Managing Separation of Unmanned Aerial Vehicles Using High-Integrity GNSS Navigation

Sam Pullen

Stanford University

spullen@stanford.edu

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Outline

- **Unmanned Aerial Vehicle (UAV) Networks**
  - **Applications**
  - **Ground-driven architecture**
  - **Local-Area Differential GNSS (DGNSS) Navigation**
- **Concept of Operations**
- **Risk Model for Safe Separation**
- **Error Model for Safe Separation**
- **Future Work: KAIST flight testing**

UAV Applications (1): *Scientific Observations, Photography*

Ice Monitoring in Arctic

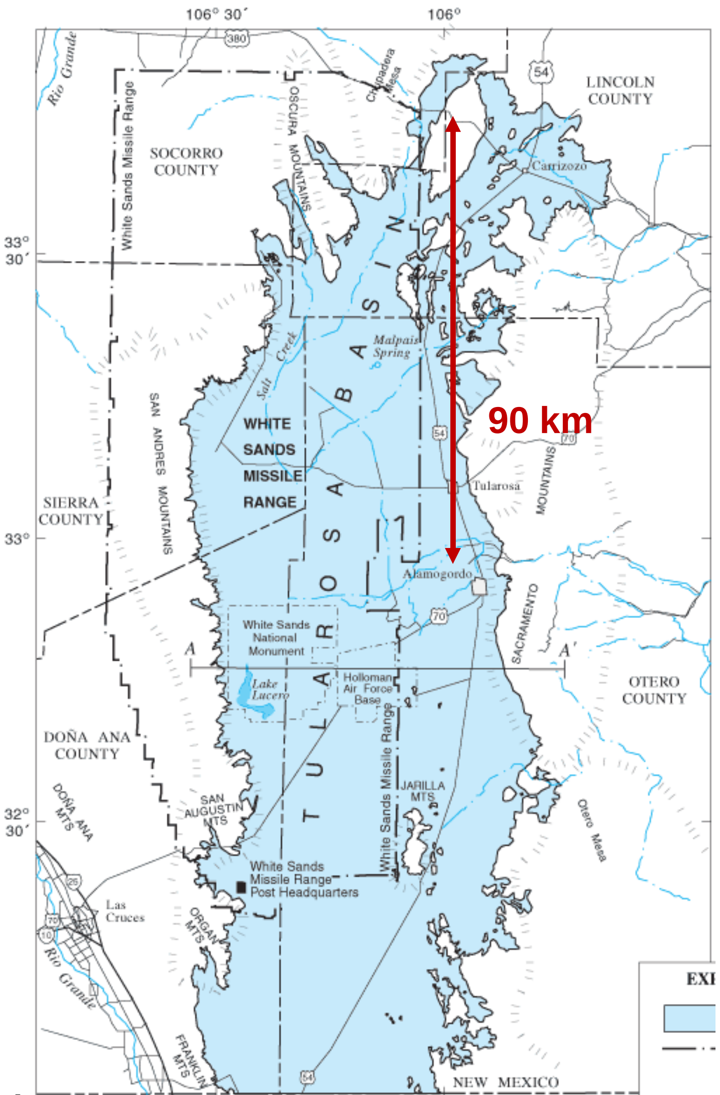
***Source*: A. Armstrong, NOAA (New York Times, Oct. 2007)**

