Realization of an Adaptive Hybrid Low-cost GPS/INS Integrated Navigation System with Switched Position-Domain and Range-Domain Filtering Strategy

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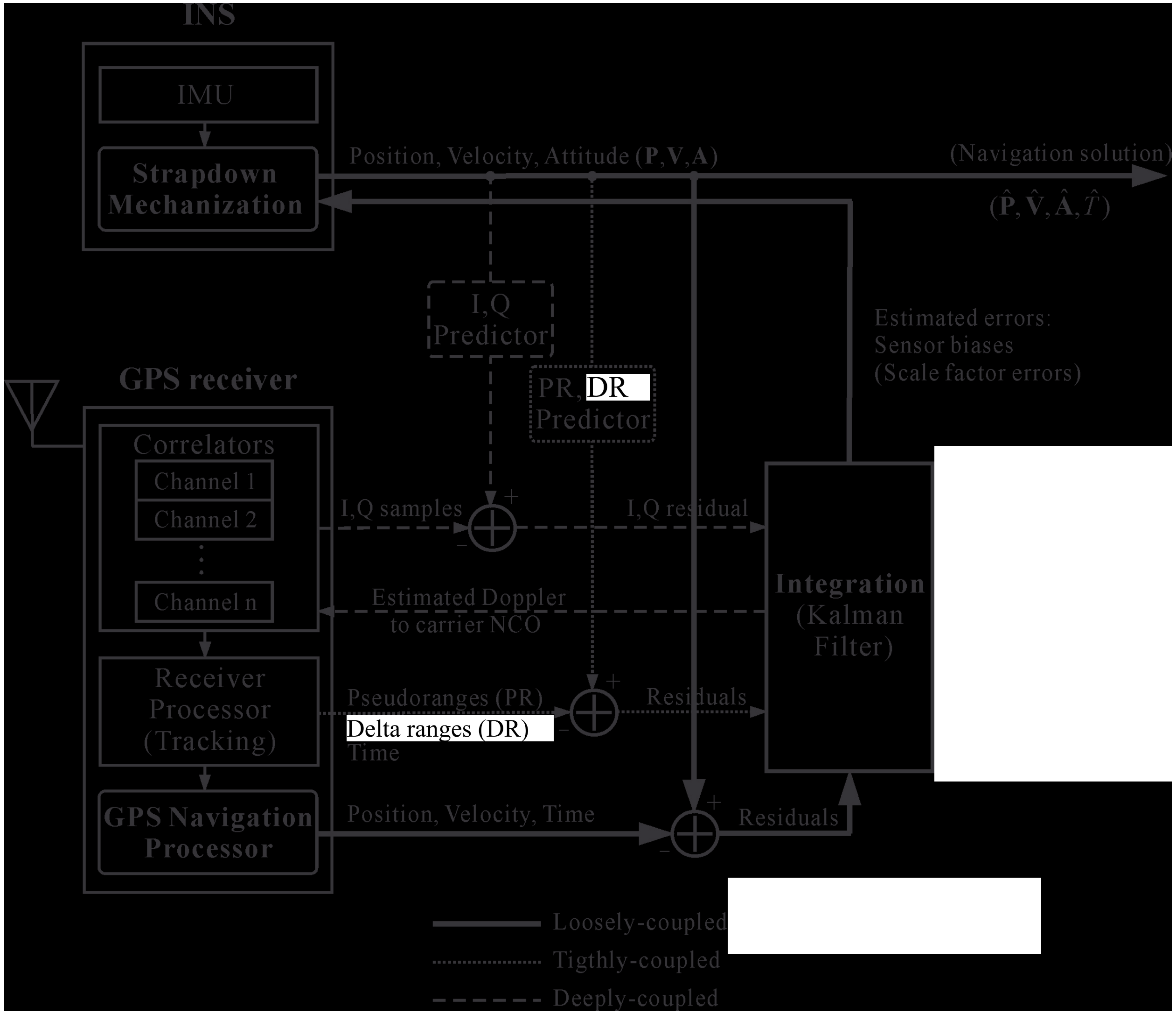
On GPS/INS integration strategies



GPS/INS indirect feedback integration architectures

On GPS/INS integration strategies

- **Loosely-coupled GPS/INS integration**
  - A decentralized estimation architecture with independent and redundant solutions from INS and GPS.
  - At least 4 satellites have to be in view to obtain an update from the GPS based measurement .
  - In case of one KF in the GPS receiver, one KF for Integration (cascaded filtering), the system may have accuracy and stability problem.
- **Tightly-coupled GPS/INS integration**
  - INS estimates are corrected by GPS when less than 4 satellites in view.
  - More complex integration KF state space and observation models.
- **Deeply-coupled GPS/INS integration**
  - INS aiding of GPS
    - GPS tracking loops bandwidth reduction
    - improved accuracy, robustness (anti-jamming)
    - faster acquisition and tracking
  - Access to the tracking loops is required.

On GPS/INS integration strategies

- **Various ways to integrate GPS and INS.**

- **What is a good design of the GPS/INS integration architecture ?**

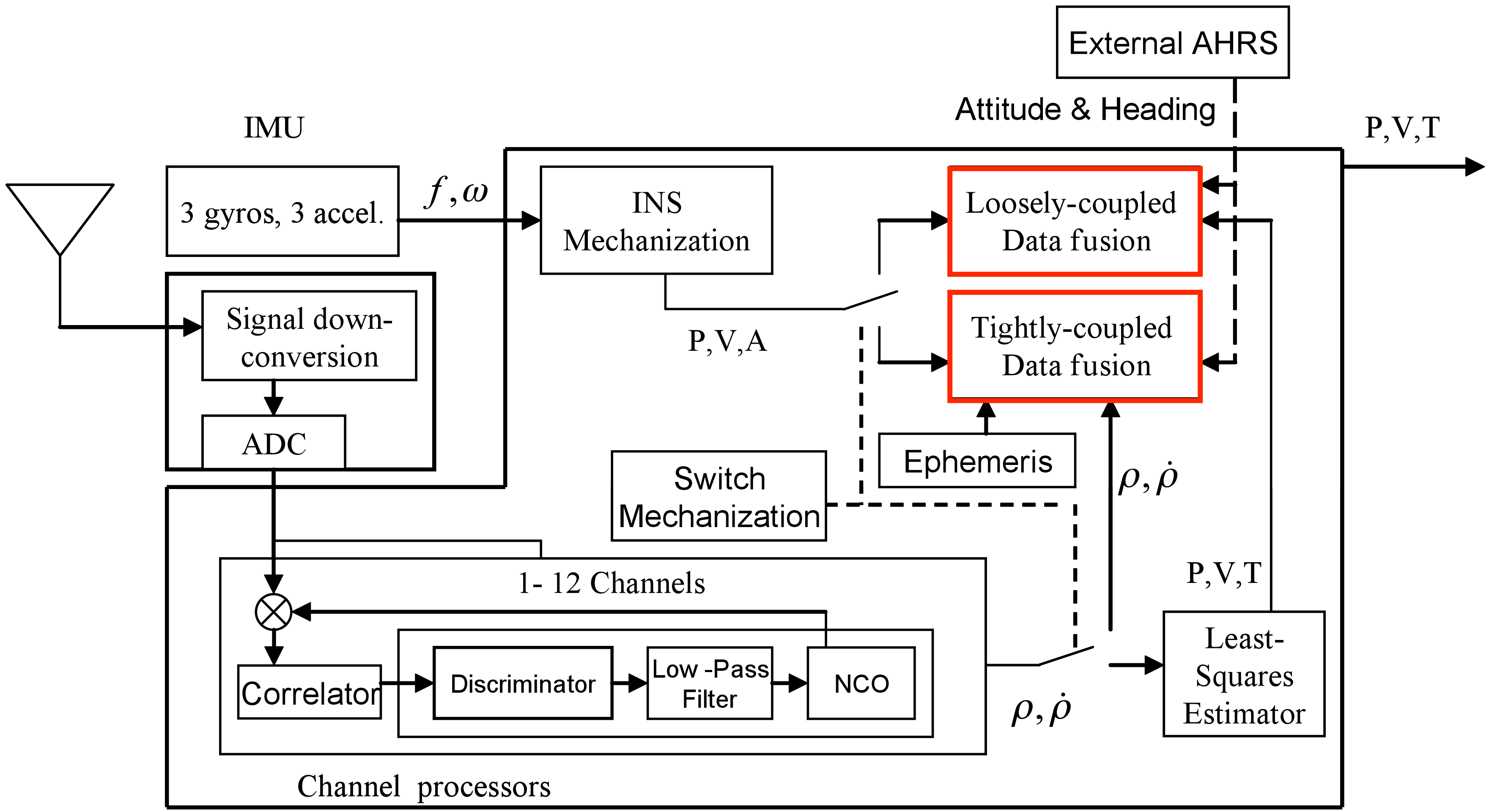
After the book: "Principle of GNSS, Inertial, and Multisensor Integrated Navigation Systems" from Dr. Paul D. Groves.

