

Tightly Coupled GPS/IRS Navigation for ADS-B

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Topics

- **Background**
 - Automatic Dependence Surveillance – Broadcast (ADS-B)
 - FAA Notice of Proposed Rulemaking for ADS-B
- **Description of tightly coupled GPS/IRS**
- **Benefits of tight coupling**
 - For RNP operations
 - Meets NPRM proposed horizontal nav requirements
 - Provides unique benefits for ADS-B
- **Summary**
- **Questions**

Tightly coupled GPS/IRS is excellent nav source for ADS-B

Automatic Dependent Surveillance - Broadcast

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- **ADS-B is critical component of Next Generation Air Transport System (NextGen)**
 - Tighter aircraft separation
 - Better approach to closely spaced parallel runways
 - And other benefits
- **Each airplane regularly transmits critical parameters to FAA ground stations and nearby airplanes**
 - Position, altitude, velocity
 - Position accuracy and integrity parameters
 - Other parameters
- **More accurate than Primary and Secondary Surveillance Radars**



Foundational technology to improve worldwide air traffic capacity

ADS-B Notice of Proposed Rulemaking (NPRM)

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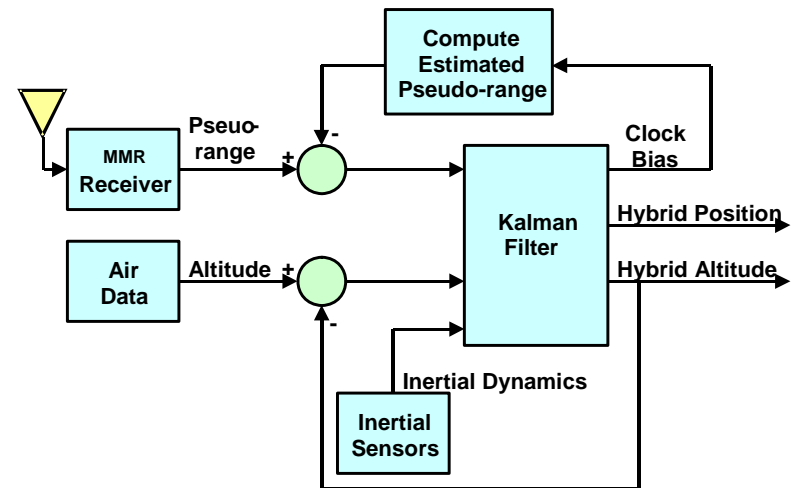
- **FAA published NPRM to require ADS-B in portions of US airspace by 2020**
- **Proposes challenging nav performance requirements**
 - **Position accuracy: 30m horizontal, 45 m vertical (95%)**
 - **Position integrity: 0.2 nm horizontal (99.999%)**
- **NPRM says WAAS is the only nav service that meets accuracy and integrity requirements with sufficient availability.**
- **FAA is considering whether other nav systems such as tightly coupled GPS/IRS are also suitable for ADS-B.**

