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GNSS+ AVIONICS SYSTEM

DESIGN & TESTING INTEGRATION WITH INERTIAL SENSORS

Wednesday, April 9, 2014

12:30 pm Pacific
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WELCOME TO

GNSS+ Avionics System Design & Testing - Integration with Inertial Sensors

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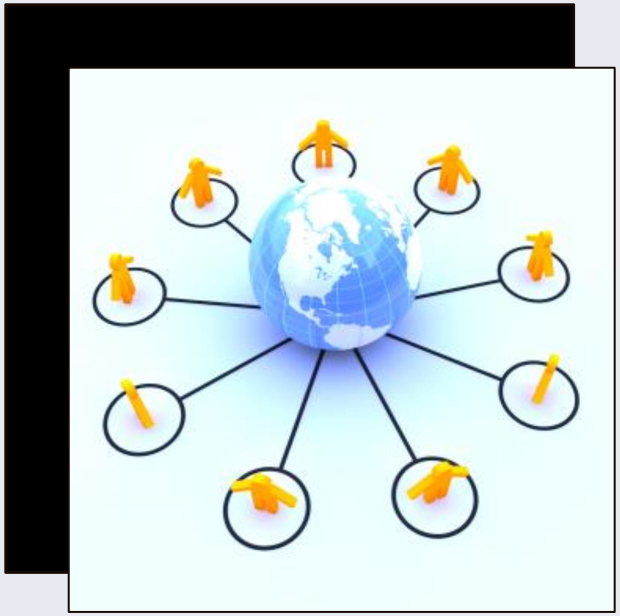
Co-Moderator: Lori Dearman, Sr. Webinar Producer

Who's In the Audience?

A diverse audience of over 500 professionals registered from 48 countries, 30 states and provinces representing the following industries:

- **20 % System Integrator**
- **18 % GNSS Equipment Manufacturer**
- **17% Product/Application Designer**
- **13% Professional User**
- **32% Other**



Welcome from *Inside GNSS*

Richard Fischer
Director of Business Development
Inside GNSS

A word from the sponsor

John Clark
Vice President
Engineering
CAST Navigation

GNSS+ Avionics System Design & Testing
Integration with Inertial Sensors

Demoz Gebre-Egziabher

Aerospace Engineer and Mechanics Faculty, University of Minnesota

Poll #1

What are GNSS/INS simulators used for?
(Select all that apply)

- *System qualification*
- *Engineering development testing*
- *System integration*
- *Algorithm development*

GNSS/INS Avionics Design and Test

Part One: GNSS/INS Avionics Design and Test

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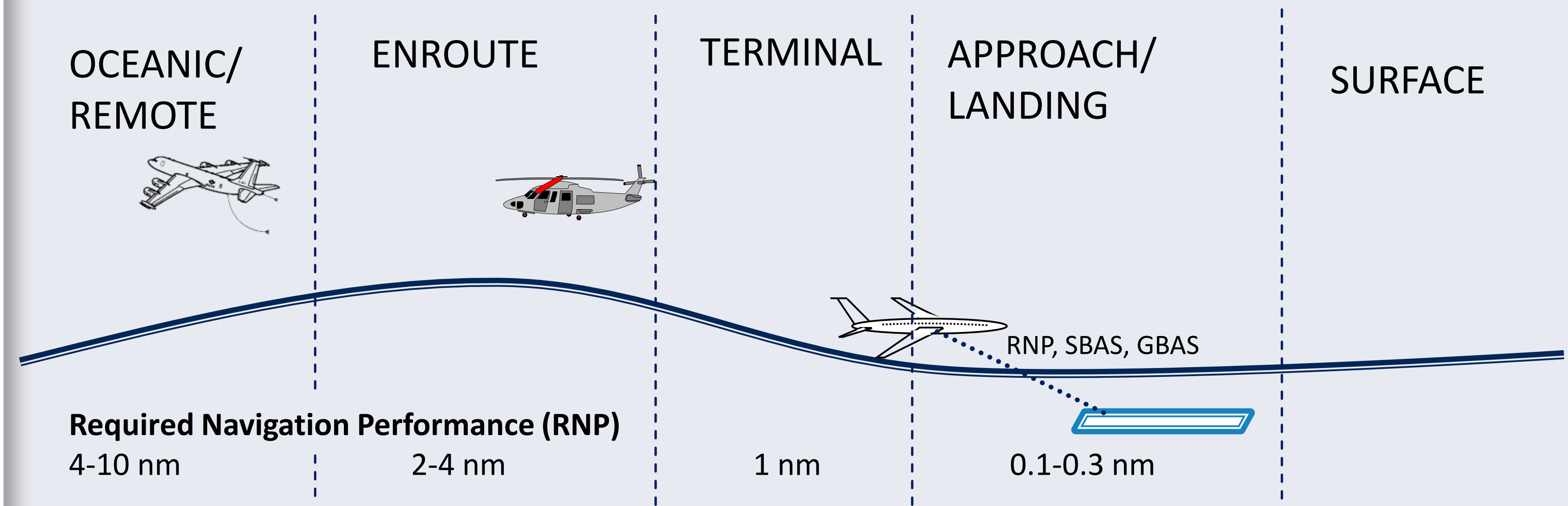
Civil Navigation Context



Current Technology Drivers

Automated Dependent Surveillance – Broadcast (ADS-B)
SBAS Localizer Performance with Vertical Guidance to 200 ft Decision Height (LPV-200)
RNP Authorization Required (RNP AR)*
Ground-Based Augmentation Systems (GBAS)
Situational awareness (Runway overrun, ground proximity, enhanced displays/vision, surface ops)*
Uninhabited Air Vehicles (UAVs)*
Modernized GNSS Signals

*Requirements for GNSS/INS

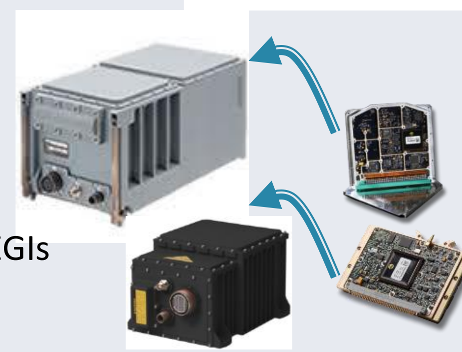
GNSS/INS Avionics Configurations

- Federated GNSS/INS configurations
  - Stand-alone GNSS receiver and Inertial Reference System (IRS)

  - Multi-mode receiver and Air Data Inertial Reference Unit (ADIRU)

  - Integrated GNSS, IMU & display systems

- Embedded GNSS/INS (EGI)

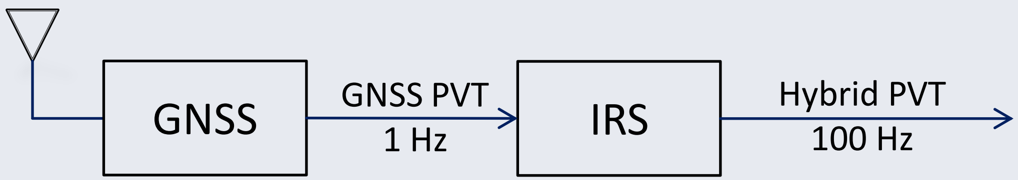


EGIs

GNSS Cards

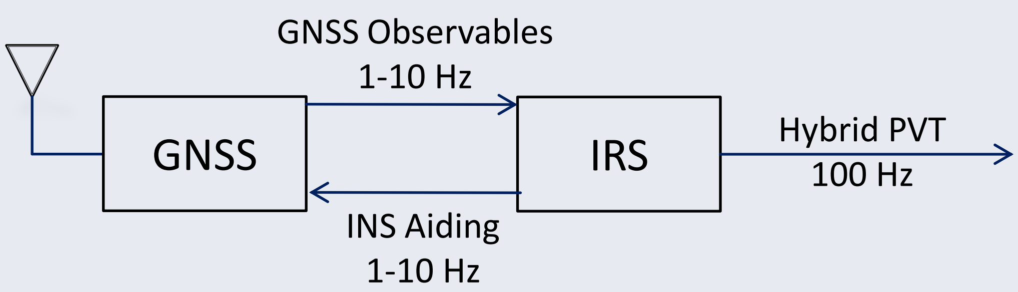
GNSS and INS Integration Options

Loosely-Coupled GNSS and IRS



- Simpler
- Less Processing
- Lower Data Bandwidth

Tightly-Coupled GNSS and IRS



- More accurate
- Better RFI rejection
- Longer coasting

Civil Avionics Certification Standards

- Federal Air Regulations (FARs) govern aircraft and component certification
  - FAR Part 23 (for General Aviation avionics), Part 25 (for Air Transport avionics)
  - FAA Advisory Circulars (e.g., AC 20-138c)
- FAA TSOs specify standard avionics equipment
  - TSO C4c (Bank and Pitch Instruments)
  - TSO C5e (Direction instrument, non-magnetic, gyroscopically stabilized)
  - TSO C6d (Direction instrument, magnetic, gyroscopically stabilized)
  - TSO-C145c (GPS/SBAS Positioning, Navigation and Timing)
  - TSO-C146c (GPS/SBAS Navigation and Guidance)
  - TSO-C161a (GBAS CAT 1)
  - TSO-C196a (GNSS for ADS-B)
- Minimum Operational Performance Standards (MOPS)
  - Technical standards referenced by FAA regulations
  - RTCA/DO-229D (GPS/SBAS), RTCA/DO-253C (GBAS)