Volcanic Ash Monitoring

***Source*: (concept) G. Gao, (picture) H. Thorburn, Wikimedia Commons, 2010**

UAV Applications (2): *Reconnaissance, Surveillance*

White Sands Missile Range, NM



***Source*: USGS/ Wikimedia Commons**

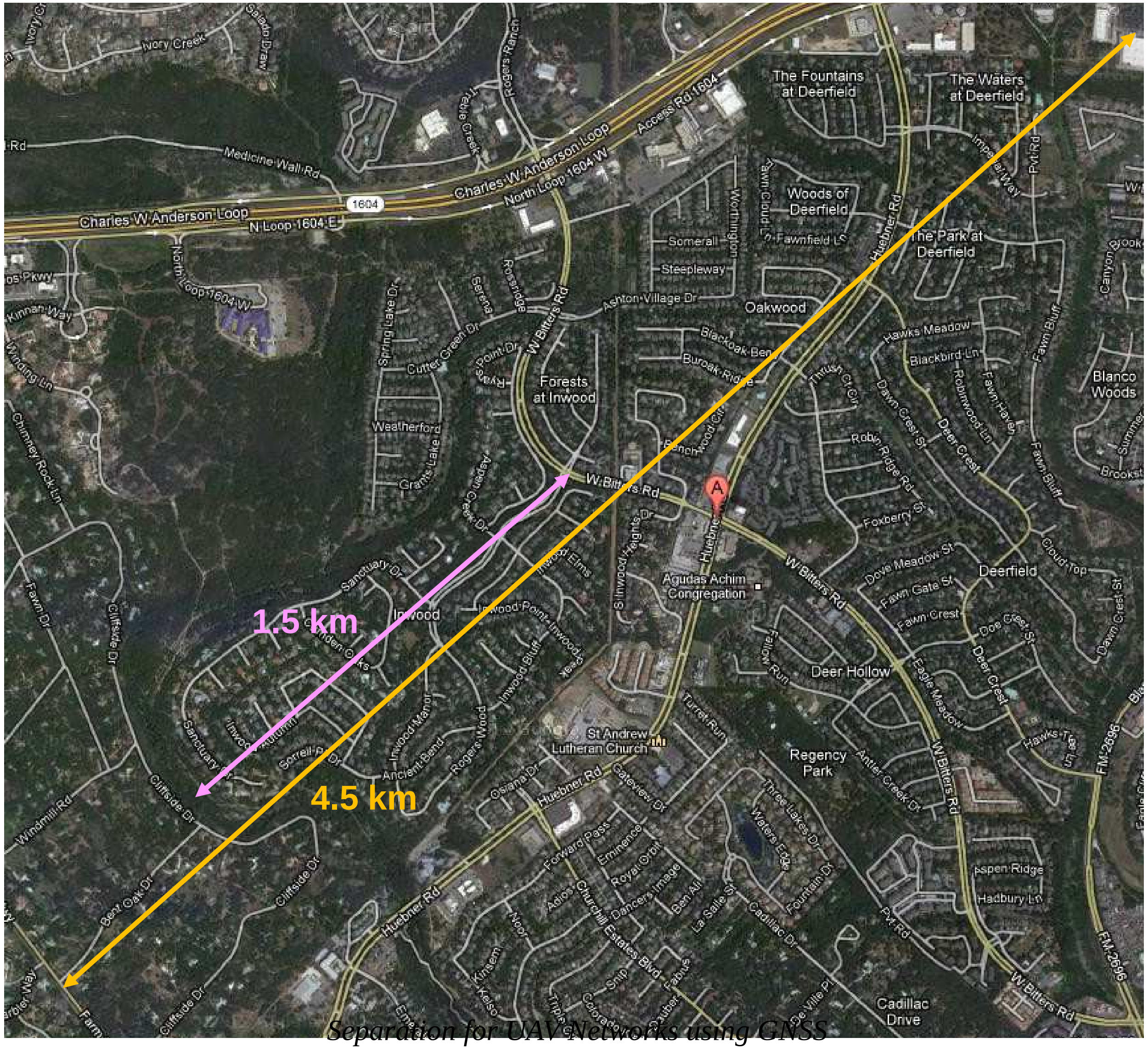
