Coordinated UAV Operations Based on Local-Area Differential GNSS Navigation and Guidance

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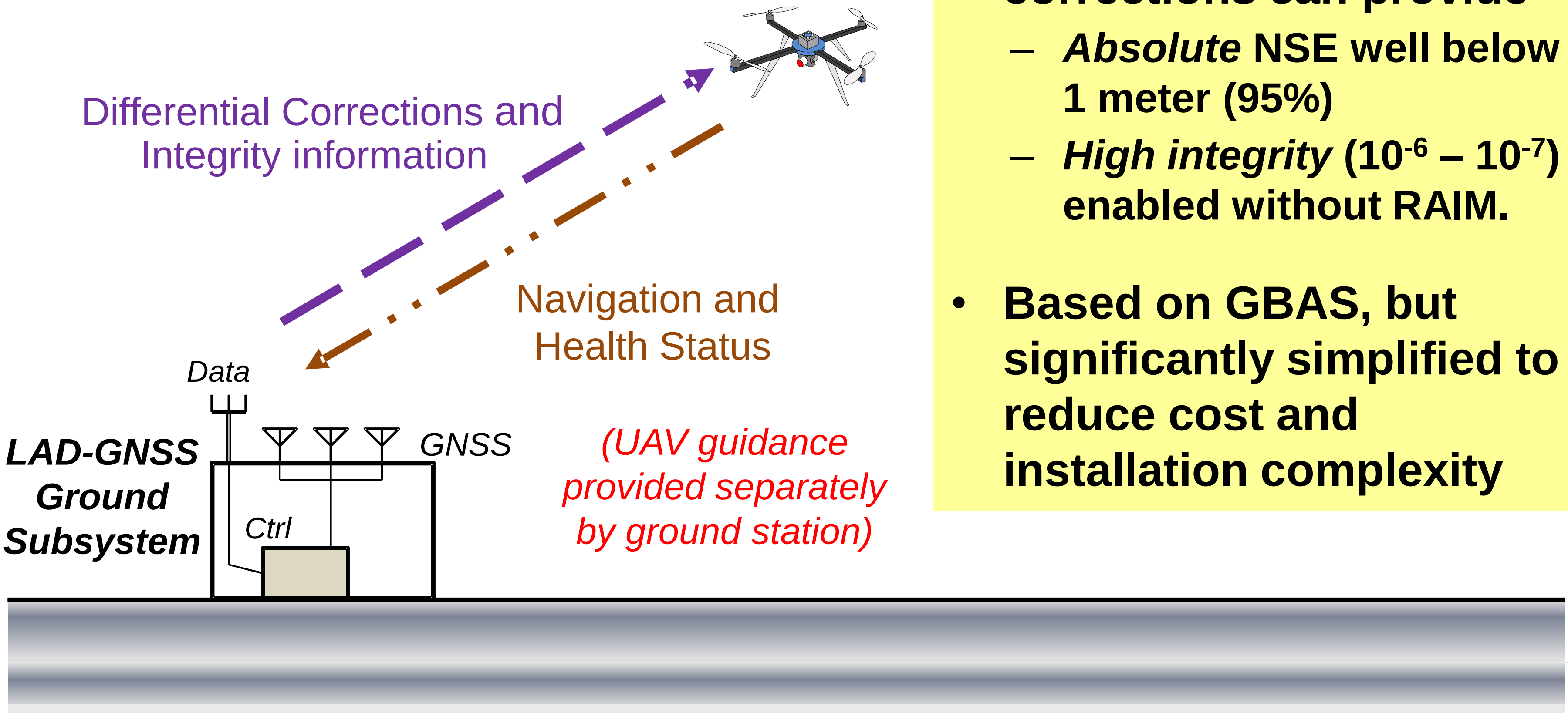
Outline

- UAV Networks using Local Area Differential GNSS (LADGNSS)
  - Simplified adaptation of GBAS to provide high-integrity navigation and separation from obstacles
  - Part of local-area (within ~ 25 – 50 km) UAV guidance system
- Coverage regions and operational zone definitions for “in-network” UAVs
- Combining operations with “out-of-network” UAVs whose location/velocity is known
- Handling “external” UAVs whose location is unknown
- Summary

