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Connecting the Mobile World

WEBINAR SERIES ON ADVANCED MOBILITY

Acknowledgement

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Reliability for Air-Ground Communications & AAM

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August 2023

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Introduction

- Much is going on in *aviation*…
- Much is going on in *radio*…

Outline

- Introduction
- Aviation growth
  - UAS (UAV, drones…), **AAM**, Passenger
- Reliability & availability concepts
- Some AAM considerations, NASA/NARI
  - Air-ground (AG)/Air-air (AA) vs. terrestrial
- PHY reliability
  - AG channel
  - Jamming
- Adversary perspective & countermeasures
- Future work

INTERNATIONAL CIVIL AVIATION ORGANIZATION
A United Nations Specialized Agency

EUROCONTROL

RTCA
THE AVIATION GOLD STANDARD SINCE 1935

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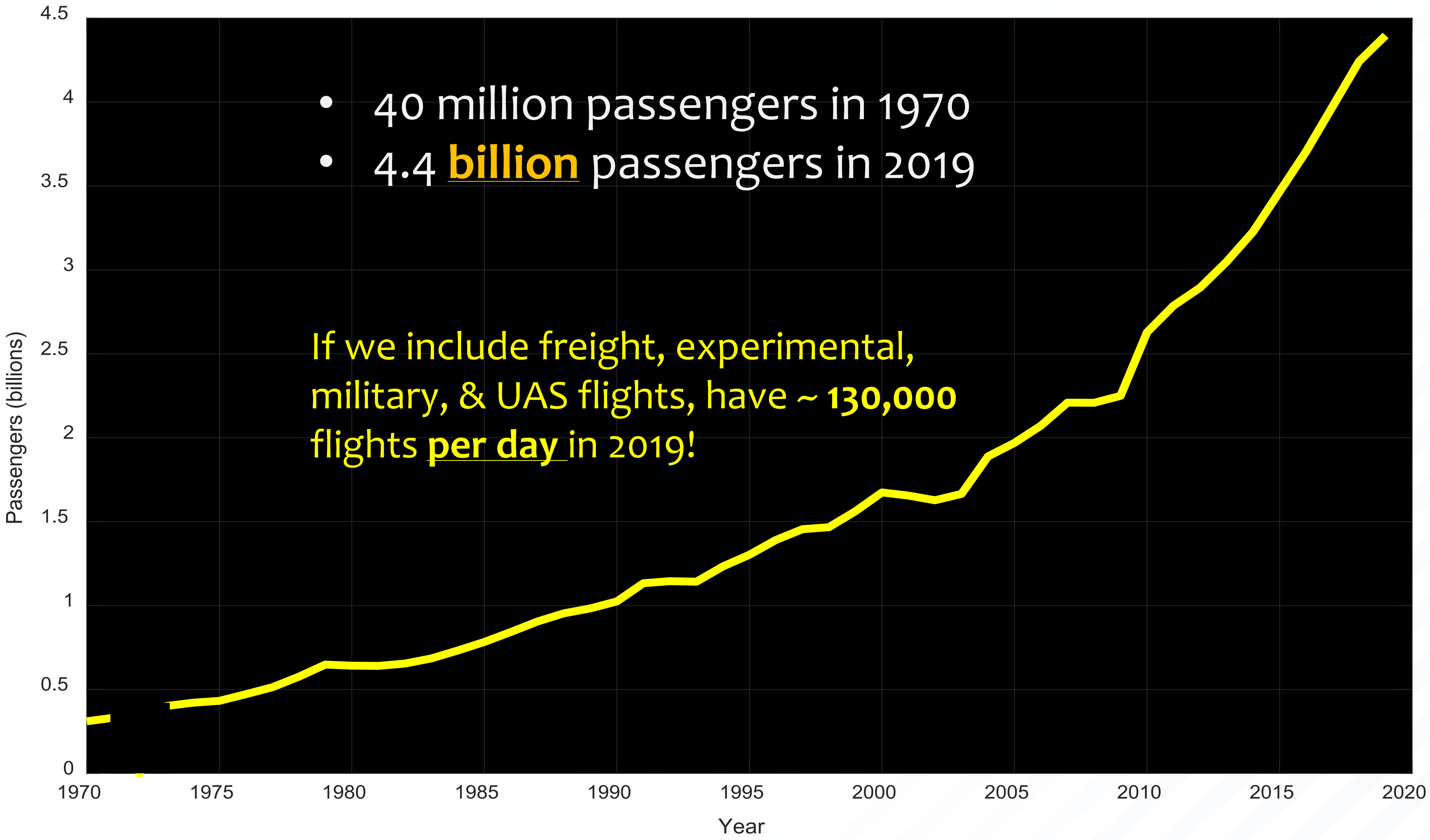
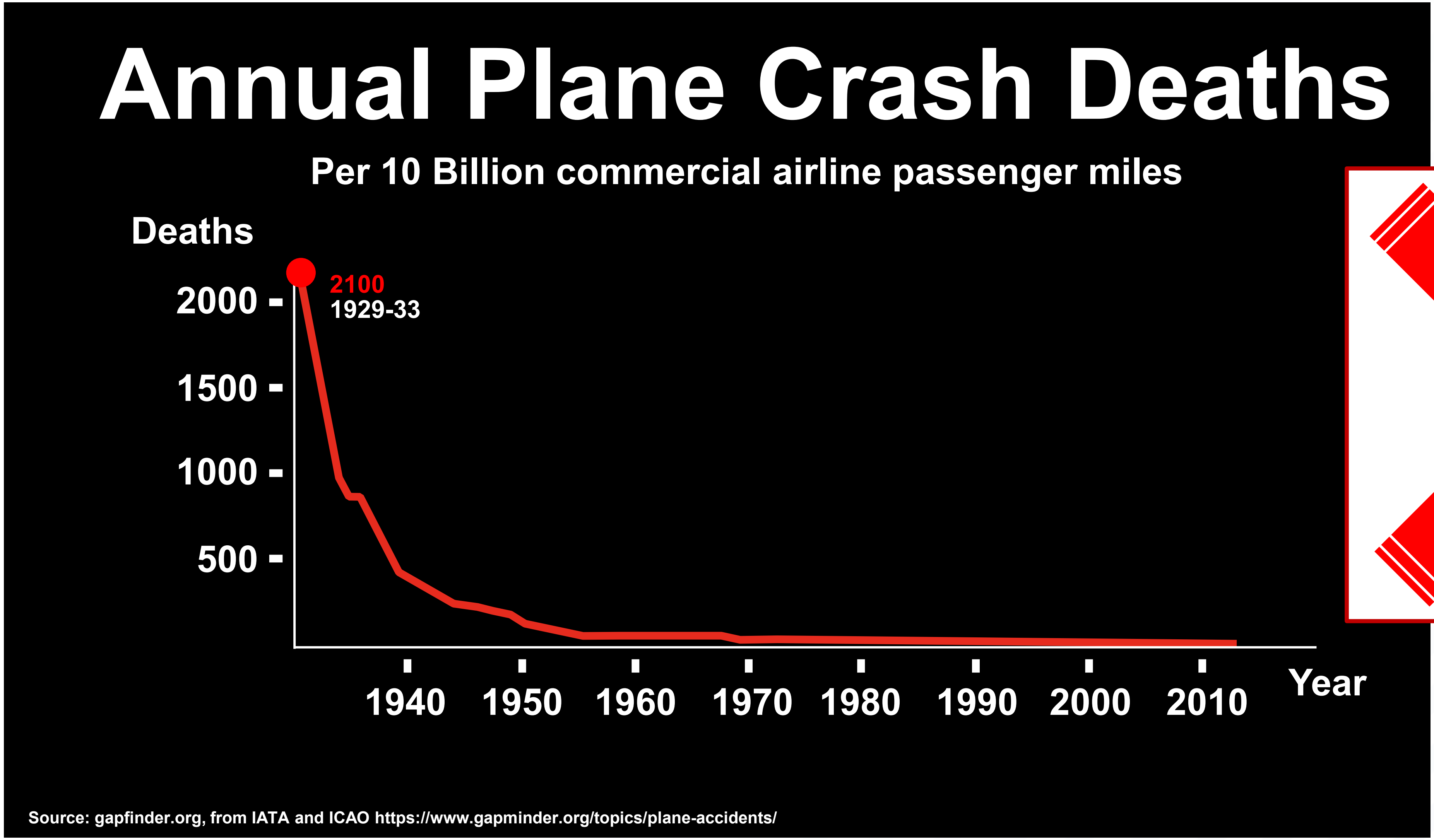
Aviation Growth: 1970-2019

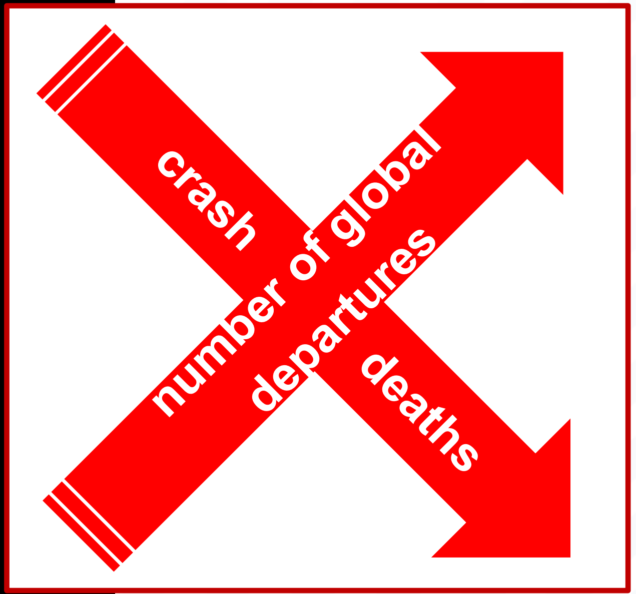


Source: **World Bank** https://data.worldbank.org/indicator/IS.AIR.PSGR

Aviation Accidents: 1930-2016



Trends



Aircraft + Radios…

- **Safe** aviation requires Air Traffic Management
- Air Traffic Management (ATM) requires CNS
  - **Communication**
  - **Navigation**
  - **Surveillance**

- UAS/AAM **new** cases…

NASA ARI Efforts

NARI
NASA AERONAUTICS RESEARCH INSTITUTE

Home Aircraft Airspace Community Crosscutting Models Files Recordings Calendar

NASA Advanced Air Mobility
Airspace Working Group

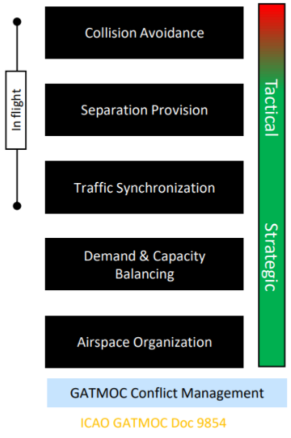
The Airspace Working Group focuses on Open, Safe and Secure National Airspace through Pillars 3 and 4. Airspace design and operations develop AAM-inspired concepts and technologies to define requirements and standards addressing key challenges such as safety, access, scalability, efficiency and predictability.

Technical Lead: Parimal Kopardekar, Ian Levitt

Coordinator: Cecelia Town

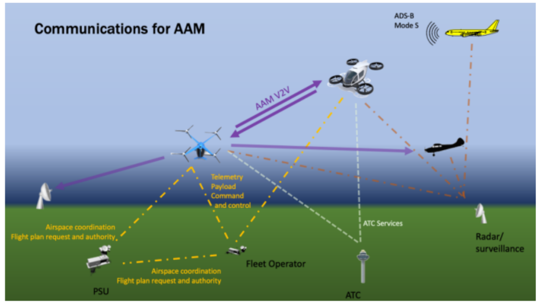
Both air-ground & air-air (V2V) comm are required

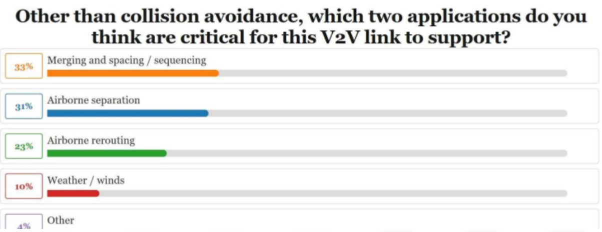
Airspace/Aircraft WG Update – Sept 20



Not all aspects of these functions will require V2V link

RTCA Advanced Air Mobility – V2V Link White Paper





Reliability

- Merriam Webster's Dictionary definition

reliable
1 of 2 **adjective**

1 **:** suitable or fit to be relied on **:** dependable
2: giving the same result on successive trials

- Wikipedia entry

a **reliable** protocol is a communication protocolthat *notifies the sender whether or not the delivery of data to intended recipients was successful*. Reliability is a synonym for **assurance**, which is the term used by the ITU & ATM Forum.

