GNSS-based Flight Inspection Systems

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2/26/2023

Introduction

- Stanford Univ. has developed Global Navigation Satellite System (GNSS)-based flight inspection systems:
  - WAAS-aided FIS: described at 14th IFIS at Toulouse
  - WAAS-based FIS
  - Standalone (unaugmented) GPS-based FIS

- The primary objective of this work was to develop a FI truth system with
  - High efficiency: onboard self-contained FIS
  - Low cost: no INS (WAAS-based FIS, standalone GPS-based FIS)

WAAS(SBAS)-based FIS

- Sensors
  - WAAS receiver (single frequency), Radar altimeter (RA), TVPS

- Positioning strategy
  - Reference position @ runway threshold from the RA & TVPS + a relative positioning algorithm, called "T-D PRP", with GPS/WAAS

- Characteristics
  - On-board self contained system
  - Does not use an INS
  - Does not need to fly over the entire runway
  - Near real-time positioning (WAAS optimized)
  - A receiver must be able to output raw GPS/WAAS measurements

- Reference
  - "WAAS-based Flight Inspection System", Journal of Aircraft, , Vol. 45, No 2, AIAA

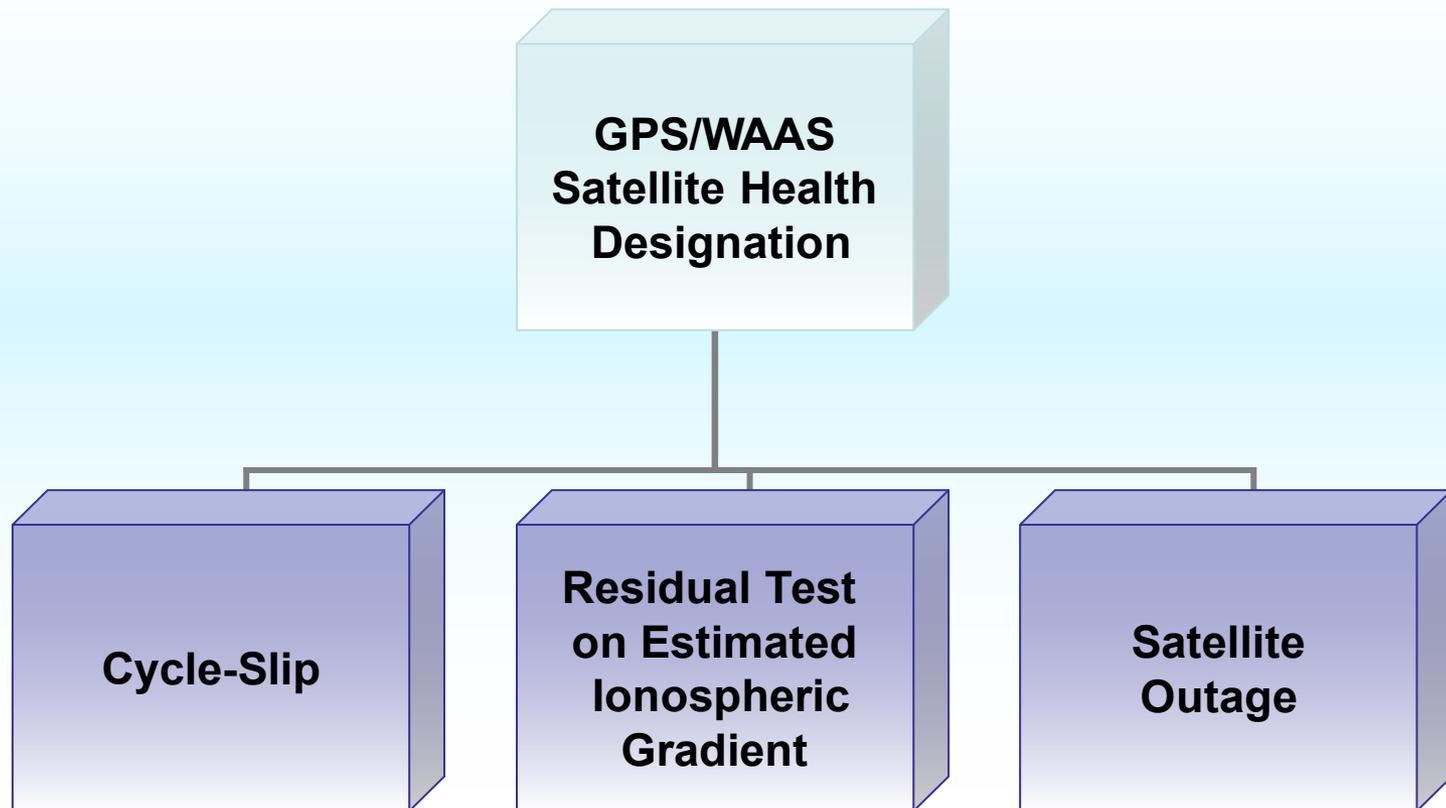2/26/2023

