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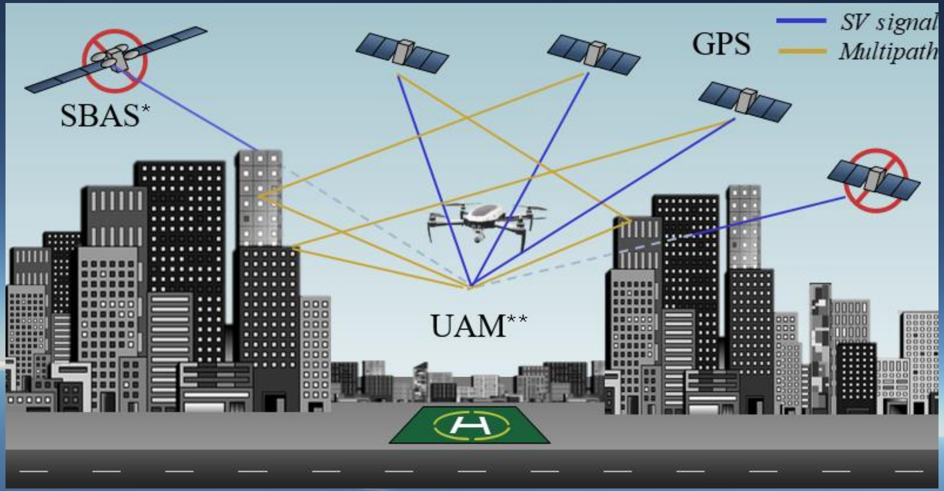
Safety of Life for Urban Air Mobility (UAM): Time-Differenced Carrier Phase (TDCP) RAIM



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Seoul, South Korea
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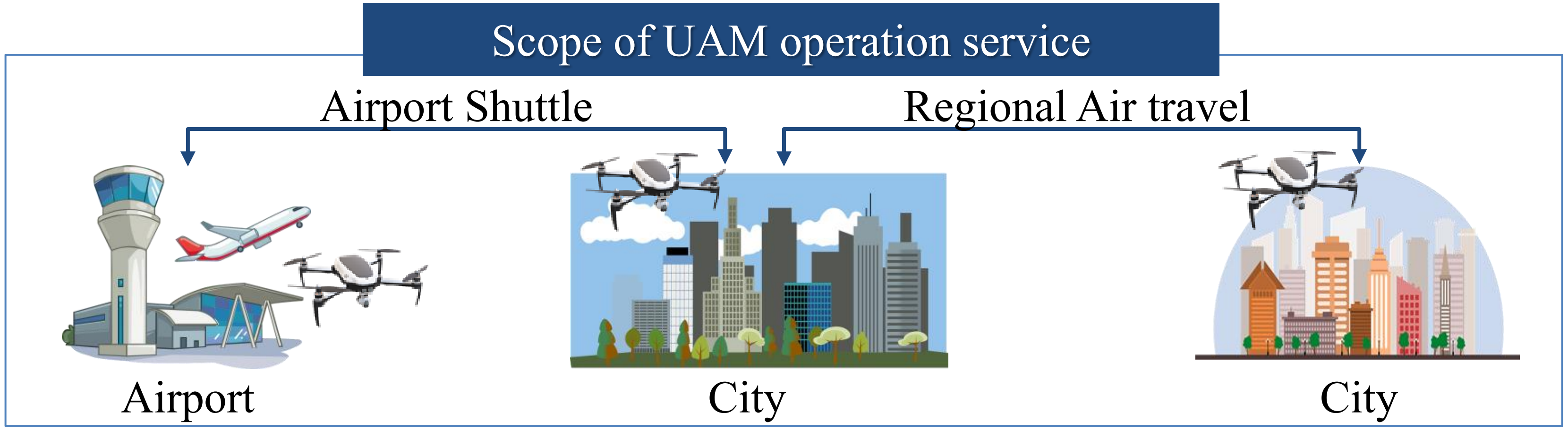
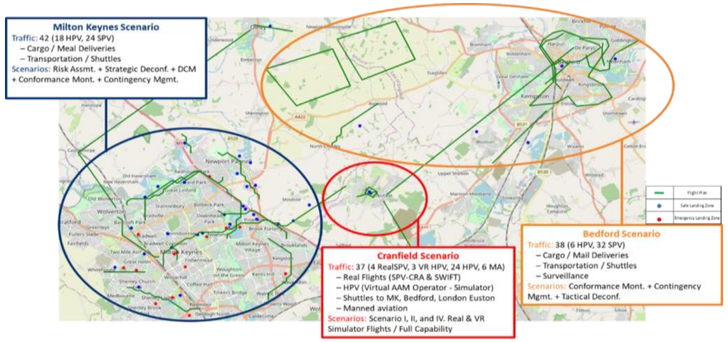
- # Urban Air Mobility
  - Highly automated, cooperative, transportation services in and around urban areas

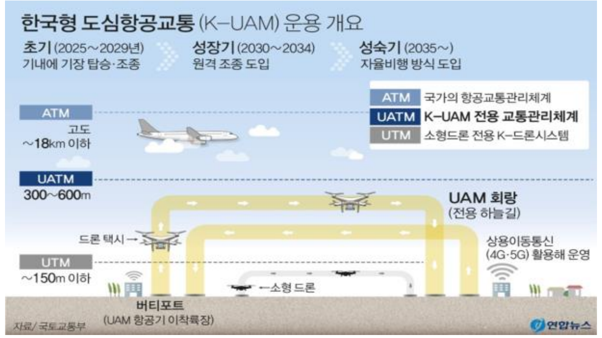


- NASA : AAM NC

- EU : AMU-LED project

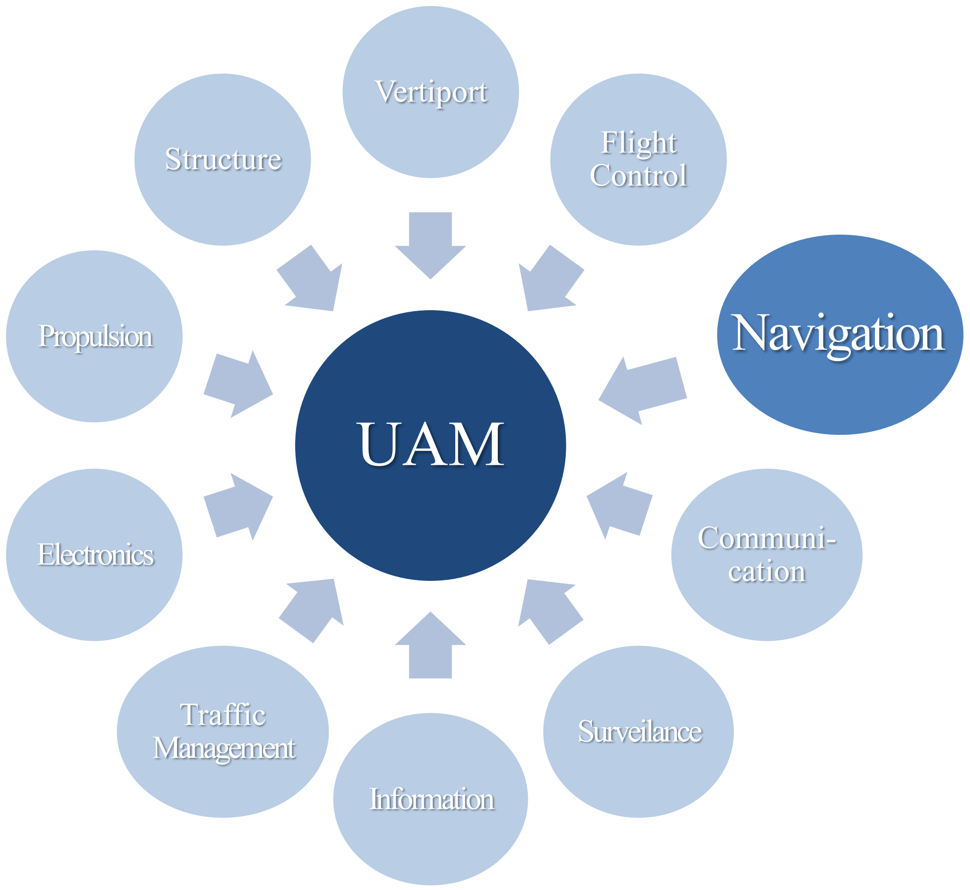


- South Korea : K-UAM



AAM NC : Advanced Air Mobility National Campaign
AMU-LED : Air Mobility Urban Large Experimental Demonstrations
K-UAM : Korean Urban Air Mobility

