Cooperative Navigation in GNSS Degraded and Denied Environments (SET 275)

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The Performance Analysis of Tactical and Navigation Grade Land Inertial Navigation System Aided with Hypothetical Measurements

AGENDA

- Introduction & Motivation
- Algorithm Structure
- Simulation Study
- Experimental Study (Field Test)
- Conclusion

Introduction & Motivation

- Inertial Navigation System (INS) is one of the fundamental mean of Navigation.

  ➔ Unbounded positioning error in time due to time integration for Pure INS.

Class	Position performance	Gyro technology	Accelerometer technology	Gyro bias	Acc bias
Strategic grade	1 nmi / 24 h	ESG, RLG, FOG	Servo accelerometer	< 0.005°/h	< 30 µg
Navigation grade	1 nmi / h	RLG, FOG	Servo accelerometer, Vibrating beam	0.01°/h	50 µg
Tactical grade	> 10 nmi / h	RLG, FOG	Servo accelerometer, Vibrating beam, MEMS	1°/h	1 mg
AHRS	NA	MEMS, RLG, FOG, Coriolis	MEMS	1 - 10°/h	1 mg
Control system	NA	Coriolis	MEMS	10 - 1000°/h	10 mg

Different Grades of Inertial Sensors [Taken from EE 495 Modern Navigation Systems Lecture Series]

- Applications that require high accuracy, need to integrate INS with external Navigation aids.

Introduction & Motivation

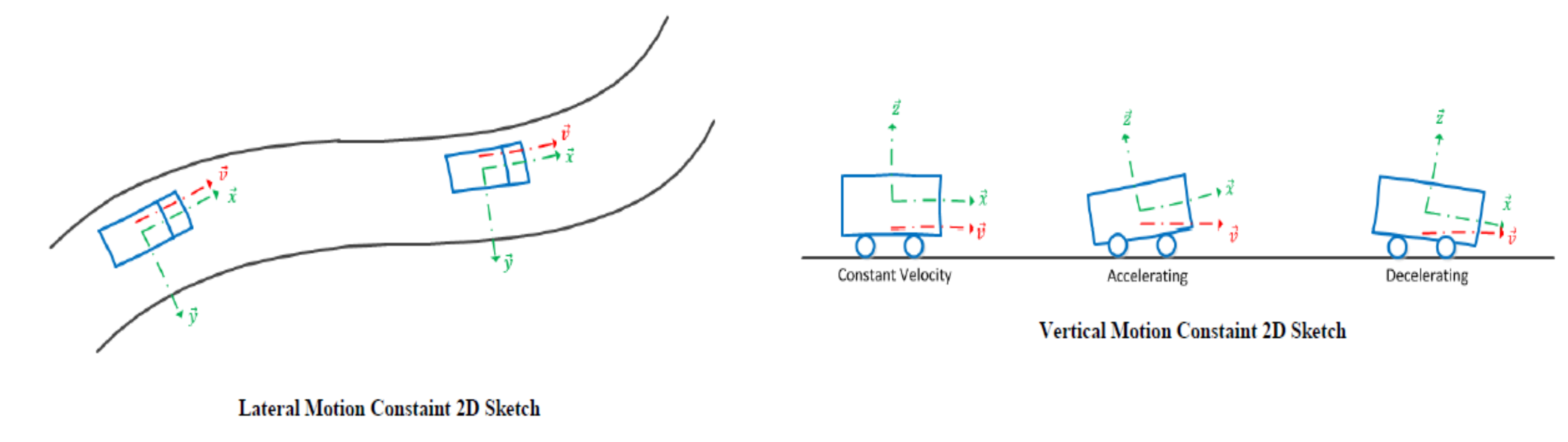
Hypothetical Measurements for Land Platforms:

- ZUPT (Zero Velocity Update)
- ZARUPT (Zero Angular Rate Update)

Valid in static condition!

- NHCs (Non-Holonomic Constraints)

Valid during the motion!



Motivation of the Study

- To analyse the performance gain that can be obtainable with hypothetical measurements for land vehicles that only have pure inertial navigation system.