RTCA C2 Datalink MOPS

- **Availability:** probability that operational transaction supported by CNPC Link System can be initiated when needed. Pr(A)

- **Continuity:** probability that operational transaction supported by the CNPC Link System can be completed within *transaction expiration time* given CNPC Link System was available at start of the transaction. Pr(TransCompleted|A)

- **Integrity:** probability that operational transaction supported by the CNPC Link System is completed with no undetected errors. Pr(TransCompleted, no err)

Availability, Continuity, Integrity

- Traditional communications engineering addresses availability & integrity
  - Availability $A = 1 - Pr(outage)$
  - Integrity in terms of FER, BER, latencies

- Ultimately, if link *UN*available, transaction canNOT be completed
  - We focus here on availability: for link to be "reliable" (can be depended upon) it must first be ***available***
  - Focus on comm link performance, not on aircraft actions or airspace operations & re-actions

Link Availability (RTCA MOPS)

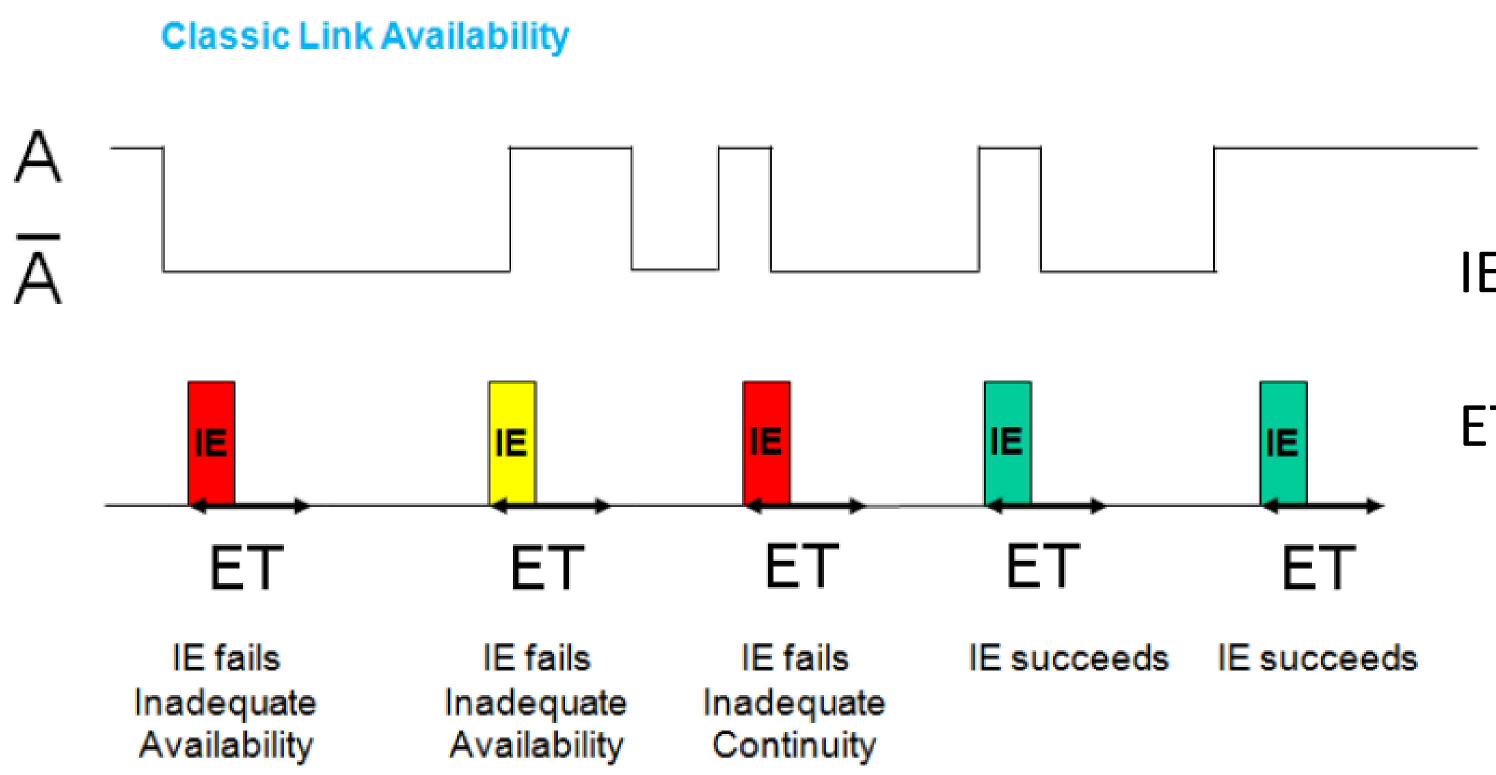


Figure K-8: Graphical Model of Link Availability and Continuity

IE = information exchange

ET = expiration time

Based on the above, Pr{Success} is related to A_{RCP} and C_{RCP} through the formula

$$Pr\{Success\} = A_{RCP} C_{RCP} + (1 - A_{RCP})R$$

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Reliability Requirements [Klugel]

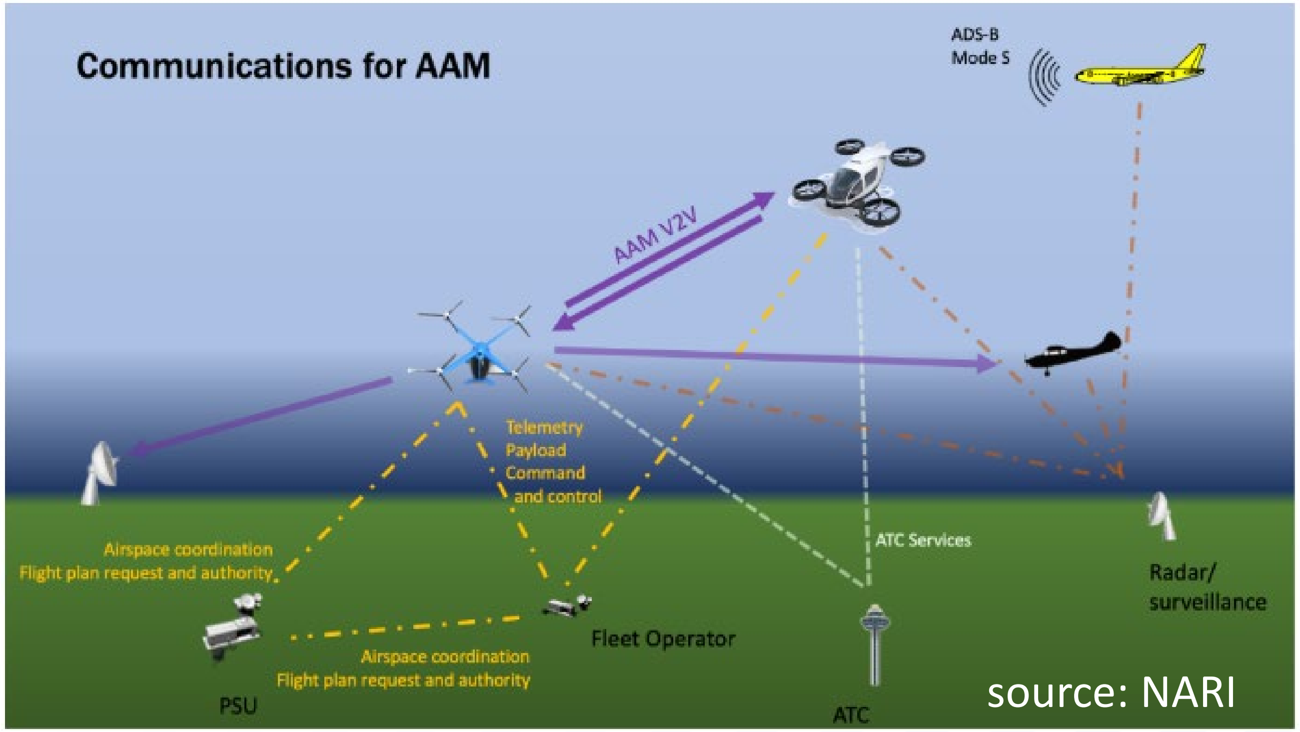
Application	Data rate (Mb/s)	End-to-end latency (ms)	Communication reliability	Ref.
ATM	0.02	<5000	99.9999%	[1, 2]
RCO	0.03	<40,000	99.999%	[2, 3]
Piloted eVTOL	0.012	<100	High	[1, 2]
RPO	10–100 (video) 0.25–1 (control/telemetry)	10-150	High	[2, 4]
FAO	0.1-1	100-500	Medium	[2, 4, 5]
UTM	0.01-0.1	<500	99.999%	[2, 4, 6, 7]

TABLE 1. Connectivity estimates for different functions.

- ATM = air traffic management
- RCO = reduced crew operation
- RPO = remote pilot operation
- FAO = fully autonomous operation
- UTM = universal traffic management

AAM Links

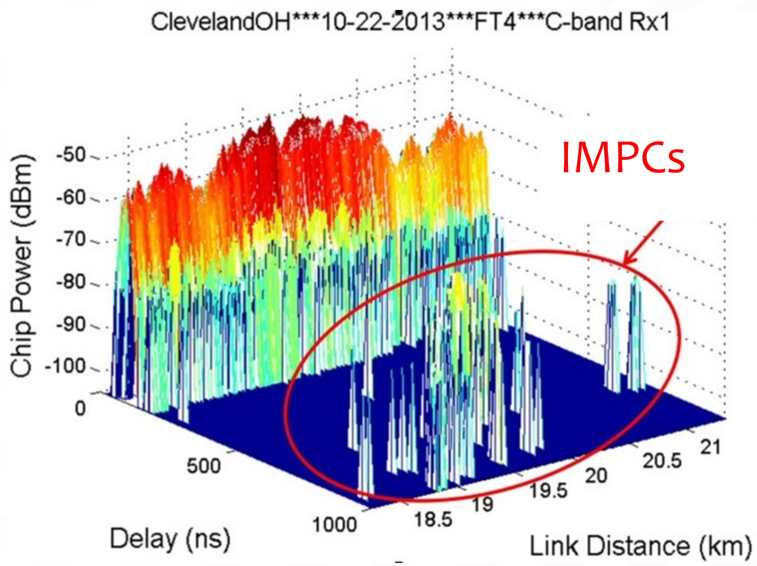
- Traditional air traffic control (ATC)
  – VHF: 25 kHz AM or VDL ~ 30 kbps
- PSU & Fleet
- Airspace coordination (~FAA)
- Air-air (V2V) for DAA



- Potential frequency bands
  – L-band (~ 970-1200 MHz) (DME, LDACs)
  – C-band (~ 5-5.2 GHz) (UAM…)
  – Cellular bands

NASA AAM/UAM

- Velocities (<100 m/s) > auto velocity
- Most links: strong LOS
- AA *and* AG
- Range < 10's km
  - 10's m: vertiports
- For C2
  - UR, some LL
  - L-band, C-band, VHF?
    - mmWave unlikely for near term, possible for vertiports

