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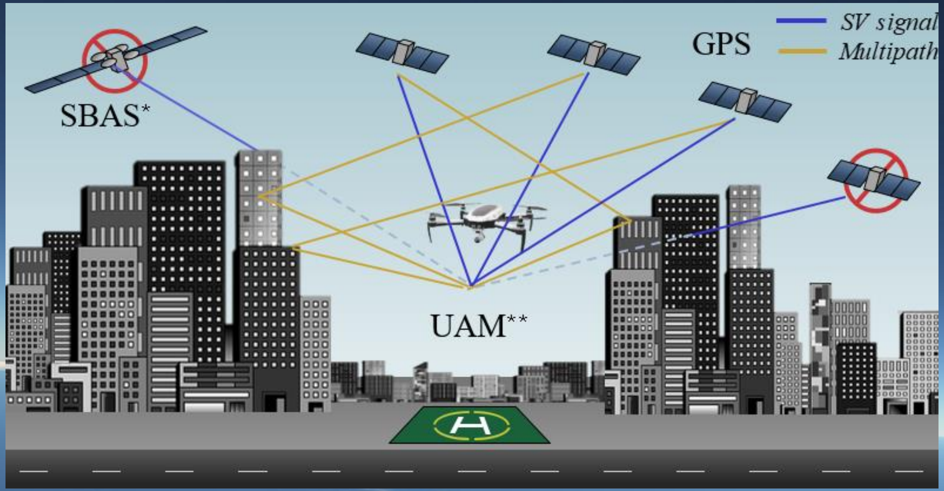
Safety of Life for Urban Air Mobility (UAM): Time-Differenced Carrier Phase (TDCP) RAIM



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63rd CGSIC Meeting
Denver, USA
September 11, 2023

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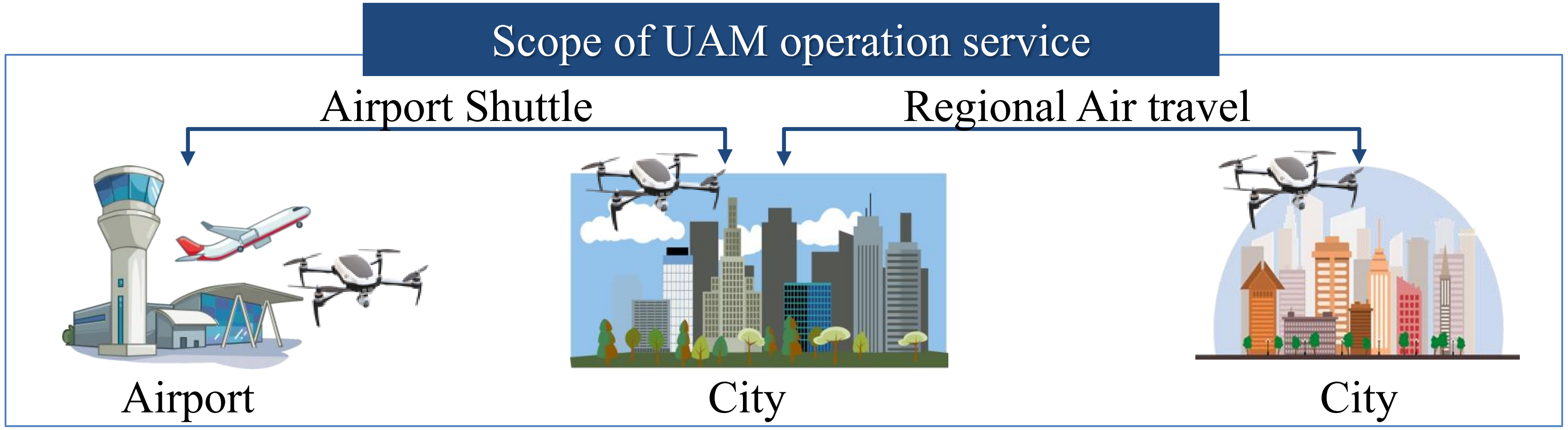
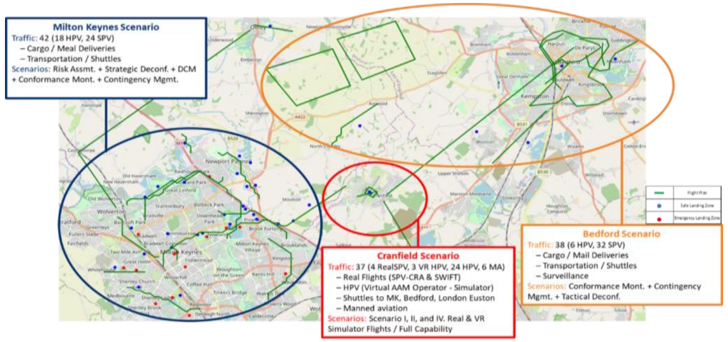
- **Relative RAIM (RRAIM) and TDCP RAIM**
- **Simulation Results**
- **Conclusions**

- **Urban Air Mobility**
  - Highly automated, cooperative, transportation services in and around urban areas

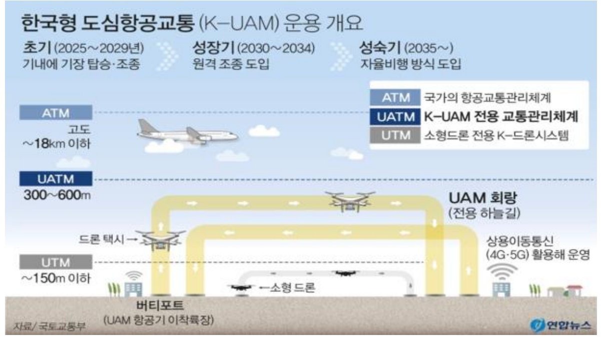


- NASA : AAM NC

- EU : AMU-LED project

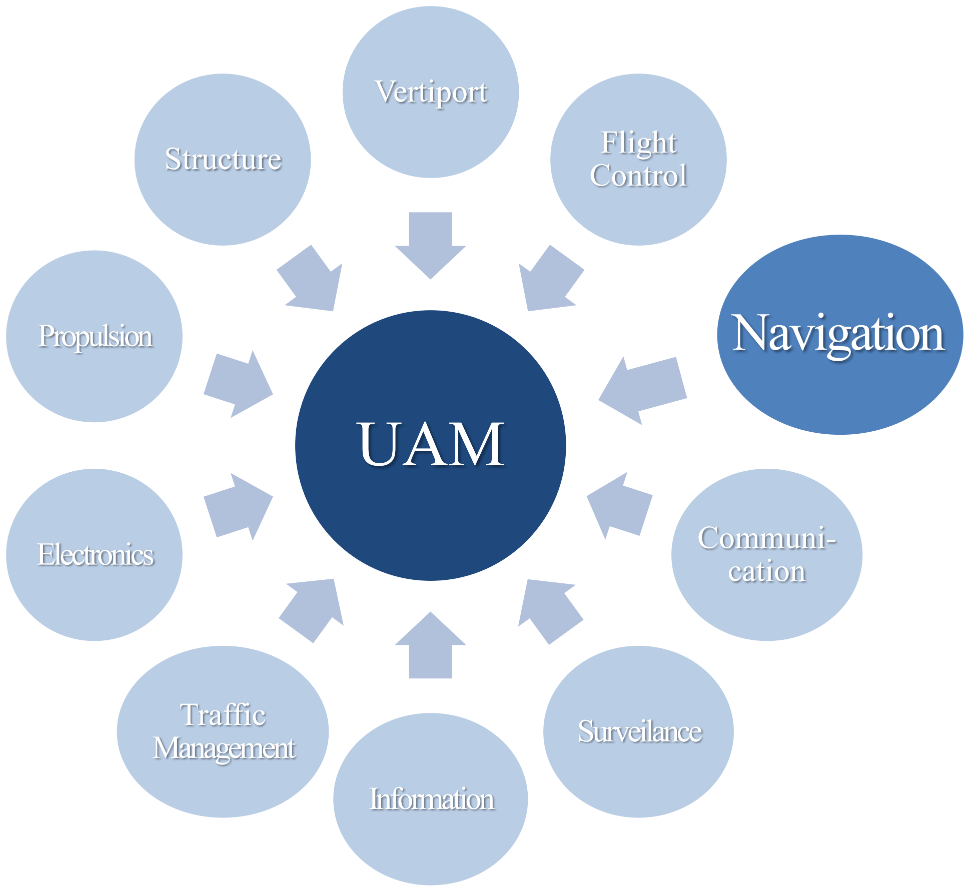


- South Korea : K-UAM



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



- 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)