Algorithm Structure

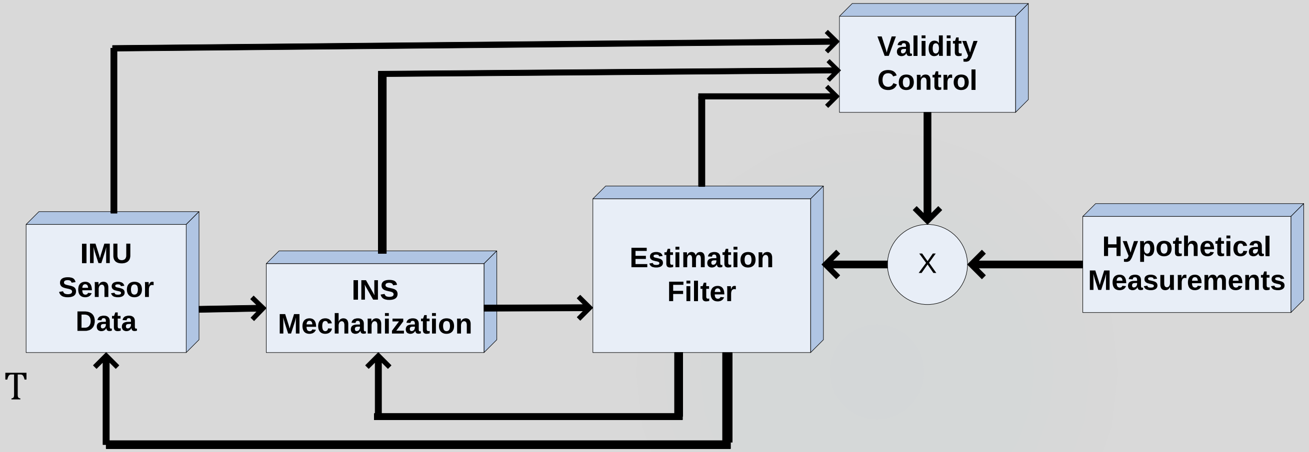
Extended Kalman Filter Structure

- Error state based

$$\delta\dot{x} = F\delta x + Gw$$

$$\delta z = H\delta x + \eta = z_{External} - z_{INS}$$

$$\delta x = \Big[\underbrace{\delta\bar{r}^{n\,T}_{b/e}}_{1x3}\ \underbrace{\delta\bar{v}^{n\,T}_{b/e}}_{1x3}\ \underbrace{\delta\bar{\psi}^{n\,T}_{b/n}}_{1x3}\ \underbrace{\bar{b}^{b\,T}_{a}}_{1x3}\ \underbrace{\bar{b}^{b\,T}_{g}}_{1x3}\ \underbrace{\delta\psi^{p\,T}_{b/p}}_{1x2}\ \underbrace{\delta\bar{r}^{p\,T}_{b/p}}_{1x3}\Big]^{T}_{1x20}$$



ZUPT Case: $z_{External} = \bar{v}^{n}_{b/n} + \bar{\eta}_{\bar{v}^{n}_{b/n}} \approx [0\ 0\ 0]^{T}$

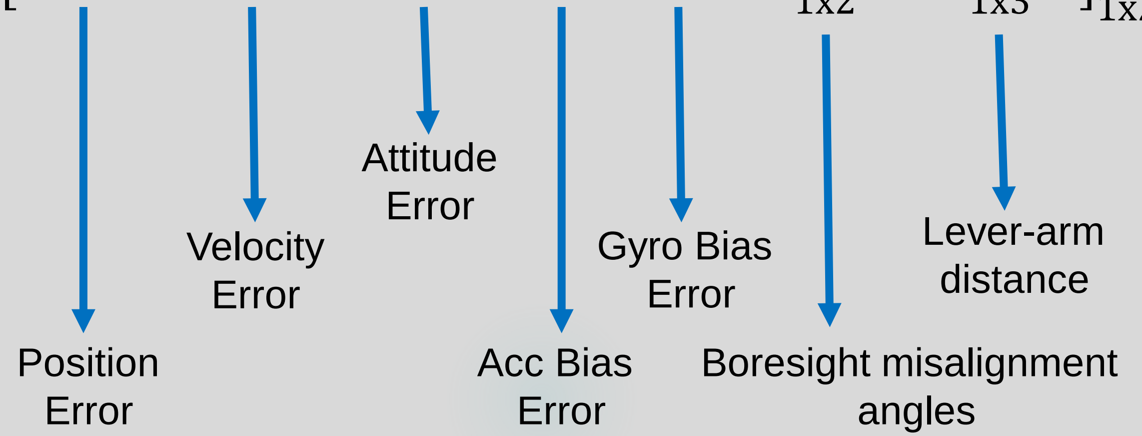
ZARUPT Case: $z_{External} = \bar{\omega}^{n}_{b/e} + \bar{\eta}_{\bar{\omega}^{n}_{b/e}} \approx [0\ 0\ 0]^{T}$

...

