Hyper-Spectral Communications, Networking & ATM (HSCNA) as Foundation for Safe & Efficient Future Flight: Transcending Aviation Operational Limitations with Diverse & Secure Multi-Band, Multi-Mode, & mmWave Wireless Links

David W. Matolak, Ph.D., PI

AIAA Aviation Conference

25 June 2018

UNIVERSITY OF
SOUTH CAROLINA

Outline

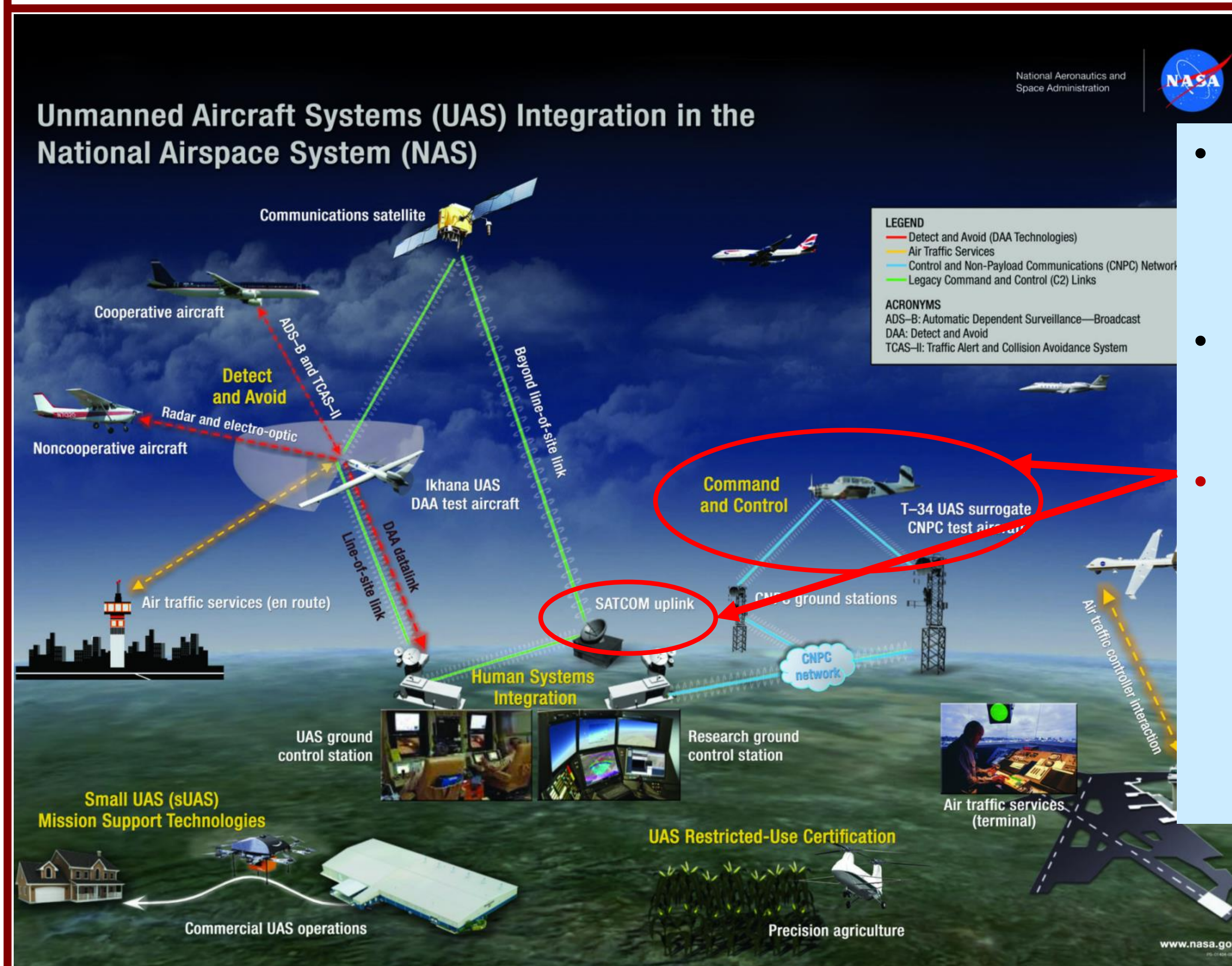
- Introduction
- Project Description
- Project Tasks
  - Tasks 1-6 & example results
- Next…
- Conclusion

Introduction

- There is a lot going on in aviation…

- Atlanta Airport…
  - https://www.youtube.com/watch?v=XX0Deuw0CkQ&list=PL3416E39D02A5BFE9&t=0s&index=7
  - https://www.youtube.com/watch?v=eWv4wyy_Jqg

NASA: UAS in the NAS



- Exploring/ validating technologies for reliable CNPC
- Medium/large aircraft

- U. South Carolina: PHY/MAC
  - Air-ground (AG) channel
  - Radio mod/demod
  - Networking

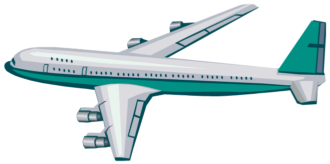
NASA: UAS Traffic Management

- **UTM** exploring/ validating ATM technologies: **LOW** altitude/ small aircraft
- Recently extended to Urban Air Mobility (UAM) (Uber Elevate)

NASA's **ULI Program**→Our Project

- SIP Strategic Thrusts
  - ***ST1:* Safe, Efficient Growth in Global Operations**
  - *ST2:* Innovation in Commercial Supersonic Aircraft
  - *ST3:* Ultra-Efficient Commercial Vehicles
  - *ST4:* Transition to Alternative Propulsion & Energy
  - *ST5:* Real-Time System-Wide Safety Assurance
  - *ST6:* Assured Autonomy for Aviation Transformation
- Our ULI Project: **HSCNA,** Co-Investigators
  - Dr. Ismail Guvenc (NC State)
  - Dr. Hani Mehrpouyan (Boise State)
  - Greg Carr (AT Corp., & Paul Davis, Ben Boisvert)

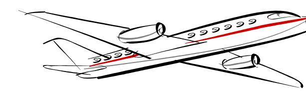
HSCNA Overview



- Three Strategic Thrust Outcomes (TOs)
  - **TO1**: More robust, efficient, reliable, & secure aviation communication & networking
  - **TO2**: ATM system capable of handling *significantly* larger air traffic density (including UAS), w/rapid & reliable, automated & collaborative ATC & ATM
  - **TO3**: Efficient airport operations to remove delays, reduce costs, & increase situational awareness

HSCNA Overview (2)

- Beneath TOs: 4 project **Research Outcomes** (ROs): *Develop Strategies & CNS Techniques*
  - ***RO1:*** increase aviation link & network capacity



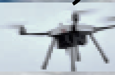
  - ***RO2:*** enhance aviation link diversity, reliability, & security
  - ***RO3:*** comprehensive ATM simulations for future air traffic density & complexity

  - ***RO4:*** improve slow & inefficient airport operations

HSCNA Overview (3)

- Project Tasks
  - **Task 1:** *multi-band* networking **ConOps** for multiple phases of flight & all communication link types & *modes*, e.g., air-X

  - **Task 2: quantify** aviation band & comm. technology **capacity /coverage/ performance** & shortcomings, growth potential
  - **Task 3:** develop analysis/simulation SW tools/prototypes, assess **adaptive link/net performance** (multi-band, -mode) in *hyper-spectral* network



HSCNA Overview (4)

- Project Tasks (continued)
  - **Task 4**: quantify **mmWave** wireless airport subnetwork **capacity/efficiency** gains. Measure, model channels, validate proto airport mmWave sys

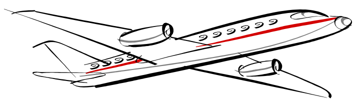
  - **Task 5**: develop novel **unauthorized UAS detection/localization** techniques to detect/track any unauthorized UAS that enters any restricted zone
  - **Task 6**: **develop realistic/comprehensive ATM simulation** capability to assess gains of hyper-spectral & mmWave networking (link performance per aircraft, supportable traffic density, multi-vehicle collaboration, & operational benefits)

What We Can Do Today

Boeing, 2017 Paris Air Show

Task 1: HSCNA Concept of Operations

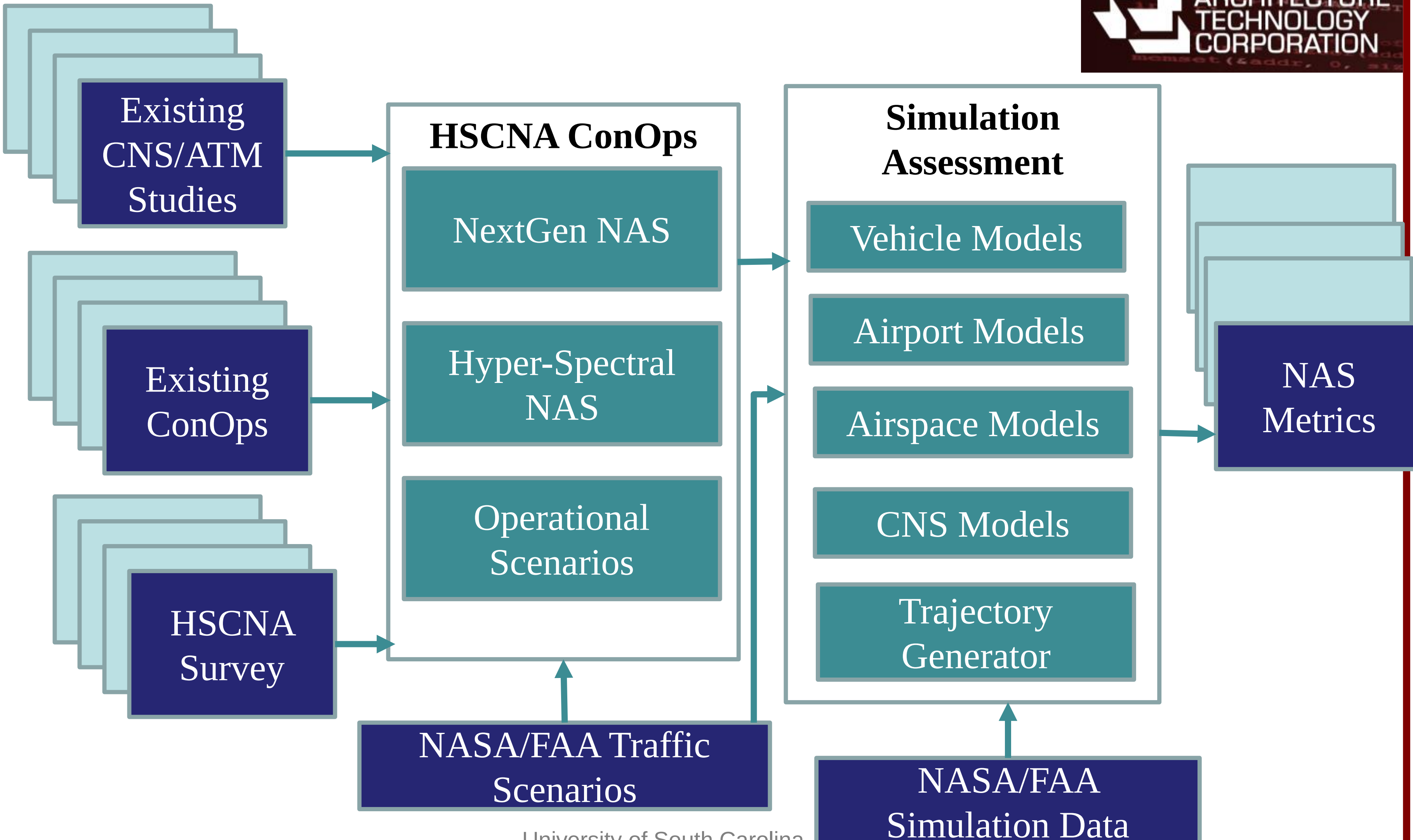
- Purpose
  - Provide operational context for HSCNA research, & basis for Simulation Assessment (Task 6)



