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INSIDE ENGINEERING, POLICY AND PRACTICE

Tuesday, June 5, 2018

10 a.m. PDT • Noon CDT • 1 p.m. EDT
6 p.m. BST • 7 p.m. CEST

WEBINAR AND VIRTUAL WORKSHOP:

ADVANCEMENTS IN GNSS+INS TECHNOLOGY AND INTEGRATION

WELCOME TO

Webinar and Virtual Workshop: Advancements in GNSS+INS Technology and Integration

Demoz Gebre-Egziabher
Professor
Aerospace Engineering and Mechanics
University of Minnesota

Andrey Soloviev
Principal
QuNav

David Gaber
Marketing & Business Development
Epson

Ryan Dixon
Chief Engineer, SPAN
NovAtel

Co-Moderator: Lori Dearman, Executive Webinar Producer

Who’s In the Audience?

A diverse audience of over 450 professionals registered from 52 countries, representing the following industries:

19 %	GNSS equipment manufacturer
18%	System Integrator
15%	Product/Application Designer
15%	Professional User
13%	Government
20%	Other

Welcome from *Inside GNSS*

Richard Fischer
Publisher
Inside GNSS
Inside Unmanned Systems

Demoz Gebre-Egziabher
Professor
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Poll #1

What does having a better quality IMU improve in INS/GNSS integrated systems? (select all that apply)

- ***a) Accuracy***
- ***b) Continuity***
- ***c) Integrity***
- ***d) Availability***

GNSS/INS Integration:

Major Trends and Implementation Example

Andrey Soloviev
Principal
QuNav

Key Trends

- From high-grade to lower SWAP-C IMUs

RLG, FOG

MEMS

- Application for GNSS-degraded and denied environments

Main Challenge

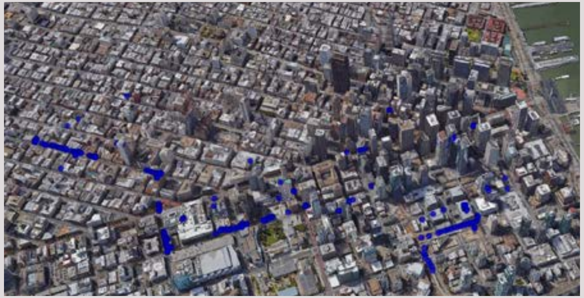
Mitigation of inertial error drift

Solutions:

- Use of ***advanced integration techniques***
- ***Integration with other sensors***

Advanced Integration Techniques

Loose coupling (integration at solution level) has ***limited benefits***



- Only sparse GNSS fixes can be obtained;
- This results in extended GNSS outages

Tight coupling and deep integration must be used:

- ***Tight coupling*** (integration at the measurement level):
  - Increases the availability of (partial) GNSS updates
- ***Deep integration*** (integration at the signal processing level):
  - Weak signal recovery
  - Multipath suppression

Integration with Other Sensors

- GNSS/INS performance can be still limited

- Integration with other sensors (and sources of navigation data) must be used:
  - *Examples*:
    - Video-cameras;
    - Motion models (non-holonomic constraints)

Integration Example:

GNSS/INS for *consumer-grade* IMUs

Main Features of Consumer-Grade Inertial

<$2-3

Key challenges:

- Large sensor errors
- Partially defined (undefined) specs (e.g., axes misalignment)
- Nonlinearities (heading drift)

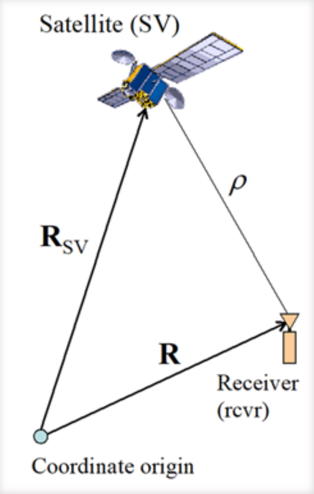
However:

- Bias (drift) stability and noise performance has improved significantly;
- This enables the use of ***consumer-grade IMUs*** for ***improved robustness of GNSS*** (coasting through outages and weak signal recovery)

Use of GNSS Carrier Measurements

- Large (but stable) biases are still present: e.g. gyro drift at a 5 deg/s level
- GNSS carrier phase (or Doppler frequency) can be utilized to estimate and remove bias components: low-noise measurements enable fast convergence

Integration with GNSS Carrier Phase



$$\varphi = \rho + \lambda N + \delta t_{rcvr} + \varepsilon + \eta$$

Noise & multipath

Clock bias

Integer ambiguity

Atmospheric delays &
SV clock

- ***Resolving integer ambiguities*** can be ***challenging***:
    - Need for a base station;
    - Limited number of SVs
- Therefore, ***carrier phase changes*** are used as ***GNSS observables***:

$$\Delta\varphi = \varphi(t_n) - \varphi(t_{n-1}) = \Delta\rho + \Delta\delta t_{rcvr} + \Delta\varepsilon + \Delta\eta$$

Directly related to INS error states

INS Error Model

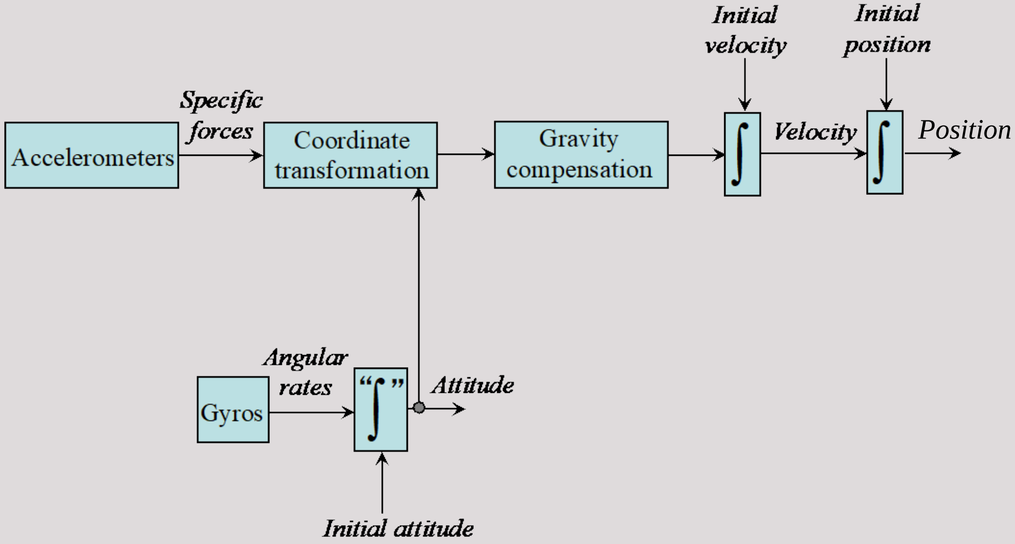
24 states:

- Position errors (3 states)
- Delta position errors (3 states)
- Velocity errors (3 states)
- Attitude errors (3 states)
- Gyro and accelerometer biases (6 states)
- Axis misalignment (6 states)

INS Navigation Mechanization

Relatively simple mechanization can be used:

- No need to compensate for non-inertial effects that are below the level of sensor errors

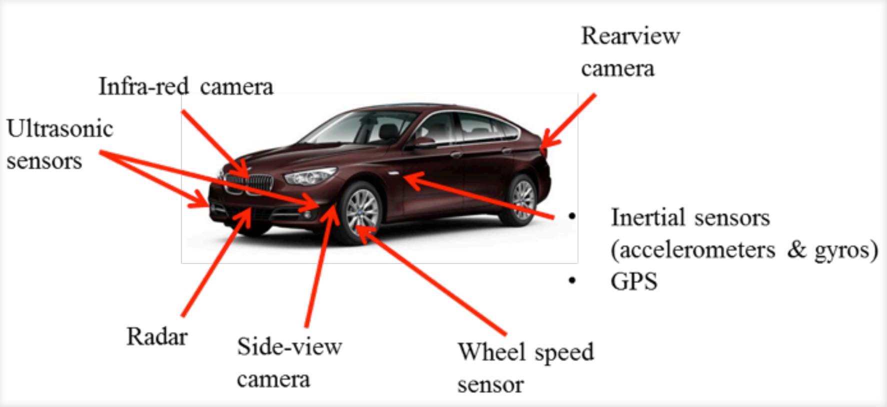


Performance of GNSS/INS integration can be still limited…

- Performance of GNSS-only solution is improved significantly
- However, some limitations remain: e.g., large position errors (tens of meters) can be present in urban canyons

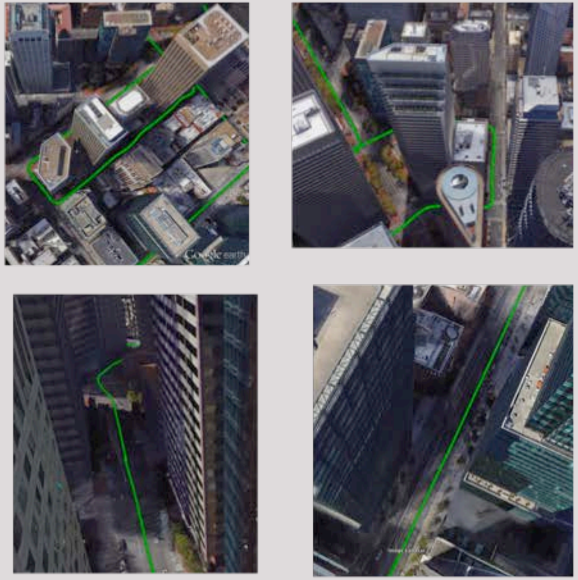
Improving performance of GNSS/INS

- Other sources of navigation information have to be used for reliable navigation
- Vehicle motion model: non-homonymic constraints
- Integration with other sensors



Example performance in urban canyons (downtown San Francisco)

Carrier phase GNSS/INS (STMicro iNEMO)/motion model/monocular video camera



Reliable positioning is maintained for the entire duration of the test

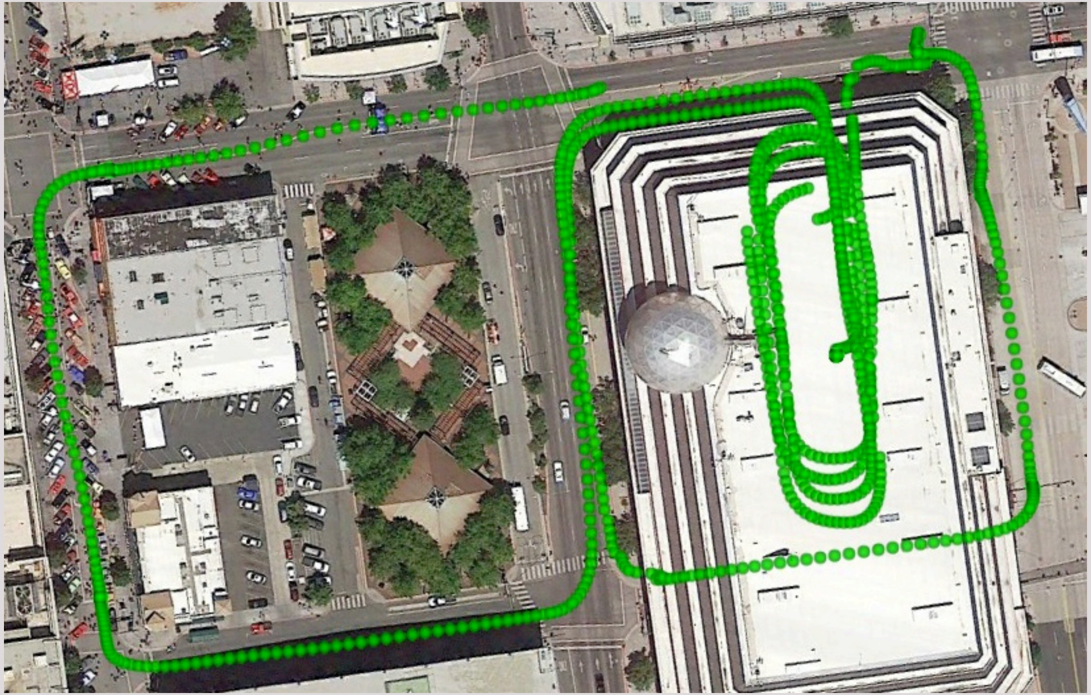
Example performance in urban canyons (downtown San Francisco)