NHCs Case: $z_{External} = \bar{v}^{p}_{p/e}(2,3) + \eta_{\bar{v}^{p}_{p/e}(2,3)} = \begin{bmatrix} 0+\eta_{\bar{v}^{p}_{p/e}(2)} \\ 0+\eta_{\bar{v}^{p}_{p/e}(3)} \end{bmatrix}$

Algorithm Functional Flow-Chart

$$\delta x = \Big[\underbrace{\delta\bar{r}^{n\,T}_{b/e}}_{1x3}\ \underbrace{\delta\bar{v}^{n\,T}_{b/e}}_{1x3}\ \underbrace{\delta\bar{\psi}^{n\,T}_{b/n}}_{1x3}\ \underbrace{\bar{b}^{b\,T}_{a}}_{1x3}\ \underbrace{\bar{b}^{b\,T}_{g}}_{1x3}\ \underbrace{\delta\psi^{p\,T}_{b/p}}_{1x2}\ \underbrace{\delta\bar{r}^{p\,T}_{b/p}}_{1x3}\Big]^{T}_{1x20}$$



Algorithm Structure

Robust Estimator

A. Measurement Validity Control

B. Adaptive Innovation Filtering

(M-estimator based adaptive Kalman gain control)

<u>Measurement Validity Control</u>

- Hypothetical measurements must comply with the actual physical condition.
- ZUPT & ZARUPT require static condition.

  Stationarity Detection Methods:

  - Gyroscope Based ➔ Superior against abrupt motion changes and low speed motion
  - INS Speed Based ➔ Superior against medium-high speed motion
  - Navigation Frame Acceleration Based ➔ Superior against abrupt motion changes

- NHCs needs to be applied during low dynamic maneuvers.

Simulation Study

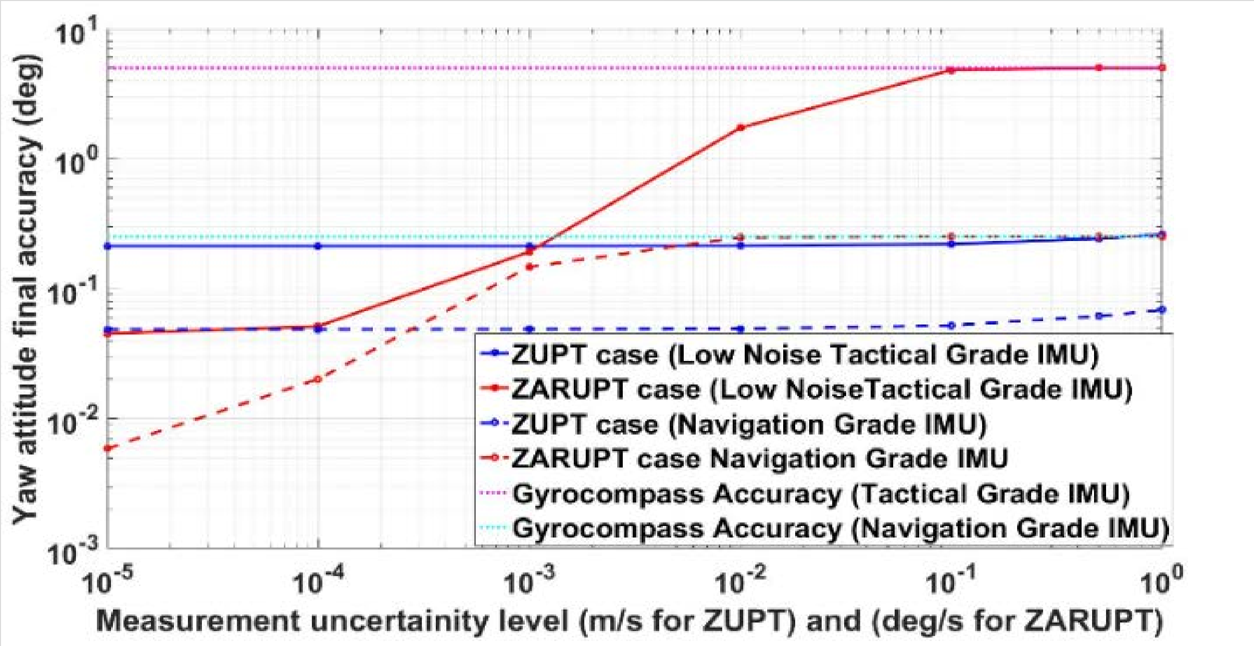
- Composed of covariance and Monte-Carlo analysis