WAAS-based FIS Architecture
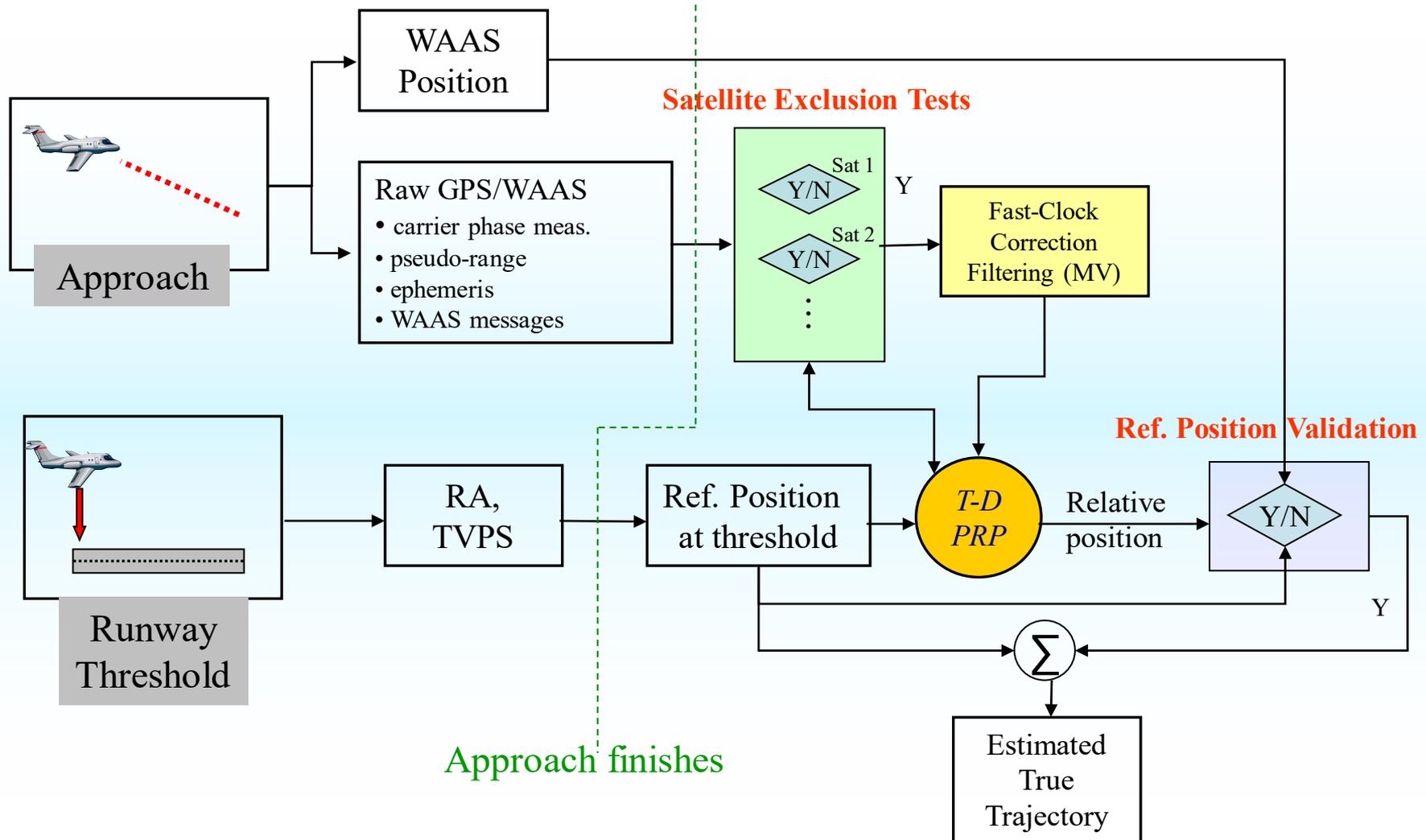
Time-Difference Precise Relative Positioning (T-D PRP)

- Ranging source
  - Time-difference of carrier phase measurements
  - Fine resolution (~cm)
  - Immune to any bias-like GPS ranging error sources

- Utilizes WAAS correction messages if available
  - Does not use WAAS ionospheric delay corrections

- Reduce ionospheric effects
  - Ionospheric delay gradient is estimated and removed using the combination of code and carrier (near real time)
  - The estimation process is further checked by exclusion tests

- Improvements
  - Fine resolution relative position (~cm)
  - Not vulnerable to abnormal ionospheric effects

Satellite Exclusion Tests

- Satellites and carrier phase measurements must pass the following checks

GPS/WAAS Satellite Health Designation

Cycle-Slip

Residual Test on Estimated Ionospheric Gradient

Satellite Outage

Reference Position Validation

- Test statistics for the reference position validation using WAAS position in vertical

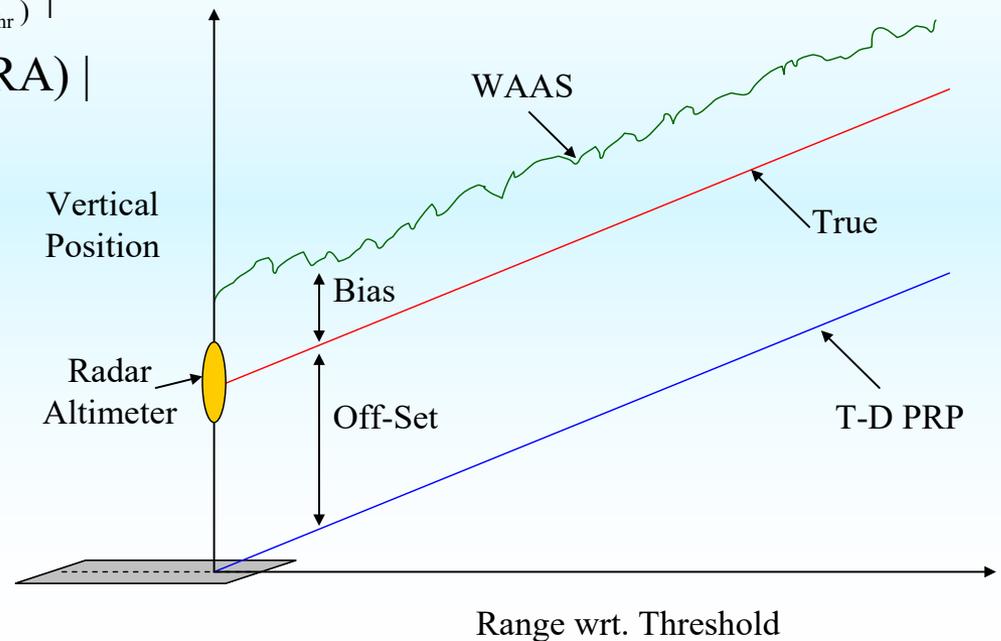$$T_V = \mid AVG_{(\text{WAAS}-\text{T-D PRP})} - \Delta_{(\text{RA}-\text{T-D PRP}_{\text{thr}})} \mid$$