- What it does
  - Describes future ATM concepts & related CNS technologies; does NOT prescribe future NAS operations
  - Focus on op scenarios that represent interactions between vehicles & ATC/ATM in controlled airspace (op interactions well-defined by FAA regs)
- What it includes
  - NextGen NAS - Future NAS as planned by FAA in 2025
  - Hyper-Spectral NAS - Future NAS including advanced ATM concepts & CNS technologies (2035+)
  - Op scenarios representing future air traffic demand including # flights, types of vehicles, missions, & other variables

ConOps & Simulation Assessment

ARCHITECTURE TECHNOLOGY CORPORATION



Draft ConOps (December 2017)

- NextGen NAS based on FAA's document "The Future of the NAS"
- Highlighted relevant systems, capabilities, & operational transformations
- Assume Hyper-Spectral NAS includes capabilities & benefits of NextGen NAS
  - Hyper-Spectral NAS will also include novel CNS/ATM capabilities **beyond** NextGen

Hyper-Spectral Technologies	Operational Transformations
Application of spectrally, temporally, & spatially efficient links in a multi-band, multi-mode, hyper-spectral network	More robust, efficient, reliable, & secure aviation communication & networking • Higher data rates ⇒ lower latency • Higher reliability ⇒fewer re-transmissions ⇒ lower latency • Higher spectral efficiency ⇒ more transmissions (users) per Hz ⇒ more aircraft per unit volume ATM system will be capable of handling significantly larger air traffic density, including UAS, through rapid, reliable, automated, & collaborative ATM. Highly efficient airport operations that reduce delays, reduce costs & increase situational awareness. High-capacity reliable communications links will enable autonomous planning & scheduling, & multi-vehicle cooperation & interoperability. Accurate & ubiquitous short-term numerical weather prediction. All aircraft are weather sensors, hence the set of aircraft aloft forms a (mobile) network of weather stations. All aircraft data gets to ATM centers (which also get additional weather data). Aircraft communicate whatever is needed to describe a weather event's "flow," severity, extent, etc. Application of link disruption mitigation techniques support threat prognosis, alerting &guidance for real-time system-wide safety assurance.

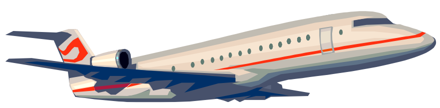
HSCNA Survey

- In May 2018, we distributed a survey to government, industry, & academia
- Survey asks for future (2025+) ATM concepts that would be enabled by significant CNS improvements
  - Concepts could improve NAS capacity, safety, efficiency, resiliency, flexibility, predictability, etc.
  - Identify barriers (technical, cost, risk) related to CNS that must be overcome to enable concept

ATM Concept	Description	CNS Barriers
Constant streaming of aircraft state, intent, & vehicle health data to Airline Operational Control (AOC) and ATM	Enables real-time monitoring of flights, supports real-time detection & alerting of hazards, & timely identification & localization of aircraft in distress	Data rate, cost, & geographic coverage
Single Pilot Operations for commercial transport aircraft	Provide continuous, secure & reliable streaming of aircraft state (telemetry) to ground station & command & control from ground to aircraft in high density operations	Requires increased cockpit automation & ground-based redundancy

HSCNA Survey – Your Help Needed

HSCNA survey includes two rounds



- Round 1 - ATM researchers identify ATM Concepts & CNS Barriers
- Round 2 - CNS researchers identify candidate future A-G & A-A technologies for Concepts & Barriers identified in Round 1

Dear Colleague,

David Matolak is the Principal Investigator for a NASA University Leadership Initiative (ULI) team led by the University of South Carolina conducting research into advanced, wireless communication networks to enhance the safety and efficiency of air traffic management for both manned and unmanned aircraft. The expected future growth in air traffic (including UAS) cannot take place without highly-reliable and efficient communications and networking among aircraft, ground stations, and other entities. Our research objectives include the development of strategies and CNS techniques for dramatically increasing aviation link and network capacity, and enhancing aviation link diversity, reliability, and security.

As part of our research effort we are soliciting inputs from government, industry and academia to identify future (2025 and beyond) Air Traffic Management (ATM) concepts that would be enabled by significant improvements in CNS compared with today's NAS. These concepts could improve NAS capacity, safety, efficiency, resiliency, flexibility, predictability, etc. We also want to identify barriers (technical, cost,
risk) related to CNS that must be overcome to enable the concept. Below we have provided two examples. We ask that you add your own ATM concepts and CNS barriers and return them to us via email. PLEASE PROVIDE YOUR RESPONSE BY June 15, 2018.

You may find out more about our NASA ULI project here:
https://sites.google.com/site/nasahscna/home

Thank you for participating in this survey and supporting our NASA-sponsored research efforts.

When you respond, please do so to the following:

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Campbell, CA, USA
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These concepts & technologies will be included in Final ConOps

Enables characterization of the Hyper-Spectral NAS

Task 2: Aviation Communications & Networking Assessment

- Collect information: all current/planned CNS systems applicable to civil aviation ✓
- Assess potential link/system capacities, reliability, & ConOps role
- Propose & evaluate ***new*** candidate technologies

NASA/CR—2006-214451 TR06027

Identification of Technologies for Provision of Future Aeronautical Communications

Tricia Gilbert, Glen Dyer, Steve Henriksen, Jason Berger, Jenny Jin, and Tony Boci
ITT Industries, Herndon, Virginia

BOEING Engineering, Operations & Technology
Boeing Research & Technology

Revolutionary and Advanced universal, reliable, always available, cyber secure and affordable Communication, Navigation, Surveillance (CNS) Options for all altitudes of UAS operations

UAS CNS Architecture Concept for Controlled Air Space

RTCA, Inc.
1150 18th Street, NW, Suite 910
Washington, DC 20036-4001, USA

RTCA

Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS) (Terrestrial)

RTCA-DO-362
September 22, 2016

Prepared by SC-228
©2016, RTCA, Inc.

NASA/CR—2015-218844

Identification and Analysis of Future Aeronautical Communications Candidates
A Study of Concepts and Technologies to Support the Aeronautical Communications Needs in the NextGen and Beyond National Airspace System

Joel M. Wichgers and James P. Mitchell
Rockwell Collins Advanced Technology Center, Cedar Rapids, Iowa

3GPP TR 36.777 V15.0.0 (2017-12)
Technical Report

3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on Enhanced LTE Support for Aerial Vehicles (Release 15)

Task 2: Example, L-band Systems

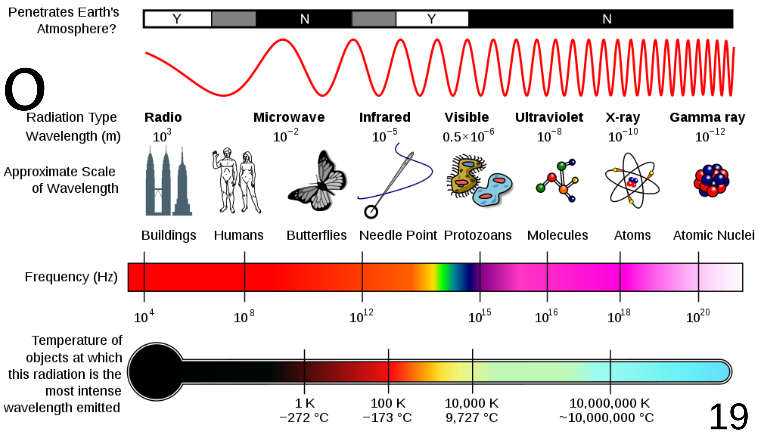
	ADS-B 1090ES (Extended Squitter)	UAT (DOC 9861) 978 MHz ADS-B	Mode S	Link 16 (JTIDS/ MIDS)	DME	GoGo Internet service (Aircell)	LDACS 1 (Advanced version of M-AMC & TIA 902 (P34))	LDACS 2 (Advanced version of LDL, AMACS)
Radio Freq. (MHz)	1030 Rx 1090 Tx	978	1030 Rx 1090 Tx (Mandate 2020)	969-1206	960-1215	850 for AG mode (to be defined & allocated for other bands in future)	FL: 985.5-1008.5 RL: 1048.5-1071.5	960-978
Channel bandwidth	2 MHz	2 MHz	1 MHz both bands	5 MHz	1 MHz	1.25 MHz	625 kHz	200 kHz
Modulation schemes	CPFSK/ GMSK	CPFSK	CPFSK/GMSK	Hybrid FH-DSSS, cyclic code-shift keying (CCSK) for M-ary symbol mod. & MSK for chip mod. Based on IS-856 TIA/EIA Std (IMT-2000)	Gaussian shaped pulses	Based on IS-856 TIA/EIA Standard (IMT-2000)	OFDM	CPFSK/ GMSK
User data rate range	1 Mbps	1 Mbps	1 Mbps	46.08-284.16 kbps 1 Mbps FHSS	Up to 2700 pulse pairs per second	Download: 500-600 kbps Upload: 300 kbps	FL+RL= 833.330 ksymbols/s	270 kbps
Capacity	1 Mbps for up to 600 targets		1 Mbps	51 channels		Total 3 Mbps for all users		
Spectral efficiency (bps/Hz)	<1	<1	<1	N/A	N/A	N/A	0.6	1.3
Duplexing/ Multiple-Access	TDD	TDD	TDD	TDMA		CDMA/TDD	FDD/TDMA	TDD
Typical range (km)	185.2-277.8	185.2-277.8	Up to 463	555	250		370	370
Network overall topology		Cellular based	N/A	Shared channel Between numerous stations.	Point-to-multipoint	Cellular	Cellular point-to-multipoint	Cellular point-to-multipoint

Task 3: Multi-Band & Multi-Mode Communications & Networking

- **MultiBand**: simultaneously and/or alternately employ different spectral bands
  - Band differences can adjust latency, reduce interference, offload to increase data rate

- **MultiMode**: traditional (AG, AS, AA) **plus** Air-X

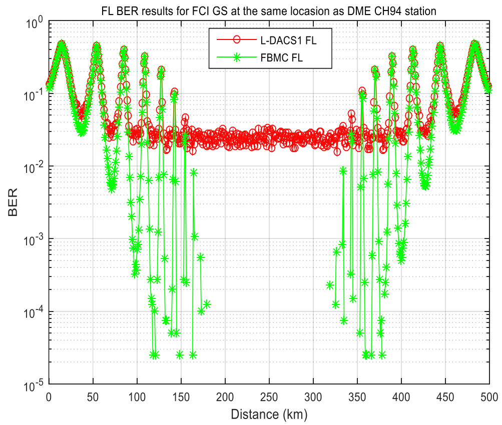
- ***Hyper-spectral***: HF to VHF to L-, C-, K-bands, mmWave bands, & higher

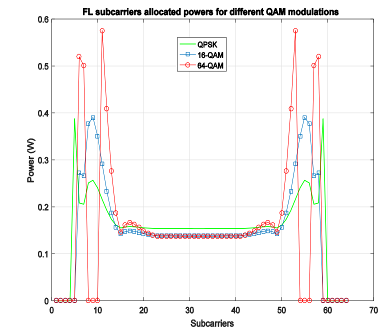


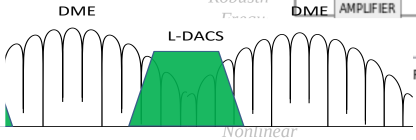
Task 3: Major Goals

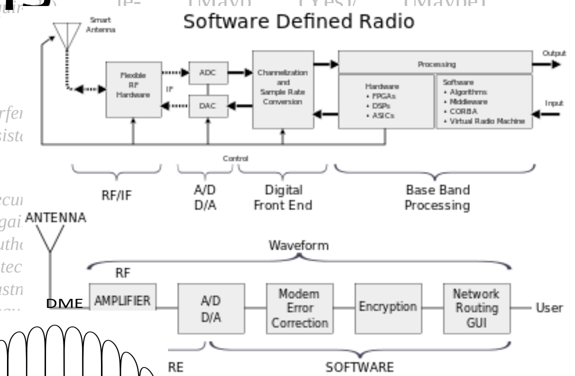
- Comprehensive multi-band comm. system analysis, designs (capacity, coverage, latency, P_b...)
  - 2- and 3-band designs, prototypes, demos