Boeing/Paine Field, WA

4.3 km

***Source*: Google Maps**

UAV Applications (3): *Reconnaissance, Surveillance*

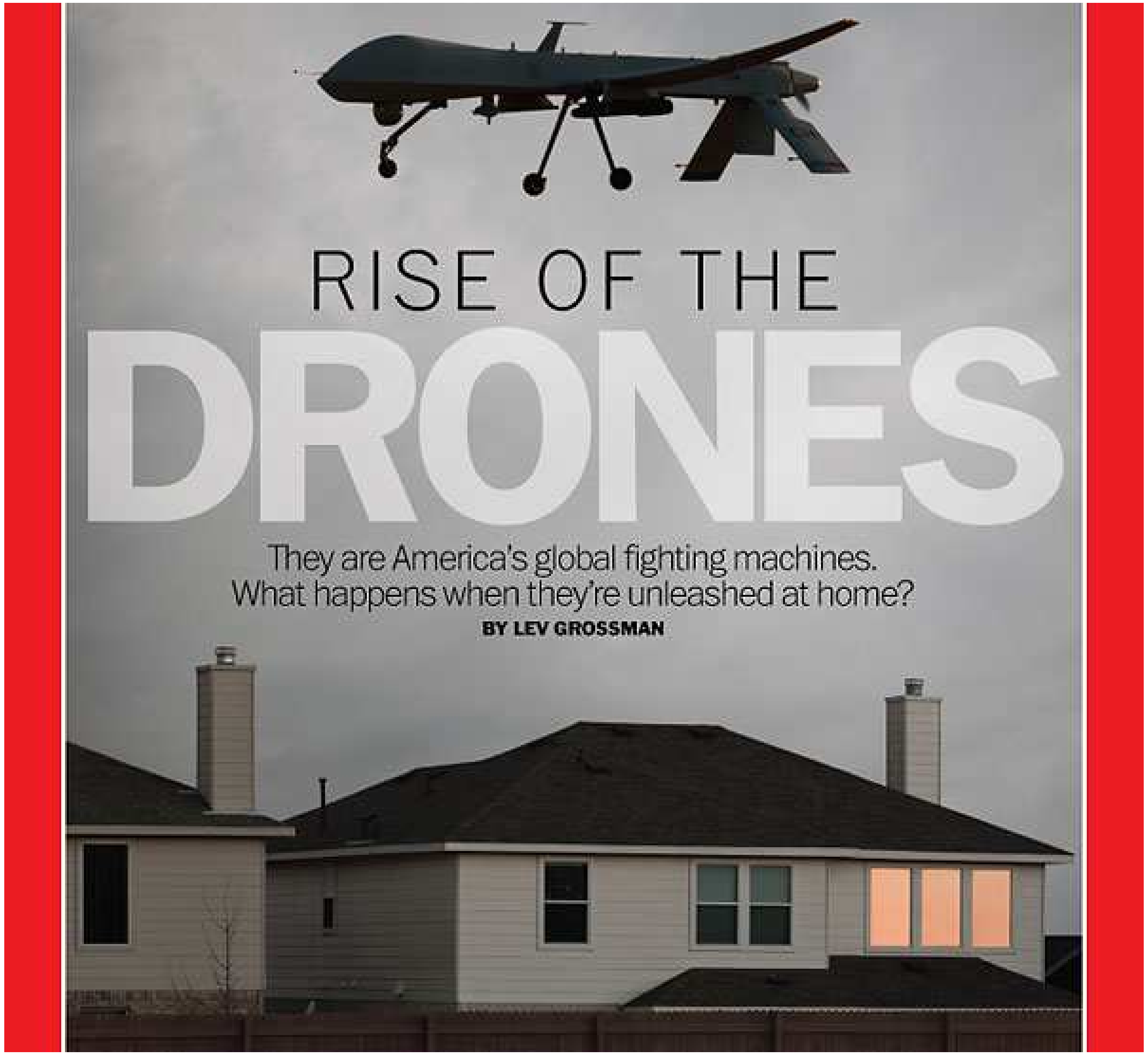
Inwood and nearby (gated) subdivisions, San Antonio, TX



