F-16 E/F Automatic Terrain Following Development:

“IT’S NOT OVER TILL IT’S OVER”

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Overview

- Super Viper Description
- TF Overview
- RTF Overwater Incident
- DBTF Desert Butte Incident
- Summary
- Lessons Re-Learned
- ????
F-16 E/F – A New Fighter

**NEW AVIONICS**
- Mission Computer
- Color Display Processor
- Fiber Optic Architecture
- Data Link, Com & Nav System
- IFF Interrogator

**ADVANCED SENSORS**
- Agile Beam Radar
- Integrated FLIR & Targeting System
- Radar Auto Terrain Following
- Internal Electronic Warfare Suite
- Countermeasures Dispenser System

**ADVANCED COCKPIT**
- Revamped Pilot Interface
- Color Glass Cockpit

**PROPULSION**
- F110-GE-132
- Autothrottle

**AIRFRAME/ SYSTEMS**
- 50,000 lb Max TOGW
- 44,500 lb Max Landing Wt
- Dual ECS
- NVIS Exterior / Strip Lighting
- Equipment Dorsal
- Conformal Fuel Tanks

**FLIGHT CONTROL SYSTEMS**
- Upgraded Digital Flight Controls
- New Air Data System
- Next Generation Autopilot
- Auto Ground Collision Avoidance System
- Pilot Activated Recovery System
- Auto Deep Stall Recovery
Full Color, All Digital Cockpit

- Three 5 x 7 inch Primary Multi-Function Color Displays
- Windowing Capability, Nine Displays Within Three
- Fused Sensor Data Presented Pilot
- Intuitive HOTAS Controls Optimized Through Combat Operations
- Fully NVIS Compatible

Combat-Optimized Man Machine Interface
PVI – Sometimes Nothing Helps
Terrain Following (TF) Capabilities

- Radar Terrain Following (RTF) – Active mode
  - *Stand-alone or interleaved radar modes*

- Database Terrain Following (DBTF) – Passive mode

- Manual or automatic capability with autopilot modes
  - *Fully coupled operation*

- System Wide Integrity Monitoring for fault detection

- RTF / DBTF - Integrated operation
Radar Terrain Following

- Radar senses terrain and generates climb / dive commands at selected Set Clearance Plane (SCP)

- Flight control system (FLCS) follows commands from radar computer
  - Control stick coupling of displayed commands in Manual RTF
  - Direct coupling in Automatic RTF

- Radar Altimeter
  - Checks operation as back-up to radar
‘E-Squared’ and Terrain Profile Display
Data Base Terrain Following

- Digital Terrain Elevation Database (DTED)
  - Scanned to generate 2D Worst Case Profile (WCP) of Terrain
- DBTF algorithm scans WCP
  - Generates climb / dive commands at selected Threshold Crossing Height (TCH)
- FLCS follows commands from digital terrain system (DTS) flight software
  - Control stick coupling of displayed commands in Manual TF
  - Direct coupling in Automatic TF
- Radar Altimeter
  - Checks operation as back-up to DTS
DBTF Functional Block Diagram

- MULTI-FUNCTION DISPLAY
  - Terrain Video

- HEAD UP DISPLAY
  - Command Cues

- PILOT

- SIDE STICK CONTROLLER

- DIGITAL FLIGHT CONTROL SYSTEM
  - Command Execution

- CONTROL SURFACE
  - Aircraft Response

- RADAR ALTIMETER
  - Altitude Above Ground Level

- Data Transfer Cartridge
  - Terrain Database

- EMBEDDED GPS/INS
  - Aircraft State Data

- AIRFRAME

- ADTE

  - TF Processing
    - Terrain Profile Selection
    - Command Generation
  - Aircraft Position in Terrain Database
  - Terrain Referenced Navigation

- Aircraft Position in Terrain Database

- Climb/Dive Command

- Manual
  - (Standard 3 only)

- Auto

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Who Needs Pilots Anyway???
**RTF Test Development**

- Robust full envelope expansion
  - *Excellent results*
- All terrain types
  - *Flat, moderate, mountainous*
  - *Low reflective (water / sand)*
- Adverse weather
- Full speed / aircraft weight range
- Interleaved radar modes
  - *Simultaneous RTF / SAR map / Air-to-Air tracks*
RTF Over Water Event

- Speed and altitude verification over water
  - *Near end of test program*

- Gulf of Mexico
  - *Perfect day*
  - *Calm water / no wind*

- Test Point
  - *Auto RTF*
  - *600 KCAS / 100 ft AGL / non-turning*

- Event
  - *Full Command -1 g pushover at 100 ft AGL*
RTF Over Water
Analysis - Automatic Ground Recovery

- Minimum of 40 ft AGL
- Full pushover command at $t = 5$ sec
- Rate limited at $-0.6g/sec$
- 4g flyup
- VCW at 84 ft
Causes and Solution

- Logic anomaly in Radar software only evident under very limited conditions
  - Few ‘real’ radar measurements
    - Smooth water
    - Low grazing angle
  - Specific sequence required
    - Last complete scan with no radar measurements
    - Current scan (in progress) with very few measurements at short range
  - Resultant RTF terrain profile contained erroneous height data

- Solution
  - Ignore any ‘no measurement’ data from previous scan
  - Use near-range radar measurements from current scan to create RTF terrain profile
DBTF Test Development

- Robust full envelope expansion
  - Excellent results
- All terrain types
  - Flat, moderate, mountainous
- Full speed / aircraft weight range
- Good performance against vertical obstacles
DBTF Twin Butte Testing

- Rough and Moderate testing completed down to 200 ft AGL
- Flat terrain tested down to 100 ft AGL

- Test Point
  - 480 KCAS / 200 ft AGL / Auto
  - Versus single vertical obstacle

- Event
  - Fly-up over Butte when 75% of TCH incursion
DBTF Twin Butte Testing
Legacy Level 1 DTED

View from aircraft:

Legacy Level 1 DTED (rendered by Mission Planning System):

Google Earth:
## DTED Levels and Sources

<table>
<thead>
<tr>
<th>DTED Level</th>
<th>Post Spacing</th>
<th>Ground Distance</th>
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<tbody>
<tr>
<td>1</td>
<td>3 arc-sec</td>
<td>~300’ (100m)</td>
</tr>
<tr>
<td>2</td>
<td>1 arc-sec</td>
<td>~100’ (30m)</td>
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</tbody>
</table>

### Source

<table>
<thead>
<tr>
<th>Source</th>
<th>Remarks</th>
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</table>
| Legacy (Photogrammetric / Topographic) | - Coverage:  
  - Level 1: ~70% of earth’s landmass  
  - Level 2: ~ 10% of earth’s landmass  
  - Issues: Non-homogenous, significant artifacts, “bare earth” |
| SRTM (Shuttle Radar Topography Mission – STS-99, Feb 2000) | - Coverage: 60 N to 56 S  
  - Issues:  
    - Not “bare earth” (some foliage and obstacles averaged in)  
    - Voids where low reflectivity (sand, flat, water, extremely steep) |
Shuttle Radar Topography Mission
Summary

- Robust Terrain Following development
  - All flight / terrain conditions
  - Mature ‘build-down’ and envelope expansion procedures
  - Rigorous test process

- Many other contributors to a test
  - Perfectly calm water exposed faulty logic path
  - Terrain data errors masked TF performance

- 2 Incidents
  - Saved by good luck or good test planning???
Lessons Re-Learned

- Never just testing a single discipline
- Spec Compliance is not necessarily Developmental Testing
- Development is a Discovery Process
- Diligence required until the end
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Questions ???