A. Azimuth Accuracy Analysis

- Target : Analysing the performance gain with ZUPT and/or ZARUPT aiding.
- INS Attitude initialization is assumed to be done with gyrocompassing technique.

$$\sigma^2_{gyrocompass}(rad) = \sigma^2_{acc\_bias}(g) + \frac{\sigma^2_{gyro\_bias}(°/hr)}{\left|\Omega_{e/i}(°/hr)\right| \cos^2(L_b)}$$

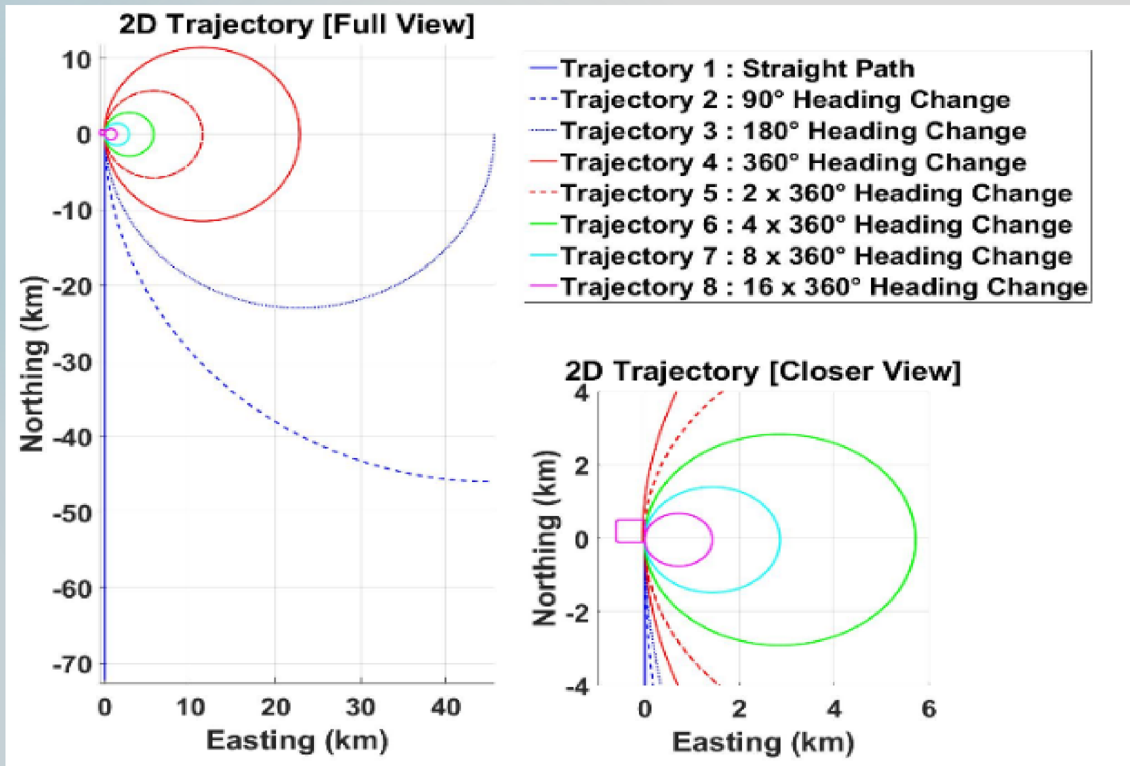
- Simple rotation around vertical axis is assumed to reduce the gyro bias effect.