Key Requirements and Verification

Typical Requirement	Example Test Criterion	Verification Method
Availability		
GNSS Acquisition	Time to First Fix	Analysis and Test
Inertial Alignment	Time to Align	Analysis and Test
Accuracy		
GNSS Accuracy	RMS Pseudorange Error	Analysis and Test
INS Accuracy	Position Velocity Attitude Error	Analysis and Test
Integrity		
Satellite Fault Detection and Exclusion	Time to Detect SV Failure	Analysis and Test

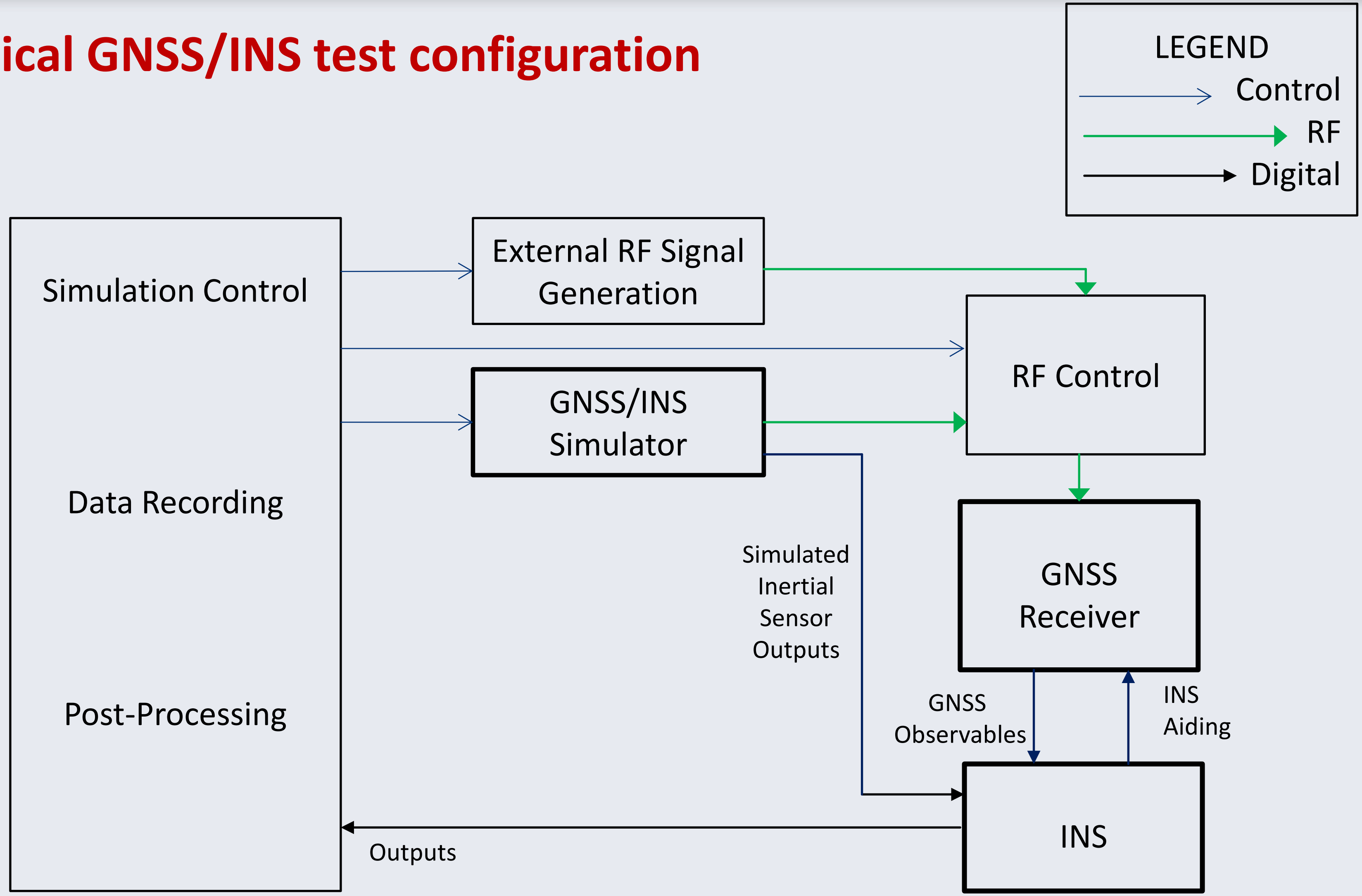
Analysis and Test Methods Critical to Certification

GNSS/INS Analysis and Test

- Accurate performance models enable separate testing of GNSS and Integrated Navigation Systems
- GNSS performance tested using GNSS simulator
  - GNSS simulator generates an RF signal simulating the GNSS constellations
  - INS outputs can be simulated using an inertial sensor model

- GNSS Simulator Plays a Key Role in Performance Testing
  - Sensor Error Models Needed for Analysis and Test

Typical GNSS/INS test configuration



GNSS and GNSS/INS Simulator Capabilities

- Generates GNSS RF signals and simulated INS sensor outputs
  - Users create and modify simulation scenarios
  - Scenarios manually initiated or through batch
- Scenarios describe
  - Satellite constellations (may include SBAS)
  - Host vehicle dynamics
  - GNSS error characteristics (more later)
  - Inertial sensor error characteristics (more later)
- Host antenna characteristics, obstructions
- Coherent RFI/jamming