Development of LADGNSS Networks for UAV Guidance

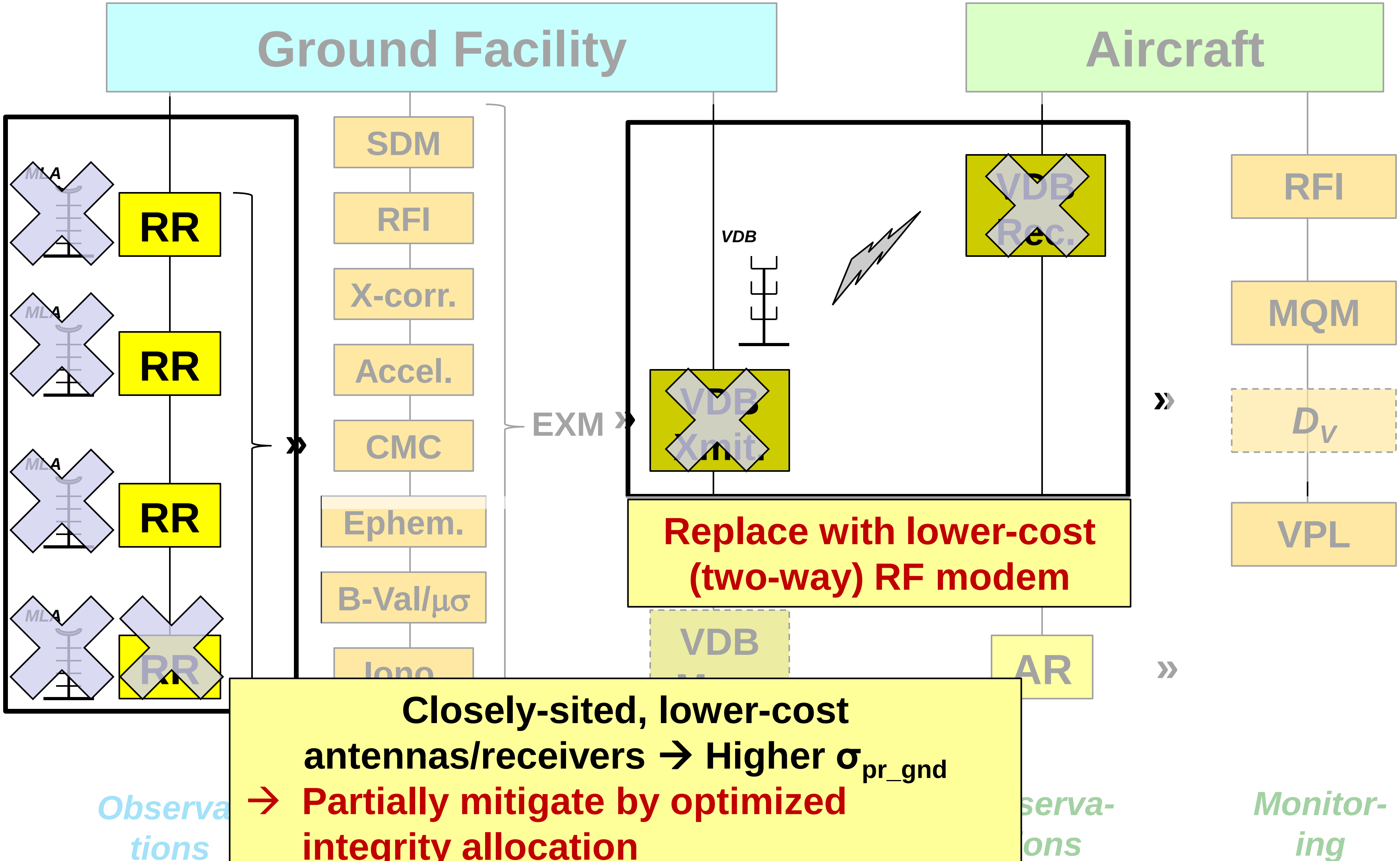
Issues addressed	Research Progress
A Concept of LAD-GNSS for UAV	• ***ION ITM 2013,*** *S. Pullen, P. Enge, J. Lee,* "LADGNSS Architectures Optimized to Support UAVs" • ***ION PNT 2013,*** *S. Pullen, J. Lee,* "Guidance, Navigation, and Separation Assurance for Local-Area UAV Networks"
UAV Operation Concept & Requirements	• ***ION PNT 2017,*** *M. Kim, J. Lee, D. Kim, J. Lee,* "Design of Local-Area DGNSS Architecture to Support UAV Networks: *Optimal Integrity/Continuity Allocations and Fault Monitoring"*
System Architecture	
Theoretical Performance Evaluation	
Prototype Development	• ***ION GNSS 2017,*** *D. Kim, J. Lee, M. Kim, J. Lee,* "High-Integrity and Low-Cost Local-Area Differential GNSS Prototype for UAV Applications*"*
Test-Bed Evaluation	
Multi-UAV Operations	• ***EIWAC 2017,*** *S. Pullen, J. Lee, M. Kim, D. Kim, J. Lee,* "Coordinated UAV Operations Based on Local-Area Differential GNSS Navigation and Guidance*"*

UAV Navigation and Guidance Using LADGNSS



- **Within 20-50 km of a central facility, LADGNSS corrections can provide**
  - ***Absolute* NSE well below 1 meter (95%)**
  - ***High integrity* (10^{-6} – 10^{-7}) enabled without RAIM.**
- **Based on GBAS, but significantly simplified to reduce cost and installation complexity**