- Multi-mode comm. link quantification
  - Realistic channel, interference, radio models
- Integration into ATM simulations



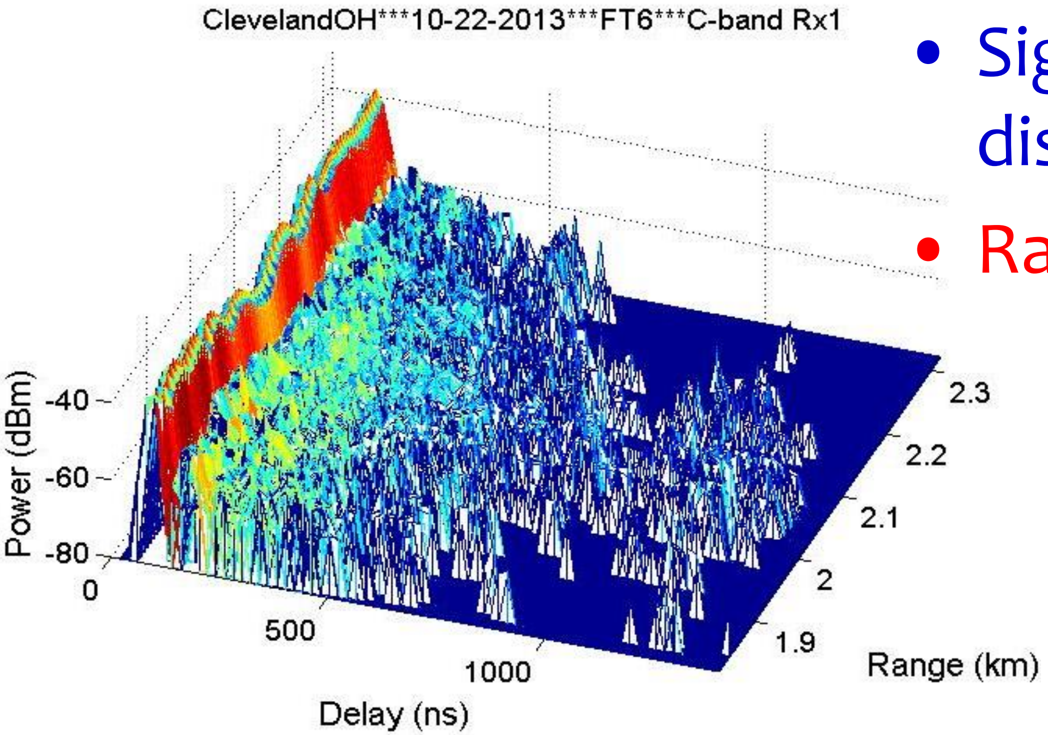




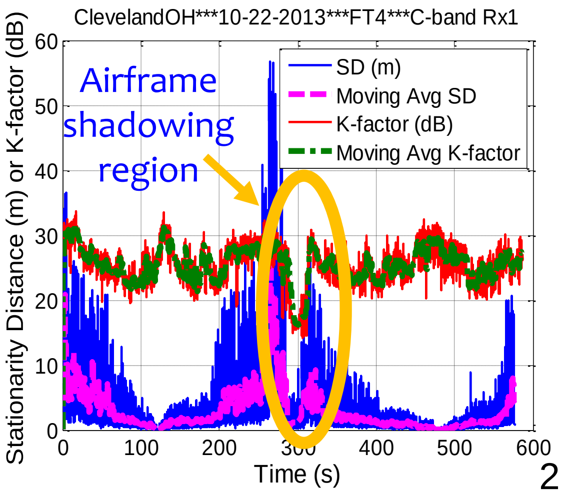


Task 3: Example Challenge

- Air-ground (AG) channel, low altitude

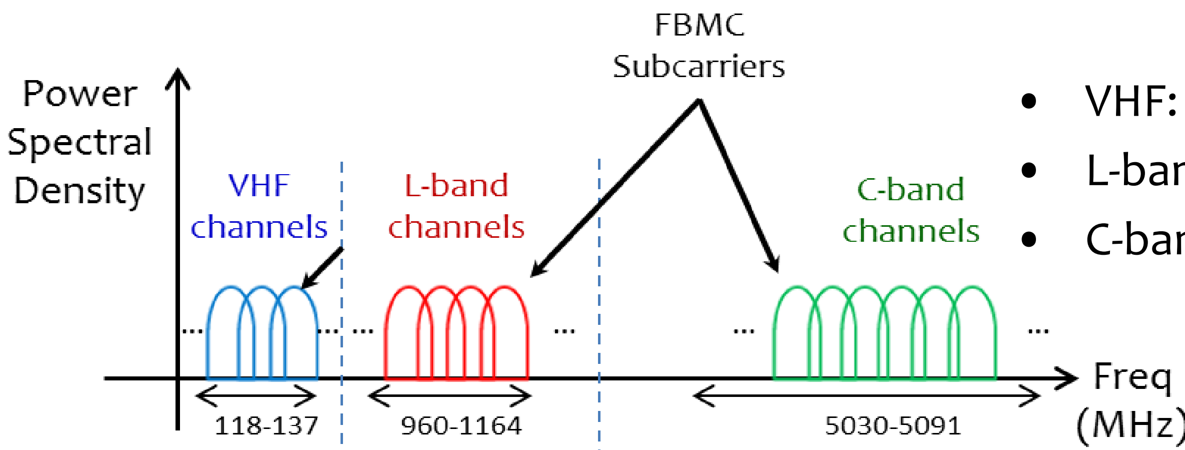


- Significant multipath dispersion (RMS-DS to 4 μs)
- Rapid time variation
- Airframe shadowing

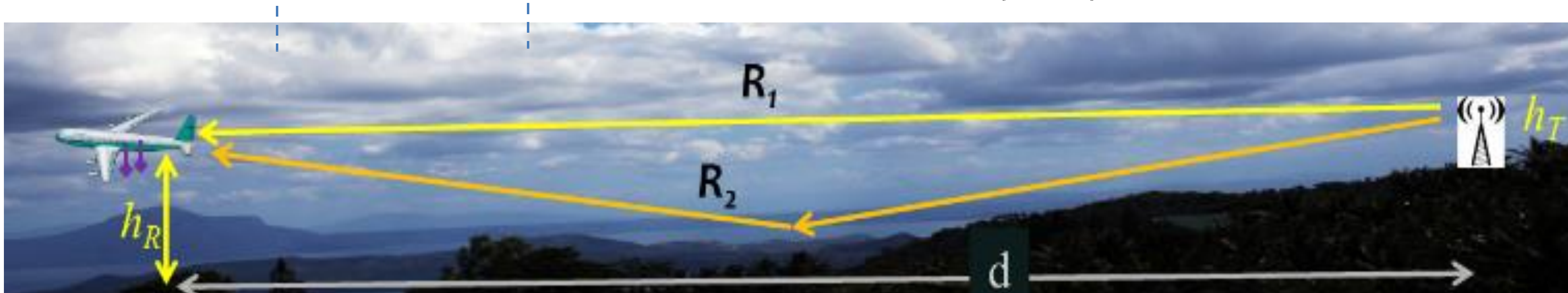


Task 3: Simple Multi-band Example

- Tri-band system: VHF (118-137 MHz), L-band (960-1164 MHz), & C-band (5.03-5.091 GHz)
- FBMC mod., AG channel: 2-ray, wet ground

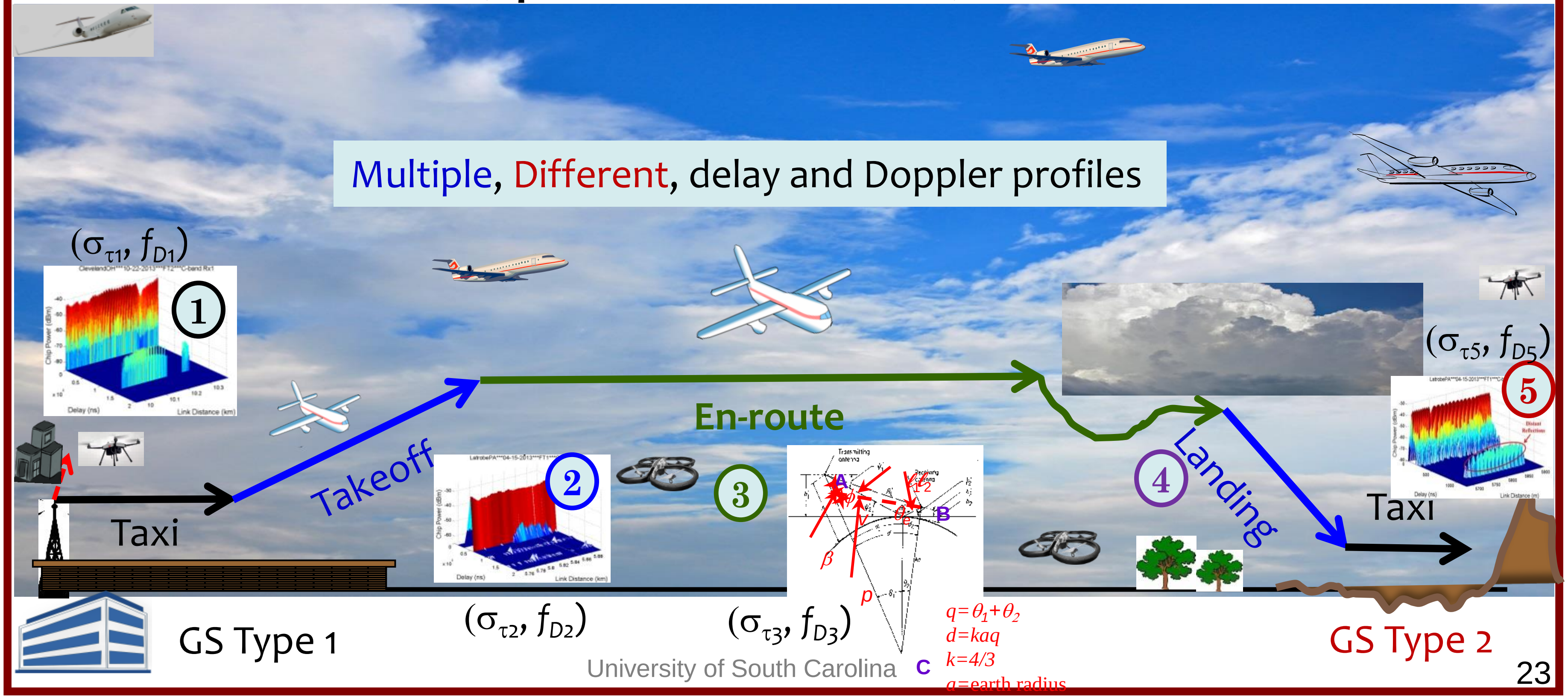


- VHF: B=25 kHz, 16 subcarriers
- L-band: B=0.5 MHz, 64 subcarriers
- C-band: B=5 MHz, 128 subcarriers