CAST-4000

Inertial Sensor Error Modeling for Simulation

Part I—Sensor Modeling

Gyro & Accelerometer
Inertial Sensor Errors
Error Modeling

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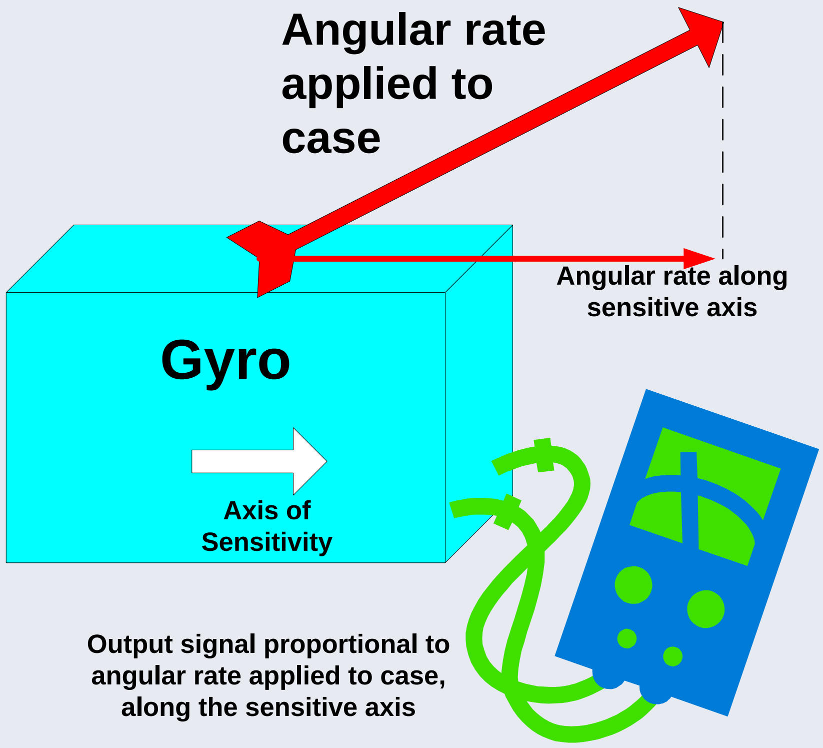
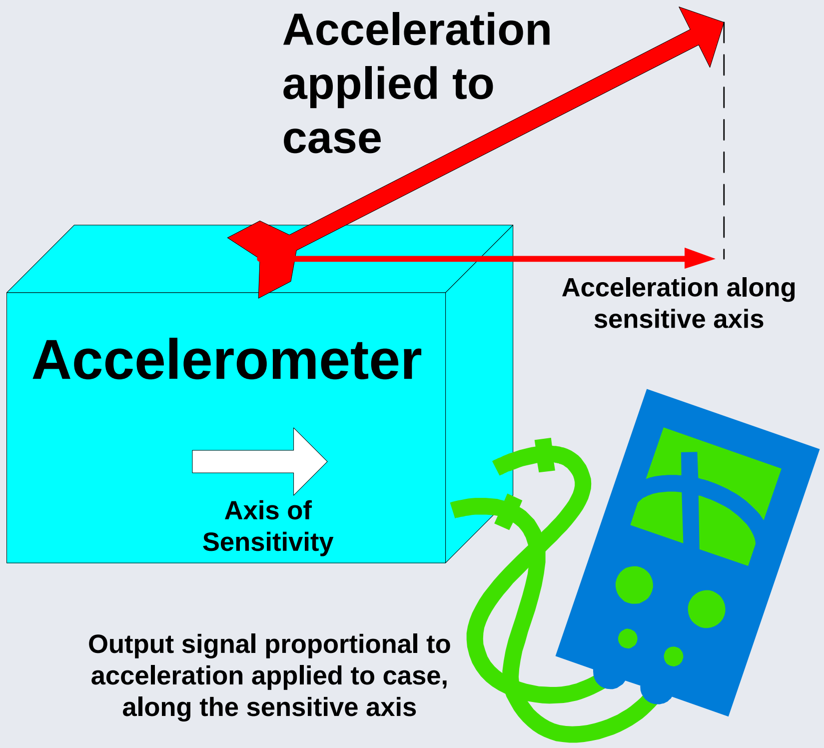
What is an Gyroscope and Accelerometer?





Inertial Sensor Errors

- Definition of error:
  - Difference between the actual & the ideal sensor
- Causes of sensor errors:
  - Temperature
  - Vibration
  - Acceleration or rotation not in the sense axis
  - Magnetic fields
  - Physical effects specific to the sensor technology
- Sensor compensation
  - Corrects errors in the sensor output

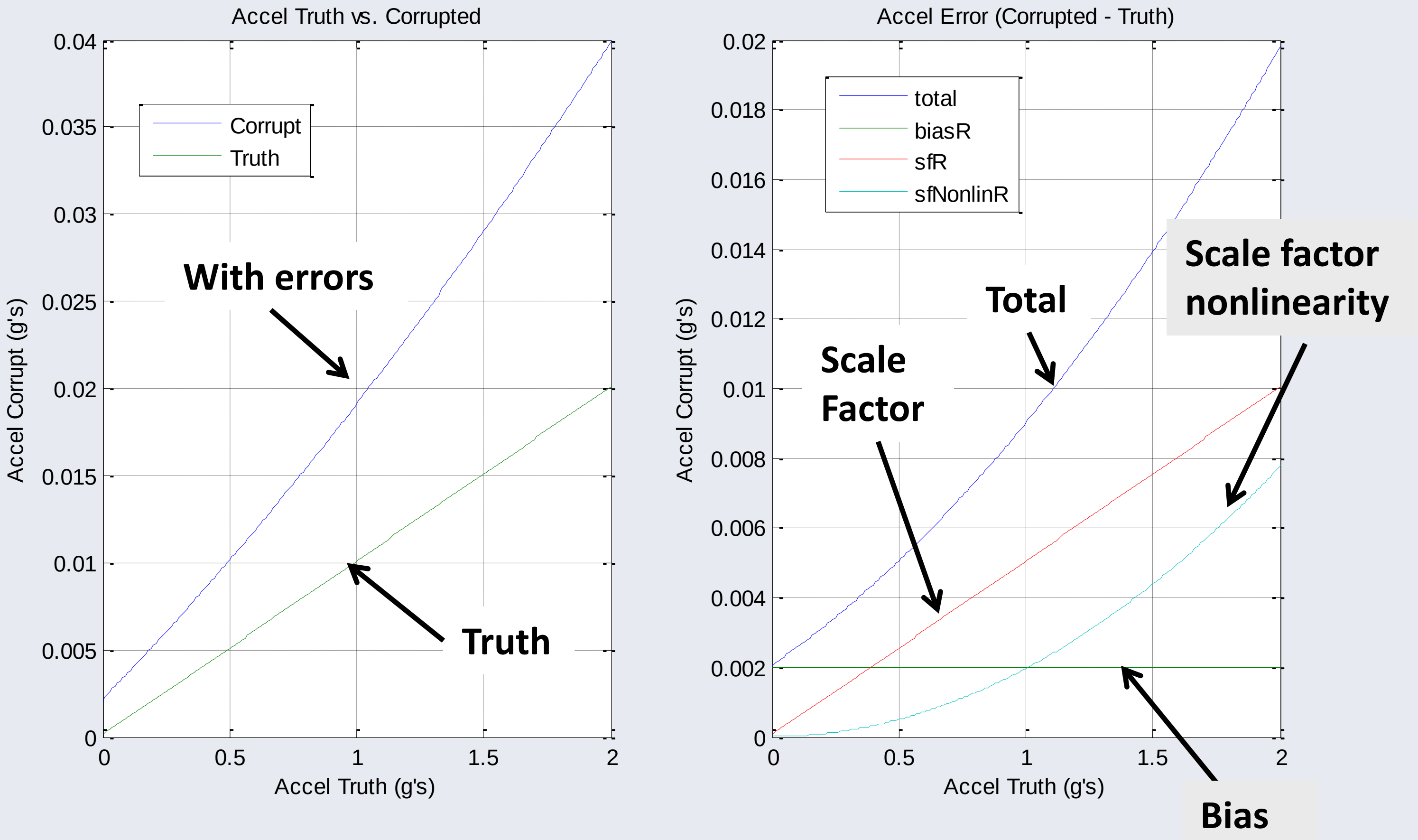
Typical Inertial Sensor Errors

- **Bias**
  - Output of sensor at zero input
- **Scale Factor**
  - Linear deviation from the expected response to a change in input
- **Asymmetry**
  - Difference in response to positive & negative inputs of the same absolute value
- **Nonlinearity**
  - Non-linear deviation from the expected response to a change in input
  - Usually expressed as polynomial coefficients
- **Misalignment/Non-orthogonality**
  - Angular misalignment that allows for sensitivity to non-input (cross) axis input
  - Sensitivity to installation angle
- **Noise**
  - Gaussian noise on the sensor output
  - Due to the physics of the sensor
- **Quantization/resolution**
  - Minimum change in output signal
- **Zero threshold/dead-band**
  - Maximum input change from zero before a change in the output signal

Inertial Sensor Modeling

- Sensor errors have two components:
  - Repeatability: Modeled by deterministic equations
  - Stability : Modeled by stochastic processes
- Deterministic models
  - Simulate error at turn-on
  - Constant over during a power cycle
- Stochastic models
  - Simulate errors during a power cycle
  - Varies as a random process during a power cycle