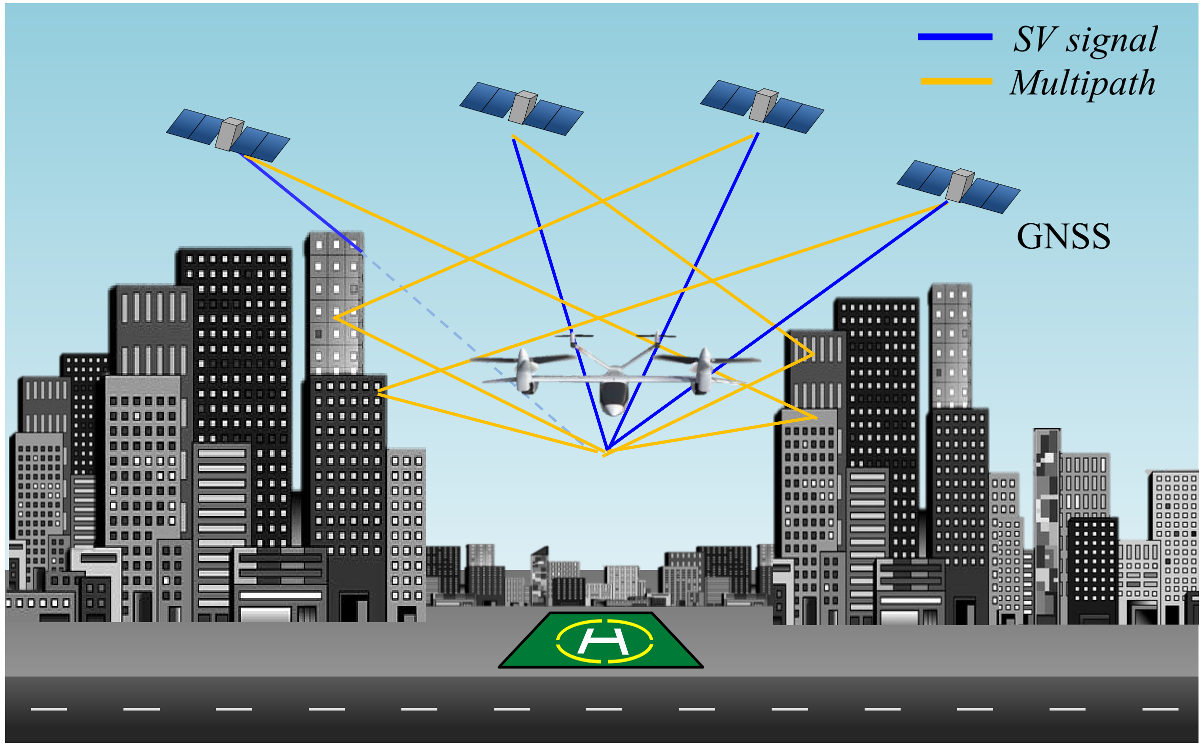
SBAS : Satellite Based Augmentation System
RAIM : Receiver Autonomous Integrity Monitoring
ARAIM : Advanced RAIM
RRAIM : Relative RAIM
PPP : Precise Point Positioning

Signal Blockage in Deep Urban Area

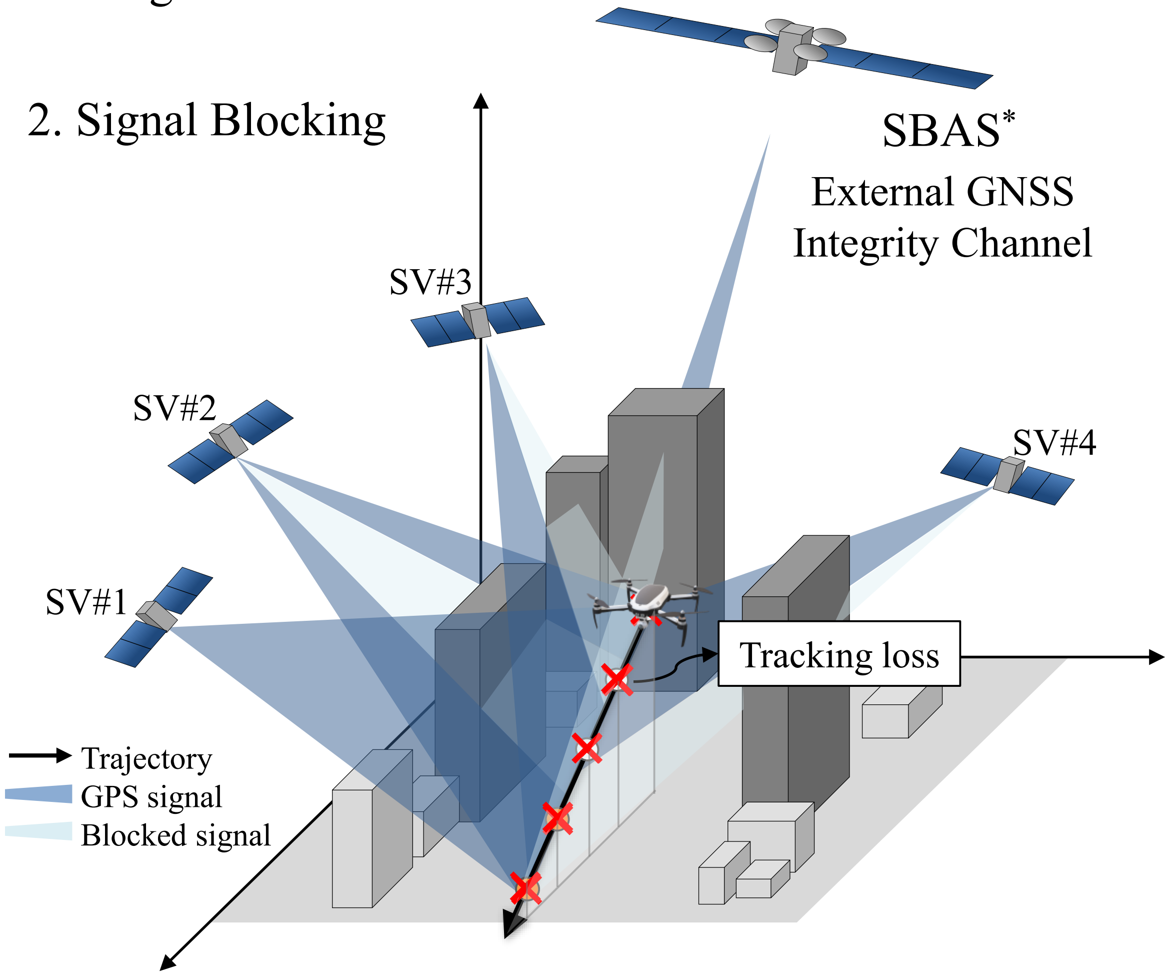
*SBAS : Satellite Based Augmentation System

- **Challenging environment for satellite navigation system**
  - Multipath interference and frequent signal blockage due to tall buildings
  - User must independently perform integrity monitoring for safe navigation