Core Technology of UAM



SBAS : Satellite Based Augmentation System
RAIM : Receiver Autonomous Integrity Monitoring
ARAIM : Advanced RAIM
RRAIM : Relative RAIM
PPP : Precise Point Positioning

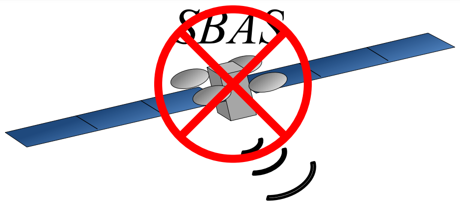
- In navigation, high accuracy and high integrity are required for safety of life
  - Ensures safety of both passengers and pedestrians
  - Guarantees
    - Accurate positioning,
    - High integrity in complex environments (ex. buildings)
- SBAS guarantees the requirements in open sky but not in deep urban (blockage by buildings)
- So far, no integrity monitoring methods meet the UAM requirements!
  - Pseudorange based (ex: RAIM, ARAIM)
  - Carrier-phase based (ex: RRAIM, PPP)

Problems

- **Open Sky (above buildings)**
  - ✓ **SBAS** Integrity Monitoring enabled

➤

- **Deep Urban**
  - ❖ SBAS signal blocked by buildings



During landing into vertiport, problems occur in integrity!

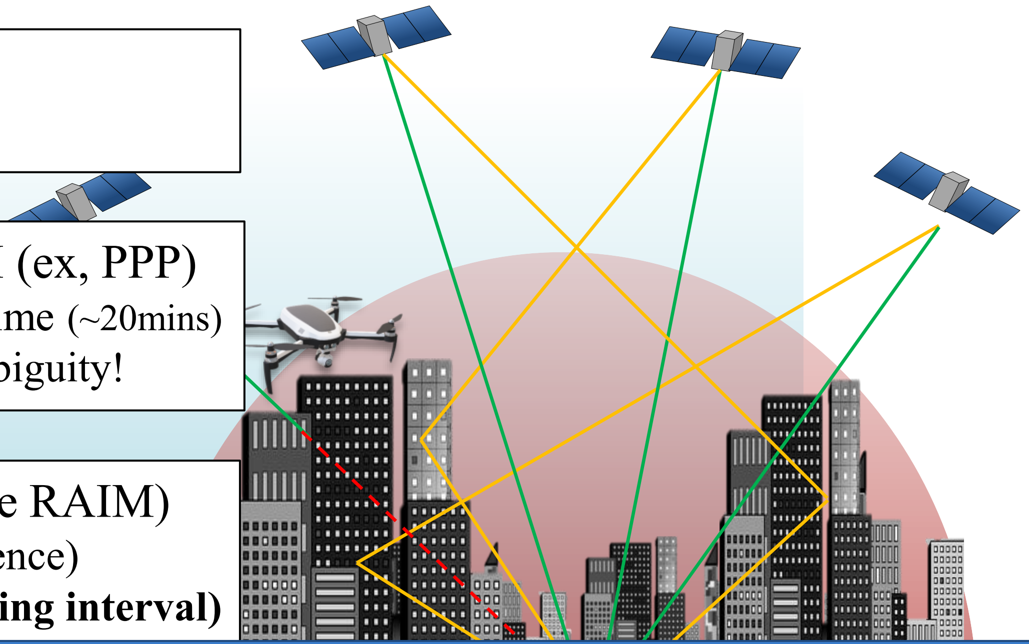
- Pseudorange measurement based RAIM
  - ➢ Extreme multipath due to buildings!

▼

- Carrier phase measurement based RAIM (ex, PPP)
  - ➢ Small multipath but long convergence time (~20mins)
  - ➢ No guarantee to find correct integer ambiguity!

▼

- Conventional method : RRAIM (Relative RAIM)
  - ➢ No more integer ambiguity (time difference)
  - ➢ **Cycle slip has to be detected (for landing interval)**



Propose a new carrier based RAIM, which works in Deep Urban environment

RAIM : Receiver Autonomous Integrity Monitoring

Conventional Integrity Method:

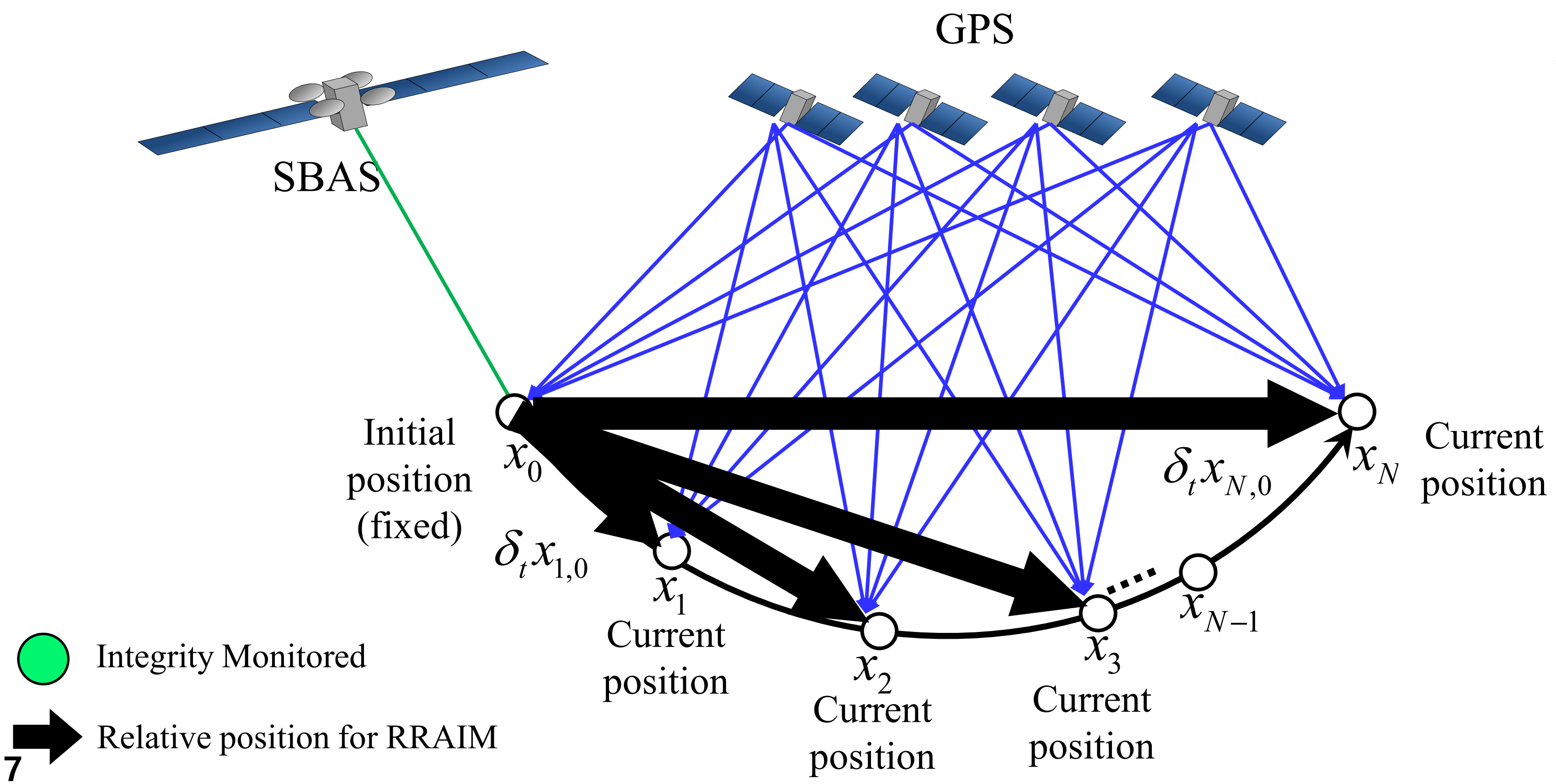
RRAIM

(Relative Receiver Autonomous Integrity Monitoring)