- **Maximizing the accuracy and robustness of the navigation solution**
- **Minimizing the system complexity**
- **Optimizing the processing efficiency**

Proposal for adaptive hybrid GPS/INS Integration system

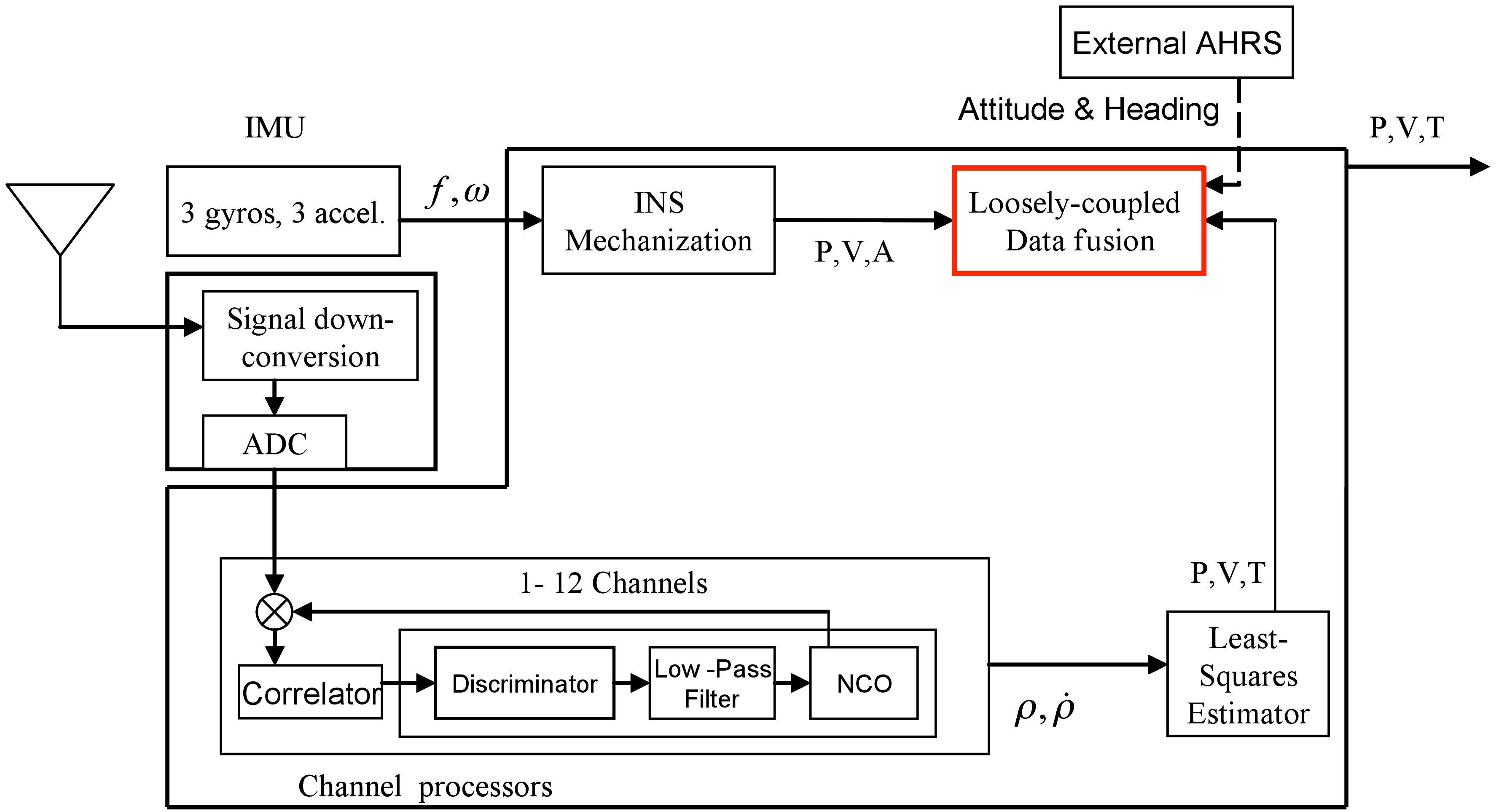
- **A system with two working modes can be a solution**
  - **Default mode (in good signal condition)**
    - **loosely-coupled integration architecture**
  - **Enhanced mode (in bad signal condition)**
    - **Tightly-coupled integration architecture**
- **Switching mechanization**
  - **A switching mechanization (based on the number of tracked satellites)**