LADGNSS Architecture from GBAS (1): *Lower-cost Hardware and Installation*

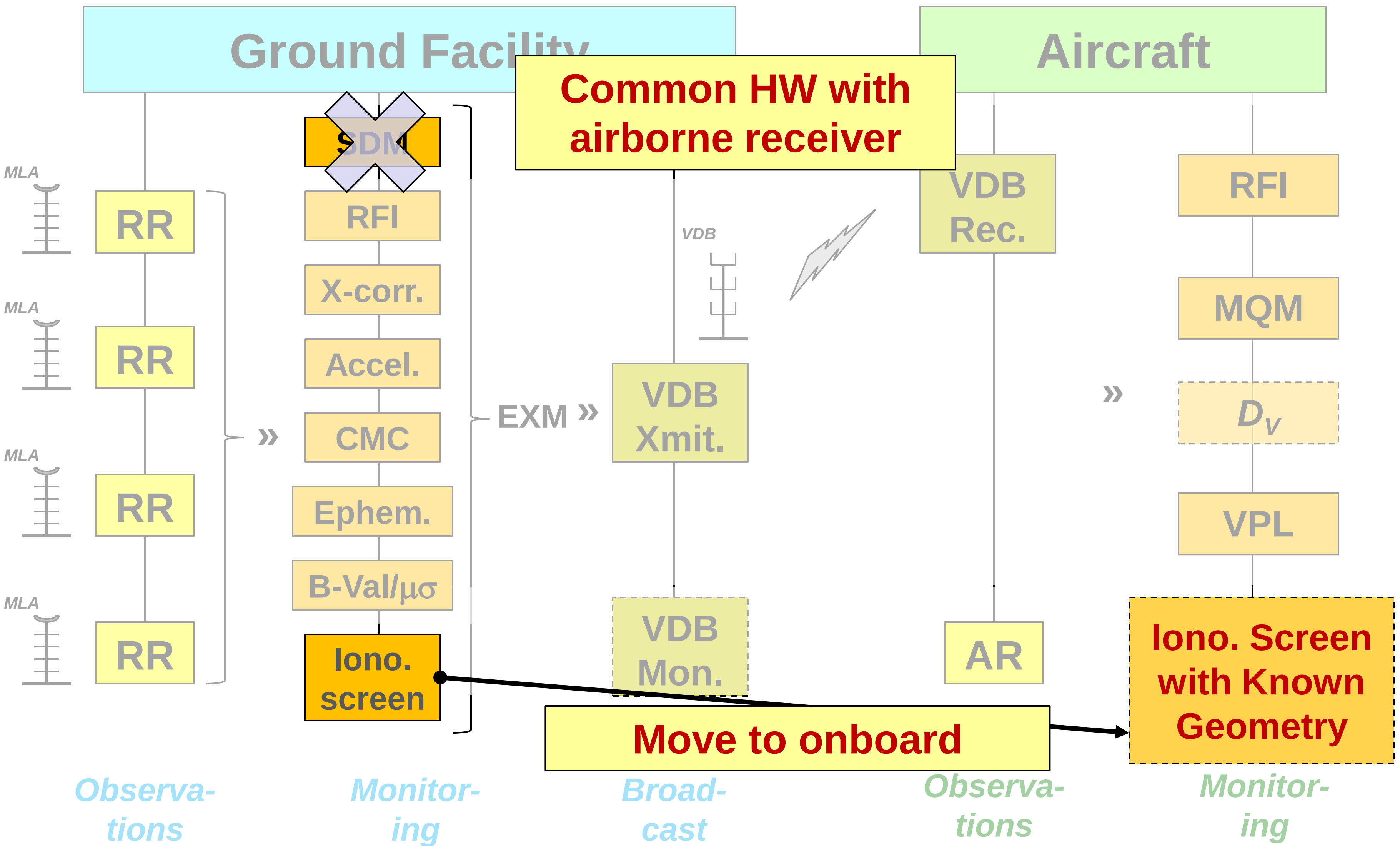


Replace with lower-cost (two-way) RF modem

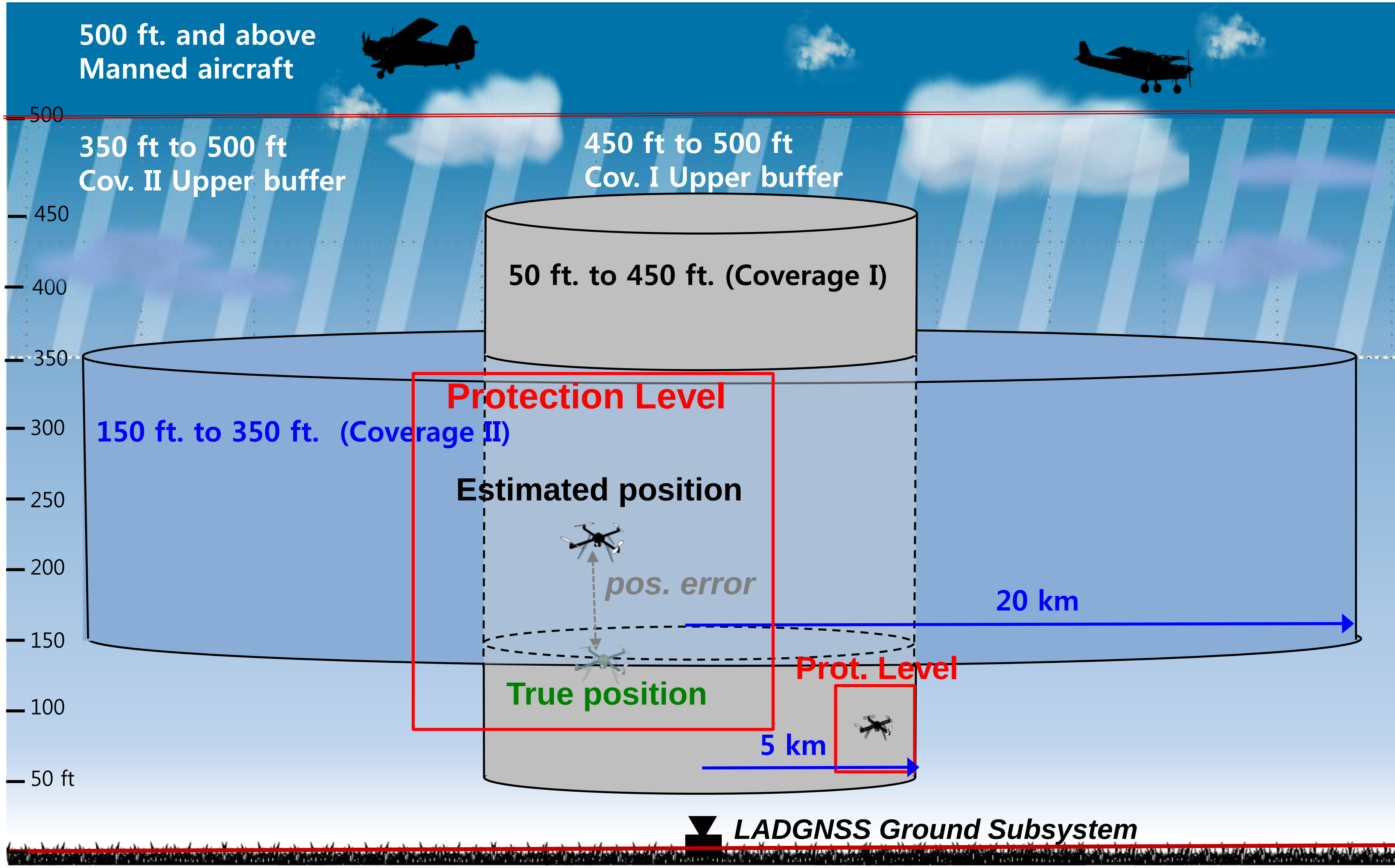
Closely-sited, lower-cost antennas/receivers → Higher σ_{pr_gnd}