Relative RAIM (RRAIM)

- **RRAIM (Relative RAIM,** use carrier phase instead of pseudorange**)**
  - Start from integrity guaranteed **initial position** using SBAS
  - [Current position] = [**Initial position**] + [Relative position between initial and current epoch]

$$x_k = x_0 + \delta_t x_{k,0}$$



$$\bar{\rho}_k = H_k \bar{x}_k + \bar{\varepsilon}_k$$

$$\bar{\phi}_k = H_k \bar{x}_k + \bar{N}\lambda_k + \bar{v}_k$$

$$\delta_t \bar{\phi}_{k,0} \triangleq \bar{\phi}_k - \bar{\phi}_0$$

$$\Rightarrow \delta_t x_{k,0} \ (\triangleq x_k - x_0)$$

$\bar{\rho}$: psudorange vector ($\sigma_\rho \approx 1$m)

$\bar{\phi}$: carrier phase vector ($\sigma_\phi \approx 1$mm)

k : epoch

H : position matrix

x : user state

$\bar{N}$: integer ambiguity

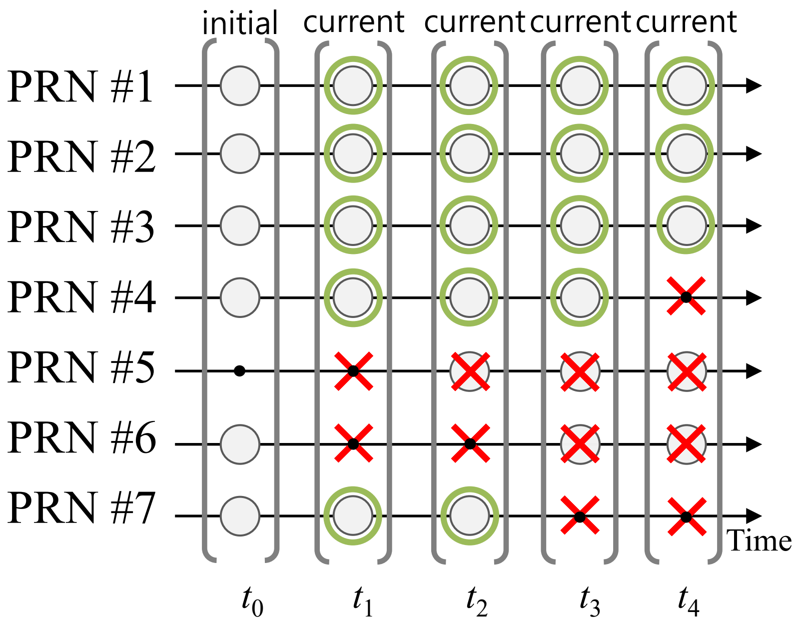
λ : wavelength

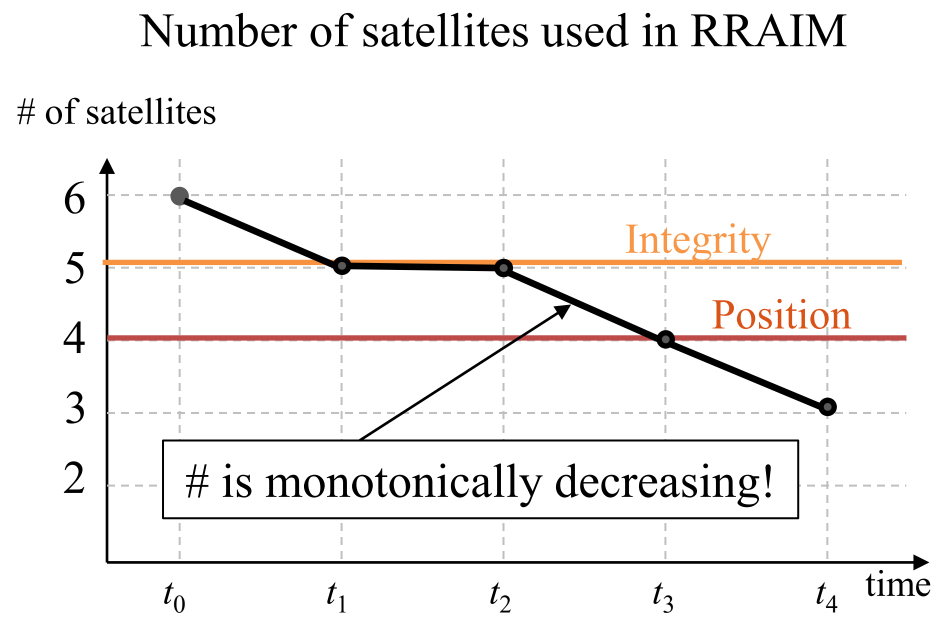
$\bar{\varepsilon}, \bar{v}$: bias error + noise

Limitations of RRAIM

- Cycle slip has to be detected (ex. for 5-10 minutes, extremely difficult for INS!)
- Sensitive to change of satellite in view
  - Only PRNs, **seen from initial throughout to current epoch**, can be used

    (# of usable satellites will be monotonically decreased)





PRN #5 : new rising SV
PRN #6 : temporarily blocked by buildings (similar to cycle slip)

New Integrity Method:

TDCP RAIM

(Time-Differenced Carrier Phase

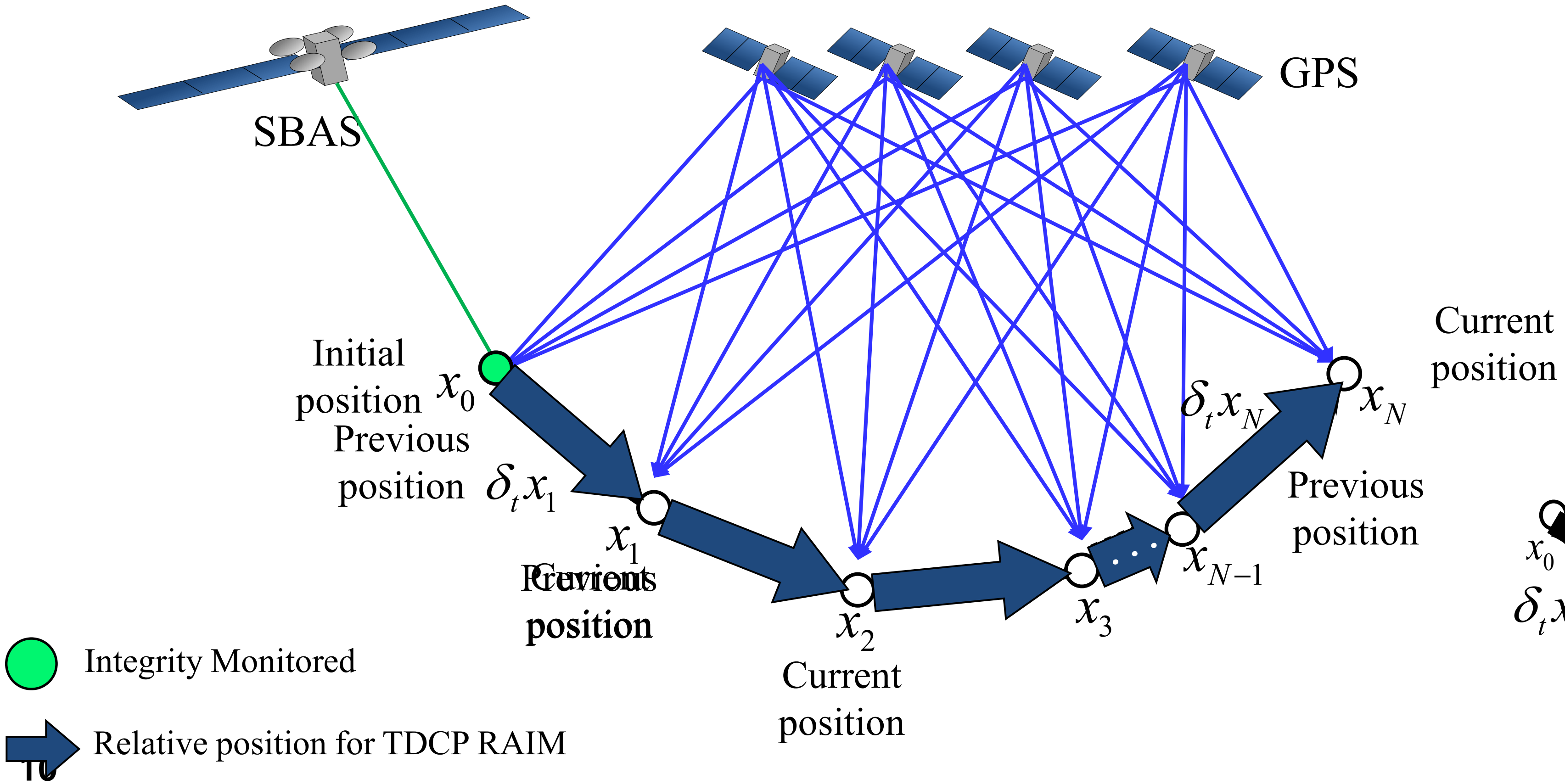
Receiver Autonomous Integrity Monitoring)