Carrier phase GNSS/INS (STMicro iNEMO)/motion model/monocular video camera

Reliable positioning is maintained for the entire duration of the test

Example performance in a parking garage

- GNSS/INS/motion model
- Consumer-grade IMU (STMicro iNEMO)
- GNSS outage duration exceeds 5 min

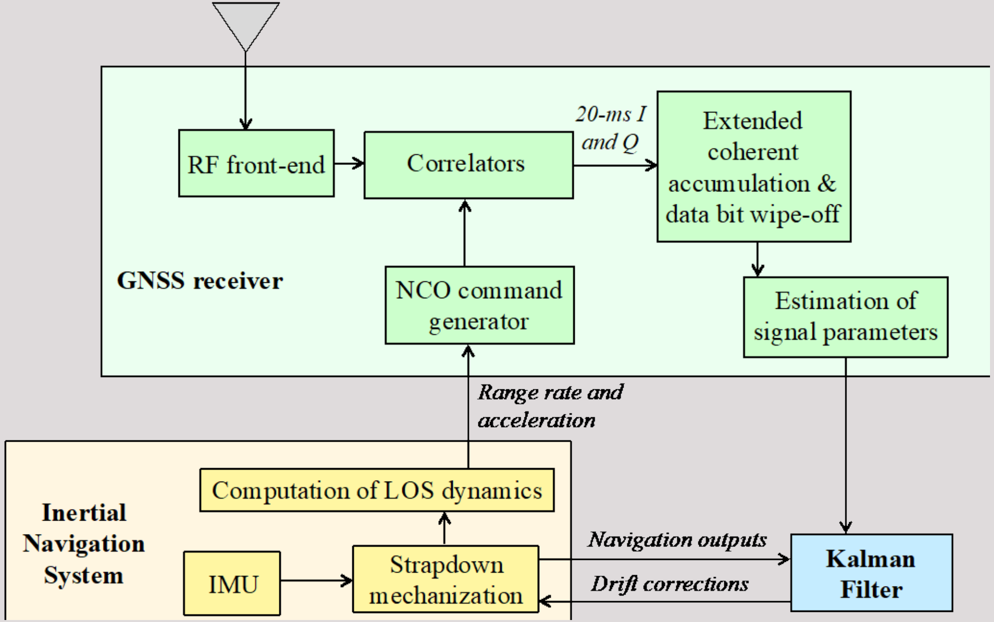


Use of consumer-grade IMU to enhance robustness of GNSS signal processing

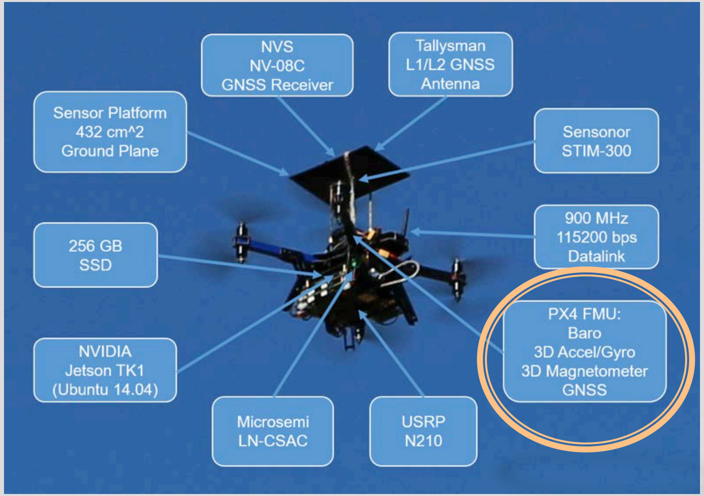
- Consumer-grade IMU is used to extend coherent accumulation of GNSS signals
- This enables:
  - Weak signal recovery (thus enhancing the GNSS signal availability)
  - Multipath suppression

Deep GNSS/INS integration with long coherent integration

- Traditionally, deep integration has been developed for navigation grade and/or tactical-grade IMUs;
- Improved performance of consumer-grade MEMS IMUs allows for deep integration with low-cost inertial sensors



UAV demonstration example


NVS
NV-08C
GNSS Receiver

Tallysman
L1/L2 GNSS
Antenna

Sensor Platform
432 cm^2
Ground Plane

Sensonor
STIM-300

900 MHz
115200 bps
Datalink

256 GB
SSD

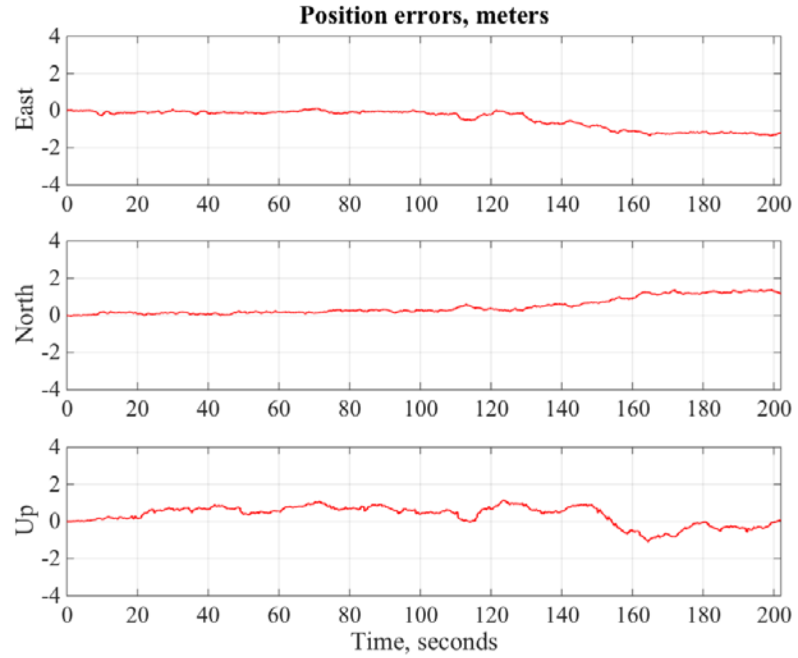
PX4 FMU:
Baro
3D Accel/Gyro
3D Magnetometer
GNSS

NVIDIA
Jetson TK1
(Ubuntu 14.04)

Microsemi
LN-CSAC

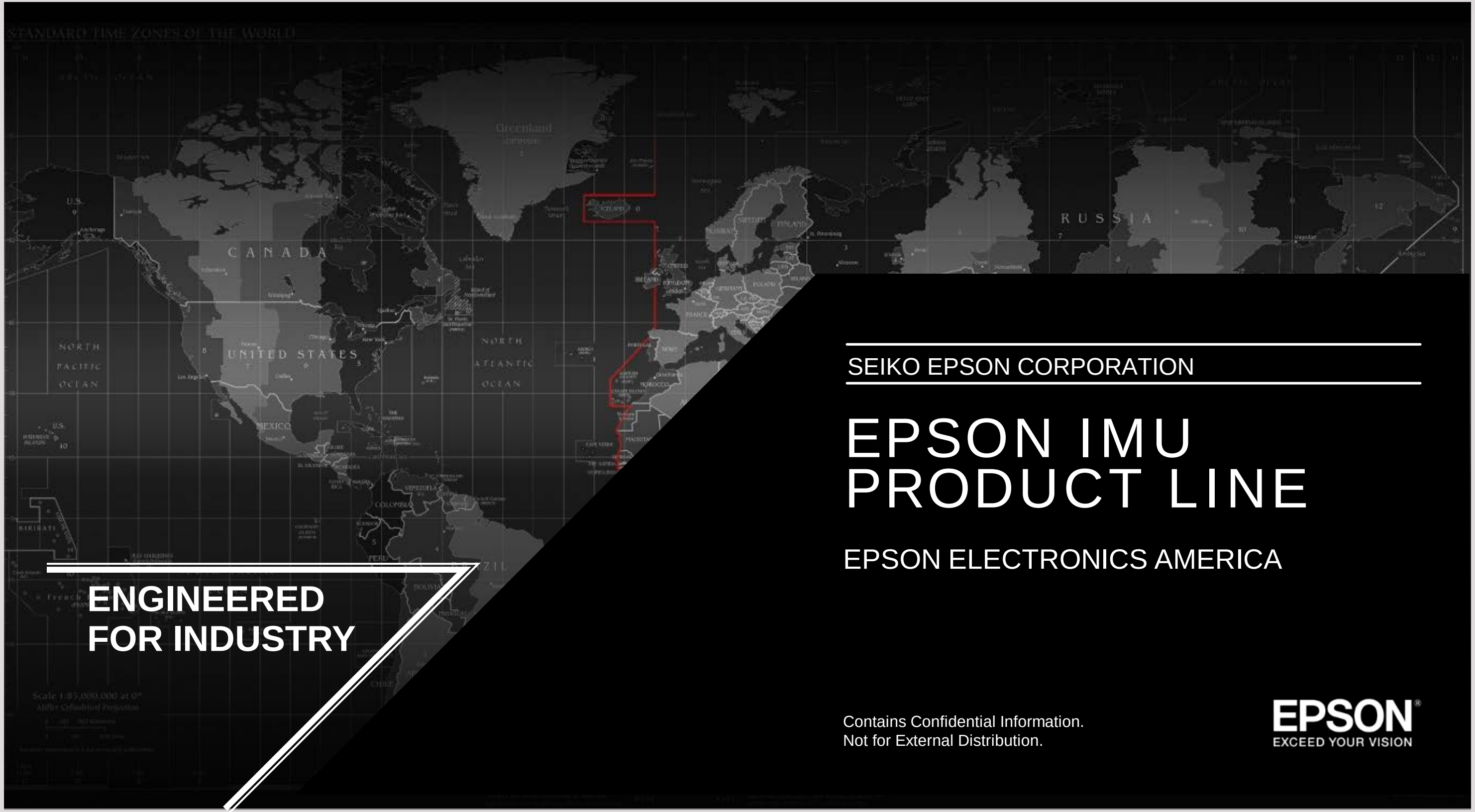
USRP
N210

Position performance under 40-dB attenuation introduced into live-sky GPS signals



EPSON IMU
FEATURE SET

David Gaber
Marketing & Business Development
Epson



SEIKO EPSON CORPORATION

EPSON IMU PRODUCT LINE

EPSON ELECTRONICS AMERICA

ENGINEERED FOR INDUSTRY

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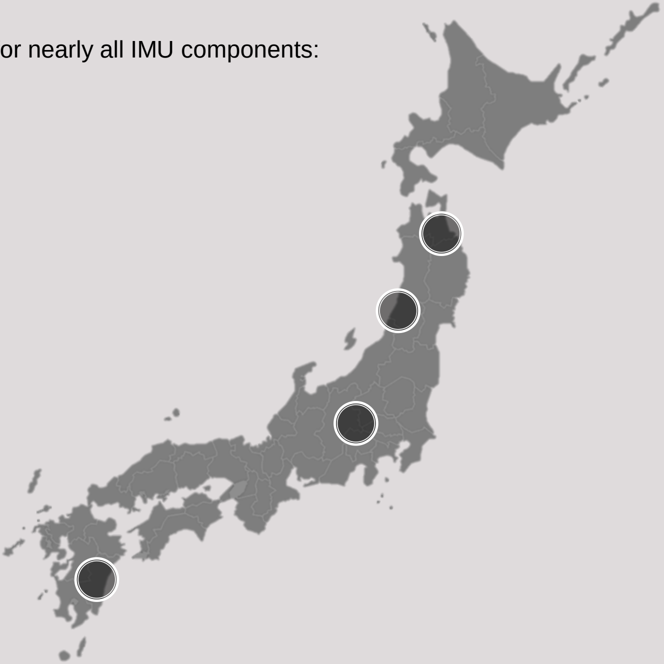
EPSON®
EXCEED YOUR VISION

SECTION I: OVERVIEW
EPSON IMU HISTORY

Vertical Integration

Epson owns and controls all manufacturing and production for nearly all IMU components:

- Synthetic Crystal Bar Production
  - Hachinohe Plant, Japan
  - Miyazaki Plant, Japan
  - Washington Plant, USA
- Wafer Processing
  - Hachinohe Plant, Japan
- IC & MCU Fabrication
  - Sakata Plant, Japan
  - Fujimi Plant, Japan
  - Suwa Minami Plant, Japan
- Gyro Fabrication
  - Ina Plant, Japan
- Oscillator Fabrication
  - Miyazaki Plant, Japan
  - Shonan Plant, Japan
- Final Assembly
  - Fujimi Plant, Japan
- Testing and Calibration
  - Fujimi Plant, Japan
  - Sakata Plant, Japan



OVERVIEW
GYRO TECHNOLOGY
IMU EVOLUTION
CURRENT PRODUCTS
NEW PRODUCTS

Epson IMU History
— Vertical Integration
— Quartz Crystal
— QMEMS
— QMEMS Uses

SECTION I: OVERVIEW
EPSON IMU HISTORY

Quartz Crystal

Epson produces and utilizes 100% synthetic quartz crystal for all inertial sensing products:

- Epson Synthetic Quartz Crystal
  - Synthesized from natural quartz crystal
  - Uniform size, shape and quality
  - Efficient wafer yielding = low production costs
- Natural Quartz Crystal
  - Found in nature but very expensive
  - Varies in size and shape
  - Contains impurities = susceptible to cracks

SECTION I: OVERVIEW
EPSON IMU HISTORY

QMEMS

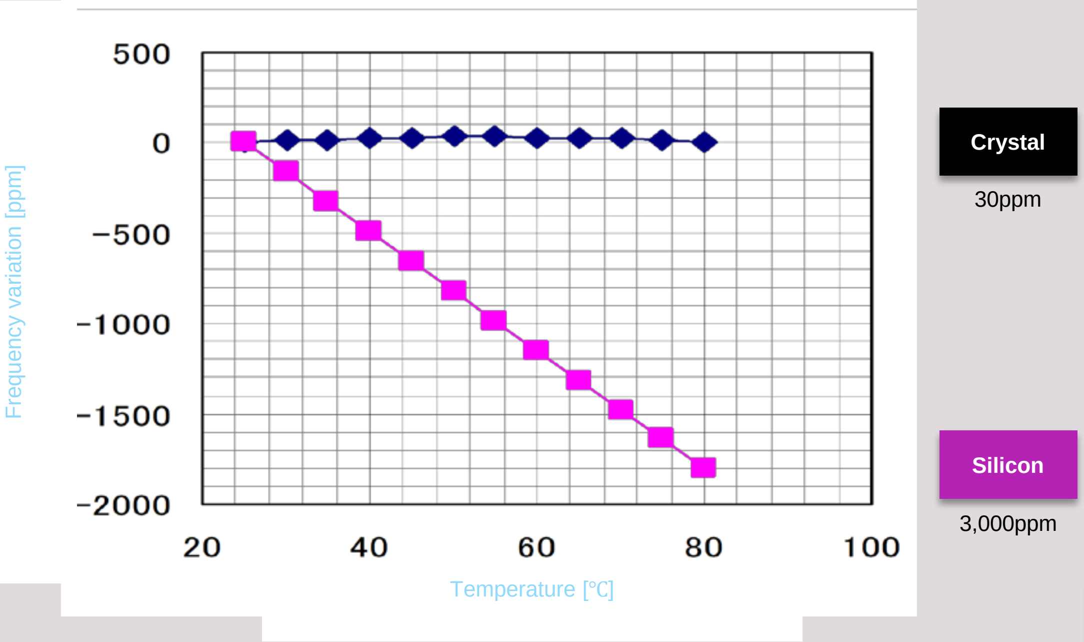
Epson’s proprietary quartz MEMS fabrication process:

- Stable Supply
    - High quality supply of synthetic quartz is available throughout Japan & United States
- Physically and Chemically Stable Material
    - Low aging = excellent long-term stability
    - Excellent workability and low variation among samples
- Extremely Low Internal Loss of Vibration
    - Low power required for oscillation = low overall power consumption
- Performance over Temperature can be Dictated by Cutting Angle
    - Proprietary cutting angle process and technology assures consistent performance

SECTION I: OVERVIEW
EPSON IMU HISTORY

QMEMS
Epson's QMEMS elements are highly stable over temperature:

— QMEMS gyroscopes offer ~100x better stability than SiMEMS.



SECTION I: OVERVIEW
EPSON IMU HISTORY

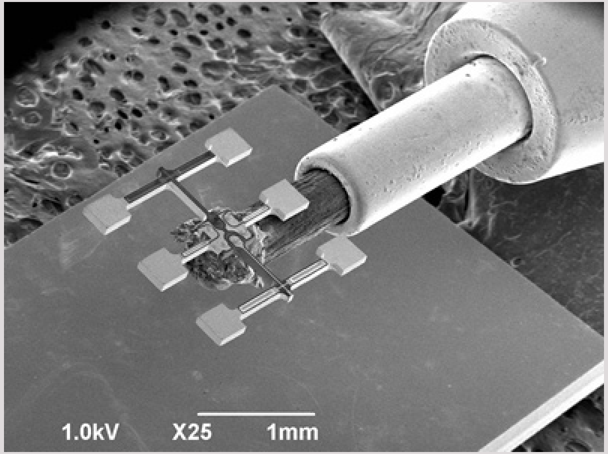
QMEMS Uses

Epson’s proprietary quartz MEMS fabrication process is used for many product lines:

— Timing Products

— Real-Time Clocks

— Inertial Sensors



A QMEMS element for a gyroscopic sensor is shown balanced on the tip of a pencil lead.

One of Epson’s QMEMS autoclaves located in Japan.

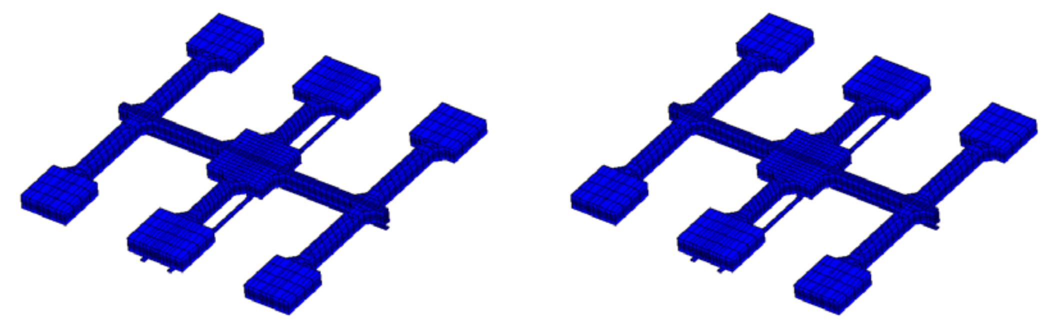
SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Physical Structure
Epson's proprietary "Double-T" quartz MEMS gyroscopic sensor:

— Operates like traditional Coriolis gyros

— Uses differential detection

— Drive and detection arms vibrate in the same plane



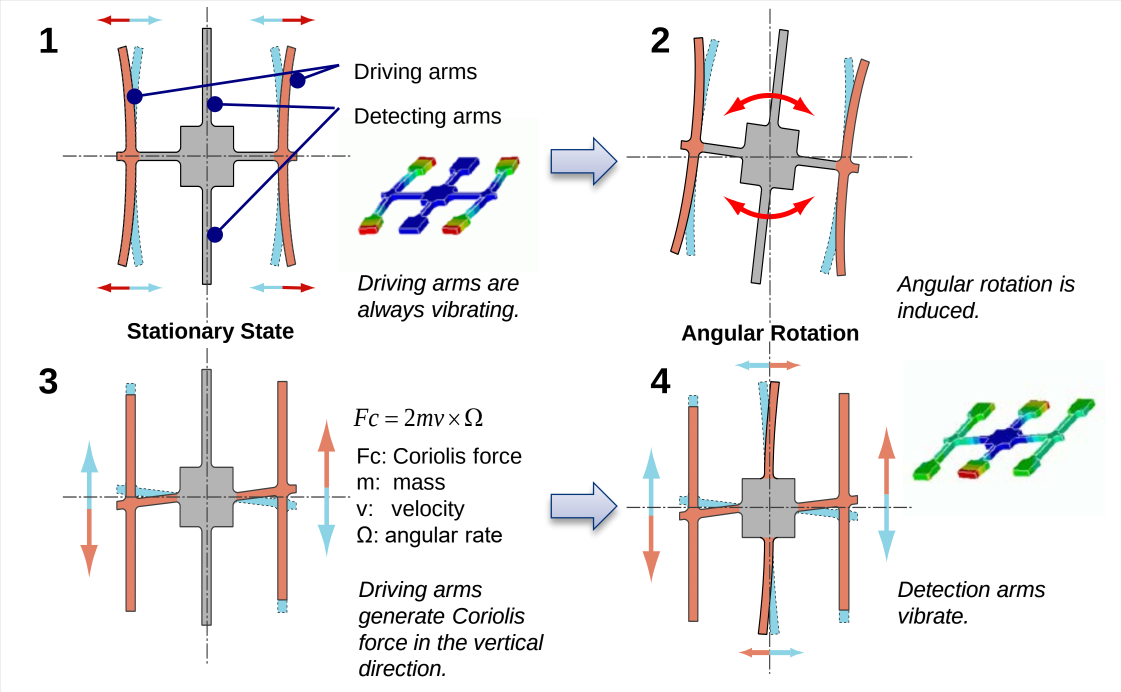
A QMEMS element shown in drive mode (left) and detection mode (right).

OVERVIEW
GYRO TECHNOLOGY
IMU EVOLUTION
CURRENT PRODUCTS
NEW PRODUCTS

Proprietary Element
— Physical Structure
— Architecture
— Differentiation
— Vibration Effects
— Shock Effects
— Temperature Effects
— Noise Density

SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Physical Structure
Epson's QMEMS Double-T gyroscopic sensor principle of operation:



Stationary State

Driving arms are always vibrating.

Angular Rotation

Angular rotation is induced.

$$Fc = 2mv \times \Omega$$

Fc: Coriolis force
m: mass
v: velocity
Ω: angular rate

Driving arms generate Coriolis force in the vertical direction.

Detection arms vibrate.

OVERVIEW
GYRO TECHNOLOGY
IMU EVOLUTION
CURRENT PRODUCTS
NEW PRODUCTS

Proprietary Element
- — Physical Structure
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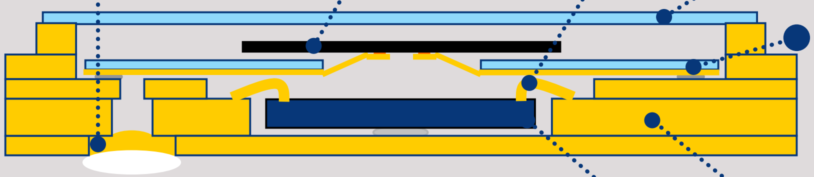
SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Architecture
Epson's QMEMS gyro components and housing:



Sealing Hole
— Vacuum packing with solder ball

QMEMS Element
— Double-T structure

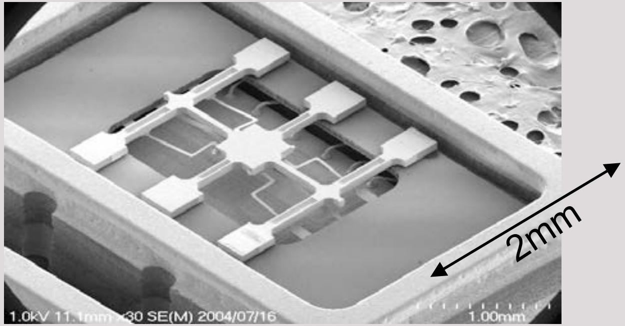
Gold Wire
— Connecting IC to package

Lid
— Seam-welded metal

Element Suspension
— Tape Automated Bonding (TAB)
— FPC Substrate

Ceramic Package
— Thermally-protected

IC
— Multi-function Epson ASIC



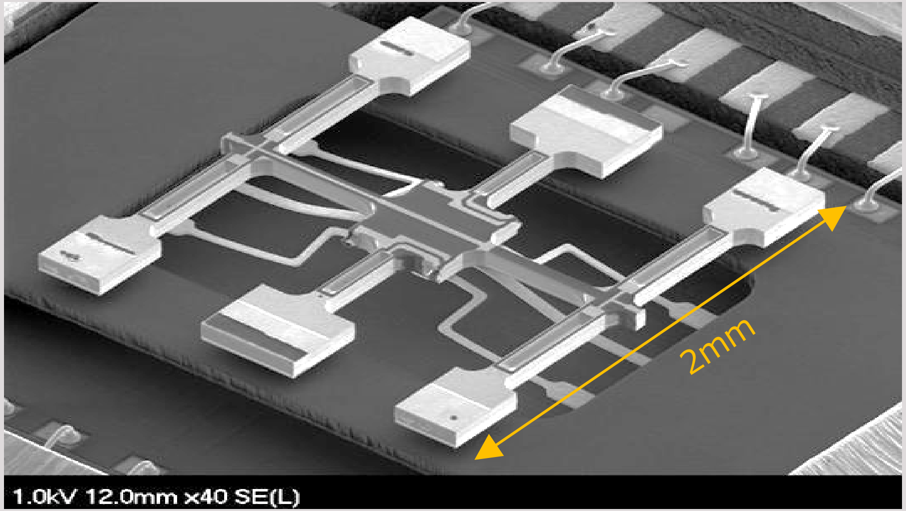
SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Architecture

Epson's QMEMS Double-T gyroscopes use a proprietary TAB mounting structure:

— Tape Automated Bonding.