Source: **Google Maps**

Concerns over Threat to Privacy

***Source*: TIME Magazine (cover), 11 February 2013.**



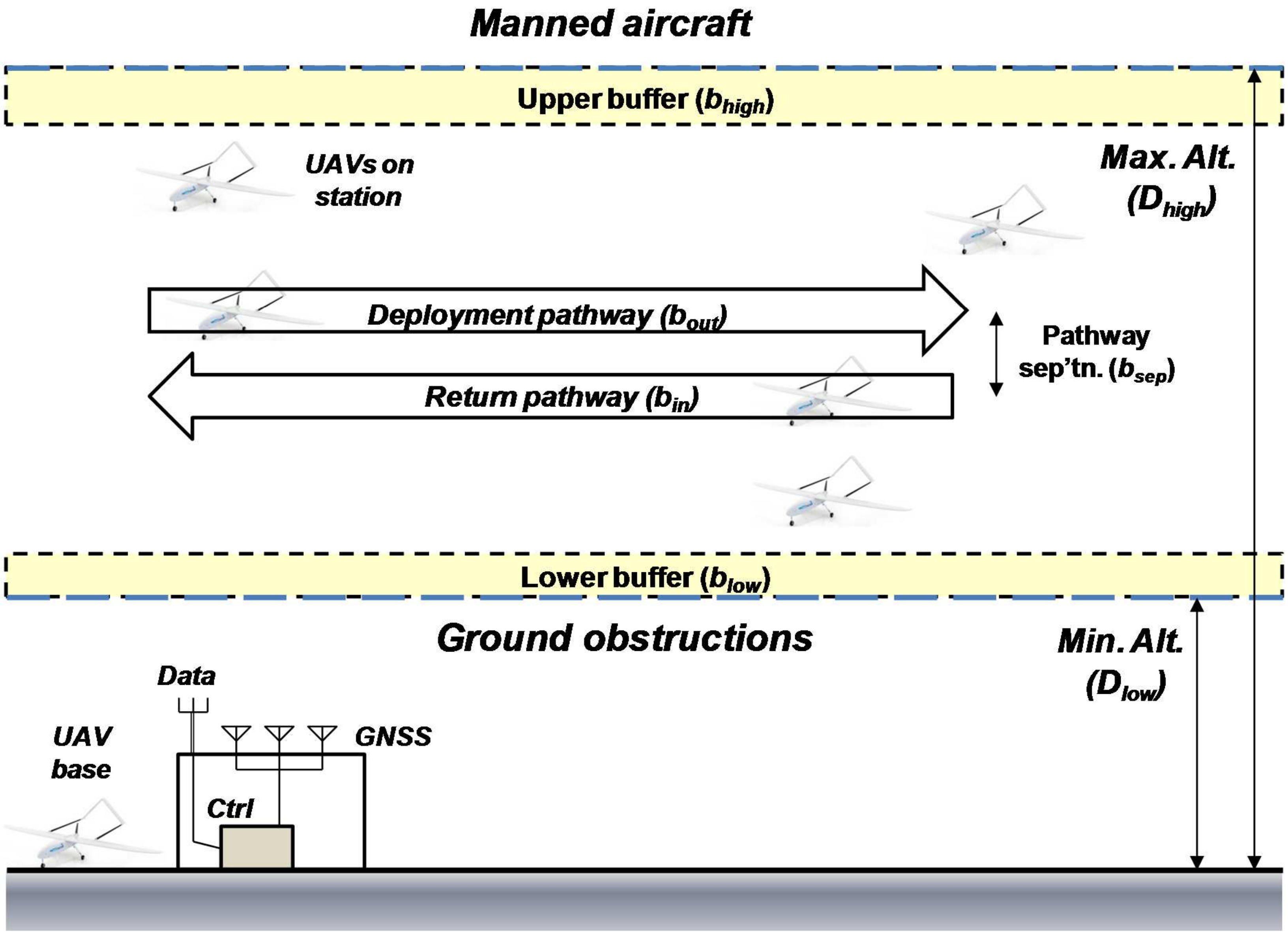
Constraints of Commercial UAV Network Environment

- ***Service must be cost-effective***

- **UAV design and flight operations dominate achievable performance**
  - **Low-power/weight/cost receiver chipsets**
  - **Airborne dynamics are larger than for manned aircraft.**
  - **Flying (relatively) close to ground objects → significant airborne multipath from ground reflections**