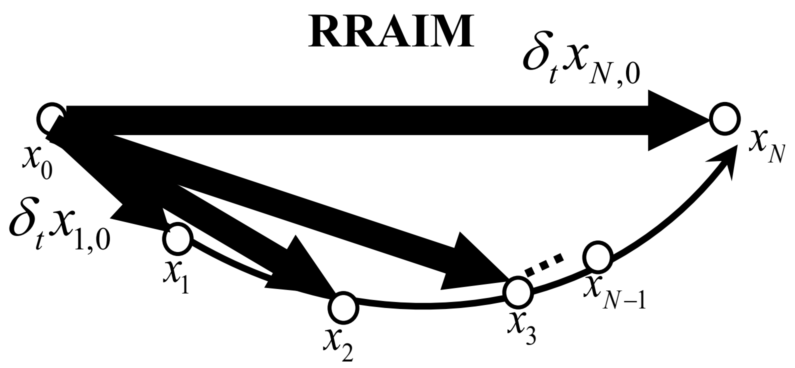
- **Time-Differenced Carrier Phase RAIM (TDCP RAIM)**
  - Start from integrity guaranteed **initial position** using SBAS (same as RRAIM)
  - [Current position] = [**Previous position**] + [Relative position between previous and current epoch]

$$x_k = x_{k-1} + \delta_t x_k \quad \left(vs.\ x_k = x_0 + \delta_t x_{k,0} \right)$$

(**typically 1 second**, or less)

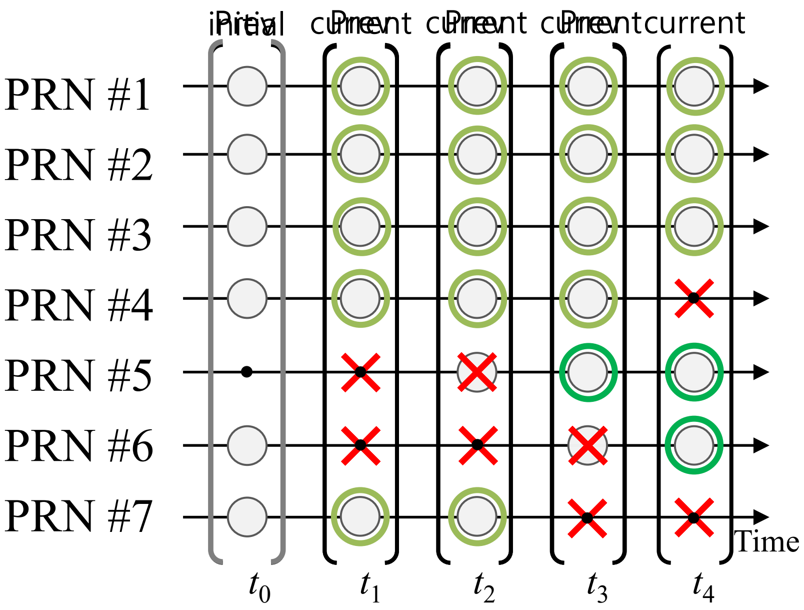
$$\delta_t \bar{\phi}_k \triangleq \bar{\phi}_k - \bar{\phi}_{k-1}$$
$$\Rightarrow \delta_t x_k \ (= x_k - x_{k-1})$$
$$(cf.\ \delta_t x_{k,0} = x_k - x_0)$$

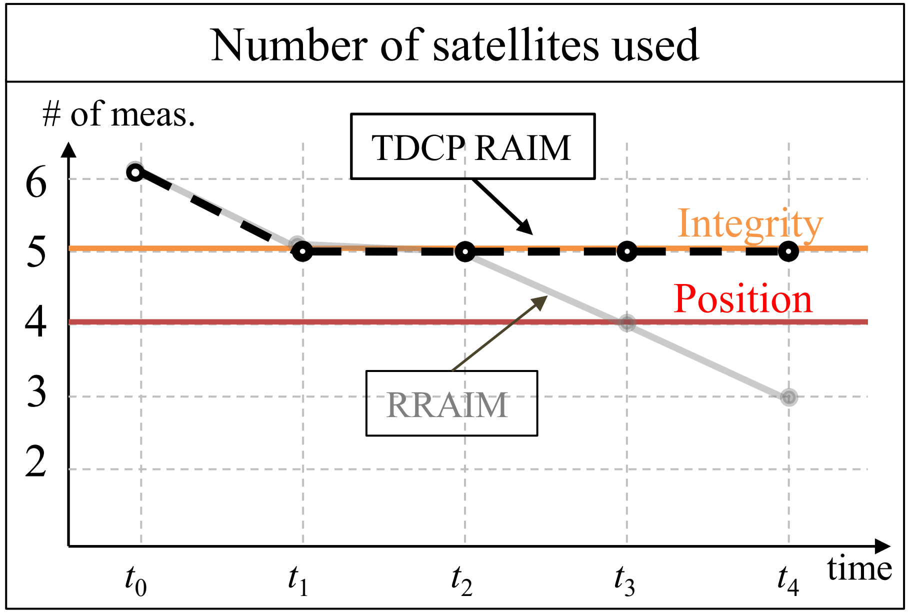




Advantages of TDCP RAIM

- Cycle slip can be easily detected for 1 second interval, or less (with commercial grade MEMS IMU)
- Robust to change of satellite in view
  - All PRNs in view (seen in **previous** and current epoch) are used





PRN #5 : new rising SV
PRN #6 : temporarily blocked by buildings

TDCP RAIM uses rising satellites and also temporarily blocked satellites!

(which is impossible for RRAIM!)