— Provides significant shock & vibration isolation.



OVERVIEW
GYRO TECHNOLOGY
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CURRENT PRODUCTS
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Proprietary Element
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SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Architecture

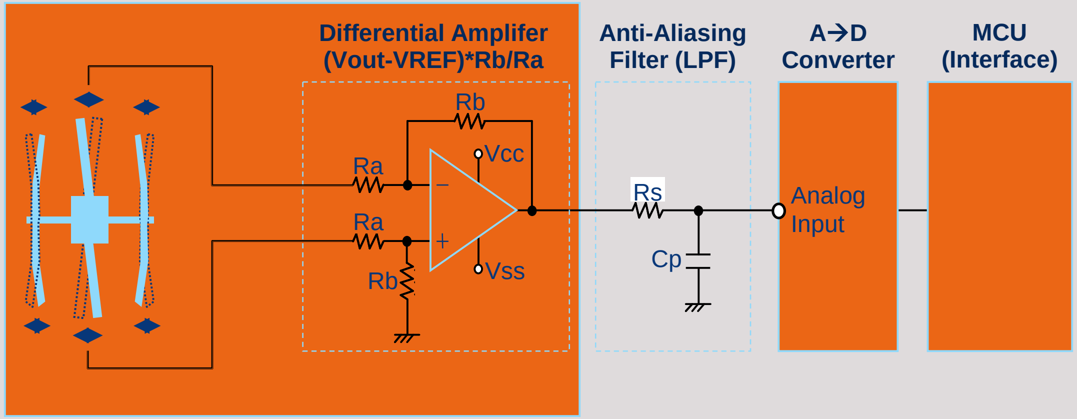
Epson’s QMEMS gyro electronics design advantages:

— Vibration and shock suppression due to differential amplification of two sensor arm signals.

— Amplification can be optimized for required gyro dynamic range.

— Individual control of anti-alias filter and A→D sampling rate.

— Intrinsic QMEMS sensor stability through temperature, including bias-drift and scale factor error.



OVERVIEW
GYRO TECHNOLOGY
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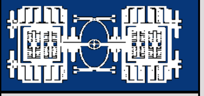
SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Differentiation

Epson’s proprietary “Double-T” quartz MEMS gyroscopic sensor offers several advantages:

- Drive and detection arms are discrete but oscillate in the same plane.
  - No vibration is induced by the drive arms.
  - Signal-to-noise ratio is very high.
- Significantly lower noise than traditional H-type vibration gyros.
- Excellent rejection of vibration and shock.
- High stability over temperature.
- Very low power consumption.

Gyroscope Element Structure	Epson Double-T 	Tuning Fork 	Silicon MEMS 
Q Value	◎ **Q=30000**	○ Q=10000	△ Q=3000
Element Support Method	◎ **Point symmetry**	△ Cantilever support	○ Center support
Detecting Structure	◎ **separation**	△ No separation	△ No separation

Ask the Experts – Part 1

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Poll #2

When considering the purchase of an INS solution, how important is the quality of the IMU in your decision?

1. ***Very important***
2. ***Important***
3. ***Somewhat important***
4. ***Not important***
5. ***Not sure***

EPSON IMU FEATURE SET

David Gaber
Marketing & Business Development
Epson

OVERVIEW
GYRO TECHNOLOGY
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Proprietary Element
— Physical Structure
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— Differentiation
— **Vibration Effects**
— Shock Effects
— Temperature Effects
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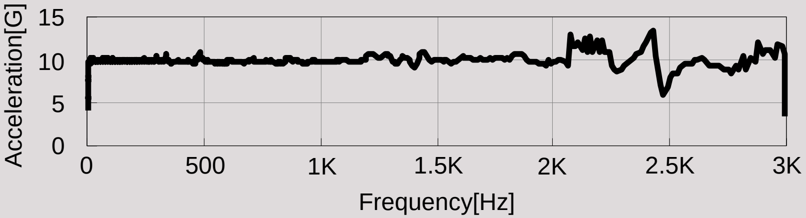
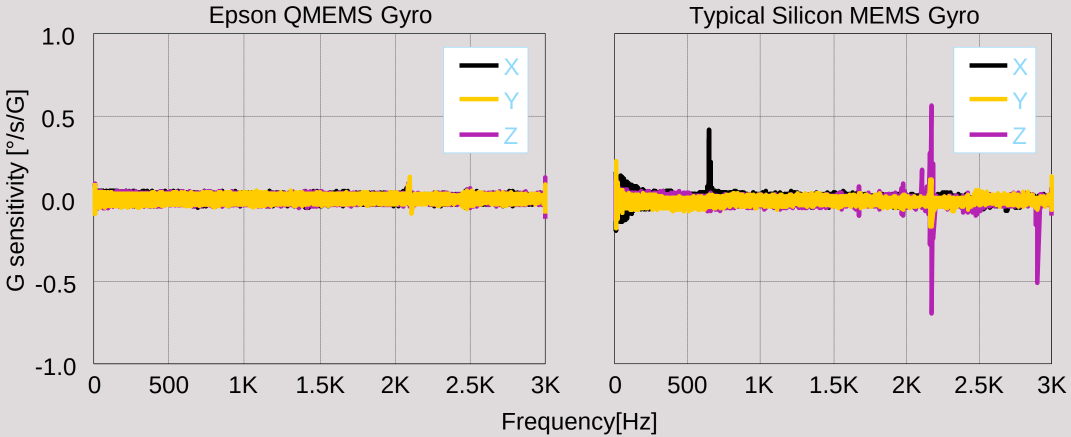
SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Vibration Effects
Epson’s QMEMS gyros offer high resilience to induced vibration error:

Input motion
f=10～3000Hz
Acceleration 10G





OVERVIEW
GYRO TECHNOLOGY
IMU EVOLUTION
CURRENT PRODUCTS
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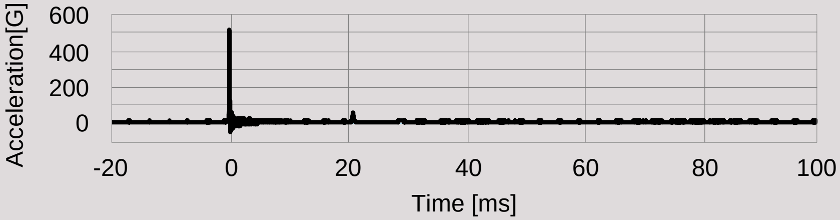
Proprietary Element
- Physical Structure
- Architecture
- Differentiation
- Vibration Effects
- Shock Effects
- Temperature Effects
- Noise Density

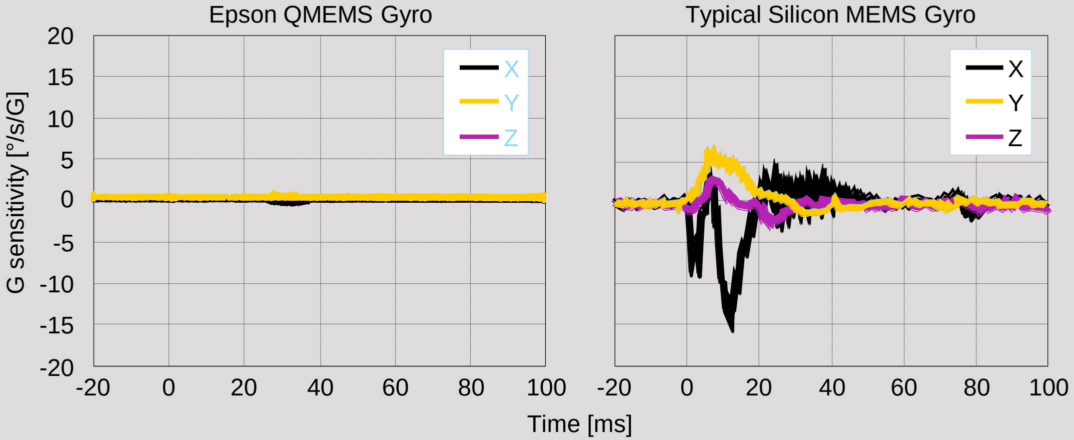
SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Shock Effects

Epson's QMEMS gyros offer high resilience to induced shock error:

Input motion
Acceleration
500G
1ms





OVERVIEW
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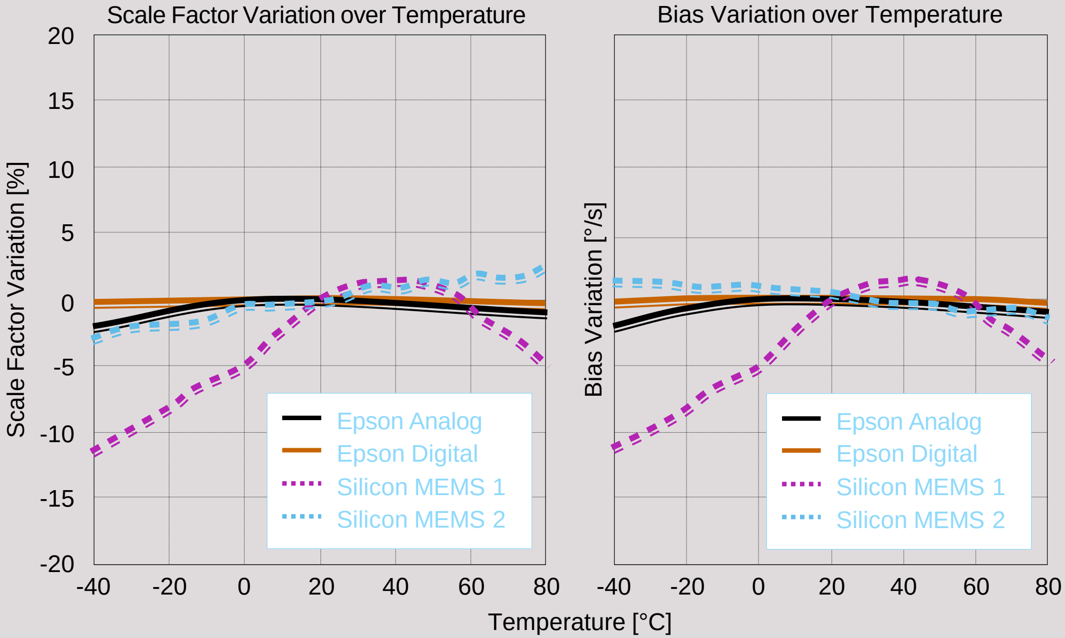
SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Temperature Effects