Proposal for an adaptive hybrid GPS/INS integration system



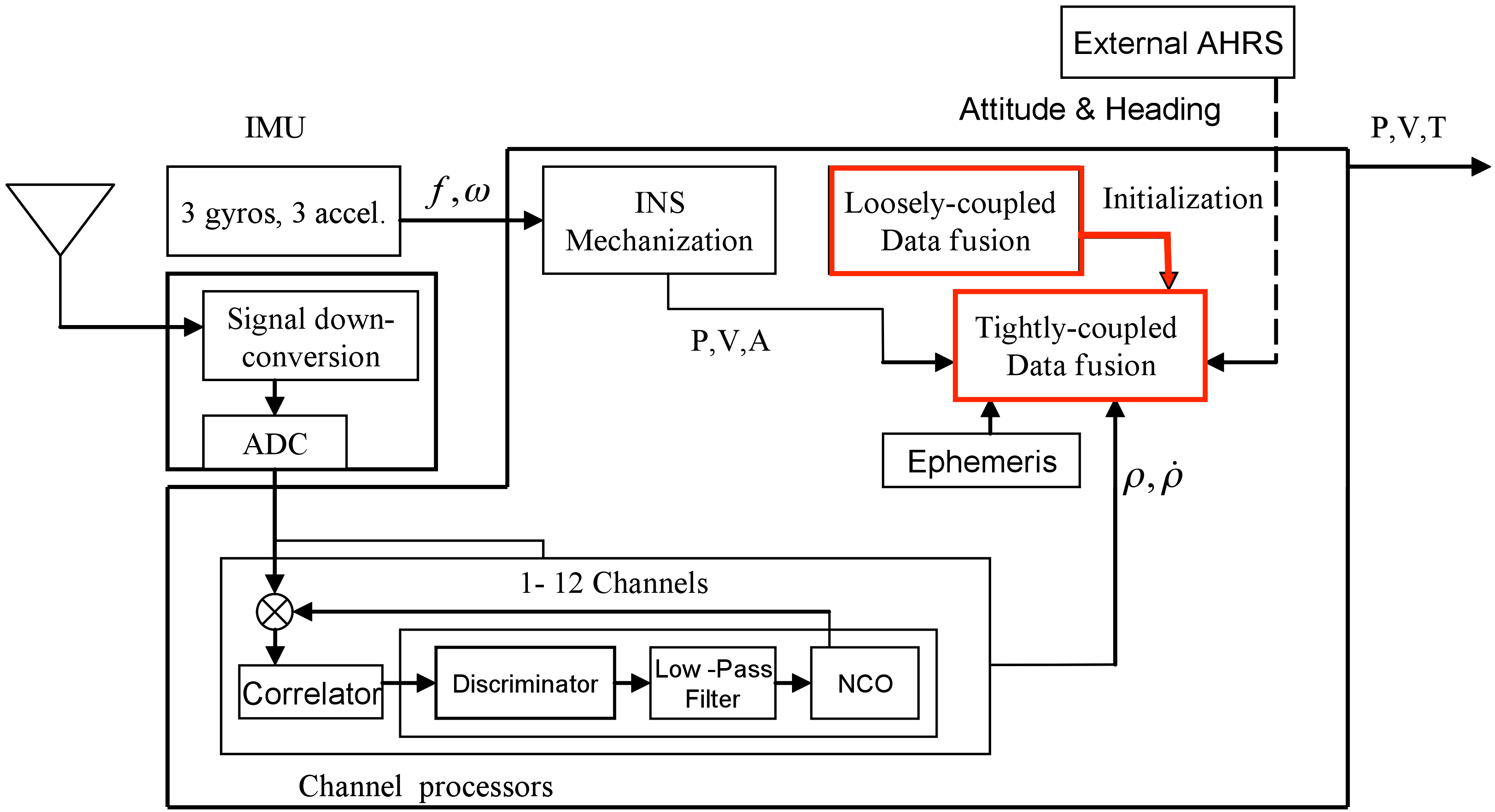
System Architecture

Proposal for an adaptive hybrid GPS/INS integration system



Default Mode

Proposal for an adaptive hybrid GPS/INS integration system



Enhanced Mode

System model

Low-cost gyroscopes can not sense Earth's rotation , and Transport rate and Coriolis terms can be neglected in the strapdown processing and in the system model for the integration Kalman filter.

➔ A simplified *n*-frame error state system model is

$$
\begin{array}{r}
\text{position error} \\ \text{velocity error} \\ \text{attitude error} \\ \text{accelerometer bias} \\ \text{gyro bias} \\ \text{clock error} \\ \\
\end{array}
\underbrace{\begin{bmatrix} \Delta\dot{\mathbf{x}} \\ \Delta\dot{\mathbf{v}} \\ \Delta\dot{\boldsymbol{\psi}} \\ \Delta\dot{\mathbf{b}}_a \\ \Delta\dot{\mathbf{b}}_\omega \\ c\Delta\dot{t}_r \\ c\Delta\ddot{t}_r \end{bmatrix}}_{\Delta\mathbf{x}_c}
=
\underbrace{\begin{bmatrix}
O & I & O & O & O & 0 & 0 \\
O & O & F_{23} & R_b^n & O & 0 & 0 \\
O & O & O & O & -R_b^n & 0 & 0 \\
O & O & O & O & O & 0 & 0 \\
O & O & O & O & O & 0 & 0 \\
O & O & O & O & O & 0 & 1 \\
O & O & O & O & O & 0 & 0
\end{bmatrix}}_{F}
\cdot
\begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{v} \\ \Delta\boldsymbol{\psi} \\ \Delta\mathbf{b}_a \\ \Delta\mathbf{b}_\omega \\ c\Delta t_r \\ c\Delta\dot{t}_r \end{bmatrix}
+ \mathbf{w}
$$

with

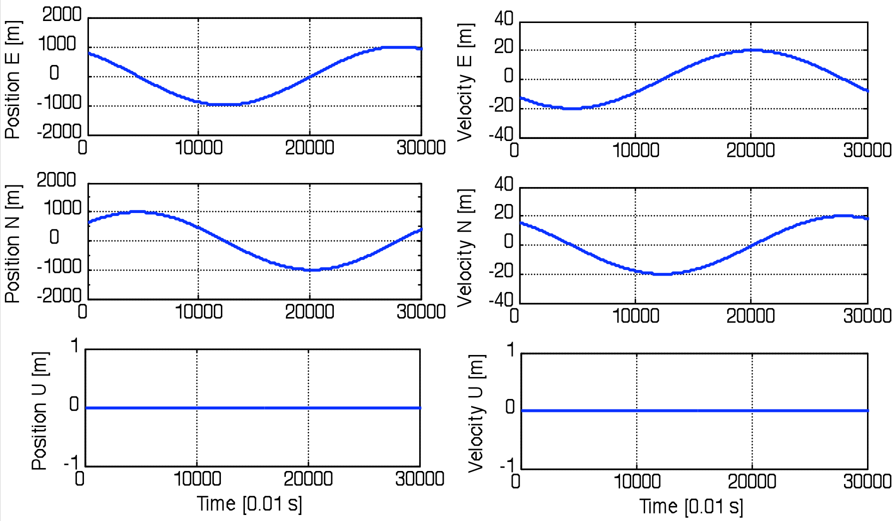
$$
F_{23} = \begin{bmatrix} 0 & -a_{ib,d}^n & a_{ib,e}^n \\ a_{ib,d}^n & 0 & -a_{ib,n}^n \\ -a_{ib,e}^n & a_{ib,n}^n & 0 \end{bmatrix}
$$

The discrete-time analogue is expressed as $\boldsymbol{\xi}(k+1)=A(k)\boldsymbol{\xi}(k)$ with

$$
A(k) = \phi((k+1)T, kT) = \phi(T) = e^{F((k+1)T-kT)} = e^{(FT)}
$$

$$
= \mathcal{L}^{-1}\left\{[sI-F]^{-1}\right\}\Big|_{t=T} = I + F\cdot T + \frac{(F\cdot T)^2}{2} + \text{h.o.t.}
$$

Experiment setup



Trajectory simulated from IFEN RF signal simulator

Gyroscope (Angular rates)	
Bias instability [°/h]	360
Scale factor [ppm]	10000
Noise (ARW) [°/√h]	3
Accelerometer (specific forces)	
Bias instability [μg]	2400
Scale factor [ppm]	10000
Noise (VRW) [μg/√Hz]	1000

Typical error of a low-cost MEMS IMU

Trajectory	
Nominal Velocity	20 m/s
Circle Center Position (LLH)	$\mathbf{x}^{LLH} = [51°\text{N} \quad 8°\text{E} \quad 360\text{m}]^T$
Circle Radius	1000 m
Start Time (UTC)	October 29, 2006, 00:11:27
Duration	300 s
GPS measurements	
Measurement rate	5 Hz
Positioning method	Single-point positioning
Error modeling	Tropospheric and ionospheric delays are estimated and corrected for.
Satellites in view	9 (unless stated otherwise)
Elevation angle	≥ 5°
IMU measurements	
Update rate	100 Hz
Error modeling	cf. Table 1
Integration	
Filter update rate	1 Hz, 0.5 Hz