1. Extreme Multipath

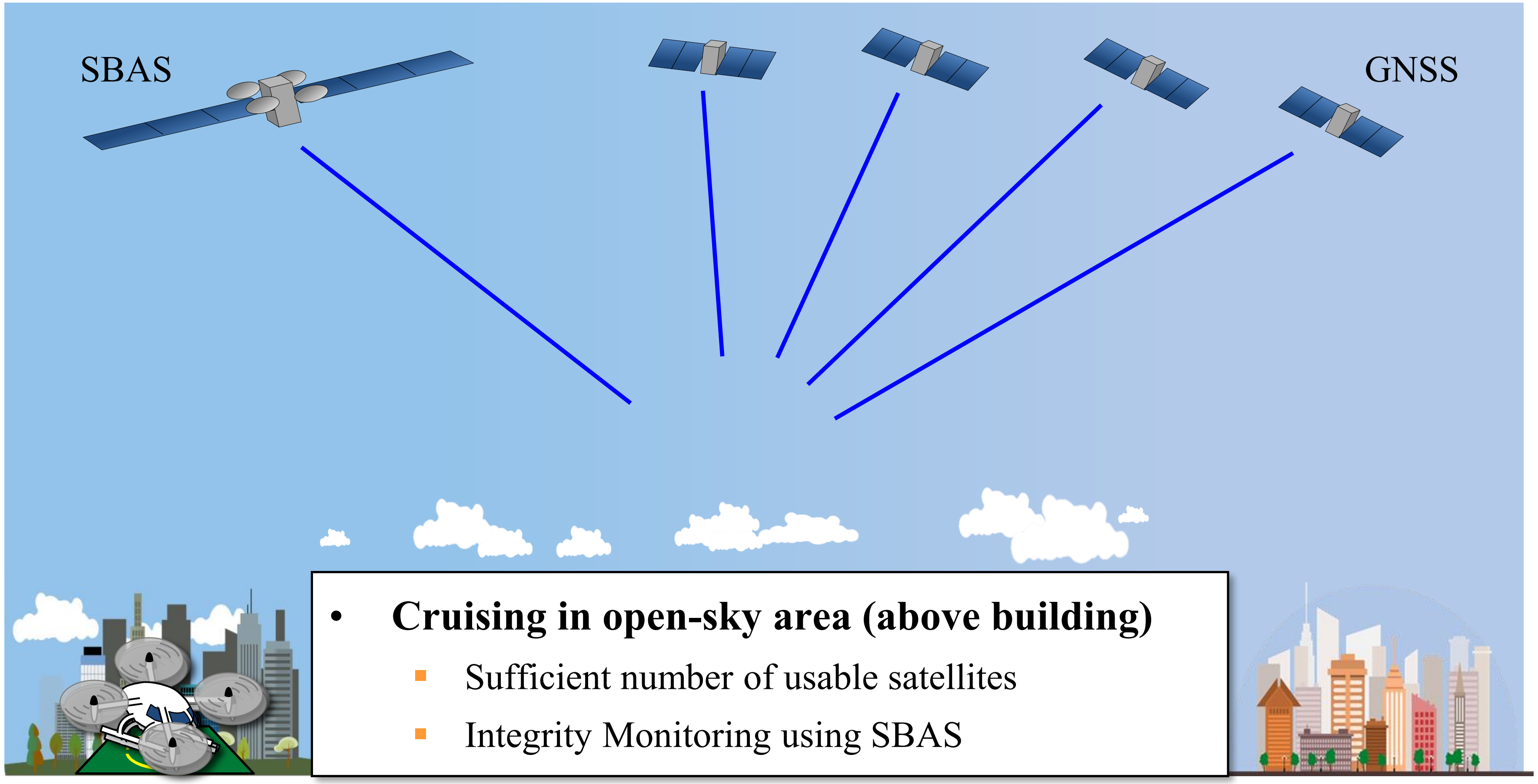


2. Signal Blocking



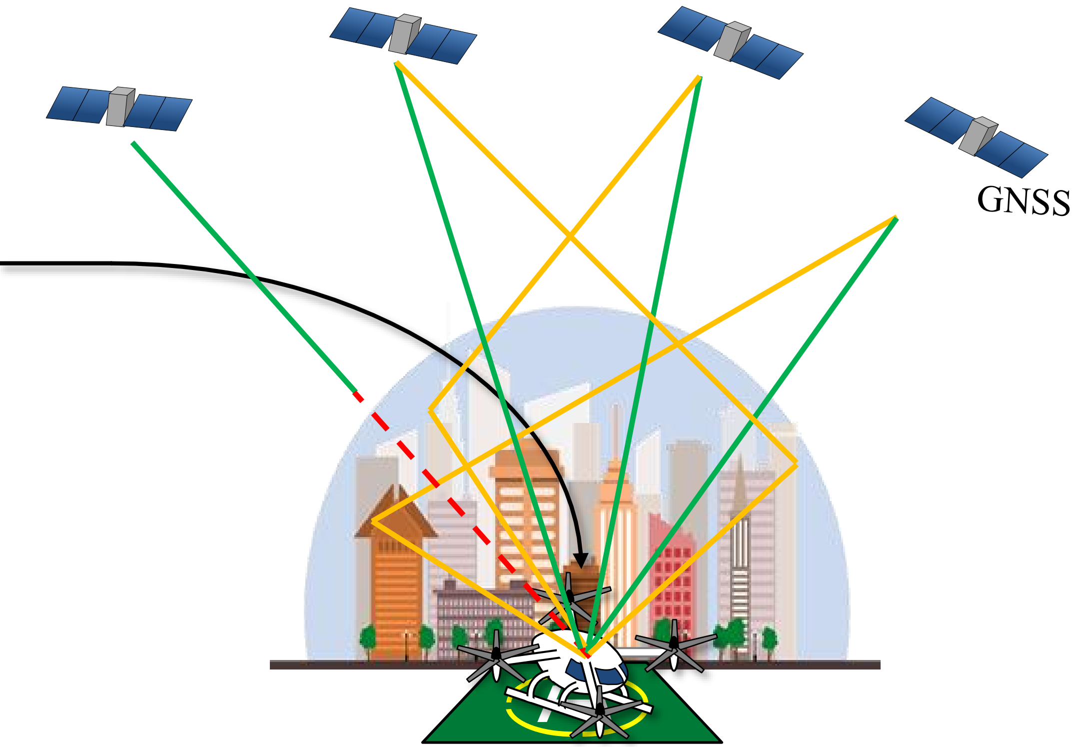
Background

- **Integrity Monitoring in UAM**
  - SBAS ensures the integrity of UAM in opensky, but may not in deep urban (blockage by buildings)
  - During landing into vertiport, problems occur in integrity



Background

- During landing into vertiport in deep urban area,
  - SBAS not available, extreme multipath, and frequent cycle slips due to tall buildings



❖ **Current Integrity Monitoring Methods in UAM**

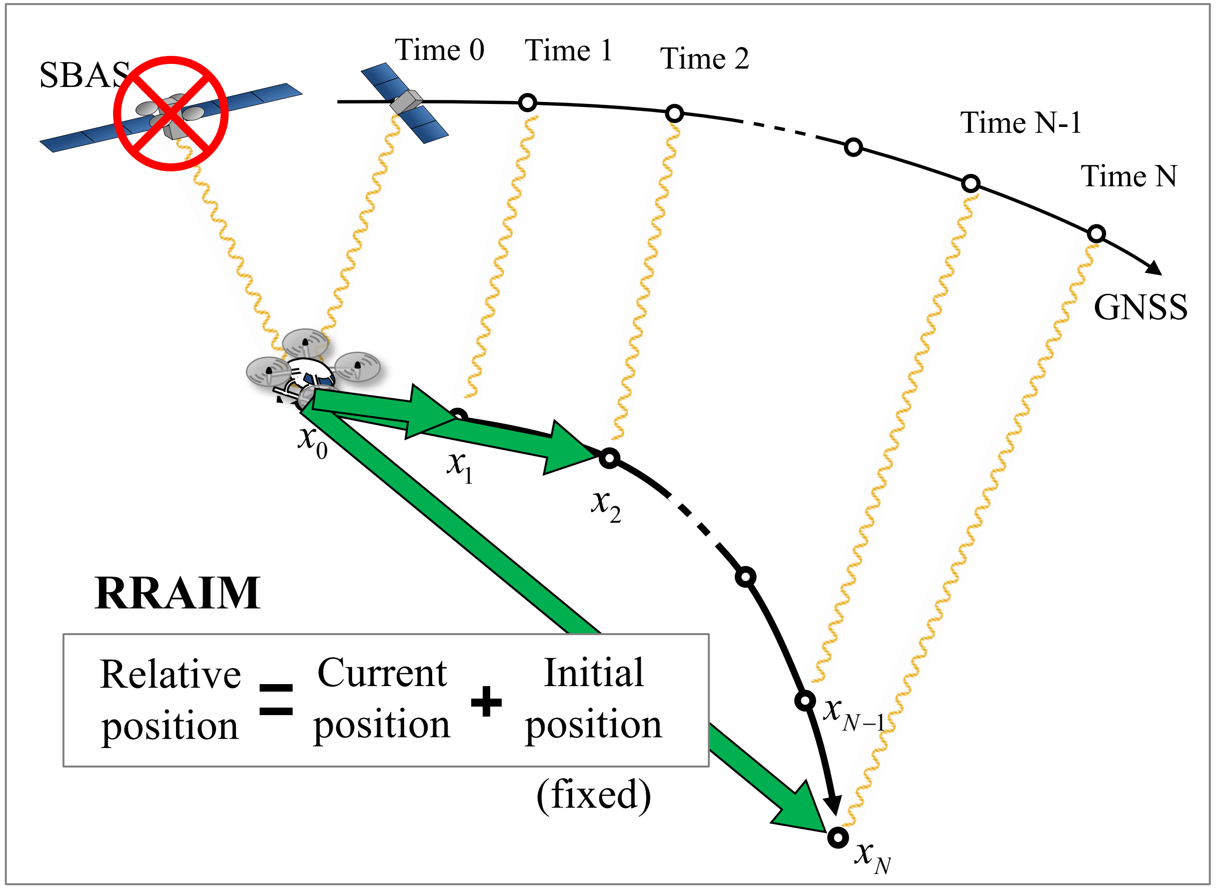
- ◆ Pseudorange measurement based (RAIM, ARAIM)
  - ➢ Strongly affected by extreme multipath environment
- ◆ Carrier phase measurement based
  - PPP (Precise Point Positioning)
    - ➢ Robust to multipath but long convergence time (~20min)
    - ➢ No guarantee to find correct integer ambiguity
    - ➢ Lack of usable satellites by signal blockage and frequent cycle slips
  - RRAIM (Relative RAIM)
    - ➢ Eliminate integer ambiguity using time difference between initial and current epoch
    - ➢ Lack of usable satellites by signal blockage
    - ➢ Very difficult to find cycle slips for long period (ex. 5mins)