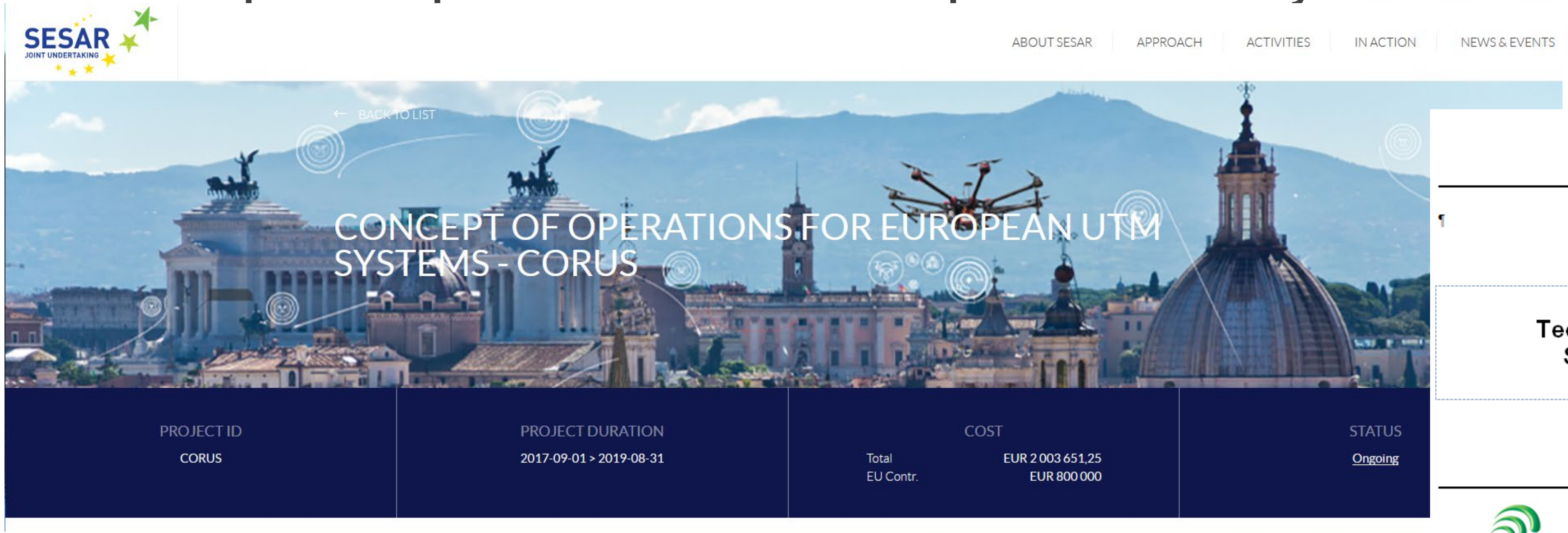


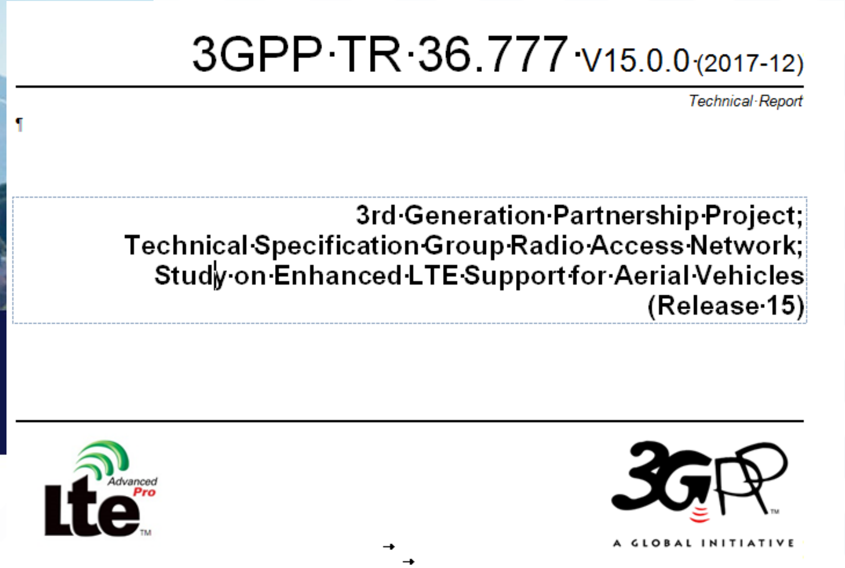
NASA AAM/UAM (2)

- Platform considerations: *limited* MIMO
  - Multiple antennas *already* (several VHF, GPS, UHF landing systems, L-band surveillance, satcom, marker beacon, etc.)
  - LOS-channel-MIMO gains require geometric "tuning," hence traditional diversity, or ST coding
  - Strongly cost-driven
- L- and C-band channels
  - 2-ray, *N*-ray w/LOS
  - Delay spreads 10's ns to few μs
  - AAM Doppler < ~ $333 f_{GHz}$ (Hz)
  - Large obstructions ⇒multi-link connectivity

Eurocontrol, 3GPP,…

- Concept of operations for European UTM Systems: CORUS





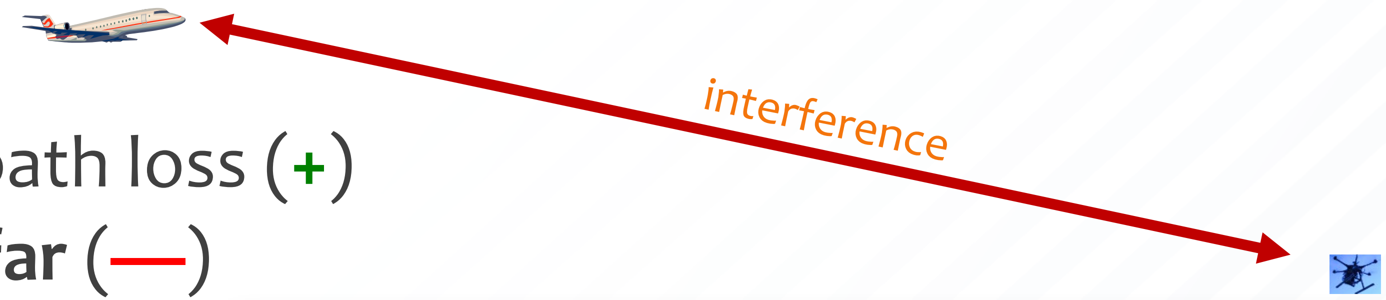
3GPP TR 36.777 V15.0.0 (2017-12)

Technical Report

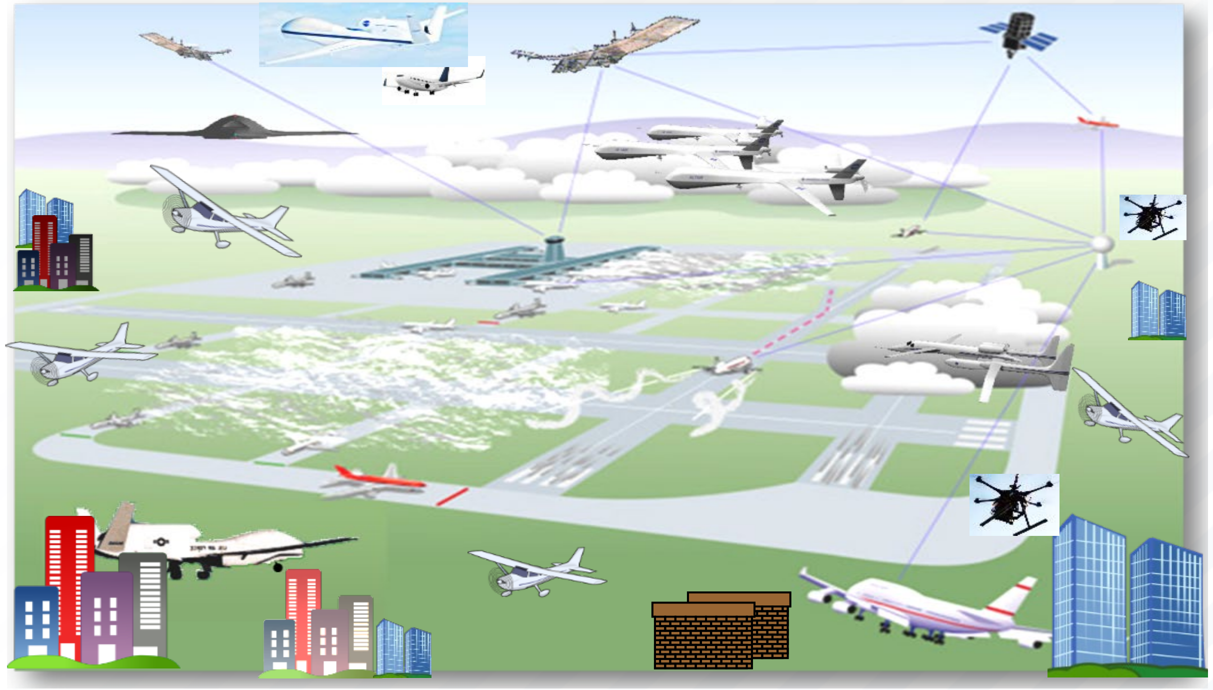
3rd Generation Partnership Project;
Technical Specification Group Radio Access Network;
Study on Enhanced LTE Support for Aerial Vehicles
(Release 15)

- 5G: Ultra-reliable, low-latency communications (URLLC)

Fundamental Features & Challenges



- Altitude
  - Larger Pr[LoS]⇒smaller path loss (+)
  - Interference propagates **far** (—)
- Mobility
  - Increased range (+)
  - Doppler shifts (—)
  - Need **accurate** navigation
  - Air traffic management (**ATM**)



AG vs. Terrestrial

Table 1. Qualitative comparison of characteristics of terrestrial and AG communications.

Characteristic	Terrestrial (~cellular)	Air-Ground
Velocities	Typically small	Potentially very large
Probability of LOS	Typically small	Potentially large
Temporal Availability	Very long	• Large for "loitering" fixed-wing aircraft • Very small for rotorcraft
Range	Small-medium	Potentially very large
Mobility Management	Well established	Well established for passenger aircraft, To-be-Defined for UAVs

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Reliability for AG Communications

- Primary PHY impediments to reliability
  - Wireless channel: multipath components (MPCs), obstructions, Doppler
  - Interference: unintentional & intentional (jamming)

- Higher layers can improve reliability
  - DL/MA format check
  - Packet "collision detection"
  - ARQ
  - Network layer routing
  - Transport layer error detection

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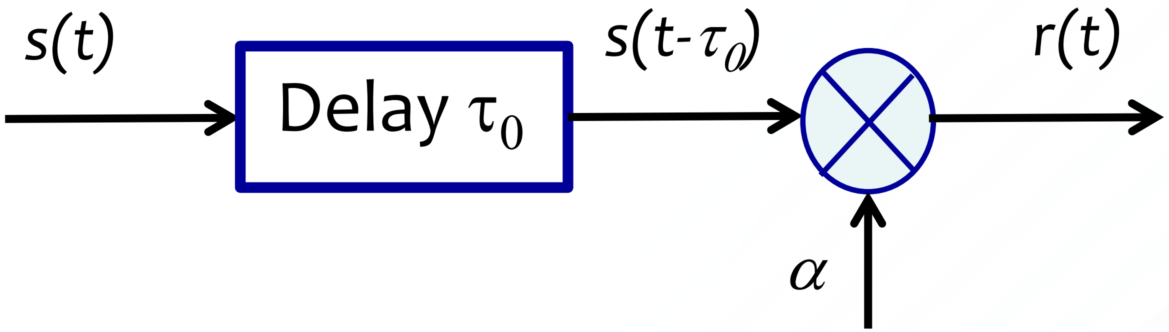
Channels

- For ANY communications (& radar, navigation, etc.), PHY channel required; simplest model is



- $s(t)$ = transmitted signal
- α = channel gain
- $r(t)$ = received signal

If the PHY does not work, remaining layers of the protocol stack don't matter

Aero vs. Terrestrial Channels

Table 2. Qualitative comparison of channel characteristics relevant to aeronautical & terrestrial communications.