$$\approx \mid \text{WAAS vertical bias} - \text{Error (RA)} \mid$$

- WAAS 95% accuracy (WAAS PAN Oct ~ Dec, 2006)
    - ✓ 1.11 m in horizontal
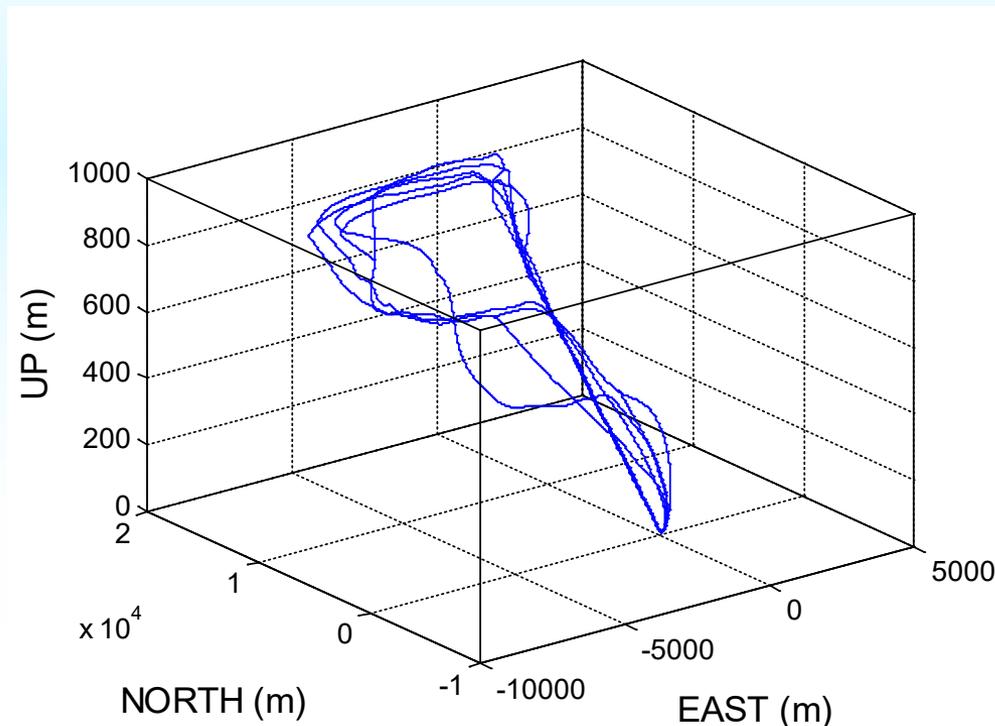   - ✓ 1.34 m in vertical
- RA and TVPS 95% Accuracy
    - ✓ RA: 15cm
    - ✓ TVPS: 15cm

<Vertical position characteristics for WAAS, RA, T-D PRP>

Flight Test Data

- Flight test during Oct 30~31, 2006 in collaboration with FAA flight inspection crews
- 23 approaches used
  - No radar altimeter or TVPS data was available, unfortunately
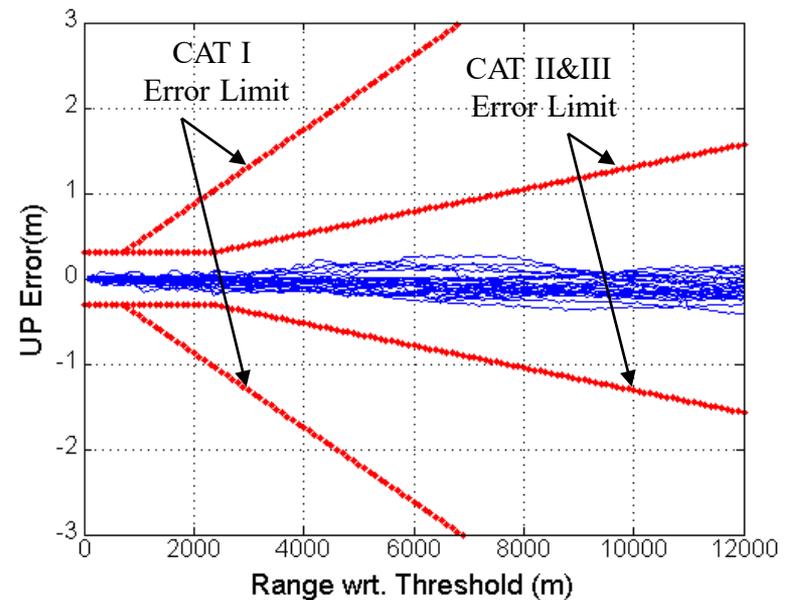- Truth source is RTK DGPS

WAAS-based FIS Test Results

- Assumes a perfect reference position
  - Radar altimeter and TVPS were not available
  - A reference position was obtained from RTK DGPS
- Graphs show only the T-D PRP algorithm errors
 - (Total error = ref. position bias (RA, TVPS) + T-D PRP error)

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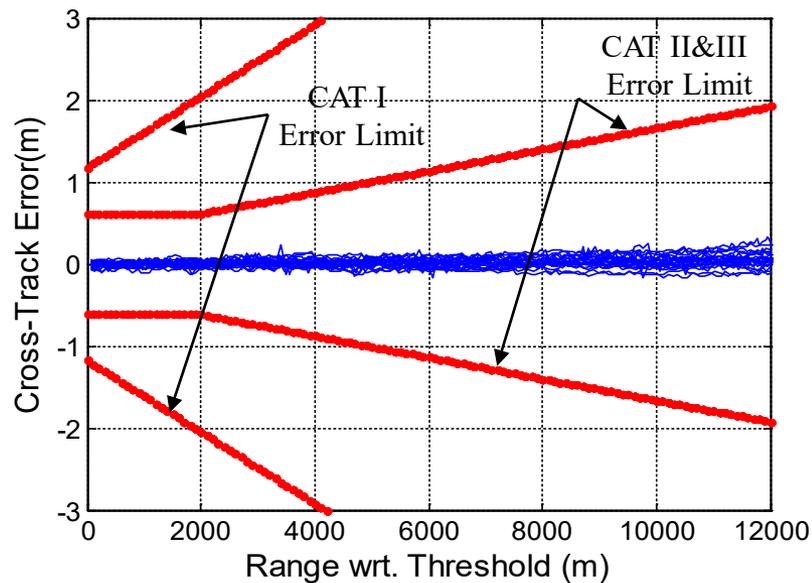
WAAS-based FIS
Accuracy (95%) at Critical Region

- Error analysis
  - T-D PRP error grows over time
  - Total errors at critical region
  - = Ref. position bias + T-D PRP error @ CR

- T-D PRP error statistics @ CR

	Up (m)	Cross-Track (m)
Mean	-0.04	0.00
Std	0.05	0.04
RMS	0.06	0.04

- Therefore, with:
  - RA accuracy (95%) : 15 cm
  - TVPS accuracy (95%) : 15 cm
  - T-D PRP Accuracy @ CR

- Total Error @ CR is:
  - Up : 18 cm < 30 cm (req.)
  - Cross-track : 17 cm < 60 cm (req.)