Task 3: Analysis/Design Framework

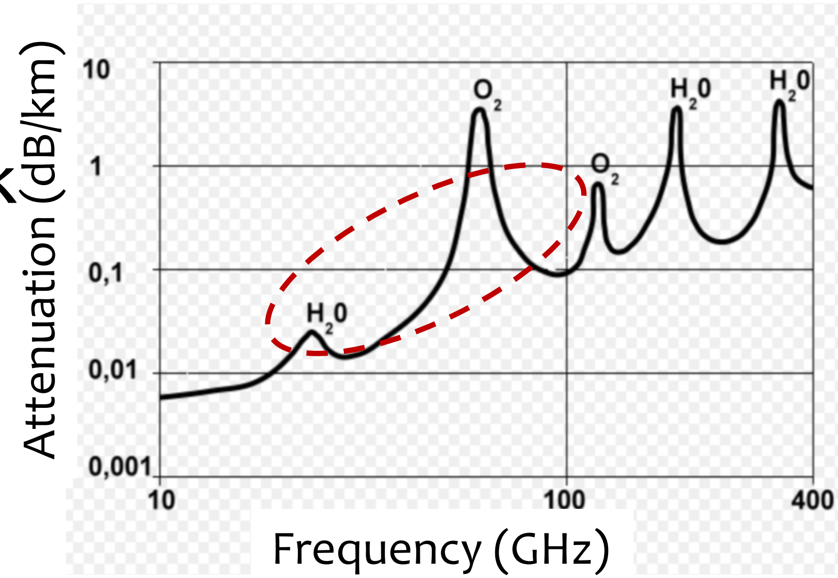
- Adaptive Aviation Waveforms
  - WithIN band, per delay/Doppler
  - INTER-band, per interference, data rate…



Task 4

BOISE STATE UNIVERSITY

- Millimeter Wave Systems for Airports & Short-Range Aviation Communications
  - Measure & model channels
  - Validate prototype airport mmWave systems
  - Quantify mmWave wireless airport subnetwork capacity/efficiency gains

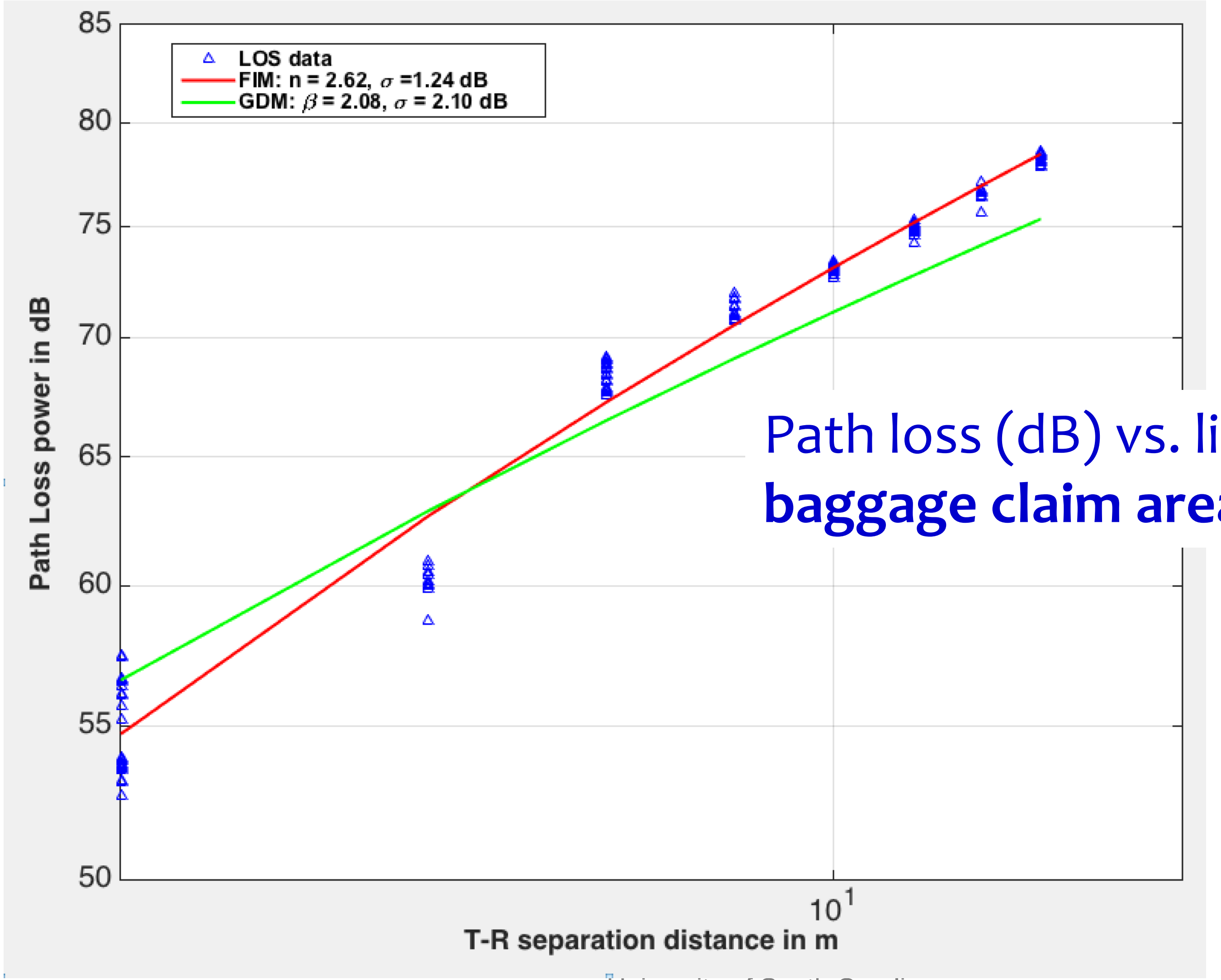


Task 4: Channel Measurement @BOI

- 60 GHz & 2.4 GHz channel measurement campaign at Boise International Airport

- 2x2 MIMO channel measurement to follow soon

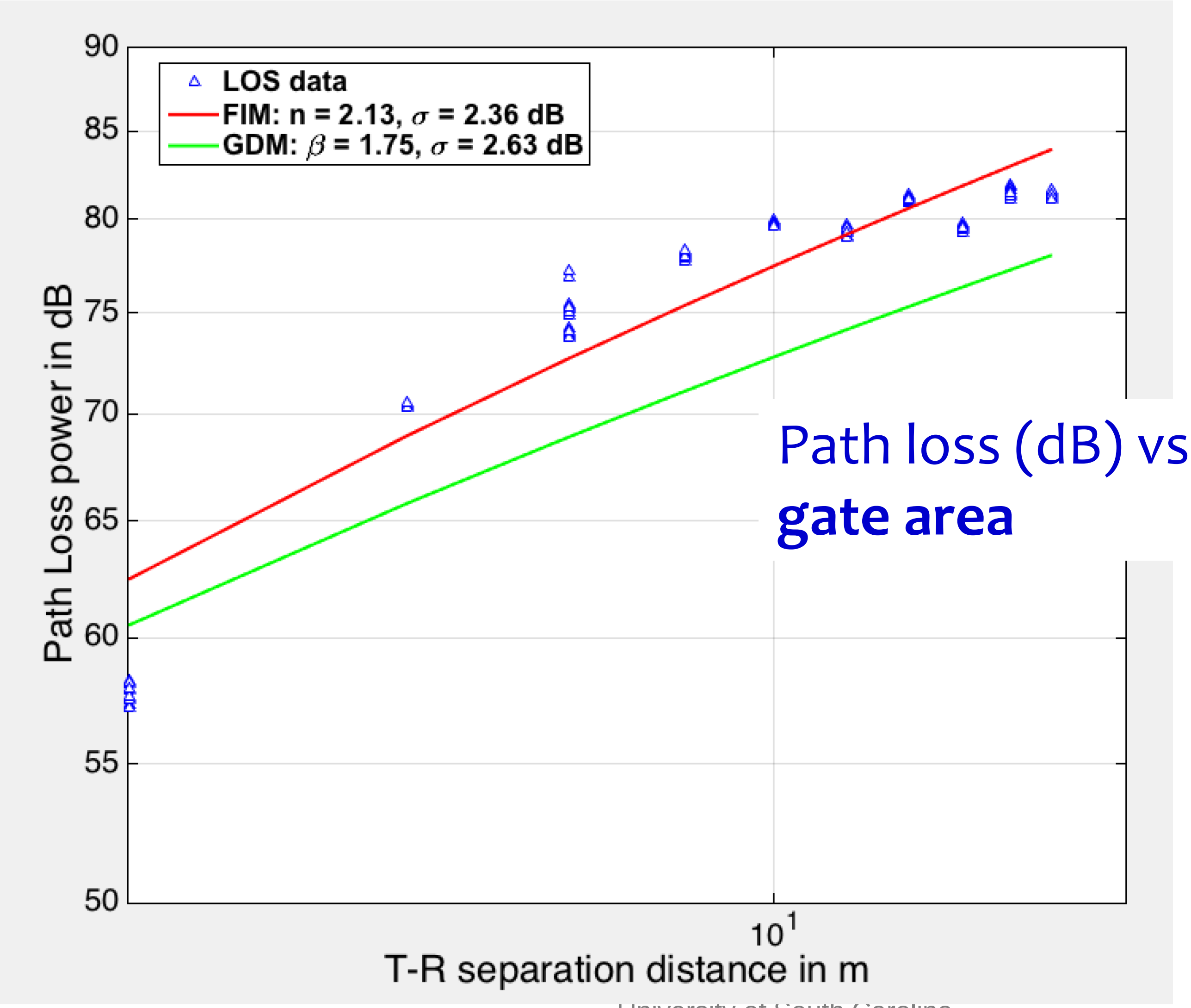
Task 4: 60 GHz BOI Airport Results



Path loss (dB) vs. link distance (m)

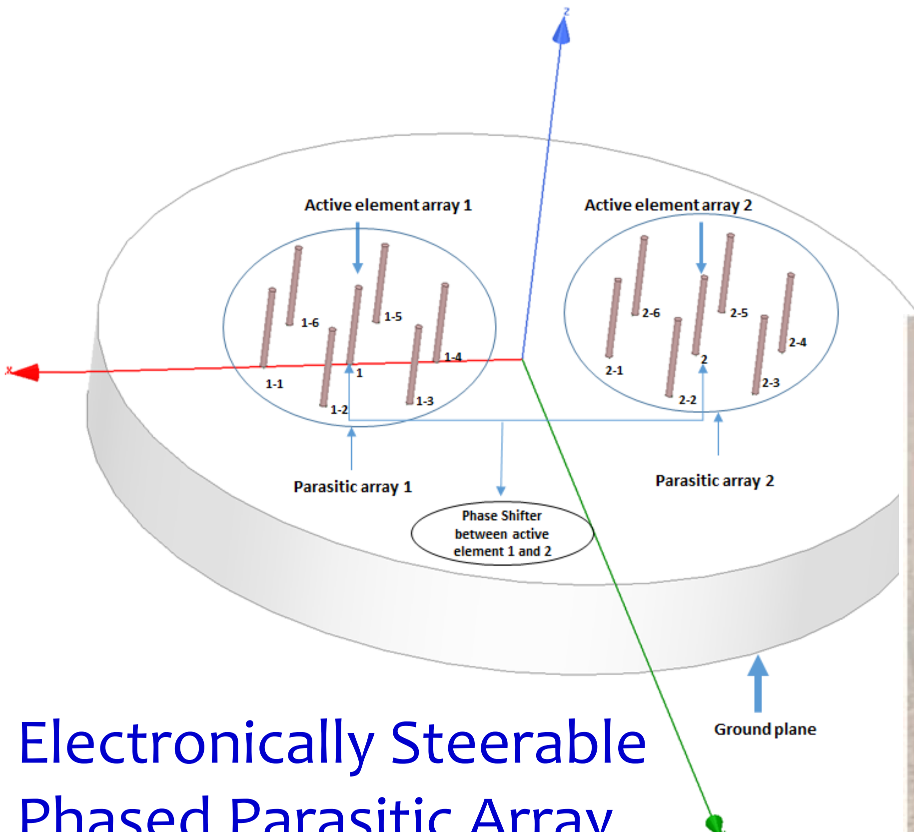
baggage claim area

Task 4: 60 GHz Airport Results (2)