- **Carrier phase measurement :** $\bar{\phi} = H\bar{x} + \bar{N}\lambda + \bar{v}$

H : position matrix
$\bar{x}$: user state
$\bar{N}$: integer ambiguity
λ : wavelength
$\bar{v}$: bias error + noise

- **TDCP RAIM time-differenced measurement ($\delta_t \bar{r}_k$)**
  - Eliminate integer ambiguity by time difference (1 second, assumed no cycle slip)

$$\bar{\phi}_k = H_k \bar{x}_k + \bar{N}_k \lambda + \bar{v}_k$$

$$-\quad \bar{\phi}_{k-1} = H_{k-1}\bar{x}_{k-1} + \bar{N}_{k-1}\lambda + \bar{v}_{k-1}$$

$$\begin{aligned} \delta_t \bar{\phi}_k &\triangleq \bar{\phi}_k - \bar{\phi}_{k-1} \\ &= H_k \bar{x}_k - H_{k-1}\bar{x}_{k-1} + \delta_t \bar{v}_k \\ &= H_k(\bar{x}_k - \bar{x}_{k-1}) + (H_k - H_{k-1})\bar{x}_{k-1} + \delta_t \bar{v}_k \\ &= H_k \delta_t \bar{x}_k + \boxed{\delta_t H_k \bar{x}_{k-1}} + \delta_t \bar{v}_k \end{aligned}$$

$$\left(\begin{aligned} &\text{where } \delta_t[\,]_k \triangleq [\,]_k - [\,]_{k-1} \\ &\bar{x} : \text{true position} \\ &\hat{x} : \text{estimated position} \\ &\tilde{x} : \text{estimation error } (\triangleq \hat{x} - \bar{x}) \end{aligned} \right.$$

Define new measurement:
(Geometry change compensated)

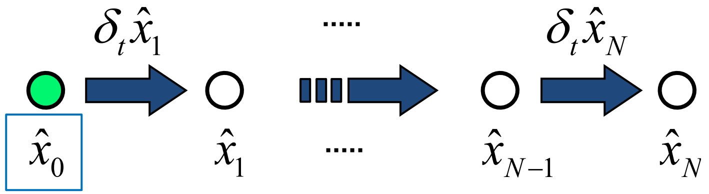
$$\boxed{\delta_t \bar{r}_k} \triangleq \delta_t \bar{\phi}_k - \boxed{\delta_t H_k \hat{x}_{k-1}} \left(\begin{aligned} &= H_k \delta_t \bar{x}_k + \delta_t H_k(\bar{x}_{k-1} - \hat{x}_{k-1}) + \delta_t \bar{v}_k \\ &= H_k \delta_t \bar{x}_k - \boxed{\delta_t H_k \tilde{x}_{k-1}} + \delta_t \bar{v}_k \quad \text{where } \tilde{x}_{k-1} \triangleq \hat{x}_{k-1} - \bar{x}_{k-1} \end{aligned} \right)$$

estimation error

very small

- **Positioning Algorithm**

Start from SBAS position →



very small

- Accumulate the relative positions from initial position

$$\delta_t \hat{x}_k = S_k \delta_t \bar{r}_k, \quad \text{where} \begin{cases} \delta_t \bar{r}_k = H_k \delta_t \bar{x}_k - \boxed{\delta_t H_k \tilde{x}_{k-1}} + \delta_t \bar{v}_k \\ S_k : \text{weighted pseudo-inverse of } H_k \end{cases}$$

$$\therefore \boxed{\hat{x}_N = \hat{x}_0 + \sum_{k=1}^{N} \delta_t \hat{x}_k} \quad \text{where } \delta_t \hat{x}_k \triangleq \hat{x}_k - \hat{x}_{k-1}$$

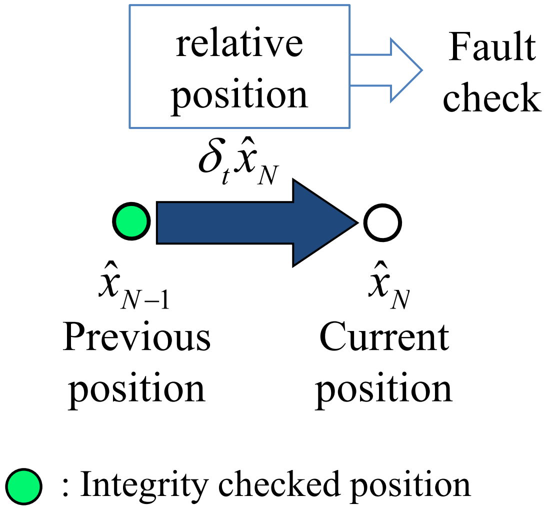
- Correlation exists in solutions between initial position error ($\tilde{x}_0$) and current epoch ($\hat{x}_1$)

$$\begin{aligned} \hat{x}_1 &= \hat{x}_0 + \delta_t \hat{x}_1 \\ &= \bar{x}_1 + (I - S_1 \delta_t H_1) \tilde{x}_0 + S_1 \delta_t \bar{v}_1 \\ &\vdots \end{aligned} \qquad \left(\begin{aligned} \text{where } \delta_t \hat{x}_1 &= S_1 \delta_t \bar{r}_1 \\ &= (\bar{x}_1 - \bar{x}_0) - S_1 \delta_t H_1 \tilde{x}_0 + S_1 \delta_t \bar{v}_1 \end{aligned} \right.$$

- Final TDCP position based on initial SBAS position error (for covariance computation)

$$\boxed{\hat{x}_N \approx \bar{x}_N + \left(I - \sum_{k=1}^{N} S_k \delta_t H_k \right) \tilde{x}_0 + \sum_{k=1}^{N} S_k \delta_t \bar{v}_k}$$

- **Integrity Monitoring (Solution Separation Method)**
  - Fault monitoring



  - Test satistics

$$\begin{bmatrix} \delta z_1 \\ \vdots \\ \delta z_{m-1} \\ \delta z_m \end{bmatrix} = -\begin{bmatrix} \bar{e}^1 & -1 \\ \vdots & \vdots \\ \bar{e}^{m-1} & -1 \\ \bar{e}^m & -1 \end{bmatrix} \cdot \delta \bar{x} + \begin{bmatrix} \delta v_1 \\ \vdots \\ \delta v_{m-1} \\ \delta v_m \end{bmatrix}$$

Subset measurement

Full- set measurement

Difference between full-set and subset solution as test statistics (q_i)

$$q_i \triangleq \left| \delta_t \hat{x}_N - \delta_t \hat{x}_{N,i} \right|$$

- **Vertical Protection Level (VPL)**
  - H_0 : normal case / H_1 : fault case

$$VPL_{H_0} = k_{ff} \times \sigma_N + \tilde{x}_{bias,\max}$$

$$VPL_{H_1} = \max_i \left(k_{md} \times \sigma_{N,i} + T_i + \tilde{x}_{bias,\max,i} \right)$$

$$VPL = \max\left(VPL_{H_0}, VPL_{H_1} \right)$$

where

$k_{ff} = Q^{-1}\left(1 - I_{REQ,H0} / 2\right)$

$k_{md} = Q^{-1}\left(1 - I_{REQ,H1} / P_{md}\right)$

$P_{md} = {}_nC_1 \times \left(1 - r_{sat}\right) \times r_{sat}^{n-1}, r_{sat} = 10^{-5} / h$