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

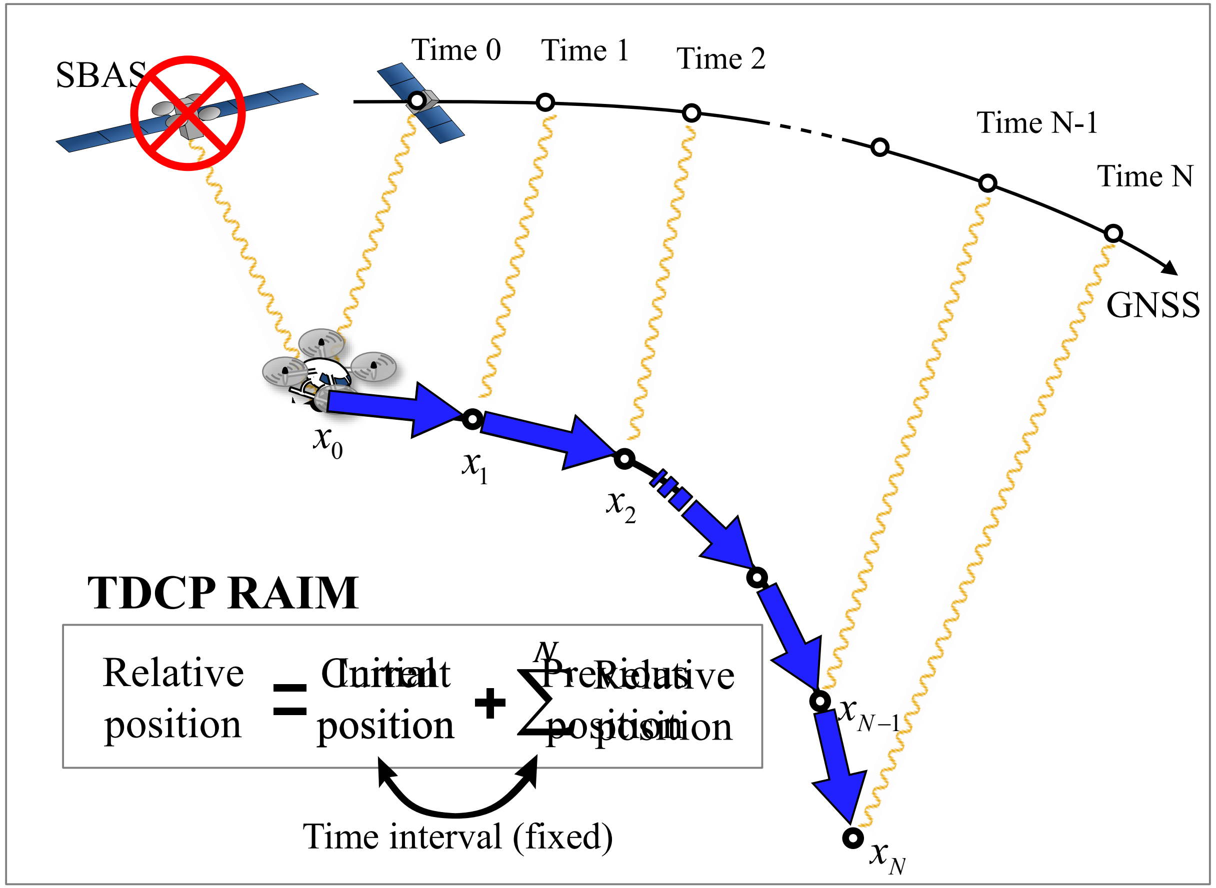
RRAIM (Relative Receiver Autonomous Integrity Monitoring) and TDCP RAIM (Time Differenced Carrier Phase RAIM)

Relative Navigation (RRAIM and TDCP RAIM)

- Both RRAIM and TDCP RAIM start with the integrity guaranteed position by SBAS
- Both methods use carrier phase measurement and time difference technique
- RRAIM uses time difference between **initial** and current epoch, But TDCP RAIM, **previous** and current
  (detection of cycle slip is very difficult!) (very easy using cheap IMU!)

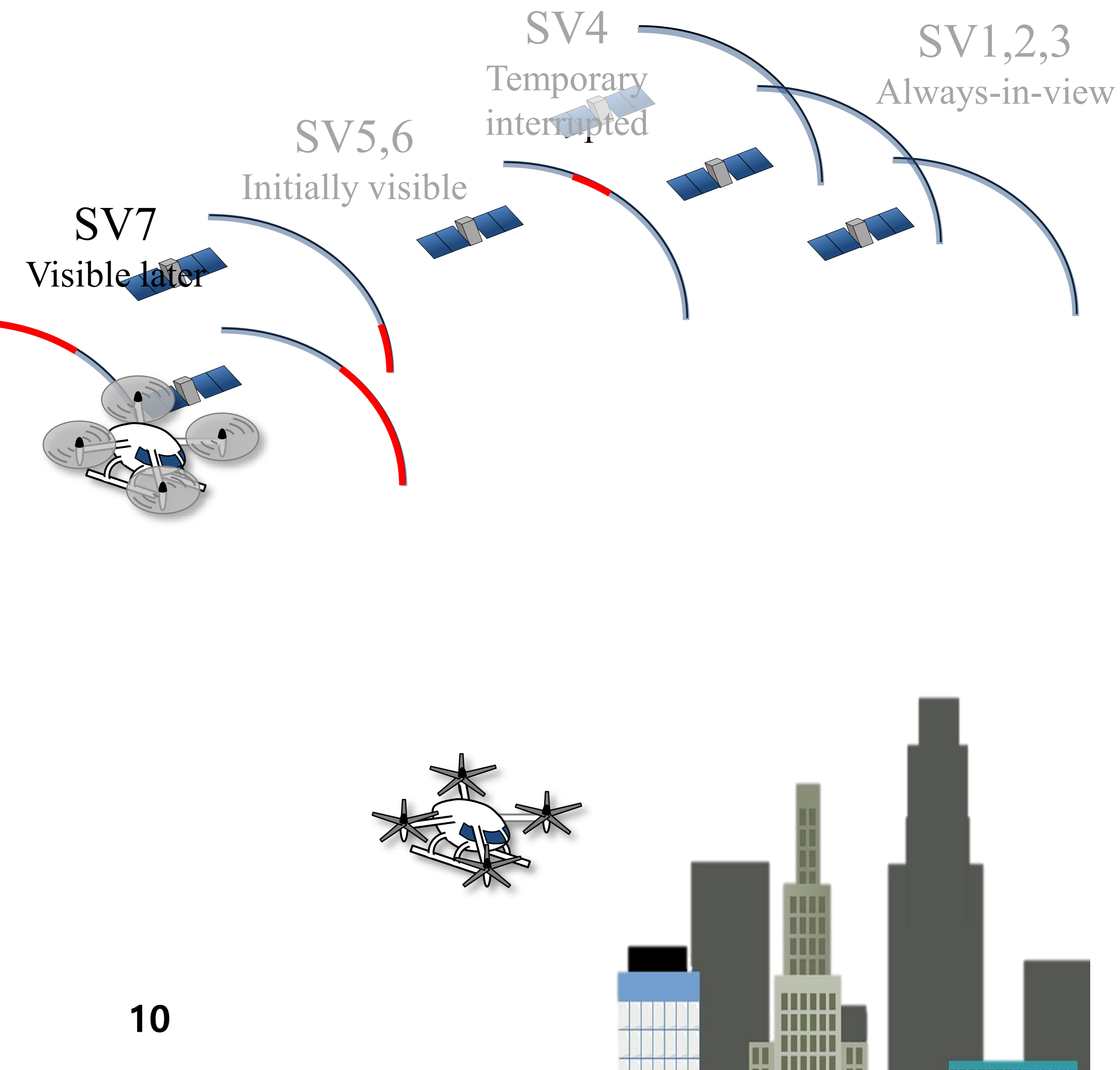


* Cycle slip detection for up to 5 min will be very hard even with expensive IMU!

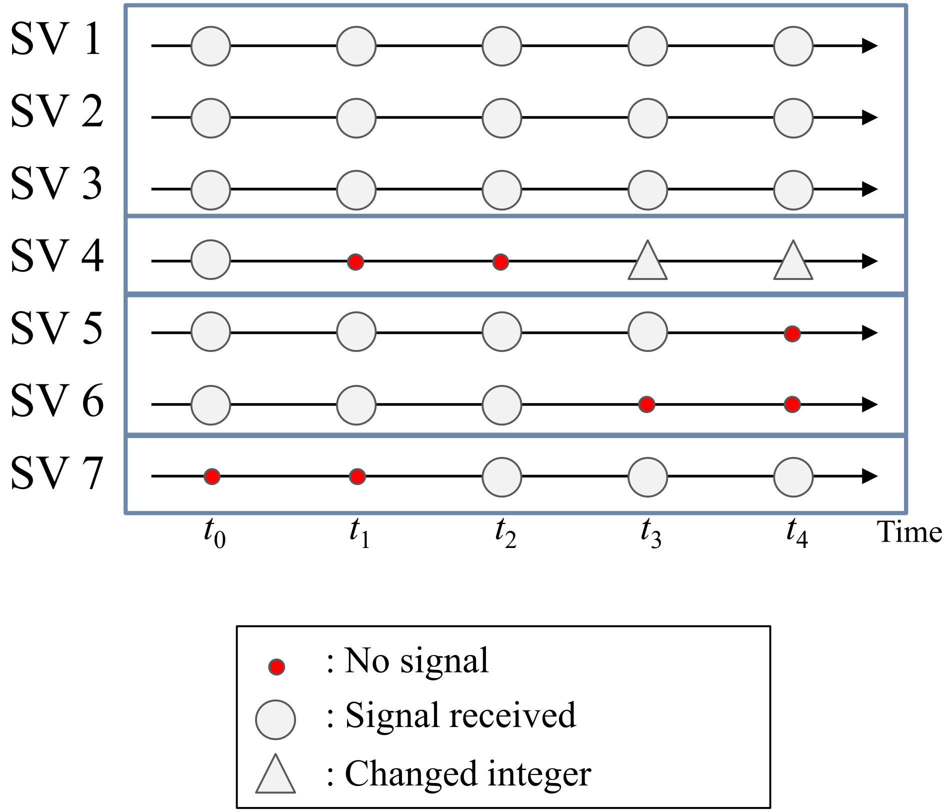


* Easy to detection cycle slip for 1 sec using even commercial grade IMU!