CR
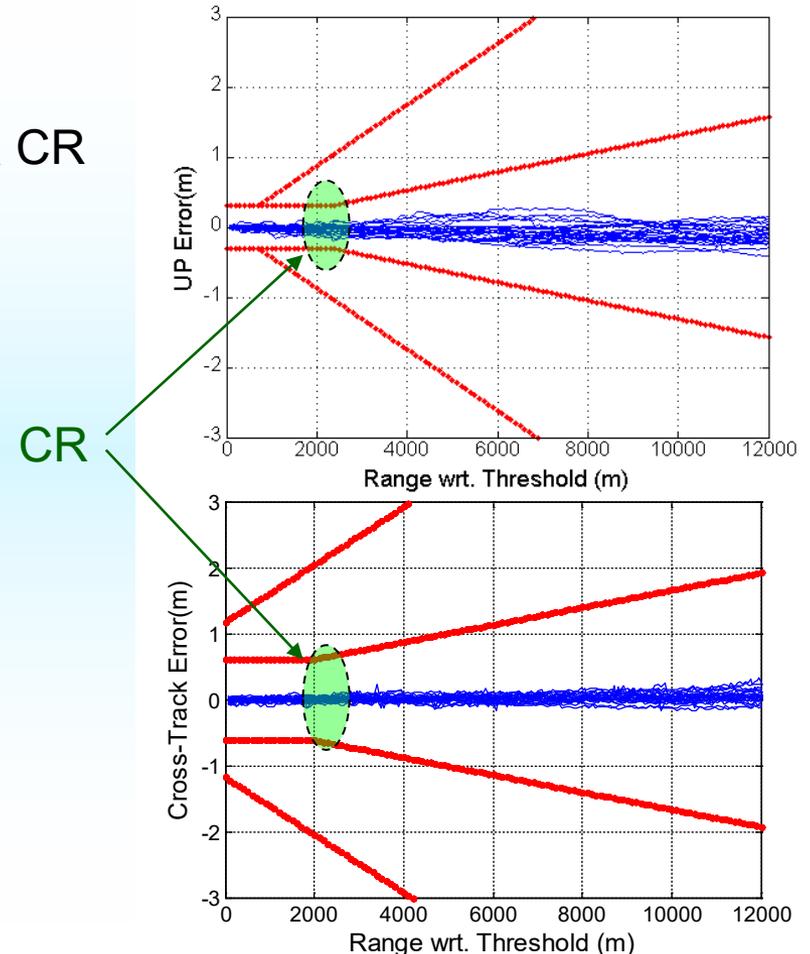
Standalone GPS-based FIS

- Sensors
  - GPS receiver (single frequency), Radar altimeter, TVPS

- Positioning strategy
  - Reference position @ runway threshold (RA, TVPS) + relative positioning using the T-D PRP algorithm with standalone GPS

- Characteristics
  - On-board self contained system
  - Does not use INS
  - Does not need to fly over the entire runway
  - Near real time positioning
  - Operational worldwide
  - A receiver must be able to output raw GPS measurements

- Reference
  - "Standalone GPS-based Flight Inspection System", ENC-GNSS 2007, Geneva, Switzerland

