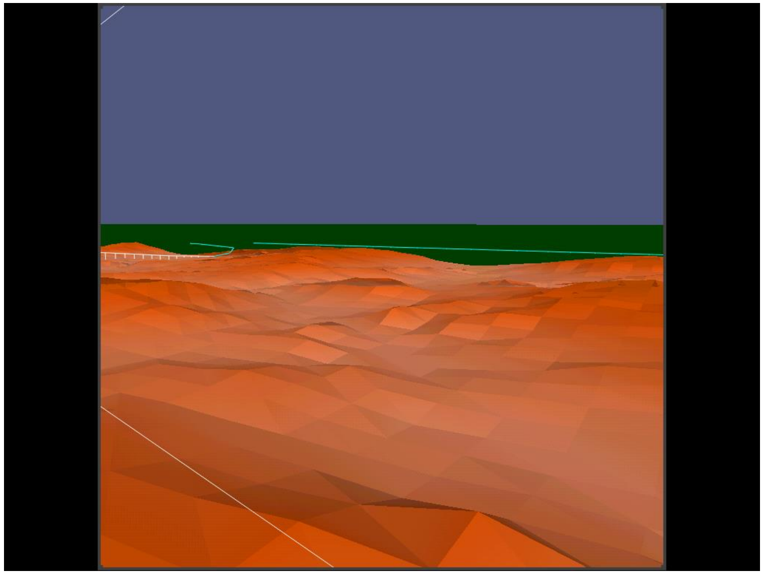


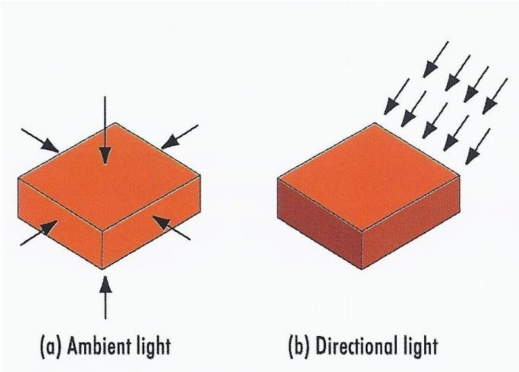
Slope-based color modulation

- Elevation-based color coding, ambient light



- Elevation-based color coding, directional light



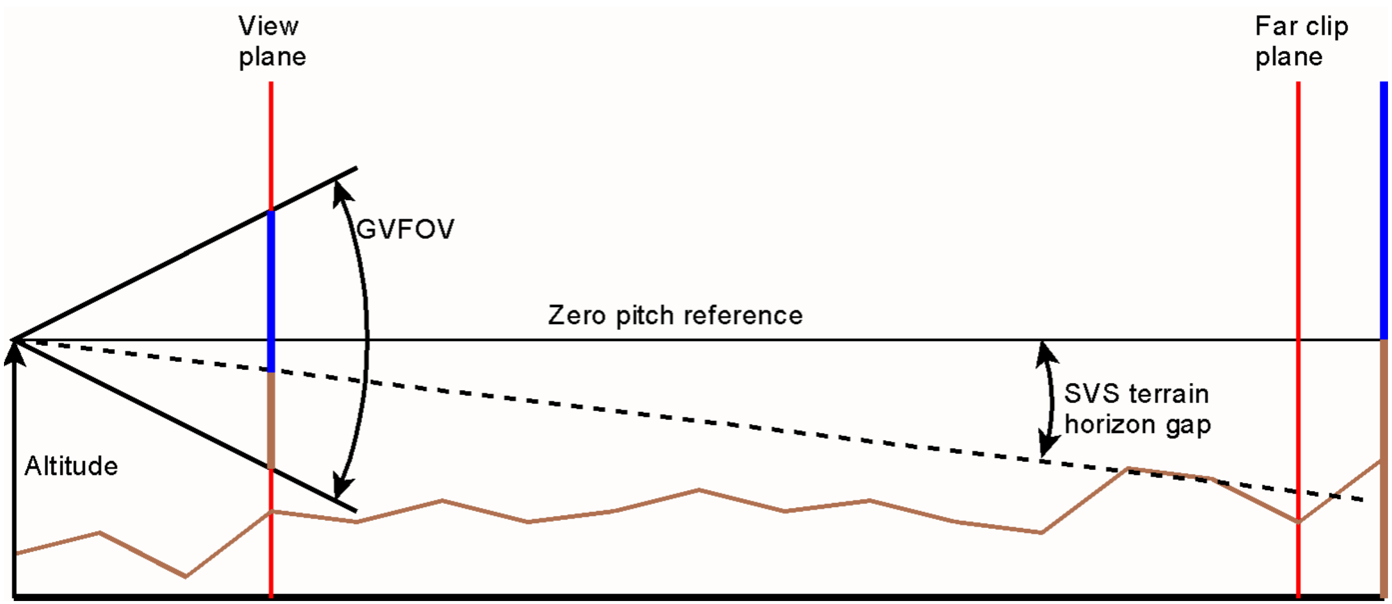


Fogging

- In computer graphics, fogging is used to convey an illusion of distance or atmospheric conditions
- In computer graphics, fogging is typically used to enhance realism
- Fogging is typically performed on a per-pixel basis
- The color of the pixel is a blend of the fog color and the color of the object pixel in which the amount of blending depends on the distance between the viewpoint and the pixel

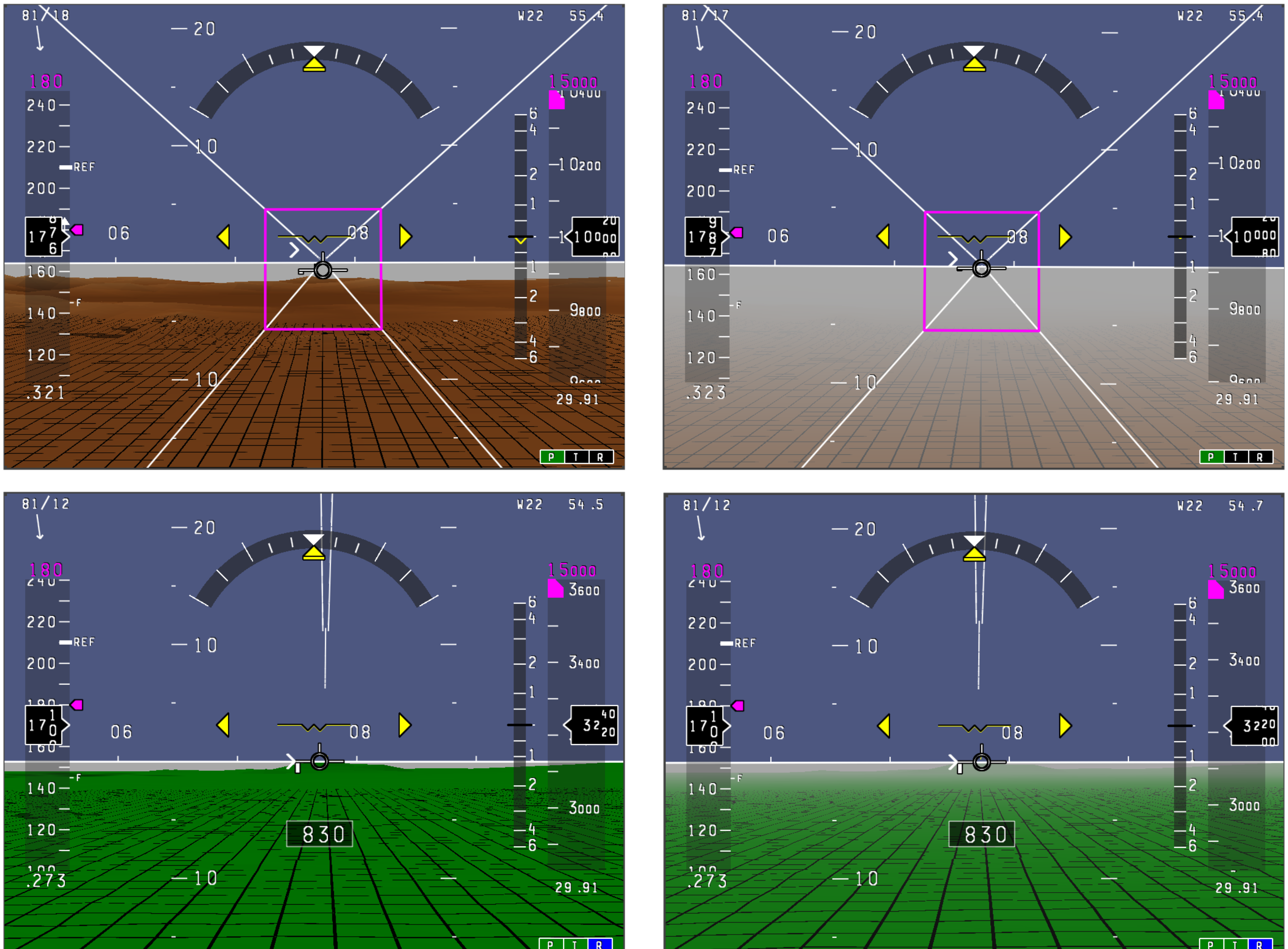
Fogging

- Unlike CGI, with SVS fogging is not intended to enhance visual realism
- The use of fogging will provide an additional depth cue
- With SVS, fogging can be used to:
  1. Emphasize nearby terrain
  2. Mask the (potential) gap between the true (pitch=0) horizon and the horizon suggested by the end of the visible terrain

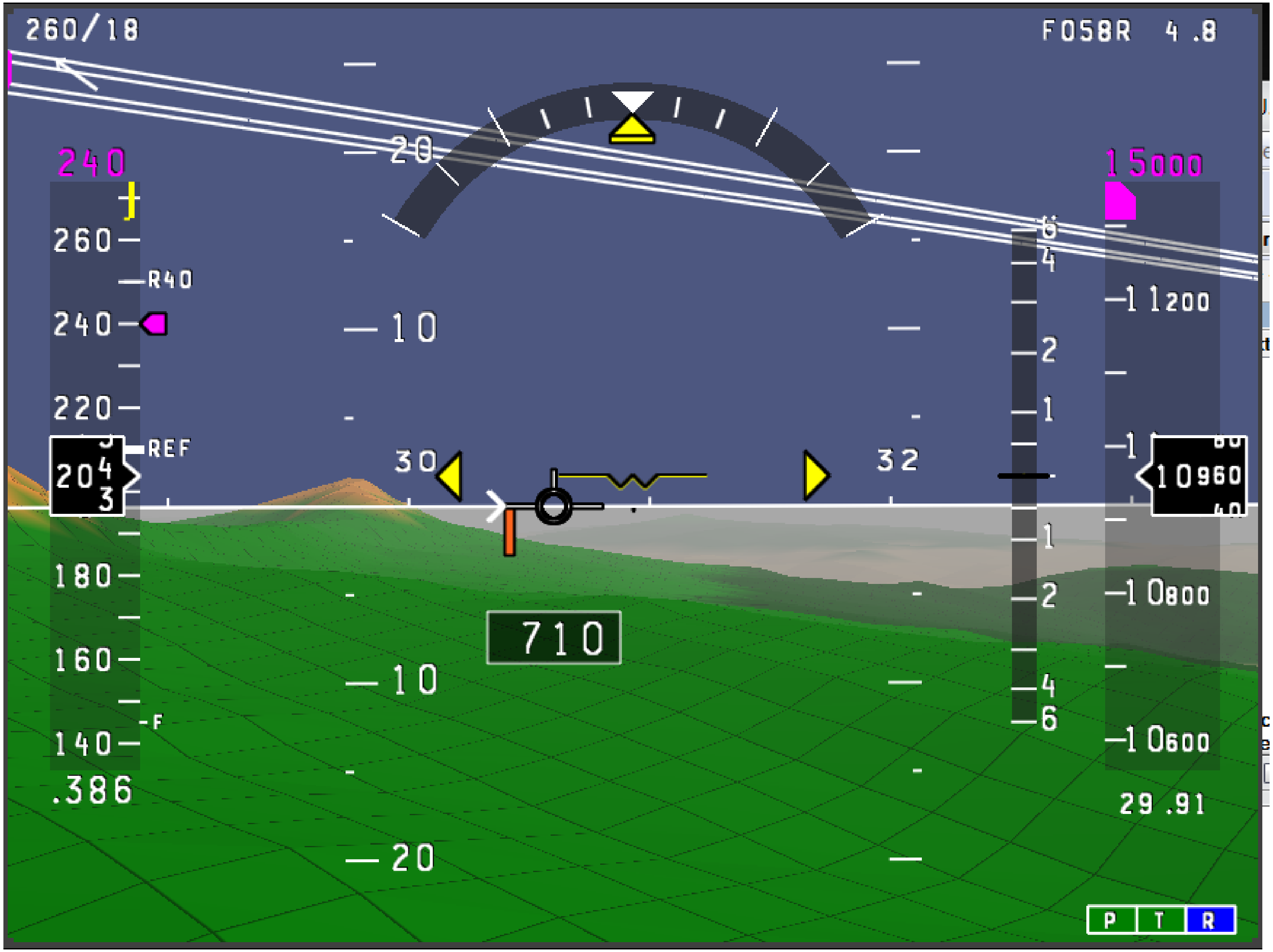


Fogging

- Blending the terrain into the horizon color

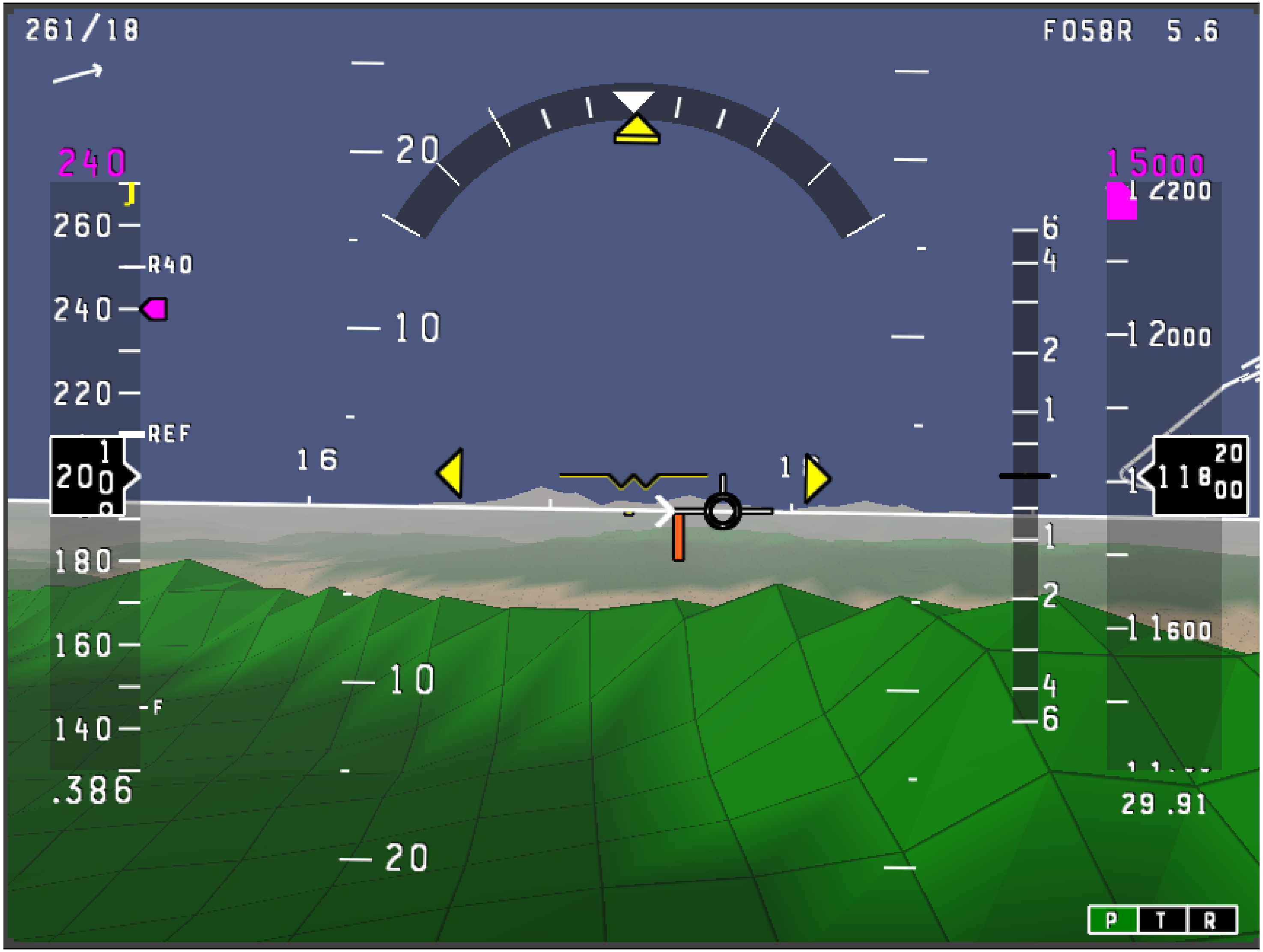


Use of fogging – example 2



The terrain is blended into the horizon color

Use of fogging – example 3



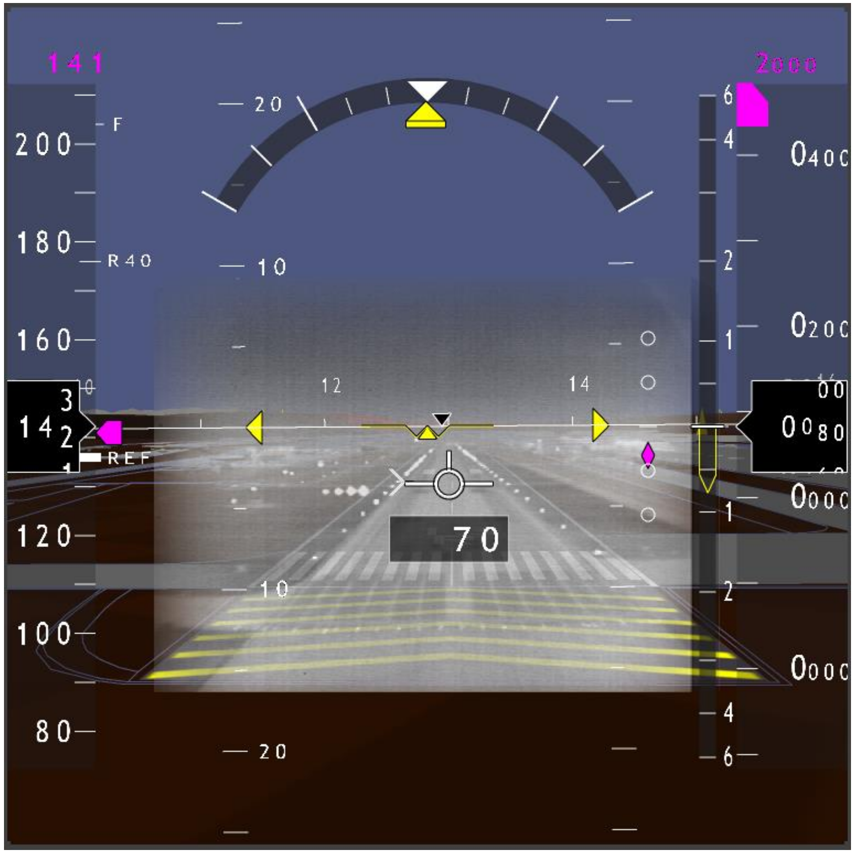
The ridge is more prominent due to the fogging

Integrating other data

- Airport data / runway database
  - DO-315B: Runway database accuracy and integrity shall be per ICAO Annex 15 and RTCA DO-201A
- Obstacle data
  - DO-315B: SV databases shall include all available physical hazards greater than 200 ft above ground level, not just terrain
  - DO-315B: Obstacles displayed shall be those deemed hazardous to the phase of flight
- Non-physical constraints
  - Static: Airspace
  - Dynamic: Separation boundaries with other traffic
- Sensor data
  - Integrated into SVS
  - Synthetic overlay

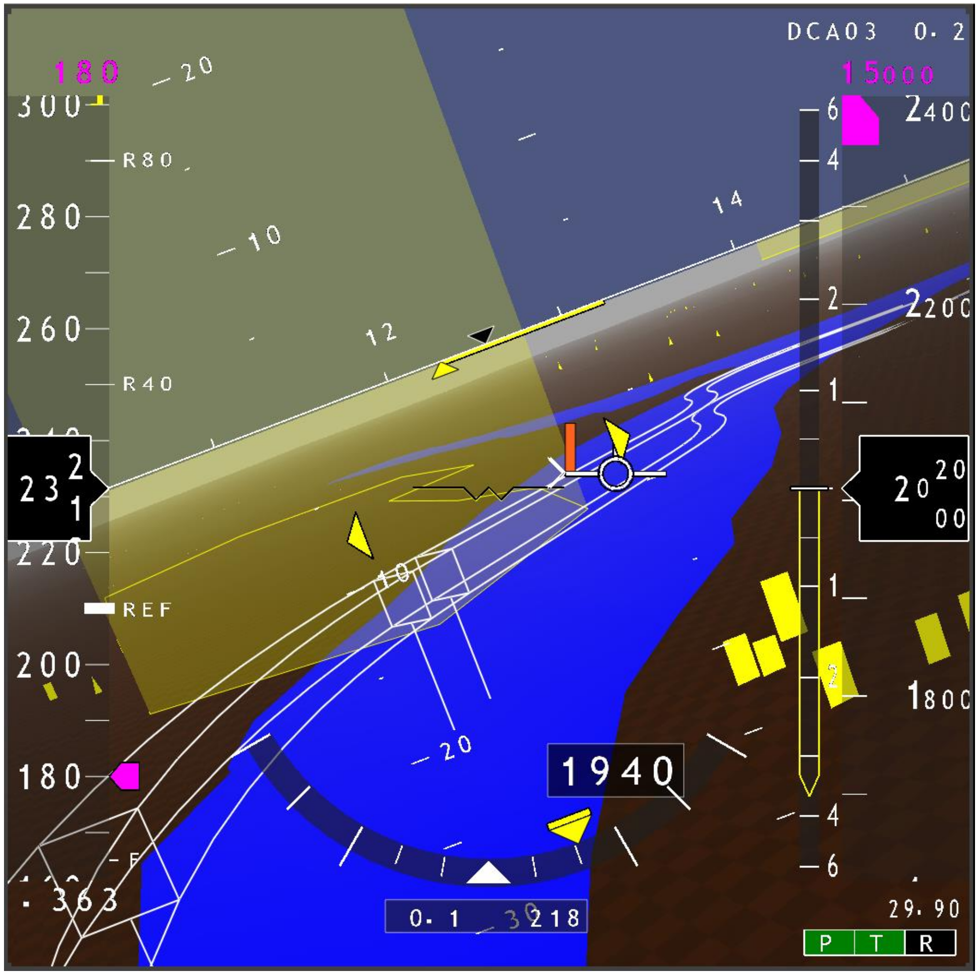
Airport data / runway database

- Elements mentioned in RTCA-DO315B
  - Runway of the intended landing
  - Threshold of the runway of the intended landing
  - A means of determining that the correct runway has been selected
  - Elements that support optical flow as a means to support speed, ground closure and altitude awareness during the approach