Tightly coupled GPS/IRS is excellent nav source for ADS-B

Tightly Coupled GPS/IRS

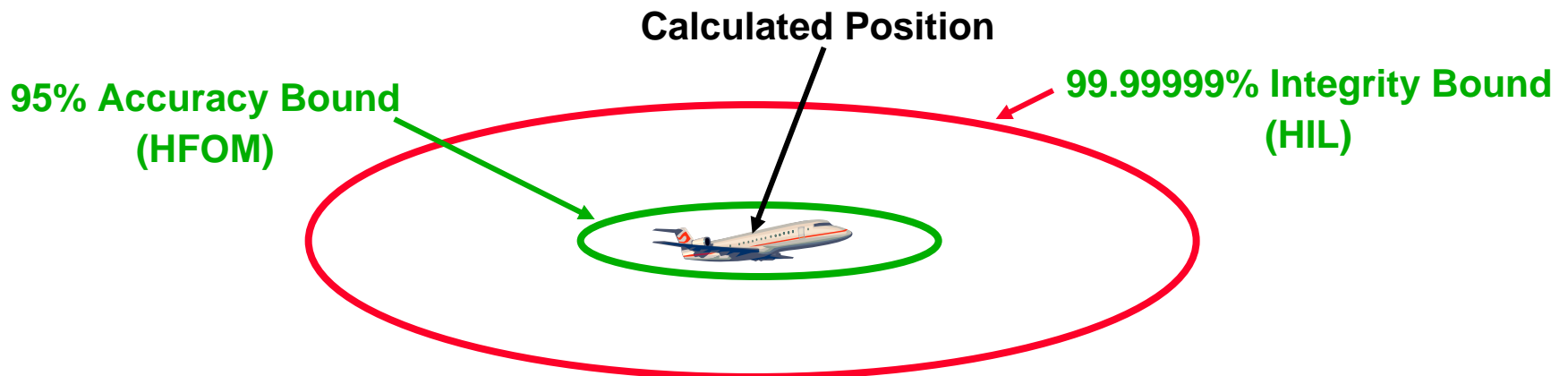
- This paper defines tight coupling as a navigation system that combines GPS pseudorange signals with IRS inertial signals
- Example: Honeywell Inertial GPS Hybrid (HIGH) algorithm
 - 36-state Kalman filter continuously estimates and compensates errors in both IRS and GPS
 - Uses highly compensated IRS signals to supplement GPS signals
 - Better performance than GPS under all conditions, but especially when GPS receiver can only track a few (or no) satellites
- Tight coupling is becoming available on air transport and many business jets, and this trend will accelerate over the coming decade

Block Diagram of HIGH Algorithm



HFOM and HIL

- Many modern aircraft navigation systems calculate HFOM and HIL signals in real time
 - HFOM (Horizontal Figure of Merit) represents horizontal nav accuracy (95% confidence level)
 - HIL (Horizontal Integrity Limit) represents maximum nav error (99.99999% confidence level)
- HFOM and HIL are critical nav signals for RNP operations and for ADS-B
 - Determine if an RNP operation is available
 - Determine nav accuracy and integrity parameters for ADS-B
 - HIL is generally more critical than HFOM



Tight Coupling benefits for low RNP

- HIGH augments GPS with highly calibrated inertial
- This reduces HFOM/HIL under all conditions
- Greatest benefit occurs when it's needed most
 - Poor satellite geometry
 - Takeoff/approach in mountainous terrain
 - GPS lost entirely – HIGH continues to calculate HFOM and HIL

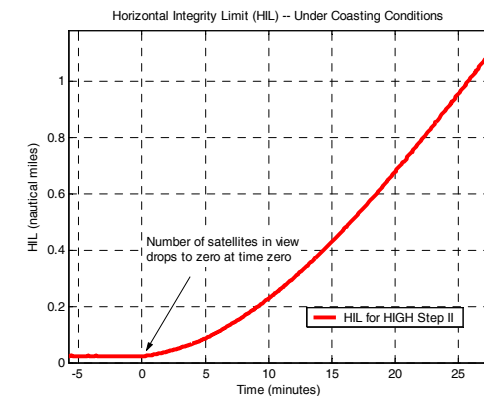
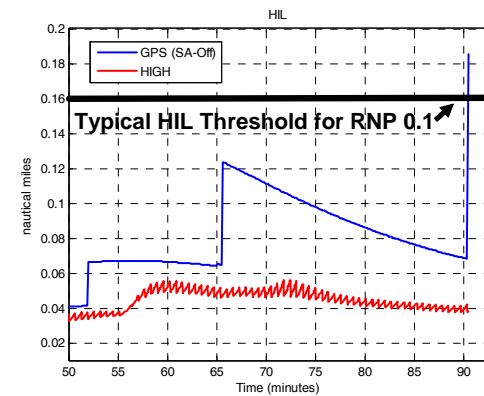
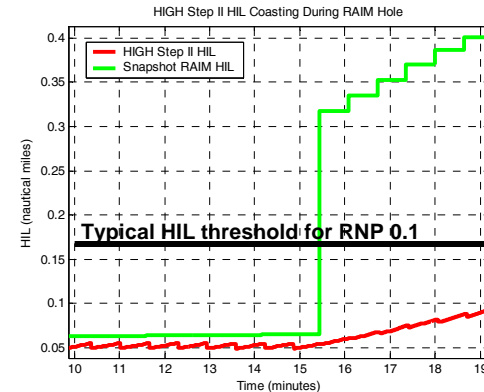
Adverse
Satellite
Geometry