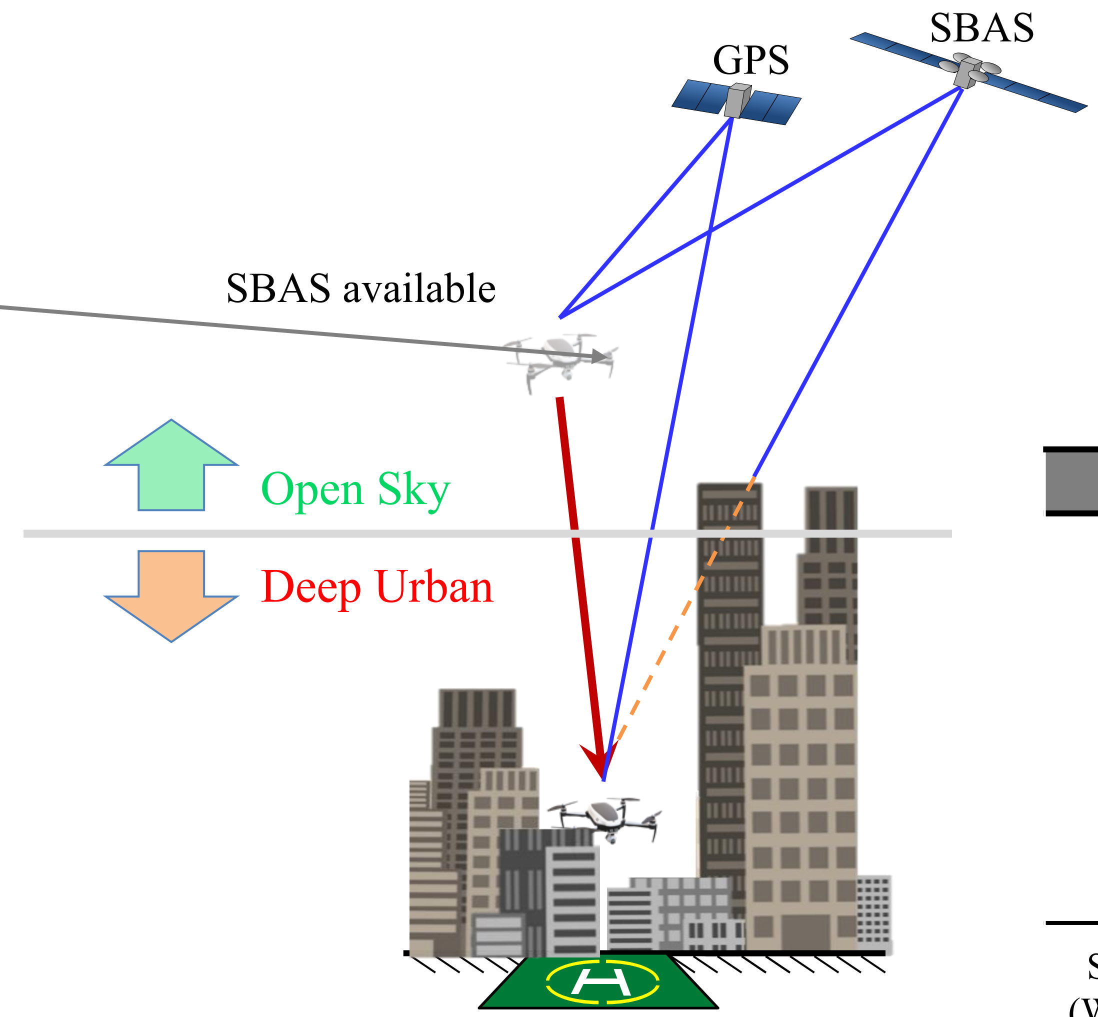
$\sigma_N : \sqrt{\mathrm{cov}\left(\hat{x}_{N-1} + \delta \hat{x}_N\right)}$

$\sigma_{N,i} : \sqrt{\mathrm{cov}\left(\hat{x}_{N-1} + \delta \hat{x}_{N,i}\right)}$

$\tilde{x}_{bias,\max}$: bias of initial position error

Simulation Results

Simulation Scenarios (Landing into Vertiport)



Landing Environment	Navigation
Open Sky	SBAS
Deep Urban	TDCP RAIM

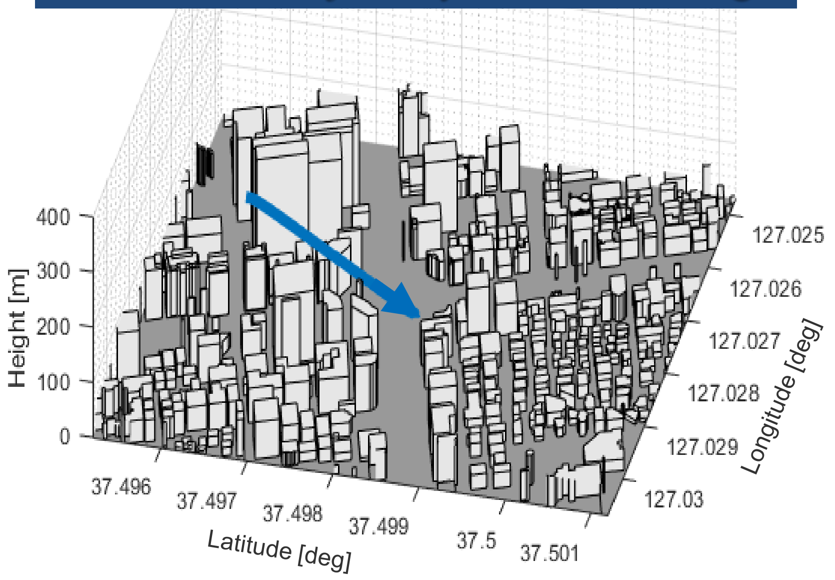
- **SBAS is available at initial epoch only**
- Integrity requirement : LPV-200, VAL = 35m

	Description	Data
GPS	Orbit error	Broadcast orbit data
	Ionospheric delay	GIM data
	Tropospheric delay	Empirical model
	Receiver noise (carrier phase)	Gaussian process
	Multipath (carrier phase)	1st order markov process σ = 13cm , τ = 7sec (10 times of open sky)
SBAS (WAAS)	Residual orbit error	'WAAS Performance analysis report'
	Residual Ionospheric error	

Simulation Scenarios (Landing into Vertiport)

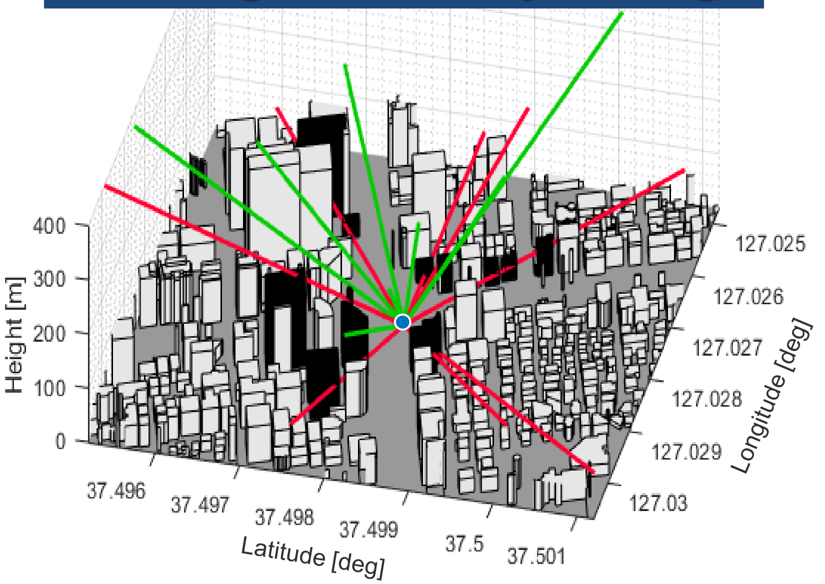
- **Landing of a drone taxi to vertiport in deep urban (ex. Kangnam in Seoul)**
  - Find visible satellites using 3D building data
  - # of visible satellites (by drone taxi) keeps changing during landing interval