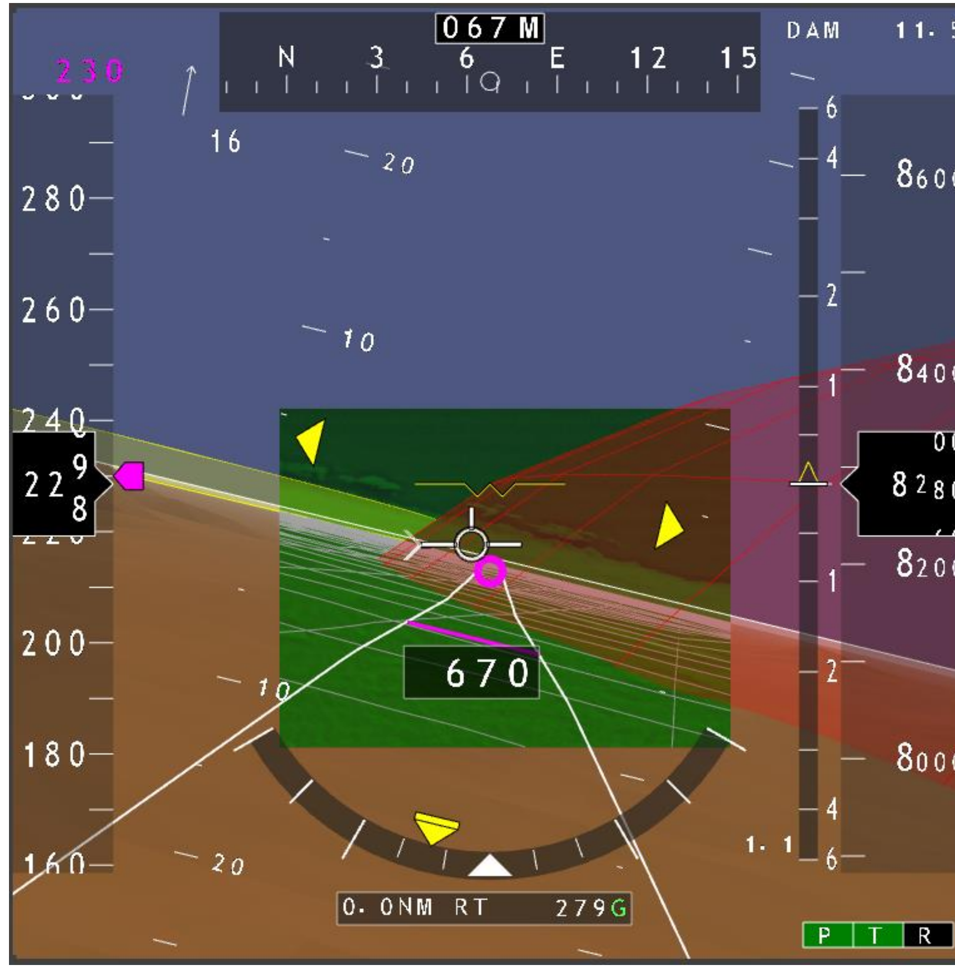
Static non-physical constraints

- Restricted airspace
  - Converted into 3-D object
  - Rendered in the background layer



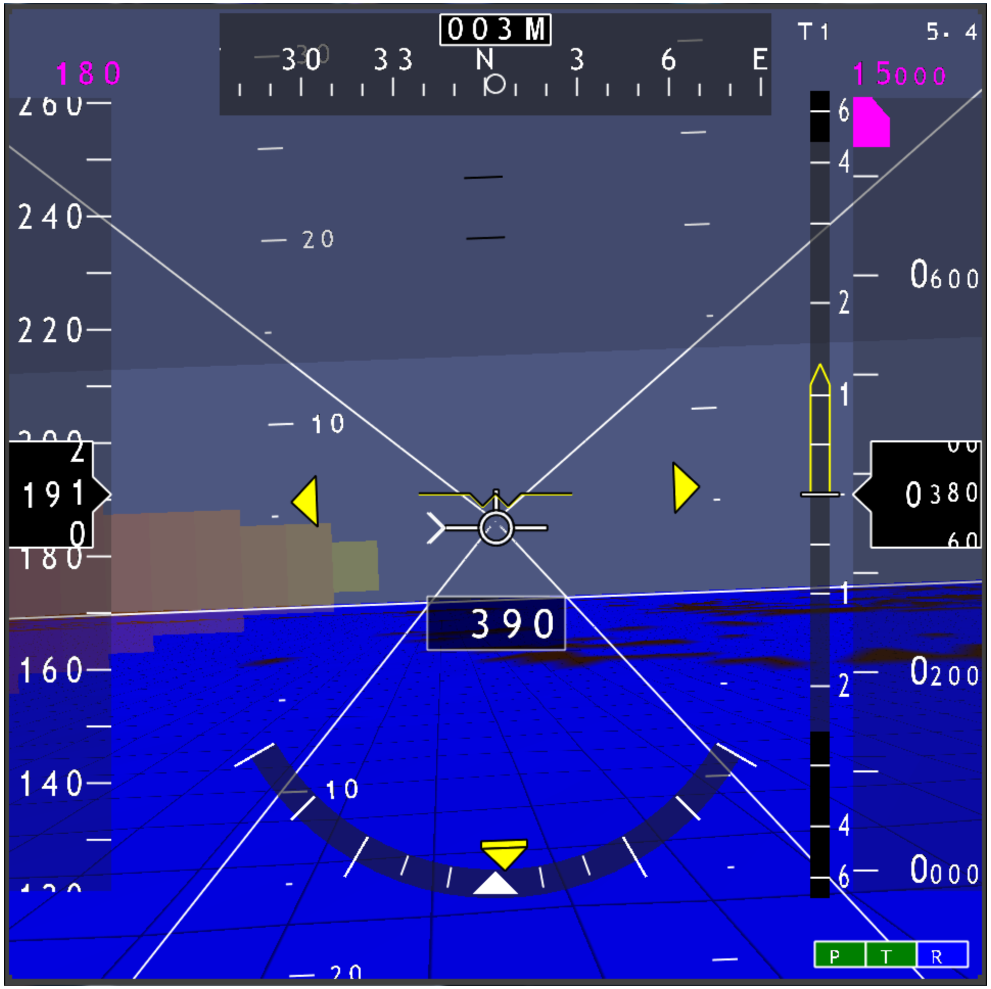
Static non-physical constraints

- Threat volumes
  - Converted into 3-D object
  - Color used to convey information about severity
  - Rendered in the background layer

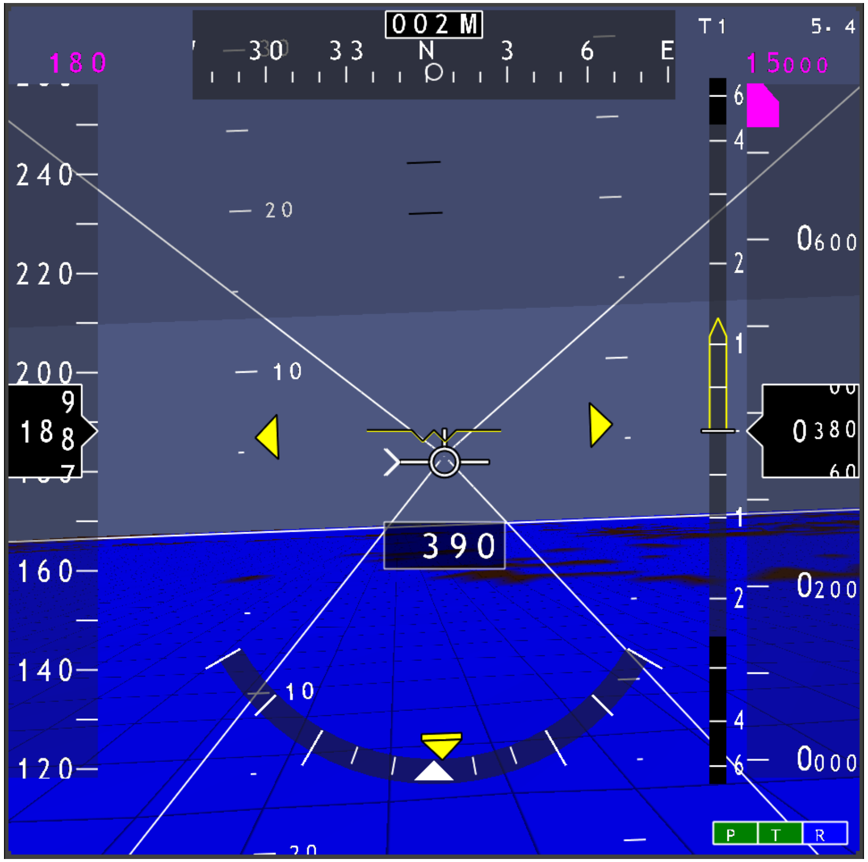


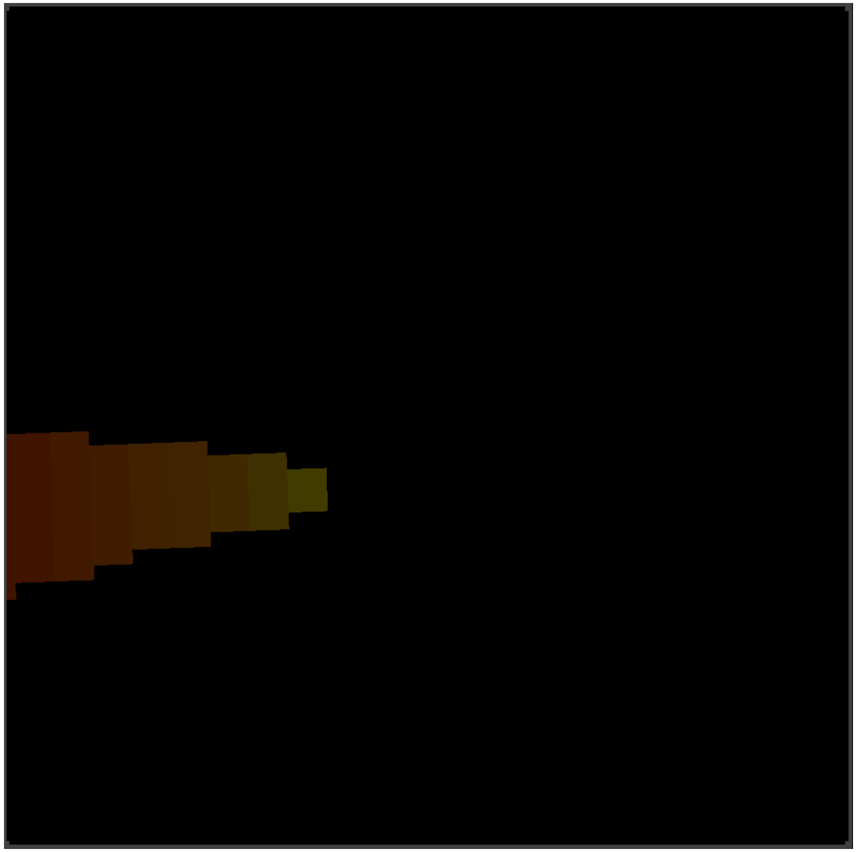
Dynamic non-physical constraints

- Space where loss of separation with other traffic would occur if maneuvering in that direction
- Computed in real-time
- Different options to represent data:
  - As a volumetric object
  - As 2-D cells for a certain relative azimuth and elevation
- Options for color:
  - Temporal proximity, or
  - Separation / collision hazard



Dynamic non-physical constraints





- Example using an azimuth-elevation matrix with cell color coding based on temporal distance to loss of separation
- Integrated as a semi-transparent overlay in the background layer

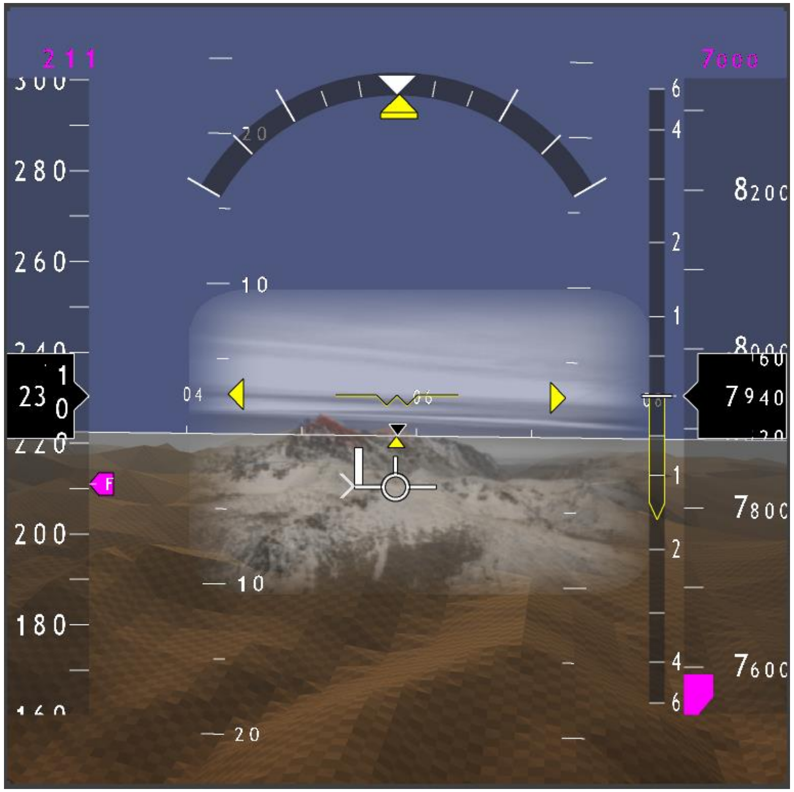
Integration of sensor images

- The integration of a real-time sensor image has been pursued to provide the capability for the timely detection of hazardous discrepancies between the real environment and the synthetic environment
- Integrity monitoring of the synthetic data is supported if certain specific elements or features from the synthetic world are clearly identifiable as such and can be correlated with their counterparts in the sensor image
- Hence, if the detection of a data error relies on the human operator to detect differences between the sensor image and the computer-generated one, fusion techniques might actually be counterproductive because they hide potential differences

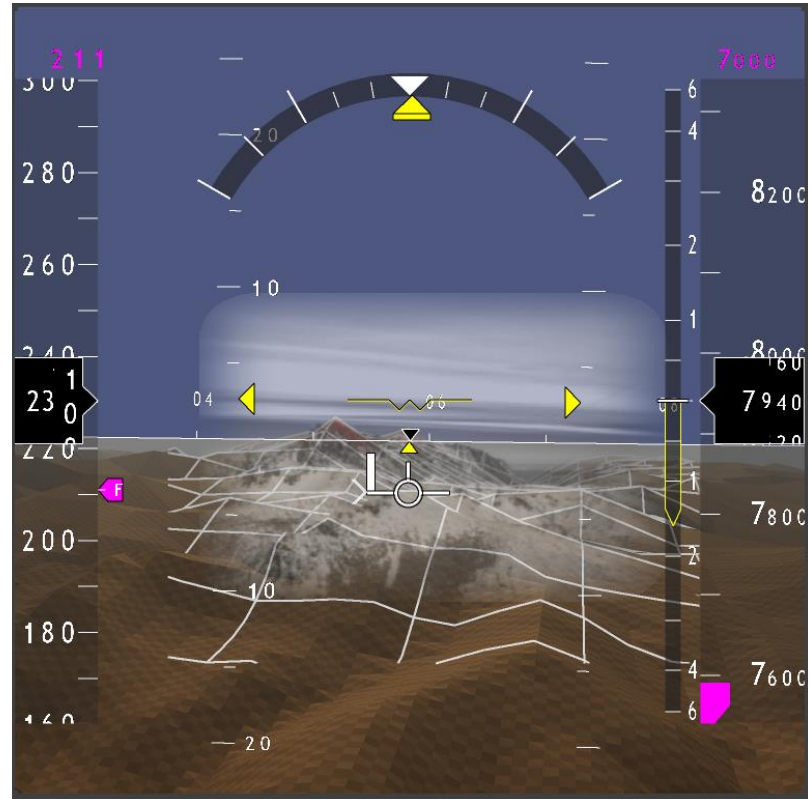
Integration of sensor images

- Goal
  - Benefit from the consistency and controllability of the SVS while using a sensor-based, enhanced vision system (EVS) to timely detect hazardous errors
- Challenge
  - To combine the sensor image and the synthetic image into a single representation in such a way that the pilot can distinguish between the two sources and determine whether the differences are within acceptable margins

Examples

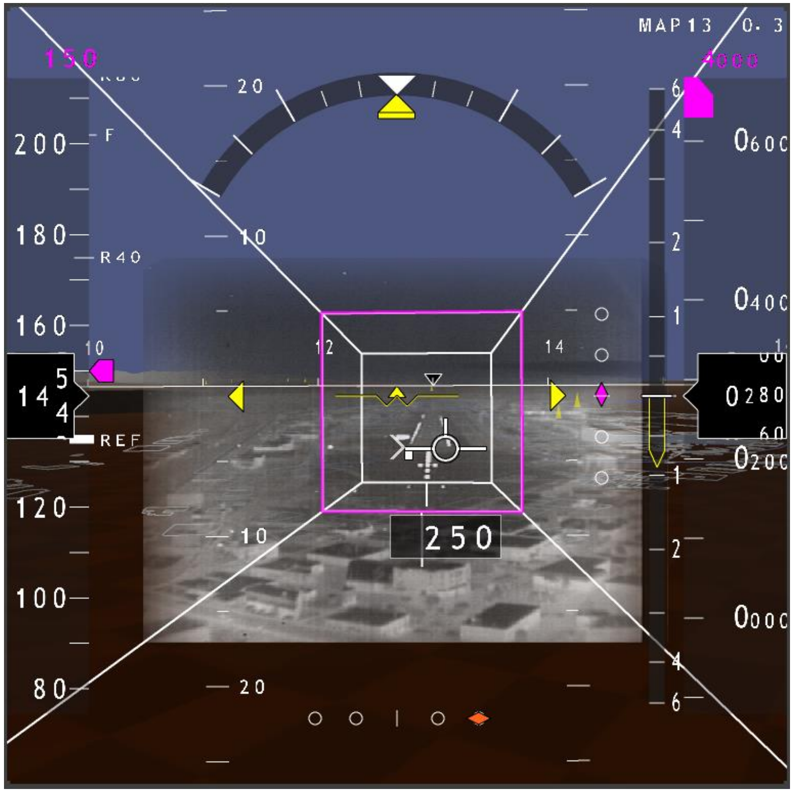


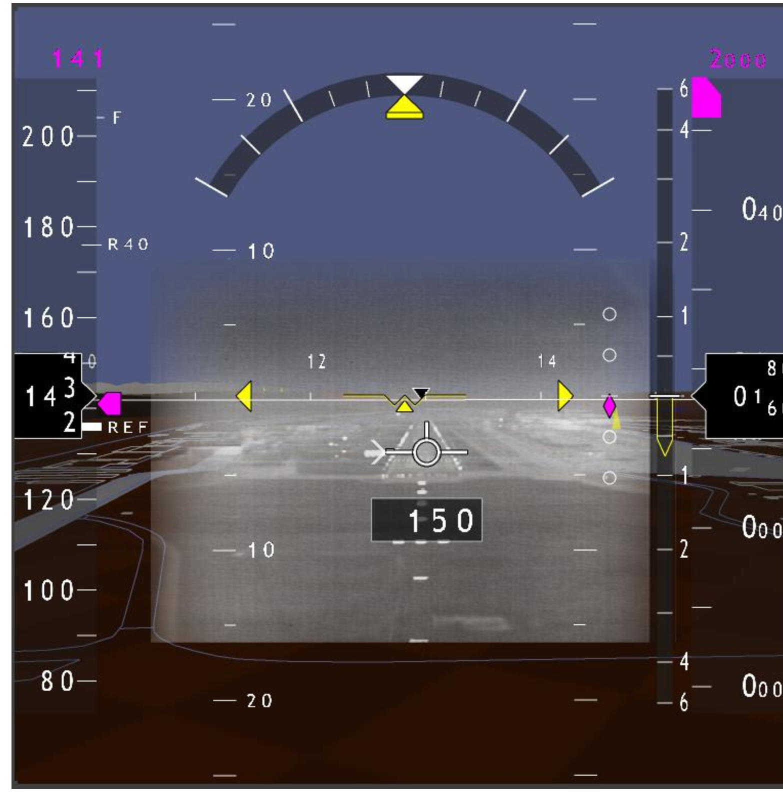
- Inserted sensor image with semi-transparent border