- **UAM landing scenario**
  - Various cases of visible satellite variations exist



Satellite in view

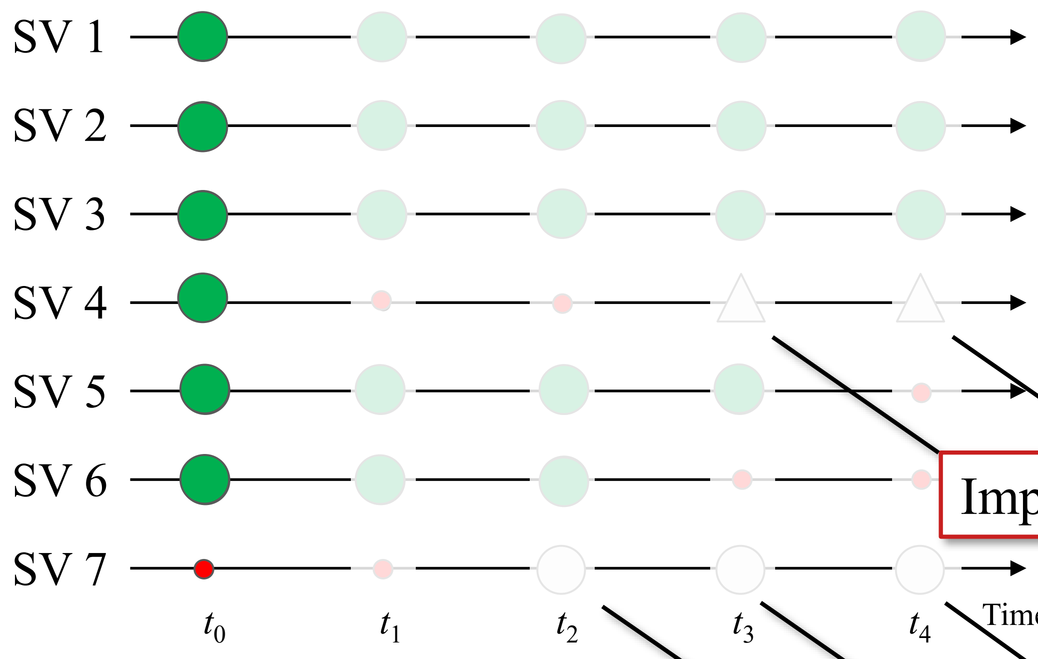


- **RRAIM**

Relative position = Current position − Initial position (fixed)

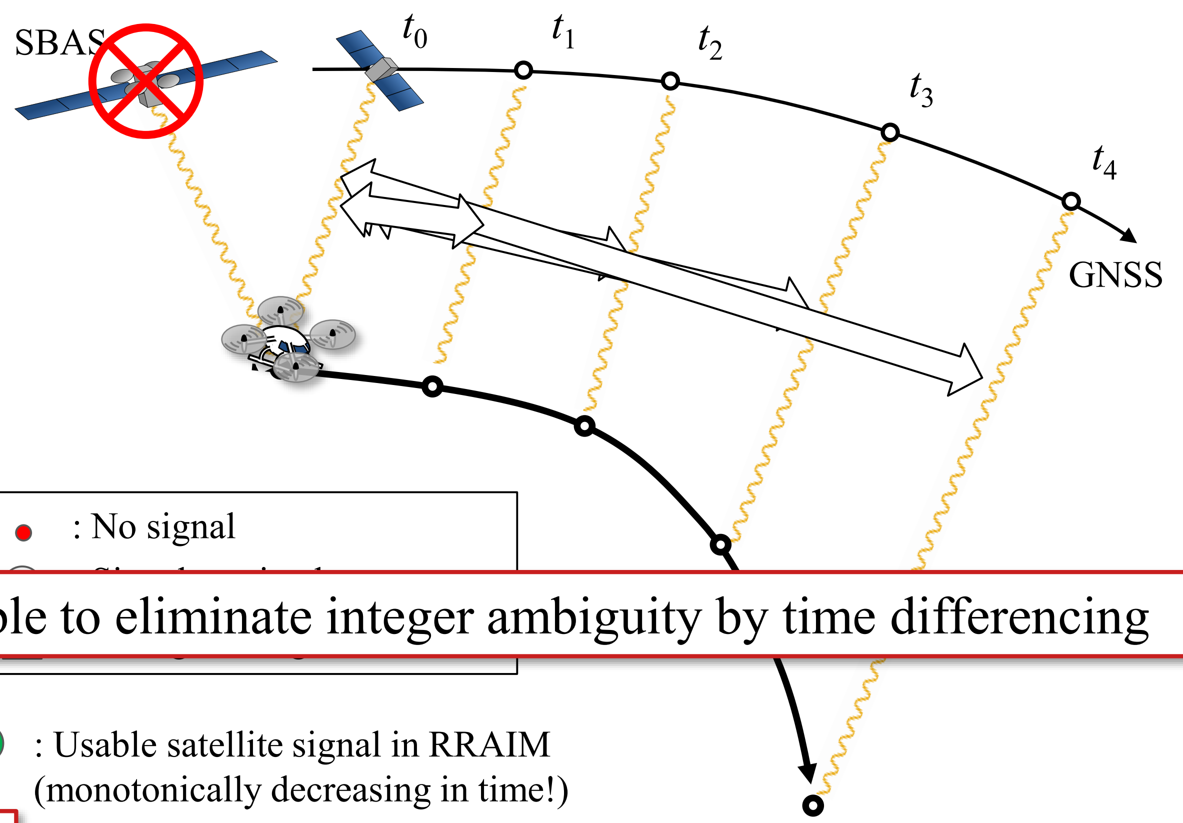
Minimum number required for integrity monitoring : 5

The number of usable satellites in RRAIM				
6	5	5	4	3



Impossible to use

Impossible to eliminate integer ambiguity by time differencing



: Usable satellite signal in RRAIM (monotonically decreasing in time!)

Usable Satellites in Urban Area

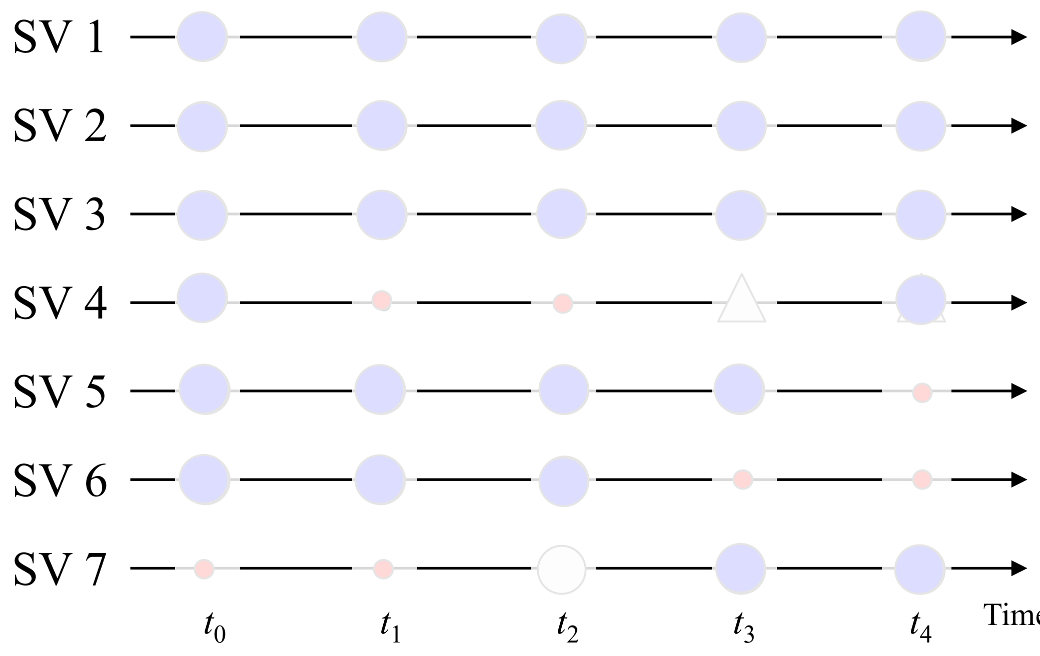
- **TDCP RAIM**

Time interval (fixed)

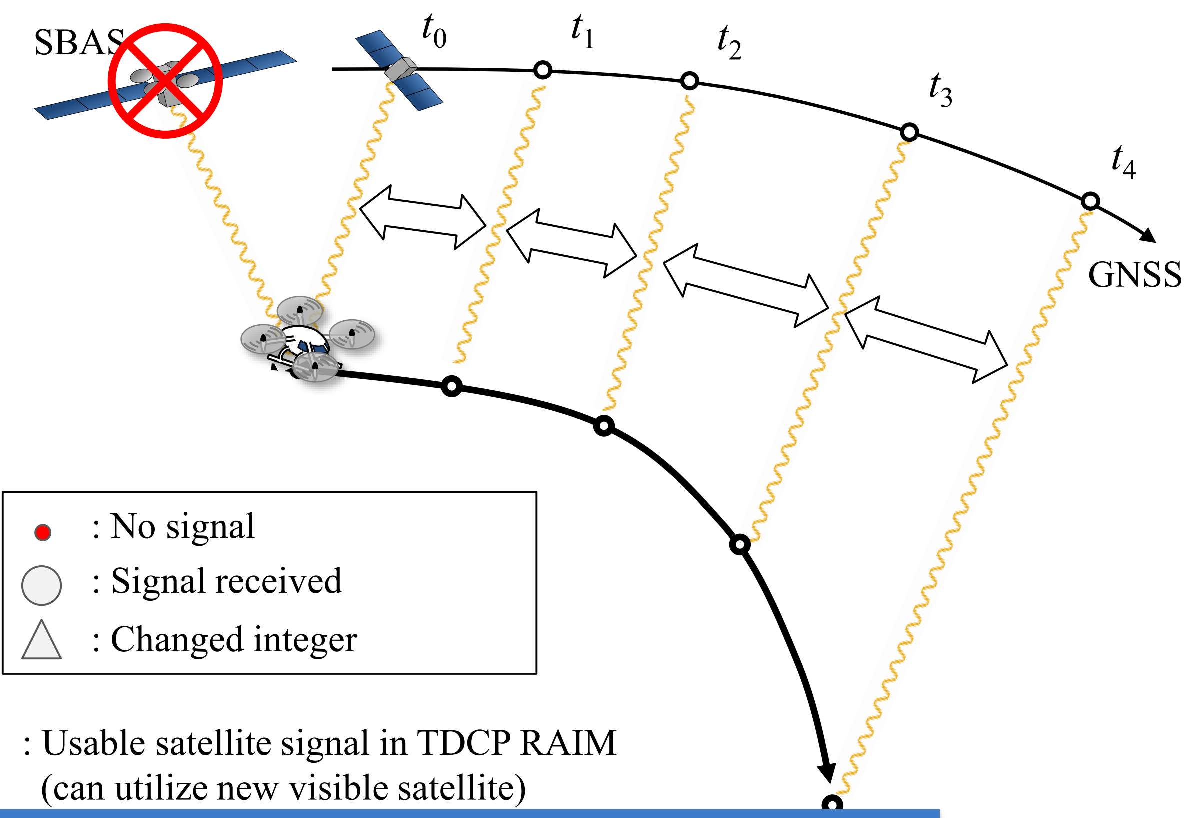
Relative position = Current position − Previous position

Minimum quantity satisfied !!