# Standalone GPS-based FIS Architecture
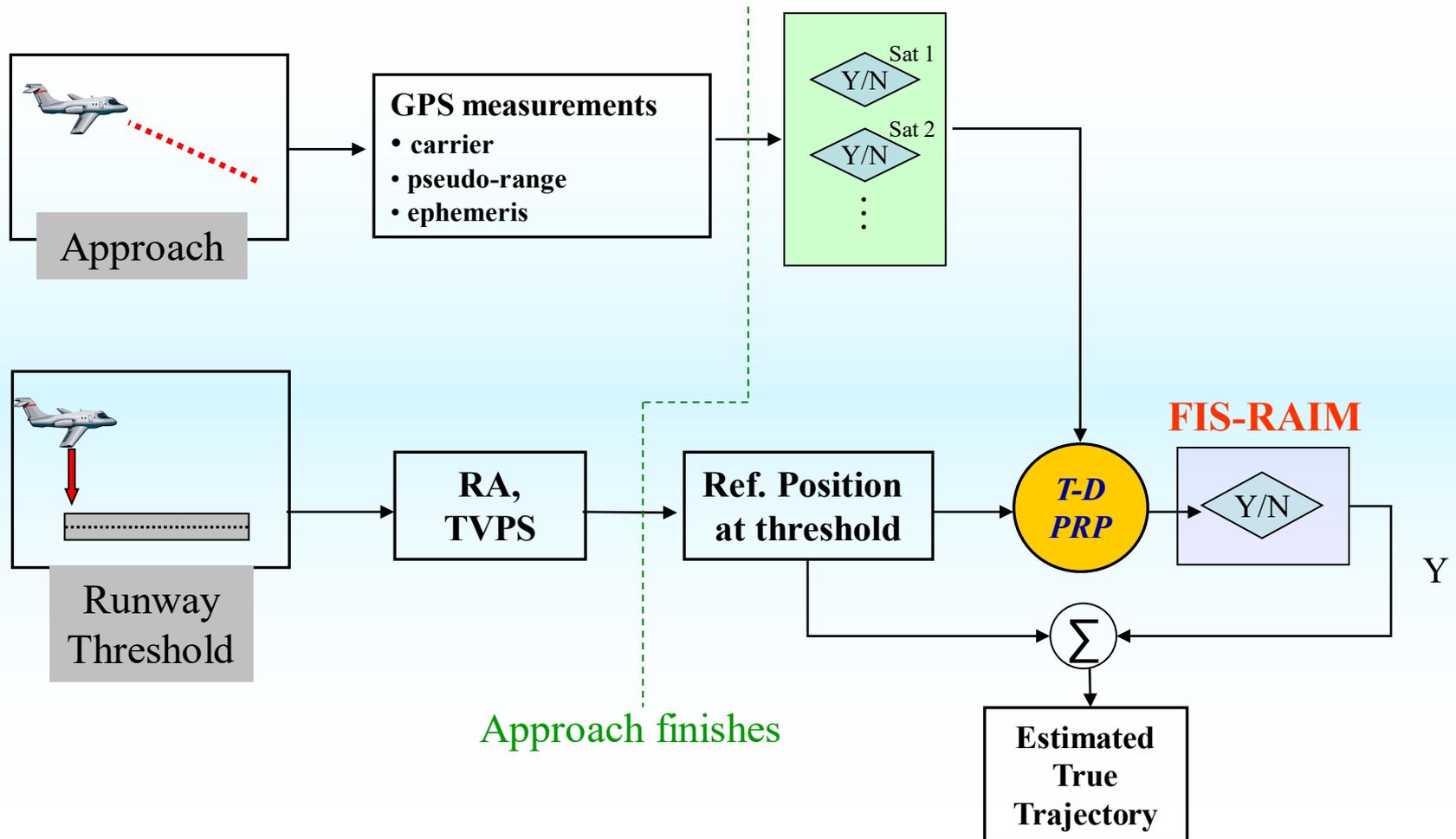
Integrity Issues

- The WAAS-based FI system derived its integrity from the underlying WAAS integrity messages.

- GPS-based FI system does not have that feature; therefore,
  - An autonomous procedure was developed to meet that need
  - Uses redundant satellite measurements to establish integrity of the FI procedure

Receiver Autonomous Integrity Monitoring (RAIM)

- Basic RAIM methods to detect satellite failures
  - Range comparison method [*Lee, 1986*]
  - Least-squares-residual method [*Parkinson and Axelrad, 1988*]
  - Parity method [*Sturza, 1989*]
 - Maximum separation of solutions [*Brown and McBurney, 1987*]

Sat 3

Sat 2

Sat 4

unhealthy

Sat 1

Sat 5

d

nominal

fault

<Illustration of separated solutions under 1 satellite failure>
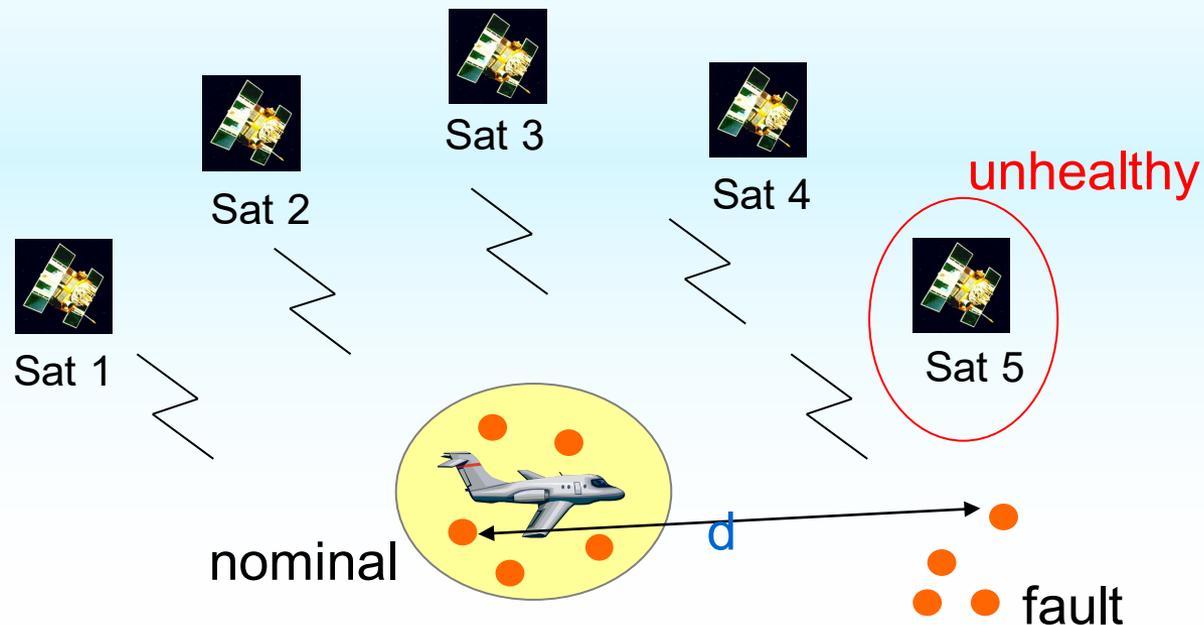
Flight Inspection System RAIM (1/3) (FIS-RAIM)

- ## Current baseline RAIM scheme
  - Not suited for high-accuracy application [*Ober,06*]
  - Detects large satellite failures

- ## Minor satellite failures
  - Slow ramp clock error (a few cm/s)
  - Low amplitude satellite clock dithering (a few meters)