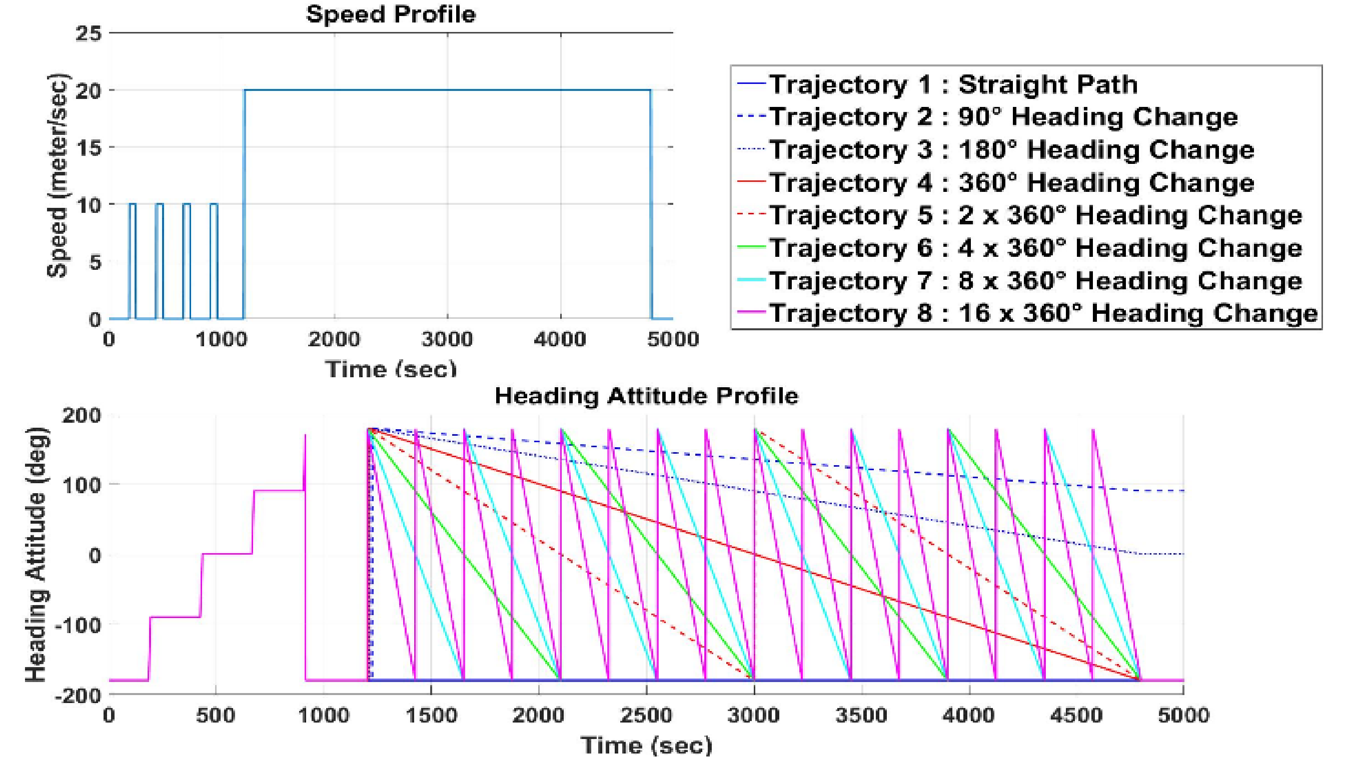


Simulation Study

B. Horizontal Positioning Accuracy Analysis

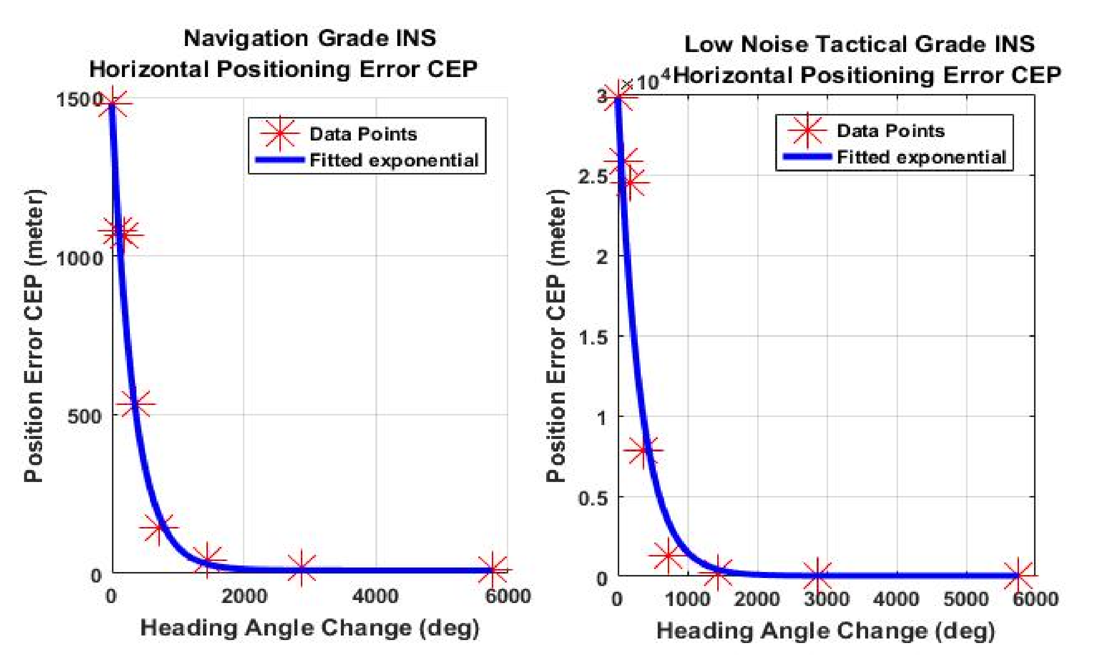
- Monte-Carlo analysis with 200 simulation run.
- Low Noise Tactical and Navigation Grade IMUs are assumed.
- Simulated trajectory: Pre-Calibration Phase + 1 Hour Constant Speed Cruise Mission