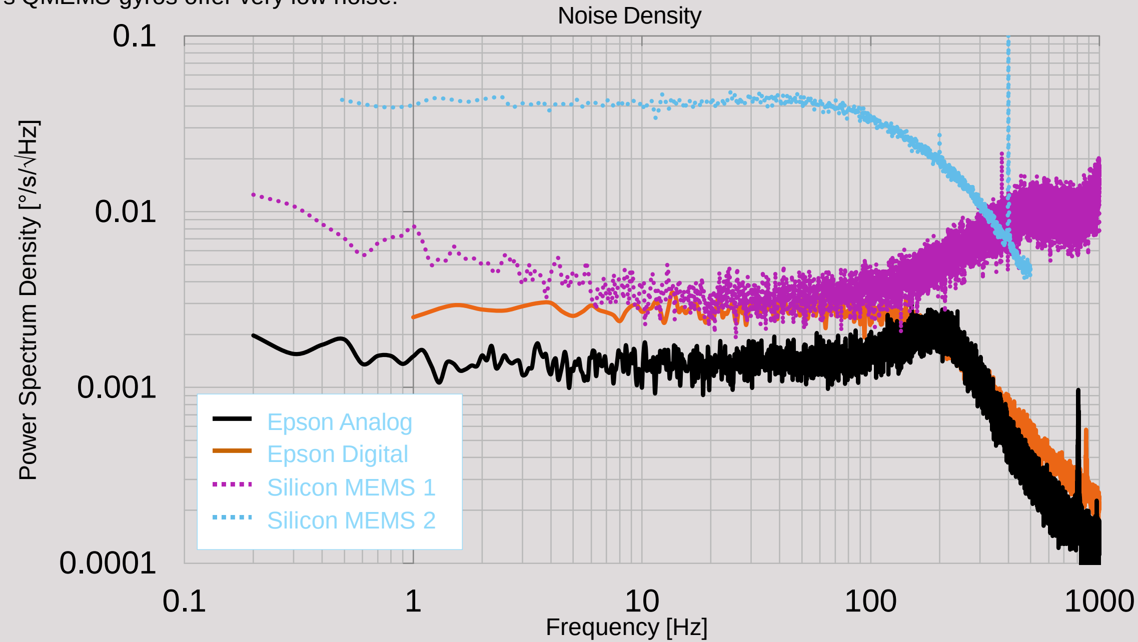
Epson's QMEMS gyros offer high stability over temperature:



SECTION II: GYRO TECHNOLOGY
PROPRIETARY ELEMENT

Noise Density

Epson's QMEMS gyros offer very low noise:



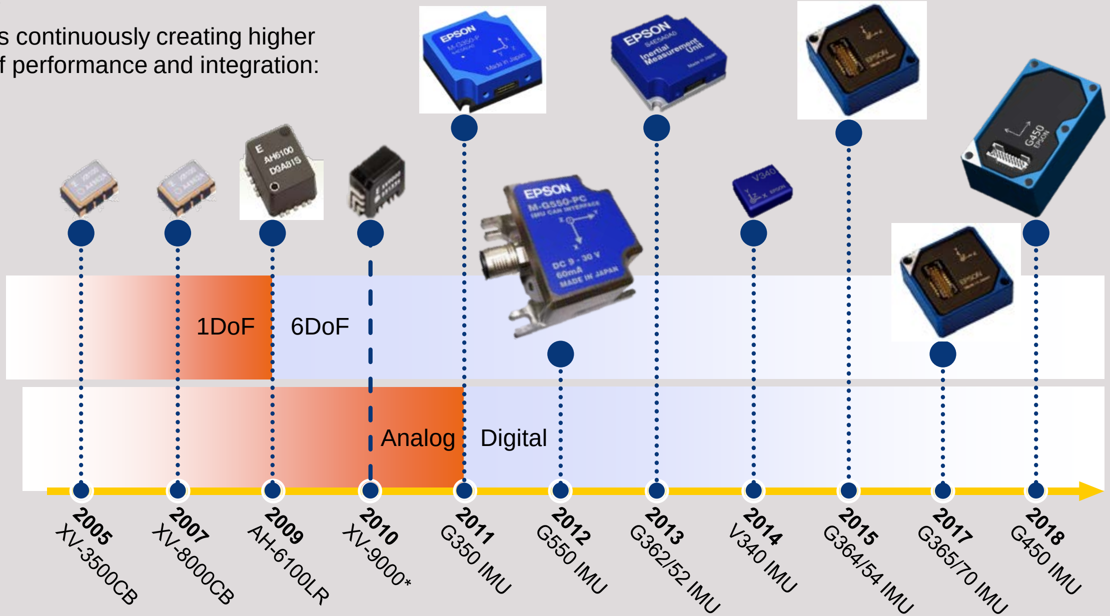
INTRODUCTION
GYRO TECHNOLOGY
IMU EVOLUTION
CURRENT PRODUCTS
NEW PRODUCTS

20 Years of R&D
— **History**
— Performance

SECTION III: IMU EVOLUTION

20 YEARS OF R&D

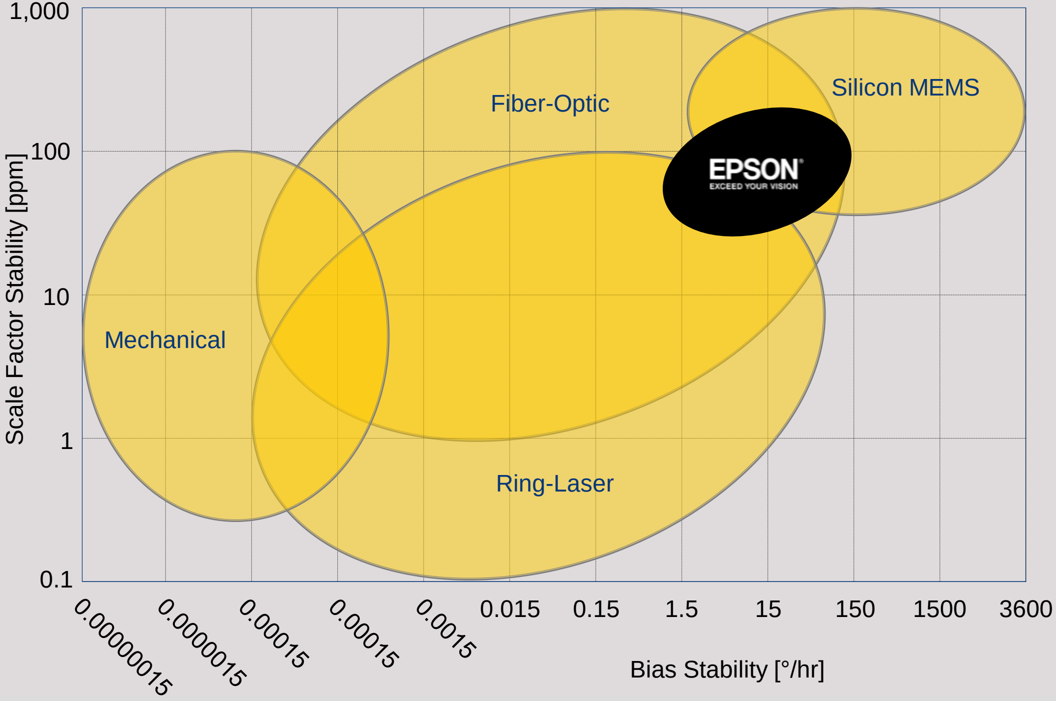
History
Epson is continuously creating higher levels of performance and integration:



*The XV-9000 is a 1DoF gyroscopic sensor produced after Epson moved to 6DoF sensor types.

SECTION III: IMU EVOLUTION
20 YEARS OF R&D

Performance
Epson IMUs deliver high performance without any export control restrictions:

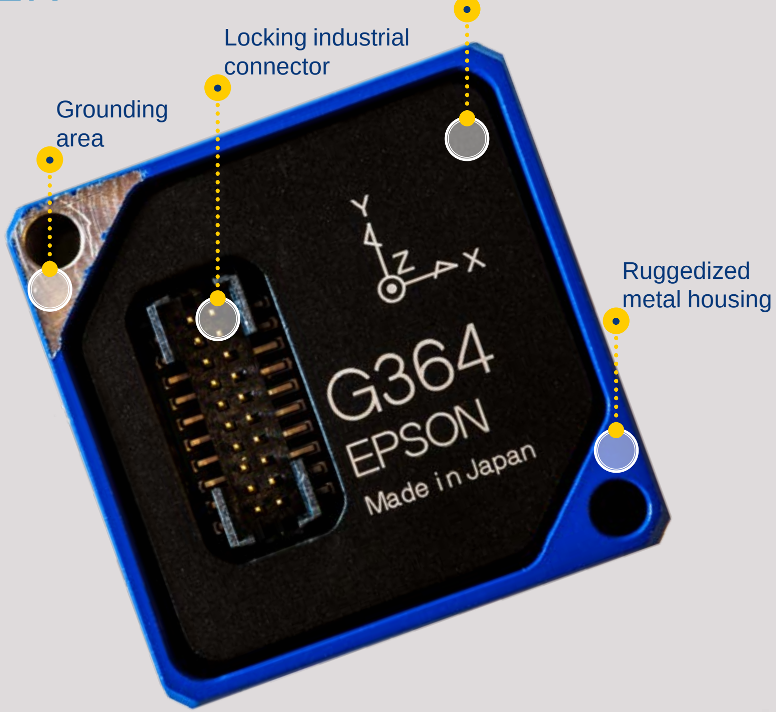


INTRODUCTION
GYRO TECHNOLOGY
IMU EVOLUTION
CURRENT PRODUCTS
NEW PRODUCTS

Flagship Products
— G3XX Series

SECTION IV: CURRENT PRODUCTS
IMU & ACCELEROMETER

G364
Narrow dynamic range:
- Ideal for slow-moving vehicles
- Epson’s highest performance IMU


Fully-isolated core
Locking industrial connector
Grounding area
Ruggedized metal housing

Increasing Performance
— G220 | G365 | G370
— G450

SECTION IV: NEW PRODUCTS

IMU

G220
G365
G370

P/N	G220	G320	G354/364	G365	G370
Status	**Sampling Now**	MP	MP	**Sampling Now**	**Sampling Now**
Gyro	±150dps	±150dps	±450/200dps	±150/450dps	±150/450dps
Bias Error [deg/sec,σ]	**0.1(z)**,0.5(x/y)	0.5	0.1	0.1	0.1
BIS[deg/hr]	**<2(z)**,8(x/y)	3.5	3/2.2	**< 1.8**	**< 0.8**
ARW[deg/√hr]	**<0.1(z)**,0.2(x/y)	0.1	0.2/0.09	0.09	**0.06**
Noise[deg/sec/√Hz]	0.004	0.002	0.002	**0.0015**	**0.001**
BW [Hz]	50	200	200	**500**	**500**
Accl	±6G	±5G	±5/3G	**±6/10G**	**±6/10G**
Bias Error [mG,σ]	(TBD)	15	5	**3**	**2**
BIS [μG]	100	100	70/50	**10**	**7**
VRW [m/s/√hr]	0.1	0.05	0.03/0.025	0.04	**0.03**
Noise[uG/√Hz]	200	100	60	70	**50**
BW [Hz]	50	200	200	**500**	**500**
Data output	16bit,< 1kSps	32bit,< 2kSps	32bit,< 2kSps	32bit,< 2kSps	32bit,< 2kSps
Attitude Output		(N/A)		**Tilt Angle (up to 200sps)**	
IF	**UART/SPI (20-pin connector)**				
PKG	**24x24x10mm**				
Temp. Operation [℃] Calibration [℃]	-40to+85 -20to+70	-40to+85 ↑	-40to+85 ↑	-40to+85 ↑	-40to+85 ↑
Power	3.3V, **16mA**	3.3V, 18mA	3.3V, 18mA	3.3V, 18mA	3.3V, 18mA

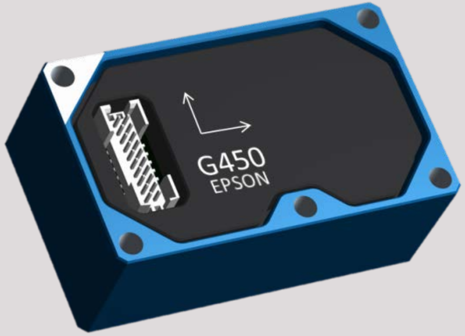
Increasing Performance
— G220 | G365 | G370
— G450