Characteristic	**Terrestrial (~cellular)**	**Aeronautical**
Path Loss Models	Log-distance	Friis, 2-ray, log-distance
Narrowband Small Scale Fading	Typically Rayleigh, occasionally Ricean	Typically Ricean, occasionally Rayleigh
Root-mean Square Delay Spreads (delay dispersion)	Typically small (<few 100 ns)	Typically small, occasionally **very** large (few μs); *varies nearly 2 orders of magnitude*
Stationarity Distance	Typically small (~few m)	Can be large (>25 m) if LOS present
Doppler Spreads	Typically small	Can be large if velocity large

Air-X: CIR & Doppler

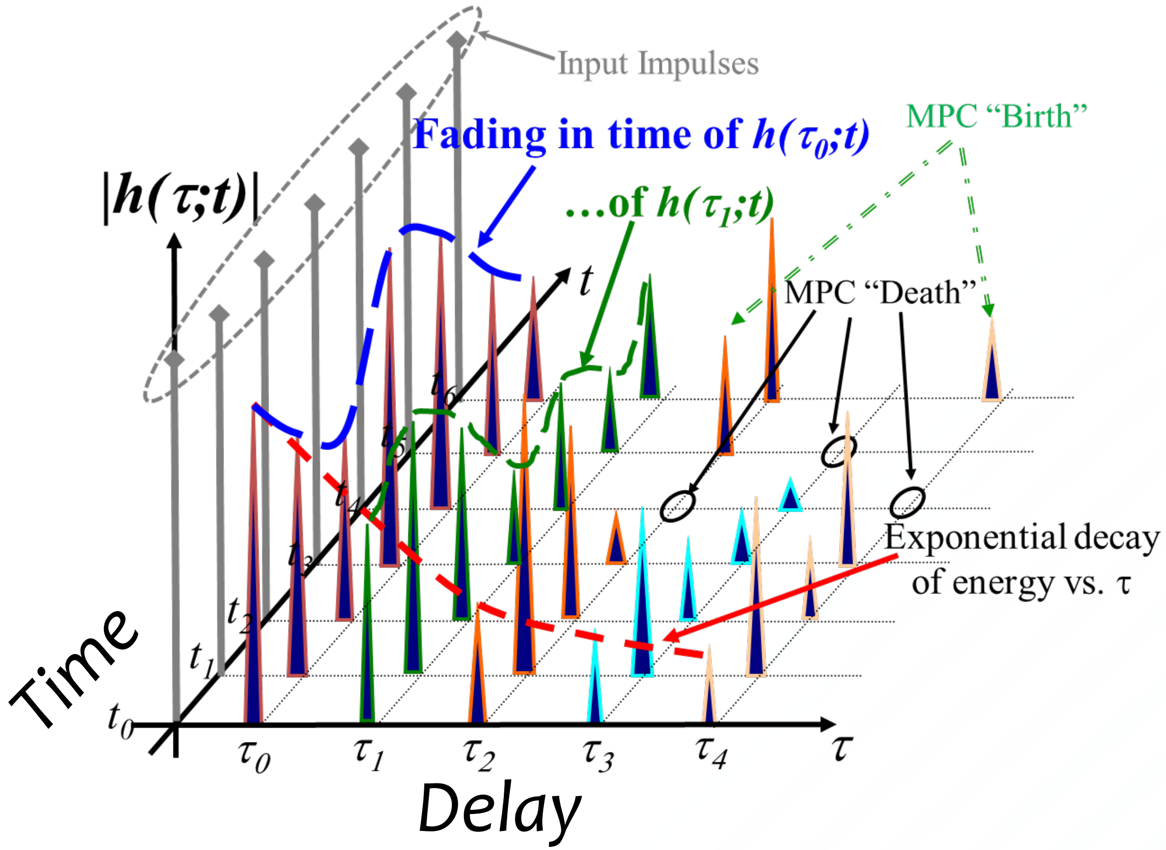
$$h(\tau;t)=\sum_{k=0}^{N-1}\alpha_k(t)\exp\{j[\omega_{D,k}(t)(t-\tau_k(t))-\omega_c(t)\tau_k(t)]\}\delta[t-\tau_k(t)]$$

amplitude — $\alpha_k(t)$

delay — $\tau_k(t)$

phase — $\omega_{D,k}(t)(t-\tau_k(t))-\omega_c(t)\tau_k(t)$

Doppler **frequency** — $\omega_{D,k}(t)$



Doppler Examples

1. 3 GHz, drone 30 m/s, Doppler =300 Hz
2. 30 GHz, medium aircraft 90 m/s, Doppler=9 kHz (LTE Δf ~15 kHz)

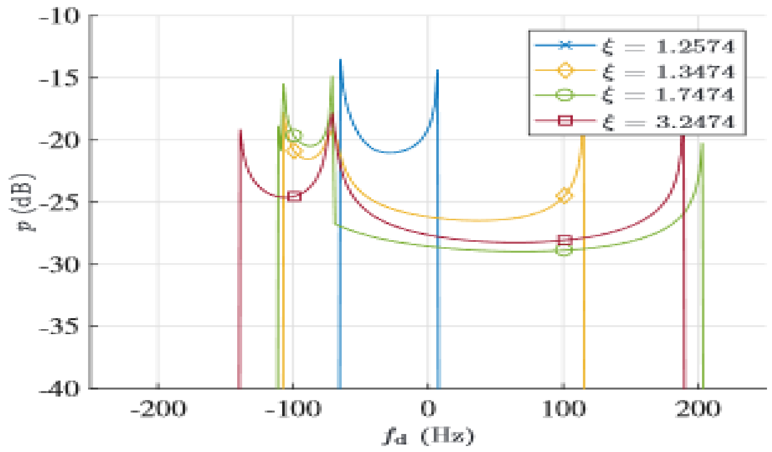
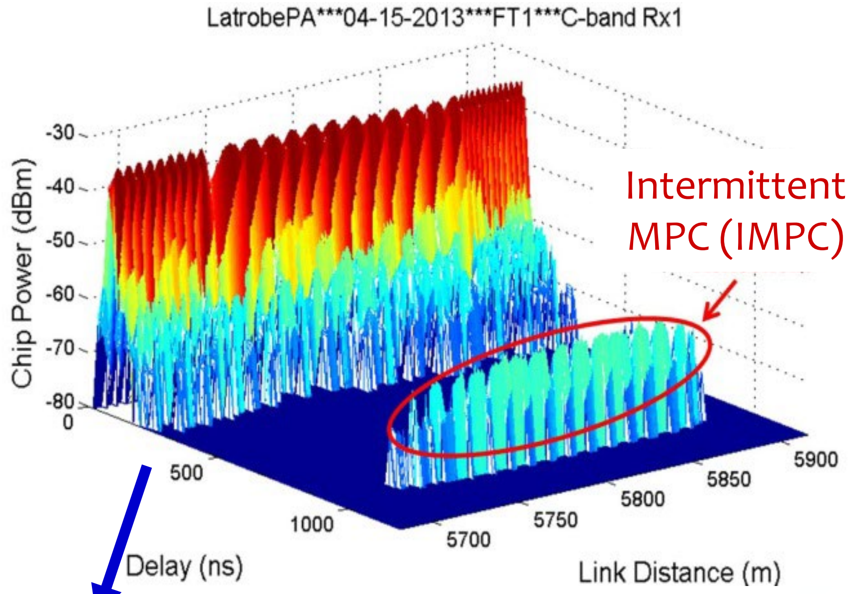


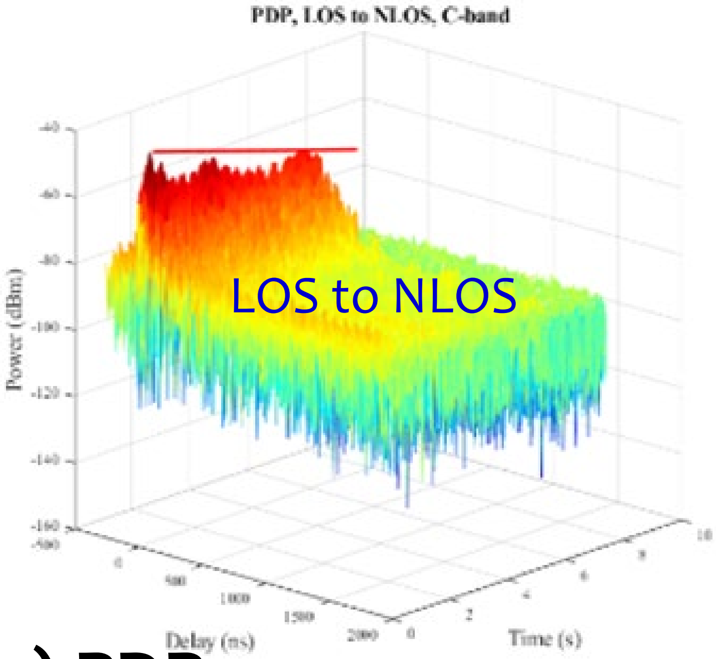
Fig. 17. Scenario 4: Specific delay-dependent Doppler pdfs $p(t^*; f_d|\xi^*)$ $\mathbf{v}_t = [200, -19, 46]^T$ km/h and $\mathbf{v}_r = [-250, -38, 92]^T$ km/h at a distance of $2l = 2628$ m.

Channel Variation (1): Air-Ground

Medium Aircraft: Hilly/Suburban

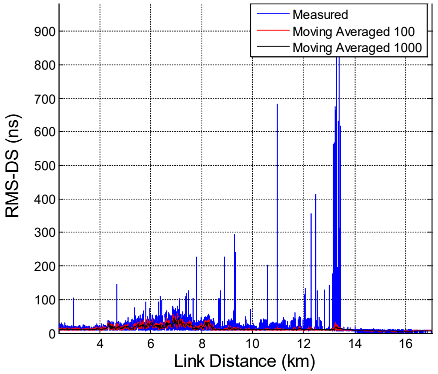


Drone: Suburban



C-band (5 GHz) PDPs

RMS-DS vs. distance



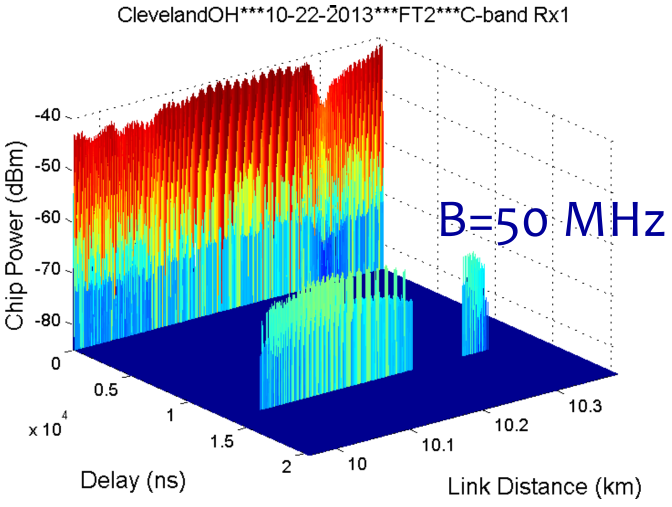
IMPC "on" ~ 100 m, often *much less*: **RAPIDLY** changing channel due to platform velocity

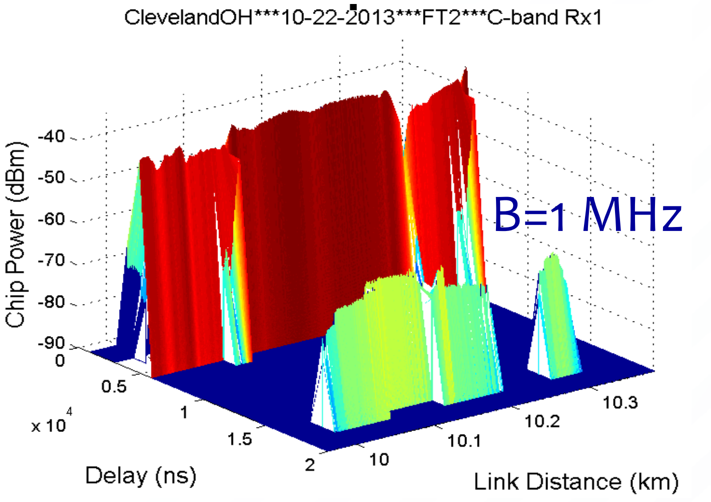
RMS-DS

	Mean	Max	σ
Medium Aircraft Alt~600 m Range ~ 27 km	36	**996**	56
Drone Alt~30 m Range < 100 m	50	171	21