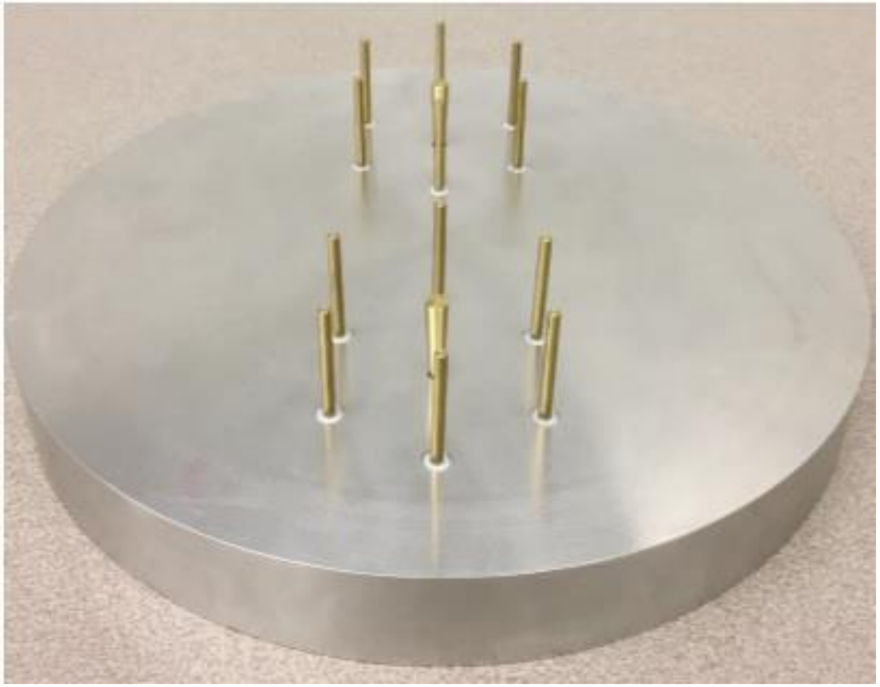


Path loss (dB) vs. link distance (m)
gate area

Task 4: 28 GHz Reconfigurable Antenna

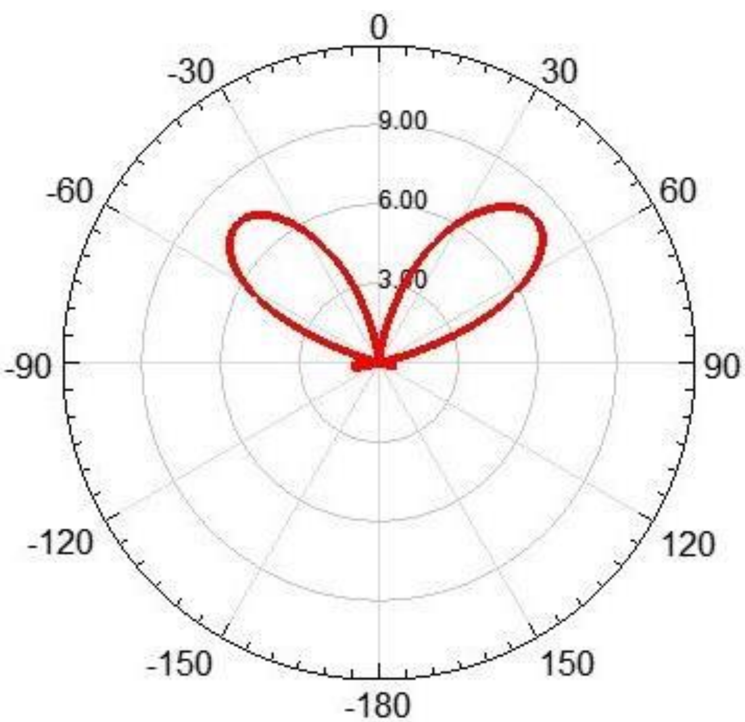


Electronically Steerable Phased Parasitic Array Radiator Antenna

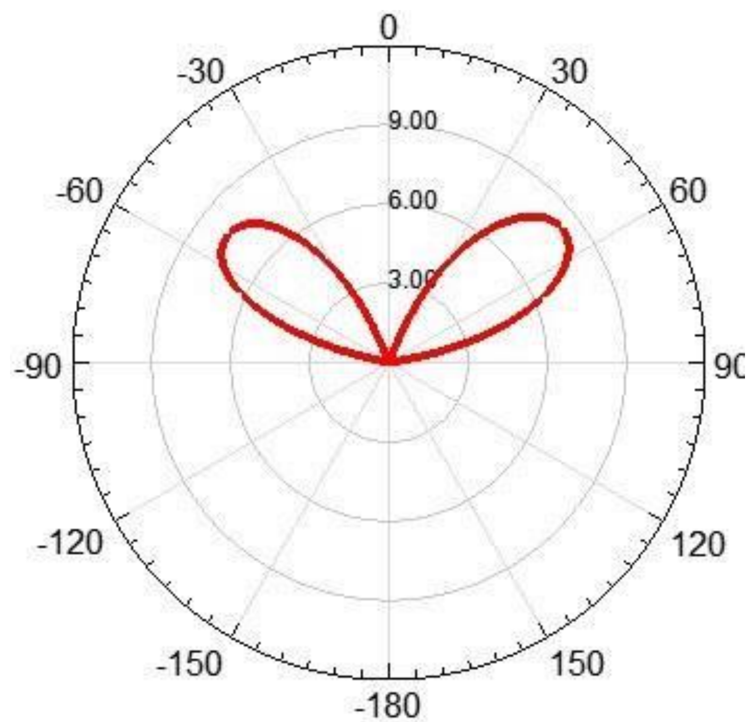


Manufactured antenna

Task 4: 28 GHz Antenna Design



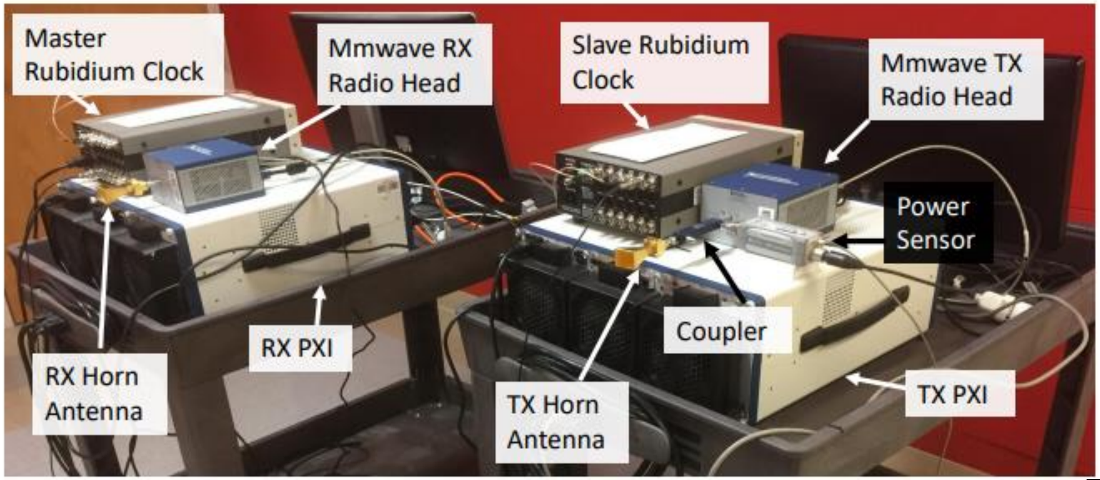
Dual beam at ± 45 degree



Dual beam at ± 50 degree

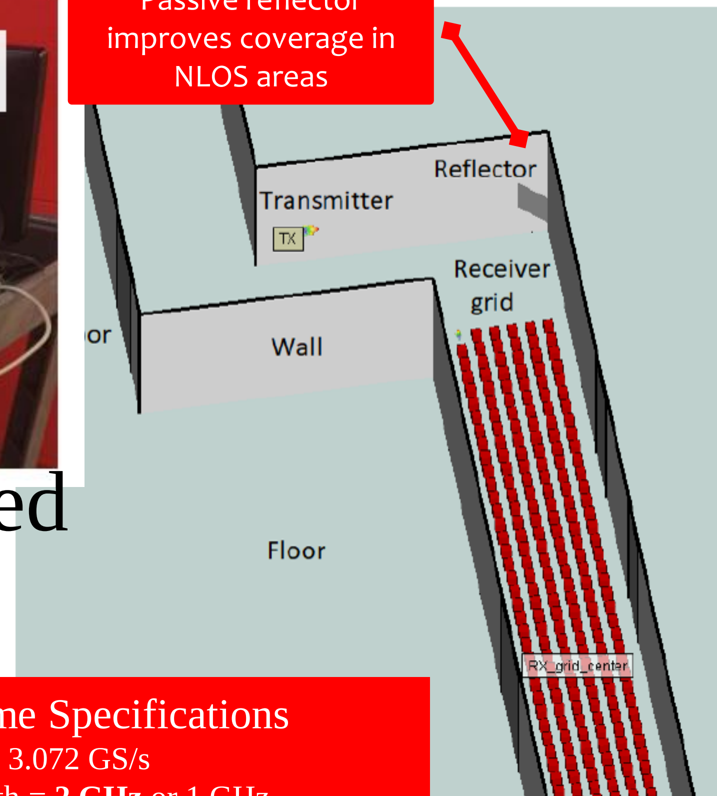
Designed antenna's radiation pattern generating two radiation lobes with one RF chain

Task 4: 28 GHz Channel Sounder



PXI Based

Passive reflector improves coverage in NLOS areas



Goals

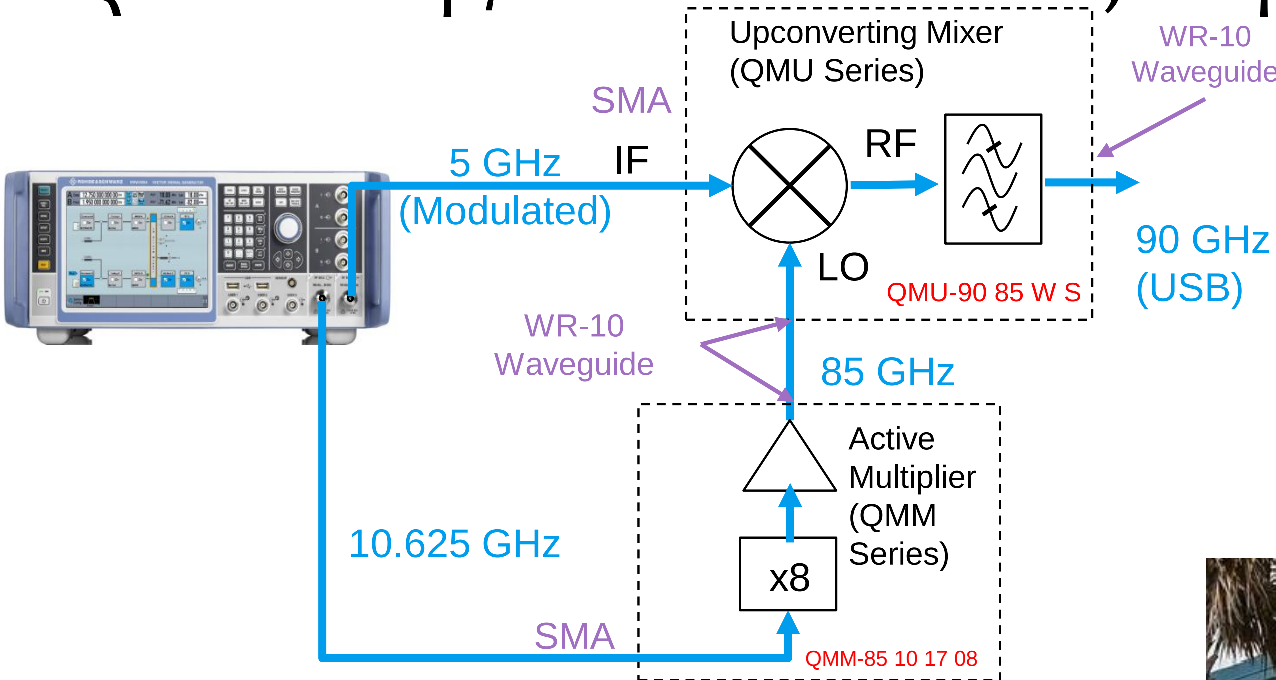
- mmWave channel sounding in indoor/outdoor environments, downtown Raleigh, & at airports
- Coverage enhancements (to overcome NLOS & blockage effects) using passive reflectors
- mmWave radar for drone detection/tracking