→ Partially mitigate by optimized integrity allocation

LADGNSS Architecture from GBAS (2): *Simplified Monitoring Algorithms*

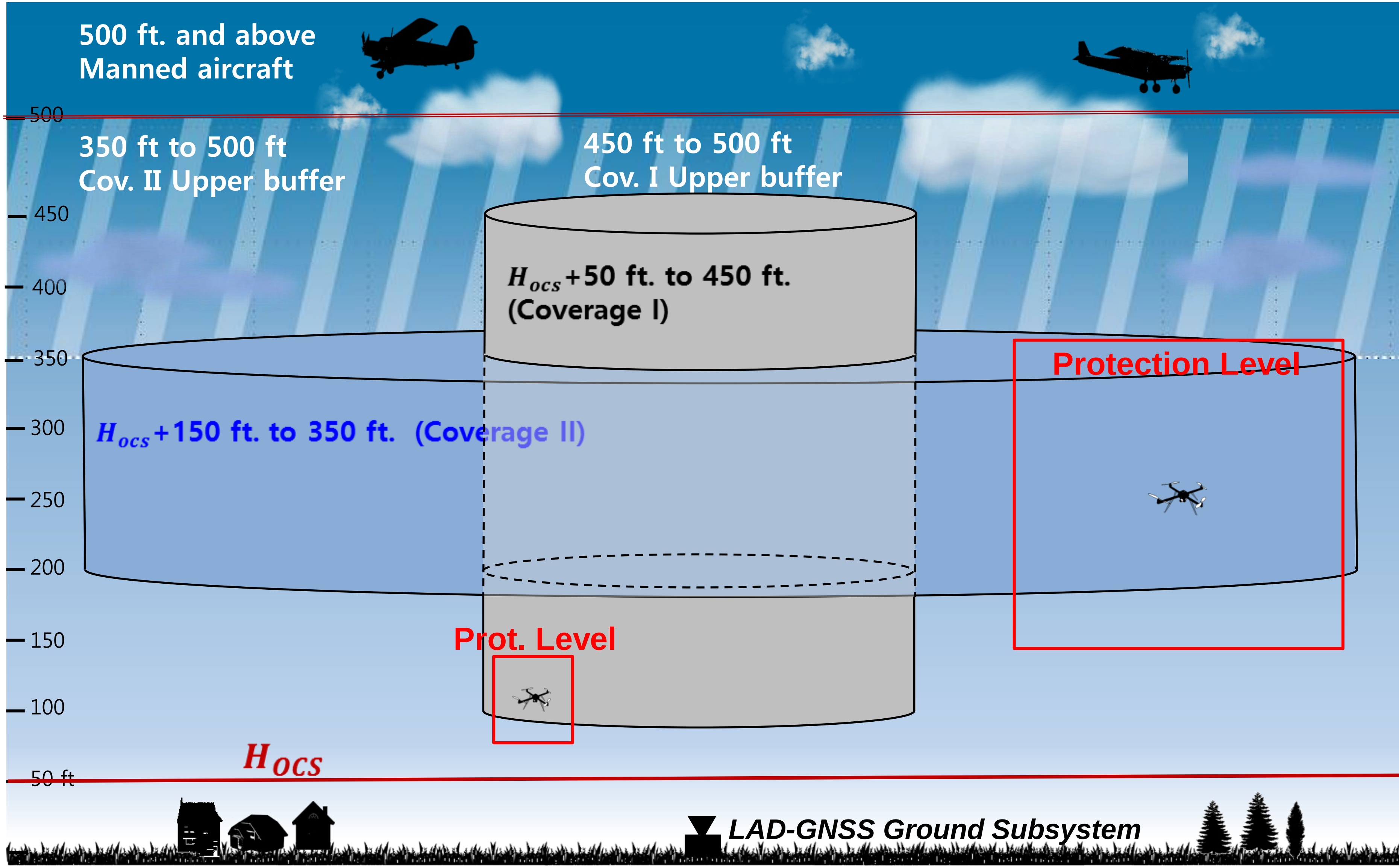


Local-Area Network Coverage Regions (1)