Mountainous
Terrain

Total loss
of GPS

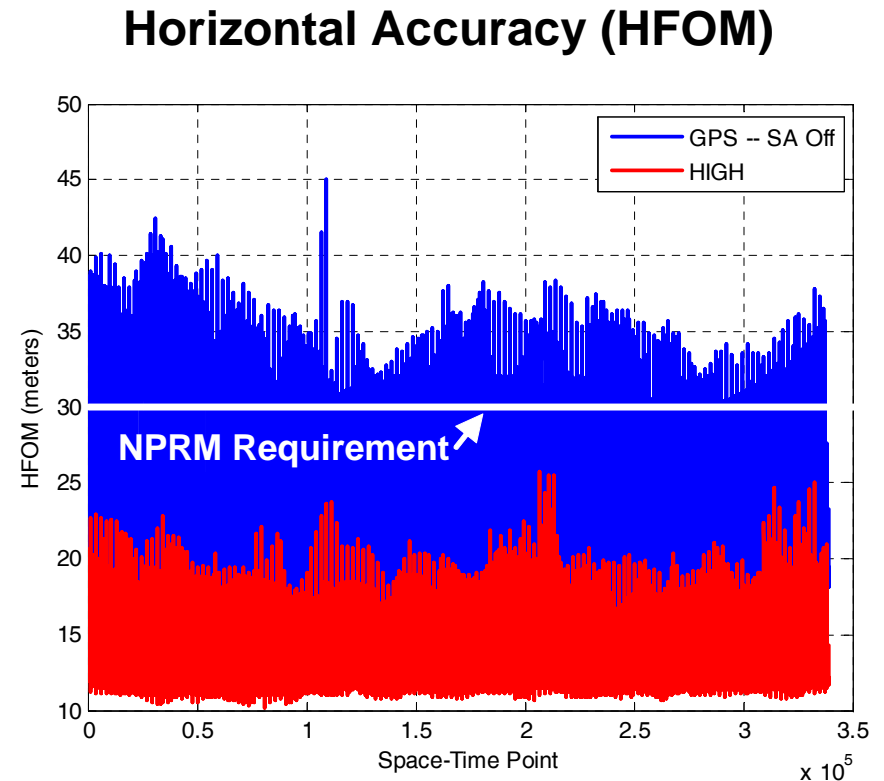
**HIGH provides robust
100% availability for RNP 0.1**

HIL Plots



NPRM Horizontal Accuracy Requirement

- Chart compares horizontal accuracy (HFOM) from GPS SA-off receiver and from HIGH
- Calculated over 338,832 worldwide space-time points using current (3/2/08) GPS constellation
- Similar result using Martinez 24 constellation – HFOM from HIGH always less than 30m.