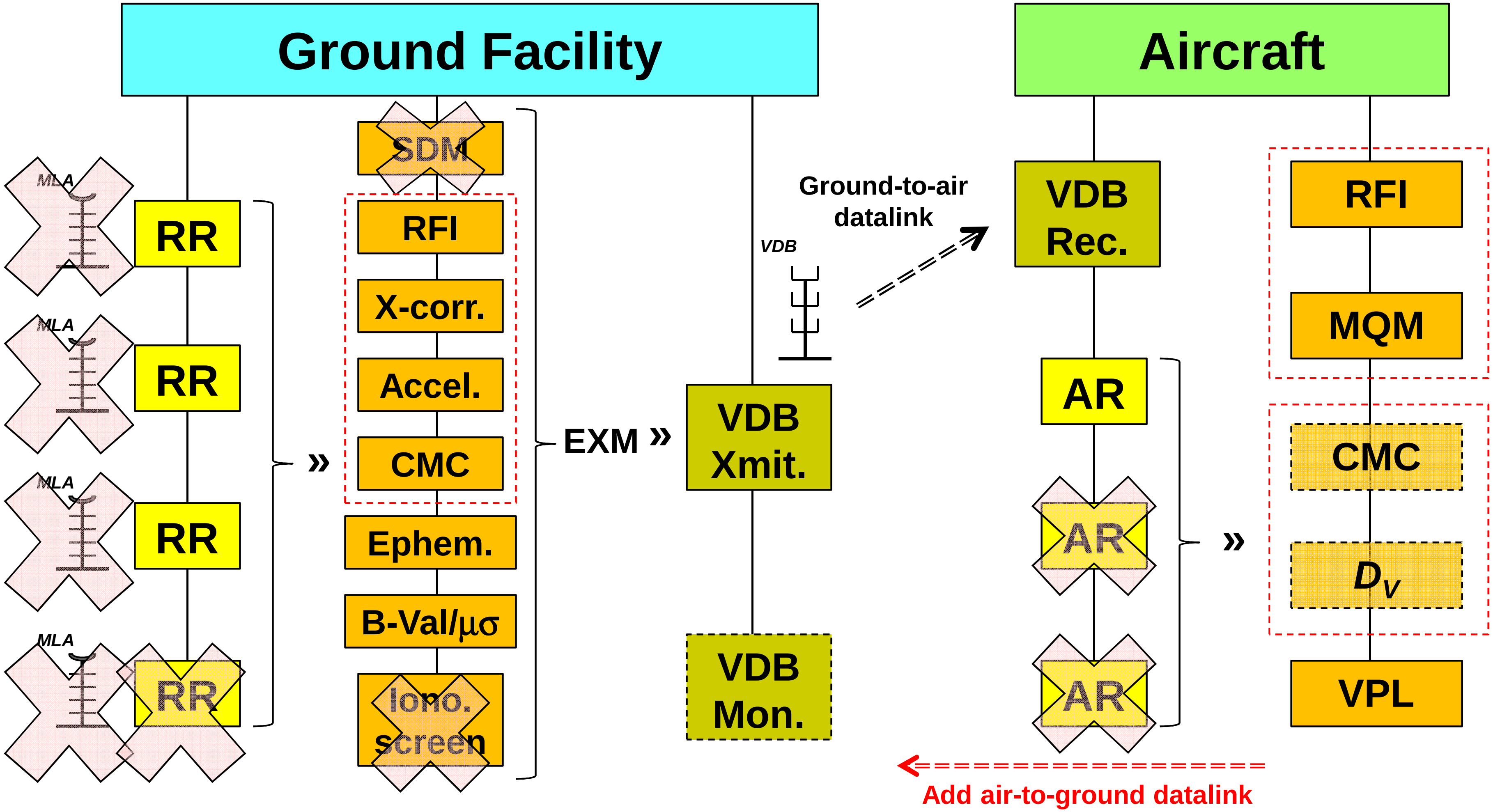
- **Two-way datalink required for guidance**
  - **Monitoring separation is a key responsibility of the ground controller**

Local-Area UAV Network Concept



Simplification of GBAS for UAV Networks

- **See: S. Pullen, *et al*, "LADGNSS Architectures Optimized to Support UAVs" *ION ITM 2013*, San Diego, CA, Jan. 2013**



Safe Separation: Definitions of Terms

- **"In-network" UAVs: UAVs in the same network**
  - **Share the same source of guidance**
  - **Share the same LADGNSS differential corrections**
- **"Out-of-network UAVs": all other UAVs**
  - **May share use of GNSS, but do not share guidance or differential corrections**
  - **Fly in the same general airspace allocated to UAVs**
- **"Manned aircraft": aircraft with human occupants**
  - **Assumed to fly in their own airspace (separate from UAVs)**
- **"Ground obstructions": the ground and any people, buildings, etc. attached to the ground**