H_{OCS}: *height of obstacle clearance surface*

Local-Area Network Coverage Regions (2)



H_{OCS}: *height of obstacle clearance surface*

Zones of Influence and Operation

- ***Zones of Influence (ZoIs)*** **bound position uncertainty around each UAV relative to nearby collision risks (e.g., buildings, other UAVs)**

- **For separation among UAVs, the Zone of Influence is the combination of navigation error protection level and margin for flight technical error.**
  - **Probabilities covered by error bounds are derived from acceptable collision risks (e.g., 10^{-6} per minute).**

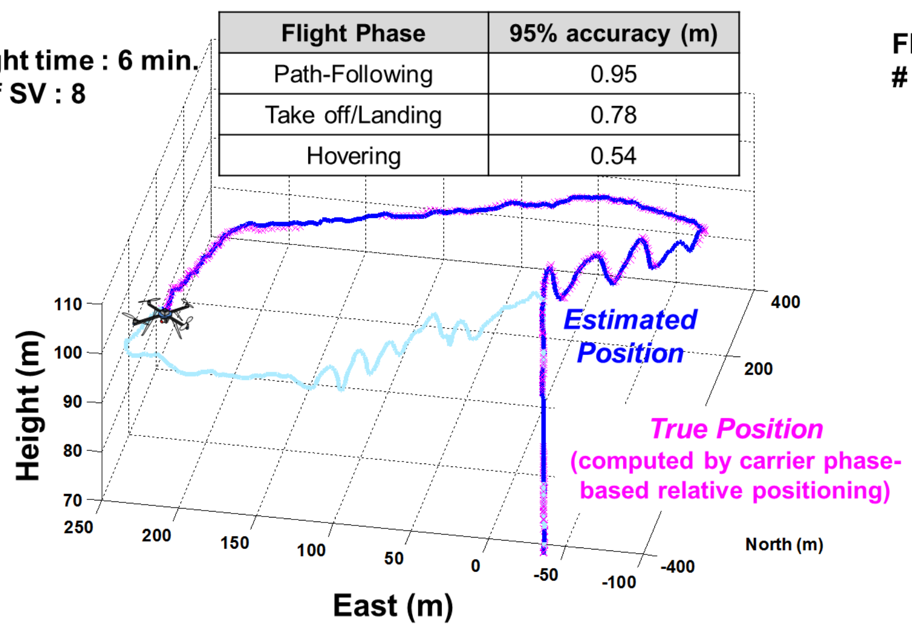
- ***Zones of Operation (ZoOs)*** **represent the assigned airspace surrounding the ZoI of each UAV.**
  - **Additional space surrounding ZoI provides margin for UAV maneuvering and delays in guidance response.**

Typical Errors and Bounds

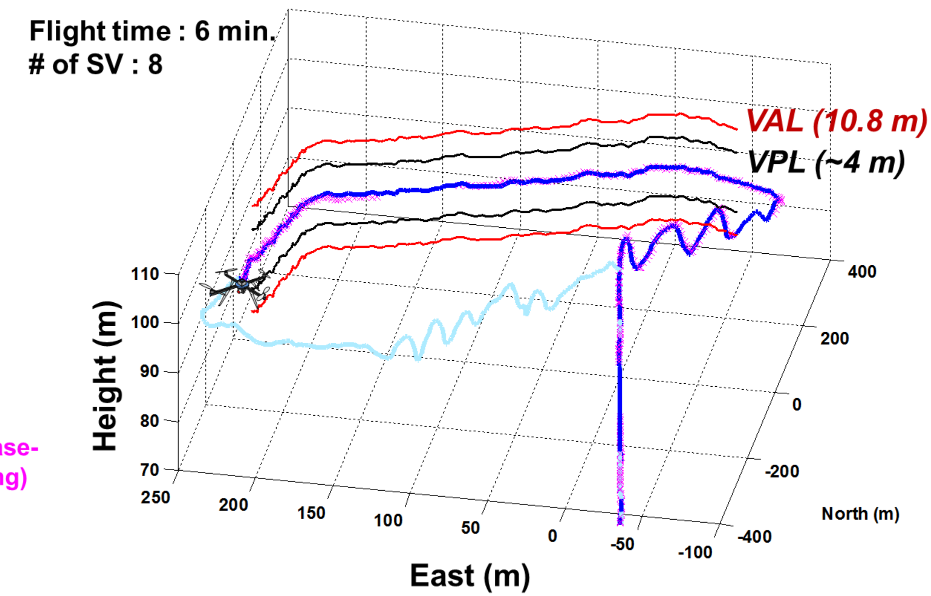
From Recent KAIST Flight Test (September 2017)

Vertical Errors

Flight Phase	95% accuracy (m)
Path-Following	0.95
Take off/Landing	0.78
Hovering	0.54



Vertical Protection Levels



- **95% vertical (and horizontal) navigation errors around 1 meter**
- **Vertical (and horizontal) protection levels well below 10.8 meter limit**

Zone-of-Operation Allocations for In-Network UAVs

Based on past analyses and flight-test results, assume (conservatively):