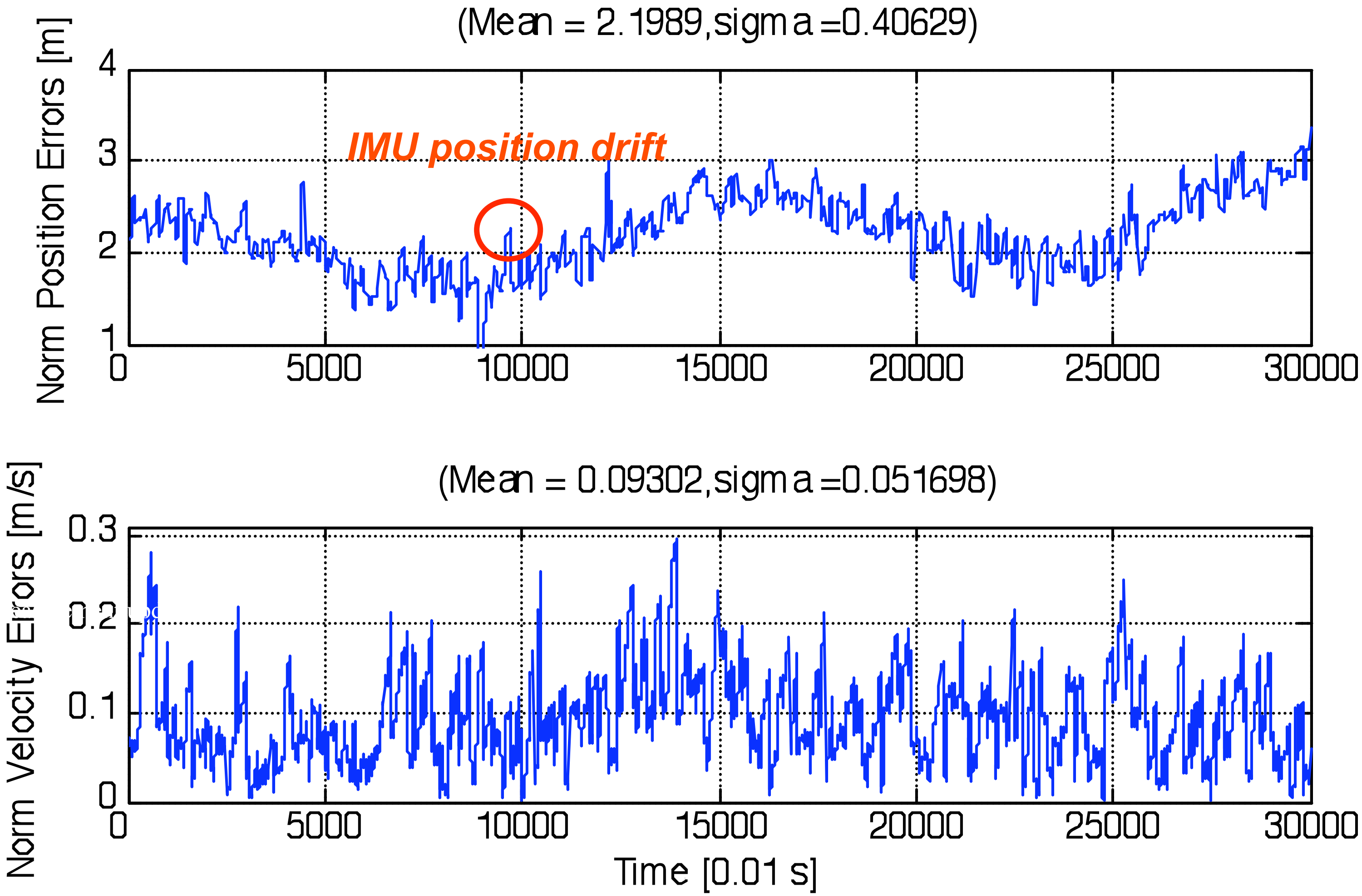
Parameters for the simulation of the following experiment.

Scenario 1: Loosely-coupled integration

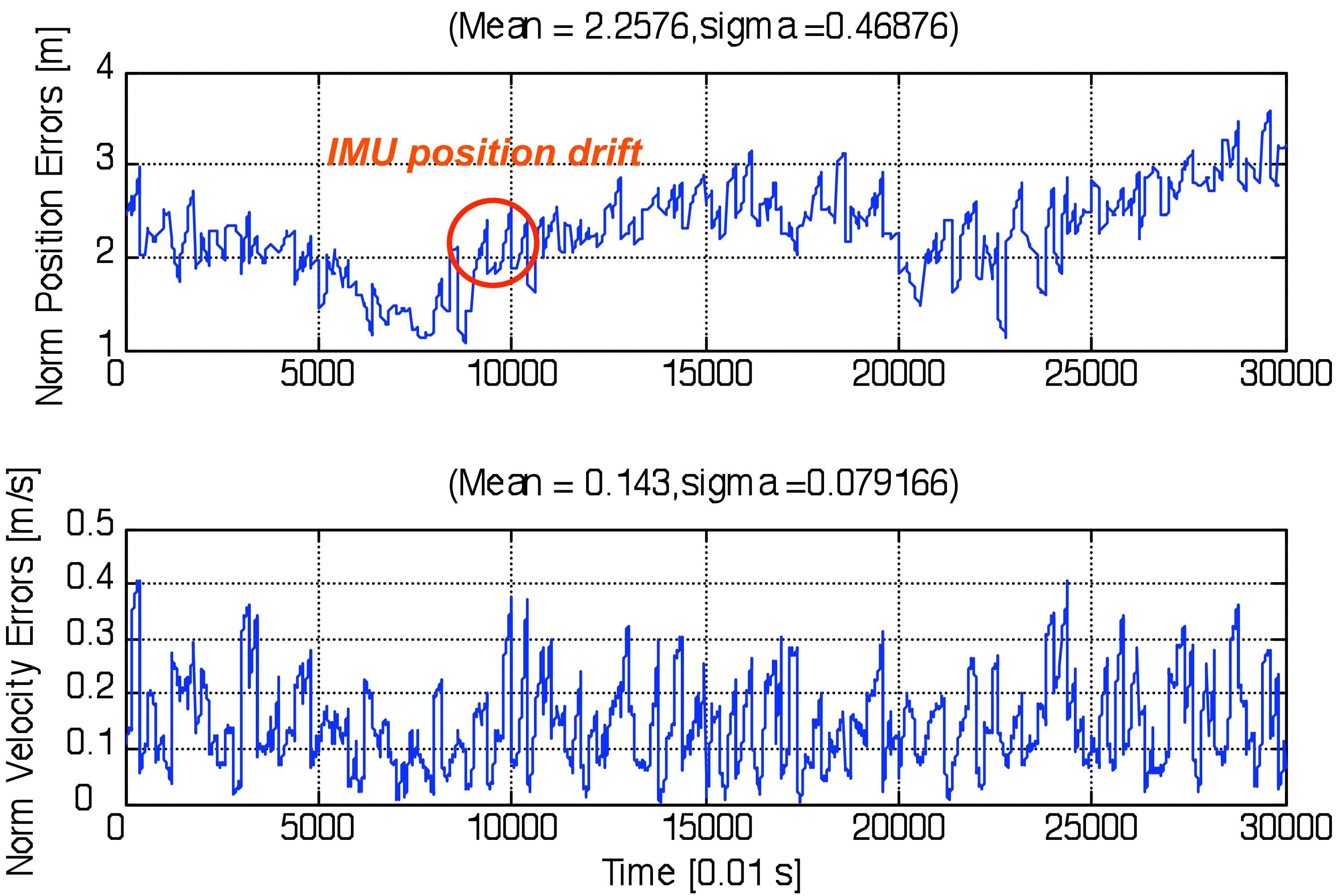
Loosely-coupled integration with the Least-squares estimator for GPS receiver, and 15-state Kalman Filter for integration with