Some Specifications

- ADC f_s = 3.072 GS/s
- Bandwidth = **2 GHz** or 1 GHz
- Max. Excess delay = **1.33 µs** or 2.66 µs
- Delay resolution = **0.65 ns** or 1.33 ns
- Dynamic range = 60 dB
- Max. measurable path loss: 185 dB
- Max. TX power = 25 dBm
- Horn antenna gain = 17 dBi
- HPBW = 26^{0} elevation, 24^{0} azimuth

Task 4: 90 GHz Channel Sounder

- R&S Signal Generator, Analyzer
- Quinstar up/downconverters, amps



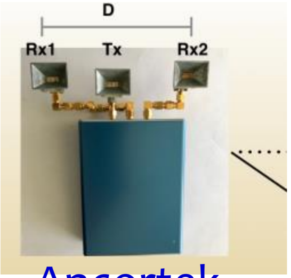
Task 5

- Detection, Localization, & Tracking of Unauthorized UAS
  - Develop novel unauthorized UAS detection/ localization techniques to detect/track any unauthorized UAS that enters any restricted zone

Task 5: Major Goals

Phantom 3 Drone

- Ancortek & NI PXI based mmWave radar experiments for drone detection/classification/tracking



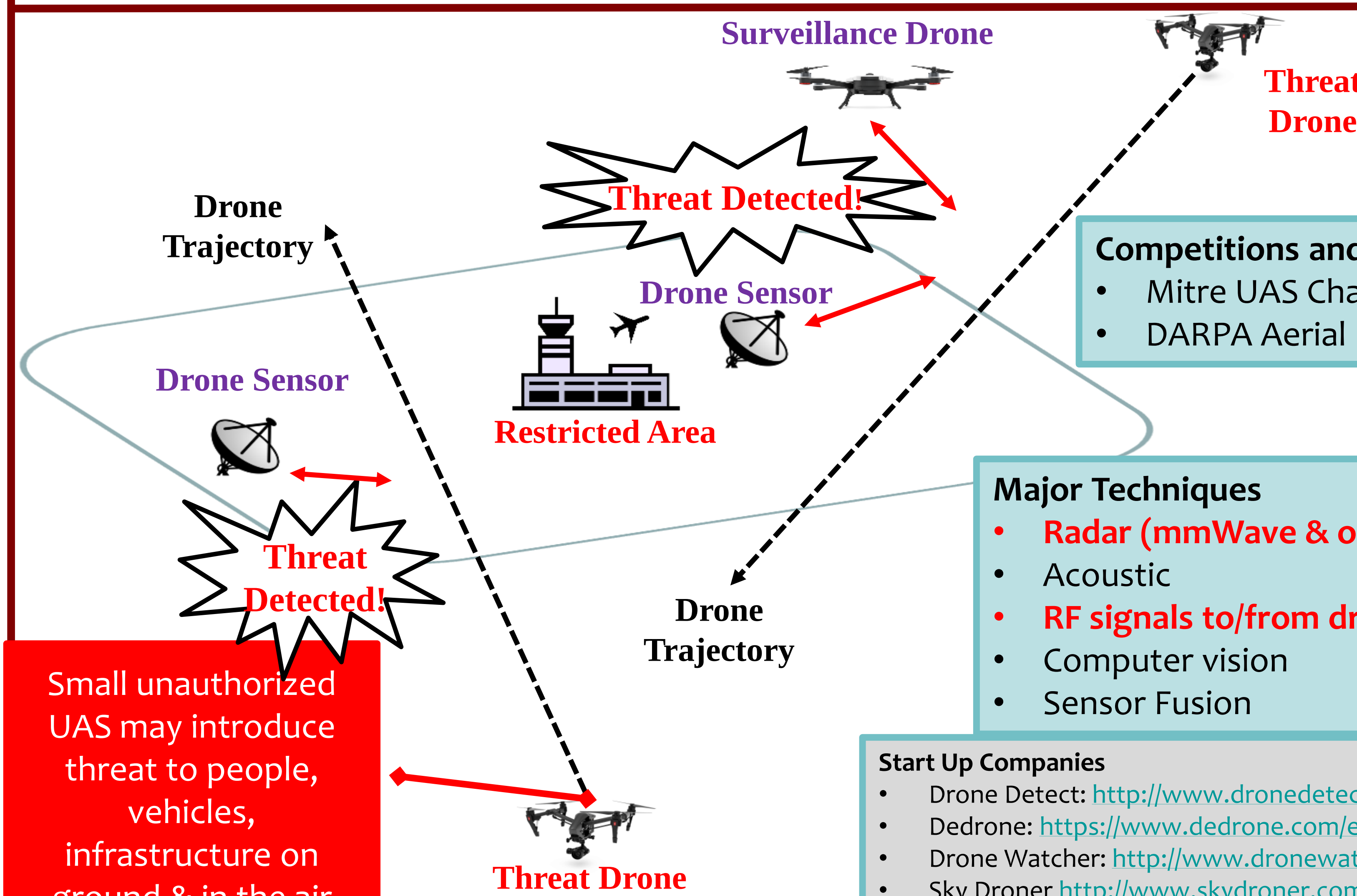
Ancortek

- UWB localization & radar experiments w/distributed UWB sensors

- Capture payload/control signals from major commercial drones w/wideband o-scopes & USRPs, develop database for drone detection

- Receding horizon drone tracking w/intermittent observations at surveillance drones

Task 5: Drone Detection & Tracking



Small unauthorized UAS may introduce threat to people, vehicles, infrastructure on ground & in the air

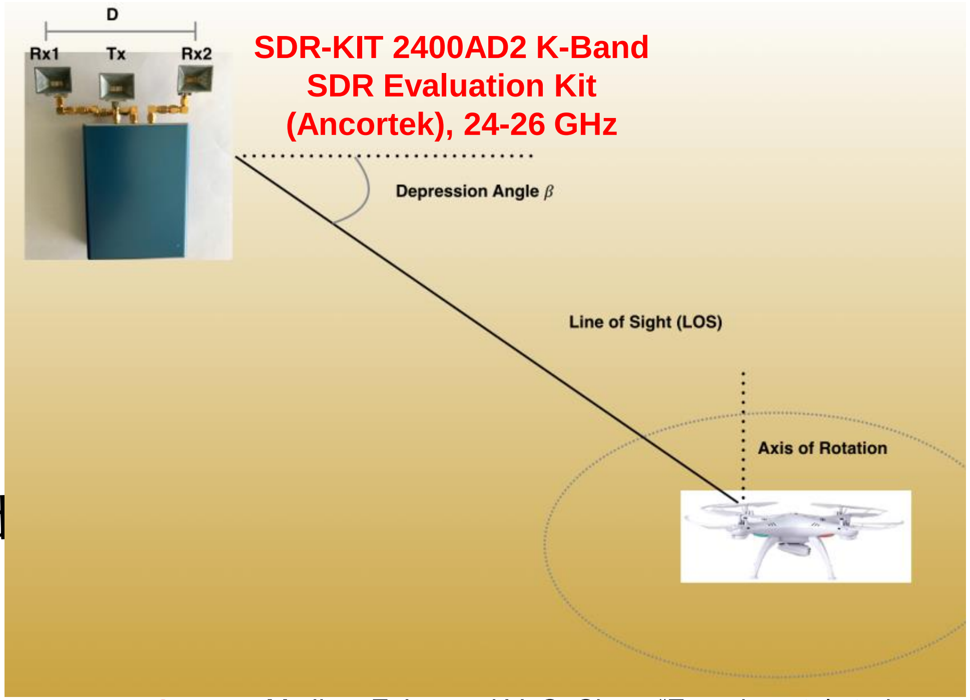
Competitions and Projects
- Mitre UAS Challenge
- DARPA Aerial Dragnet

Major Techniques
- **Radar (mmWave & other)**
- Acoustic
- **RF signals to/from drones**
- Computer vision
- Sensor Fusion

Start Up Companies
- Drone Detect: http://www.dronedetector.com/
- Dedrone: https://www.dedrone.com/en/
- Drone Watcher: http://www.dronewatcher.com/
- Sky Droner http://www.skydroner.com/
- Sky Safe: https://www.skysafe.io/

mmWave 24-26 GHz Ancortek Radar

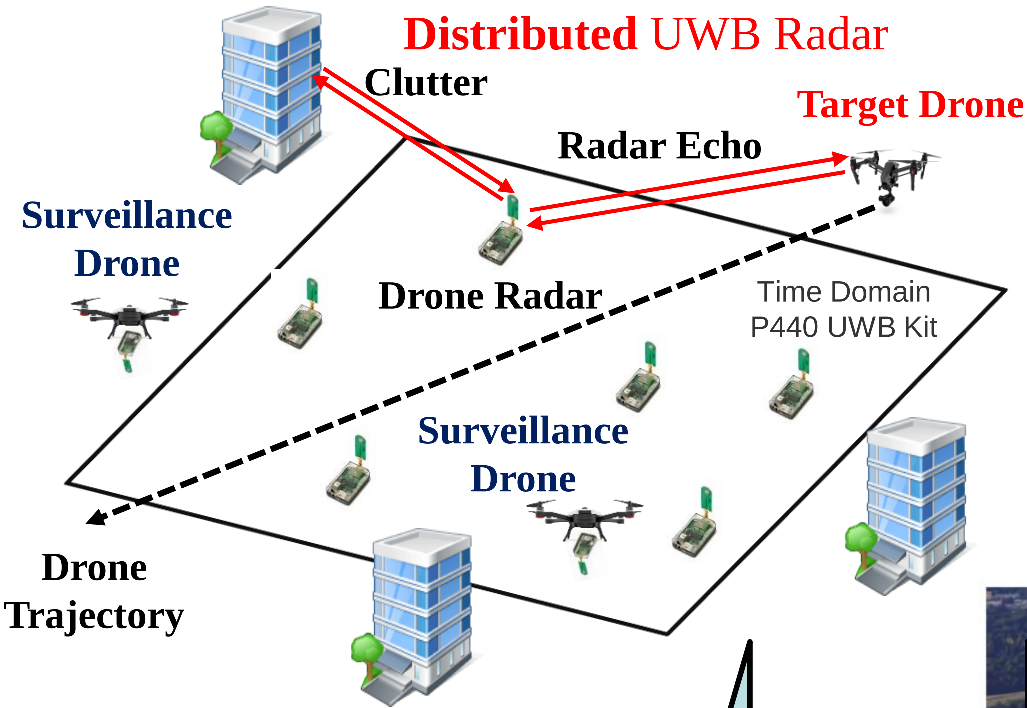
- Large bandwidth in mmWave spectrum enables good range resolution, possibility to extract unique micro-Doppler drone signature
- Compared to visible/infrared based techniques, less susceptible to rain, fog, obstacles