- ## FIS-RAIM
  - Designed to detect the violation of CAT I error limit
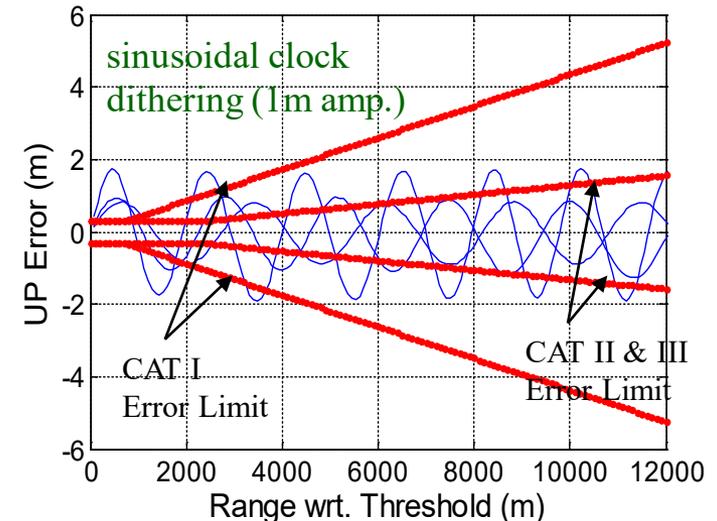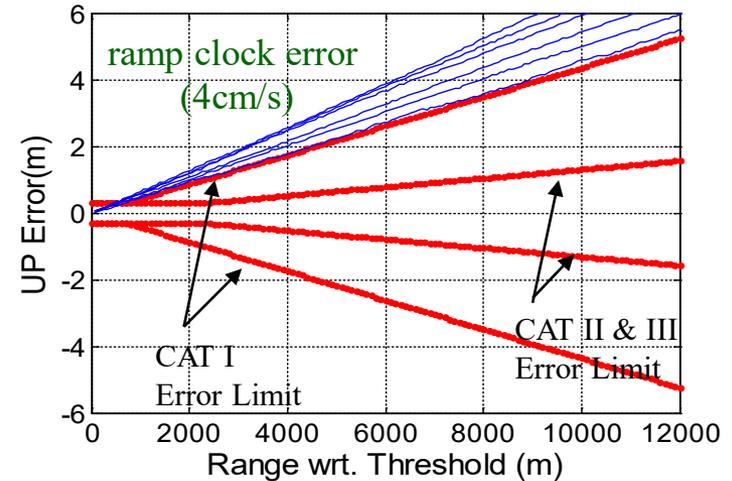
Flight Inspection System RAIM (2/3) (FIS-RAIM)

- FIS-RAIM

    - Uses maximum separation of solutions of T-D PRP in vertical

    - Uses full measurements during approach

    - Uses 2 test statistics
        - A slope of observed maximum separated solutions using linear regression (ramp clock error)
        - RSS for the residual test on the regression (clock dithering)

sat. clock ramp error (4cm/s)

sat. clock dithering (1m amp.)
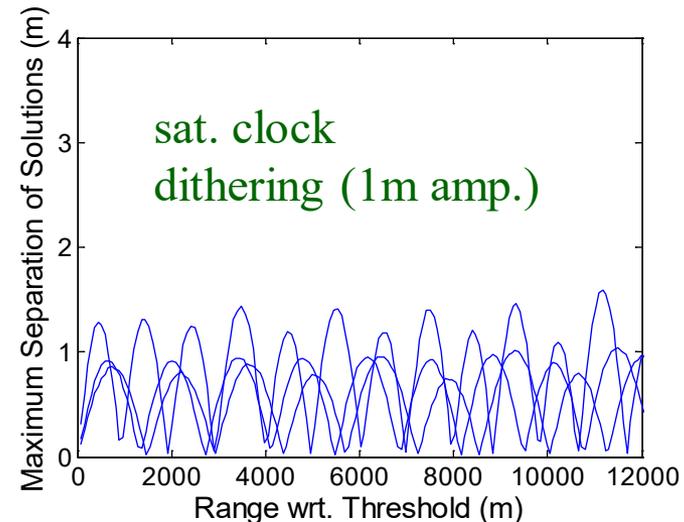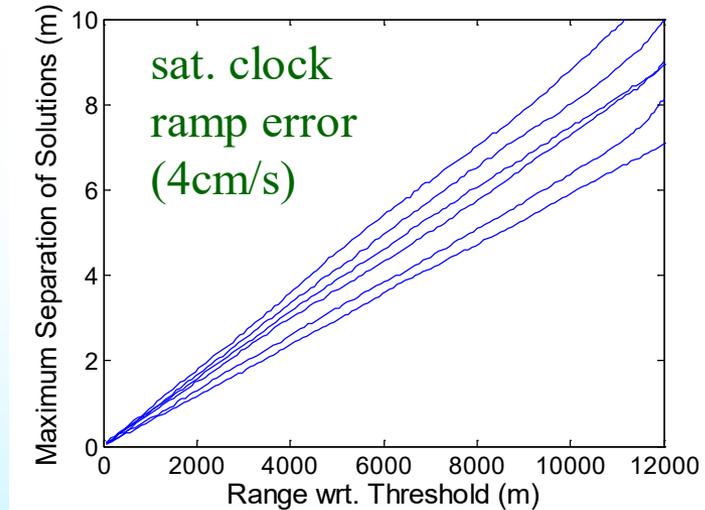
Flight Inspection System RAIM (3/3) (FIS-RAIM)