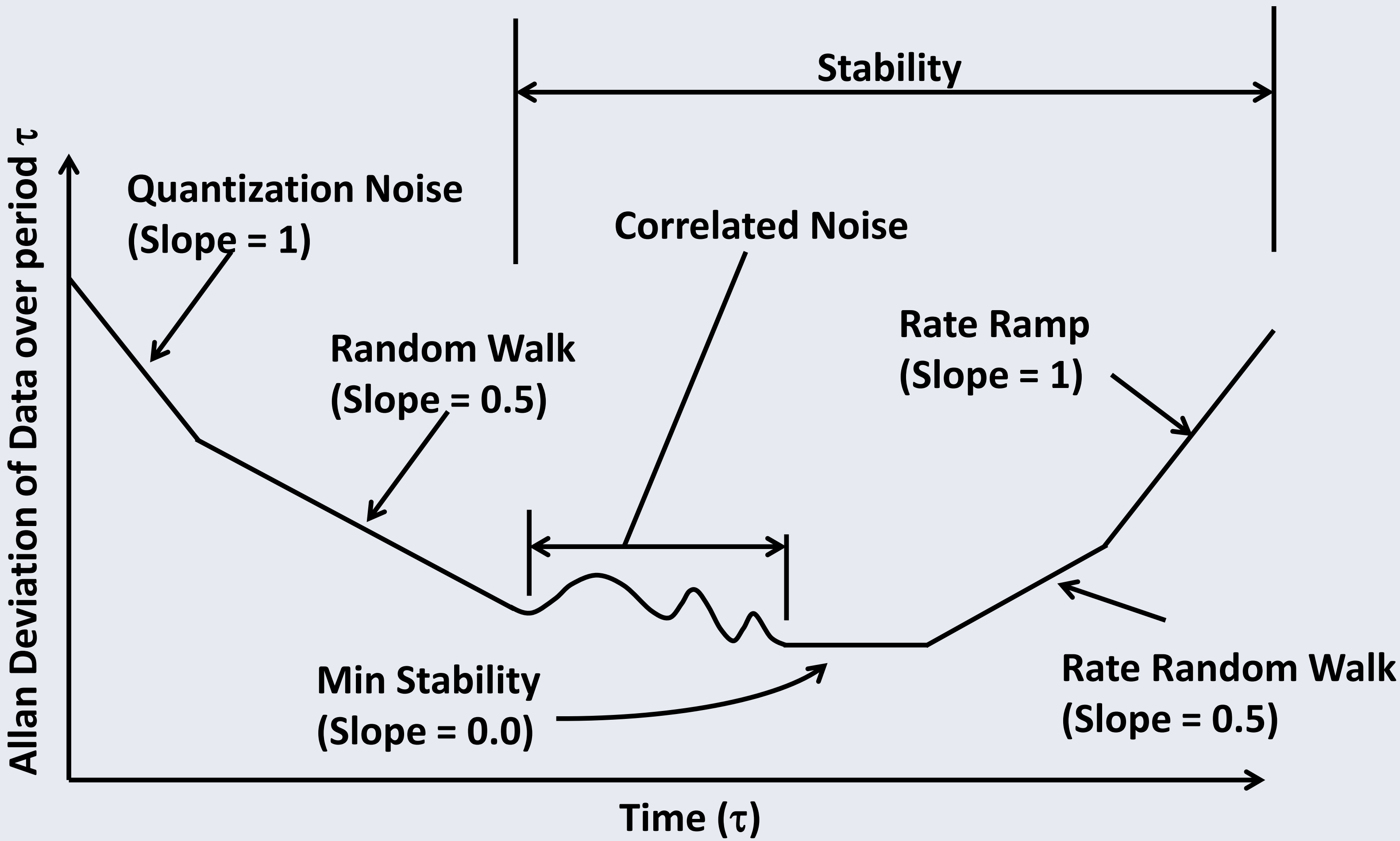
Example of Deterministic Errors



Stochastic Error Models

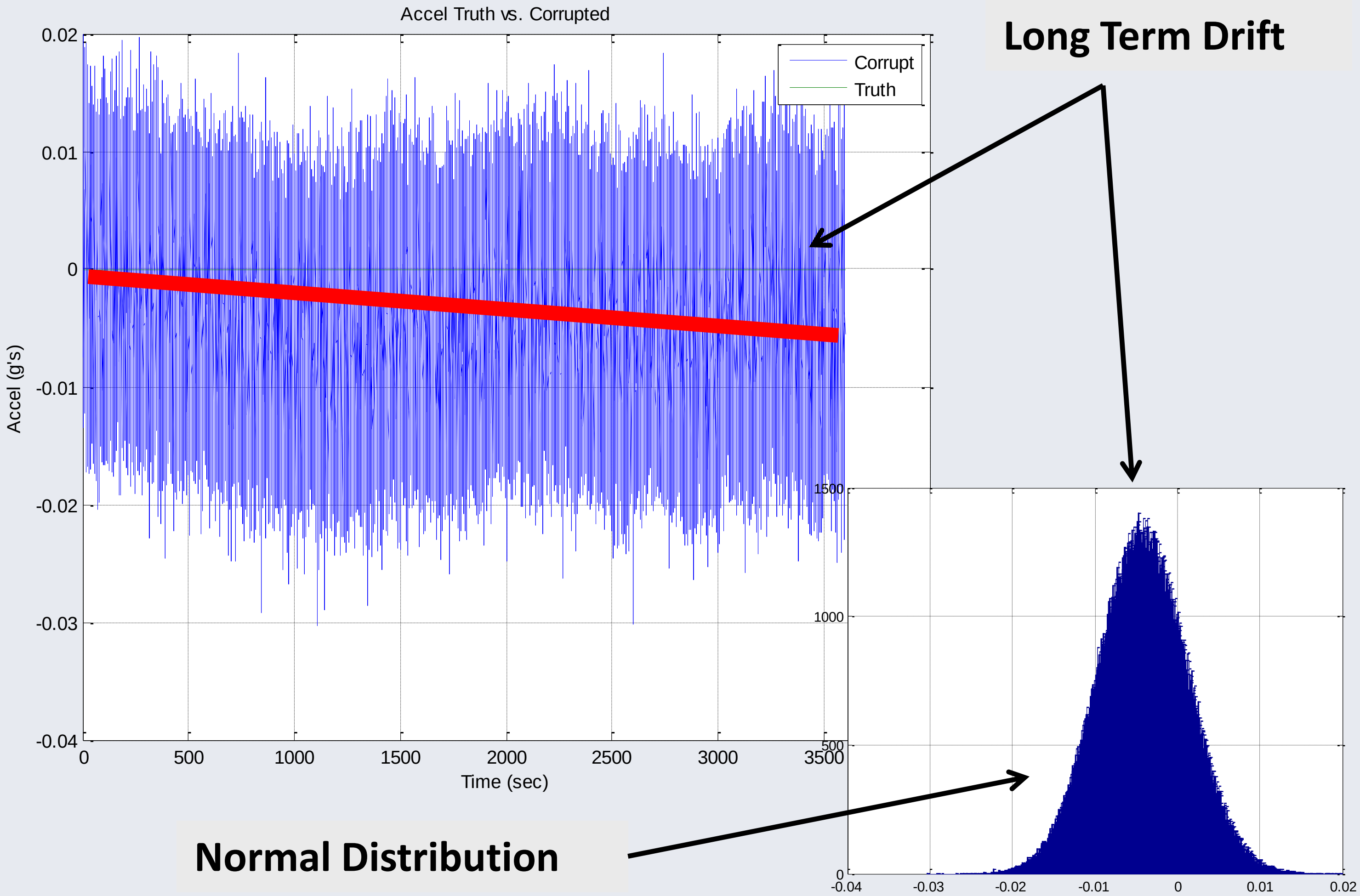
- Errors that change while the system is operating
  - Change during a single power cycle of the system
  - Change often depends on environmental factors
- Commonly modeled stochastic errors are
  - Bias stability
  - Scale factor stability
  - Quantization or non-integrating white noise
  - Random walk or integrating white noise
- Allan Variance or Deviation plots can be used to quantify these errors