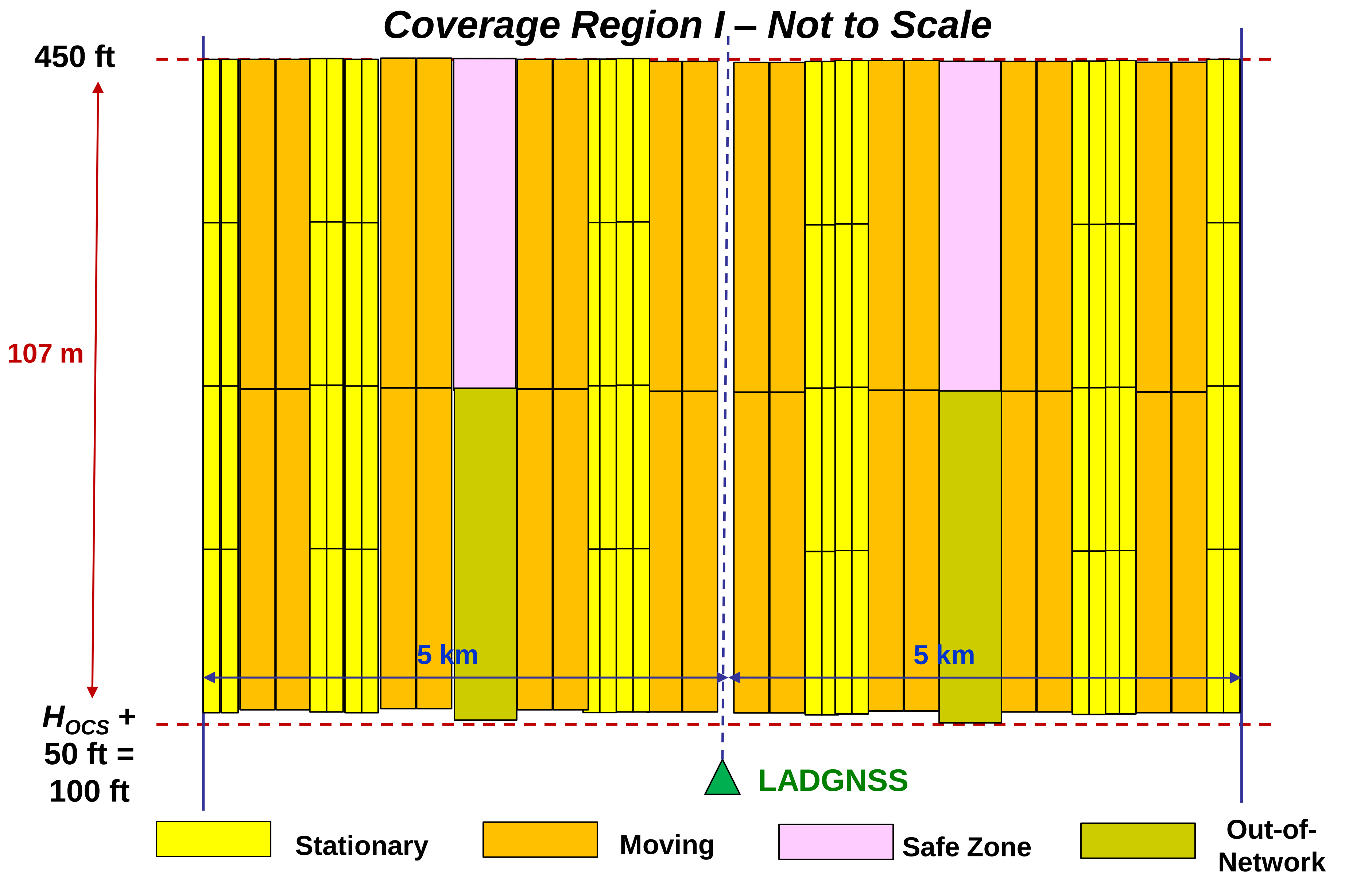
Coverage Region	HPL (m) *Horizontal Protection Level*	VPL (m) *Vertical Protection Level*	FTE (m) *Flight Technical Error*	ZoI (m) *Zone of Influence*	ZoO (m) *Zone of Operation*
I (inner)	7.5	10	10	15	25
II (outer)	15	20	10	25	40

$$\text{ZoI} \approx \{ [\max(\text{HPL}, \text{VPL})]^2 + \text{FTE}^2 \}^{0.5}$$

Multi-UAV Coordination for In-Network UAVs

- In-network UAVs are grouped into "moving" and "stationary" categories.
  - "Stationary" includes slow speeds that are easy for guidance to keep up with (e.g., less than $|v| \approx$ 5 m/s $\approx$ 16 km/hr)
- Airspace is assigned to stationary in-network UAVs in rectangles of size ZoO.
- Separate paths are assigned to moving UAVs with rectangles of size (ZoO + ZV), where ZV accounts for the extra guidance margin (for prediction) required.
  - ZV is TBD but is notionally about 3.3 $|v|$, with $|v|$ in m/s
- Moving UAVs slow to within "slow speed" constraint before they can be inserted into "stationary" airspace rectangles (of size ZoO).