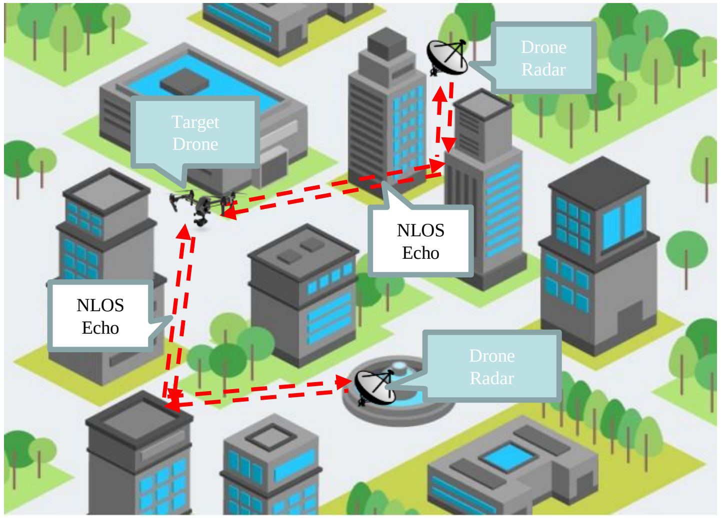
Source: M. Jian, Z. Lu, and V. C. Chen, "Experimental study on radar micro-Doppler signatures of unmanned aerial vehicles," in Proc. *IEEE Radar Conference (RadarConf)*, pp. 854-857, 2017.

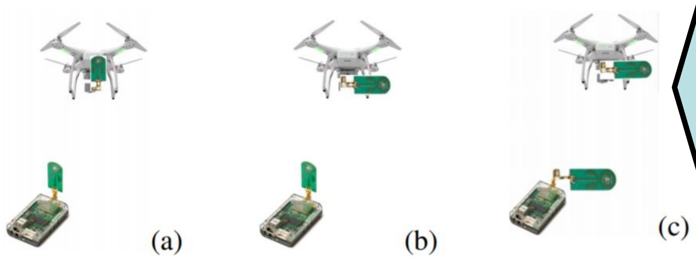
Goals
- Drone detection/tracking based on mmWave radar returns
- Drone classification based on micro-doppler signatures
- Limitation: short range due to low power

UWB for Detecting/Tracking Drones

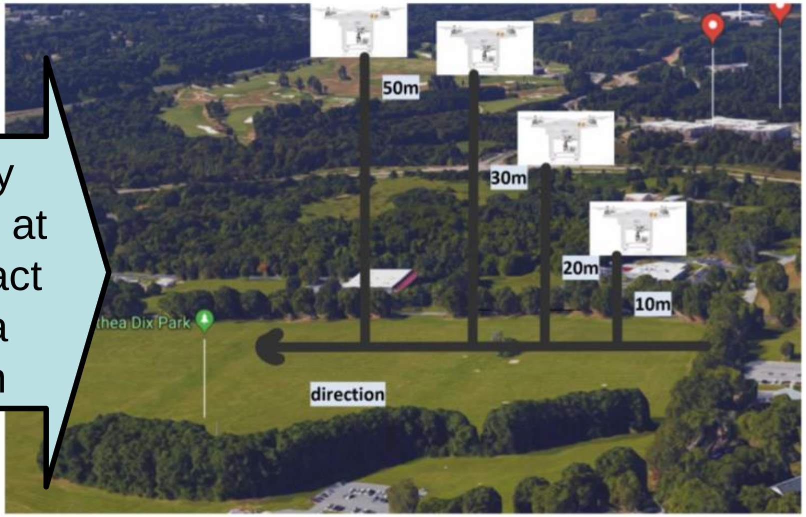


NLOS Radar

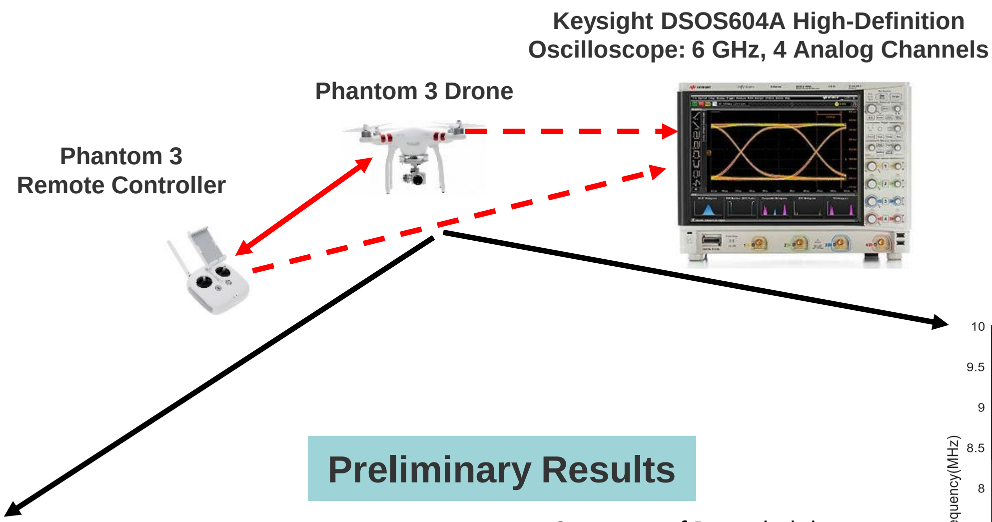




Preliminary experiments at NCSU: impact of antenna orientation



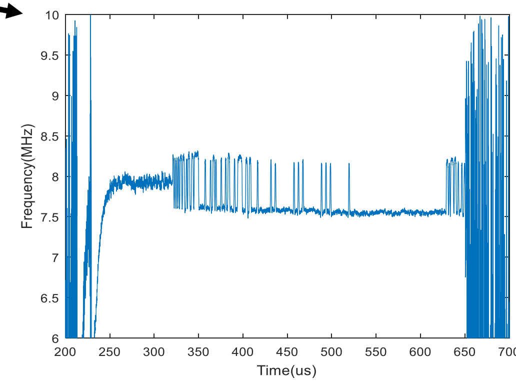
Machine Learning Based UAV Detection/ Classification via UAV RF Radiated Signals



Goals

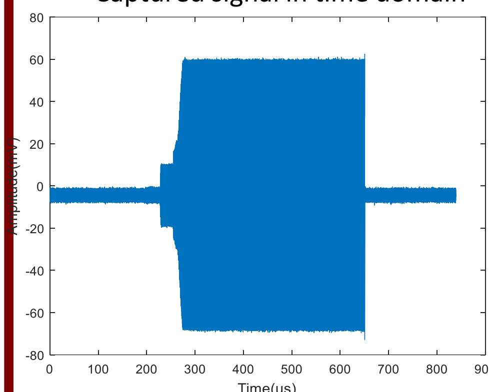
1) Identify & classify different types of drones using their unique signatures
2) Develop database of major commercial drones for classification

FM Demodulation (Zoomed In)

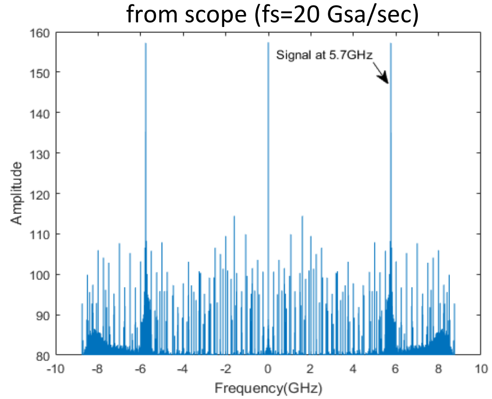


Preliminary Results

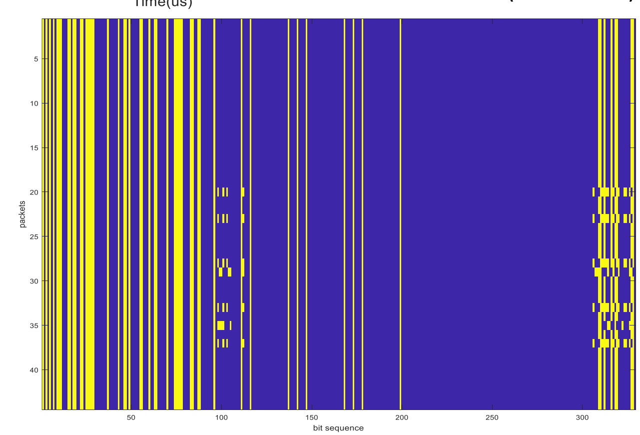
Captured signal in time domain



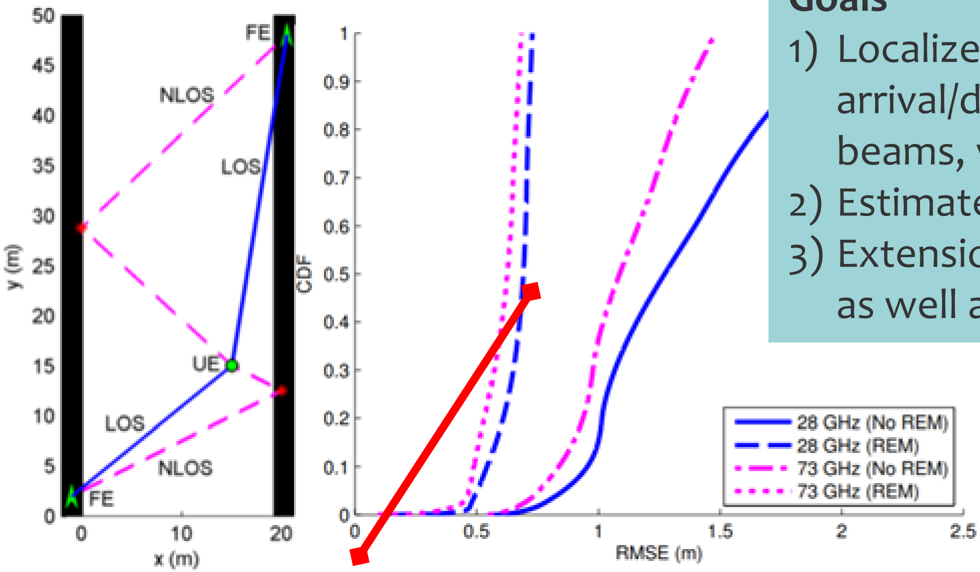
Spectrum of Recorded data from scope (fs=20 Gsa/sec)



Decoded packets (1's and 0's)