- Use of a grid overlay to emphasize terrain shape

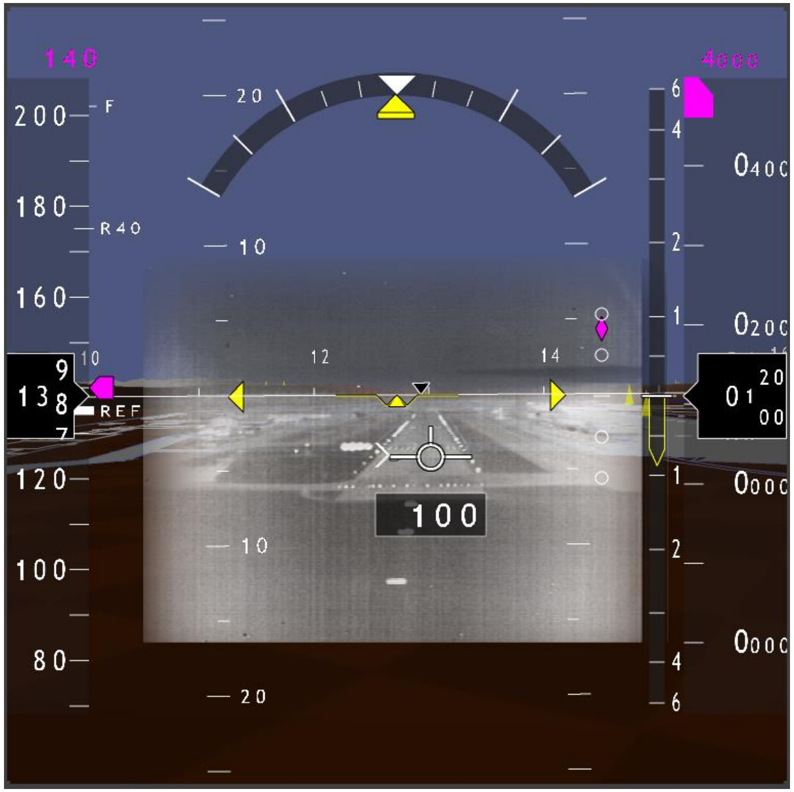
Examples

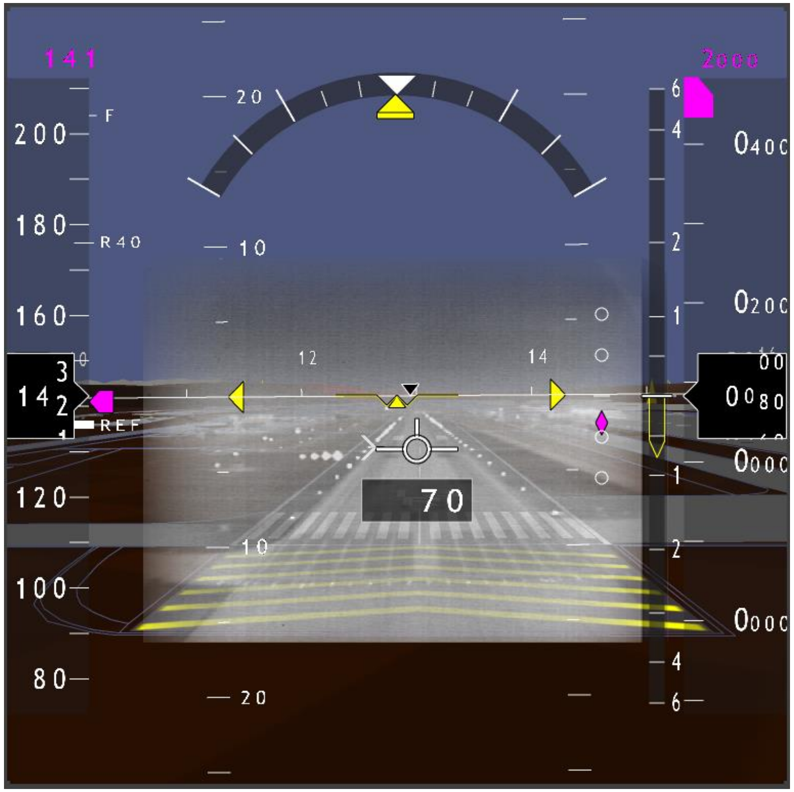




- Use of an IR sensor inset during approach and landing

Examples

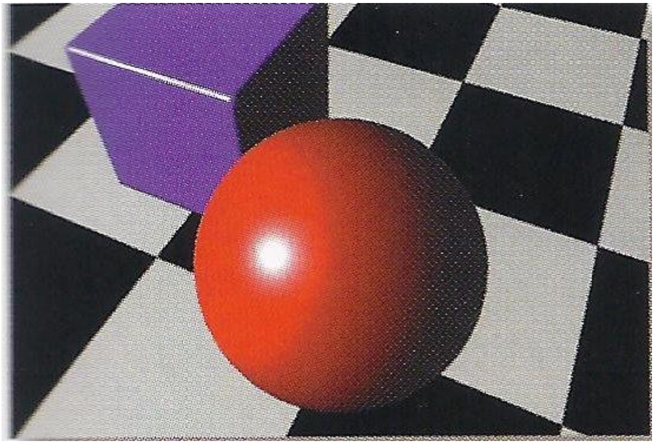


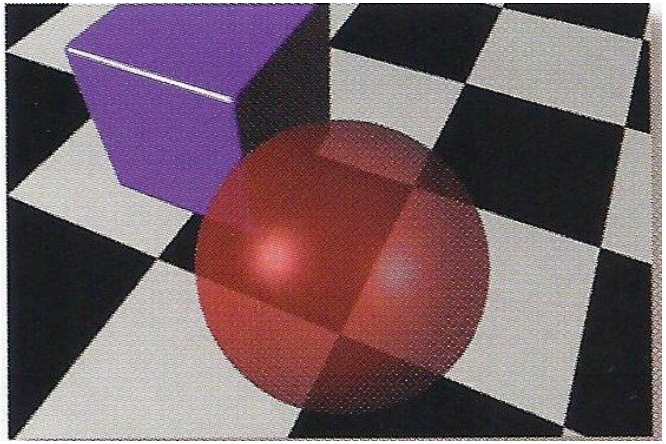


- Use of an IR sensor inset during approach and landing

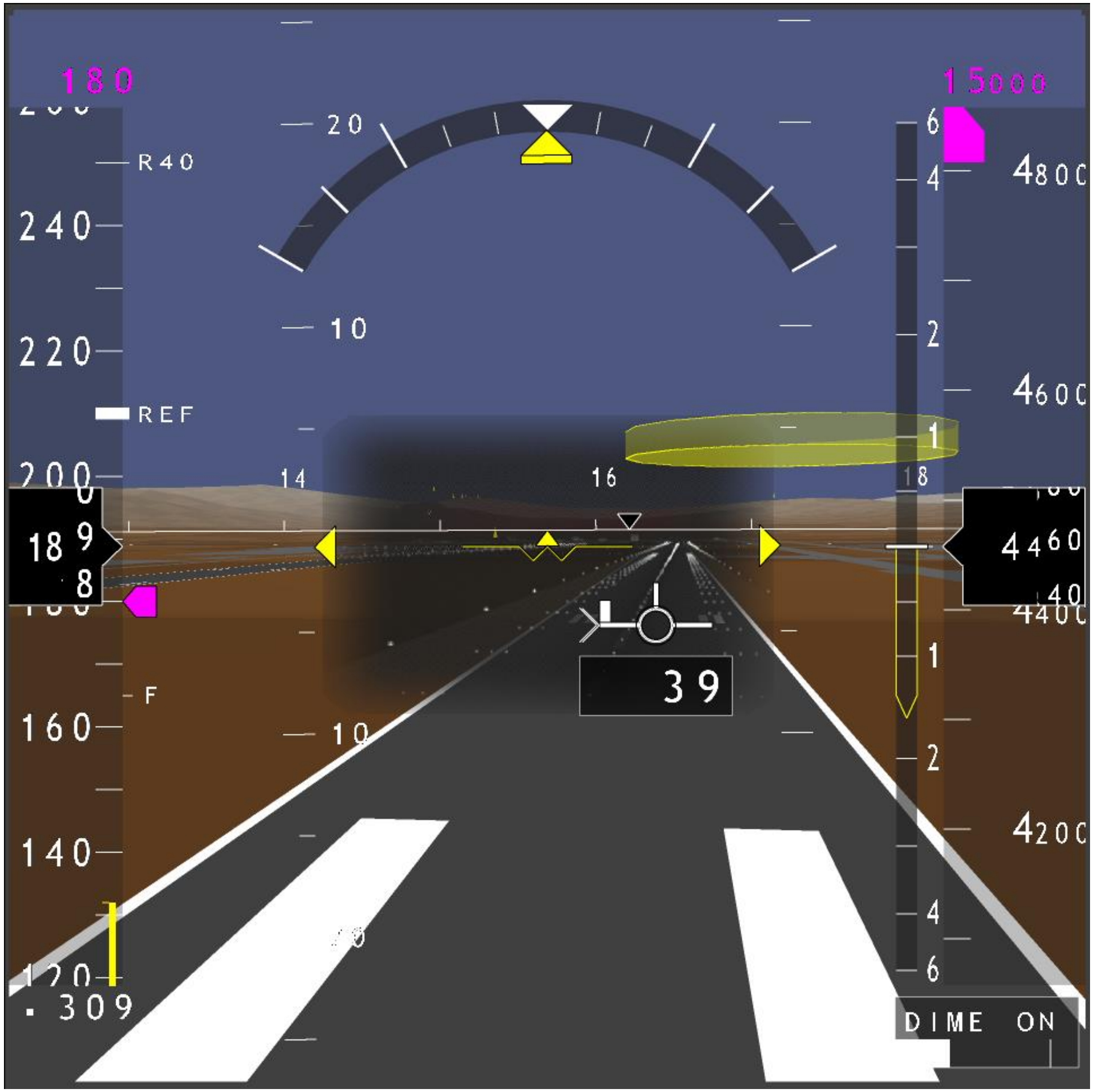
Blending

- Integration of a sensor image into a synthetic picture can use different forms of blending



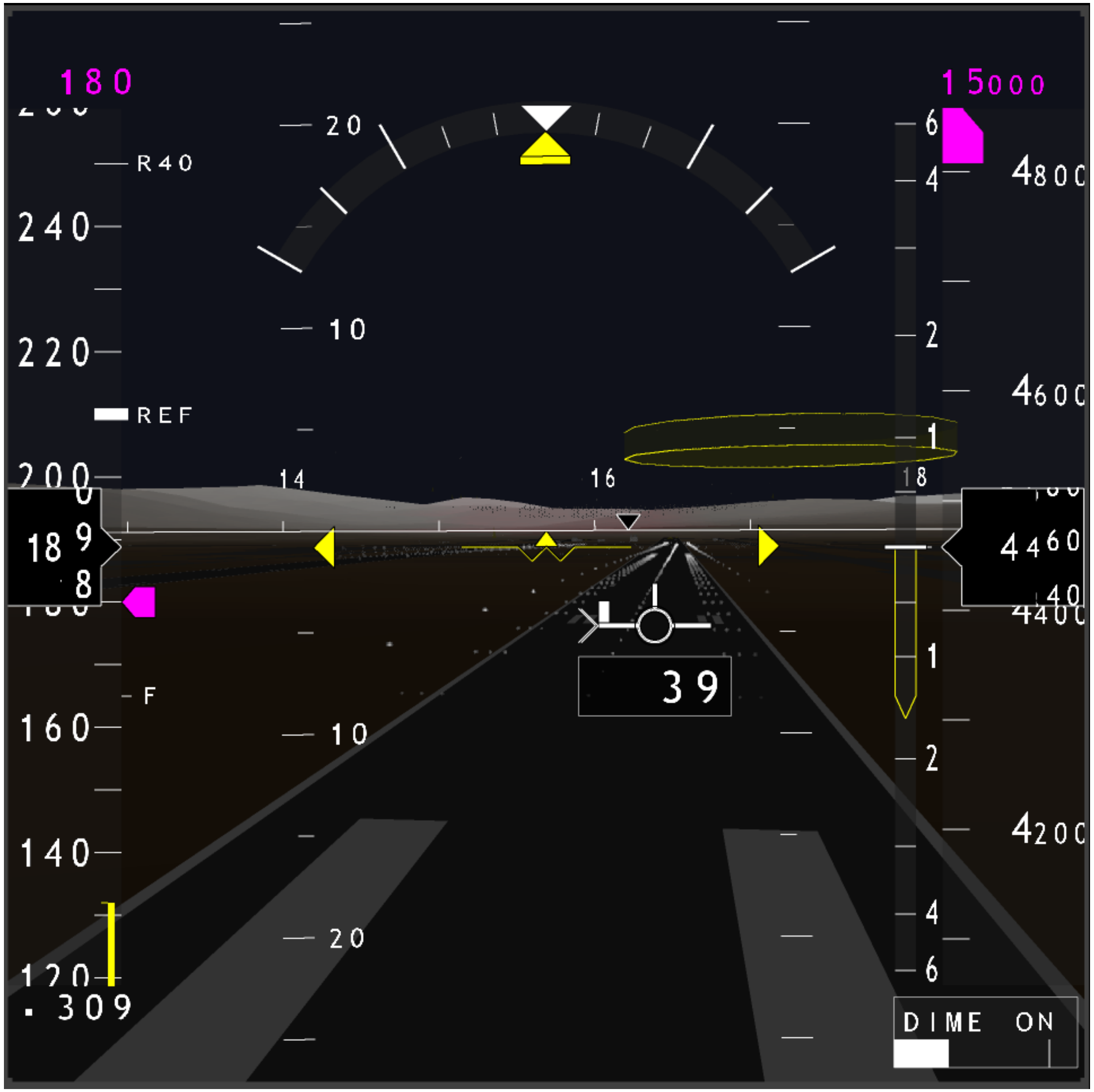


Blending



- Unfiltered EVS, hi-intensity SVS

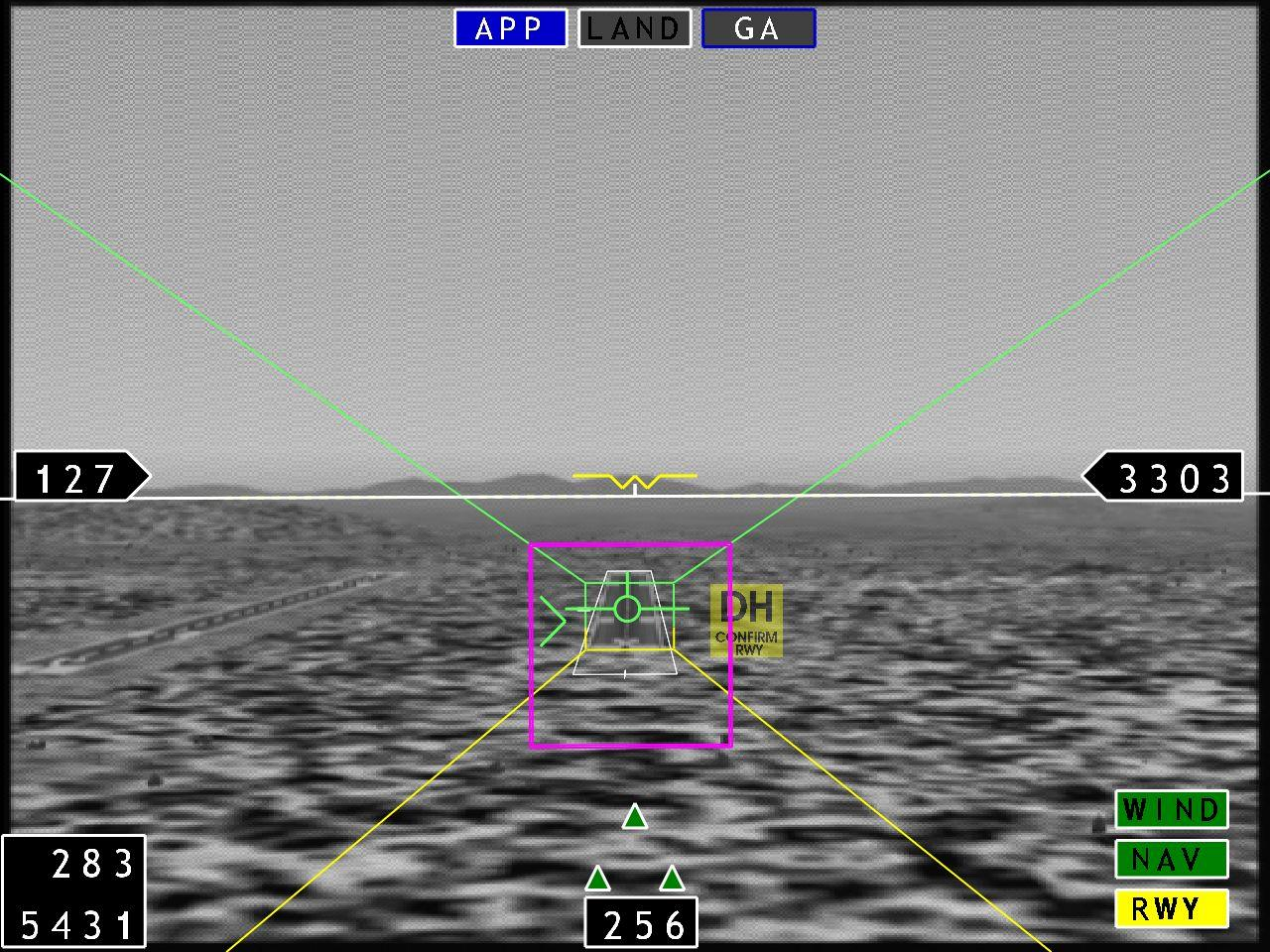
Blending

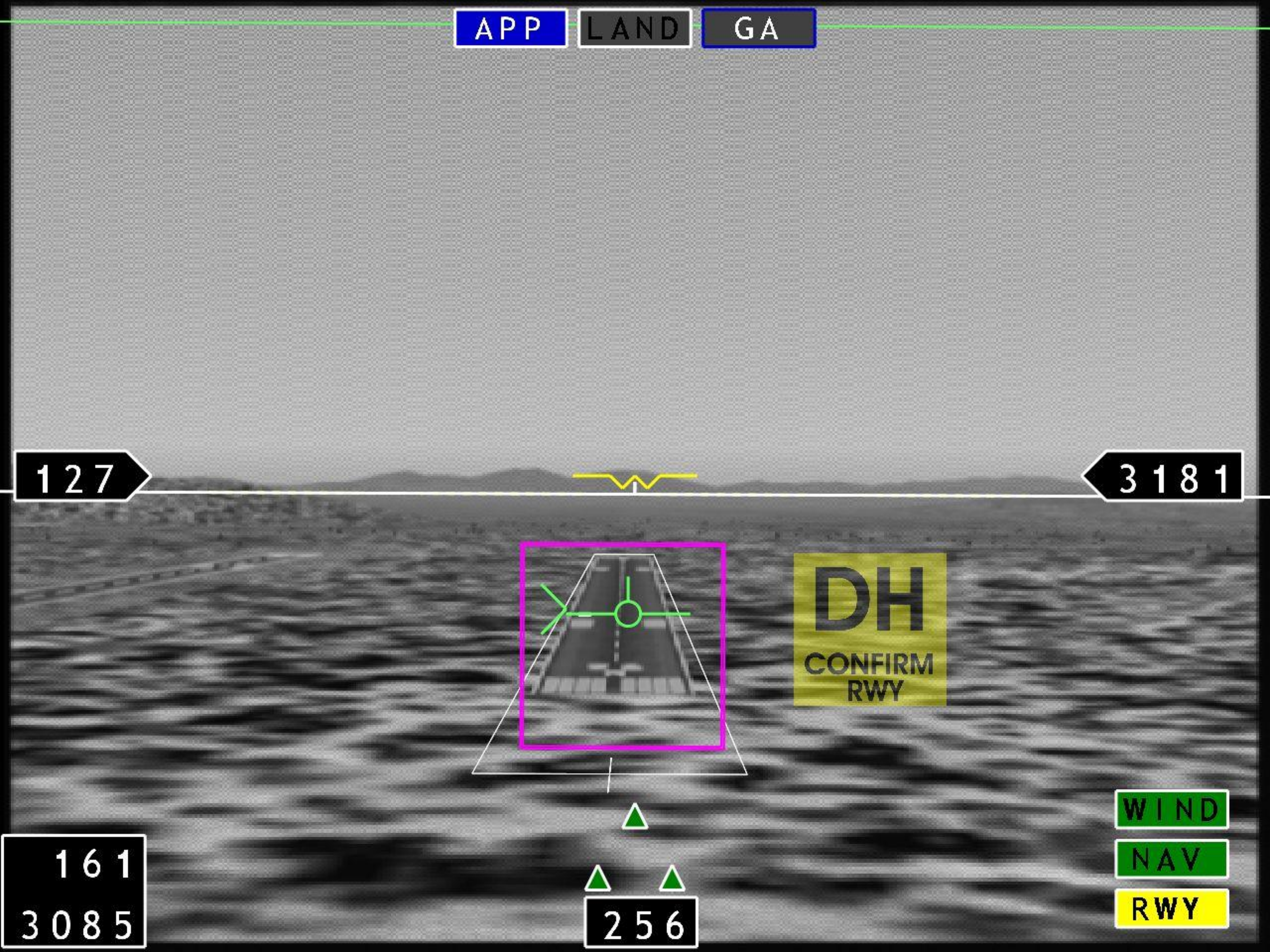


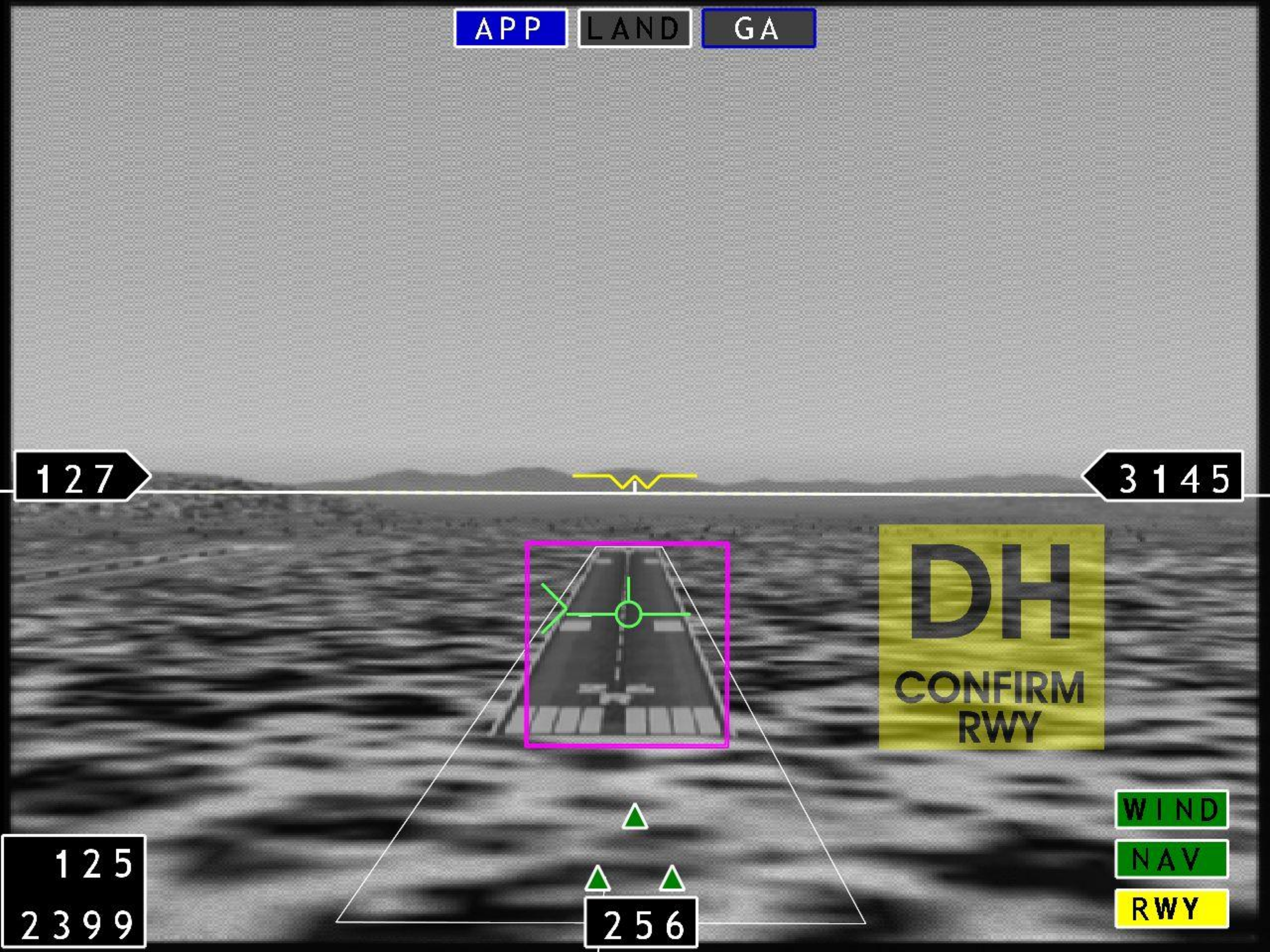
- Filtered EVS, low-brightness SVS

Synthetic overlay

- If a match between one or more specific elements in the real world with their counterparts in the database is the basis for integrity assessment, a synthetic overlay can be used
- The following three slides show a full-screen sensor image, with a synthetic overlay of the approach path and the 95% containment contour of the runway
- To assess the integrity of the autoland guidance reference, the pilot needs to verify that the runway in the sensor image lies within the synthetic containment contour


APP
LAND
GA
127
3303
DH
CONFIRM
RWY
WIND
NAV
RWY
283
5431
256

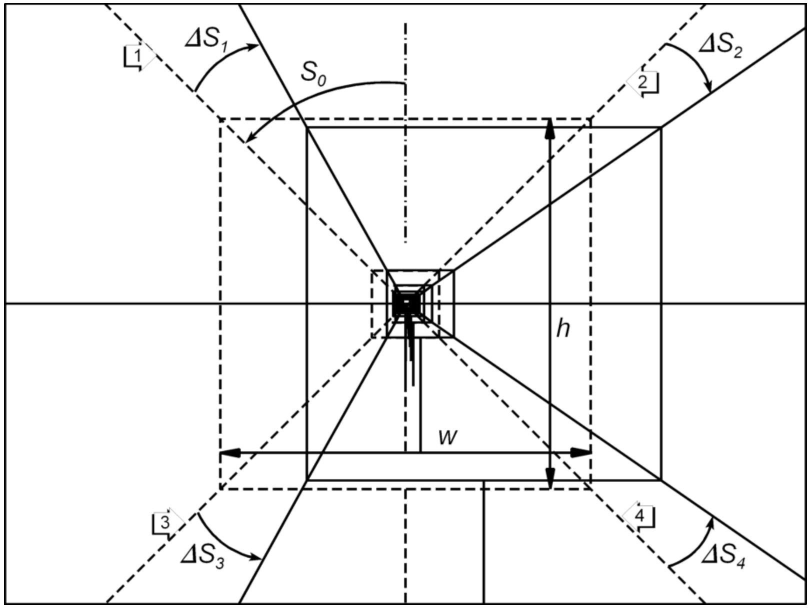

APP
LAND
GA
127
3181
DH
CONFIRM
RWY
161
3085
256
WIND
NAV
RWY


APP
LAND
GA
127
3145
DH
CONFIRM RWY
WIND
NAV
RWY
125
2399
256

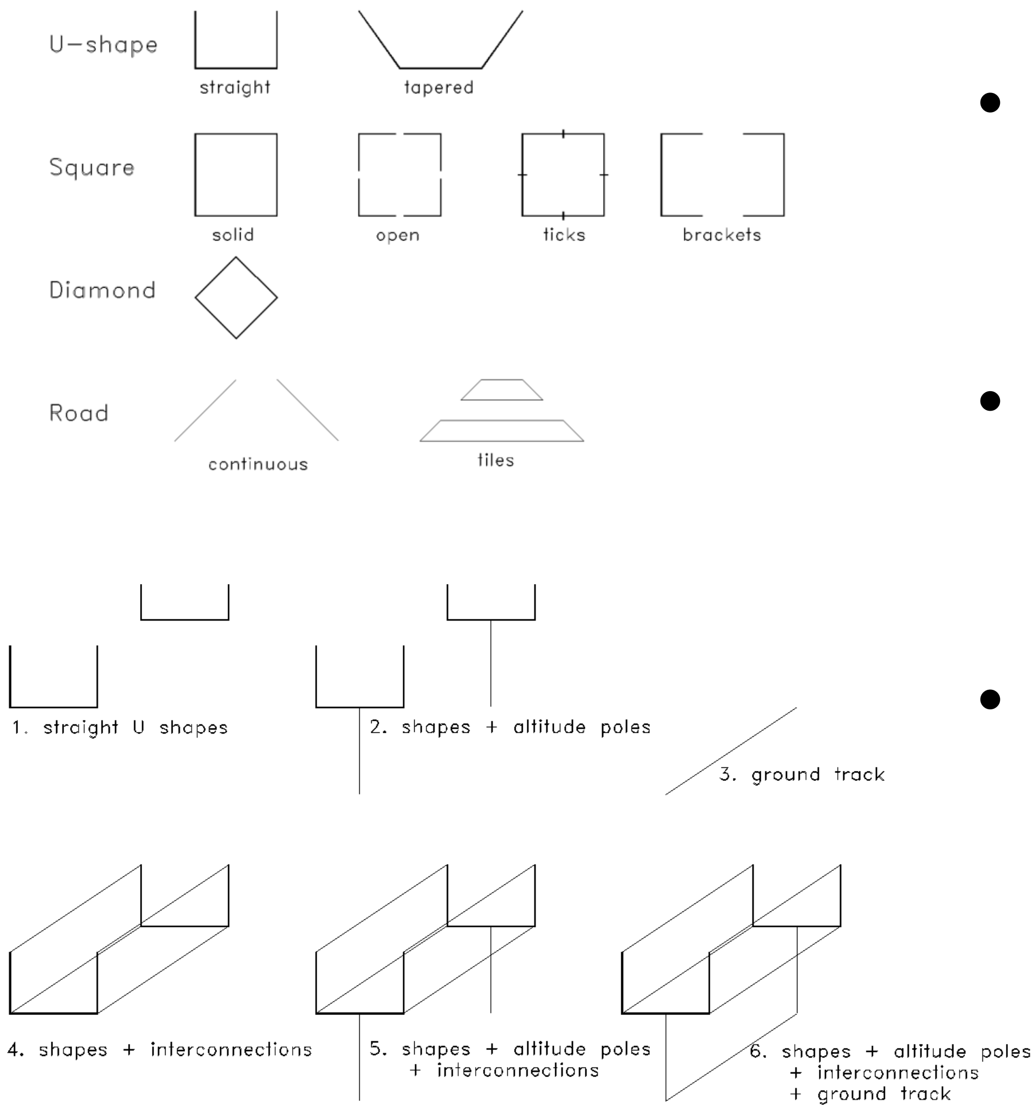
The guidance layer

The guidance layer

- Trajectory data
  - Preview on the future planned trajectory
  - To monitor the conformance and anticipate changes
  - To apply a control strategy which is a mix of anticipatory, compensatory, and error-neglecting control