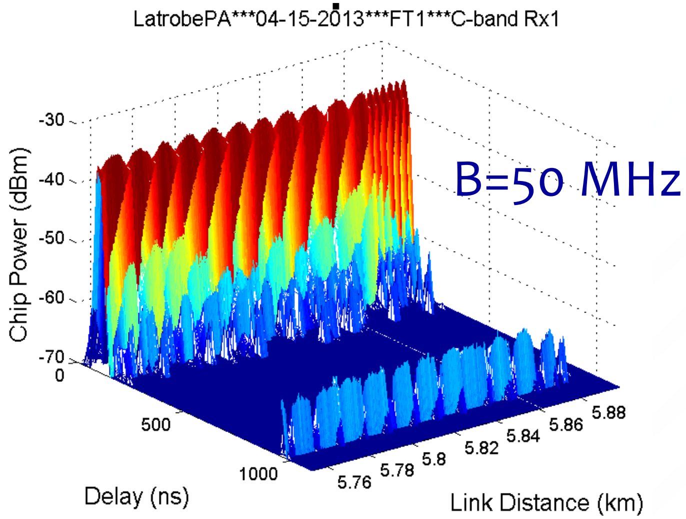
Channel Dynamics

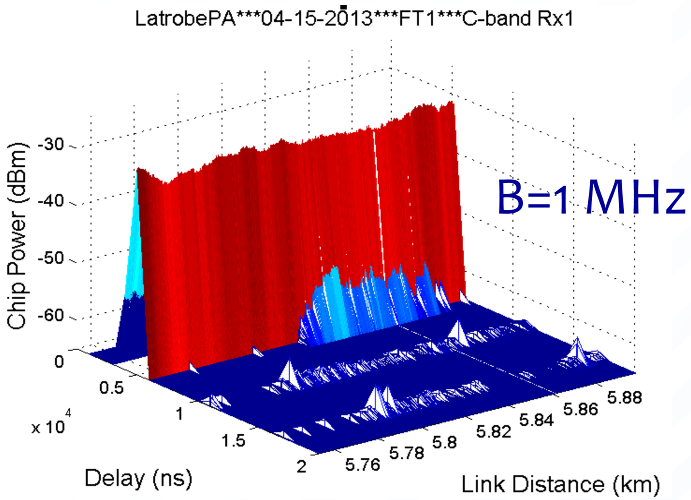
- MPCs come and go (“birth/death”)





- Fresh H_2O

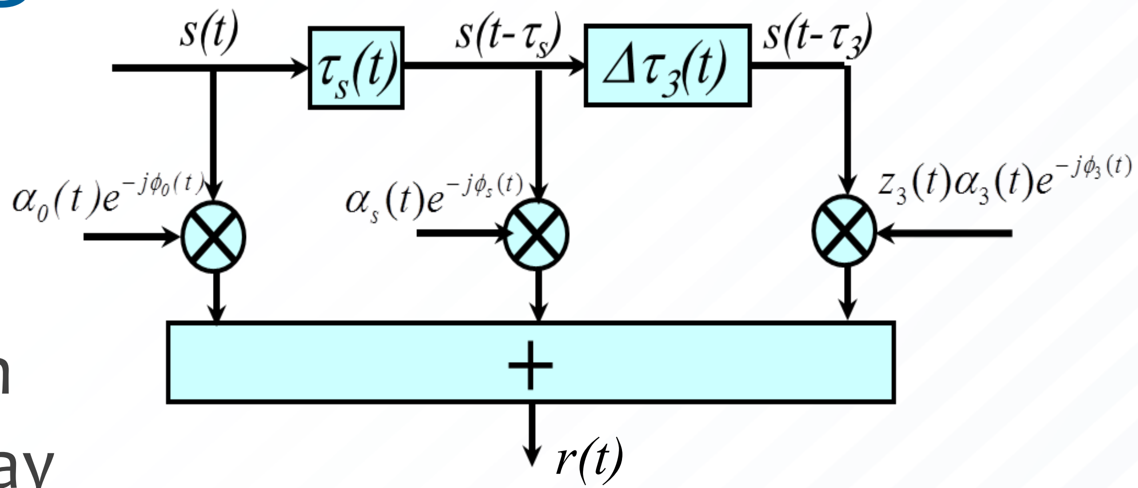


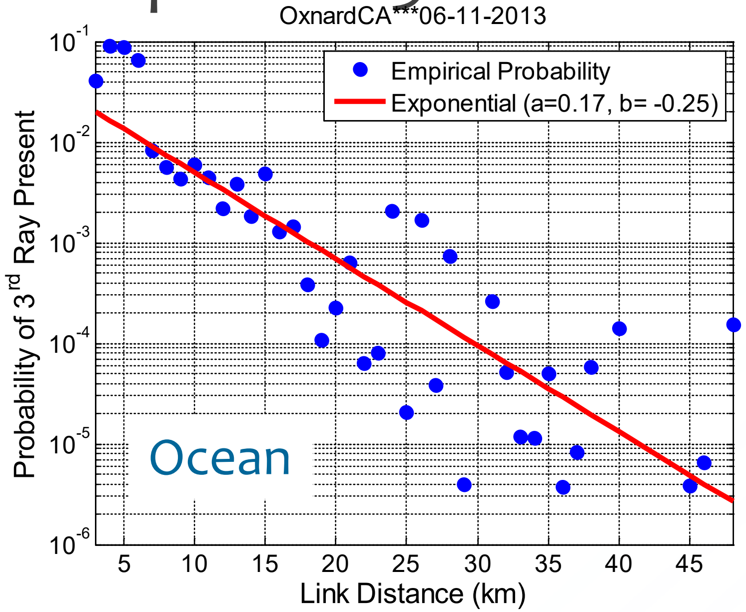


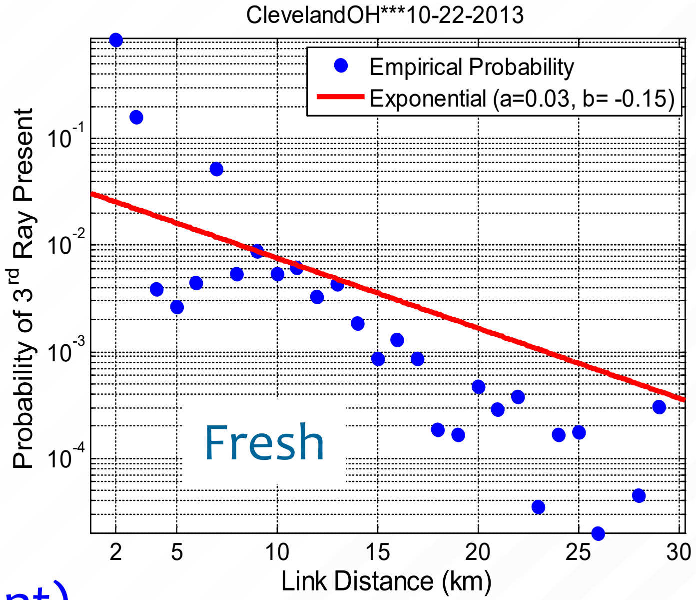
- Hilly terrain

Wideband Modeling

- Traditional TDL
  - For over-water
    - component 1=LOS
    - component 2=surface reflection
    - component 3=*intermittent* 3rd ray



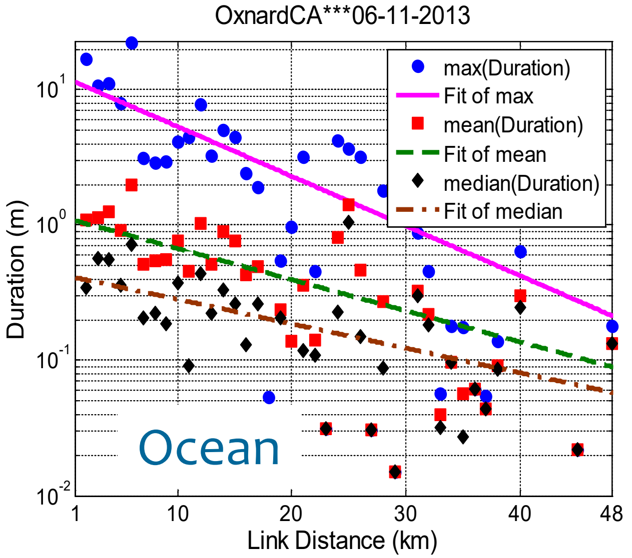


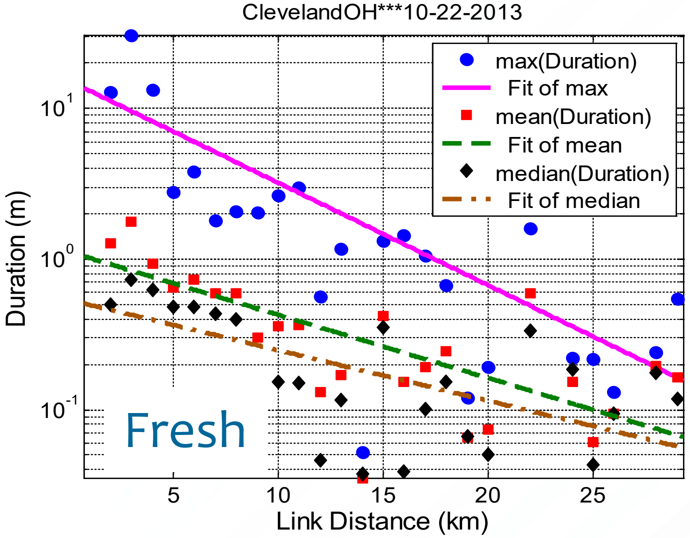


Pr(3rd ray present)

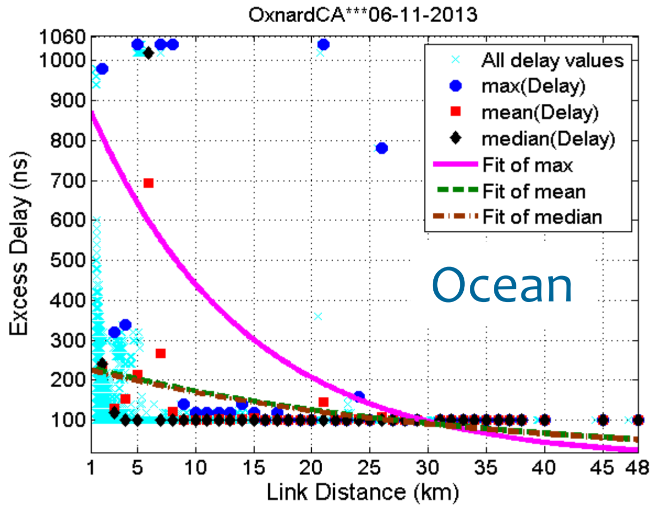
Wideband Modeling (2)

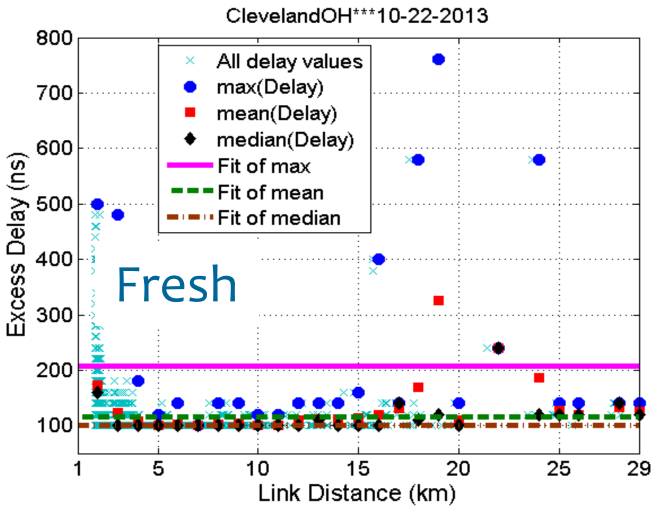
- **Over-water**: intermittent 3rd ray statistics