The number of usable satellites in TDCP RAIM				
6	5	5	5	5



Satellite in view



: Usable satellite signal in TDCP RAIM (can utilize new visible satellite)

TDCP RAIM uses more visible satellites compared to RRAIM!

TDCP RAIM

- **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)

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

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

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

where $\delta_t [\,]_k \triangleq [\,]_k - [\,]_{k-1}$
$\bar{x}$: true position
$\hat{x}$: estimated position
$\tilde{x}$: estimation error ($\triangleq \hat{x} - \bar{x}$)

Define new measurement:
(Geometry change compensated)

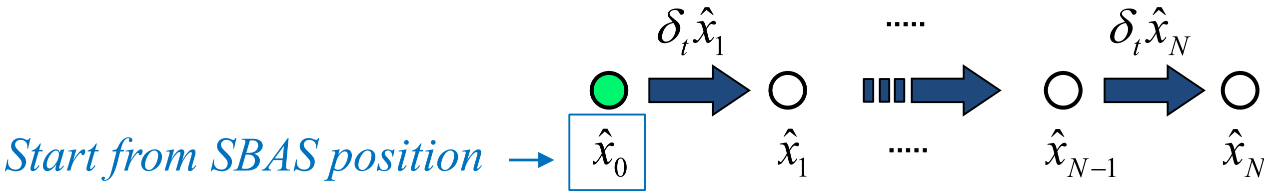
$$\boxed{\delta_t \bar{r}_k} \triangleq \delta_t \bar{\phi}_k - \boxed{\delta_t H_k \hat{x}_{k-1}}$$

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

estimation error

very small

- **Positioning Algorithm**



  - Accumulate the relative positions from initial position

very small

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

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

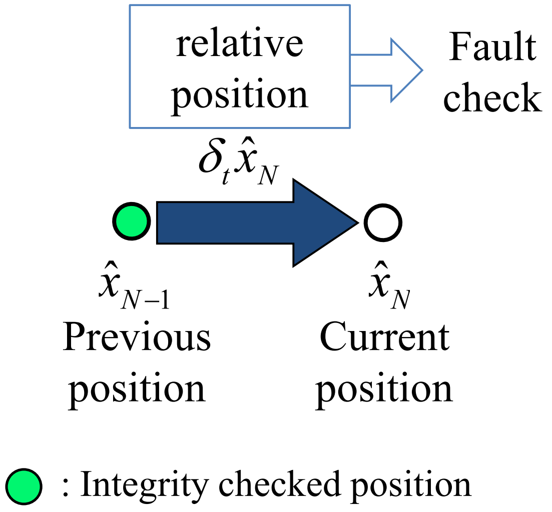
  - Correlation exists in solutions between initial position error ($\tilde{x}_0$) and current epoch ($\hat{x}_1$)

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

  - 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

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

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

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

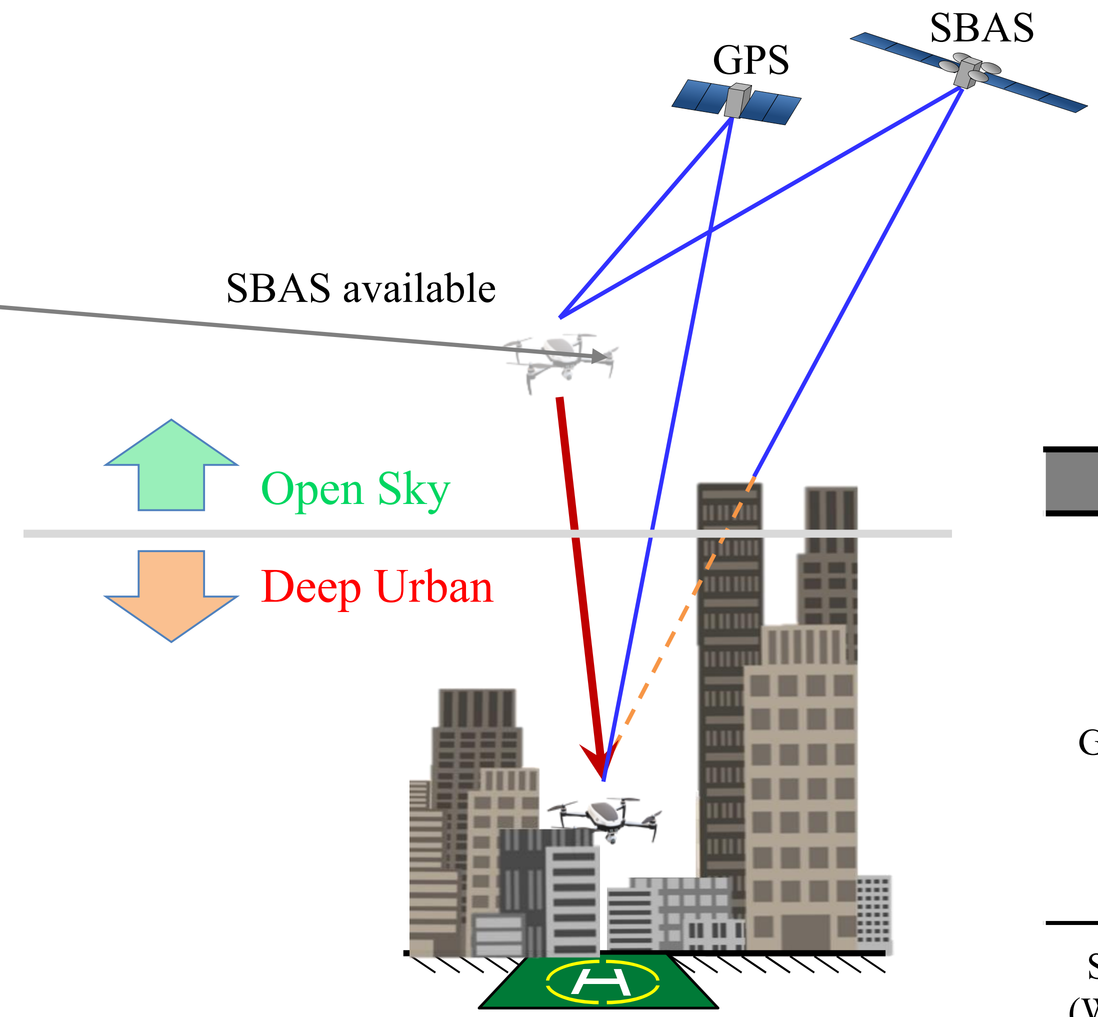
$\sigma_N : \sqrt{\operatorname{cov}\left(\hat{x}_{N-1} + \delta \hat{x}_N\right)}$

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

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

Simulation Results

Simulation Scenarios (Landing into Vertiport)