Trajectory representation



- Cross sections
  - To visualize spatial constraints
- Interconnections
  - To create an object with emergent features
- Altitude poles
  - To anchor the path to a ground reference

Static, dynamic and hybrid paths

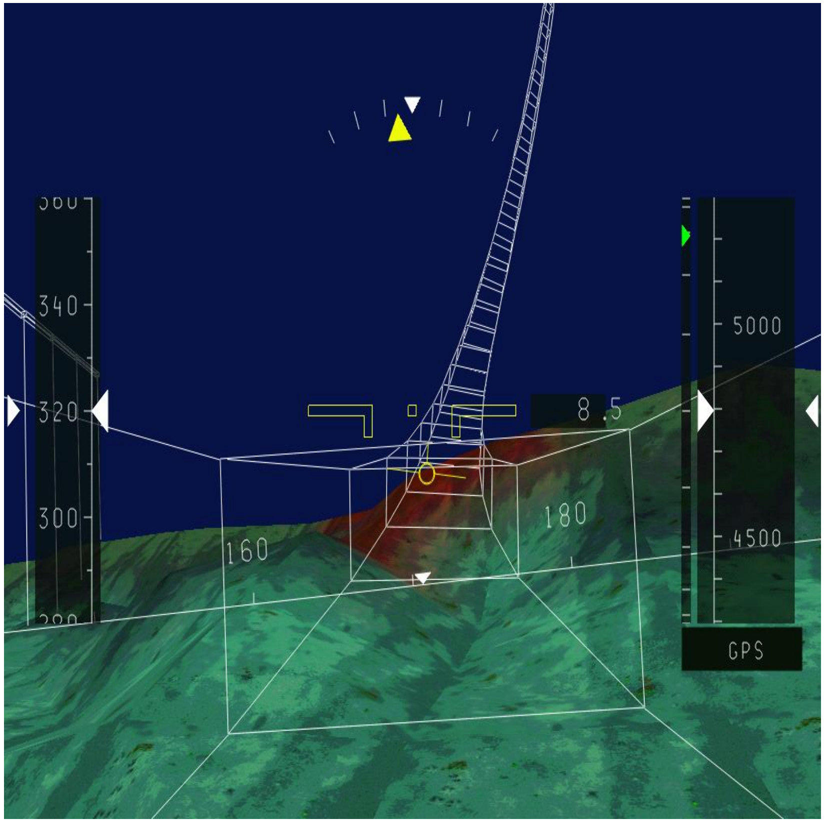
- Static path is defined in 3-D
- Dynamic path is computed from ownship state and a reference such as terrain
- Hybrid paths are defined (fixed) in one dimension and dynamic in the other dimension

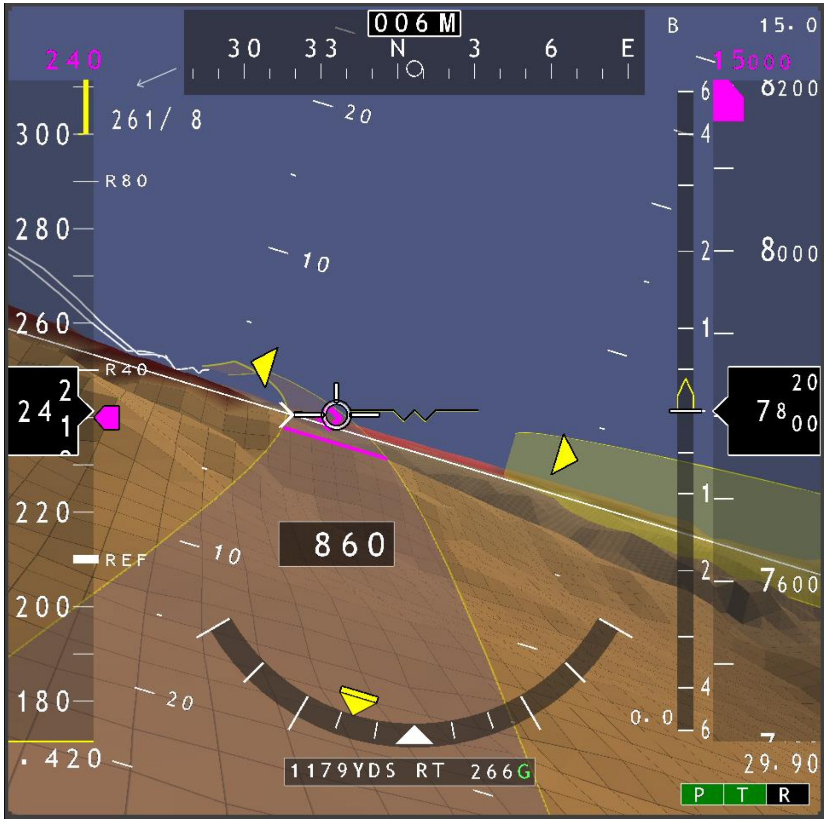
- For rendering, all paths need to be transformed into a 3-D object (points & vertices)

Static Path

- Defined as a set of 3-D waypoints
- Transformed into a 3-D object

Dynamic path

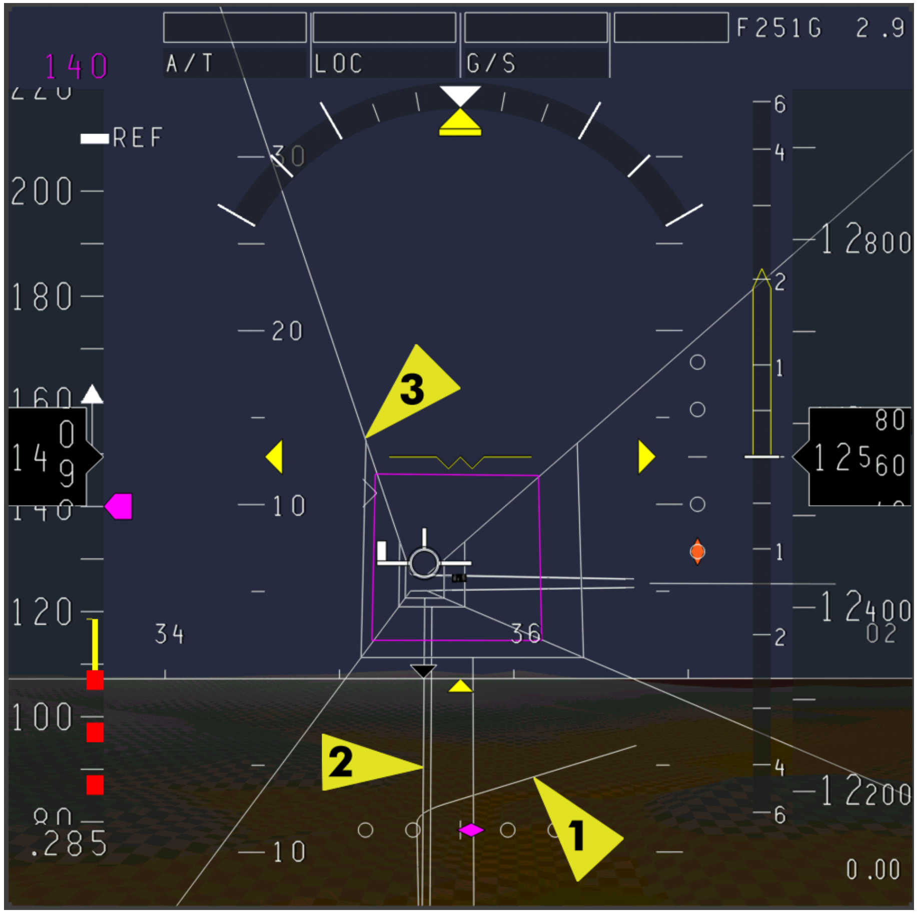




- Based on ownship state relative to terrain
  - Terrain avoidance in case ownship state points into terrain
  - Terrain following

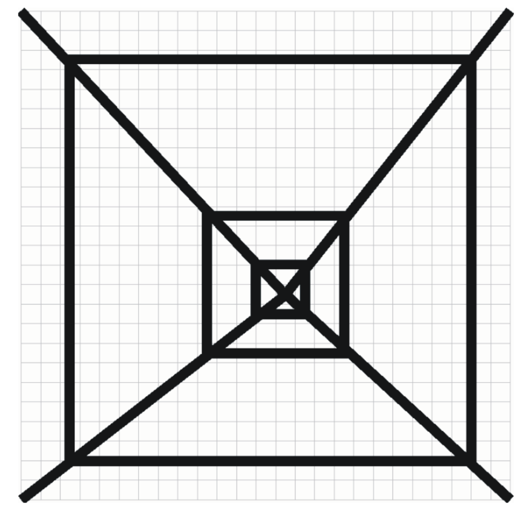
Hybrid path

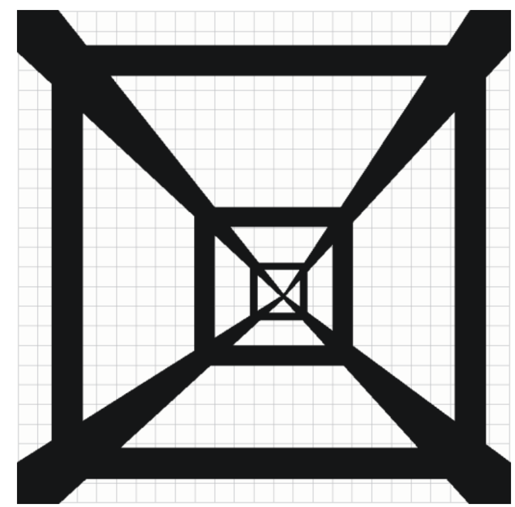
- Applications:
  - Take-off path
  - Missed approach guidance
- Defined in horizontal dimension
- Computed based on ownship state in the vertical dimension
  - Starts at ownship altitude
  - Extends along FPA or PFPA vector



LOD and clutter control

- Perspective transformation of 3-D points to 2-D and connecting them with lines to represent the tunnel object does not affect the width of a line
- Local intensity per area of the flight path display increases with an increase in distance from the viewpoint
- Mitigation strategies
  – Render path as true 3-D object
  – Control level of detail of path as a function of distance
  – Intensity control of lines (e.g. distance based fogging)



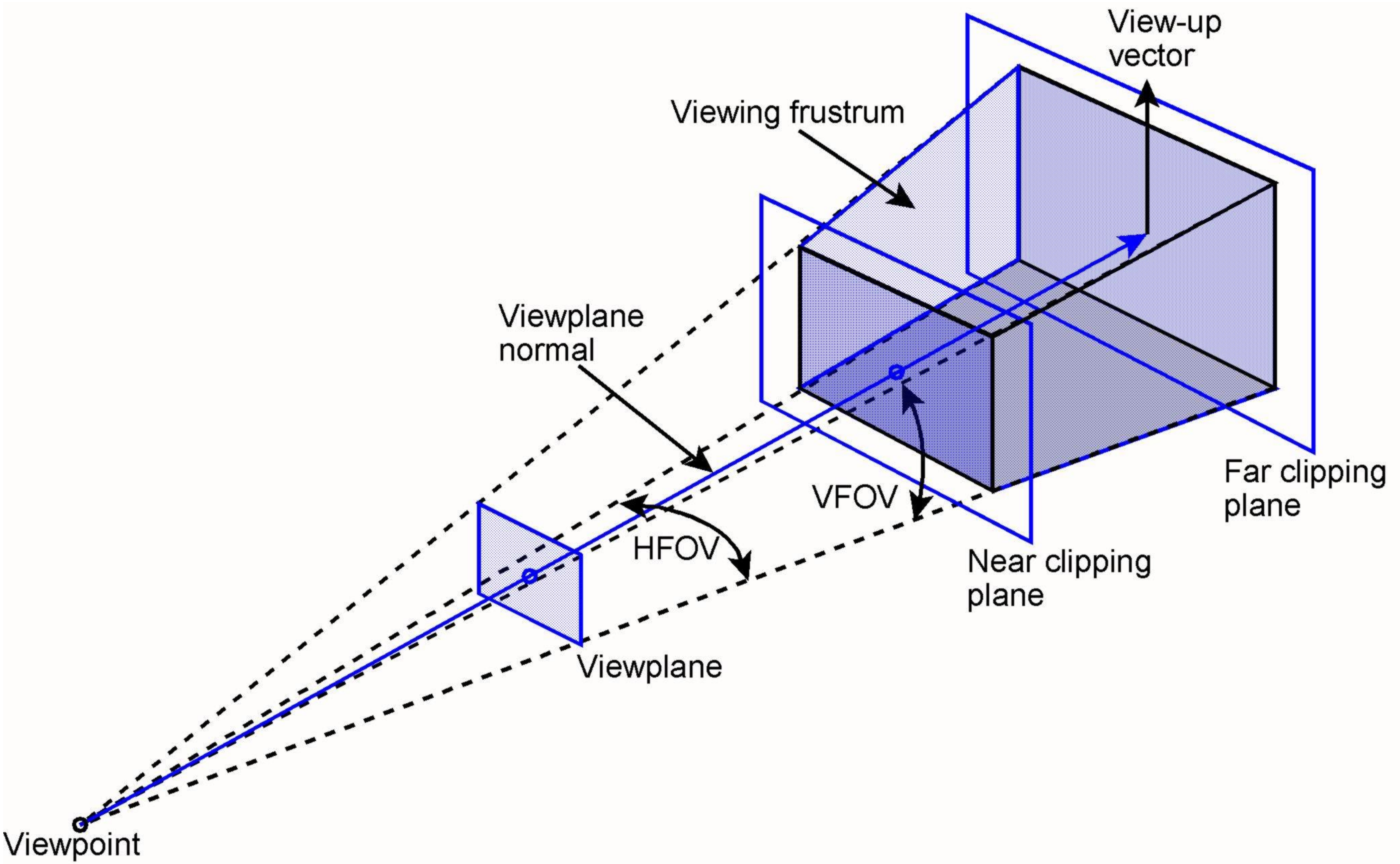


From data to a presentation

Mapping of the 3-D representation to a 2-D display

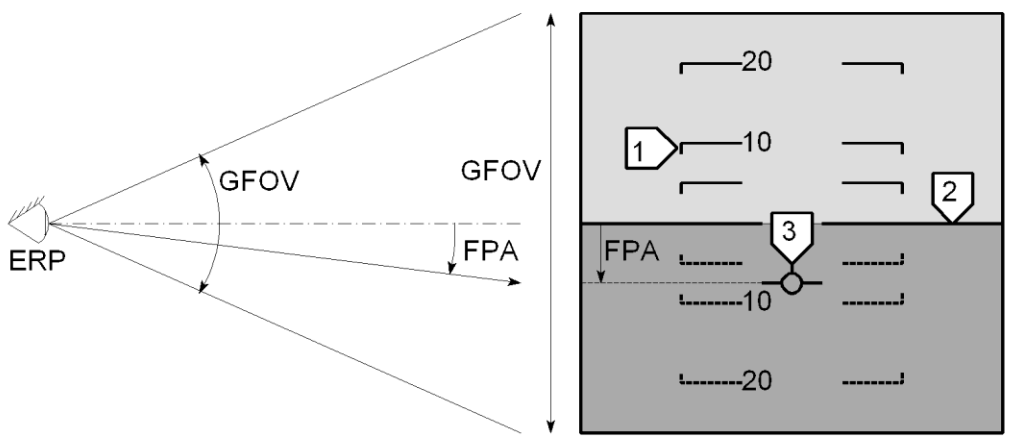
- Mapping of the representation to a viewport requires choices regarding:
  - Projection method
  - Viewpoint
  - Viewing direction
  - Field of view
  - Clipping distance
- To generate an ego-referenced, perspective display:
  - The location of the viewpoint is coupled to ownship position
  - The viewing direction is either coupled to ownship attitude or the velocity vector
  - The vertical field of view has to be based on conformality with the required pitch range in the PFI layer, which in turn is based on visible pitch range and resolution requirements

Mapping of the 3-D representation to a 2-D display



Projection

- For Head-Down SV displays, the FOV used in the projection in general is larger than the observer Geometric FOV
- If conformality with the outside world view is required (e.g. On a HUD), the GFOV determines the FOV used for the projection



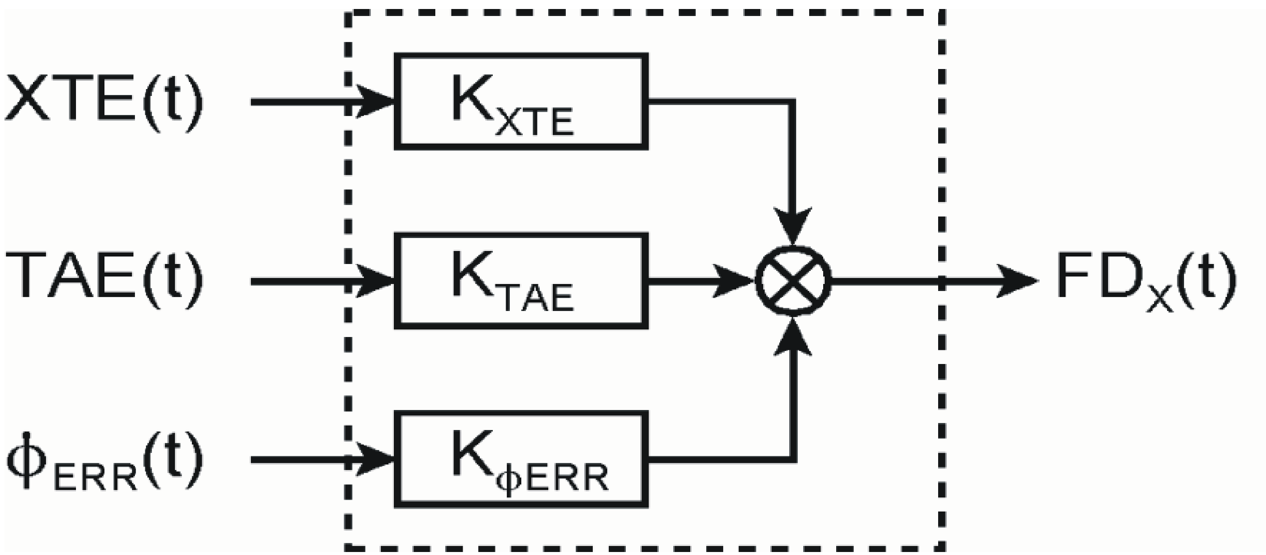
Guidance augmentation

Guidance augmentation

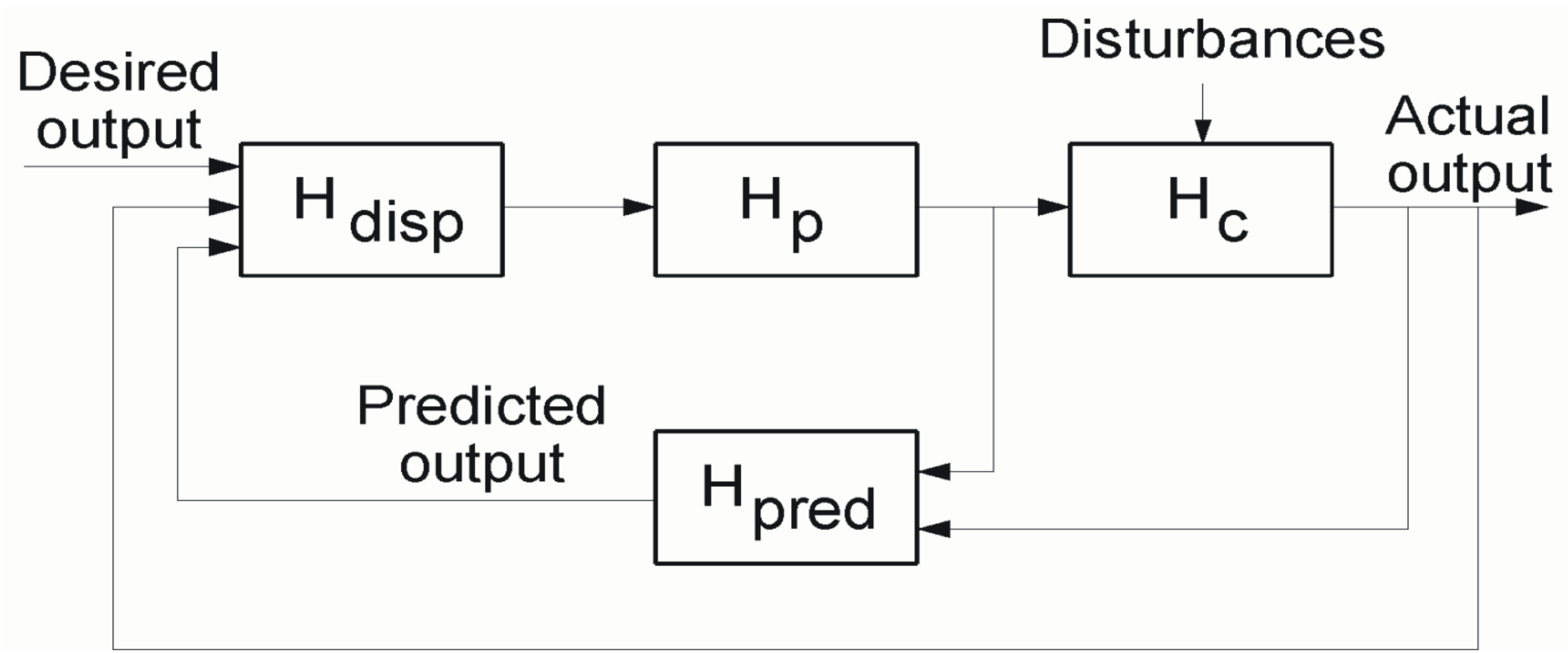
- Why?
  - The perspectively presented flight path does not provide cues that aid in dealing with the higher-order system dynamics of the aircraft
- Types of augmentation:
  - Compensatory Command
  - Pursuit Command
  - Predictive

Command display

- McRuer et al. (1971): ‘*The nub of the dynamics design problem is the selection of the appropriate mix of signals to make up the steering commands*’