Components of Separation Budget

"In-network" UAV

UAV Navigation Error (U_{nav})

UAV Path-Following Error (U_{path})

UAV Guidance Error ($U_{guidance}$)

Target Guidance Error ($T_{guidance}$)

Target Path-Following Error (T_{path})

Target Navigation Error (T_{nav})

Min. Sep. (b_x)

Altitude Limit or Other Vehicle ("Target")

Risk Model for Total Separation
(example numbers for suburban applications)

$$\Pr(HH \mid SV) \;=\; \Pr(HH \mid CO) \times \Pr(CO \mid SV)$$

harm to humans (HH) — *separation violation* (SV) — *collision* (CO)

Scenario	Pr (CO|SV) (mean)	Pr (HH|CO) (mean)	Pr(HH|SV) (mean)	Pr(HH|SV) (worst case)
In-network UAV	10^{-4}	10^{-5}	10^{-9}	10^{-5}
Out-of-network UAV	10^{-5}	10^{-4}	10^{-9}	10^{-4}
Upper limit (manned a/c)	10^{-7}	10^{-2}	10^{-9}	10^{-2}
Lower limit (ground)	10^{-4}	10^{-3}	10^{-7}	10^{-3}

Required Prob. of Separation Violation

Solve for Pr(SV) to meet total safety requirement:

$$Pr(HH \mid SV) \times Pr(SV) \leq 10^{-9}$$ ← Target level of safety

Scenario	Pr(SV) (mean)	Pr(SV) (worst case)
In-network UAV	1.0	10^{-4}
Out-of-network UAV	1.0	10^{-5}
Upper limit (manned a/c)	1.0	10^{-7}
Lower limit (ground)	0.01	10^{-6}

Preliminary Error Budget (3-D separation between in-network UAVs)

Error Source	Bounding Sigma (meters)
User navigation	0.2
User path-following	0.6
User guidance	0.3
Target navigation	0.2
Target path-following	0.6
Target guidance	0.3
RSS	***1.0***

Very highly correlated

highly correlated

Preliminary Error Budget
(vertical separation from manned aircraft)

Error Source	Bounding Sigma (meters)
User navigation	1.5
User path-following	2.0
User guidance	1.0
Target navigation	3.0
Target path-following	4.0
Target guidance	N/A
RSS	***5.7***

potentially correlated, but assumed independent

Out of Network UAVs: *"Sense and Avoid"*

- **Safe separation from out-of-network UAVs requires some form of "sense and avoid" technology.**
- ***Most practical solution*: requirement for UAVs to broadcast position information at regular intervals**
  - **"ADS-B-OUT" for UAVs, but with much simpler, miniaturized components.**
  - **Report aircraft type, position, velocity, and source of navigation (e.g., a variation of GNSS)**
  - **"ADS-B-IN" function may be delegated to ground controller for short-range systems**
- **Guidance adaptation to out-of-network UAVs, particularly "non-friendly" ones, is a major challenge.**