Landing Environment	Navigation
Open Sky	SBAS
Deep Urban	TDCP RAIM

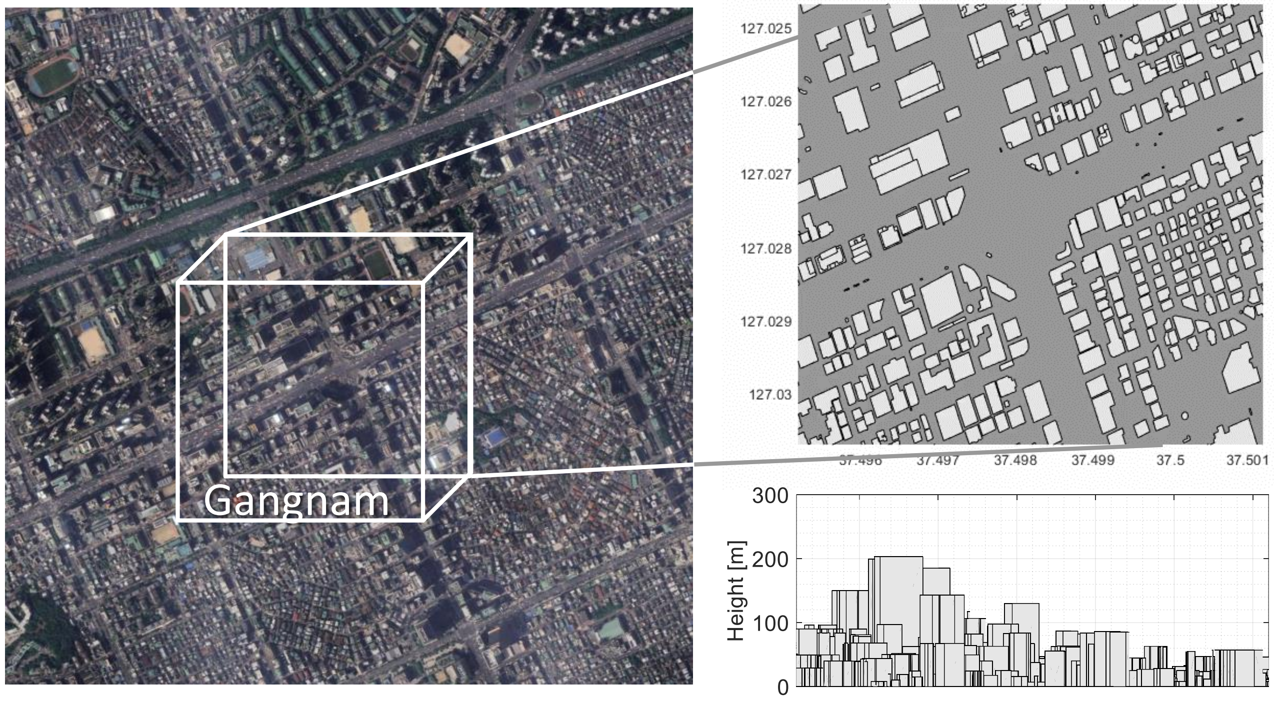
- **SBAS is available at initial epoch only**
- Integrity requirement : LPV-200, VAL = 35m

	Descirption	Data
GPS Galileo	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	

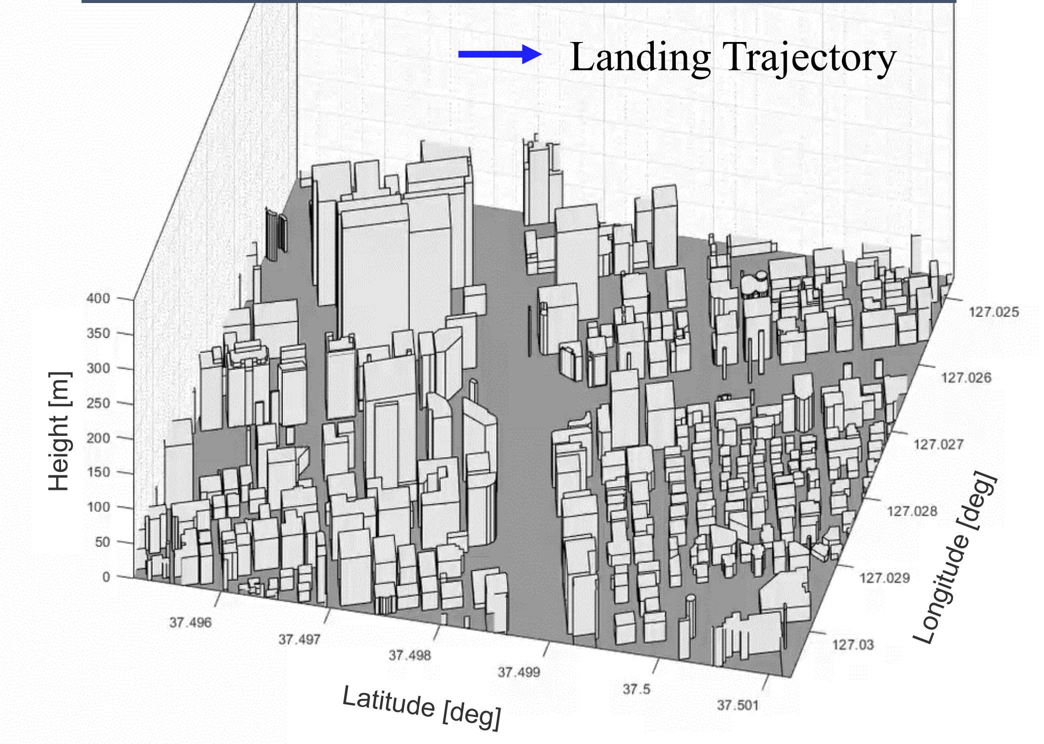
Simulation Scenarios (Landing into Vertiport)

- **Deep Urban Area simulations using 3D building model**
  - Center of Gangnam, Seoul, South Korea

3D City Model

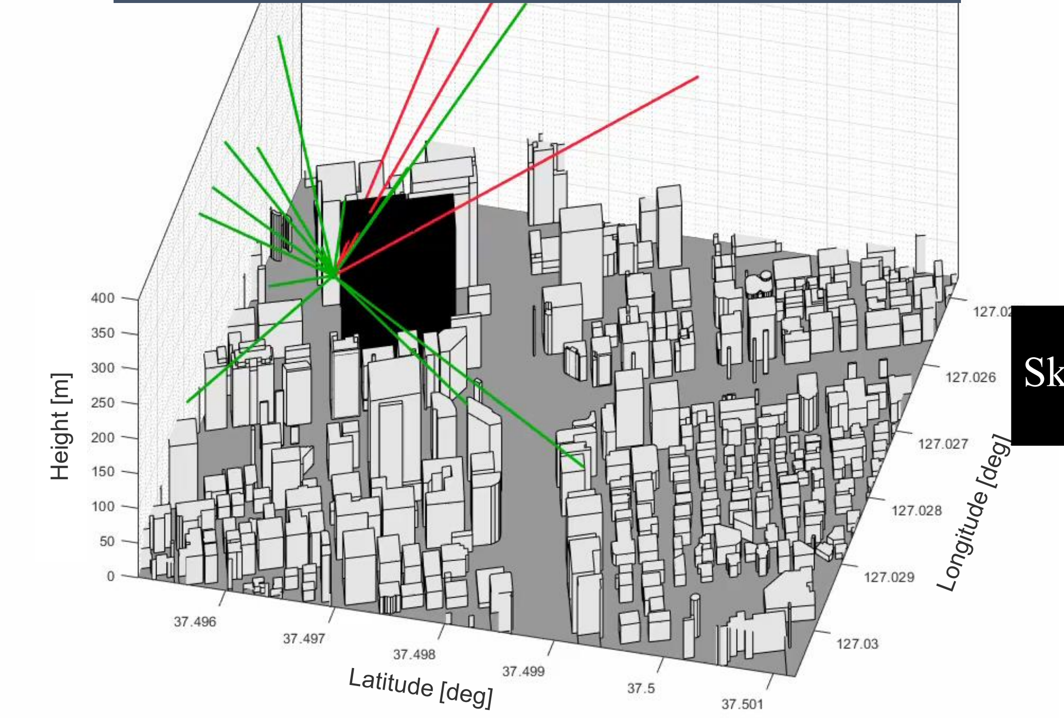


UAM Trajecotry



- **Deep Urban simulations using 3D building model**
  - Simulating signal blockage by buildings