Simulation Study

Trajectory ID	Horizontal Positioning Error CEP (1 hour mission)	
	Low Noise Tactical Grade IMU	Navigation Grade IMU
Trajectory 1	29720 meter (41.28% DT)	1478 meter (2.06% DT)
Trajectory 2	25864 meter (35.92% DT)	1078 meter (1.50% DT)
Trajectory 3	25453 meter (35.35% DT)	1062 meter (1.48% DT)
Trajectory 4	7845 meter (10.90% DT)	534 meter (0.74% DT)
Trajectory 5	1339 meter (1.86% DT)	144 meter (0.20% DT)
Trajectory 6	257 meter (0.36% DT)	39 meter (0.05% DT)
Trajectory 7	96 meter (0.13% DT)	16 meter (0.02% DT)
Trajectory 8	43 meter (0.06% DT)	10 meter (0.01% DT)



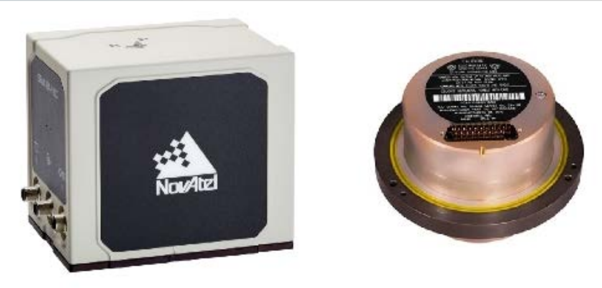
Exponential shape performance correlation

$$\delta p(\Delta\psi)=a_0+a_1 exp(a_2\Delta\psi)$$

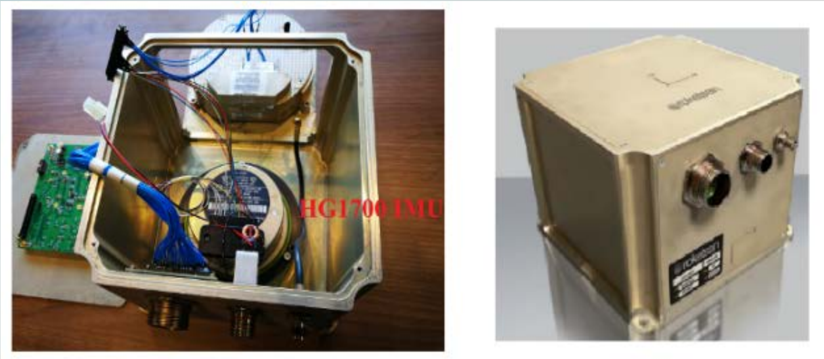
Constants	Low Noise Tactical Grade IMU	Navigation Grade IMU
a_0	43 meter	10 meter
a_1	29677 meter	1468 meter
a_2	-0.003 deg $^{-1}$	-0.003 deg $^{-1}$

Experimental Study

- Experimental study is in the form of field test
  - Honeywell HG1700 and Northrop Grumman Litef ISA-100C IMUs
  - Novatel SPAN (ISA-100C + Propak 6 GNSS Receiver) for reference Navigation data