•1 Hz, 0.5 Hz Hz filter update rates
•100 Hz IMU measurements

Scenario 1: with 1 Hz filter update rate



Scenario 1: with 0.5 Hz filter update rate

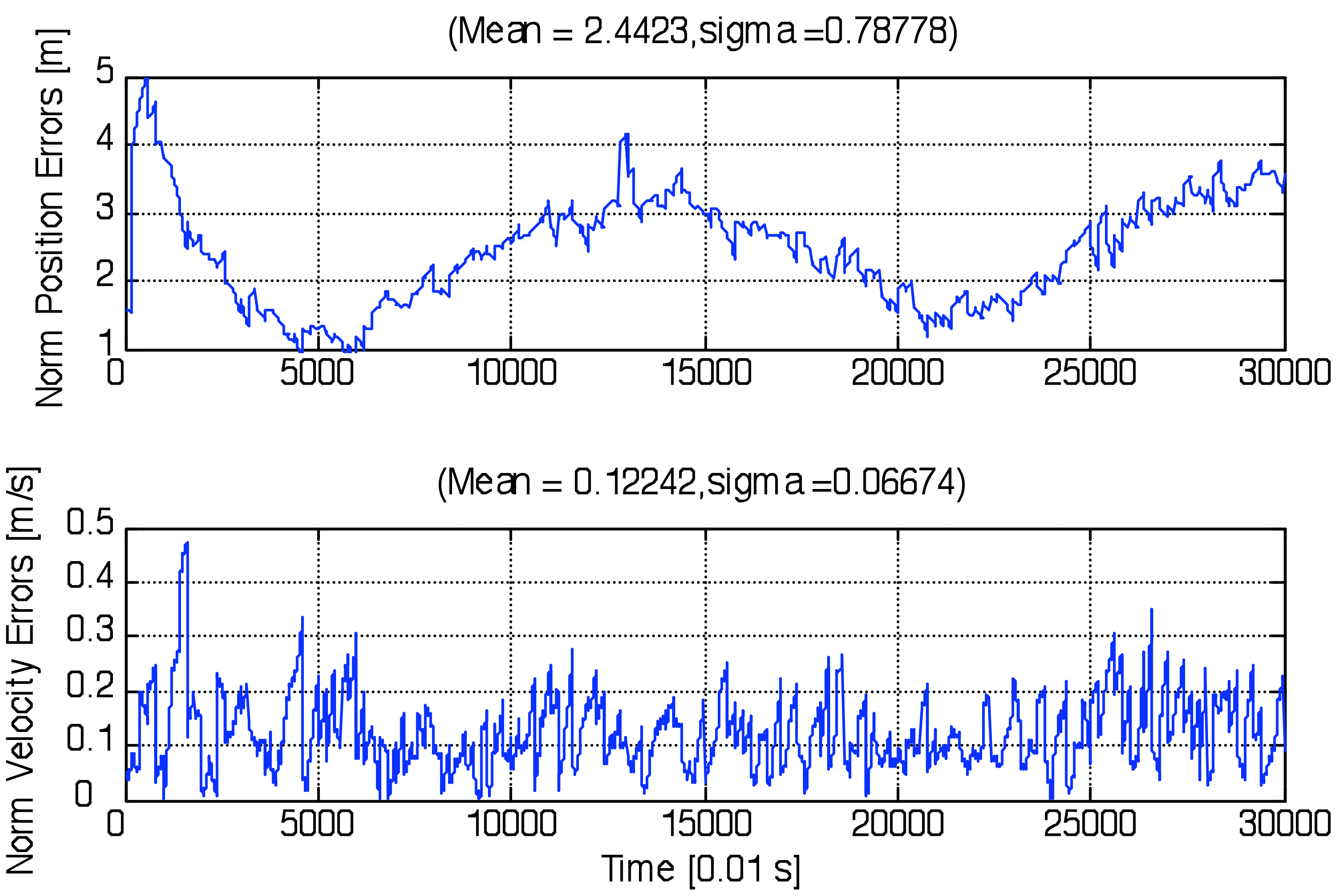


Scenario 2: Tightly-coupled integration

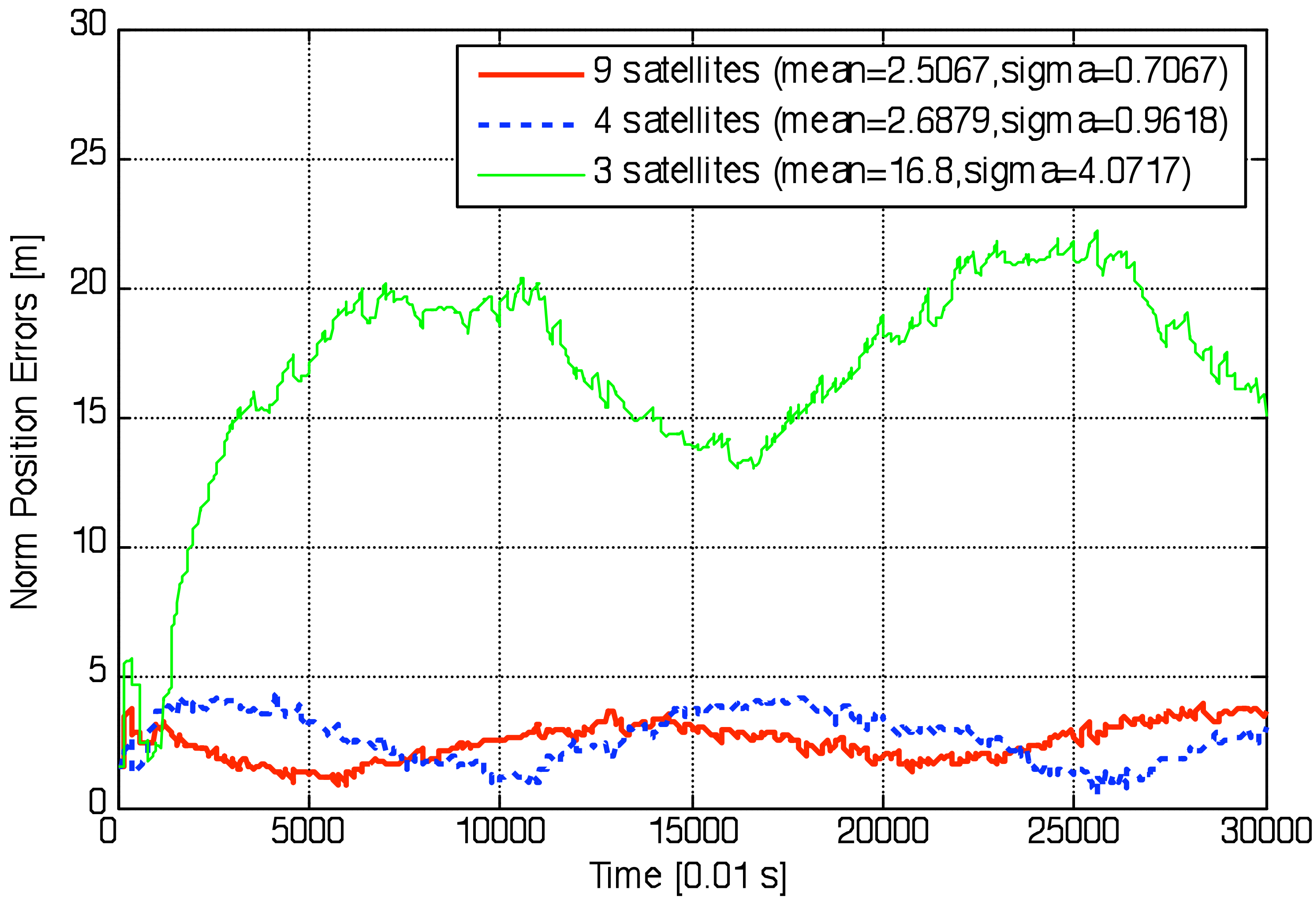
Tightly-coupled integration with using centralized 17-state Kalman Filter with