Definition of Allan Deviation

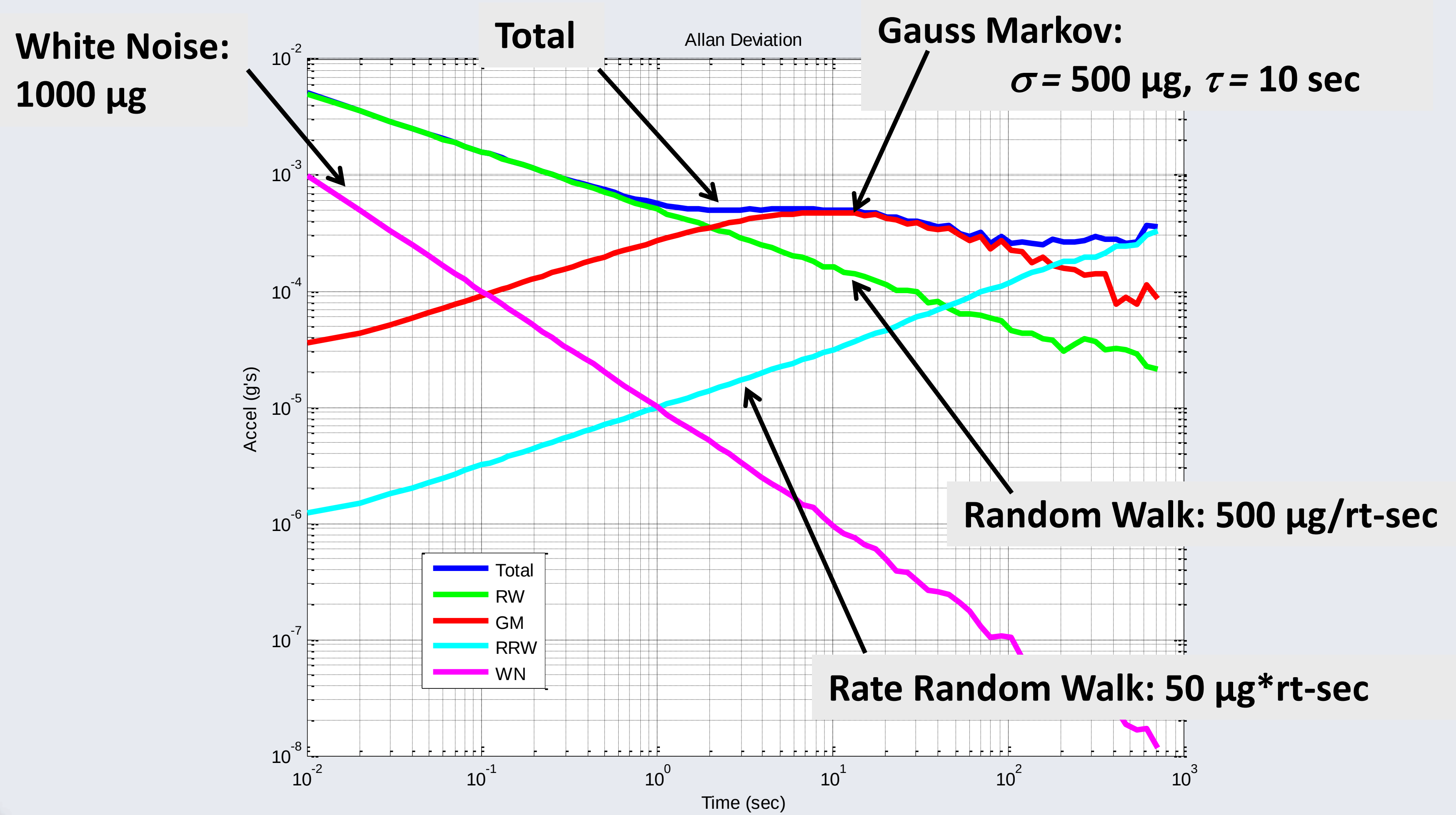


Reference: IEEE Std 962-1997 (R2003) Standard Specification Format Guide and Test Procedure for Single-Axis

Simulated Accel Data with Stochastic Errors



Allan Deviation Plot, Multiple Stochastic Processes



Summary

- Described typical inertial sensors errors
- Inertial sensor error components
  - Repeatability
  - Stability
- Sensor stability errors are modeled with stochastic processes
  - Allan Variance or Deviation is useful in understanding the types of stochastic error

Ask the Experts – Part 1

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Poll #2

The GNSS-INS sensor error models used in simulation are:
(Select all that apply)

- *GNSS standardized in MOPS, etc*
- *GNSS customized by the user*
- *INS standardized in MOPS, etc*
- *INS customized by the user*

GNSS/INS Avionics Design and Test

Part Two: GNSS Error Modeling and GNSS Simulation

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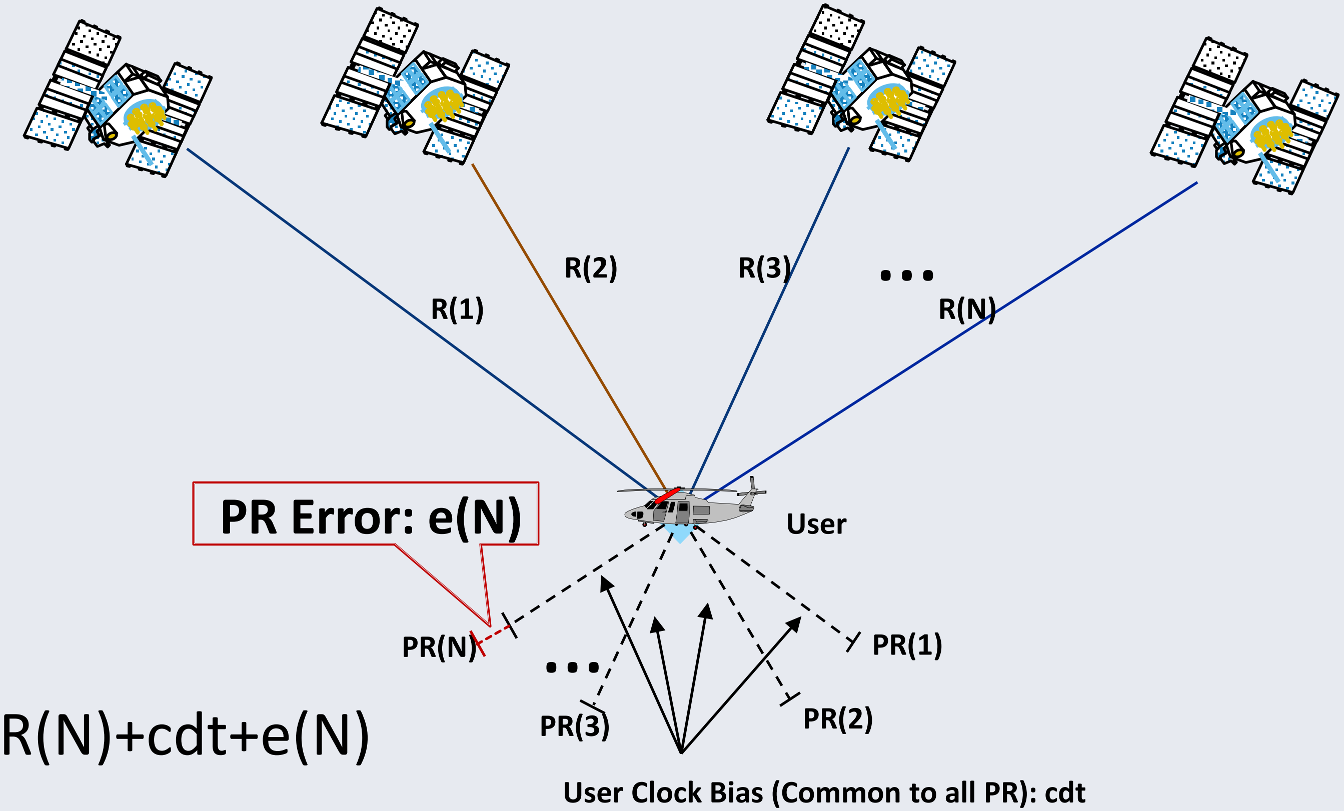
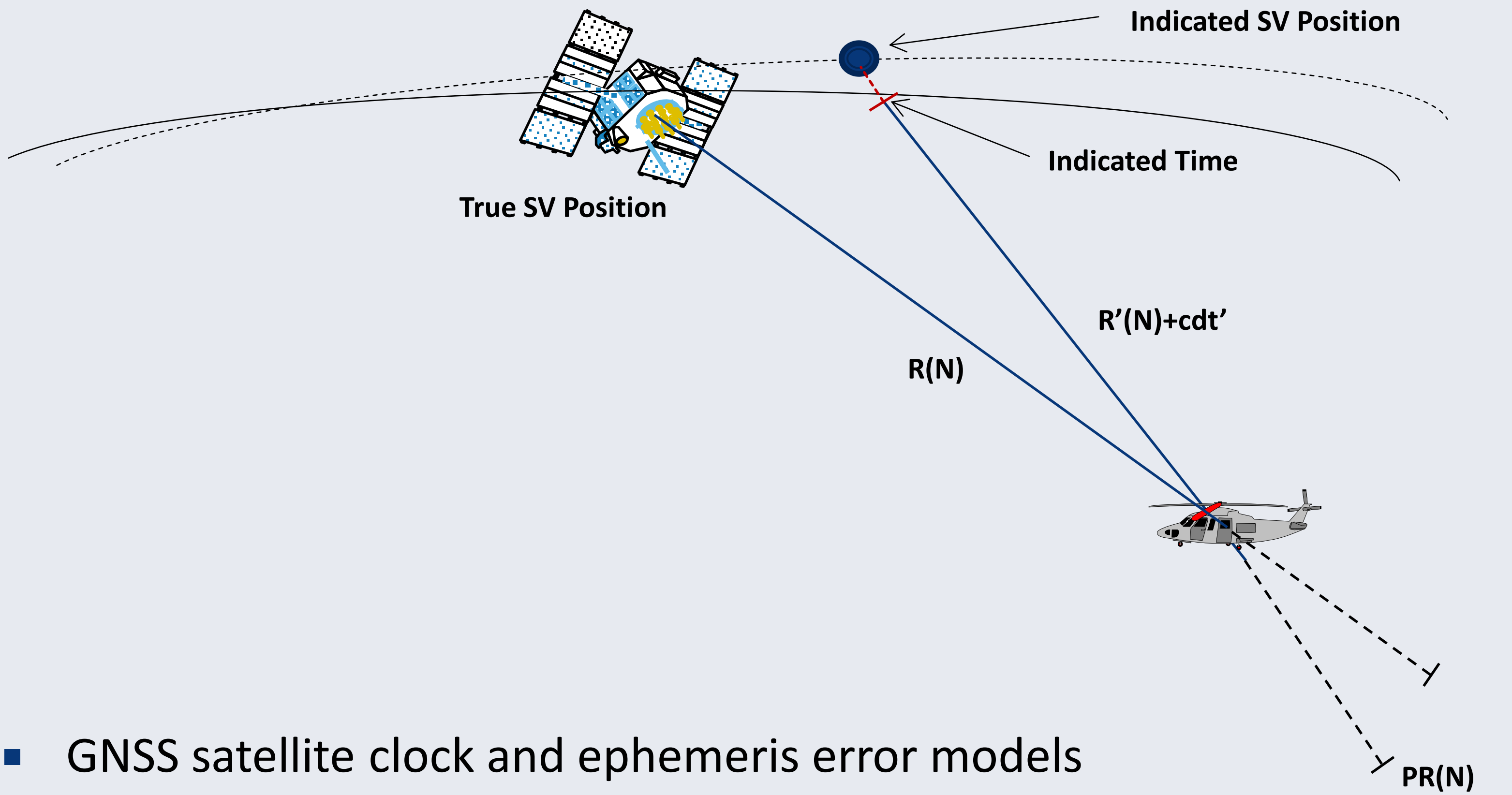
GNSS Pseudo-range Error Model