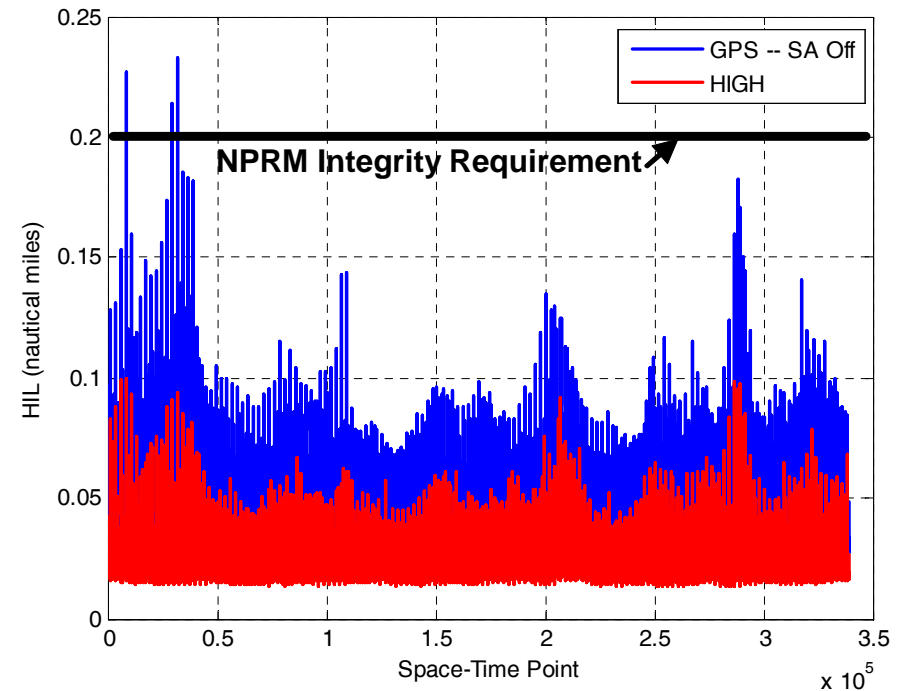


HIGH provides 100% availability for NPRM horizontal accuracy

NPRM Horizontal Integrity Requirement

- Chart compares horizontal integrity (HIL) from GPS SA-off receiver and from HIGH
- Assumes current (3/2/08) GPS constellation.
- Similar result using Martinez 24 constellation – HIL from HIGH always less than 0.2 nm.

Horizontal Integrity (HIL)

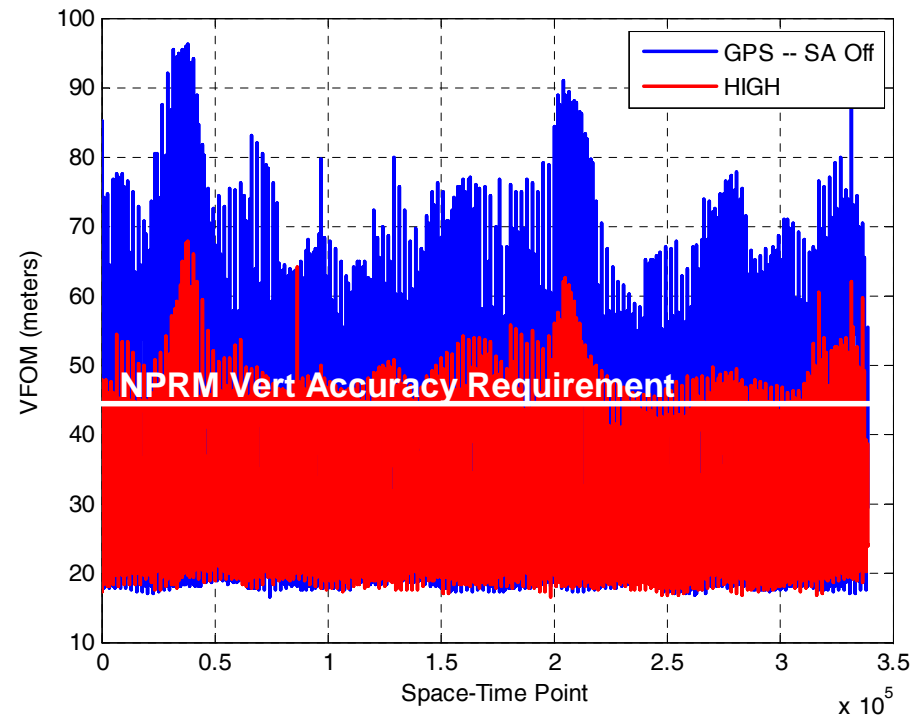


HIGH provides 100% availability for NPRM integrity

NPRM Vertical Accuracy Requirement

- VFOM signal indicates current vertical accuracy (95%)
 - Applies to GPS geometric altitude, not pressure altitude
- Neither GPS receiver nor HIGH provide good availability against 45m requirement
- But consider:
 - Aircraft separation is based on pressure altitude, not geometric altitude
 - Surface ops drives horizontal accuracy reqt, but surface ops don't require geometric altitude because airplanes are on the runway

Vertical Accuracy (VFOM)



Does ADS-B need 45m accuracy for geometric altitude?