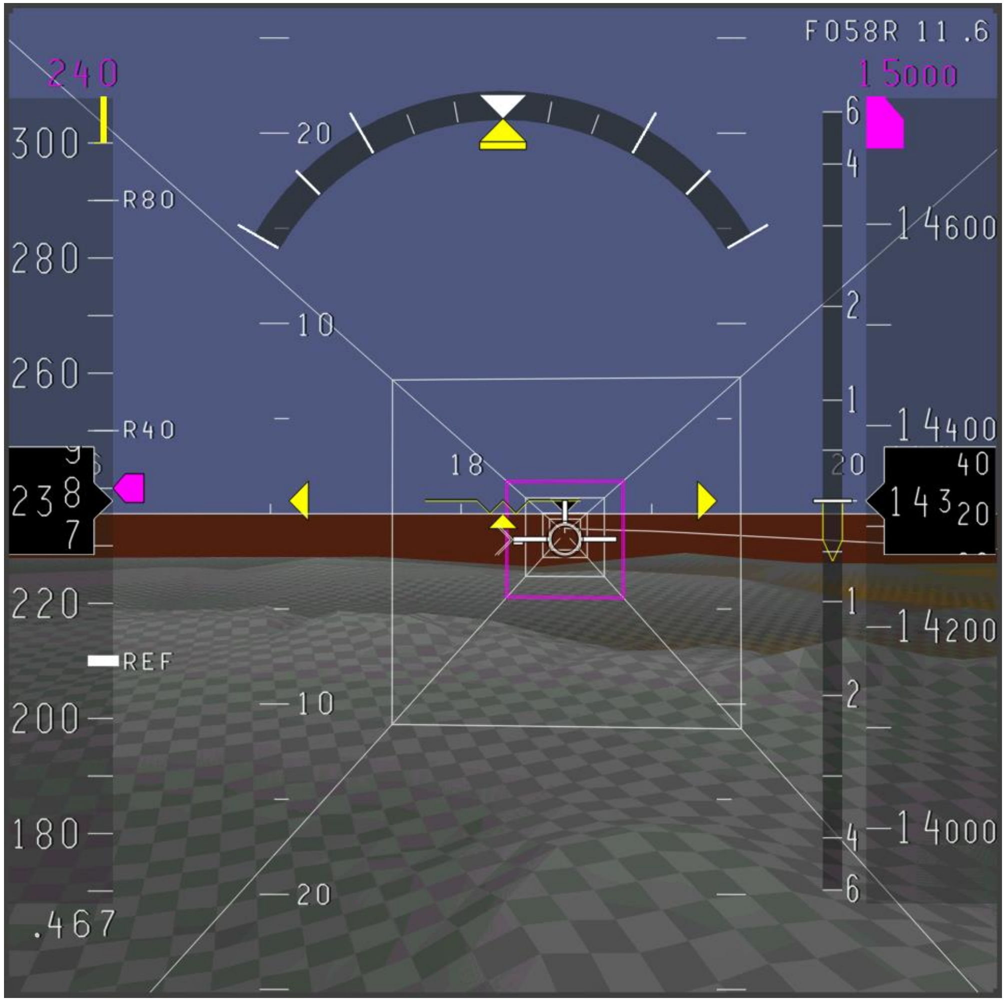


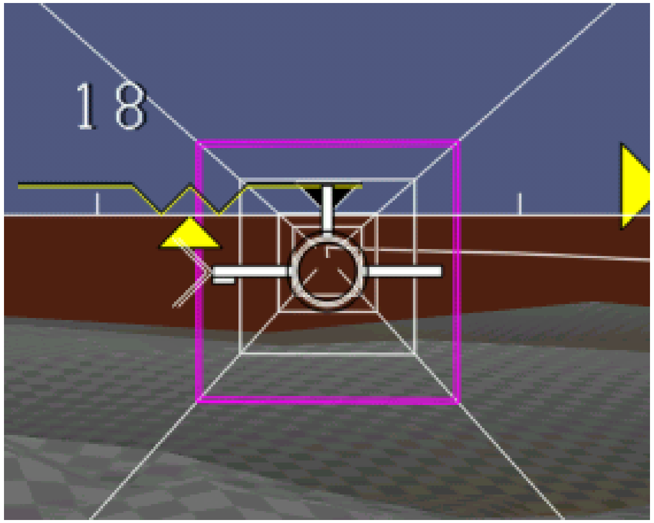
Predictor



- '*In contrast to the compulsory information provided by flight directors (compensatory command display), the information provided to the pilot by the predictor is optional. This, for example, allows the pilot to leave the predictor for several seconds to scan other parts of the display to return to it later*' [Grunwald, 1996]

Predictor

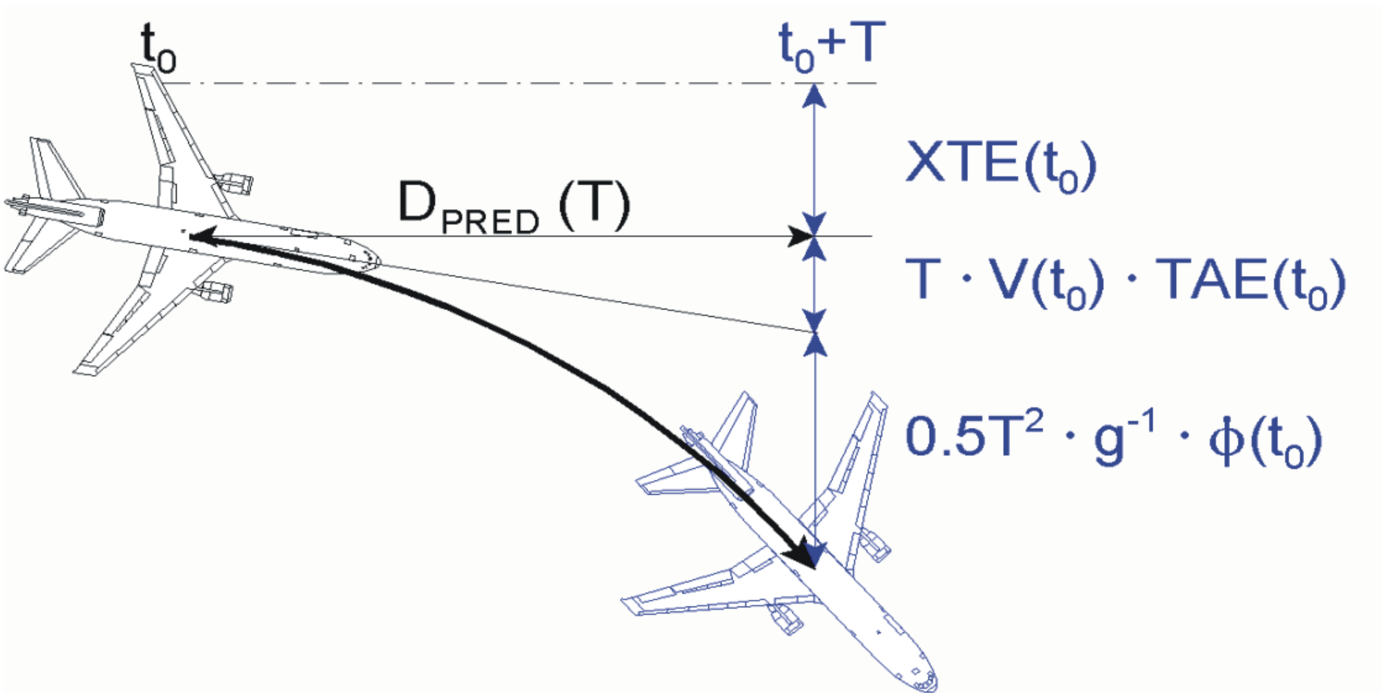




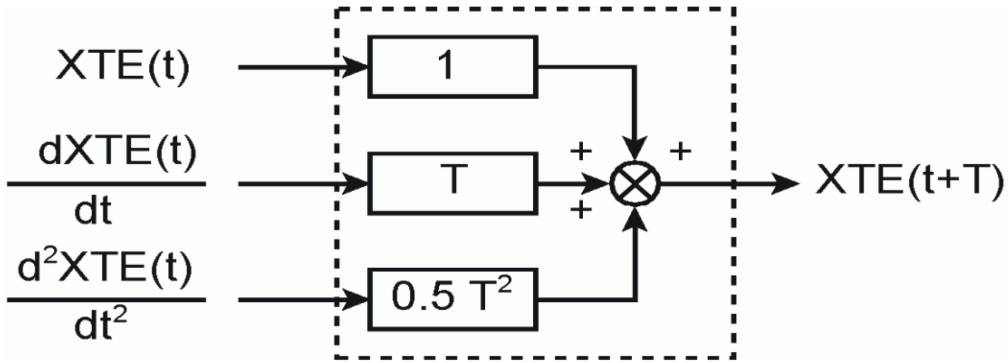
- The magenta box indicates the cross section with the path at the predicted distance
- The predictor symbol shows the predicted position

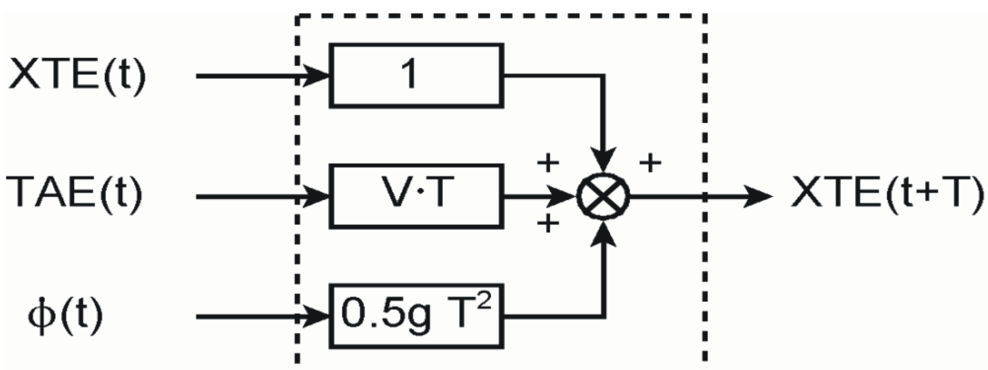
2^{nd} order horizontal position predictor

Top view of current and predicted future position



2^{nd} order horizontal position predictor





- The signals driving the predictor are the same as those driving the FD
- The weighting is based on the look-ahead time

Integrity

Flightcrew Alerting

FAR Part 25 Section 25.1322 (Eff. 1/3/2011)

a) Flightcrew alerts must:

1) Provide the flightcrew with the information needed to:
   i. Identify non-normal operation or airplane system conditions, and
   ii. Determine the appropriate actions, if any.
2) Be readily and easily detectable and intelligible by the flightcrew under all foreseeable operating conditions, including conditions where multiple alerts are provided.
3) Be removed when the alerting condition no longer exists.

b) Alerts must conform to the following prioritization hierarchy based on the urgency of flightcrew awareness and response.

1) **Warning**: For conditions that require **immediate flightcrew awareness** and **immediate flightcrew response**.
2) **Caution**: For conditions that require **immediate flightcrew awareness** and **subsequent flightcrew response**.
3) Advisory: For conditions that **require flightcrew awareness** and may require **subsequent flightcrew response**.

Advisory Circular 25.1322-1

Alerting System Reliability and Integrity (Section 7)

a. The alerting system, *considered alone and in relation to other systems*, should meet the safety objectives of the relevant system safety standards (for example, § 25.901(b)(2), § 25.901(c), and § 25.1309(b)). ***The reliability and integrity of the alerting system should be commensurate with the safety objectives associated with the system function, or airplane function, for which the alert is provided***.

d. Assess the reliability of the alerting system by evaluating the ***reduction in the safety margin if the alerting system fails***. The evaluation should address: (1) Loss of the complete alerting function. (2) A malfunction.(3) Loss or malfunction of one alert in combination with the system condition for which the alert is necessary.

e. The ***integrity of the alerting system should be examined because it affects the flightcrew's trust and response when assessing an alert.***.

Required Performance

Integrity:	The ability of a system to provide timely and valid warnings to the user when the system should not be used for its intended function.
Availability:	The ability of a system to perform its intended function at the initiation of the intended operation.
Continuity-of-Service:	The ability of a system to perform its intended function without interruption during the intended operation.
Accuracy:	The ability of a system to operate within specified operating limits (see navigation accuracies in AWOP)

Integrity Defined

Integrity: The ability of a system to provide timely and valid warnings to the user when the system should not be used for its intended function.

Δt

A system failure occurs
(the system can no longer perform its intended function)

↓

The system failure is detected

↓

A warning is generated

Important: specification of the system's INTENDED FUNCTION

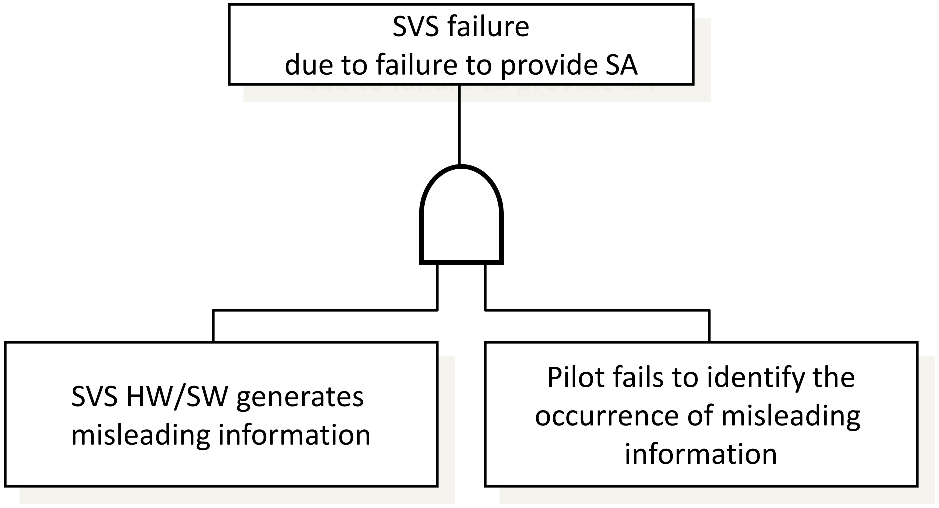
Synthetic Vision System

Intended Function: Provide guidance and terrain situational awareness during the missed approach procedure in low-visibility conditions.

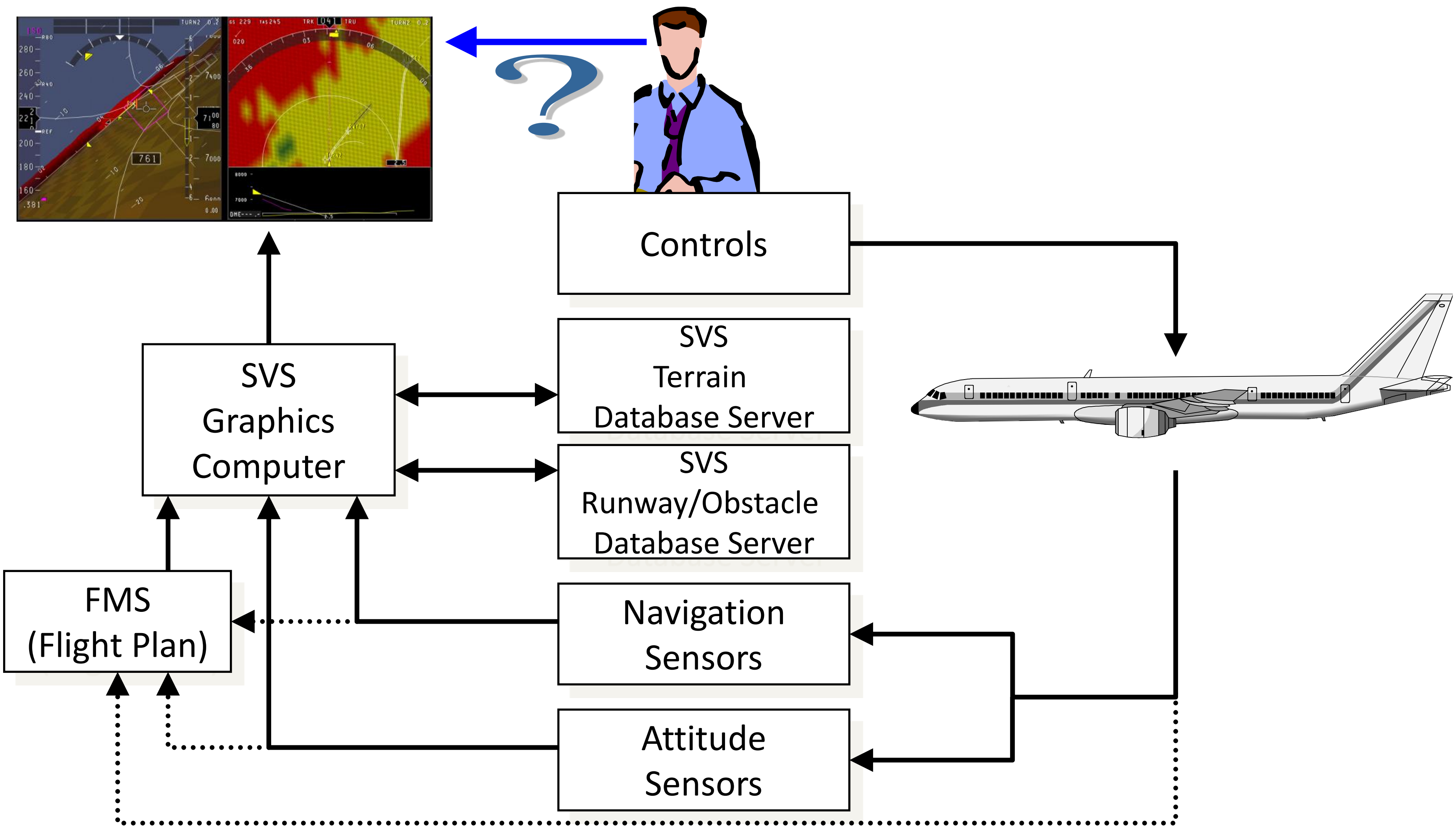
Example of SVS failures:

failure to provide guidance during missed approach.
failure to provide situational awareness during missed approach,

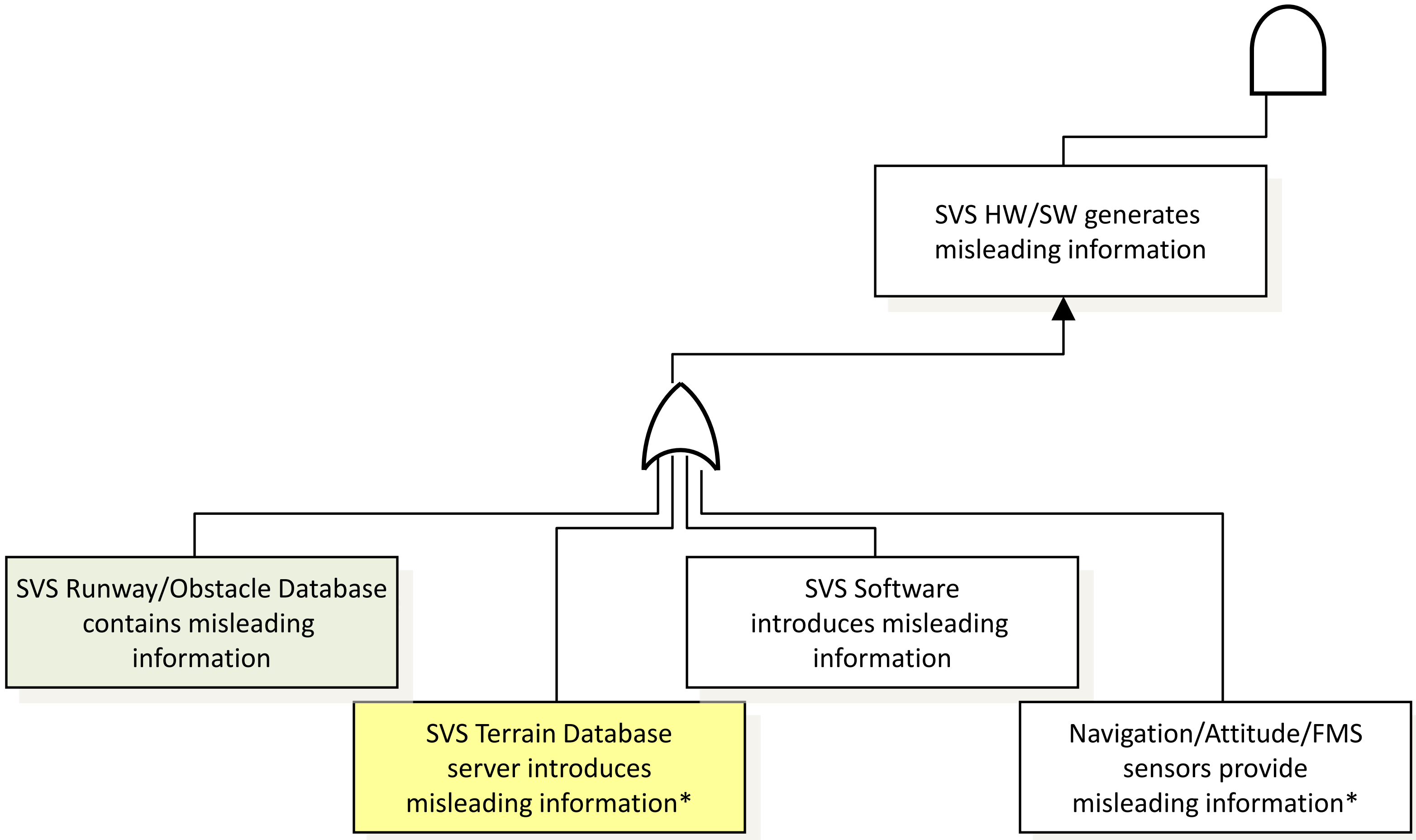
this event could occur if **misleading information** is generated by the SVS hardware/software and this information is used by the pilots to make tactical decisions.



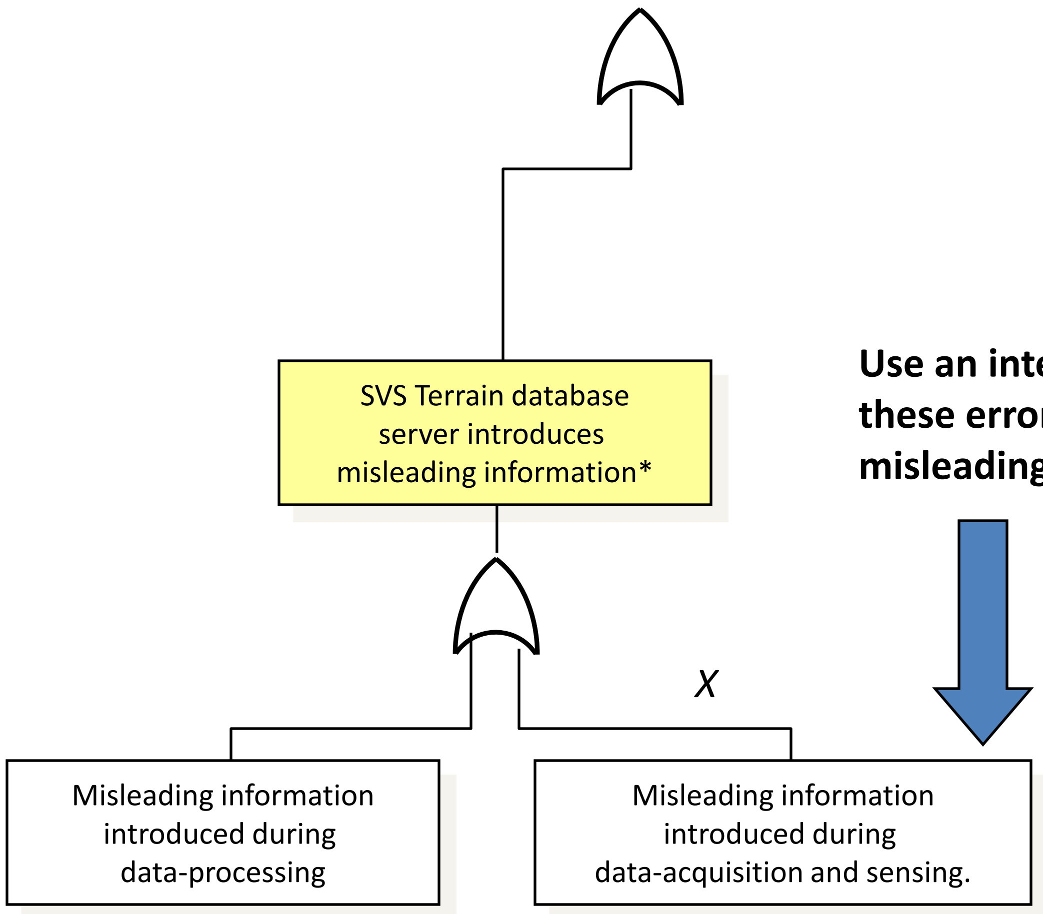
Synthetic Vision System



Safety Assessment: Fault Tree



SVS Fault Tree



Use an integrity monitor to "catch" these errors and flag the pilots if misleading information is detected !