$$PR(N)=R(N)+cdt+e(N)$$

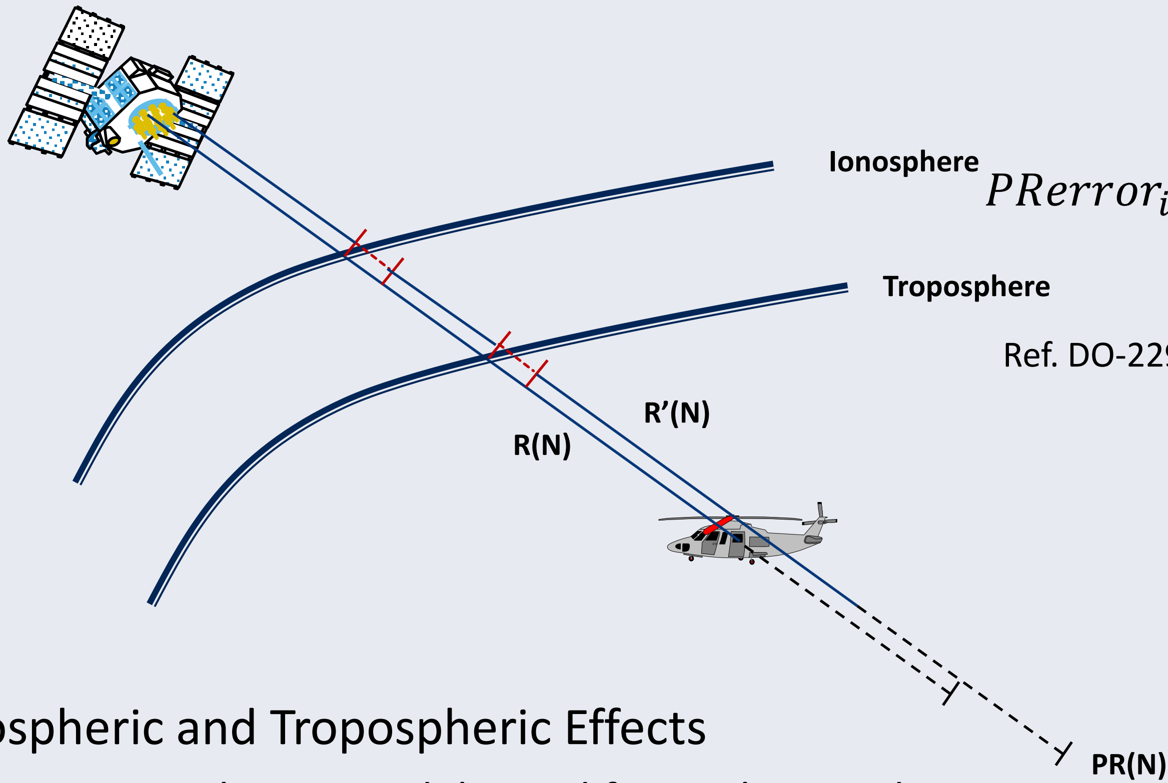
- e(N) can be modeled as a sum of errors: space & control segment, atmospheric propagation, multipath, and receiver error

Space and Control Segment Error Modeling



- GNSS satellite clock and ephemeris error models
  - Simulation typically uses zero mean, normally distributed Gauss-Markov noise (0-3 m)
  - Deterministic models include ramp errors of 0.01-5 m/sec