- The thresholds are
  - Slope: 0.05/2 deg (determined for CAT I error limit)
  - RSS : $(20cm)^2 * chi2inv(99.9\%, n-2)$
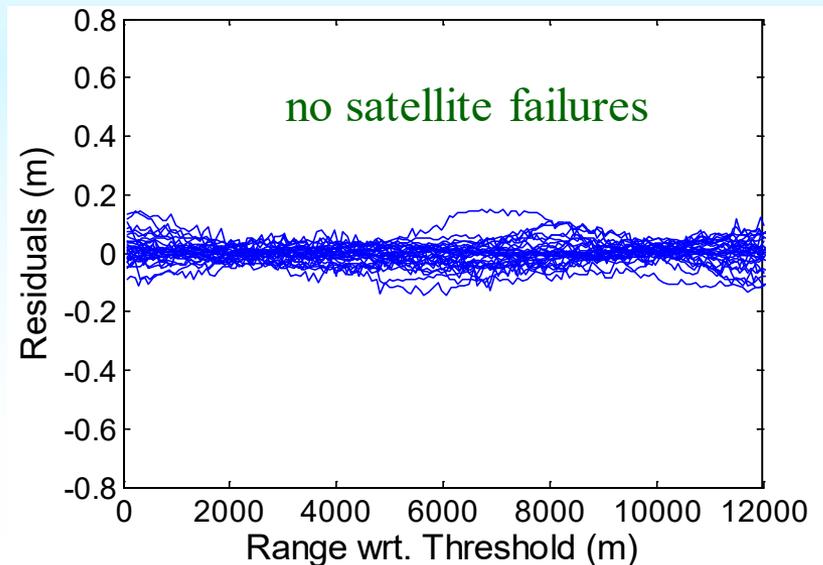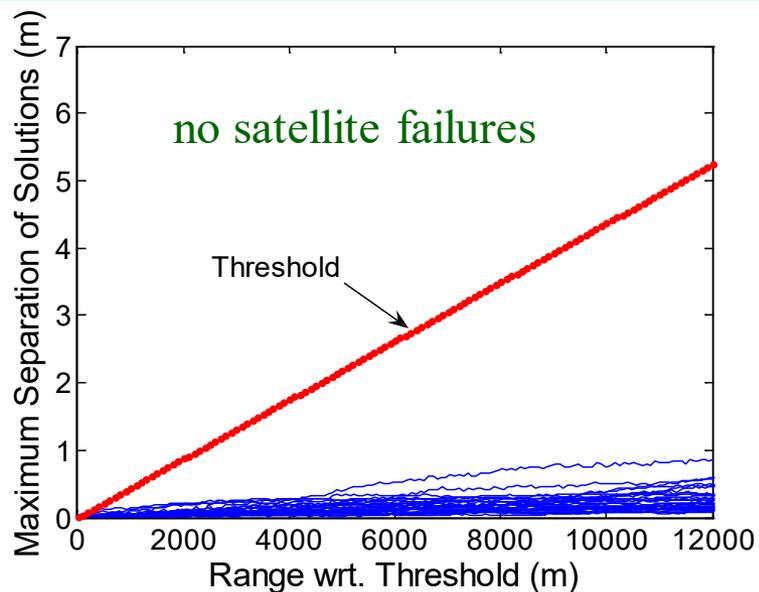
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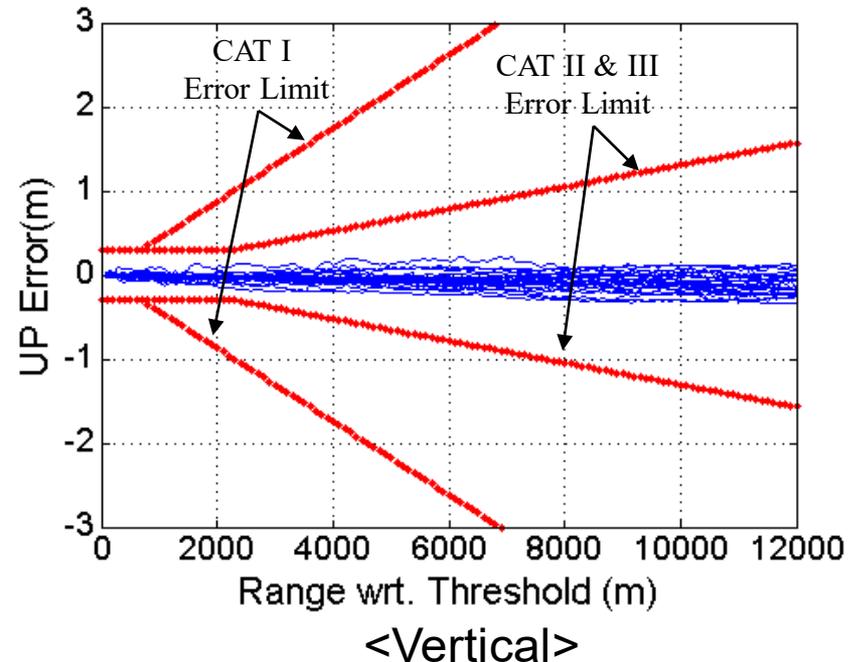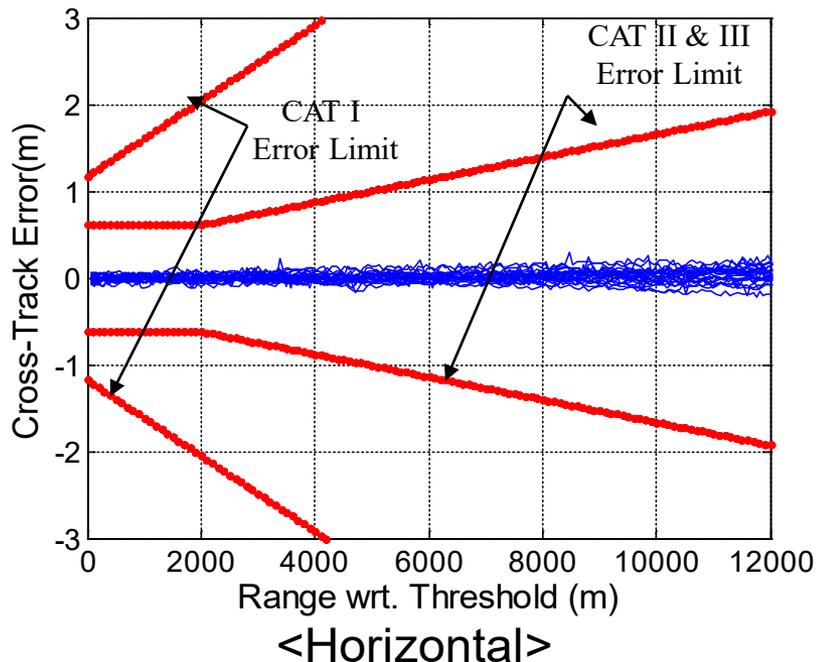
Standalone GPS-based FIS Accuracy (95%) at Critical Region (CR)

- Error analysis
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  = Ref. position bias + T-D PRP error @ CR