- 0.5 Hz filter update rates
- 100 Hz IMU measurements

Scenario 2-1: with 0.5 Hz filter update rate

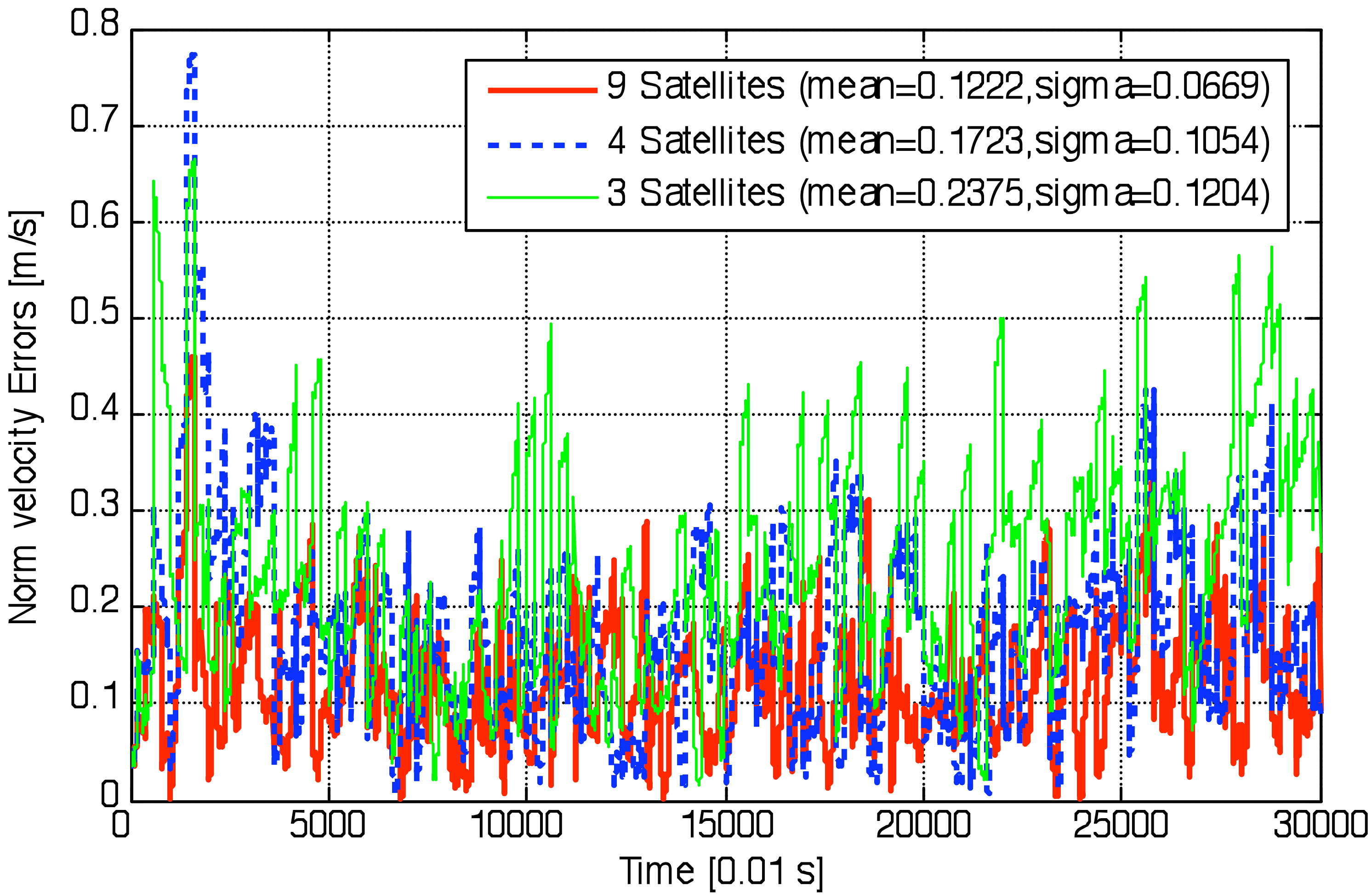


Scenario 2-2: Tightly-coupled integration with 3, 4, 9 satellites



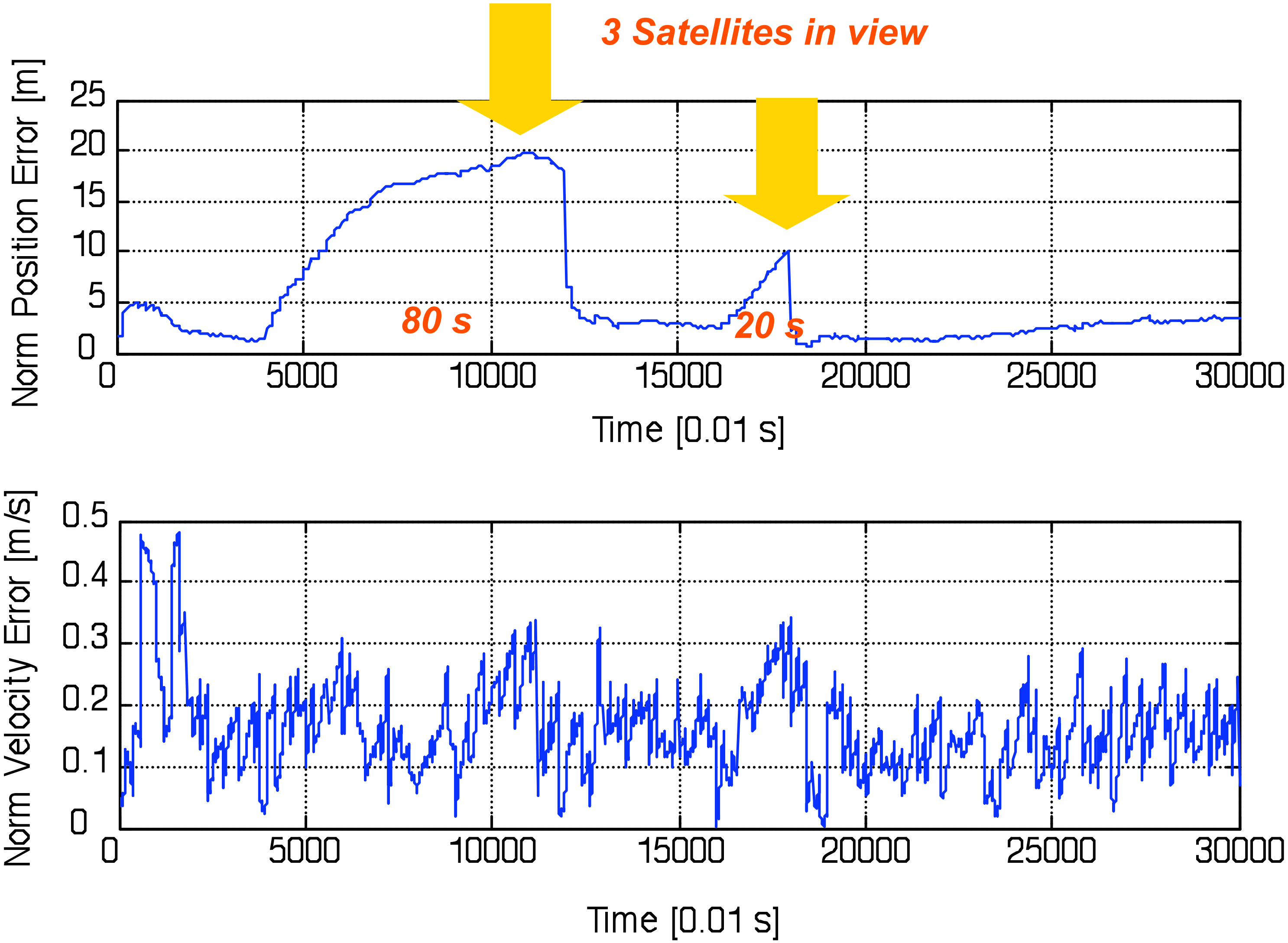
Position errors and their dependencies on the number of satellites in view