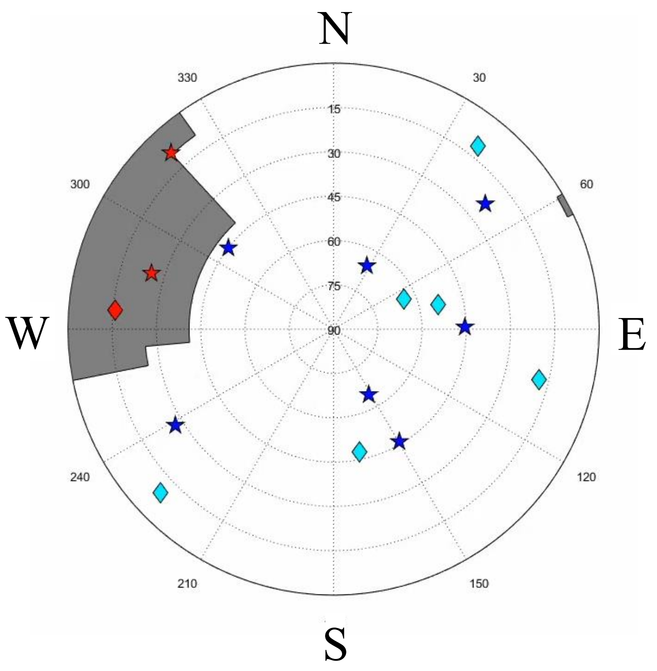
GNSS signal blocked by buildings

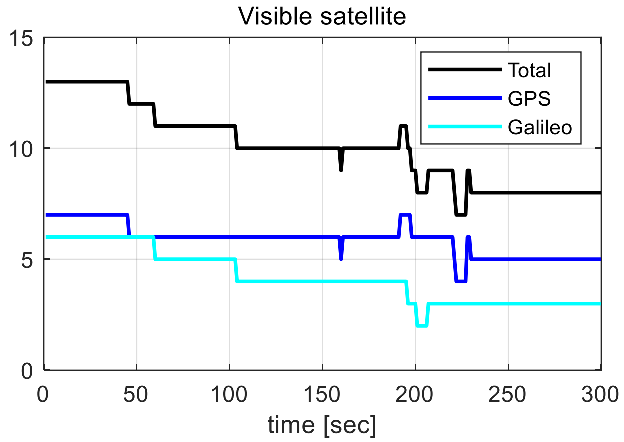


Blocked signal
Direct signal

Skyplot

The number of visible satellite with 3D City Model

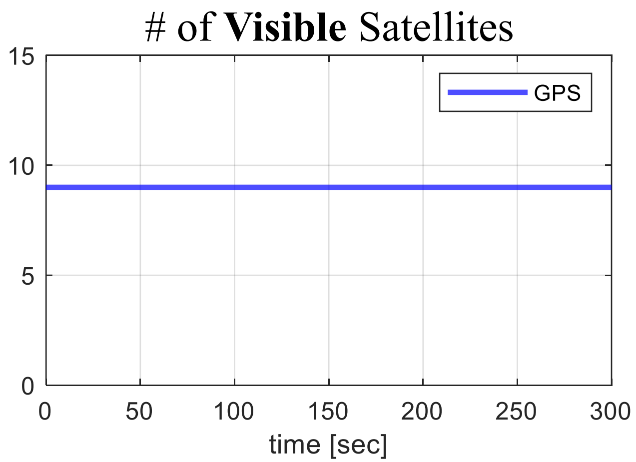


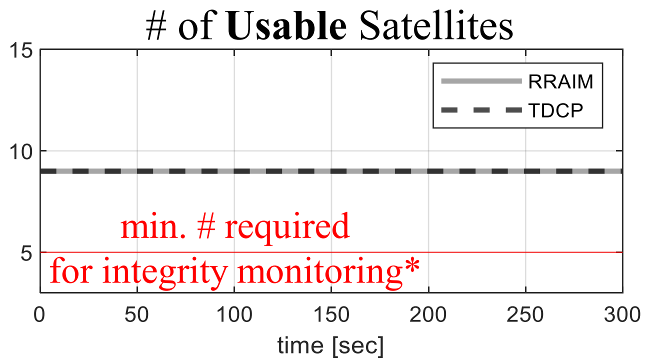


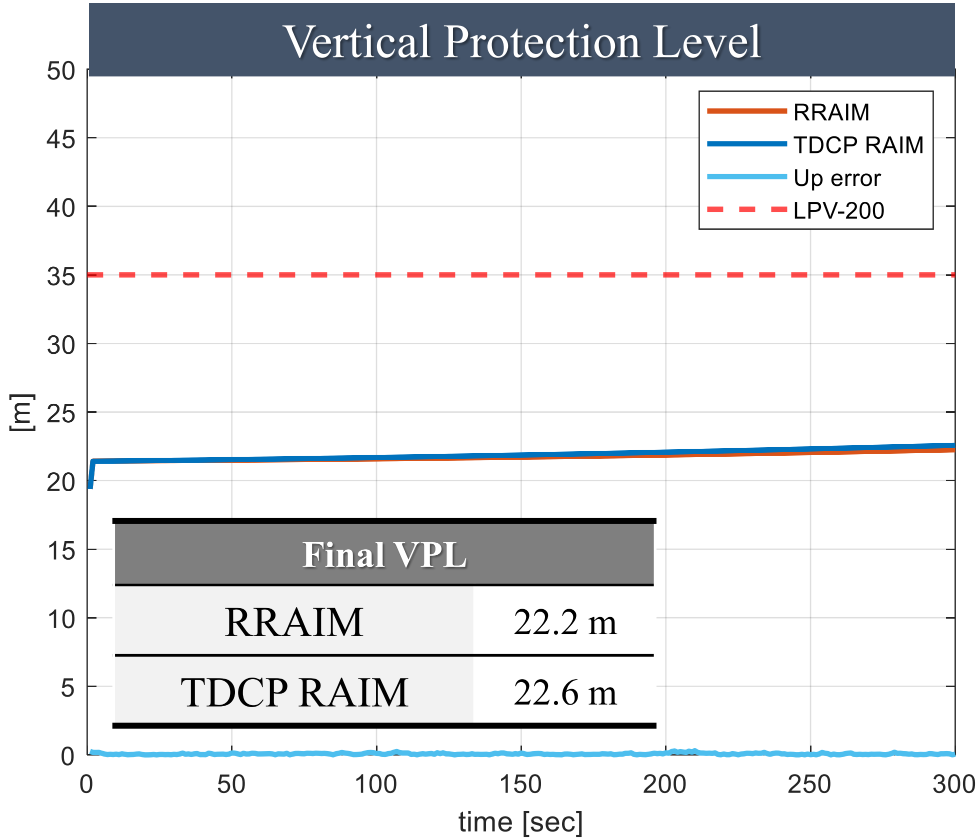
: GPS : Galileo

Simulation Results (Open Sky)

- **Open Sky (GPS only)**







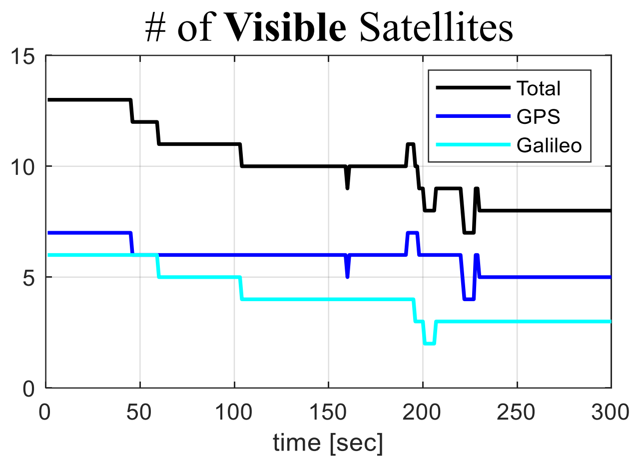
Final VPL	
RRAIM	22.2 m
TDCP RAIM	22.6 m

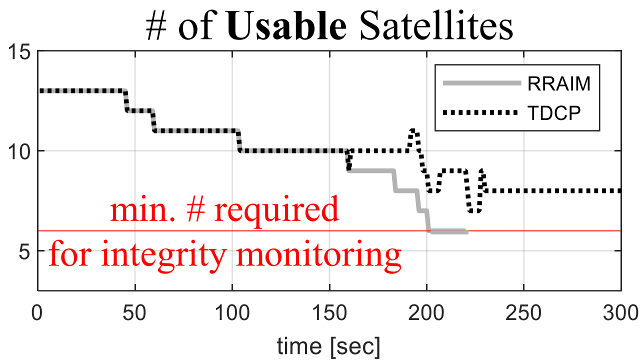
*: min # is 6 instead of 5 because of GGTO between GPS and Galileo

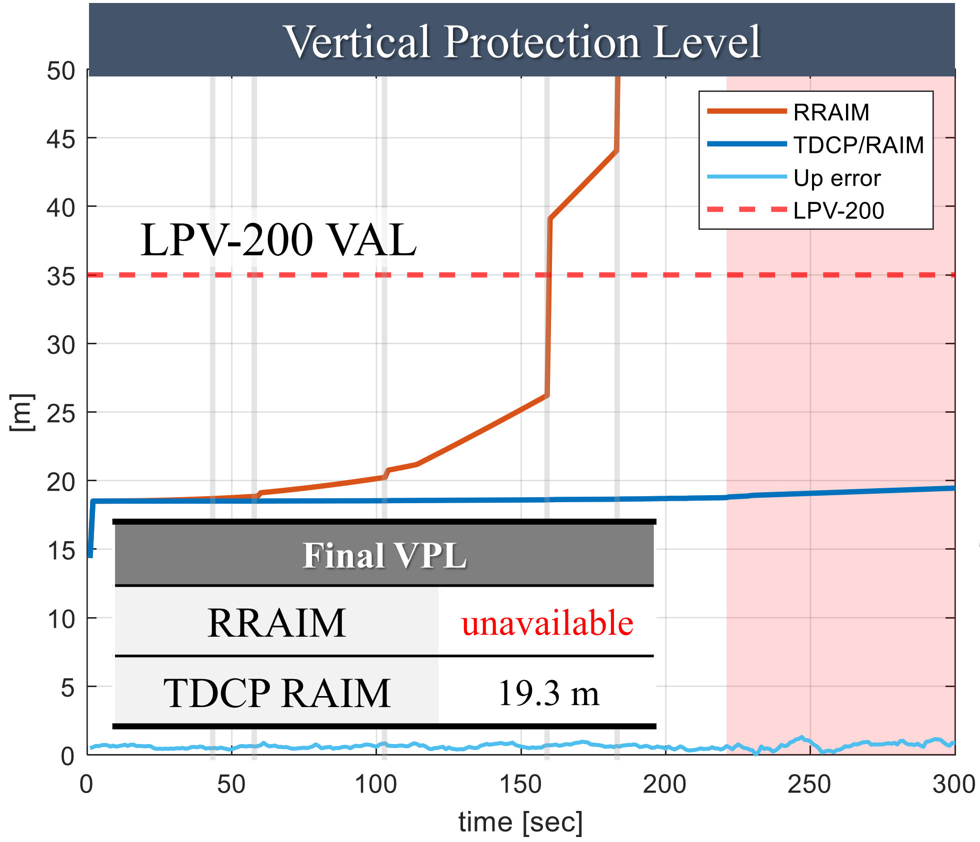
TDCP RAIM has almost same performance as RRAIM

Simulation Results (Deep Urban)

- **Deep Urban (GPS+Galileo)**







Final VPL	
RRAIM	unavailable
TDCP RAIM	19.3 m

Available Only for TDCP RAIM

Only TDCP RAIM is available in deep urban scenario!

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 (utilizes newly visible satellites)
  - Integrity maintained for 5 mins or more throughout landing on vertiport
  - Can be applied in Integrity Monitoring of autonomous vehicles and drones 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!***