RTCA DO-276B / EUROCAE ED-98
"User Requirements for Terrain and Obstacle Data"

Database products could be verified by the database providers

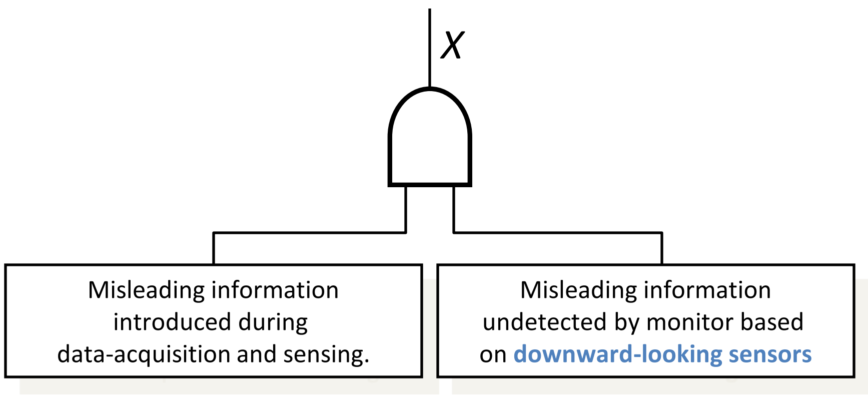
Threat Models

Two Failure Modes are considered:

(A) Misleading information in the form of a *vertical* bias (systematic error)
(B) Misleading information in the form of a *horizontal* bias (systematic error)

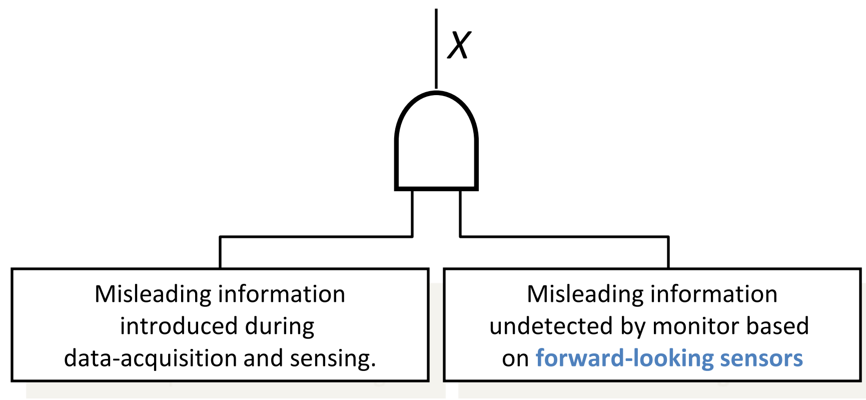
Integrity Monitor

Failure Mode (A)



Integrity Monitor

Failure Mode (B)



Note that if the integrity monitor detects a failure the pilot is notified automatically error

Database Integrity Monitor

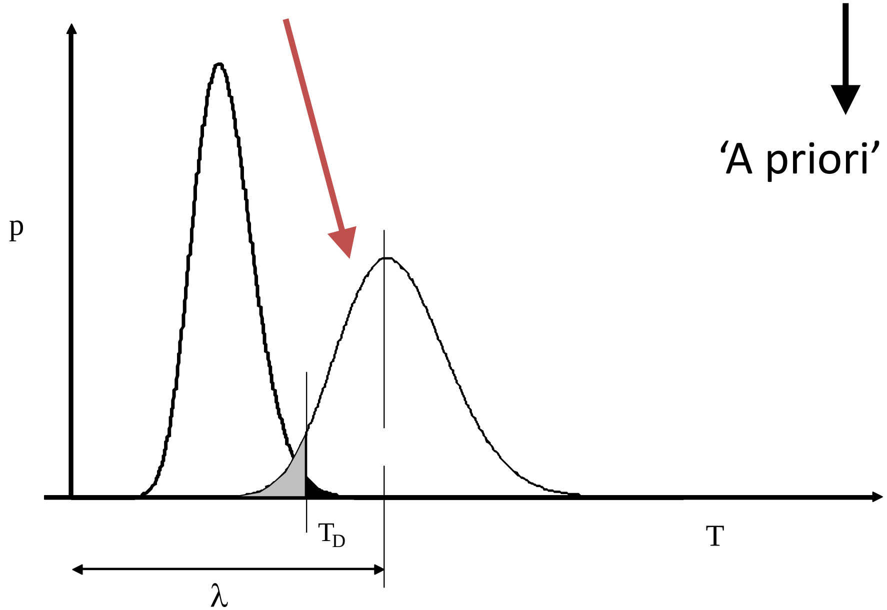
Mathematically Speaking …

Probability of an SVS failure due to a DEM failure such as a vertical bias:

$$P(\text{IM missed detection} \cap \text{DEM failure is present}) \cdot P(\text{Pilot missed detection} \cap \text{DEM failure is present}) \cdot P(\text{DEM failure degrades situational awareness})$$

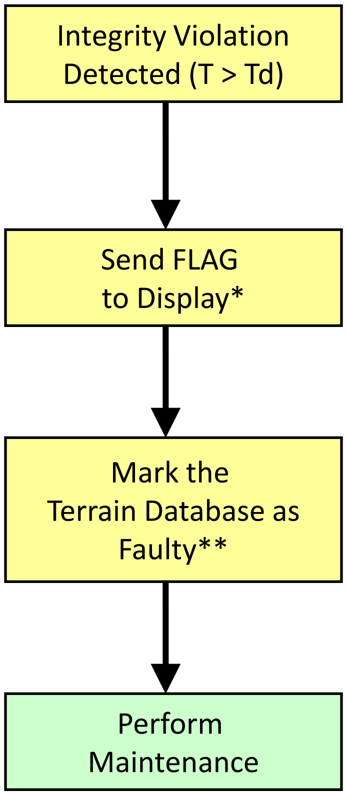
$$P(\text{IM missed detection} \mid \text{DEM failure is present}) P(\text{DEM failure is present})$$

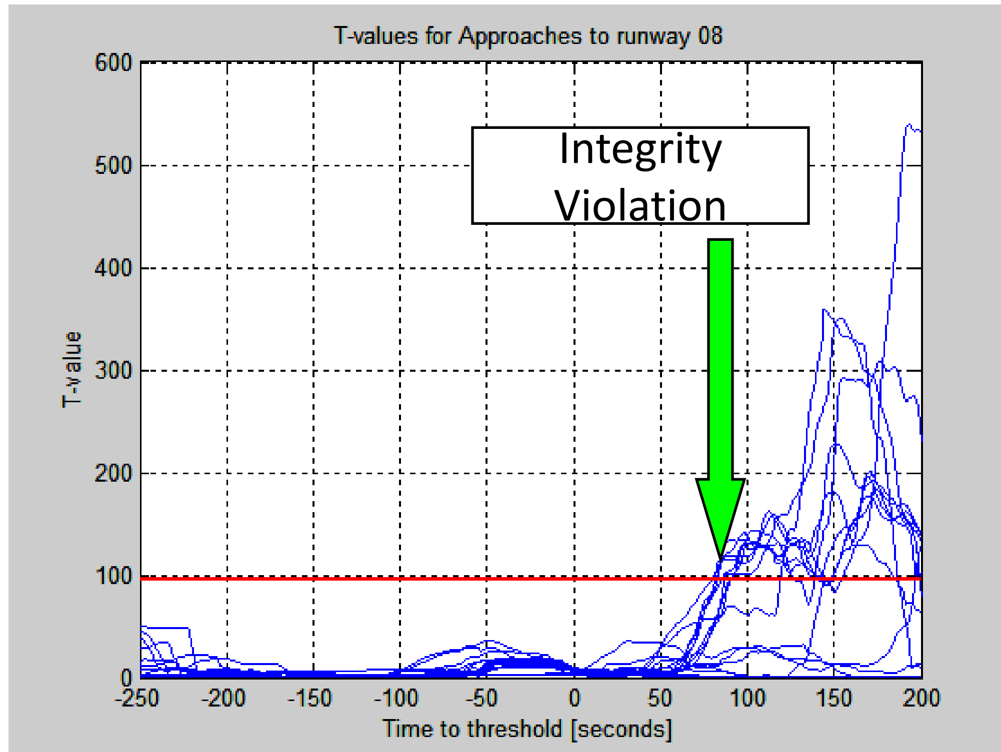
'A priori' or '1'



Function of
visual cues present, etc.

Operational Considerations



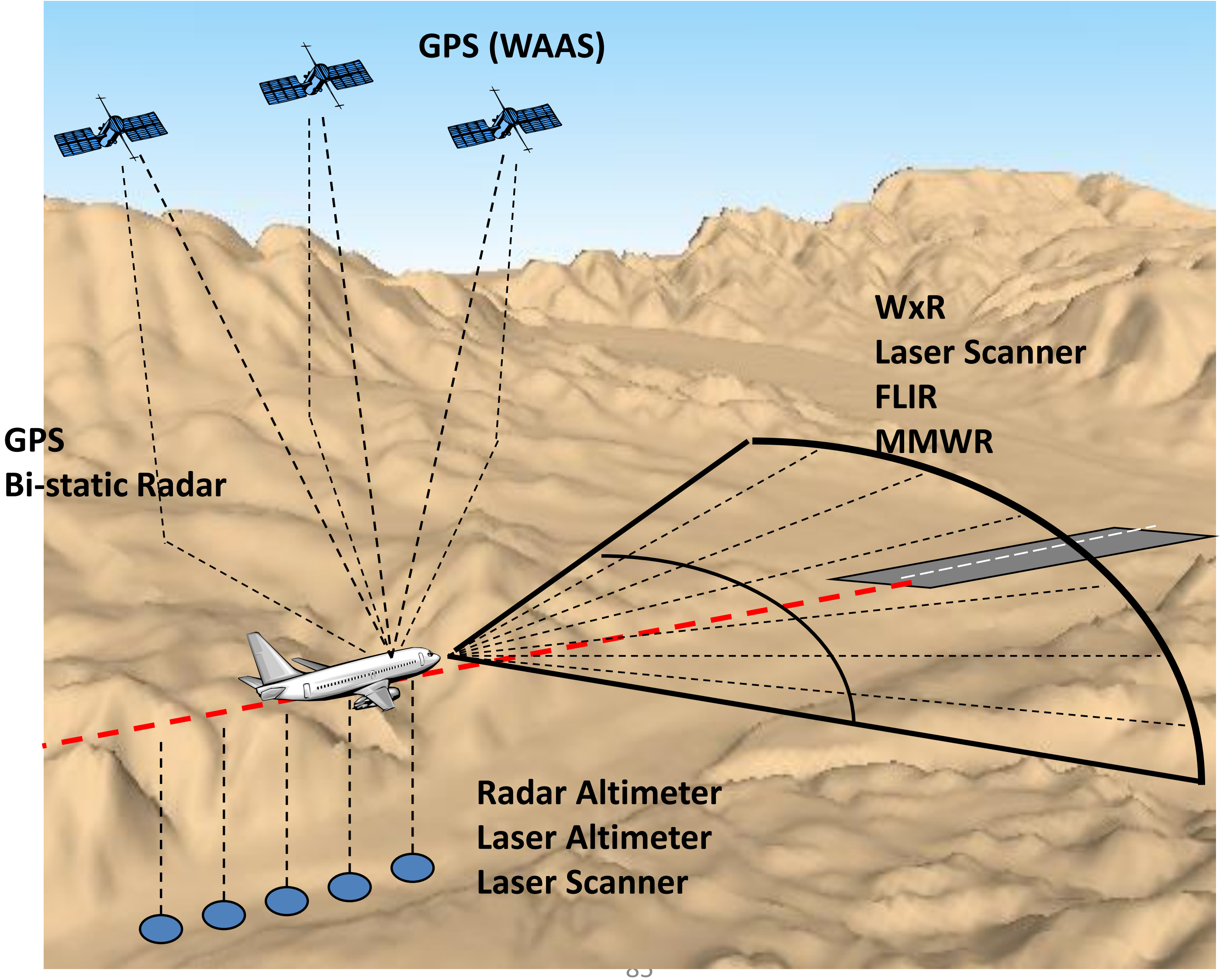


* It must be determined how this is accomplished (flag, level, etc.)

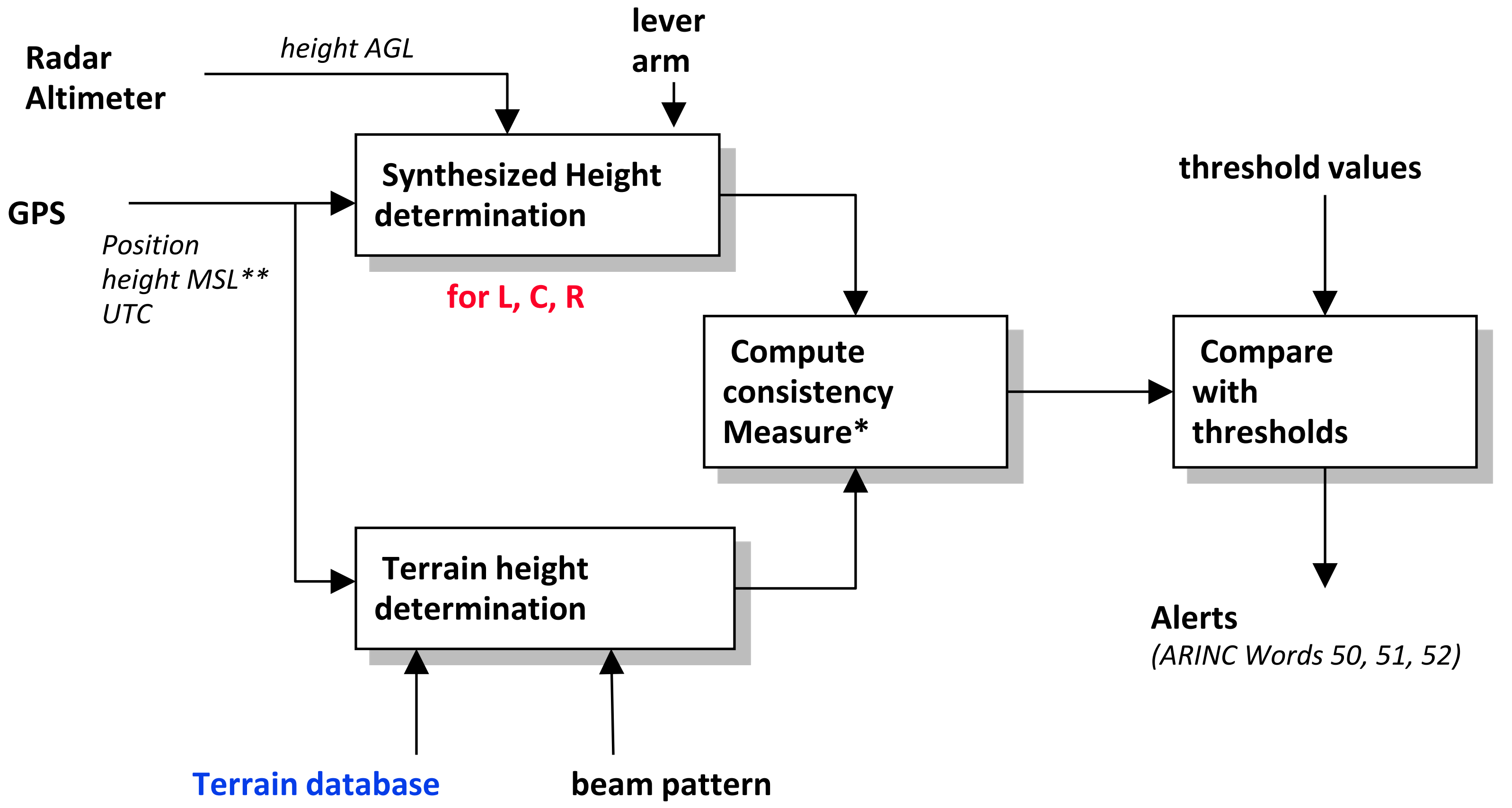
** A database "systematic error" such as a vertical bias is a permanent condition and would not allow for use of the database without a maintenance action

Integrity Monitoring: Concept

Compare Sensed with Stored Geo-spatial Data



Use of a Downward-looking Sensor



* Mean square Difference or Midvalue Select

**It is important that the MSL of GPS corresponds to the MSL used in terrain database

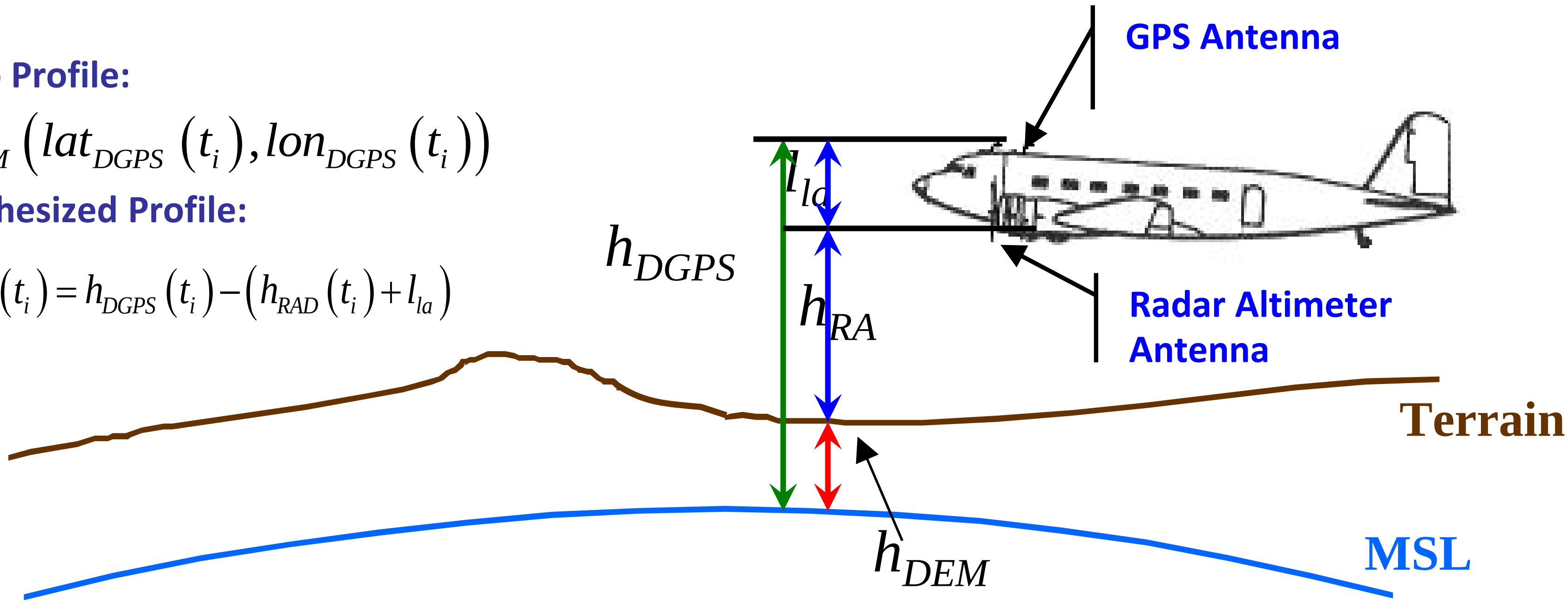
IM: Basic Mathematics

Map Profile:

$$h_{DEM}\left(lat_{DGPS}\left(t_i\right), lon_{DGPS}\left(t_i\right)\right)$$

Synthesized Profile:

$$h_{SYNT}\left(t_i\right) = h_{DGPS}\left(t_i\right) - \left(h_{RAD}\left(t_i\right) + l_{la}\right)$$



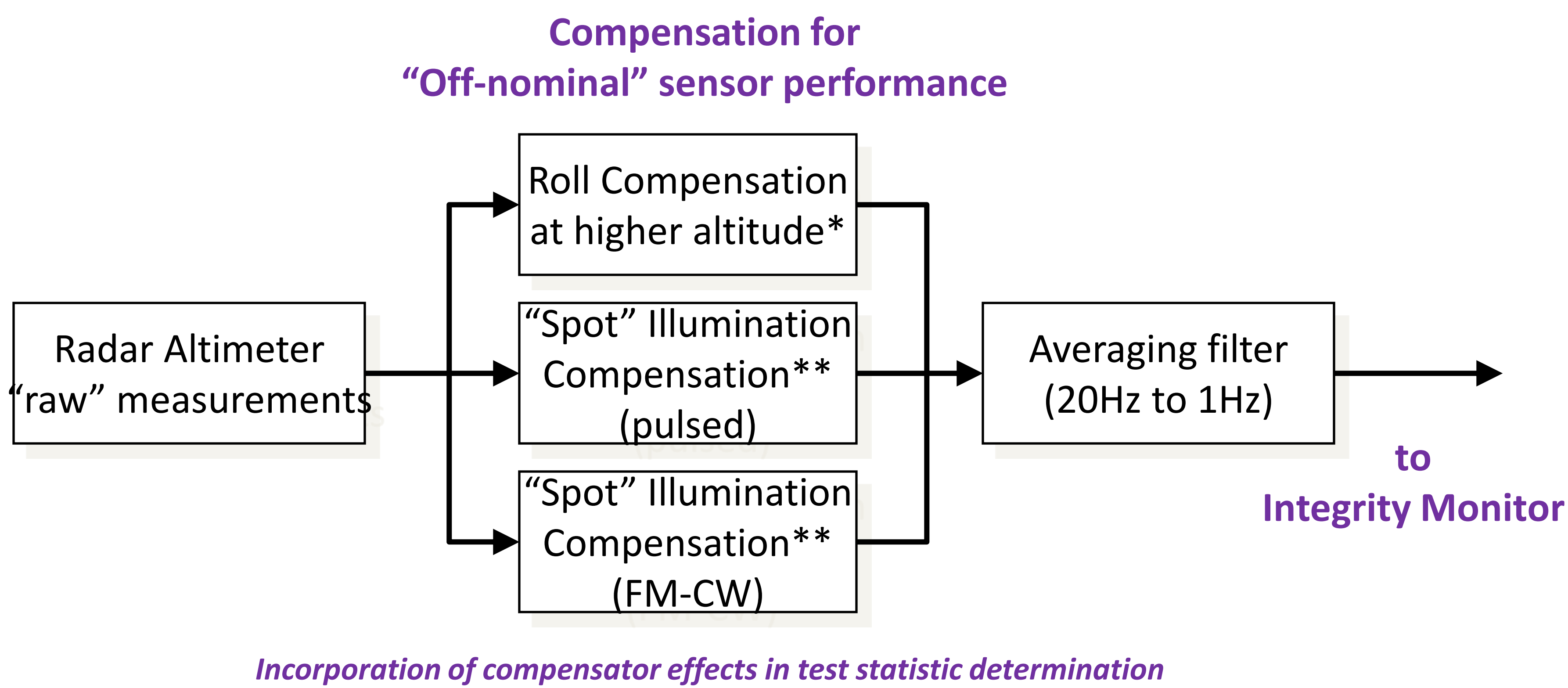
Consistency Metric: **Absolute Disparity**

$$p(t_i) = h_{SYNT}(t_i) - h_{DEM}\left(lat_{DGPS}\left(t_i\right), lon_{DGPS}\left(t_i\right)\right)$$

Test Statistics:

$$T = \frac{N}{\sigma_p^2} MSD_{AD} = \frac{1}{\sigma_p^2} \sum_{i=1}^{N} p^2(t_i) \qquad Z = \frac{1}{2\sigma_p^2} MSD_{SD} = \frac{1}{2\sigma_p^2 (N-1)} \sum_{i=1}^{N} s^2(t_i)$$

Required Sensor Compensation



*function of beamwidth

**function of sensor measurement mechanism

Extensive Flight Testing


OU King-Air – Juneau, AK (2002)

OU DC-3 – Asheville, NC (2001)