2-D Illustration of Airspace Allocation for In-Network UAVs



Continual Reallocation of UAV Airspace

- **The airspace allocations to blocks of stationary and moving UAVs change with time due to:**
  - **Stationary UAV mission requirements (e.g., observation vehicles migrating to new positions)**
  - **Moving UAV deployment needs (to reach specific zones within the airspace)**
  - **Providing space for out-of-network or external UAVs as they appear**
- **Handling changes to in-network UAV assignments should be straightforward.**
- **Handling out-of-network or external UAVs is challenging because their appearance or objectives cannot be predicted in advance.**

Handling Out-of-Network UAVs

- ***Out-of-network UAVs*** **are those that broadcast their position, velocity and other useful information.**
  - **Indicating source of guidance (e.g., GNSS and which type) would help reduce conservatism in ZoI calculations.**
- **A standard UAV-UAV or UAV-ground datalink and message definition is needed to make this possible.**
- **ZoIs and ZoOs for out-of-network UAVs will be larger than those for in-network UAVs due to lack of navigation commonality and greater guidance lags.**
- **Space must be reserved in Coverage Region II to be ready for out-of-network UAV appearance.**
  - **Adjust existing airspace to "move away from" incoming UAVs**

Handling External UAVs (1)

- ***External UAVs*** **are defined as those that do not provide any information to the ground station or individual UAVs.**

- **Maintaining guaranteed safe separation is only possible if external UAVs can be reliably detected and their position and velocity can be determined accurately.**

- **Two possible means to do this:**

  1. **Active UAV location-determination capability within the LADGNSS ground station (e.g., radar)**

  2. **Use in-network UAVs with "sense-and-avoid" capability to track external UAVs detected within covered airspace.**

Handling External UAVs (2)

- **If external UAVs can be tracked by local ground station or UAVs, they can be treated as out-of-network UAVs, but with additional margin in ZoIs and ZoOs.**
  - **Ground or UAV tracking is likely to be significantly less accurate than location information provided by UAVs.**
- **Failing this, special precautions must be in placed to prevent incursions from external UAVs.**
  - **Regulations should be enacted to protect UAV airspace where safety-critical operations are being conducted.**
  - **How would these regulations be enforced?**
- **External UAVs represent the largest challenge to providing beyond-visual-range UAV guidance with guaranteed safe separation.**

Summary

- **Local-area networks based on high-integrity differential GNSS can be the basis for beyond-visual-range UAV guidance with guaranteed safe separation**
  - **Simplification of GBAS is more flexible and affordable**

- **Local-area network supports two coverage regions within 25 – 50 km of LADGNSS reference station**

- **Zones of Influence and Operation derived from previous work to define airspace allocation strategy for in-network UAVs**

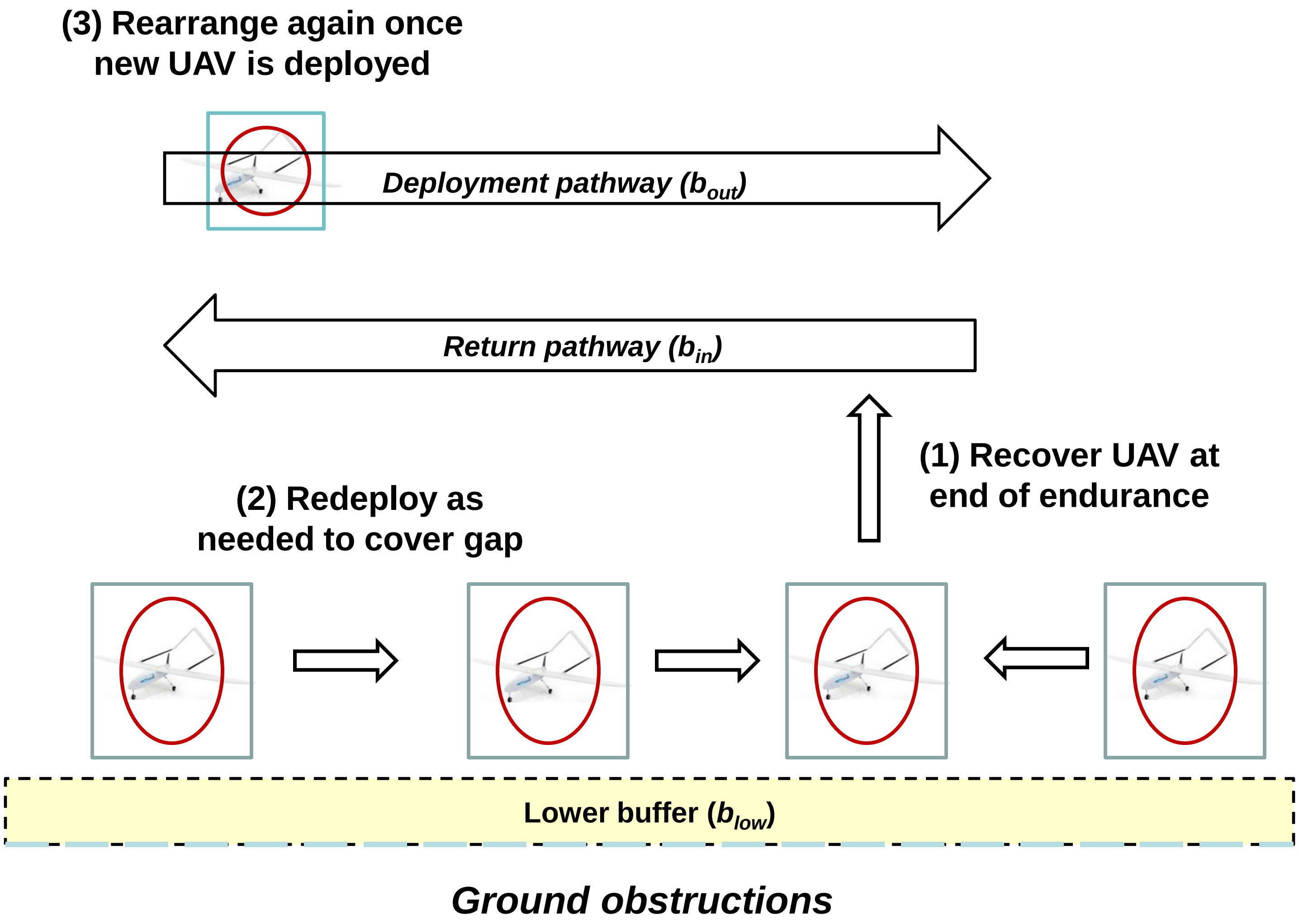
- **This approach can be adapted to out-of-network UAVs that provide position information, but external UAVs that do not pose a serious challenge.**