Unique benefits of tight coupling for ADS-B

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- **Worldwide operation**
 - Tightly coupled nav solution can be used everywhere
- **Mitigates air traffic disruption even if GPS is lost entirely**
 - Aircraft ADS-B continues to report airplane position and accuracy and integrity parameters
 - Short duration outage - virtually seamless ADS-B operation
 - Extended duration outage - ATC can continue to draw containment circles around aircraft's reported position
 - Beneficial even if not all aircraft are equipped with tightly integrated GPS/IRS

Benefits, continued

- **Allows ATC to know aircraft position more accurately**
 - Lower latency for nav position (160 msec vs 500 msec reqt)
 - Faster update rate (12.5 Hz)

- **GNSS lost during oceanic operations**
 - **Concepts have been proposed to use ADS-B for oceanic tactical operations**
 - ◆ Passing maneuvers
 - ◆ In-trail climb/descent
 - ◆ etc.
 - **If GNSS is lost, tightly coupled GPS/IRS provides more accurate position and smaller HFOM and HIL than loosely coupled GPS/IRS to execute these operations**

Summary

- **Tightly coupled GPS/IRS is becoming available on air transport and business aircraft**
- **It meets the NPRM's proposed accuracy and integrity requirements for horizontal position**
- **It offers worldwide operation**
- **It provides additional benefits for ADS-B, especially when GPS signals or constellation becomes degraded**

Tightly coupled GPS/IRS is excellent nav source for ADS-B

BACKUP SLIDES

HIGH Kalman Filter Error Estimates

- **9 navigation states in each filter**

- 3 attitude error
- 3 velocity error
- 3 position error

- **2 clock states**

- frequency, phase

- **6 inertial sensor states**

- 3 gyro bias
- 3 accelerometer bias

- **1 altitude bias**

- **15 pseudo-range bias**

- **3 ionospheric error states**

HIGH Applications

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- **HIGH currently available on Honeywell 4 MCU on A380**
- **Future availability on Honeywell Laseref V, Laseref VI and 4 MCU IRU/ADIRUs**
 - **Air Transport & Regional:**
 - ◆ A320/330/340
 - ◆ Embraer 170/175/190/195
 - ◆ Boeing 787
 - ◆ Boeing 737/747/757/767
 - **Business Jets:**
 - ◆ Gulfstream G100 Retrofit, G350, G450, G500, and G550
 - ◆ Raytheon Hawker 4000
 - ◆ Dassault Falcon 900EX, 2000EX, and 7X
 - ◆ Beechcraft King Air Retrofit
 - **Tankers & Transports:**
 - ◆ C5-AMP Retrofit
 - ◆ C-130 Retrofit
 - ◆ B-707 Retrofit
 - **High Performance Aerobatic Trainers**
 - ◆ T-38N Trainer Retrofit
 - ◆ Pilatus PC-21, PC-7, and PC-9 Trainers
 - **Helicopters**
 - ◆ Eurocopter AS-365

Assumed error uncertainty (RMS)