Atmospheric Propagation Effects

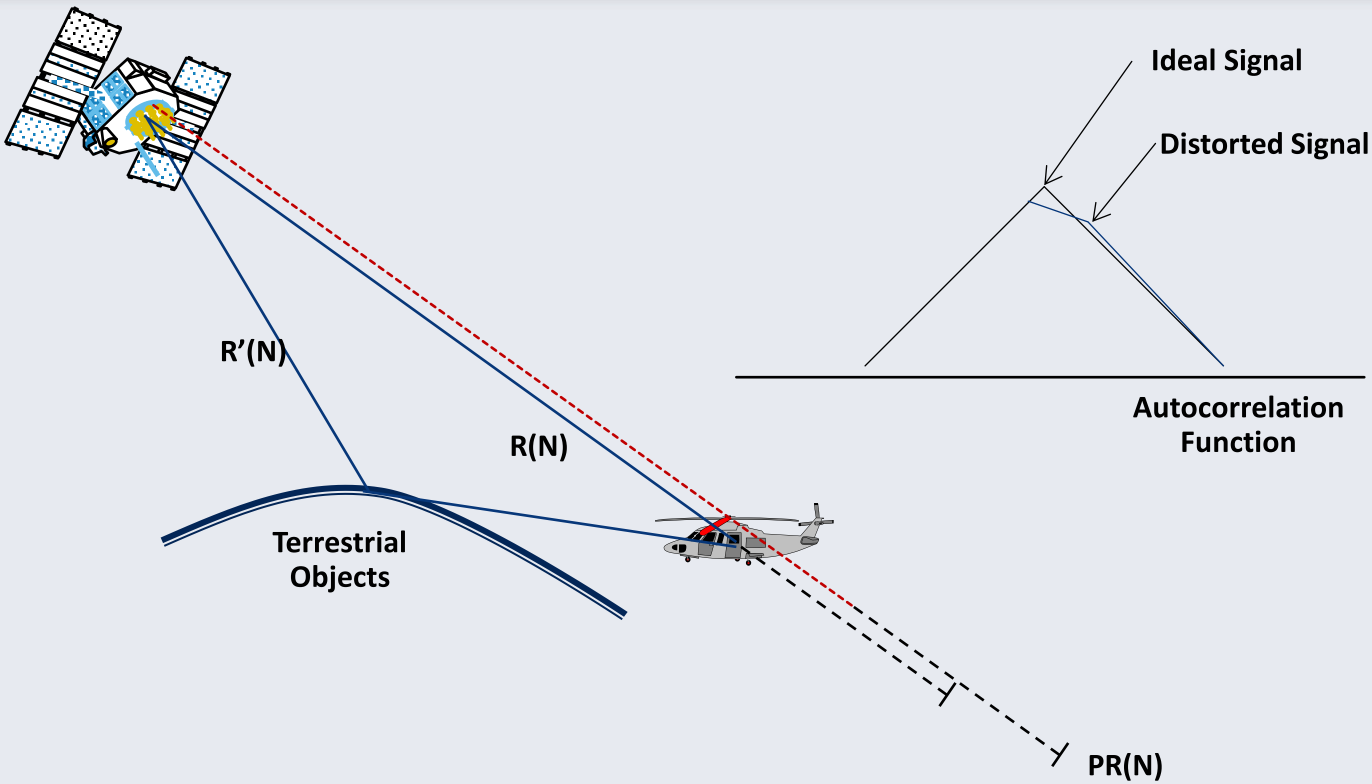


$$PRerror_{iono} = \frac{40.3TEC}{\sin(el)f^2}$$

Ref. DO-229D, A4.2.4

- Ionospheric and Tropospheric Effects
  - Parametric physics models used for analysis and test
  - Simulator parameter defaults based on empirical observation
  - Anomalous effects (parameter adjustment, manual control)

Multipath



- Reflected signals typically distort the true signal structure
  - Additional simulator channels can be used for deterministic and stochastic test cases
  - Distorted waveforms also can be created via manual control
  - Manufacturers may use detailed tracking loop models for analyses

Receiver Error

- For analysis, a simplified receiver error model is:

$$\sigma_u = \lambda_c \sqrt{\frac{dB_L}{2(S/N0)(1-2B_L T_d)}}$$

where: λ_c = Code wavelength
d = early-late chip spacing
BL = Code loop bandwidth
T_d = Predetection interval
S/N0 = carrier to noise ratio in ratio Hz

- For GNSS simulator testing, the receiver under test creates the error (so no need to model it)

Position-Domain Error

- Most simplified model scales the composite PR error, using Horizontal Dilution of Precision (HDOP):

$$rms\ Position\ Error = HDOP * Composite\ PR\ Error$$

where:

$$Composite\ PR\ Error = \sqrt{\sum (PR\ Error\ Components)^2}$$

  - Over-simplified (conservative) for weighted and over-determined navigation solutions typical of modern avionics
  - HDOP depends on almanac, time and user position; typically a single (conservative) value is used
  - PR error is dependent on elevation angle; typically a single (conservative) value is used

- A more realistic model uses the navigation solution weighing to map PR error to the position domain

$$rms\ Position\ Error = \sum_{i=1}^{N} {S_H}^i (Composite\ PR\ Error)^i$$

where ${S_H}^i$ maps from the PR for satellite "i" to the local horizontal plane

  - ${S_H}^i$ depends on almanac, time and user position

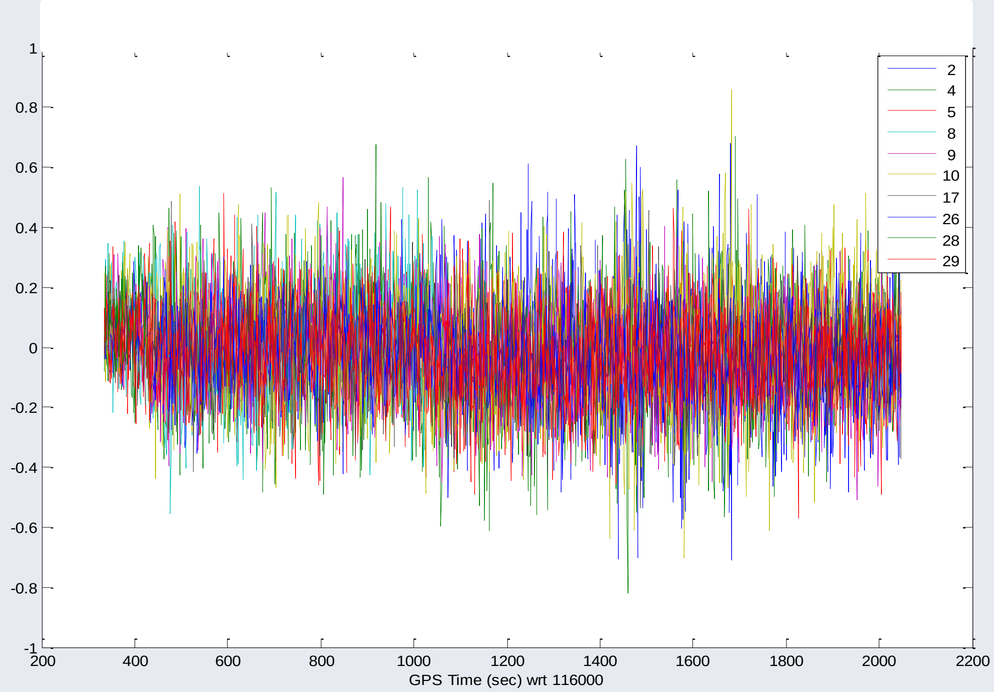
Antenna modeling for GNSS Simulation Testing

- Fixed Reception Pattern Antenna (FRPA) passive gain response
  - Enter known antenna gain characteristics (from manufacturer)
  - Or use minimum values from certification standards
- FRPA Low Noise Amplifier (LNA)
  - Adjust composite RF signal for effective noise temperature at the receiver input
    - Typically combine RF noise source
    - RF noise level accounts for thermal noise generated at simulator output
  - For passive antennas (no LNA), simulator signal power may require adjustment to compensate for higher thermal noise of simulation system (typically 290-300°K vs. sky noise of 100°K)
- Multi-aperature Controlled Reception Pattern Antenna (CRPA) arrays
  - Advanced receivers coherently process an array of antennas for improved performance
  - Testing requires multiple, coherent RF signal generators to simulate CRPA response
  - Wavefront Simulators tie multiple signal generators together to generate multiple coherent RF outputs

Radio Frequency Interference (RFI) Simulation and Test

- Civil certification standards requires RFI testing (e.g., RTCA/DO-229D)
  - 100kHz Broad-band Interference (BBI)
  - 20 MHz BBI
  - Out-of-band Continuous-Wave Interference (CWI)
  - In-band coherent CWI
  - Pulsed interference
- Coherent in-band CWI
  - Generate using GNSS simulator for coherence with GNSS signal
- Other RFI cases
  - For avionics using FRPAs, other interference sources typically generated externally
  - For avionics using CRPAs, RFI must be coherently simulated

Example Result: Pseudorange accuracy test



- GNSS receiver pseudorange error from dynamic GNSS simulation
- Clock, ephemeris, atmospheric effects multipath disabled
- Resulting rms pseudorange accuracy of ~15 cm

Part 2 - IMU Modeling Example

Select Sensors
Manufacturer Specifications
Approximations for Modeling

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Honeywell Aerospace

Comparison Of Different IMUs

- Error Budgets for
  - VectorNav VN-100 IMU/AHRS
    - http://www.vectornav.com/Downloads/Support/PB-12-0002.pdf
  - KVH 1750 FOG IMU
    - http://www.kvh.com/ViewAttachment.aspx?guidID={A7B9D37D-82D2-4B12-9A22-1637D7CDE439}
  - Northrop Grumman LN 200
    - http://www.northropgrumman.com/Capabilities/LN200sInertial/Documents/ln200s.pdf
  - Honeywell HG1930
    - http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Missiles-Munitions/HG1930_Datasheet.pdf
- Each IMU is specified differently
- Estimate a common error budget for each IMU