Backup Slides follow…

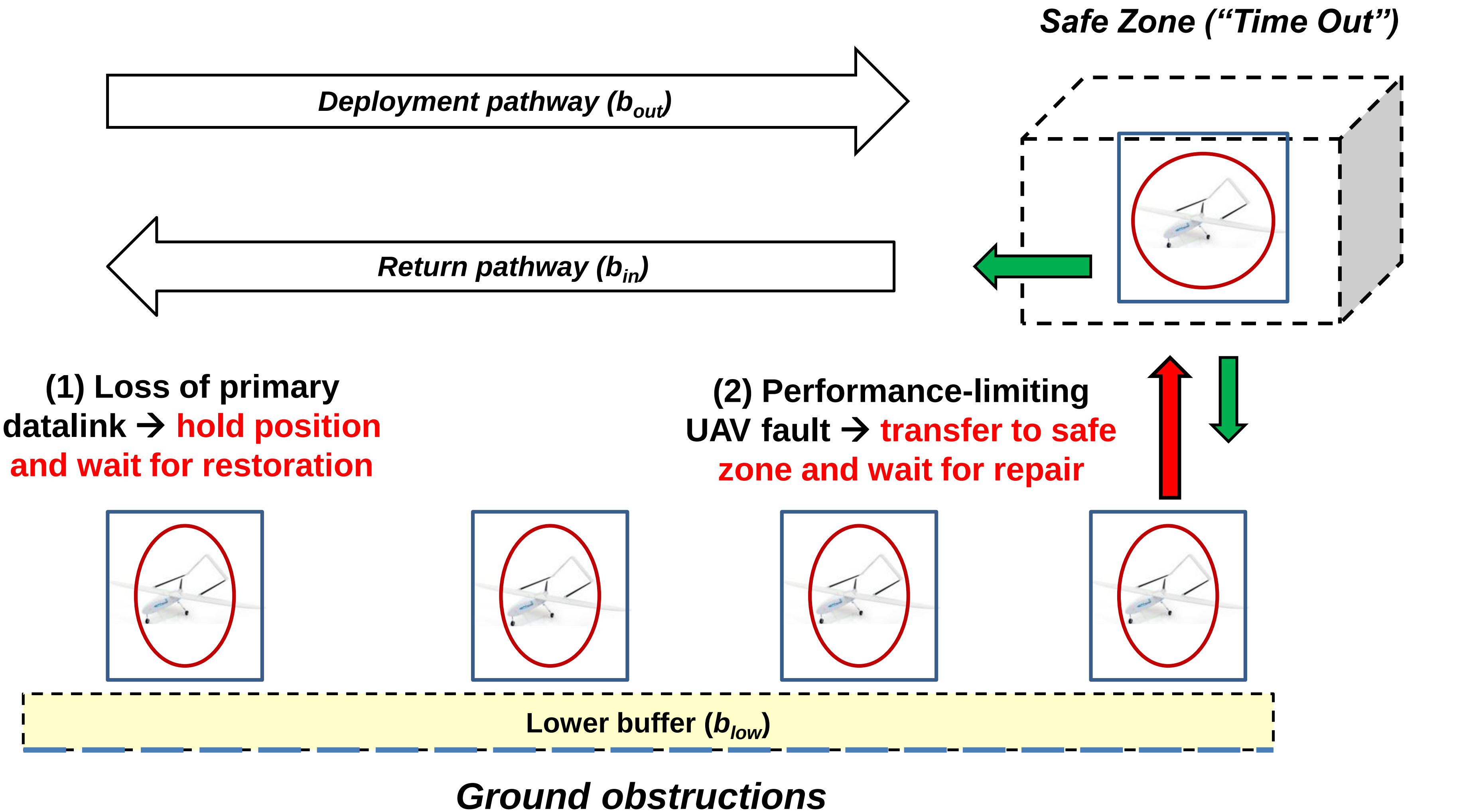
UAV Navigation and Guidance Using LADGNSS

- ***Objective*: achieve UAV error bounds < 10 meters at probabilities of 10^{-6} or below within a local region**
  - **Based on a simplification of Ground-based Augmentation Systems (GBAS)**
  - **The GBAS ground station also provides automated UAV guidance and maintains safe separation of UAVs**
- **This capability has been developed and tested over the last several years**
  - **Initial concept development from 2013 to 2015**
  - **Detailed modification and testing of simplified GBAS ground station from 2014 to 2017**
  - **Flight testing under static and mobile regimes from 2015 to 2017**

Typical Guidance Actions



Anomaly Response Actions (1)



Anomaly Response Actions (2)

Critical UAV Fault leading to loss of flight control (e.g., sudden descent)

(1) Ground control orders "guided recovery" (to safe zone or base)

(2) If unsuccessful, UAV attempts "autorecovery" (to safe zone or base)

(3) If unsuccessful, attempt to cushion descent and land in safest possible place