- Fig. 19: **Duration vs. distance** ~ exponential





- Fig. 20: **Excess delay vs. distance** ~ exponential

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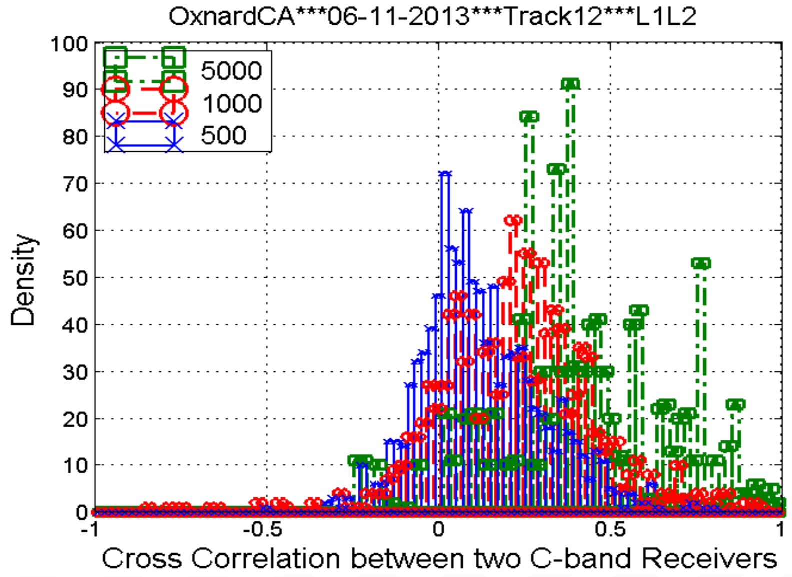
Stationarity Distance

- For estimating channel stats, require estimate of spatial extent over which stats ~ constant
  - Stationarity Distance (SD)



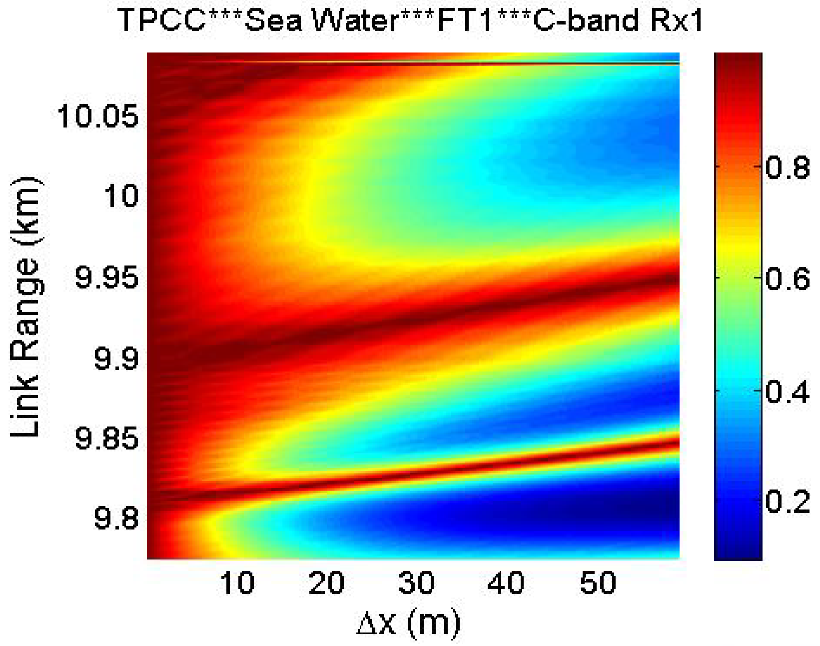
- Seeing much recent attention

for rapidly time-varying channels (V2V, railway)

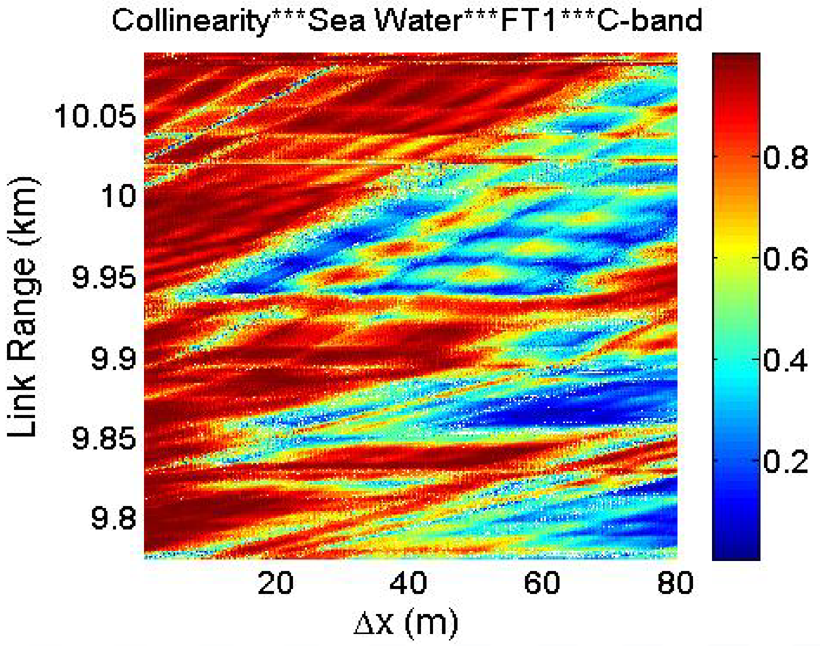
- Multiple methods for estimating SD
  - We employ two: TPCC & Spatial Autocorrelation Collinearity

Stationarity Distance Example

- Example SD measured results (Oxnard, FT1)



c(Δx,d)

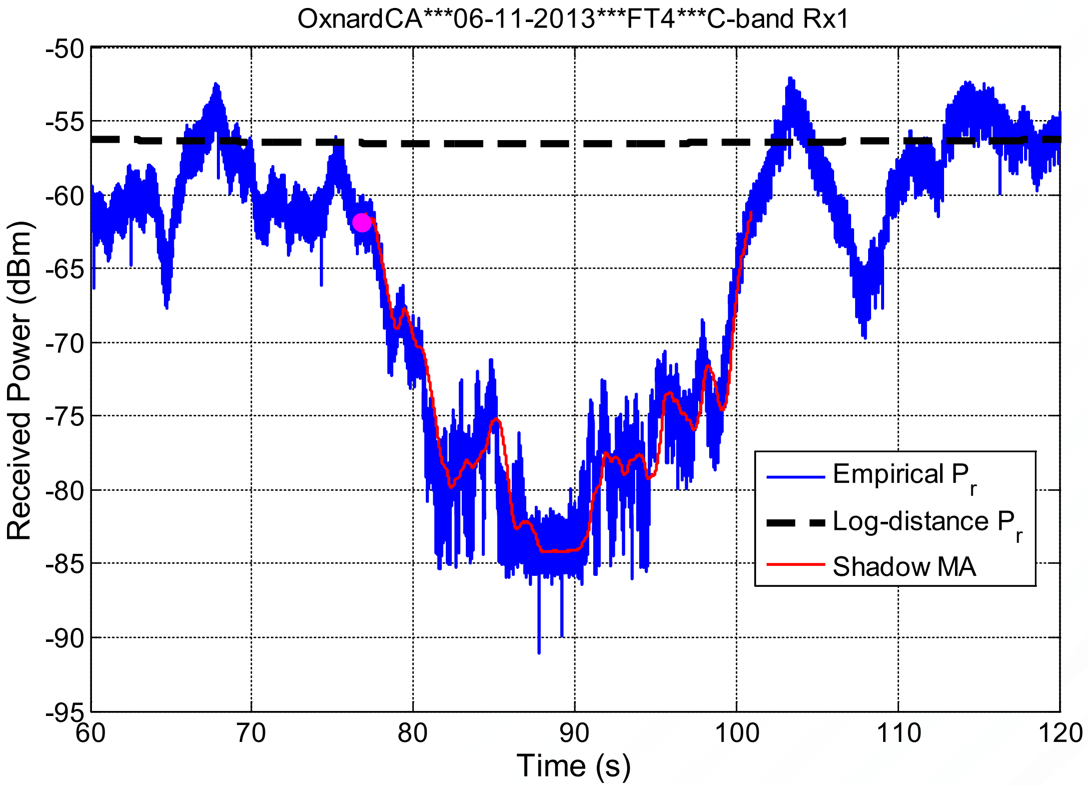


coll(Δx,d)

- LOTS of stats gathered for *c* & *coll*
- Over-water: median *SD(c)*~**15 m**, median *SD(coll)*~6.4 m

Airframe Shadowing

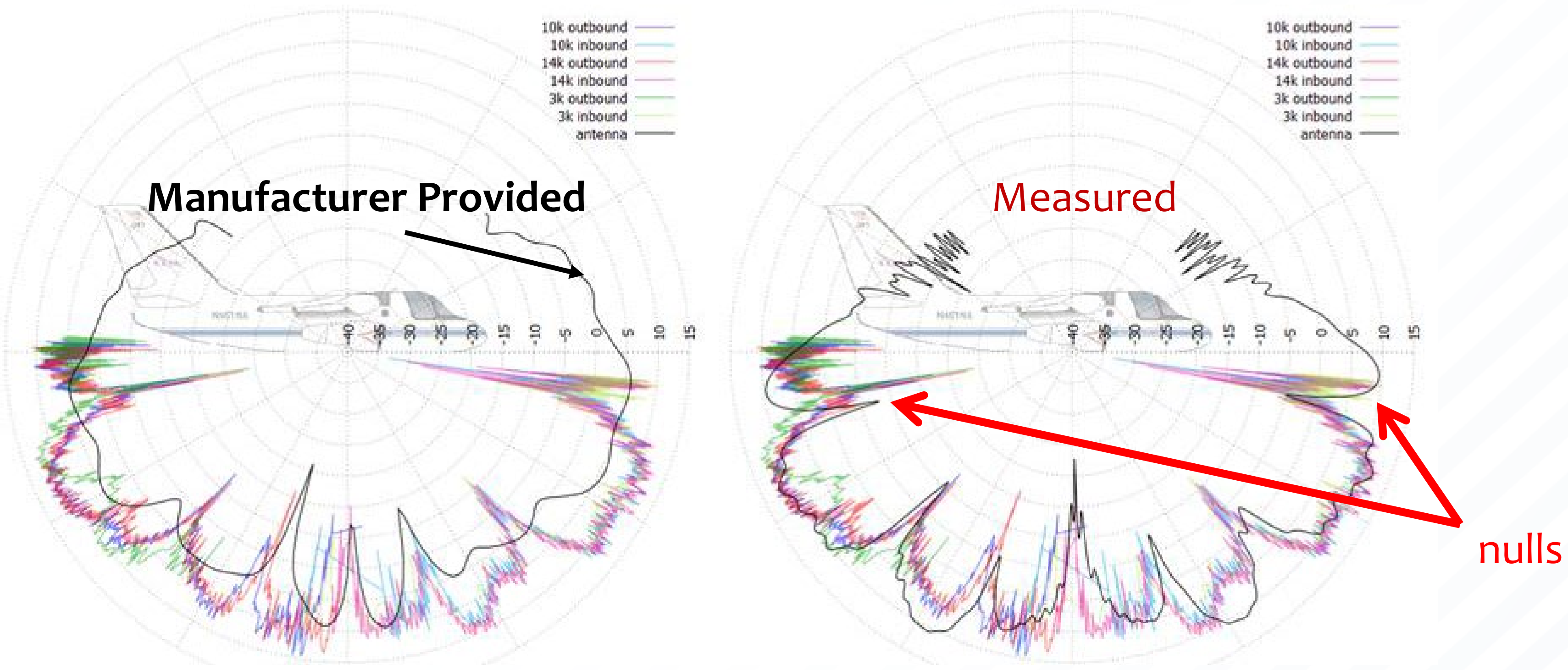
- Example shadowing measured results (Oxnard, FT4)