SECTION IV: NEW PRODUCTS

IMU

G450

	Units	**G450** (Draft)
Gyro (Range)	deg/sec	100 / 450
SF Error	%（σ）	0.05
Bias Error	deg/sec（σ）	0.1
Bias Instability	deg/hr	0.5
ARW	deg/√hr	0.03
Accel (Range)	g	3 / 6
SF Error	%（σ）	0.05
Bias Error	mG（σ）	2
Bias Instability	mG	0.01
VRW	m/sec/√hr	0.007
Output Data Rate	Hz(max)	1,000
Resolution	bits	16 / 32
Interface	-	SPI/UART
External Trigger Accuracy	μsec	100
Attitude Output Function	-	Quaternion / Euler
Cal Temp Range	Deg.C	-40 to 85
Power Supply	V / mA	3.3 /（TBD）
Size	㎜	(24 x 50 x 17)

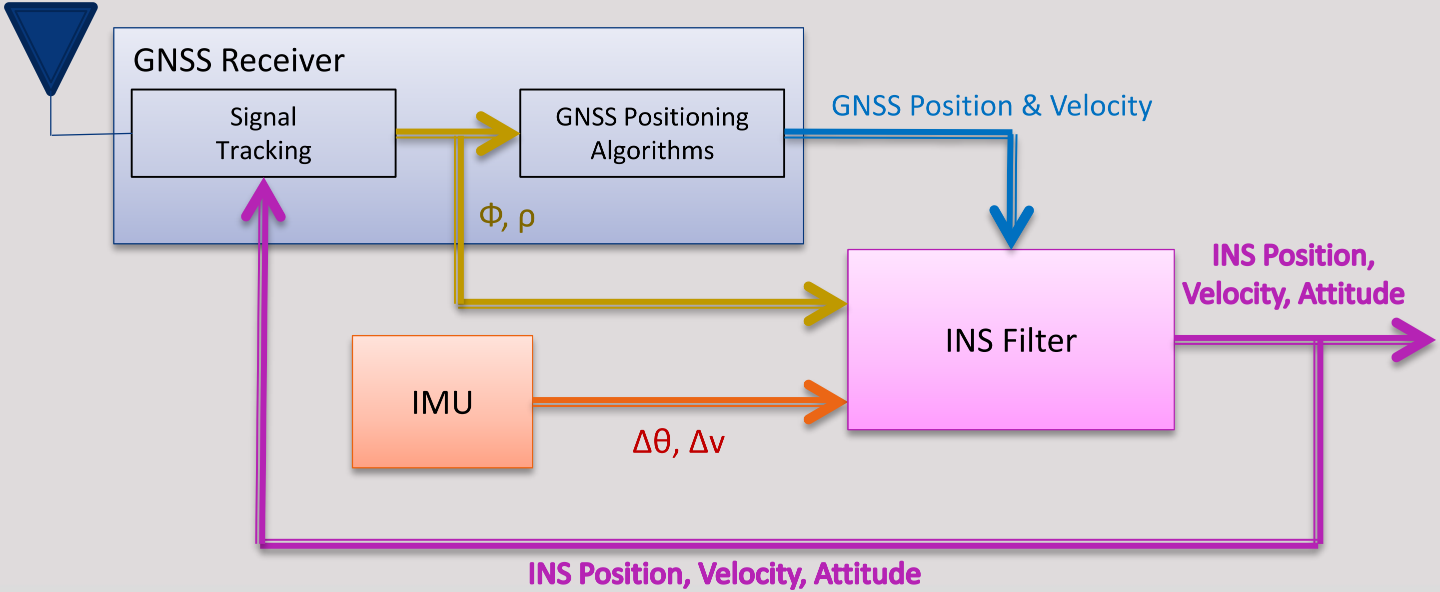


Performance Differentiation in a GNSS/INS Solution

Ryan Dixon
Chief Engineer, SPAN
NovAtel

SPAN

- NovAtel’s GNSS/INS product line
- SPAN = “Synchronized Position Attitude Navigation”
- Combining a range of IMU sensors with NovAtel GNSS receivers
- Deeply (Ultra-Tightly) coupled architecture



Sensor Integration History at NovAtel

2003 OEM4 & RLG / Quartz

2005 FOG/ Quartz

2008 OEMV & FOG / MEMS

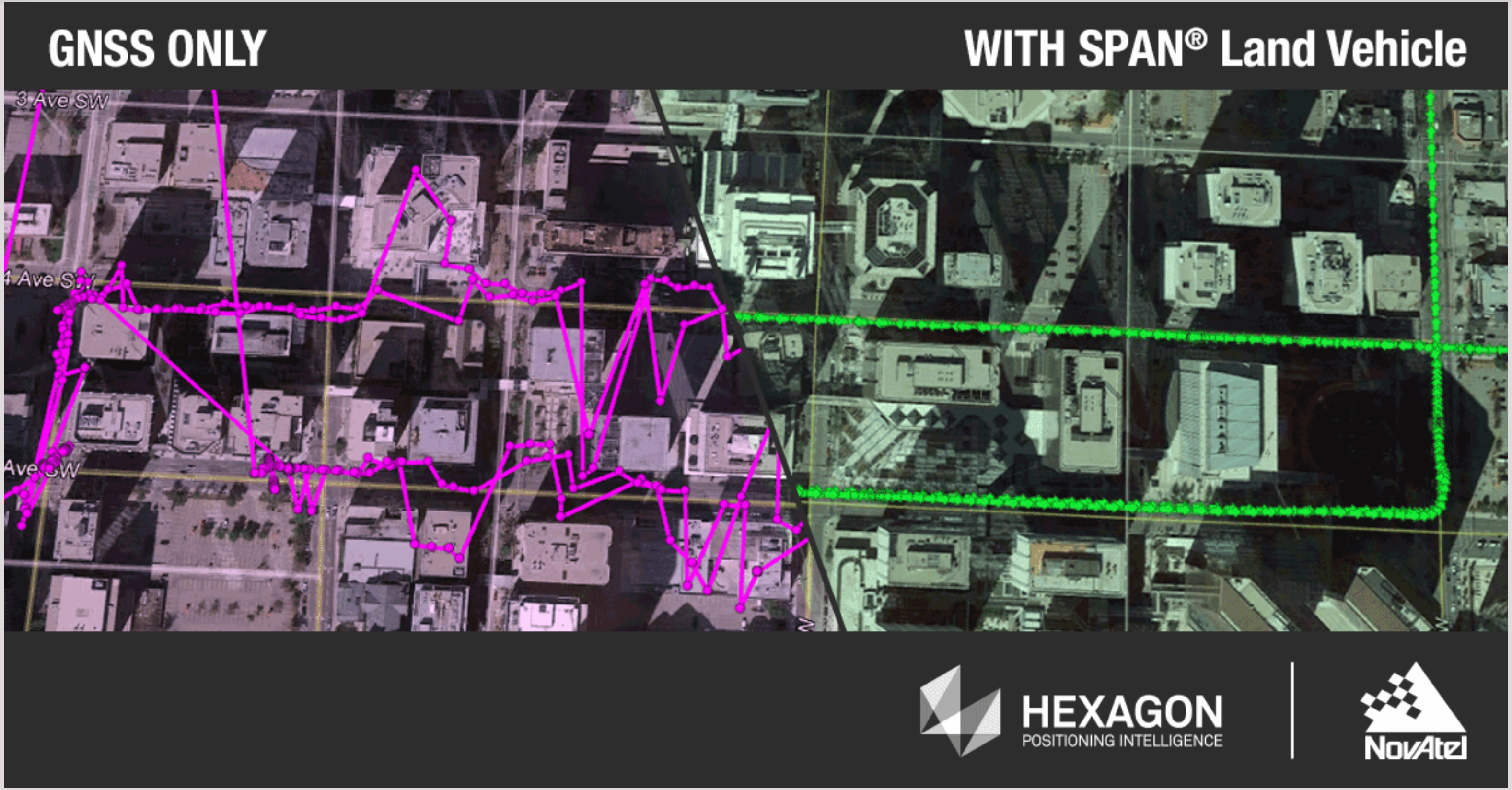
2012 OEM6 & MEMS

2016 OEM7 & MEMS

2017 Land Vehicle Tech

…

SPAN vs. GNSS in Urban Canyon

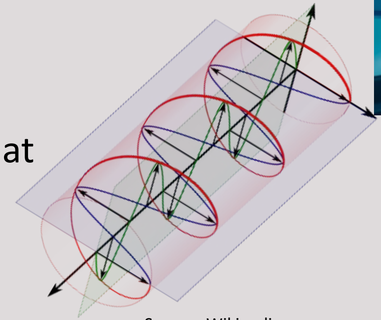


Land Vehicle Technology

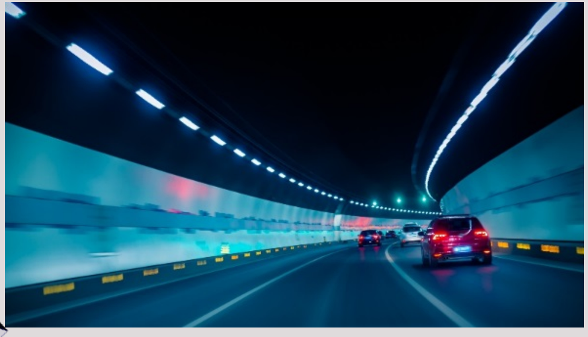
Designed to apply a variety of constraints to any fixed wheel land vehicle for a variety of applications

Land Vehicle Technology

- **Vehicle velocity constraints**
  - Non-holonomic constraints
  - Dead Reckoning
  - If you don't have GNSS
- **Phase wind-up relative attitude**
  - Relative azimuth update method looking at the circular polarization of GPS signals
  - Greatest improvements in low motion environments
- **Robust kinematic alignments**
  - Allow alignments as easily as possible. Do not force a specific alignment procedure
  - Automatically detect forward or backwards start



Source: Wikipedia



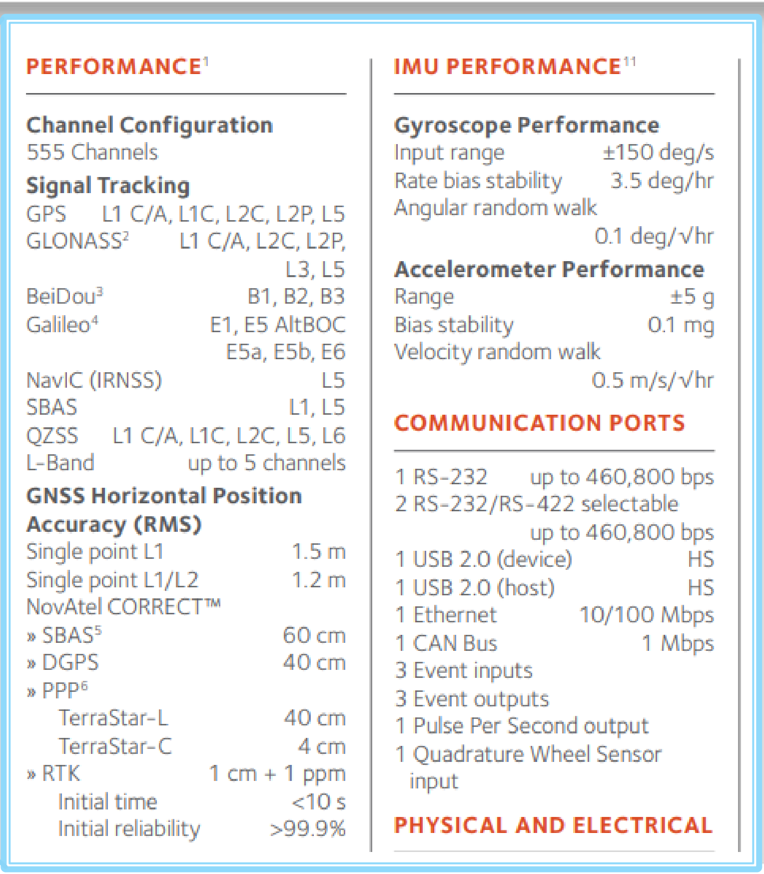
Test Data

Three test cases to examine:

- Urban Canyon
- Low Dynamics
- Extended GNSS Outage

Tests use GNSS and INS only. No aiding sensors used and only single antenna GNSS solution

Equipment Used – PwrPak7-E1



PERFORMANCE[1]