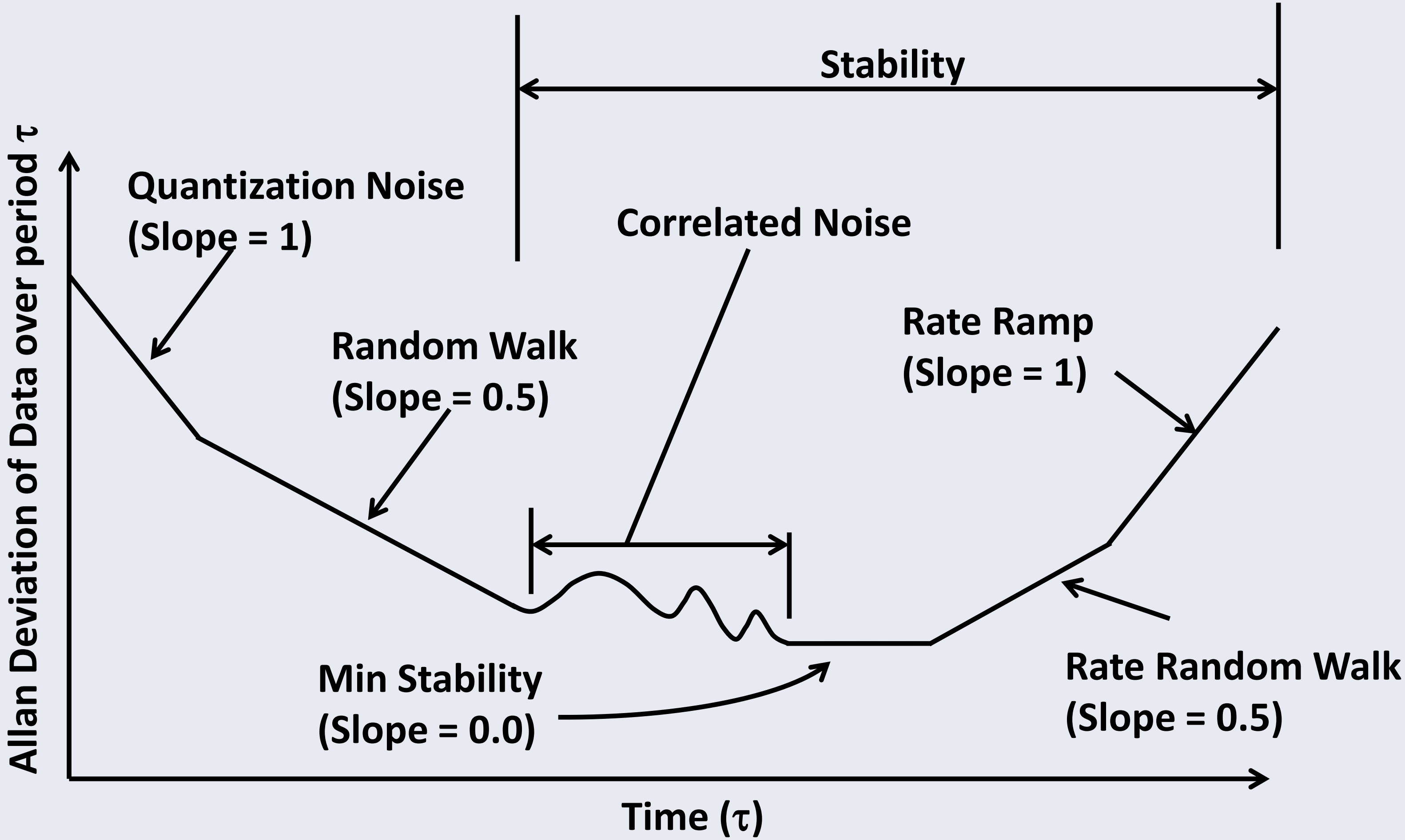
Gyro Error Budgets

Parameter	Units	VN100	KVH1750	LN200	HG1930
Bias					
Repeatability	°/hr		2.0	1	20
Stability (60 min)	°/hr	10	0.7	0.1	1
Stability (minimum)	°/hr		0.05		
ARW	°/rt-hr	.3	0.012	0.07	0.083
Scale factor					
Repeatability	ppm	1000	2,000		
Stability (60 min)	ppm		200		
Stability (minimum)	ppm				
Nonlinearity	ppm/°/hr		50		
Nonorthogonality	µrad	600	280	700	
Misalignment	µrad	600	280	700	
Quantization	deg				

Accel Error Budget

Parameter	Units	VN100	KVH1750	LN200	HG1930
Bias					
Repeatability	mg		7.5	0.3	5
Stability (60 min)	mg		1		0.3
Stability (minimum)	mg		0.05		
VRW	mg/rt-Hz	0.4	0.12	0.035	0.154
Scale factor					
Repeatability	ppm			300	
Stability (60 min)	ppm	500	100		
Stability (minimum)	ppm				
Nonlinearity	ppm/g		9		
Nonorthogonality	µrad	870	1000	100	
Misalignment	µrad		n/a		

Definition of Allan Deviation



Reference: IEEE Std 962-1997 (R2003) Standard Specification Format Guide and Test Procedure for Single-Axis

Estimation of Remaining Errors

- Best approach is to measure the data using the actual sensors, if possible
- Repeatability
  - Specified as aging or offset
- Temperature stability
  - Application specific
  - For this example, assume a time constant of 60 min
- Room temperature
  - Floor of the Allan Deviation
- Misalignment/non-orthogonality
  - Gyro: Split specified misalignment 50/50 (rss) between misalignment & nonorthogonality
  - Accel: Nonorthogonality is not applicable

Estimation of Remaining Errors

- Accel bias
  - Estimate from AHRS pitch & roll error: $bias = \tan(\alpha)$
- To estimate repeatability, stability @ 60 min, & stability @ minimum:
  - Use data from competitor's specification of the same device
  - If only minimum (constant temperature) stability is specified then:
    - Implement Gauss Markov or rate random walk process
    - Intersects the ARW slope at the minimum specified stability
  - Assume a factor of 10 between repeatability, stability, & the minimum
    - Stability is 10x better than repeatability
- On the following slide to complete the tables:
  - Parameters in red with an asterisk (X*) are specified using the above rules

Gyro Error Budgets

Parameter	Units	VN100	KVH1750	LN200	HG1930
Bias					
Repeatability	deg/hr	100*	2.0	1	20
Stability (60 min)	deg/hr	10	0.7	0.1	1
Stability (minimum)	deg/hr	1*	0.05	0.01	0.01
ARW	deg/rt-hr	.3	0.012	0.07	0.083
Scale factor					
Repeatability	ppm	1000	2,000	100*	1000*
Stability (60 min)	ppm	100*	200	10*	100*
Stability (minimum)	ppm	10*	20*	1*	10*
Nonlinearity	ppm/°/hr	n/a	n/a	n/a	n/a
Nonorthogonality	µrad	600	280	700	600*
Misalignment	µrad	600	280	700	600*
Quantization	deg				

Accel Error Budget

Parameter	Units	VN100	KVH1750	LN200	HG1930
Bias					
Repeatability	mg	9*	7.5	0.3	5
Stability (60 min)	mg	0.9*	1	0.03*	0.3
Stability (minimum)	mg	0.09*	0.05	0.003*	0.03*
VRW	mg/rt-Hz	0.4	0.12	0.035	0.154
Scale factor					
Repeatability	ppm	5000*	1000*	300	5000*
Stability (60 min)	ppm	500	100	30*	500*
Stability (minimum)	ppm	50*	10*	3*	50*
Nonlinearity	ppm/g	9*	9	3*	9*
Nonorthogonality	µrad	870	1000	100	870*
Misalignment	µrad	n/a	n/a	n/a	n/a

Conclusion

- Selected four types of IMU to model
- Established guidelines for deriving a model from the available data
- Described the estimated models for the selected IMUs

Next Steps

Visit www.insidegnss.com/webinars for:

- PDF of Presentations (including additional slides)
- Bibliography

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- Alex Stratton – dastratt@rockwellcollins.com

Poll #3

What are your top 2 issues that occur during vehicle integration that could have been mitigated by simulation?
(Please select your top two)

- *Algorithm errors*
- *Hardware design issues*
- *Software errors*
- *Missed requirements*
- *Data communication issues*

Ask the Experts – Part 2

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CAST Navigation

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