- T-D PRP error statistics @ CR

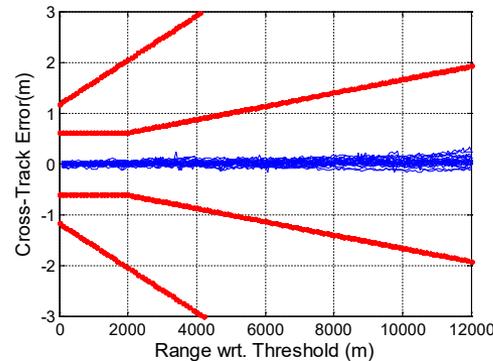|	Up (m)	Cross-Track (m)
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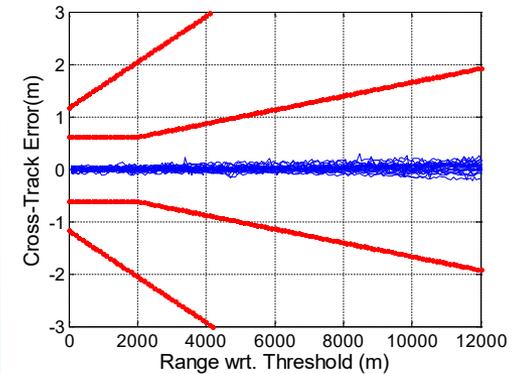 - Cross-track : 17 cm < 60 cm (req.)
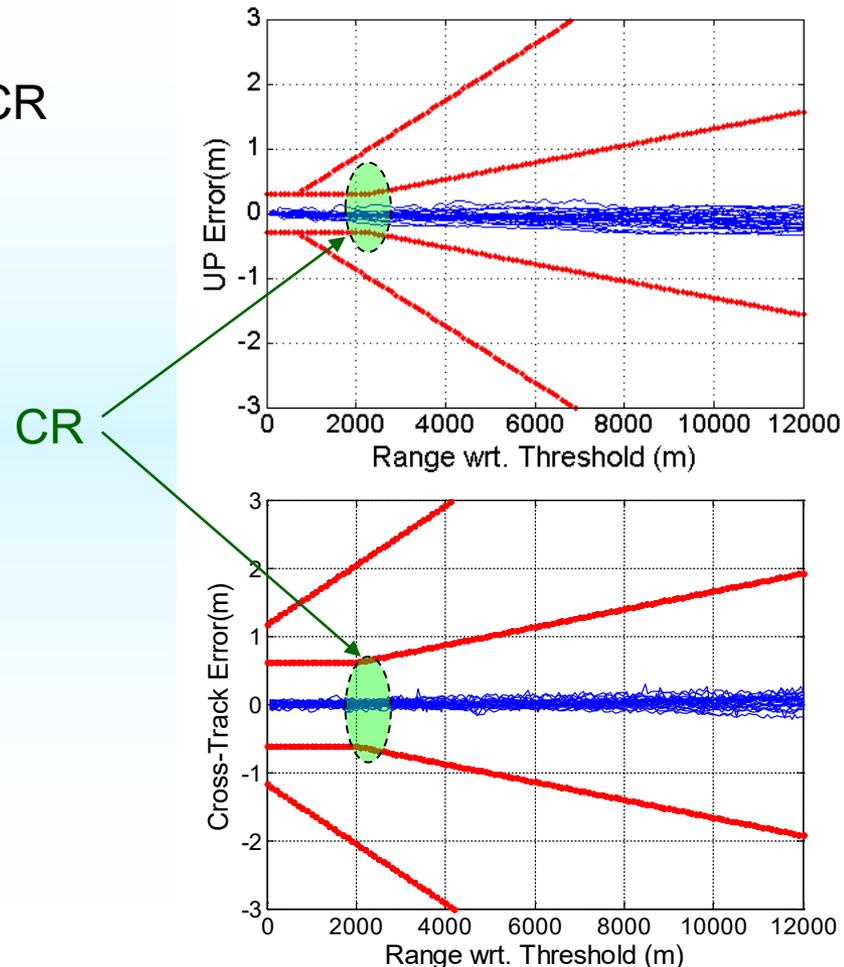
WAAS-based FIS vs. GPS-based FIS

- Almost identical accuracy
  - Strong temporal correlation in satellite clock-ephemeris residual correction error of WAAS and GPS (usual)
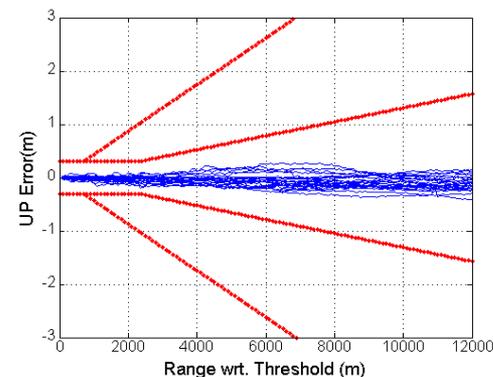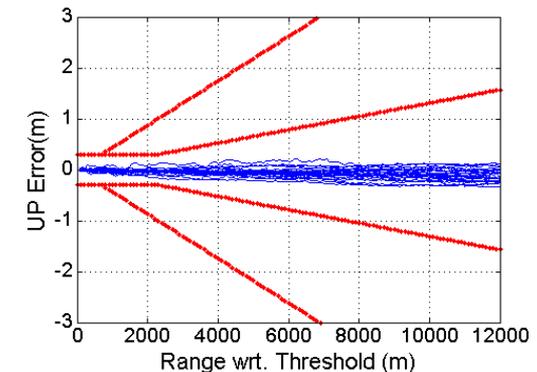 - A FI approach occurs over a very short time

Summary of WAAS-based FIS

- WAAS-based FIS Accuracy (95%)
  - Meets flight inspection system accuracy requirement for CAT III ILS calibration
    - Up : 18 cm < 30 cm (req.) @ CR
    - Cross-track : 17 cm < 60 cm (req.) @CR

- Benefits
  - Firm integrity
    - Satellite health from WAAS integrity messages
    - Protect against sharp and nonlinear ionospheric delay gradient
    - Reference position validation
  - Low cost and high efficiency

- Limitation
  - Operational where WAAS (or any SBAS) is available

Summary of Standalone GPS-based FIS

- Standalone GPS-based FIS accuracy (95%)
  - Meets flight inspection system accuracy requirements for CAT III ILS calibration
    - Vertical : 18 cm < 30cm (req.) @ CR
    - Cross-track : 17 cm < 60cm (req.) @CR

- Advantages
  - Firm integrity
    - Satellite health from FIS-RAIM
    - Protect against sharp and nonlinear ionospheric delay gradient
  - Low cost and high efficiency for worldwide use

- Limitation
  - Not able to check the integrity of a reference position

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Comparison with Current FIS's

	Accuracy	Efficiency	Cost-Effect.	Worldwide Usefulness
Inertial-based AFIS	★★★	★★★★	★	★★★★★
DGPS-based AFIS	★★★★★	★	★★★	★★★★★
WAAS(SBAS)-based FIS	★★★★	★★★★★	★★★★★	★★★
Standalone GPS-based FIS	★★★★	★★★★★	★★★★★	★★★★★

Thank you !

Special thanks to FAA AVN for the generous support in this research