Drone taxi trajectory in 3D buildings



: Landing Trajectory

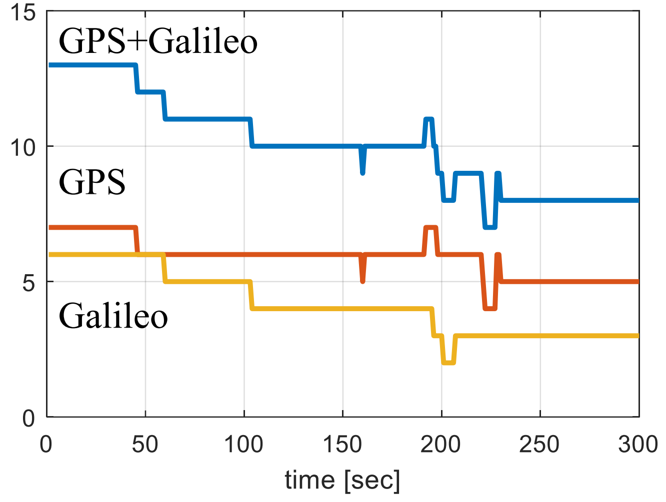
GNSS signal blocked by buildings



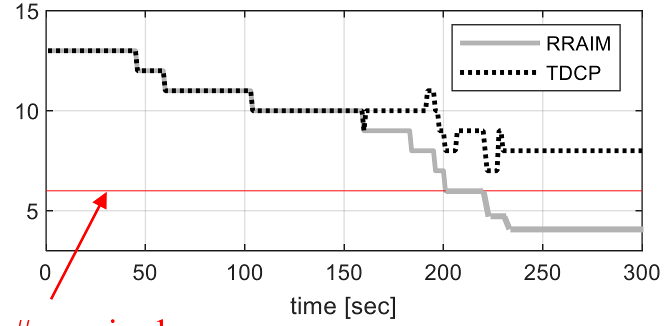
: Direct signal

: Blocked signal

of **Visible** Satellites



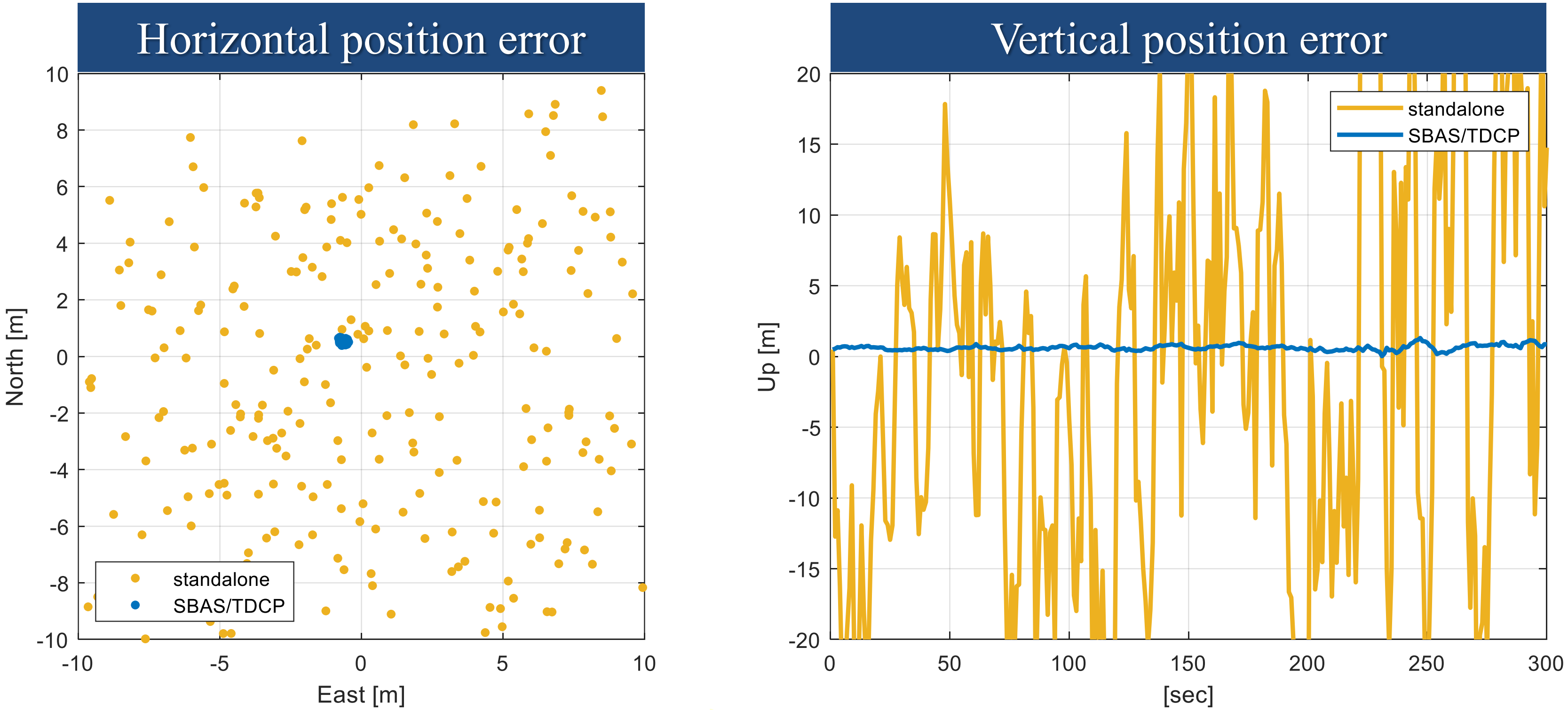
of **Usable** Satellites



min. # required
for integrity monitoring

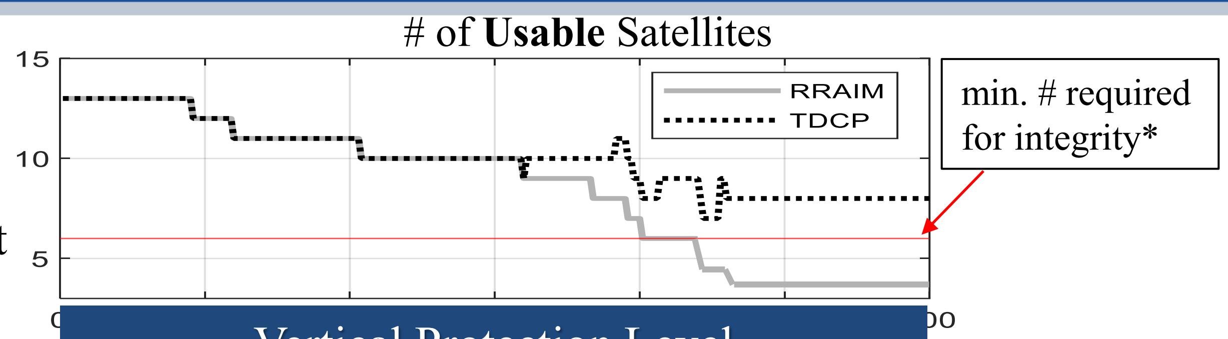
Simulation Results (Accuracy)

- **After SBAS blocked by buildings (Deep Urban)**
  - Standalone position (using pseudorange) degraded severely due to multipath by buildings
  - TDCP navigation with SBAS correction (received before the blockage)
    - Maintain SBAS level position accuracy throughout landing

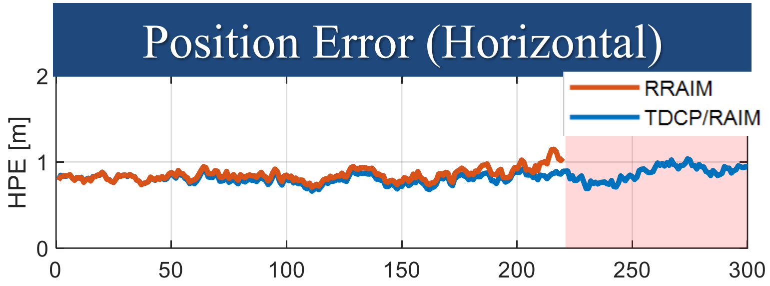


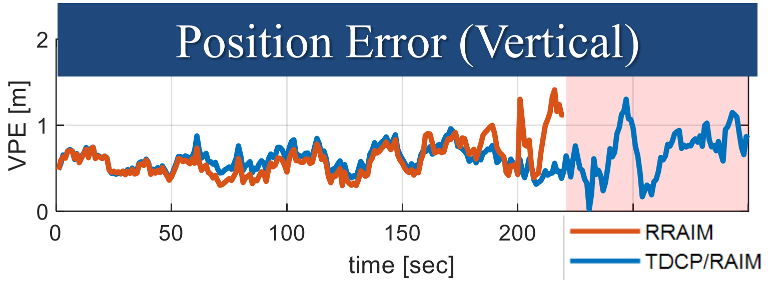
Simulation Results (Integrity)