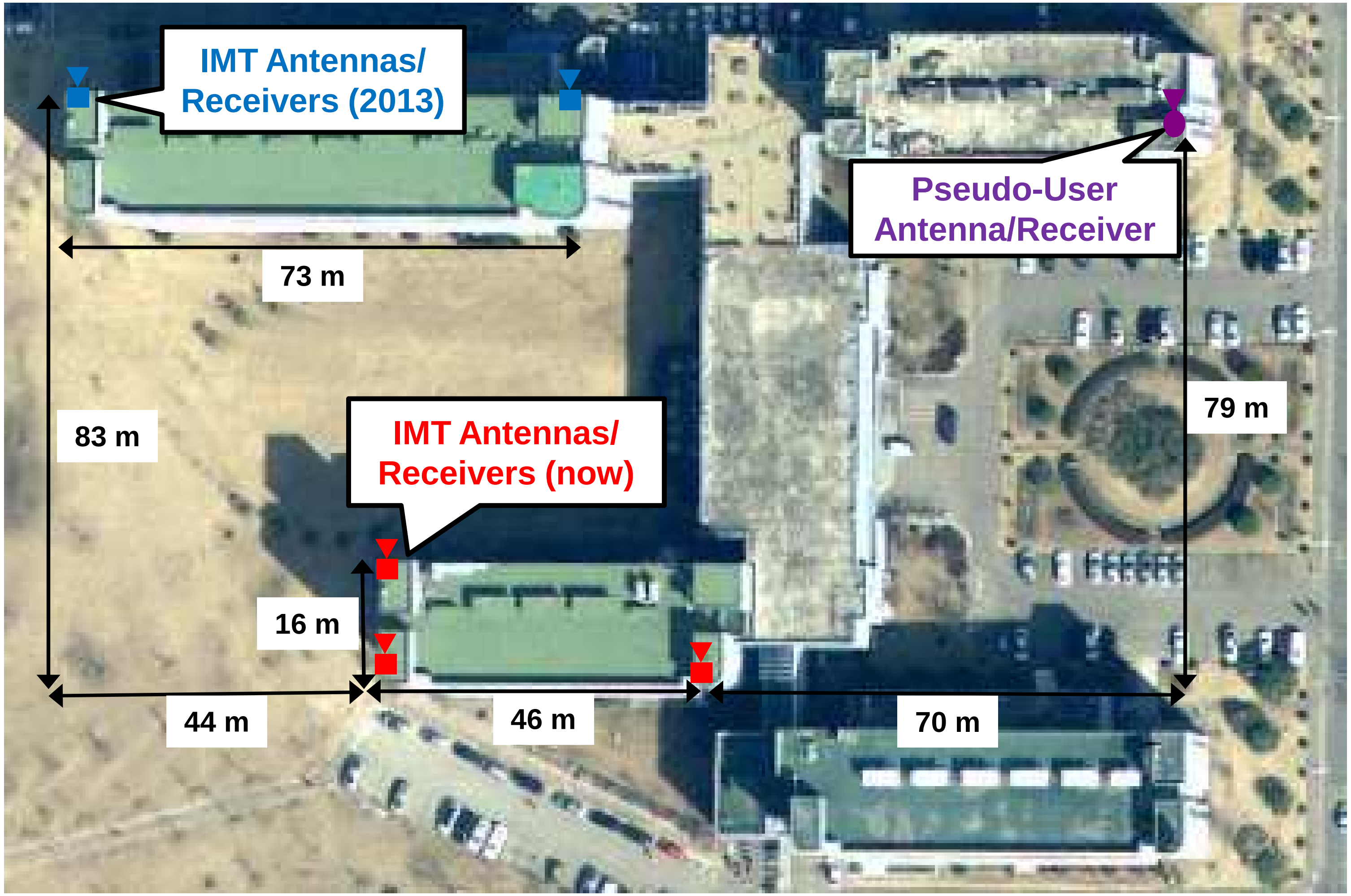
Future Work: KAIST Experiments

- **Test elements of UAV network architecture with flying airborne vehicles.**

- **Utilize "IMT" GBAS prototype developed by Prof. Jiyun Lee at KAIST (Daejeon, Korea) along with existing commercial DGPS system.**

- ***Key test objectives*:**
  - **Examine receiver performance of existing UAVs in different environments (using static "pseudo-user" as control).**
  - **Evaluate correlated errors of UAVs close to each other.**
  - **Map resulting UAV error models to separation standards proposed here.**

GBAS IMT Reference Receivers at KAIST



Vicinity of KAIST GBAS

Summary

- **A concept for autonomous UAV networks supported by local-area DGNSS has been proposed.**
  - **Medium-range photography / data-collection**
  - **Short-to-medium reconnaissance / surveillance**
- **A model for separation standards between networked UAVs and obstacles/other aircraft (including other aircraft) has been developed.**
  - **Based on risk and consequences of potential UAV collisions**
- **Flight tests to come using KAIST GBAS prototype.**
  - **Identify UAV navigation and flight technical errors under various conditions.**

Ending

- Thank you for your attention。

  ご清聴、ありがとうございました。

- Questions are welcome!

  ご遠慮なく、英語でも日本語でも質問してください。

Backup Slides follow…

GBAS Architecture Overview
(supports CAT I Precision Approach)