Scenario 2-2: Tightly-coupled integration with 3, 4, 9 satellites



Velocity errors and their dependencies on the number of satellites in view

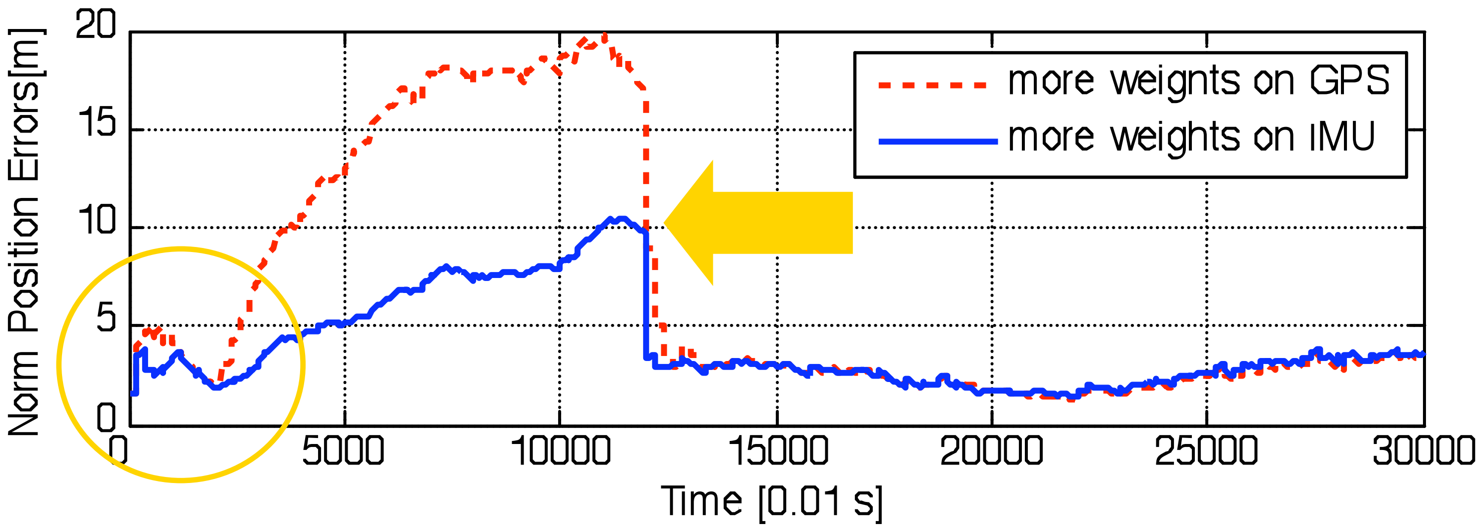
Scenario 2-3: Tightly-coupled integration with GPS signal outages



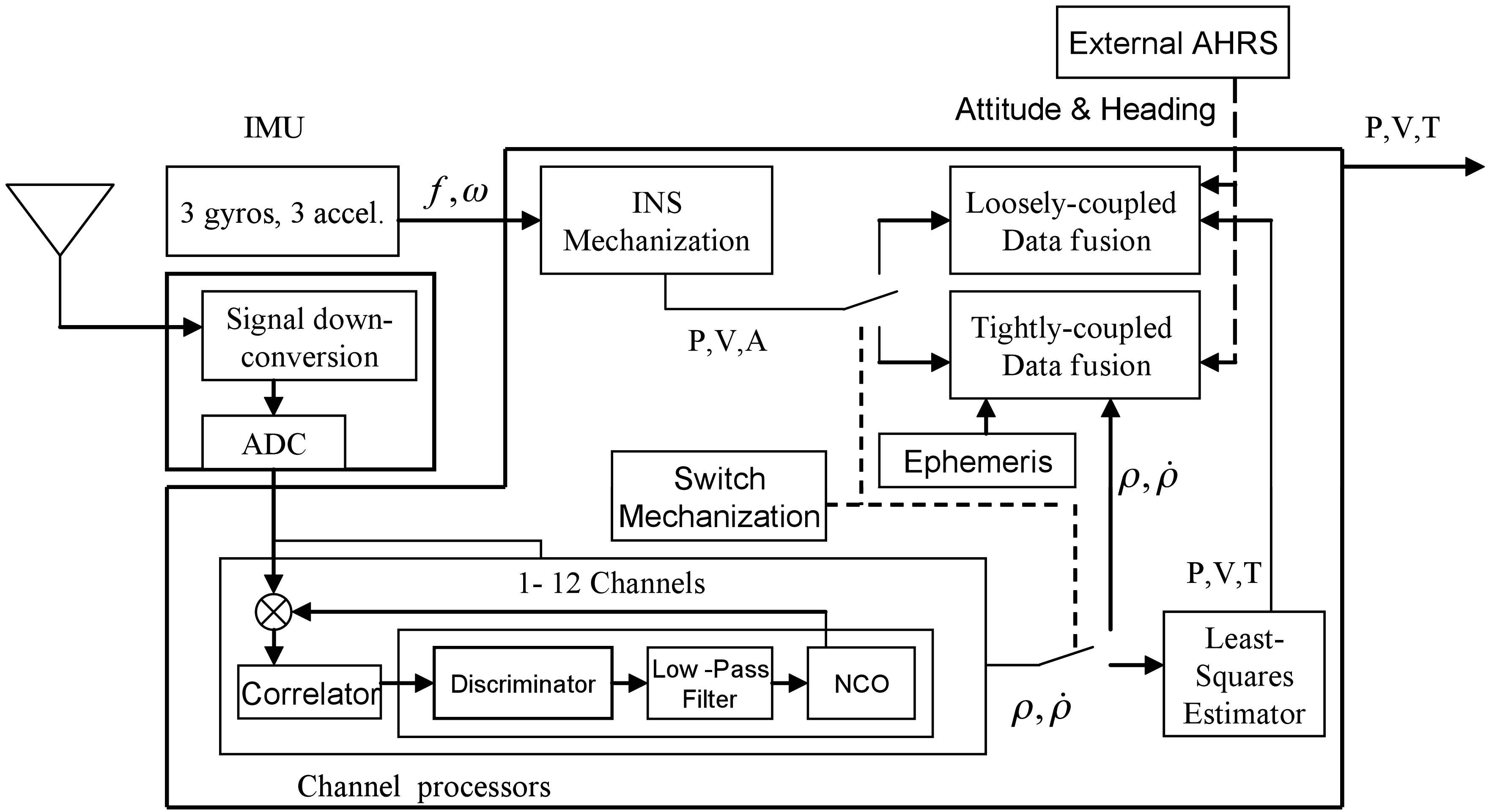
Scenario 2-4: Using the higher grade IMU (tactical grade)

Gyroscope (Angular rates)	
Bias instability [°/h]	1
Scale factor [ppm]	200
Noise (ARW) [°/√h]	0.01
Accelerometer (specific forces)	
Bias instability [μg]	50
Scale factor [ppm]	500
Noise (VRW) [μg/√Hz]	200