Channel Configuration

555 Channels

Signal Tracking

GPS	L1 C/A, L1C, L2C, L2P, L5
GLONASS[2]	L1 C/A, L2C, L2P, L3, L5
BeiDou[3]	B1, B2, B3
Galileo[4]	E1, E5 AltBOC E5a, E5b, E6
NavIC (IRNSS)	L5
SBAS	L1, L5
QZSS	L1 C/A, L1C, L2C, L5, L6
L-Band	up to 5 channels

GNSS Horizontal Position Accuracy (RMS)

Single point L1	1.5 m
Single point L1/L2	1.2 m
NovAtel CORRECT™	
» SBAS[5]	60 cm
» DGPS	40 cm
» PPP[6]	
TerraStar-L	40 cm
TerraStar-C	4 cm
» RTK	1 cm + 1 ppm
Initial time	<10 s
Initial reliability	>99.9%

IMU PERFORMANCE[11]

Gyroscope Performance

Input range	±150 deg/s
Rate bias stability	3.5 deg/hr
Angular random walk	0.1 deg/√hr

Accelerometer Performance

Range	±5 g
Bias stability	0.1 mg
Velocity random walk	0.5 m/s/√hr

COMMUNICATION PORTS

1 RS-232	up to 460,800 bps
2 RS-232/RS-422 selectable	up to 460,800 bps
1 USB 2.0 (device)	HS
1 USB 2.0 (host)	HS
1 Ethernet	10/100 Mbps
1 CAN Bus	1 Mbps
3 Event inputs	
3 Event outputs	
1 Pulse Per Second output	
1 Quadrature Wheel Sensor input	

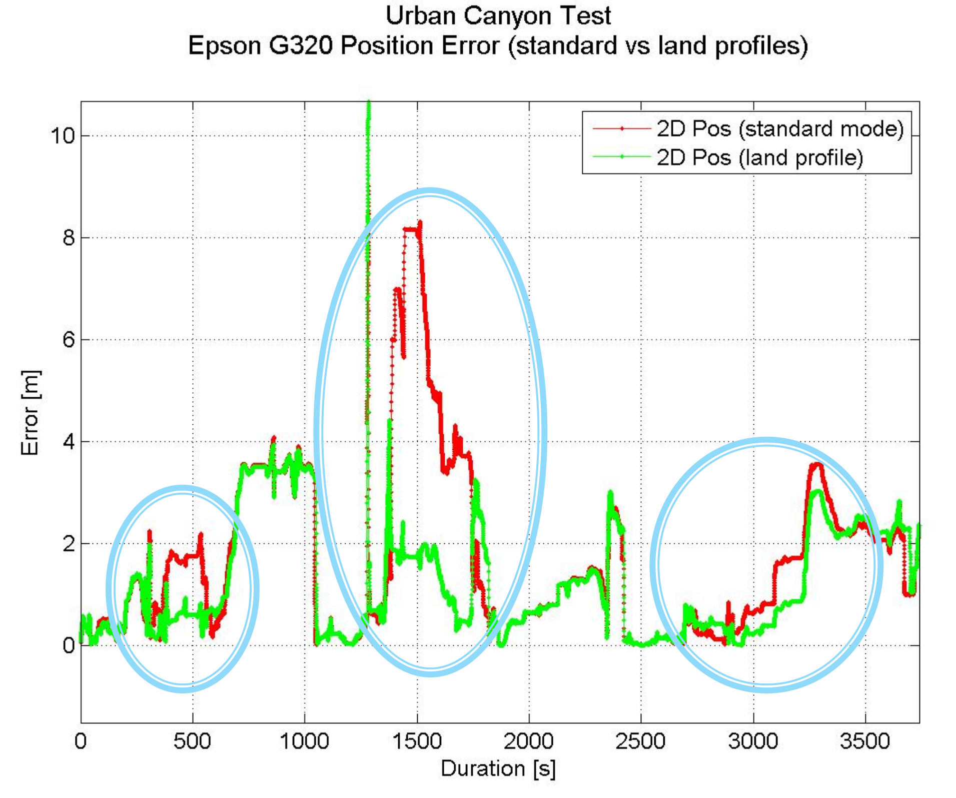
PHYSICAL AND ELECTRICAL

Test Case 1: Urban Canyon

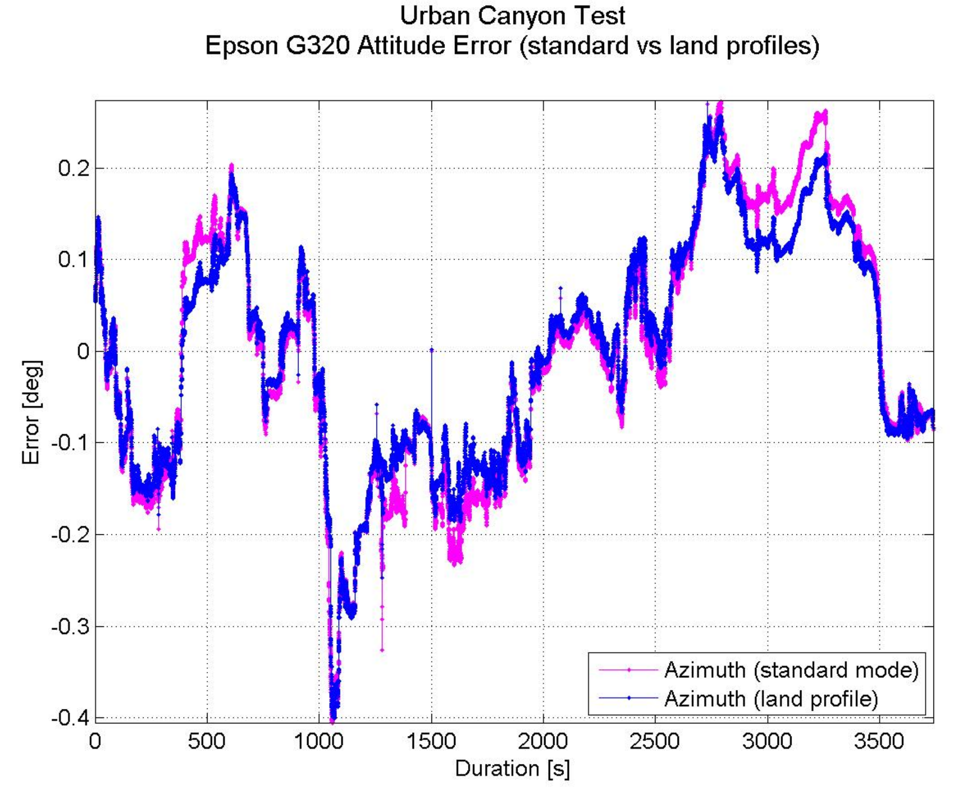
- Downtown Calgary, Canada
- Difficult GNSS conditions
- Benefits largely from SPAN tightly-coupled architecture; use of partial GNSS information
- SPAN Land Vehicle technology aids during the most difficult periods

Source: Google Earth

Urban Canyon Results: Horizontal Position

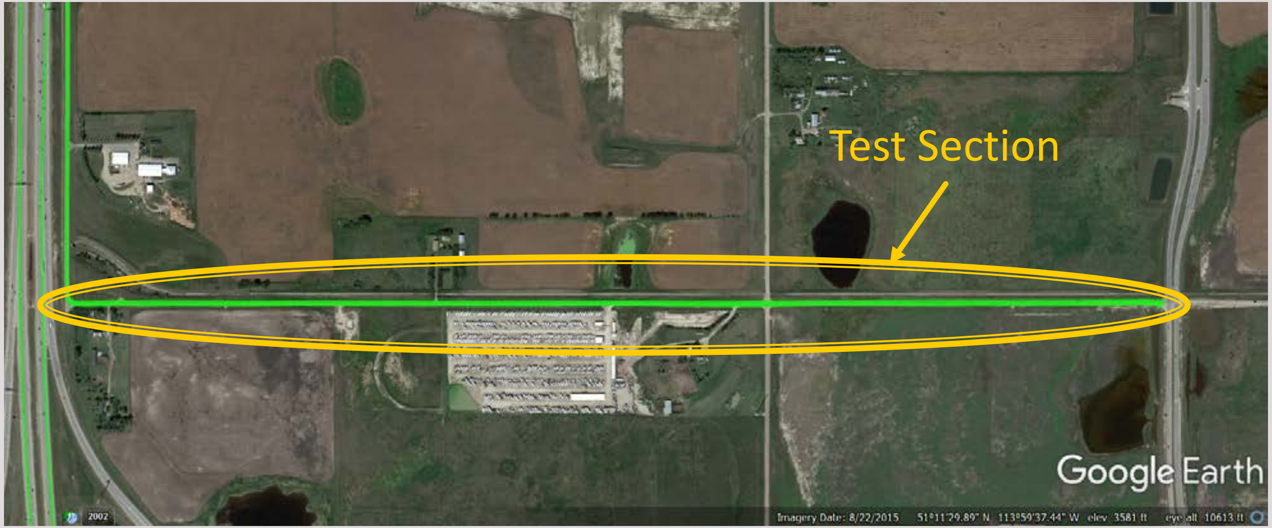


Urban Canyon Results: Azimuth



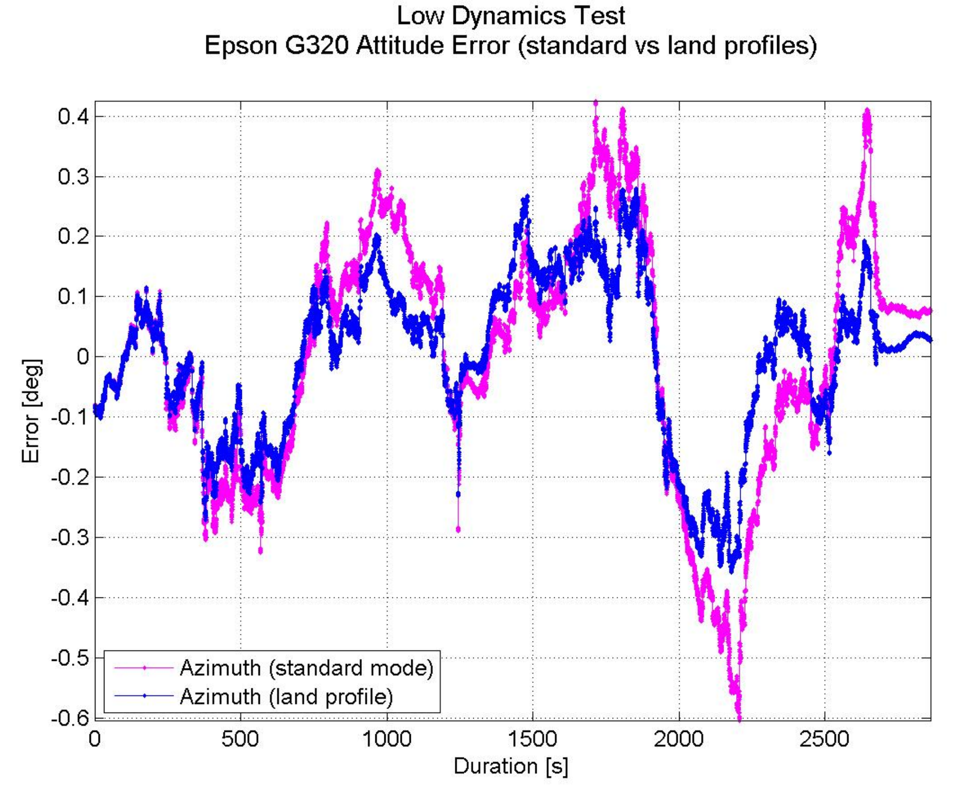
Test Case 2: Low Dynamics

- Vehicle moving straight on 2 Km rural road at 10-15 Km/h
- Ideal GNSS conditions
- Difficult INS conditions; limited observable motion
- Benefits from vehicle motion constraints and phase windup attitude updates