ISA-100C & HG1700 IMUs



Roketsan Albatros INS/GNSS System

View from the Instrumented Land Vehicle

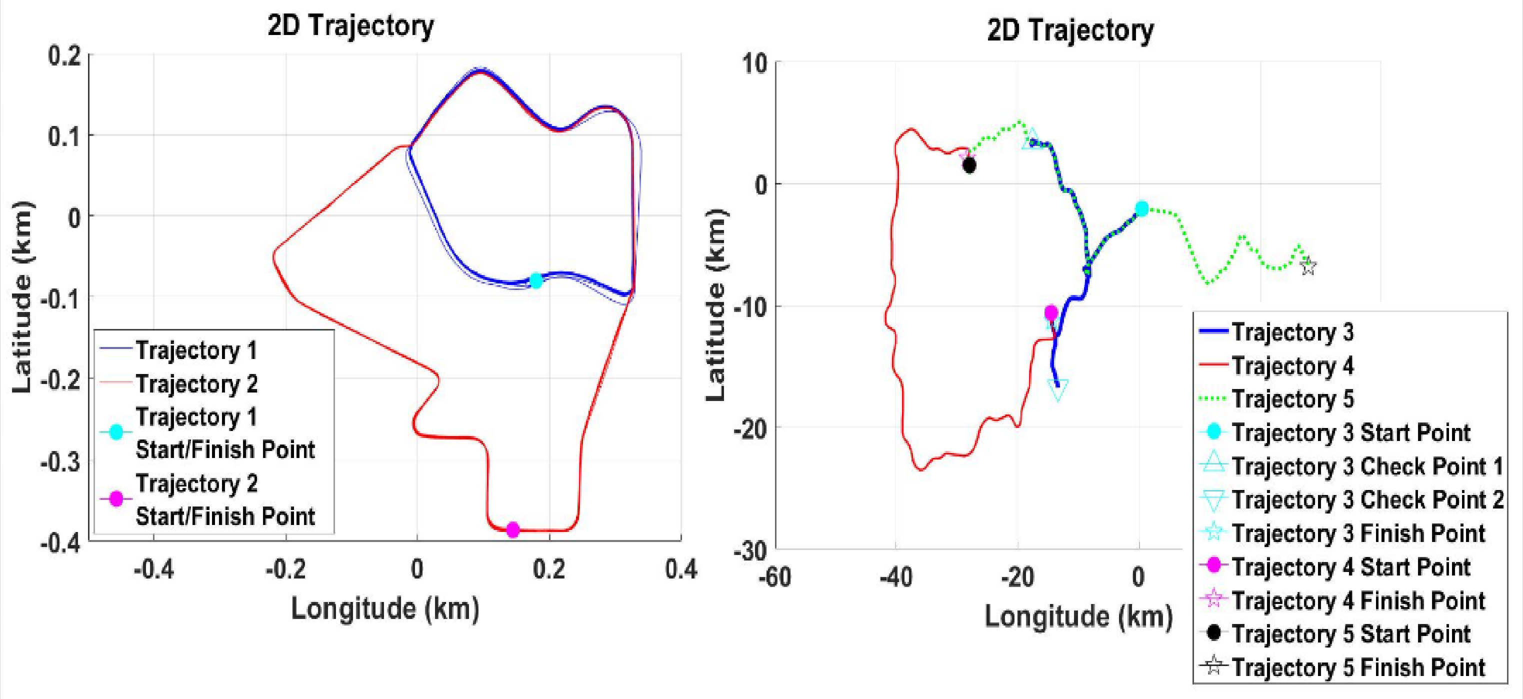
Experimental Study

Horizontal Positioning Test (Navigation Survey Test)