- Fade depths exceed **30 dB**
- Fade rates (here) ~ 15 dB/sec

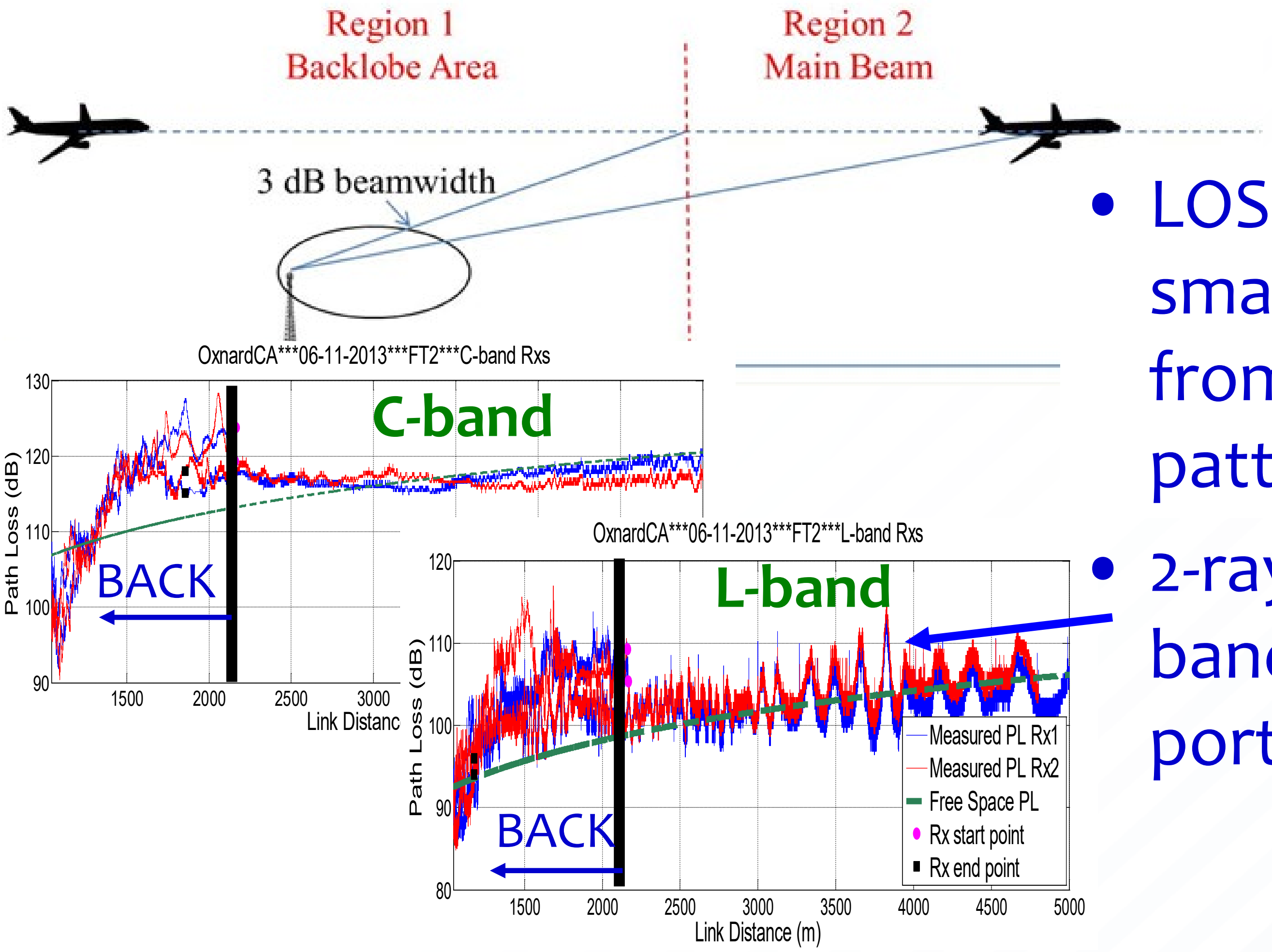
Antenna Effects

- Example Ku-band Aircraft Antenna Pattern



Antenna Effects (2)

- Aircraft flying over GS to main beam



- LOS channel, small-scale fading from antenna patterns
- 2-ray fading for L-band, over water portion

URC: Example Numbers

- For C2 R_b=100 kbps, T_b=10 μs. A 100-bit command packet has duration T_{pack}~1 ms
- Small drones can fly up to v~40 m/s
  - Distance traveled over T_{pack} is $d_{Tpack}=vT_{pack}$=4 cm
  - C-band (~5 GHz), ~2/3 wavelength, thus small scale fading occurs over packet

- ***IF*** fading were Rayleigh (NLOS), Pr[10n dB fade] ~ 10^{-n} (e.g., P(20 dB fade)=0.01, or 1% of the time!)
- For Ricean fading, K=10 dB, fade > 20 dB occurs ~10^{-5} of time

  ⇒ 20 dB margin?!

Alternatives: antenna diversity, multi-band links, SS overlay

Blockage/Obstruction

- Depends on terminal altitude w.r.t. local h_o
- For AG, can estimate *Pr(LoS)* via geometry

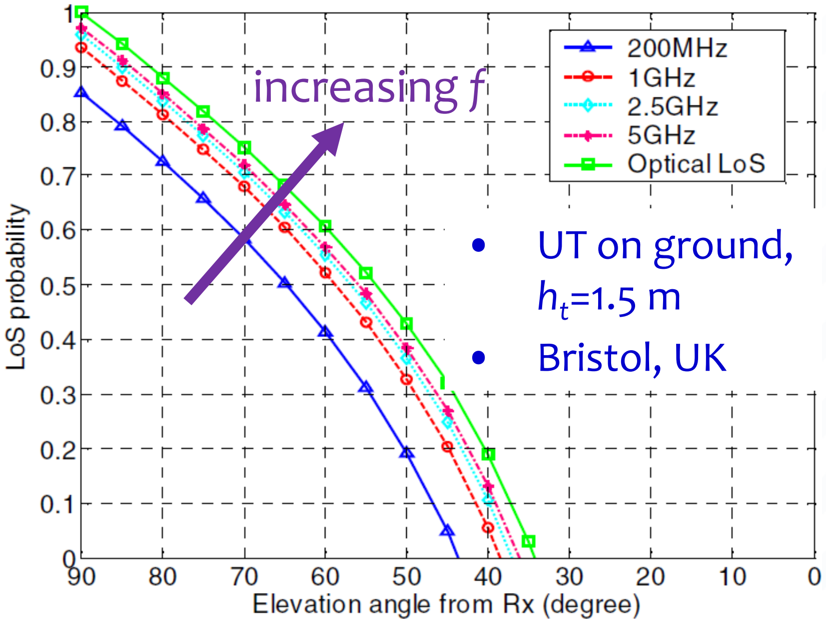


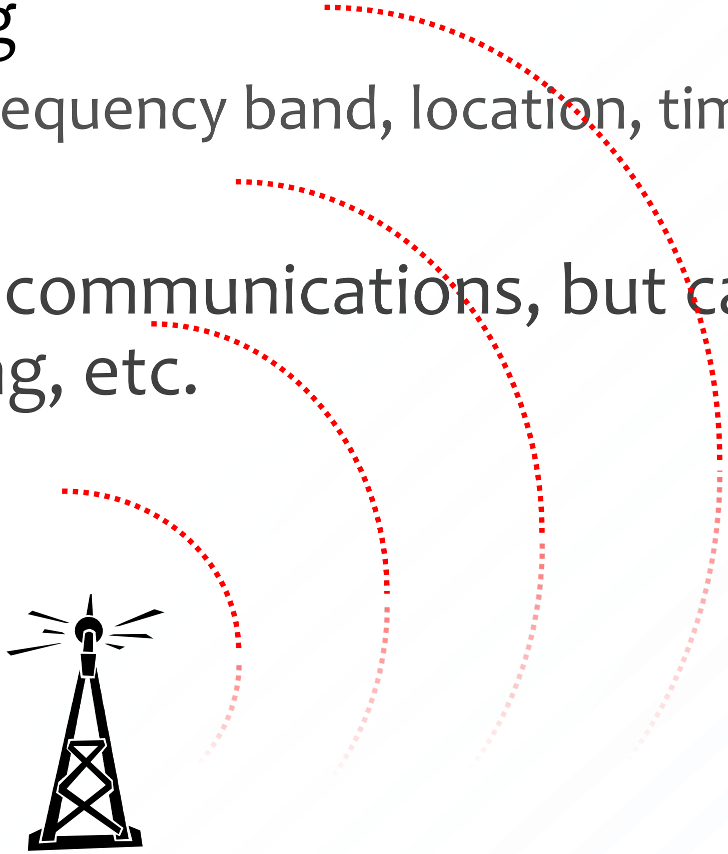
Fig. 2. LoS probability in street level (street angle 90°)

Q. Feng, E. K. Tameh, A. R. Nix, J. McGeehan, "Modeling the likelihood of Line-of-Sight for Air-to-Ground Radio Propagation in Urban Environments," *Proc. Globecom*, San Francisco, CA, 27 November – 1 December 2006.

Jamming Fundamentals

- Jamming Definition
  - Intentional radiation of electromagnetic signals for purpose of disrupting signaling
    - within particular frequency band, location, time
- Signaling often for communications, but can also be for navigation, surveillance, sensing, etc.