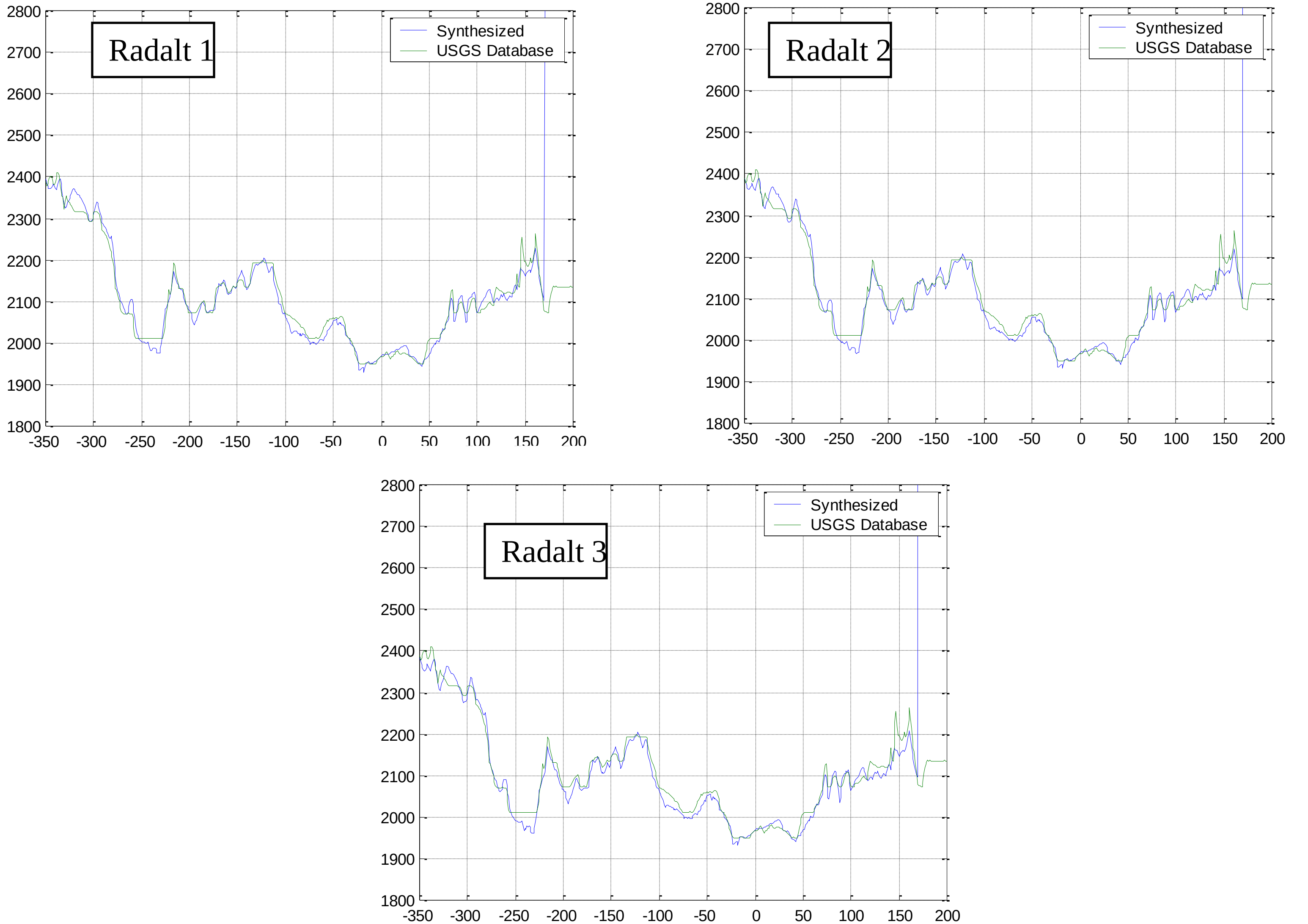
Veridian TIFS – Asheville, NC (2000)


Gulfstream GV – Reno, NV (2004)

NASA DC-8 – Edwards, AFB (CA)

NASA B757 – Eagle-Vail, CO (2001)

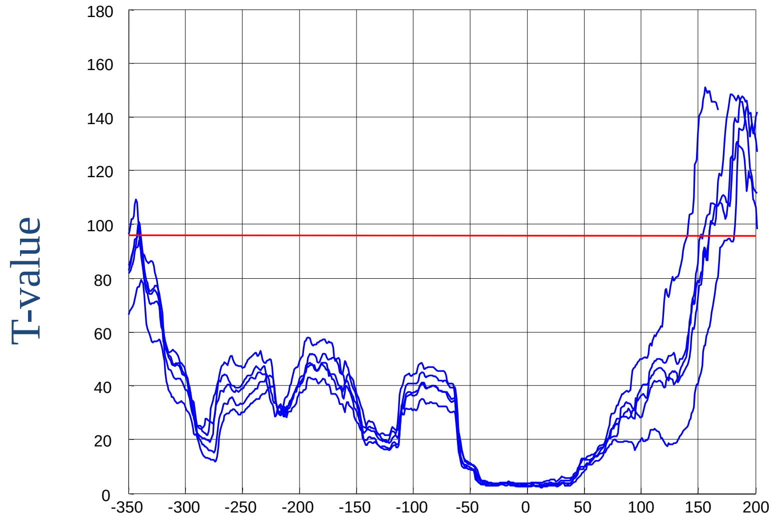
Terrain Profiles : Approach to runway 7 – Run 10 – 09/01/01
DEM: USGS Data; DGPS: WAAS



Height (m)

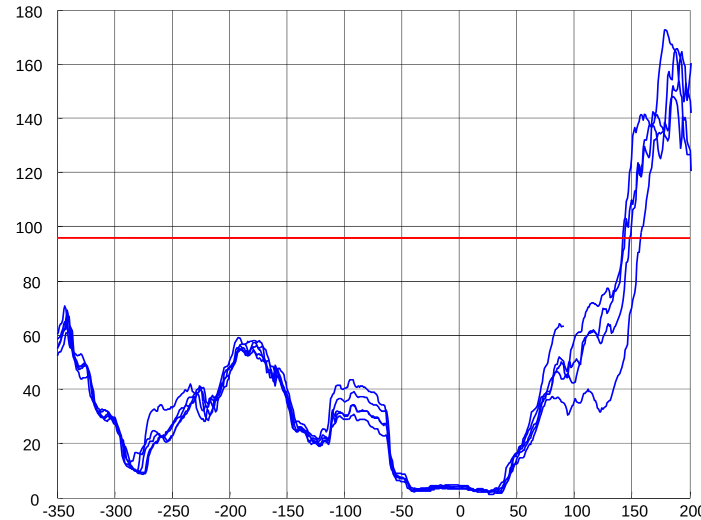
(Time) minus (Threshold Crossing Time) (sec)

WAAS



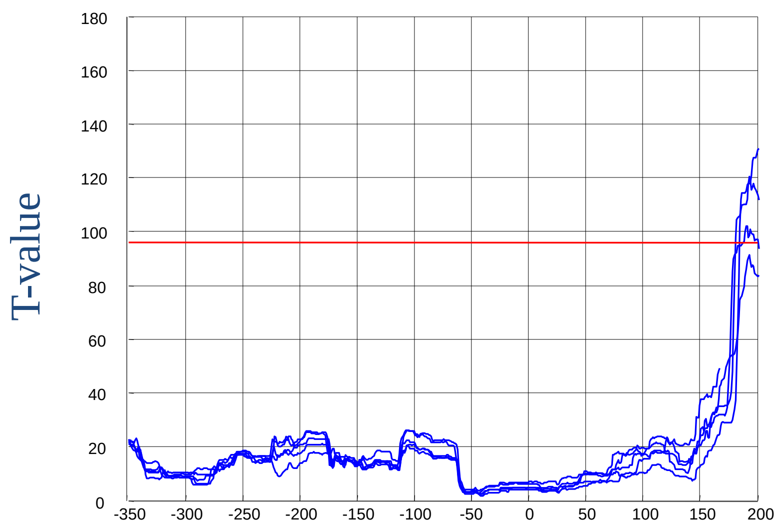
(a)

KGPS



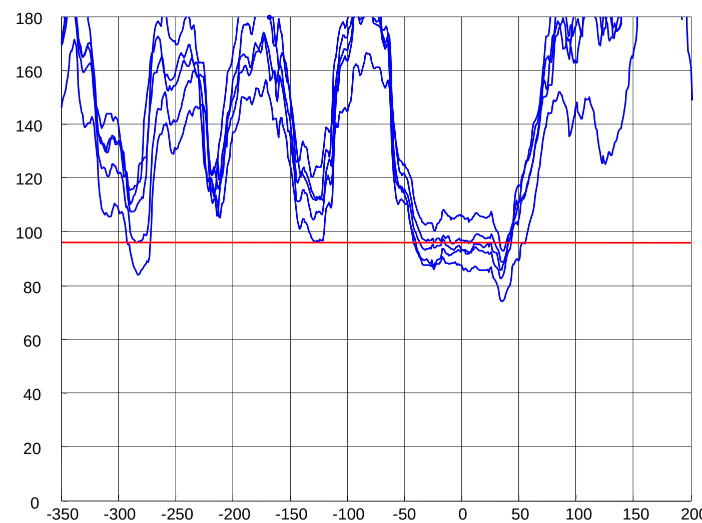
(b)

WAAS + RADALT Compensation



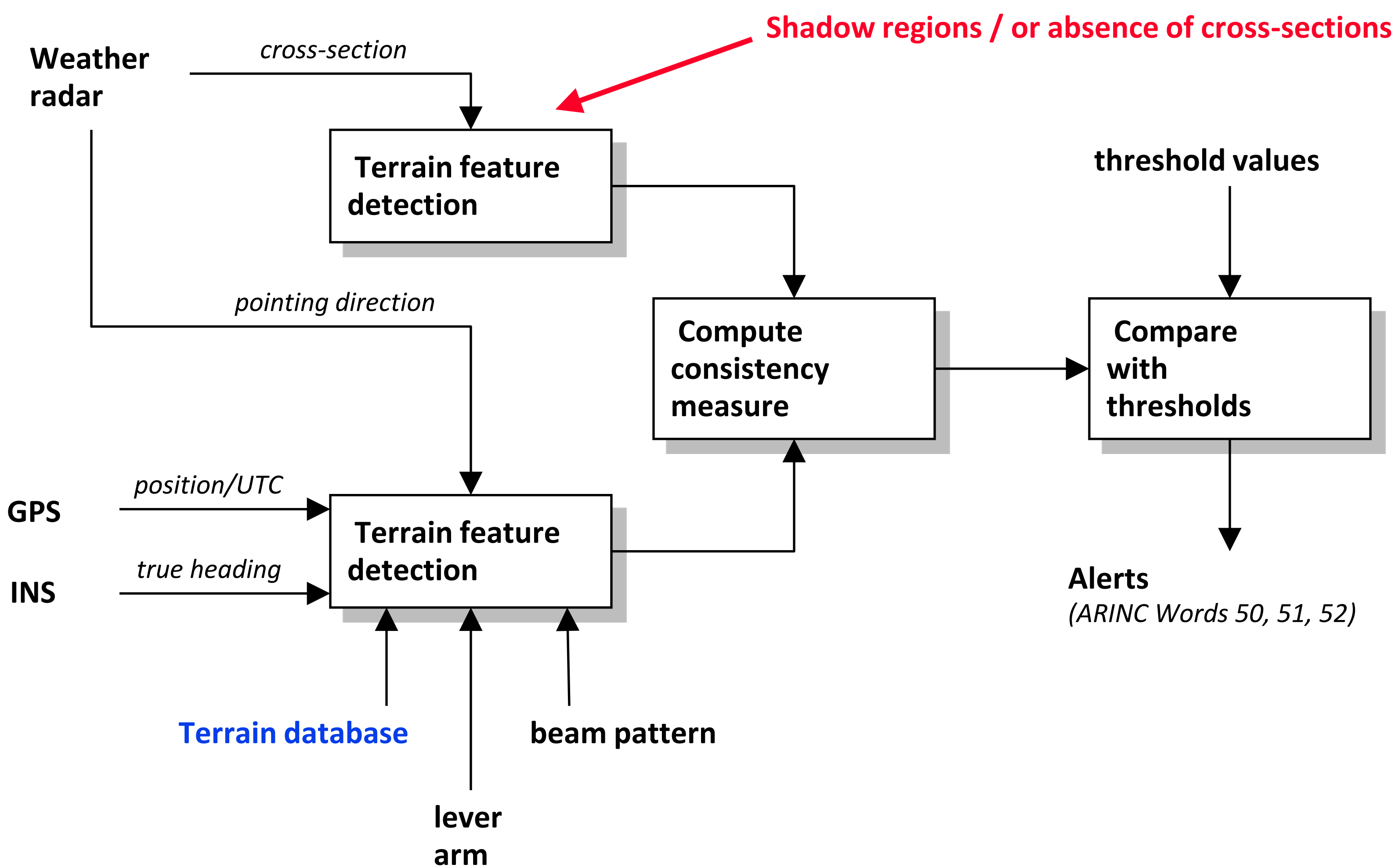
(c)

WAAS + RADALT Compensation + Bias

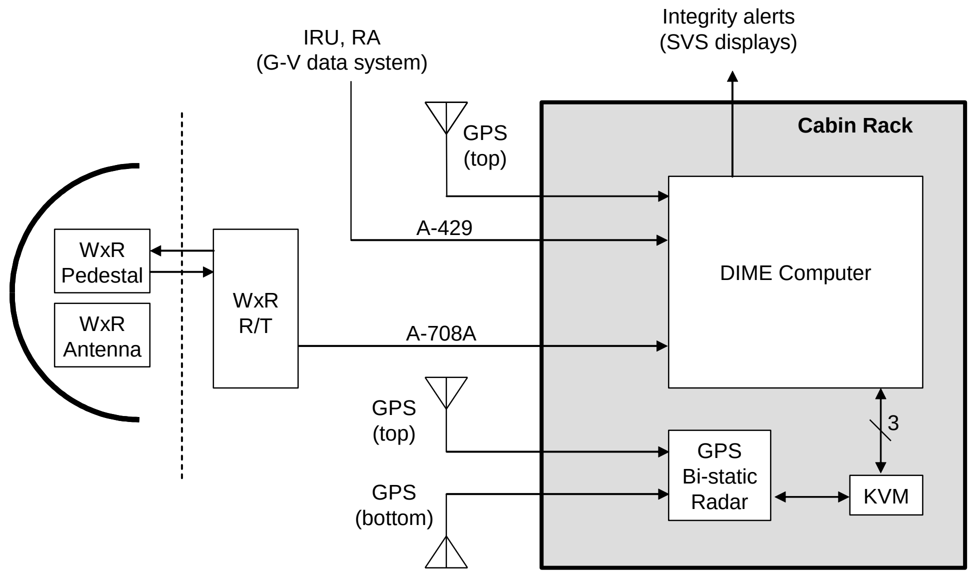


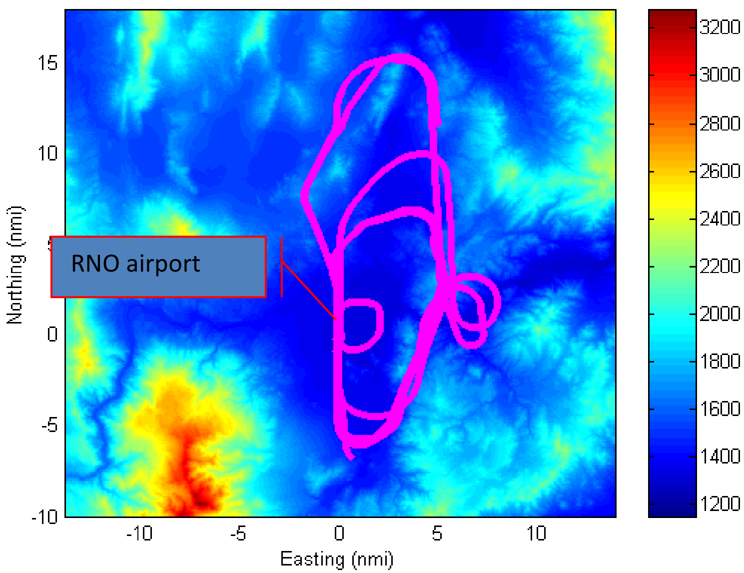
(d)

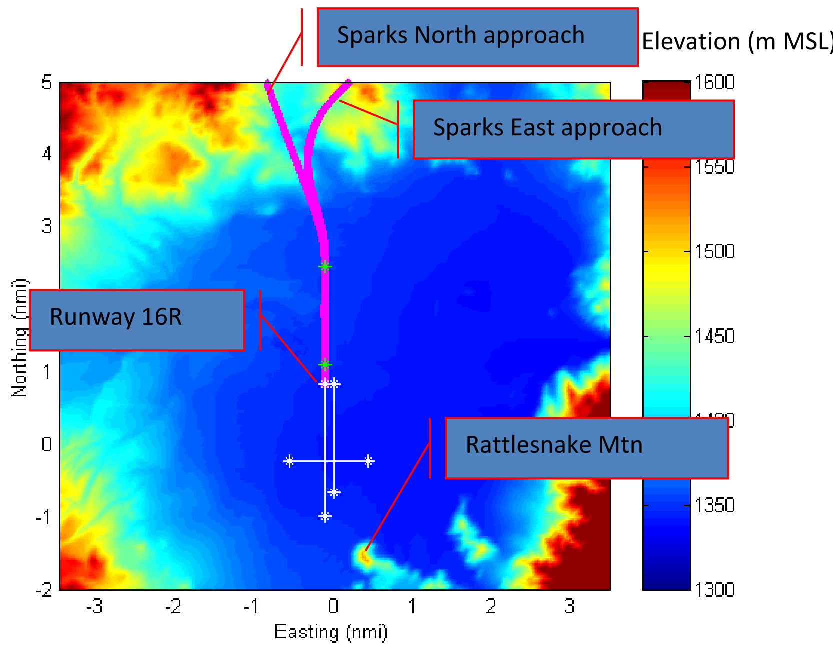
Use of a Forward-looking Sensor



Reno, NV

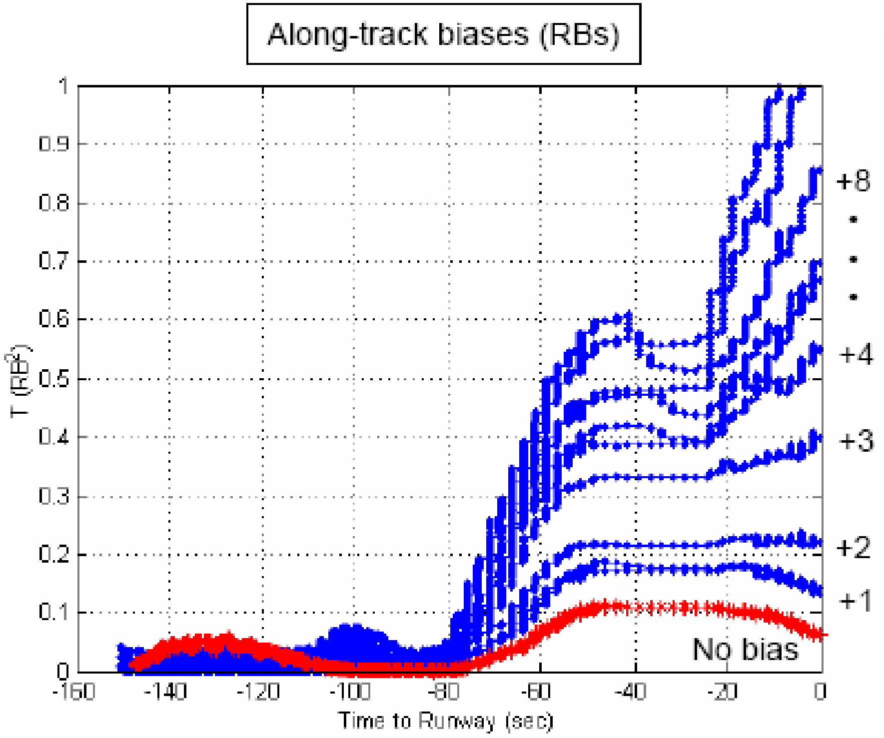

Integrity alerts
(SVS displays)
IRU, RA
(G-V data system)
Cabin Rack
GPS
(top)
A-429
DIME Computer
WxR
Pedestal
WxR
Antenna
WxR
R/T
A-708A
GPS
(top)
3
GPS
Bi-static
Radar
GPS
(bottom)
KVM

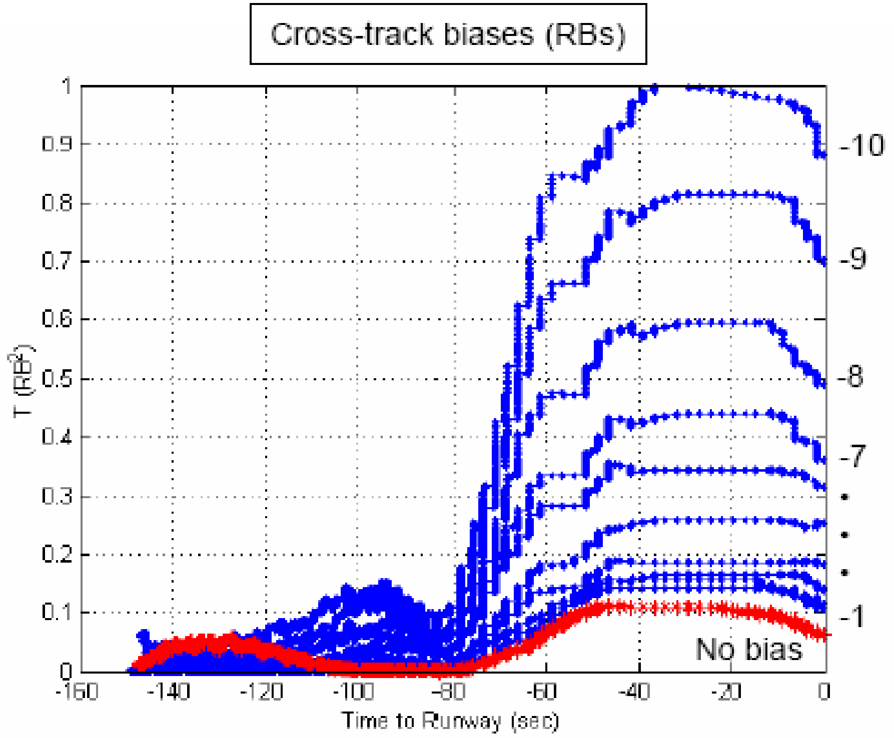

RNO airport
Northing (nmi)
Easting (nmi)
15
10
0
-5
-10
-10
-5
0
5
10
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200


Sparks North approach
Elevation (m MSL)
Sparks East approach
Runway 16R
Rattlesnake Mtn
Northing (nmi)
Easting (nmi)
5
4
3
1
0
-1
-2
-3
-2
-1
0
1
2
3
1600
1550
1500
1450
1350
1300

SVS Database Integrity Monitoring

“Looking Forward”





Display of Traffic: Surveillance

- TCAS II:
  - Range, Altitude, Bearing
- ADS-B:
  - Position, velocity reports
  - ADS-B Out: broadcast of ADS-B transmissions from aircraft (“out” of the aircraft)
  - ADS-B In: reception of ADS-B transmissions by aircraft (“in”to the aircraft)

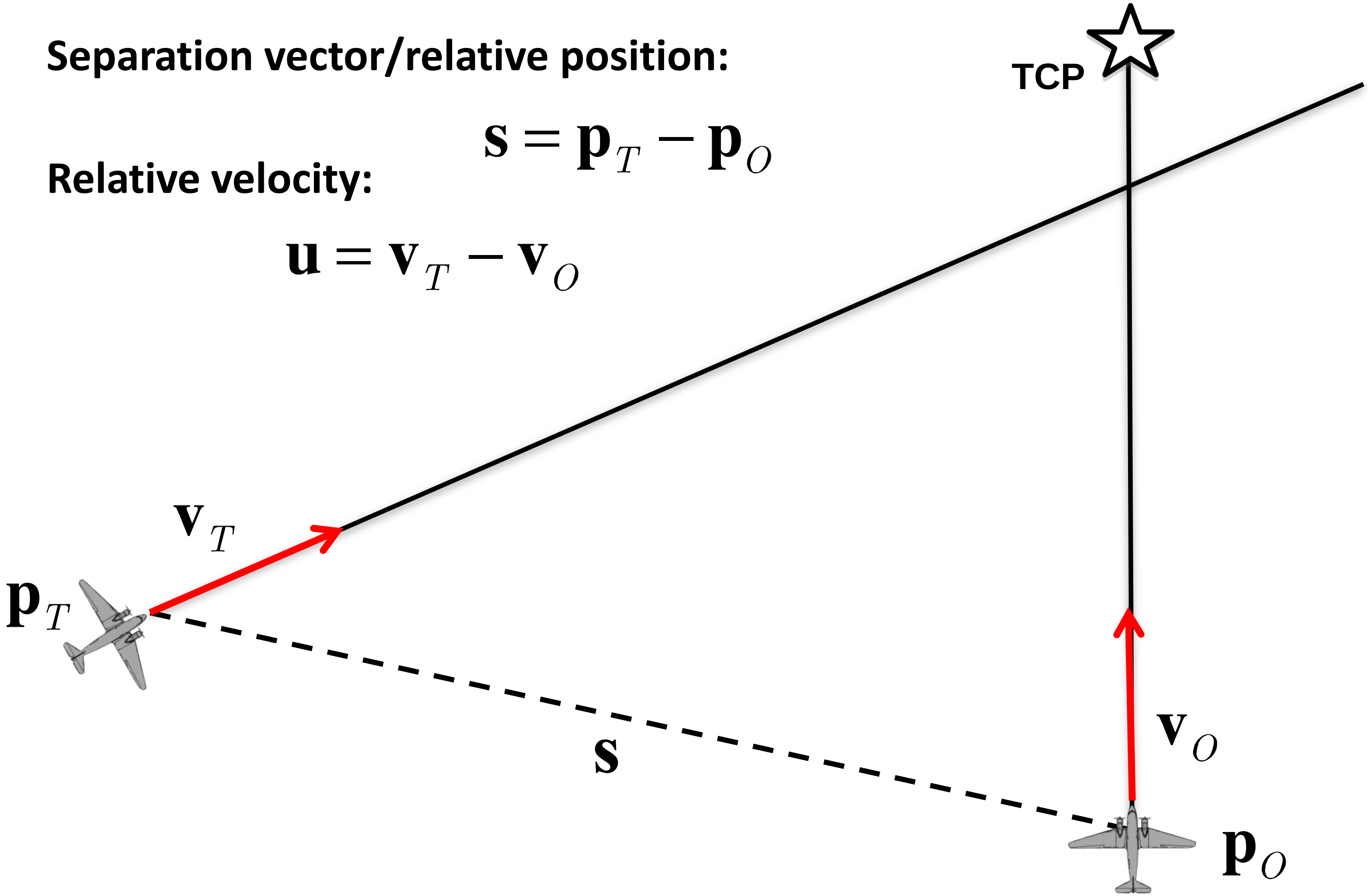
Tracking Traffic: Motion on a Line

Separation vector/relative position:

$$\mathbf{s} = \mathbf{p}_T - \mathbf{p}_O$$

Relative velocity:

$$\mathbf{u} = \mathbf{v}_T - \mathbf{v}_O$$



3D Traffic Tracking

Relative acceleration

Ownship velocity equals 0 in case of a ground station.