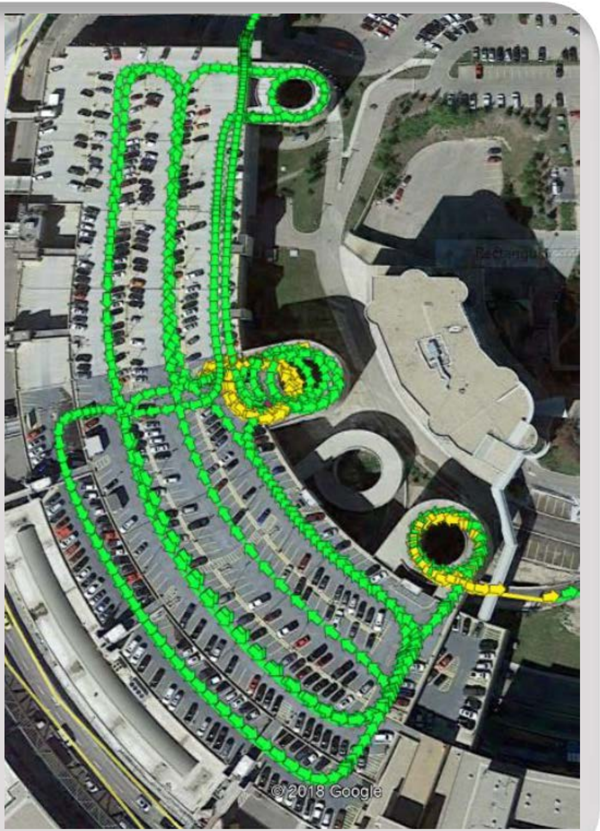
Source: Google Earth

Low Dynamics Results: Azimuth



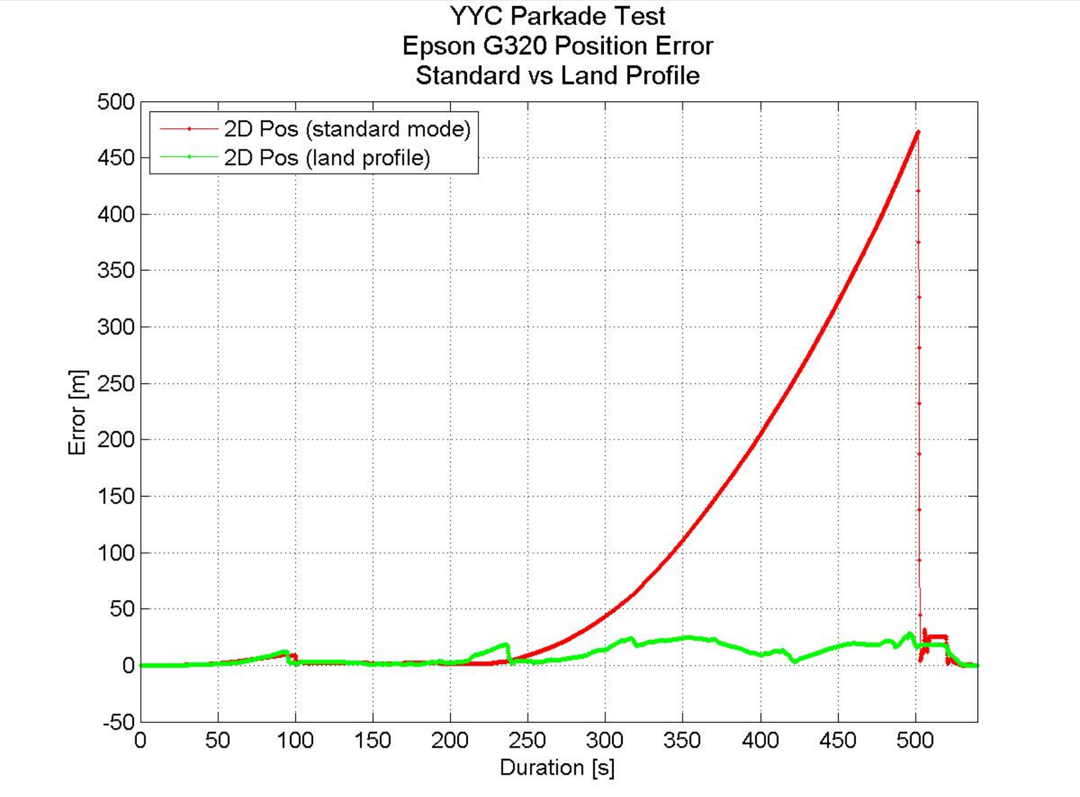
Test Case 3: Extended Outage

- Parking Garage – extended GNSS outage
- Relying on the propagated INS solution
- Performance driven by IMU and application of land vehicle constraints

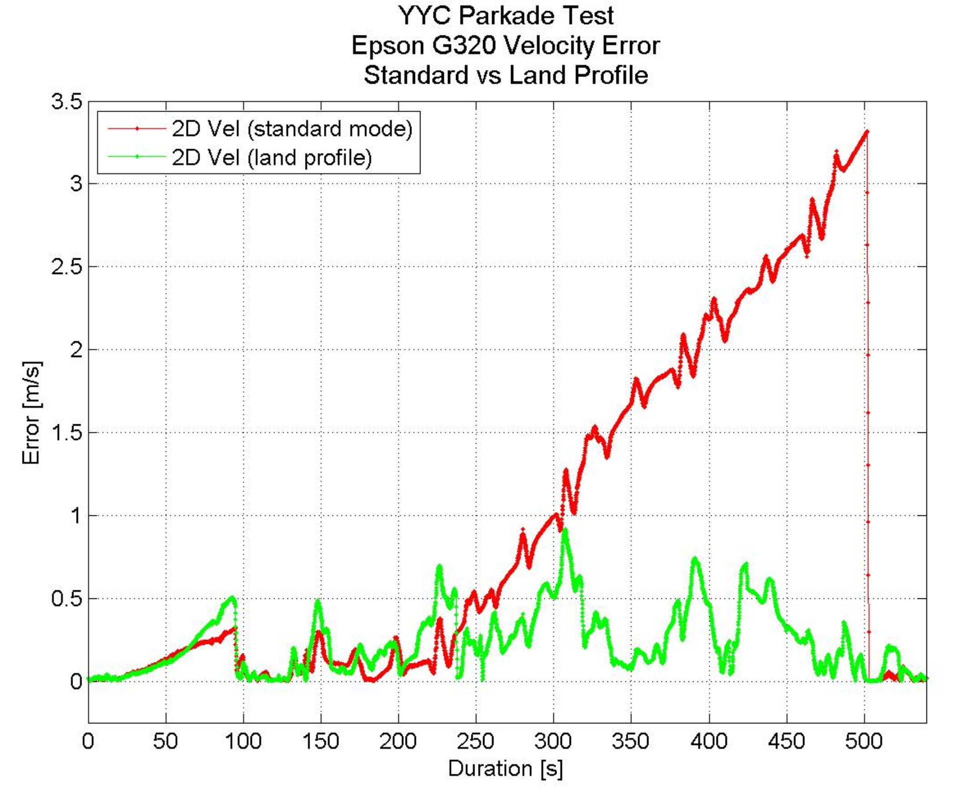


Source: Google Earth

Parking Garage Results: Horizontal Position



Parking Garage Results: Horizontal Velocity

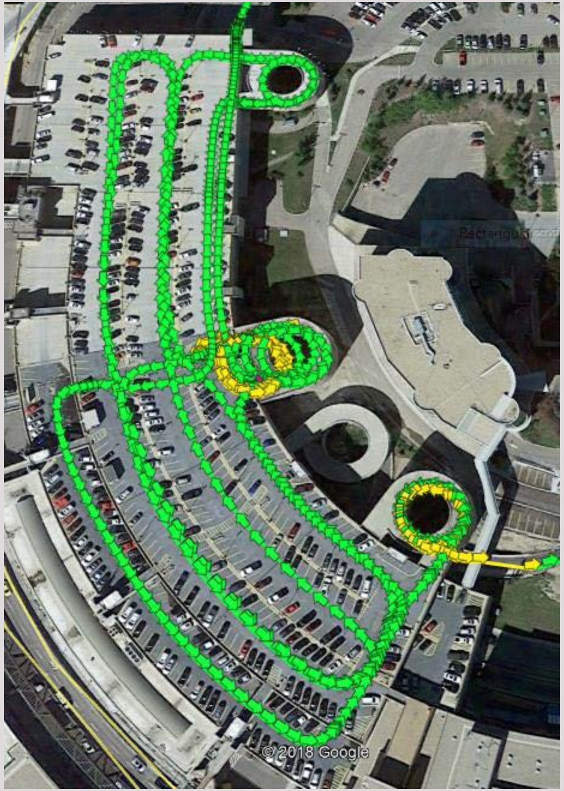


Parking Garage Results: Visual

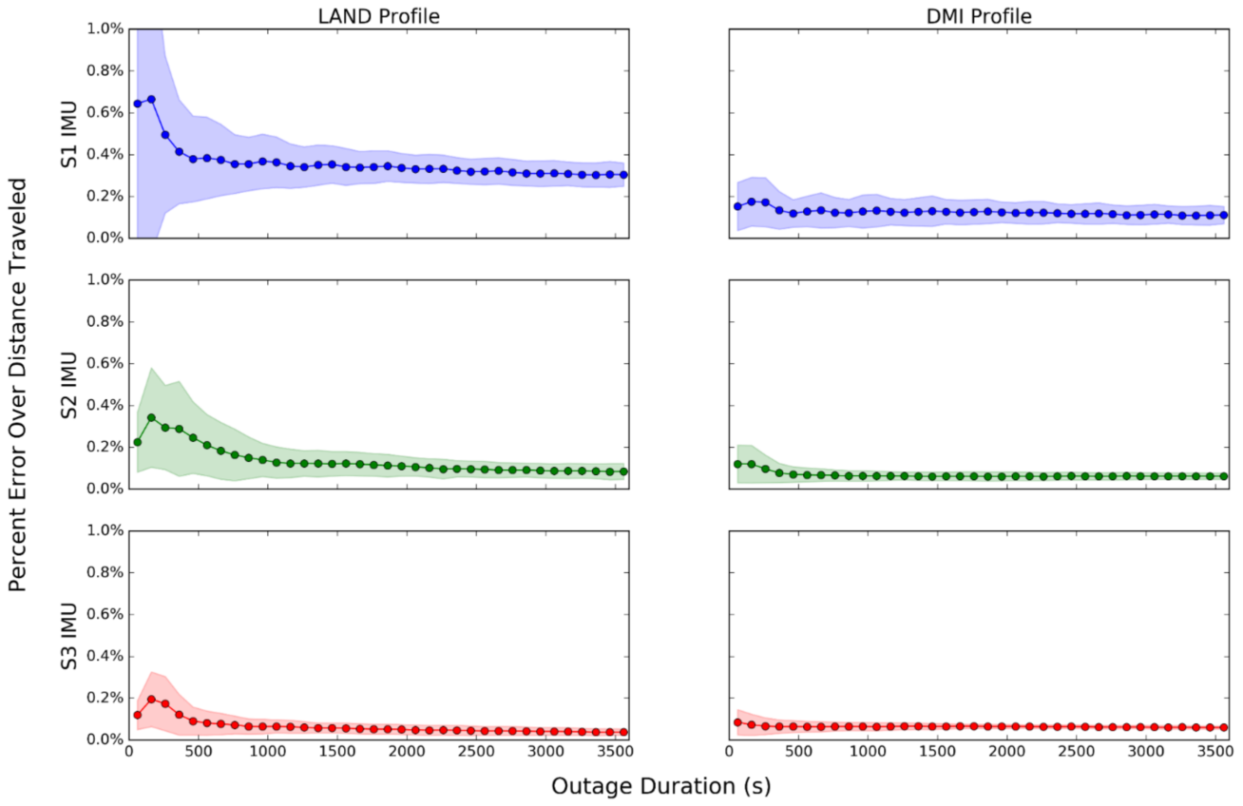
OEM6 SPAN

OEM7 Default SPAN

OEM7 with SPAN Land Vehicle



Error / Distance Travelled



Conclusions & Discussion

- Remarkable performance is now achievable with the latest MEMS IMUs but be informed
- IMU selection remains crucial
- INS algorithms differentiate performance
- System selection is very important
  - Know what the desired environment(s) are
  - Know the key performance metric(s)

Poll #3

In what harsh GNSS environments do you struggle to provide high accuracy positioning? (top three)

- *A. Urban canyons and/or foliage*
- *B. Jammed*
- *C. Spoofed*
- *D. Indoors*
- *E. Tunnels/Underground/Pipeline*

For More Information

SPAN Land Vehicle Performance Analysis Paper:
NovAtel's SPAN Land Vehicle Performance Analysis.

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