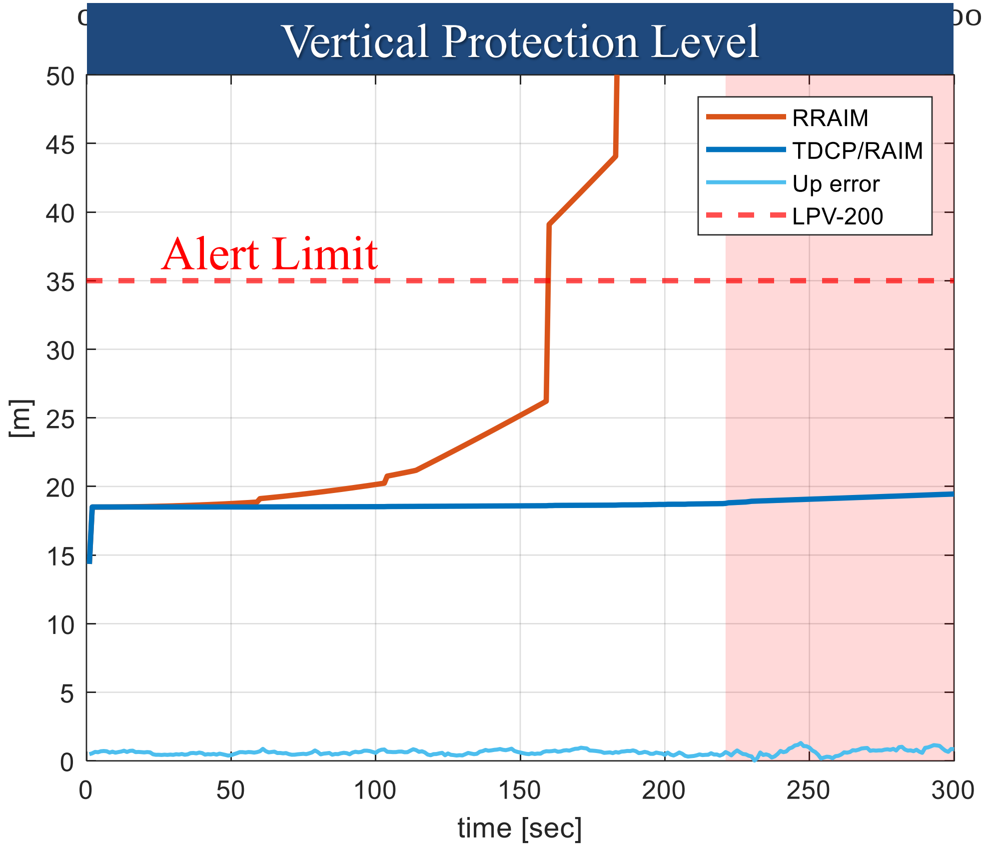
- **Protection Level (Integrity)**
  - RRAIM : Not available due to lack of usable satellites
  - TDCP RAIM : Keep Protection Level below Alert Limit



Final VPL (at touch down)	
RRAIM	-
TDCP RAIM	19.3 m



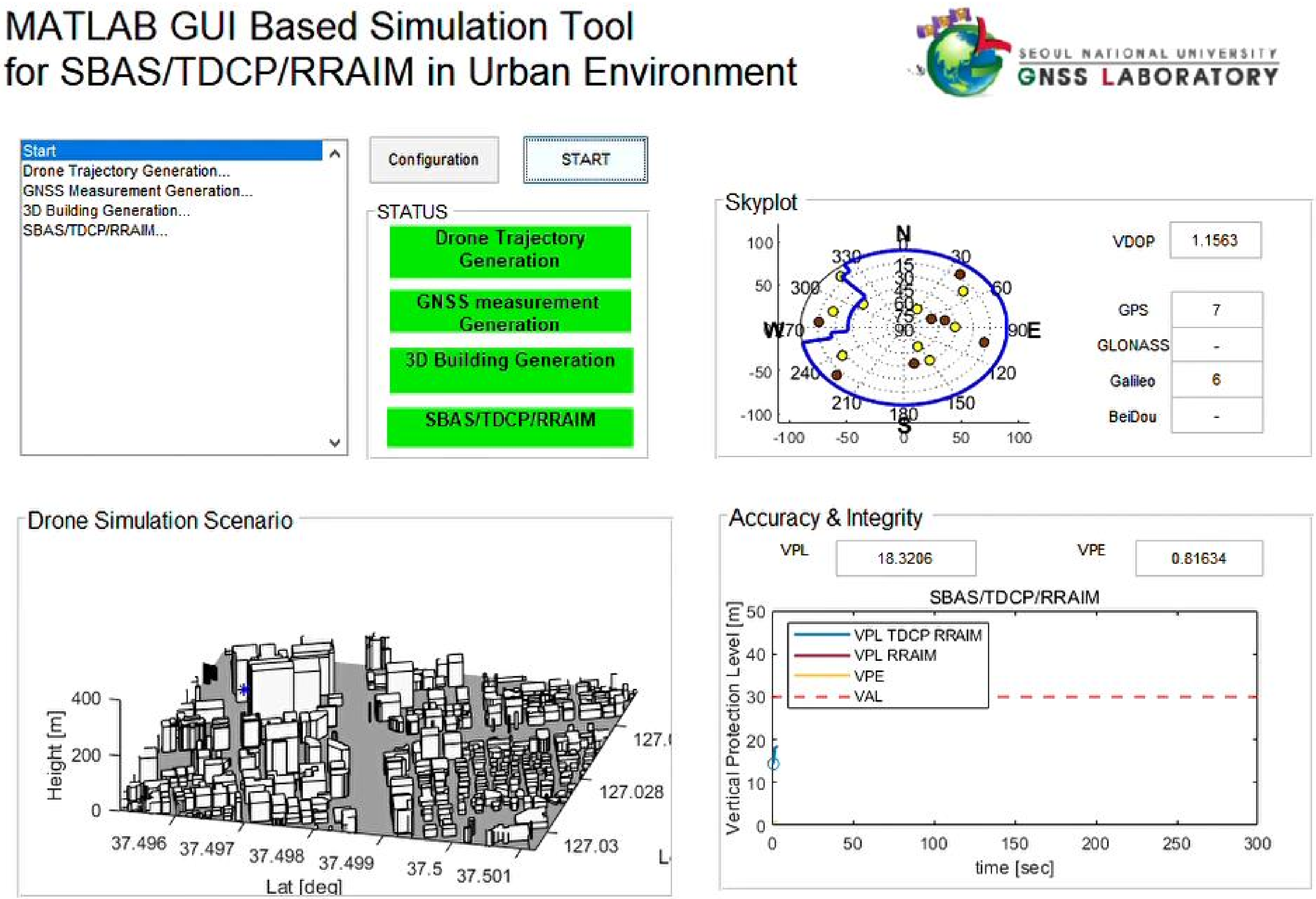




Only TDCP RAIM is available!

*: min # is 6 instead of 5 because of GGTO between GPS and Galileo

Simulation Results (Animation)



Conclusions

Conclusions

- UAM requires high accuracy and **high integrity** for safety of life in Deep Urban
- SBAS guarantees the requirements in open sky but not in Deep Urban
- So far, no integrity monitoring methods meet the UAM requirements
- Proposed TDCP RAIM for UAM
    - Uses 1 sec time-differenced carrier phase measurement (instead of 5 mins for RRAIM)
    - Cycle slip detection for 1 sec interval is absolutely possible (with commercial grade MEMS IMU)
    - Robust to change of satellite in view (utilize newly visible satellites)
    - Integrity to be maintained for 5 mins or more throughout landing on vertiport
    - Can be applied in Integrity Monitoring of Autonomous Vehicle operated in Deep Urban
- Simulation Results for Landing Approach of Drone Taxi to Vertiport in Deep Urban
    - RRAIM: available at the beginning but failed in the middle of approach (lack of usable satellites)
    - TDCP RAIM was available throughout the whole approach to vertiport
- Results show that ***TDCP RAIM guarantees safety of life for UAM!***