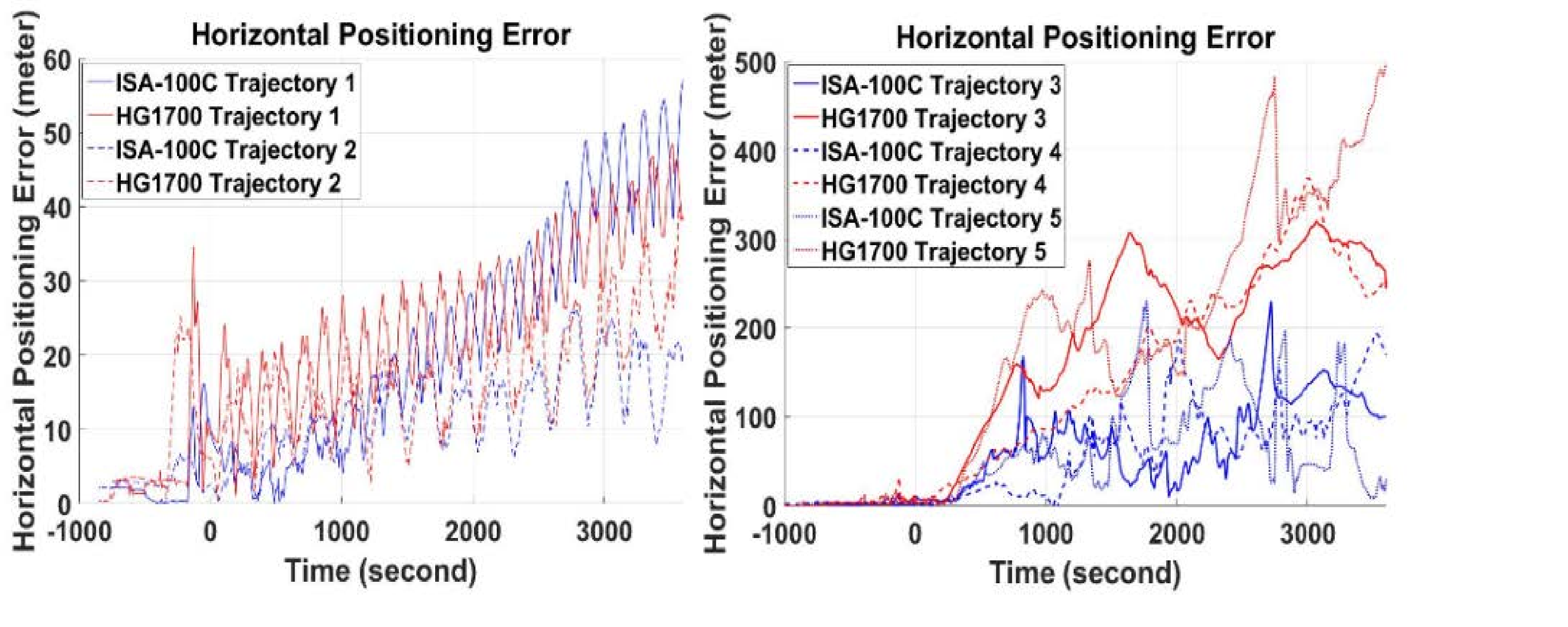
- Five distinct field tests are carried out.

Test Plan:

INS Initialization with Gyrocompass feature + Precalibration + 1 Hour Cruise without any stop



Experimental Study



		Field Test No*				
		No1	**No2**	**No3**	**No4**	**No5**
	Travelled Distance (DT)	23.8 km	23.3 km	60.8 km	66.7 km	69.8 km
	Spanned total heading angle	15650°	15865°	4448°	2707°	3020°
IMU ISA-100C	**Horizontal positioning error** (1 hour) [% DT]**	52.5 m (%0.22 DT)	21.7 m (%0.09 DT)	100.1 m (%0.16 DT)	29.5 m (%0.04 DT)	169.4 m (%0.24 DT)
IMU HG 1700	**Horizontal positioning error** (1 hour)**	41.9 m (%0.18 DT)	39.0 m (%0.17 DT)	245.5 m (%0.40 DT)	251.0 m (%0.38 DT)	496.8 m (%0.71 DT)

* Test numbers are compatible with the trajectory numbers. For instance, no1 represents the first trajectory.

** Horizontal positioning error is the final error value taken at the end of 1 hour operation where inertial navigation system is only aided with NHCs measurements

Conclusion

- This paper targets the attainable performance gain of the pure INS aided via hypothetical measurements for Land Vehicle Navigation.
- ZUPT & ZARUPT aidings are both effective for azimuth angle refinement if the azimuth motion is introduced.
- Simulations ➔ The horizontal positioning accuracy is correlated with the spanned heading angles
- Field Tests verify that ➔ 0.25% DT horizontal positioning accuracy with ISA-100C IMU
  0.75% DT horizontal positioning accuracy with HG1700 IMU
- NHCs measurement is very effective as long as the vehicle does not follow near straight line type trajectory.

THANK YOU