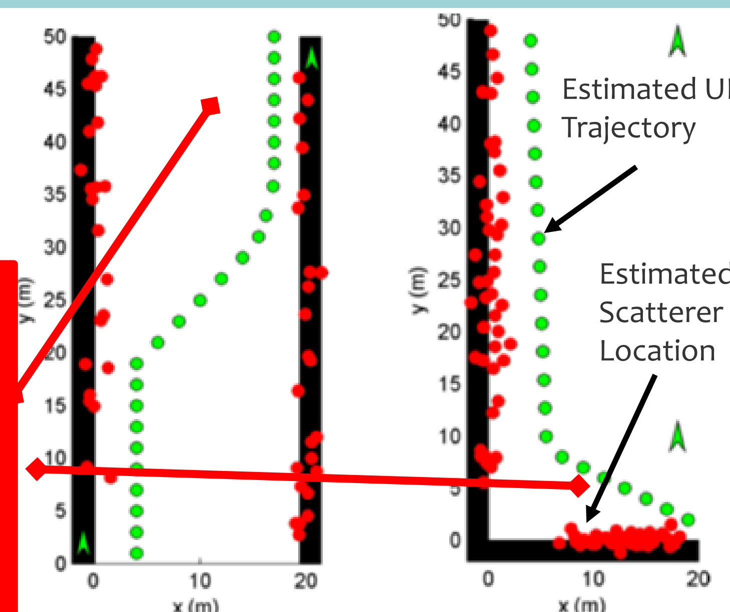


mmWave Localization & Tracking w/ Environment Mapping



Goals

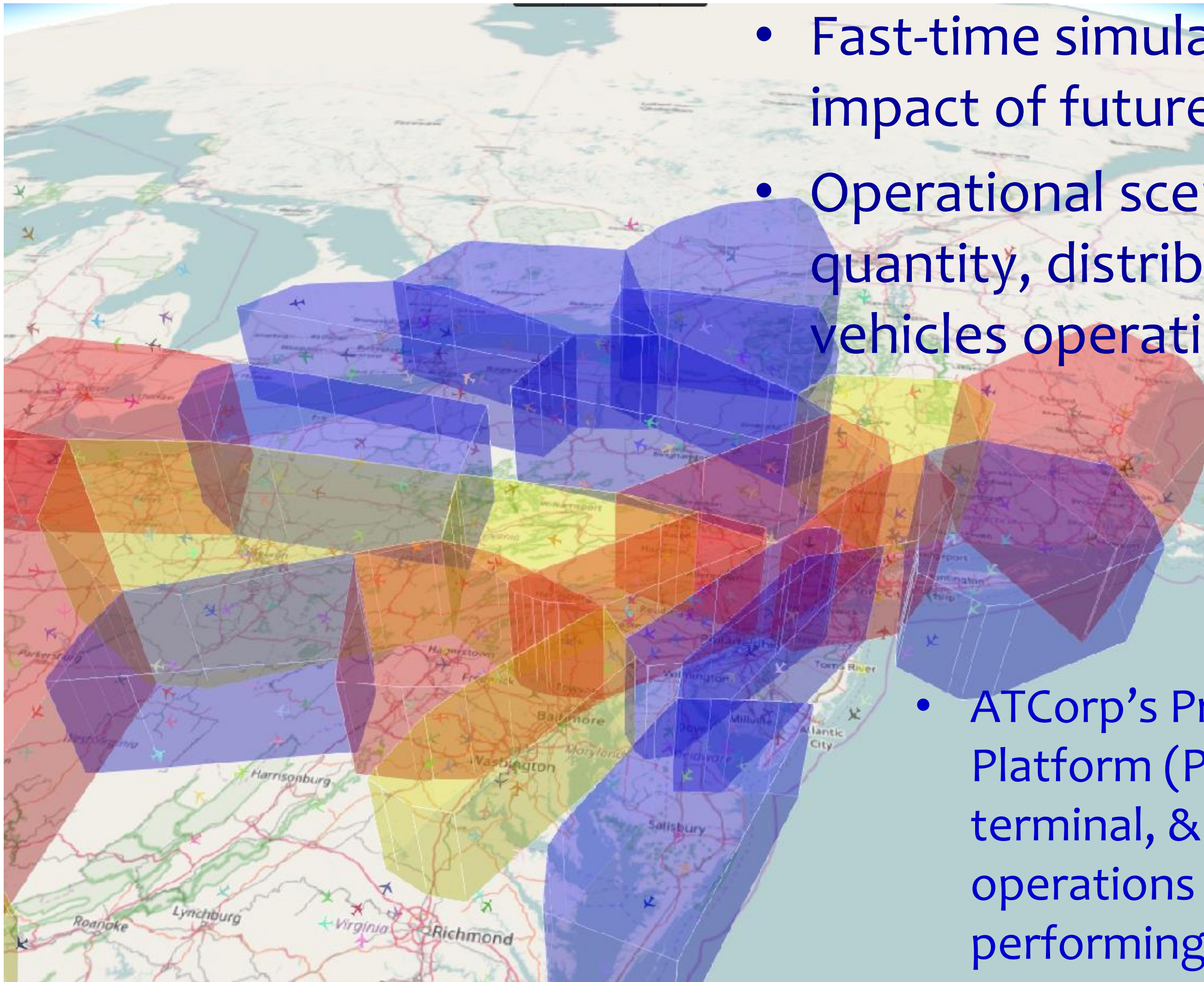
1) Localize target user using angle of arrival/departure & ToA of narrow mmWave beams, various LOS/NLOS directions
2) Estimate scatterer locations as well in parallel
3) Extensions to user/inventory tracking at airports, as well as accurate localization/tracking of drones



- Two mmWave fixed equipment (FE) to track user equipment (UE) using LOS/NLOS beams in urban canyon environment
- Radio environmental mapping (REM) assumes scatterer locations perfectly known

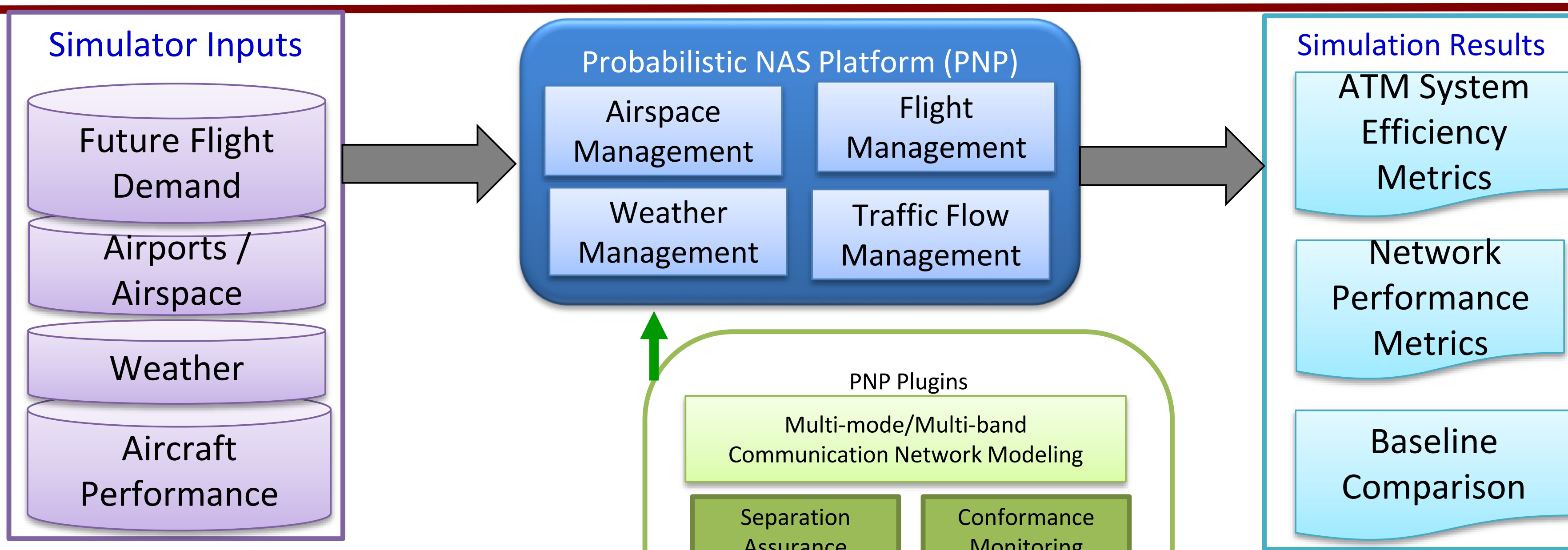
Simultaneous UE localization & environment mapping w/mmWave signals in urban canyon & urban corner settings (2 FEs)

Task 6: Simulation Assessment

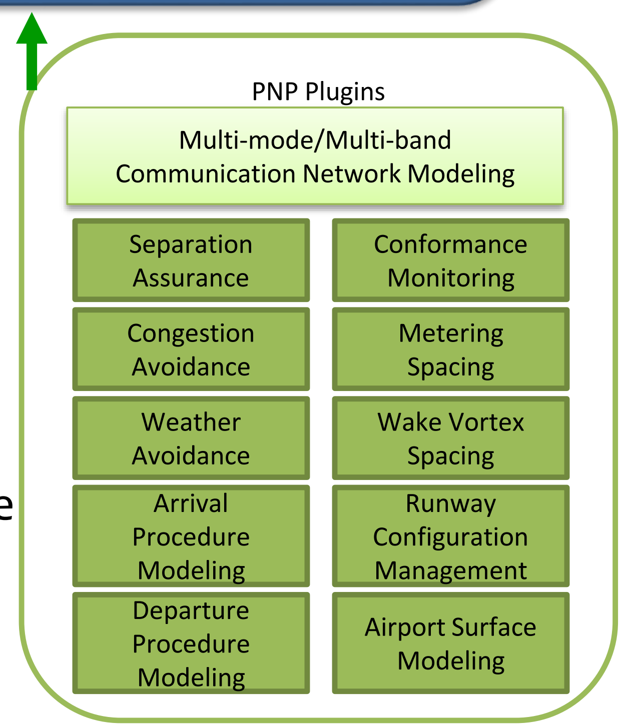


- Fast-time simulation assesses impact of future CNS/ATM
- Operational scenarios describe quantity, distribution, & types of vehicles operating in the NAS
- ATCorp's Probabilistic NAS Platform (PNP) models enroute, terminal, & airport surface operations & is capable of performing both regional & NAS-wide simulations

Task 6: Simulation Assessment



- Operational scenarios drive new PNP modeling capabilities
- Leverage NASA/FAA work in modeling & simulation of future NAS concepts, technologies
  - Future Traffic Scenarios
  - Future Airport Capacities
  - Future Airspace Capacities



- We have had multiple discussions w/NASA /FAA about leveraging prior work
  - Thank you to Confesor Santiago, Kee Palopo, & Jim Murphy, NASA Ames
  - Thank you to Joe Post, Kimberly Noonan, & Sanjiv Shresta at FAA

Next…

- Task 1: incorporate survey data → final ConOps
- Task 2: finish quantification of current system gaps, initial eval of new candidate comm tech's

- Task 3: develop quantitative multi-band/mode eval framework; analyses, simulations, SDR experiments…

Next…(2)

- Task 4: + mmWave airport chan. measurements, model development; mmWave link/network performance analyses, simulations…

- Task 5: mmWave radar drone detect/tracking; drone signature eval

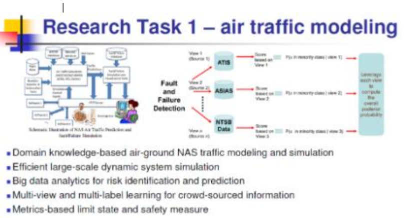
- Task 6: follow Task 1,

gather information

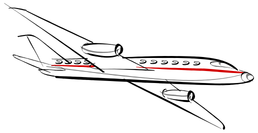
Long Term Outlook

- Deployment!
  - Potential field trials for various systems
  - Most likely airport settings

- Standards
  - Inputs to various standards bodies
    - RTCA, 5GmmWave Chan Alliance, IEEE…
- Potential/New collaborations
  - Academia: ULI group at Arizona St. U., VT, GT…
  - *Industry*
  - NASA!



Conclusion



- HSCNA project has 6 Tasks for **Safe, Efficient Growth in Global Operations**
  - ConOps
  - Comm System Assessment & Gaps
  - MultiBand/MultiMode link/net designs
  - mmWave airport & UAS links
  - Unauthorized UAS detection
  - All incorporated into ATM simulations

In a Few Years

Thank You