Error characteristic of the tactical grade IMU

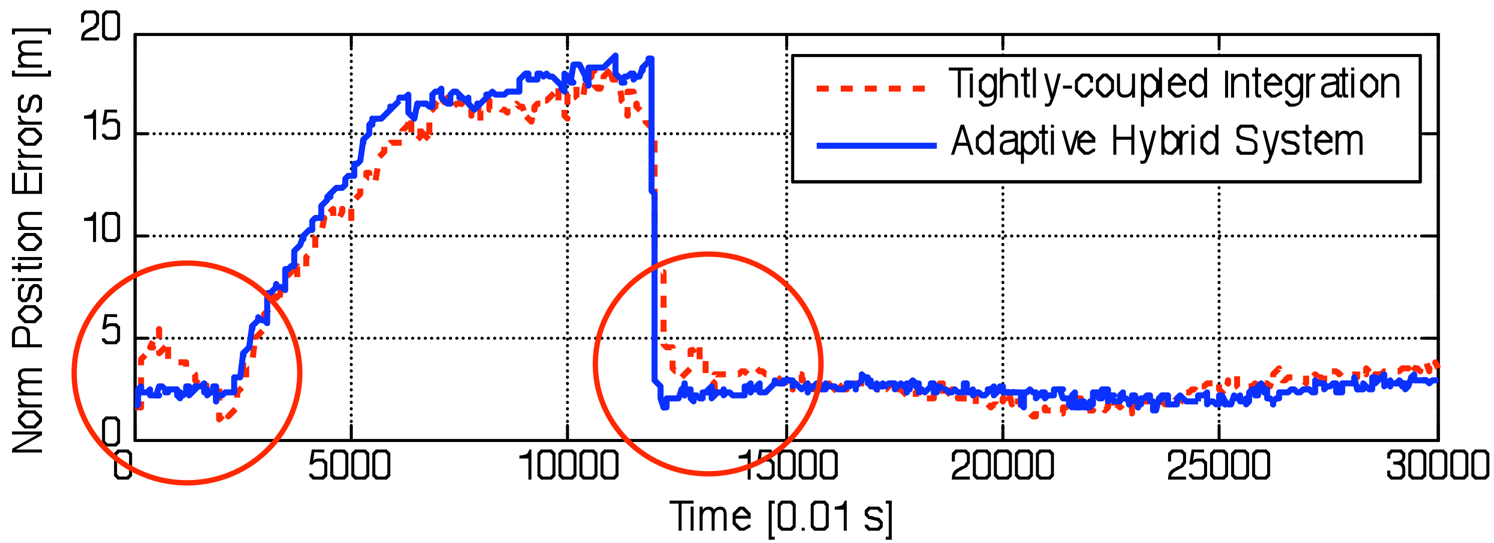


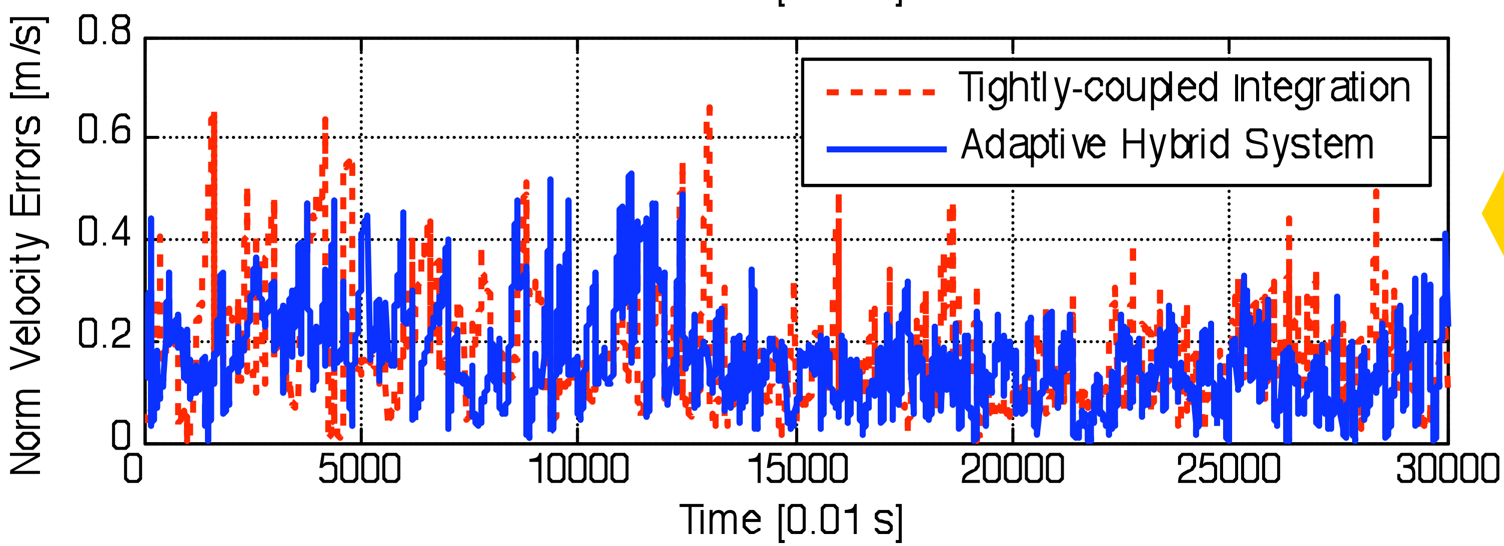
Scenario 3: Adaptive hybrid integrated navigation system



System Architecture

Scenario 3: Adaptive hybrid integrated navigation system





Scenario 3: Adaptive hybrid integrated navigation system

Tightly-coupled Integrated navigation system	
Position Error (mean/sigma)	2.4368/0.6665 (m)
Velocity Error (mean/sigma)	0.1378 /0.0777 (m/s)
Adaptive hybrid navigation system	
Position Error (mean/sigma)	2.3524/0.4756 (m)
Velocity Error (mean/sigma)	0.1181/0.0680 (m/s)

Position and velocity errors (after 120 s) of tightly-coupled and adaptive hybrid navigation system

Tightly-coupled Integrated navigation system	
Position Error (mean/sigma)	2.4274/0.6423 (m)
Velocity Error (mean/sigma)	0.1278 /0.0717 (m/s)
Adaptive hybrid navigation system	
Position Error (mean/sigma)	2.3435/0.4556 (m)
Velocity Error (mean/sigma)	0.1055/0.0611 (m/s)

Mean position and velocity errors after 10 runs

Conclusions:

- **Scenario 1 (Loosely-coupled Integration)**
  - **For low-cost MEMS-based IMU, GPS measurement update rate is an important factor regarding the accuracy of the navigation solution.**
- **Scenario 2 (Tightly-coupled Integration)**
  - **2-1: Proper initialization of the integration Kalman filter is important.**
  - **2-2: With more satellites in view, the results will be better. When less than 4 satellites are in view, INS estimates can be corrected from measurements of remaining satellites, but navigation solution is obviously biased.**
  - **2-3: For long time GPS signal outages, positioning errors are bounded. For short time GPS signal outages, positioning errors seem to be unbounded (drift over time).**
  - **2-4: With high grade IMU, the single-point GPS positioning errors are the dominant part of the total errors rather than the drift from IMU.**
- **Scenario 3 (Adaptive Navigation System)**
  - **There is no convergence problems for initializing the integration algorithm.**
  - **Fast convergence when system leaves challenging signal environments.**
  - **System complexity has been reduced when system is navigating under good signal conditions, with higher GPS measurement update rate.**

Thank you for your attention!