Relative velocity :

$$\mathbf{u}_m = \mathbf{u}_{m-1} + \mathbf{a}_m \left(t_m - t_{m-1}\right) =$$

$$= \mathbf{u}_{m-1} + \mathbf{a}_{Tm} \left(t_m - t_{m-1}\right) - \mathbf{q}_m$$

$$\mathbf{q}_m = \mathbf{V}_{Om} - \mathbf{V}_{Om-1}$$

Known estimated ownship acceleration

Relative position:

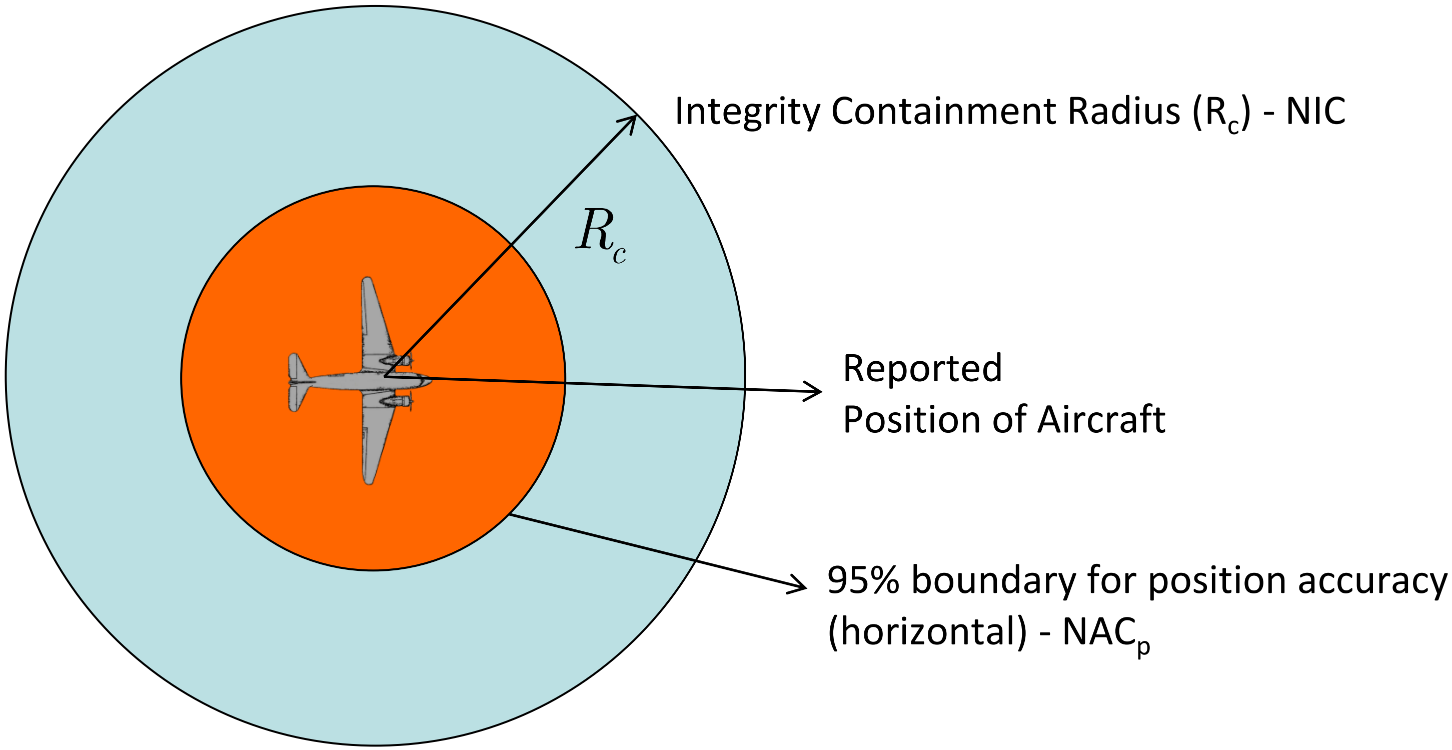
$$\mathbf{s}_m = \mathbf{s}_{m-1} + \mathbf{v}_{m-1} \left(t_m - t_{m-1}\right) + \tfrac{1}{2} \mathbf{a}_{Tm} \left(t_m - t_{m-1}\right)^2 - \mathbf{Q}_m$$

$$\underbrace{\begin{bmatrix} \mathbf{s}_m \\ \mathbf{u}_m \\ \mathbf{a}_{Tm} \end{bmatrix}}_{\mathbf{x}_m} = \underbrace{\begin{bmatrix} \mathbf{I} & \left(t_m - t_{m-1}\right)\mathbf{I} & \tfrac{1}{2}\left(t_m - t_{m-1}\right)^2 \mathbf{I} \\ 0 & \mathbf{I} & \left(t_m - t_{m-1}\right)\mathbf{I} \\ 0 & 0 & \mathbf{I} \end{bmatrix}}_{\mathbf{\Phi}(t_m, t_{m-1})} \underbrace{\begin{bmatrix} \mathbf{s}_{m-1} \\ \mathbf{u}_{m-1} \\ \mathbf{a}_{Tm-1} \end{bmatrix}}_{\mathbf{x}_{m-1}} - \begin{bmatrix} \mathbf{Q}_m \\ \mathbf{q}_m \\ 0 \end{bmatrix}$$

$$\mathbf{Q}_m = \int \mathbf{q}_m \, dt$$

$$dt = t_m - t_{m-1}$$

ADS-B Navigation Quality Parameters



At a SIL of 2, a NIC of 11 means the probability of exceeding the horizontal containment radius of R_C < 7.5m is less than or equal to 10^{-5} (similarly for the vertical with the VPL<11m).

NAC_p, NAC_v, SIL

NAC_P	95% EPU and VEPU	Comment
0	EPU ≥ 10nmi	Unknown accuracy
1	EPU < 10nmi	RNP-10 accuracy
2	EPU < 4nmi	RNP-4 accuracy
3	EPU < 2nmi	RNP-2 accuracy
4	EPU < 1nmi	RNP-1 accuracy
5	EPU < 0.5nmi	RNP-0.5 accuracy
6	EPU < 0.3nmi	RNP-0.3 accuracy
7	EPU < 0.1nmi	RNP-0.1 accuracy
8	EPU < 0.05nmi	e.g. GPS (with SA on)
9	EPU < 30m and VEPU < 45m	e.g. GPS (SA off)
10	EPU < 10m and VEPU < 15m	e.g. WAAS (SBAS)
11	EPU < 3m and VEPU < 4m	e.g. LAAS (GBAS)

NIC	Containment Radius (R_C) and VPL
0	R_C unknown
1	R_C < 20 nmi
2	R_C < 8 nmi
3	R_C < 4 nmi
4	R_C < 2 nmi
5	R_C < 1 nmi
6	R_C < 0.6 nmi
6	R_C < 0.5 nmi
7	R_C < 0.2 nmi
8	R_C < 0.1 nmi
9	R_C < 75m and VPL < 112m
10	R_C < 25m and VPL < 37.5m
11	R_C < 7.5m and VPL < 11m

NAC_V	Horizontal Velocity Error (95%)	Vertical Velocity Error (95%)
0	Unknown or ≥ 10m/s	Unknown or ≥ 50fps*
1	< 10m/s	< 50fps
2	< 3m/s	<15fps
3	< 1m/s	< 5fps
4	< 0.3m/s	< 1.5fps

SIL	Probability of exceeding R_C
0	Unknown
1	$1x10^{-3}$ per flight hour or per operation
2	$1x10^{-5}$ per flight hour or per operation
3	$1x10^{-7}$ per flight hour or per operation

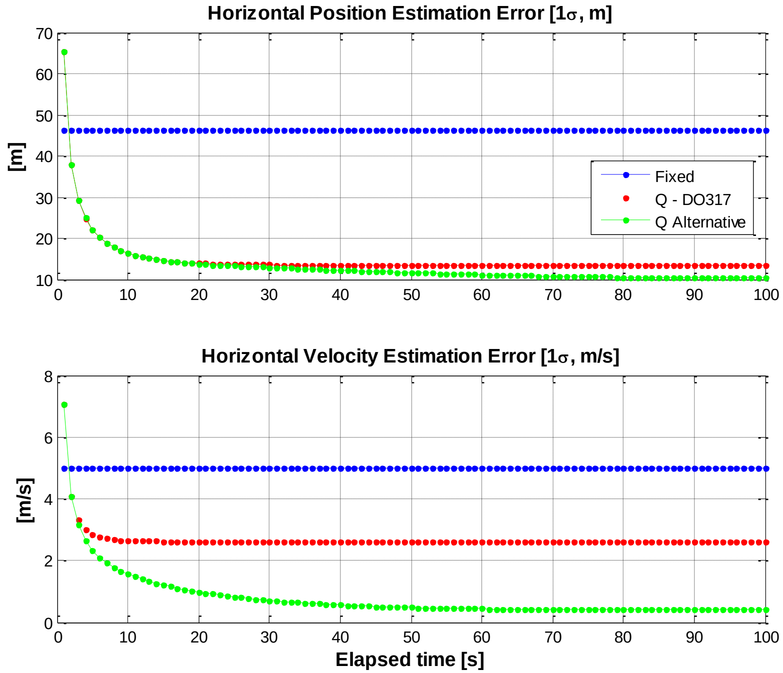
Ref: RTCA SC-186, December 2, 2009, Minimum Operational Performance Standards (MOPS) for 1090 MHz Extended Squitter Automatic Dependent Surveillance-Broadcast (ADS-B) and Traffic Information Services-Broadcast (TIS-B), RTCA/DO-260B, Washington, DC, RTCA, Inc.

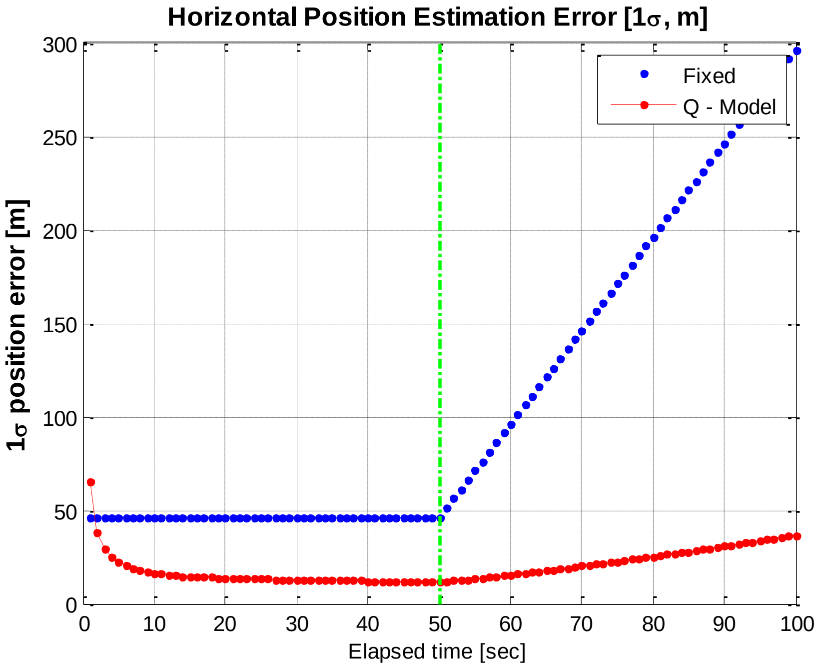
Effect of Estimate Uncertainty

- Example from *NASA/OU IAN Simulink* simulator
- $NAC_p = 8$, $NAC_v = 1$

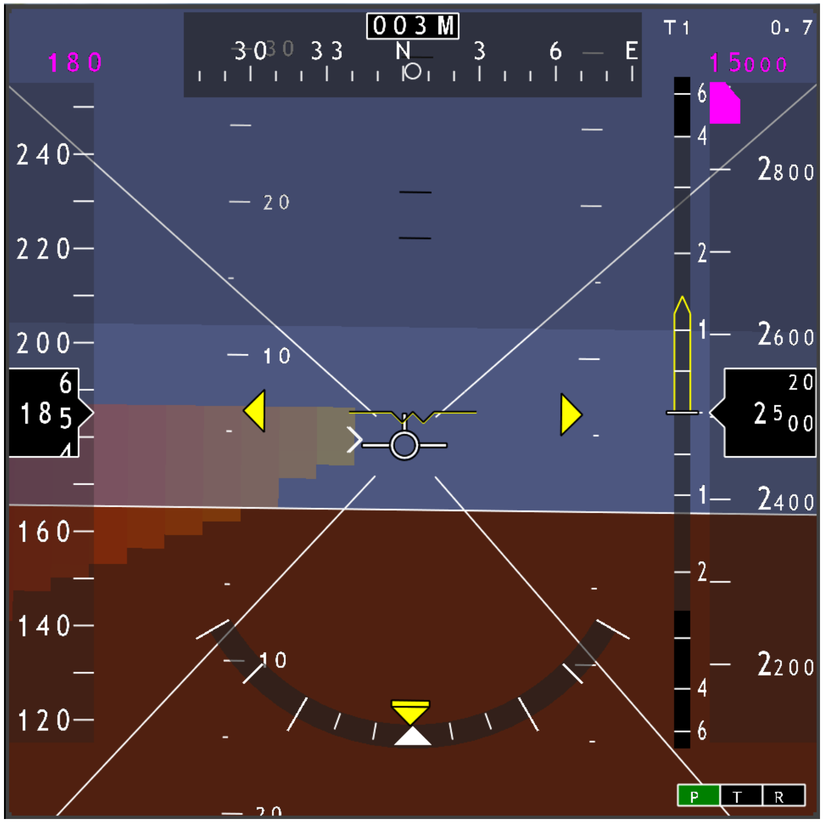
< 92.6m / < 92.6m
95%

< 10m/s / < 15.2 m/s
95%

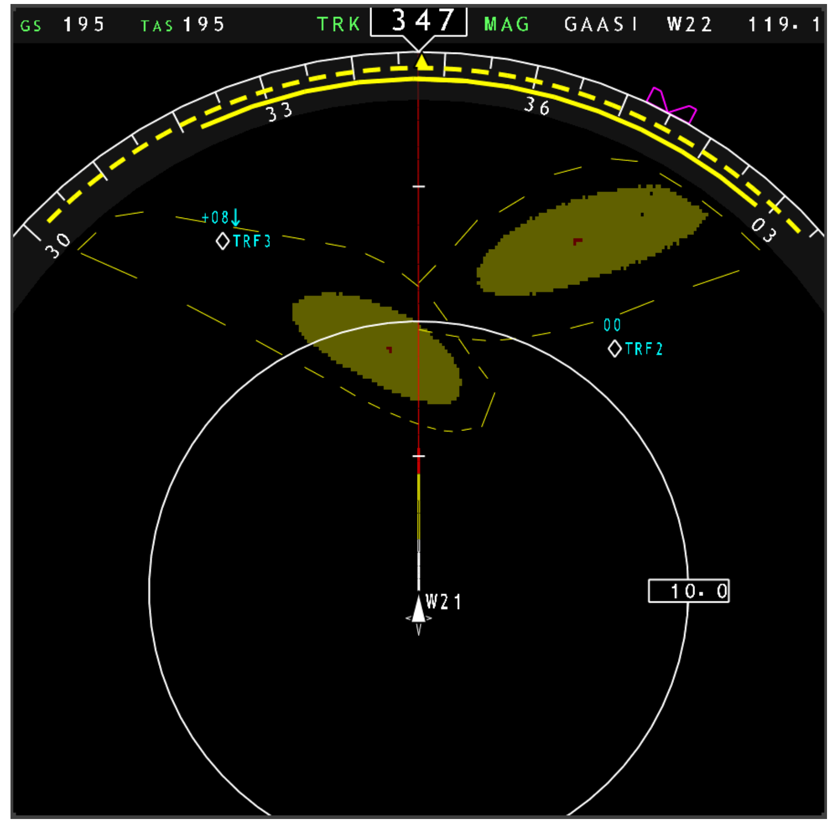




Effect of Estimate Uncertainty



Conflict Probes



Impact of Uncertainty on Probes

From Design to Implementation

From Design to Implementation

- Data requirements
- Hardware and software

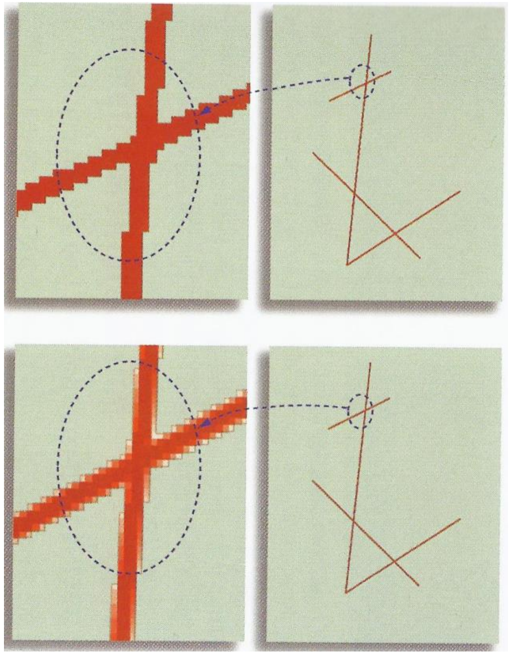
Data Requirements

- Accuracy and Resolution
  - In context of RNP, the impact of position data resolution on PDE should be negligable
- Update-rate
  - Impacts the stability of the control loop in case of manual control
  - PFI layer: Requirements comparable to PFD
  - SV layer: >15 Hz (RTCA DO-315B)
- Latency
  - Impacts the stability of the control loop in case of manual control
  - Requirements comparable to PFD
- Integrity
  - The Achilles-heel of any database-oriented system is that errors in the database can cause terrain hazards present in the flight path of the aircraft not to be depicted

Hardware and Software

- Display generation
  - Anti aliasing
  - Texturing
  - Graphical Processing Unit (GPU)
- API's
- Rapid prototyping

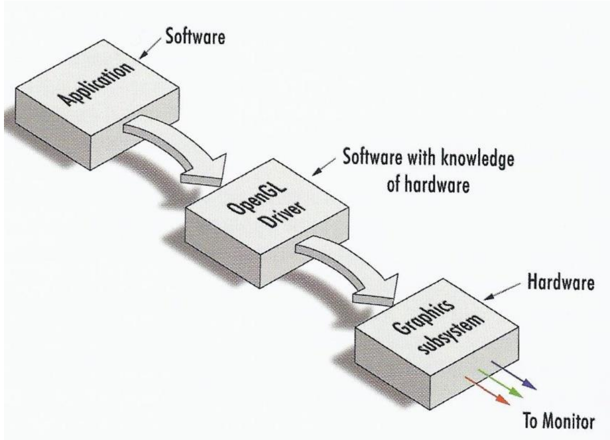
Display Generation



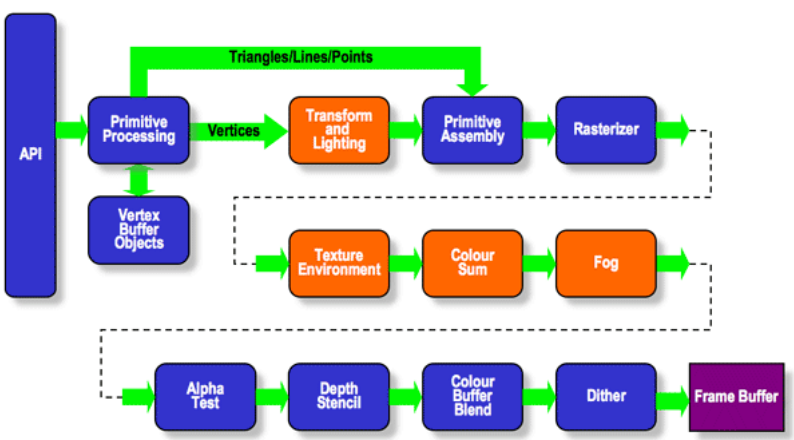
- Anti-aliasing
  – Required when using raster-based display devices such as AMLCD
- Texturing
  – Required when going beyond wire-frame or shaded terrain
- GPU: Computing device that processes graphics and creates or renders the display
  – Transformation
  – Texturing
  – Lighting
  – Rasterization

Application Programming Interface (API)

- OpenGL
  - Standardized API
- OpenGL ES
  - Well-defined subset for embedded systems
  - Multiple profiles: common, safety critical



- Functions comprise:
  - Matrix-based geometry transformations
  - Viewport and clipping regions
  - Textured geometry



Rapid Prototyping

- Tools to reduce the manual coding effort by enabling:
  - Design of the instrument overlay graphics objects
    - Generate autocode from the design specification, or
    - Use a data-driven approach for the object rendering
  - Load terrain data and create terrain objects
  - Visualize terrain objects and instrument overlays
  - Design and integrate moving 3-D objects
  - Migrate between different platforms (hardware, OS)
- Typical limitations:
  - Ability to efficiently deal with dynamic objects (changing geometry during run-time)
    - Dynamic paths
    - Dynamic conflict space

Summary

- The concept of synthetic vision for aviation dates back to the Army-Navy Instrumentation Program (ANIP) that started in 1952
- The design of a synthetic vision system requires questions concerning content, representation and presentation to be addressed
- The options to be considered depend on the intended function(s)
- To allow a systematic design, a distinction was made between:
  - The awareness layer (containing terrain, obstacles, hazards, constraints)
  - The guidance layer (containing trajectory preview) and
  - The Primary Flight Information layer
- Design guidance & requirements for the awareness and guidance layers can be found in:
  - SAE ARP5589
  - RTCA SC-213 DO-315B
- To go from design to an implementation, choices concerning hardware and software have been addressed
- This tutorial provided an overview of the main design questions, options and associated issues

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