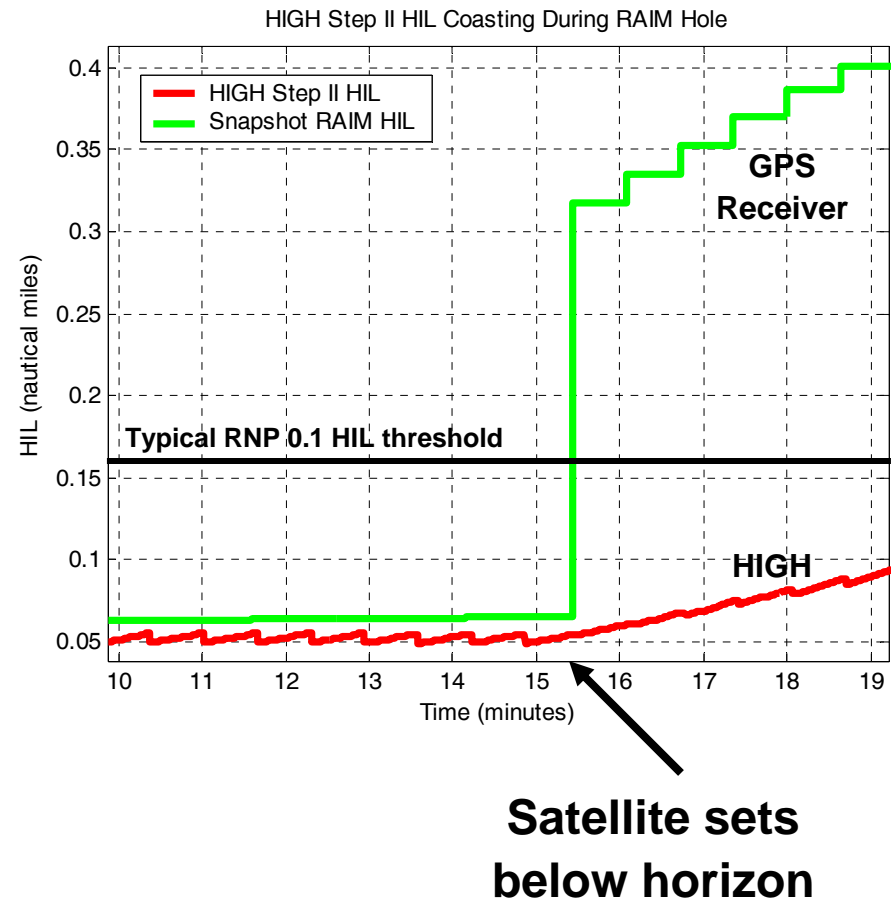
- **Clock and Ephemeris: 5 meters**
 - Compromise between older receivers (~10m) and newer receivers (~2m)
- **Receiver Noise and Multipath: 2.7 meters**
- **Troposphere: 0.12 – 2.68 meters**
- **Ionosphere: Thin Shell Model (4.5m – 28m)**
- **Altitude: 60 meters**
- **2 deg mask angle**

References

- **1 October 5, 2007, “Automatic Dependence Surveillance – Broadcast (ADS-B) Out Performance to support Air Traffic Control (ATC) Service”, Federal Register, Volume 72, Number 193, p. 56956.**
- **2 Call, Curt, Mike Ibis, Jim McDonald, Kevin Vanderwerf, May, 2006, “Performance of Honeywell’s Inertial/GPS Hybrid (HIGH) for RNP Operations”, Proceedings of Position Location and Navigation Symposium-2006, Monterrey, CA.**
- **3 McDonald, Jim, Joshua Kendrick, “Benefits of Tightly Coupled GPS/IRS for RNP Operations in Terrain Challenged Airports”, Proceedings of Position Location and Navigation Symposium-2008, Monterey, CA.**

Performance with adverse constellation

- HIGH provides lower HFOM and HIL than GPS SA-Off receiver under all conditions
- Benefit is strongest when it's needed most – when GPS constellation is marginal
- Chart compares HIL from HIGH and snapshot RAIM (equivalent to GPS SA-Off receiver) under adverse constellation.
- HIL from GPS receiver takes large step when a critical satellite sets
- HIGH supplements GPS data with highly compensated IRS data to avoid the step function.



Performance at Terrain Challenged Airport

- Many RNP 0.1 operations are at airports surrounded by high mountains (e.g., Quito, Ecuador and Queenstown, New Zealand)
- Mountains block low elevation satellites during takeoff and approach
- Chart compares HIL from GPS SA-Off receiver and from HIGH
 - RNP 0.1 approach to Queenstown using adverse constellation of 9/15/07.
 - Approach unavailable using GPS receiver
 - ♦ HIL exceeds threshold as airplane descends toward runway
 - Approach available using HIGH
 - ♦ HIGH uses highly calibrated IRS data to supplement missing satellite data.
 - ♦ HIL remains well below threshold