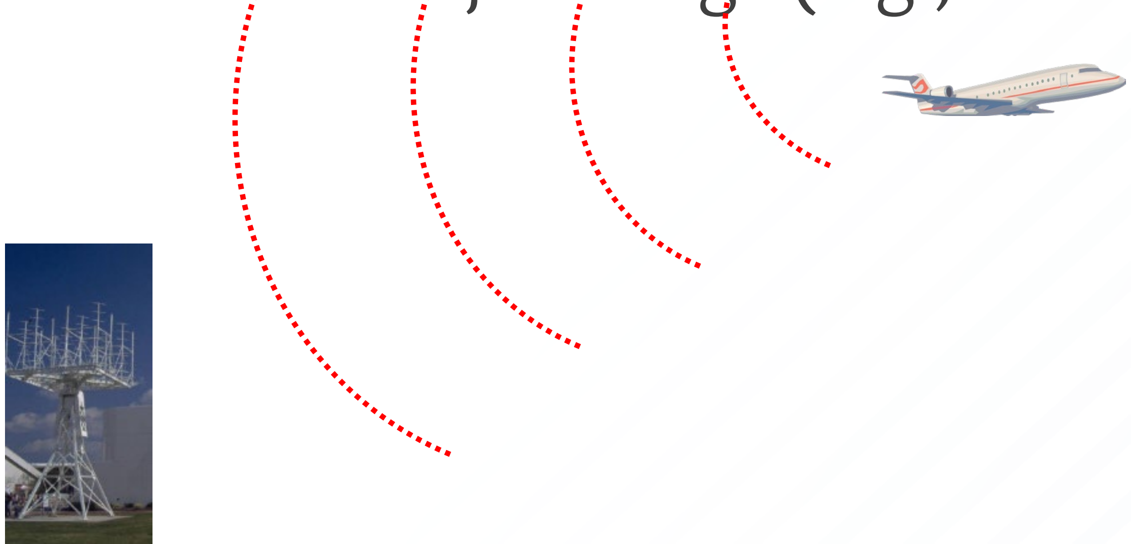
Jammer



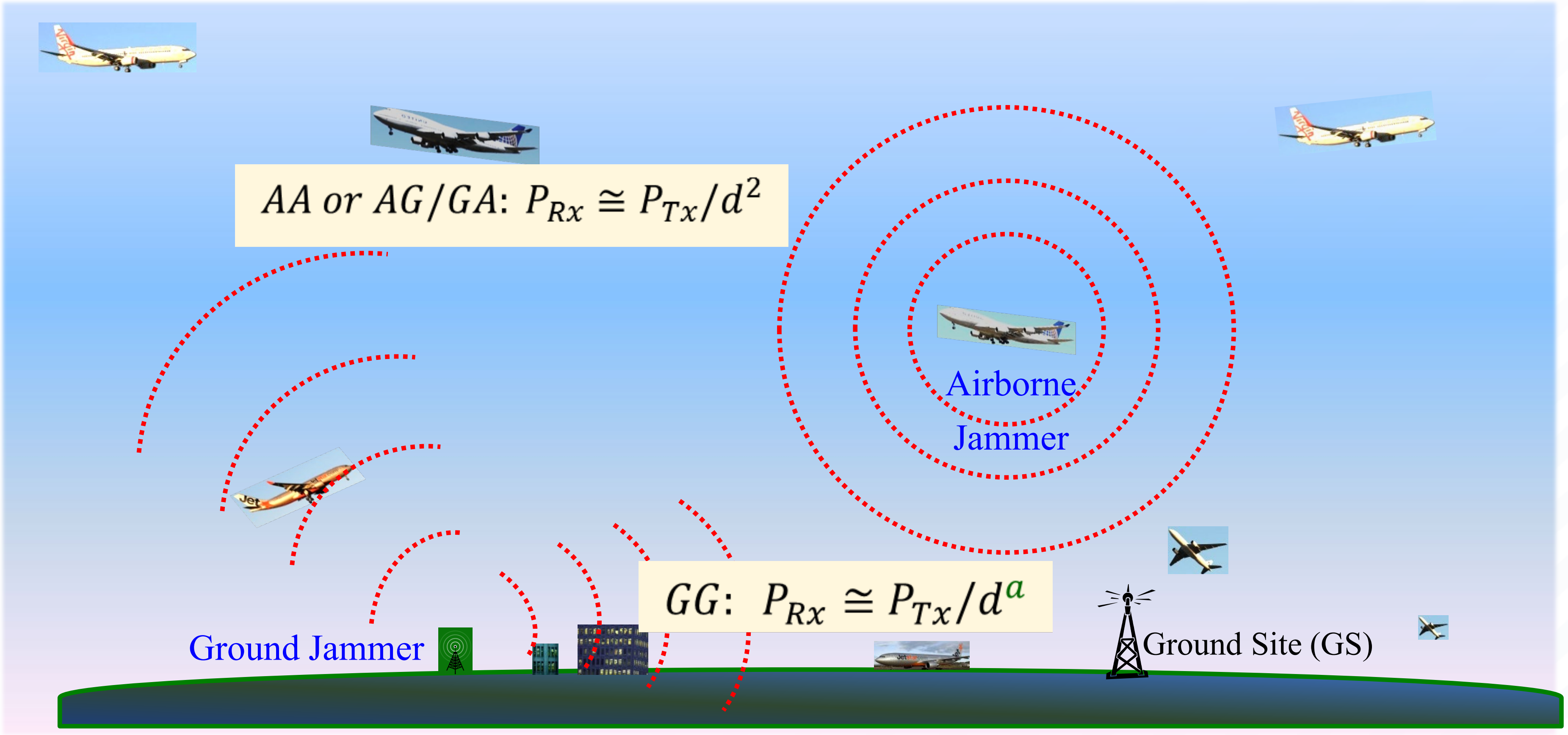
Jamming Fundamentals (2)

- Jamming Definition (2)
  - Part of broader area of electronic warfare (EW)

  - EW also includes
    - Spoofing ("masquerading" as legitimate signaler to disrupt)
    - System overloading (e.g., "flooding" control channels)
    - Mechanical "jamming" (e.g., chaff to confuse radar)



Settings



Jammer effectiveness depends on

- Power
- Propagation ($\alpha \sim 2\text{-}4$)

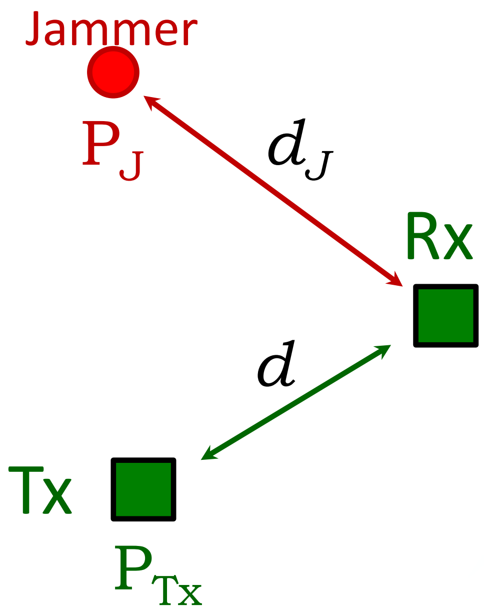
Photos © J. R. Thomson, Airliners.net

Basic Jamming Math

- Communicator performance depends on *SNIR*

$$SNIR = \frac{S}{N + J}$$

- *S*= desired received signal power
- *N*= noise power
- *J*= received jammer power



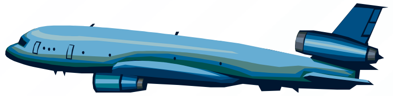
If *J/N* large, *SNIR* ≃ *S/J*, which yields

$$SNIR \simeq \frac{P_{Tx}}{P_J} \frac{d_J^{\alpha_J}}{d^{\alpha}}$$

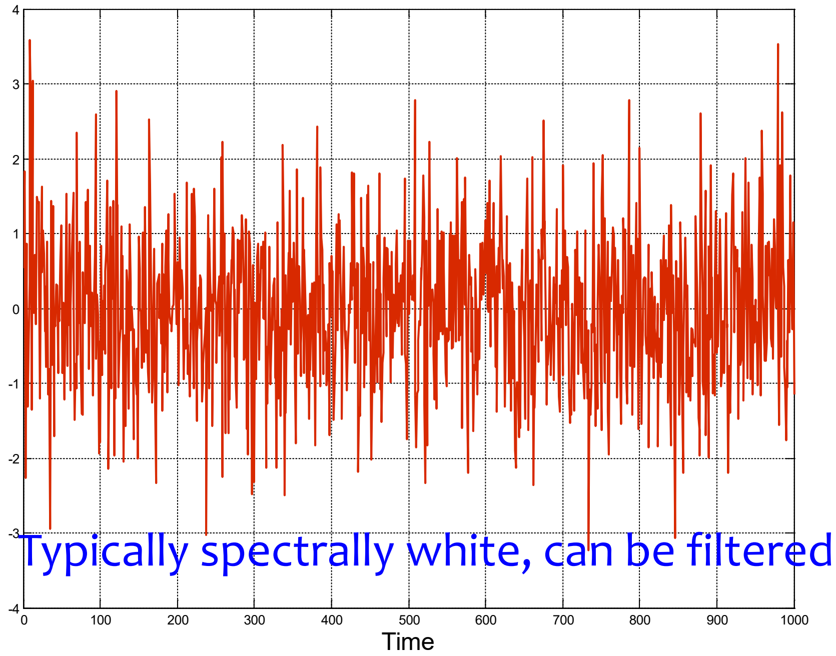
As P_J/P_{Tx} ↑, SNIR ↓

As d^{α}/d_J^{α} ↑, SNIR ↓

Jammer Signals

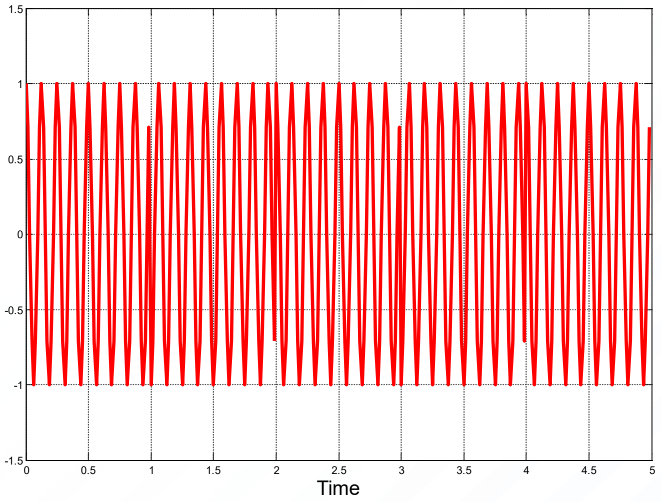


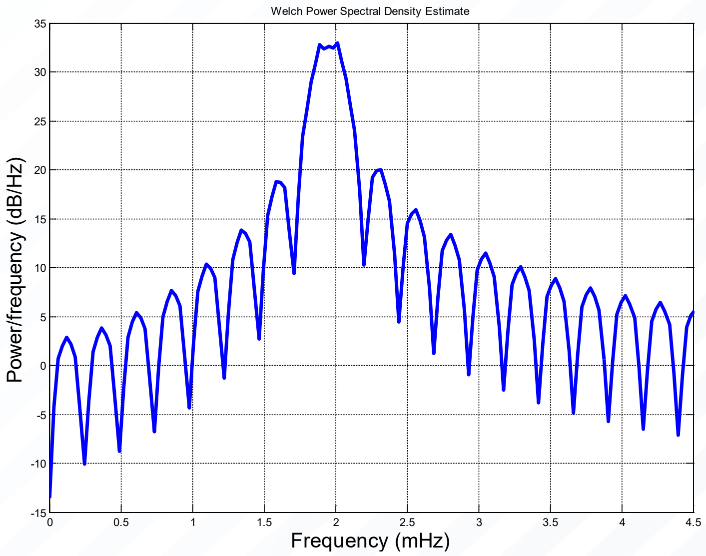
- "Noise-like"
  - Easy to generate
  - High PAPR



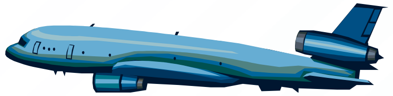
Typically spectrally white, can be filtered

- Most effective: modulated signal of same type
  - Typically digital
  - PSK, FSK, QAM…

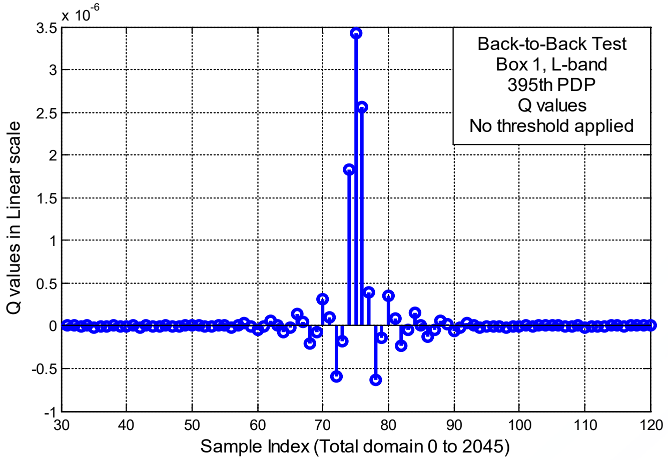


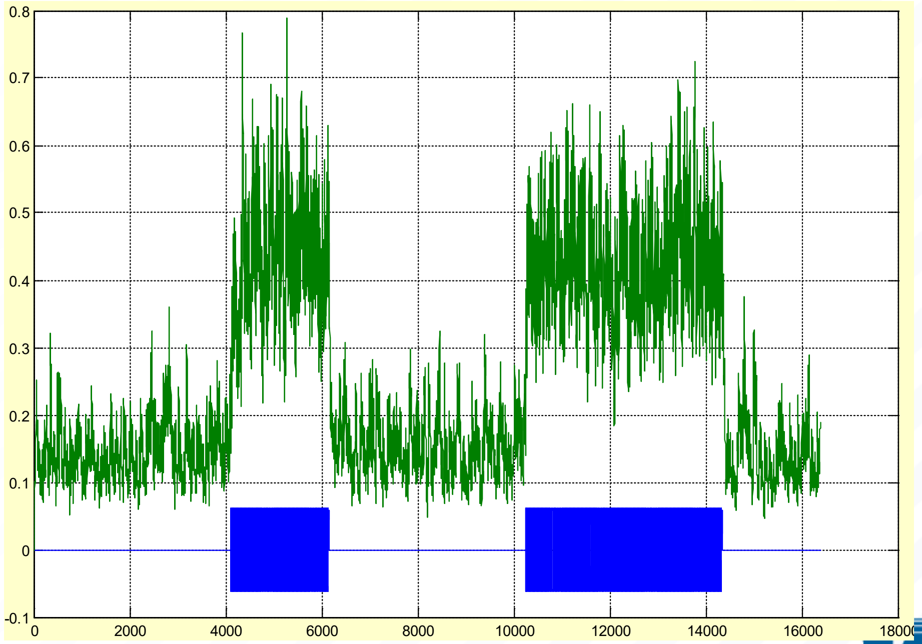


Jammer Signals (2)



- Other jammer signals
  - "Repeat-back" (or, "follower")
  - Frequency hopped
- Each signal type can also be
  - Continuous or pulsed
  - Full-band or partial band





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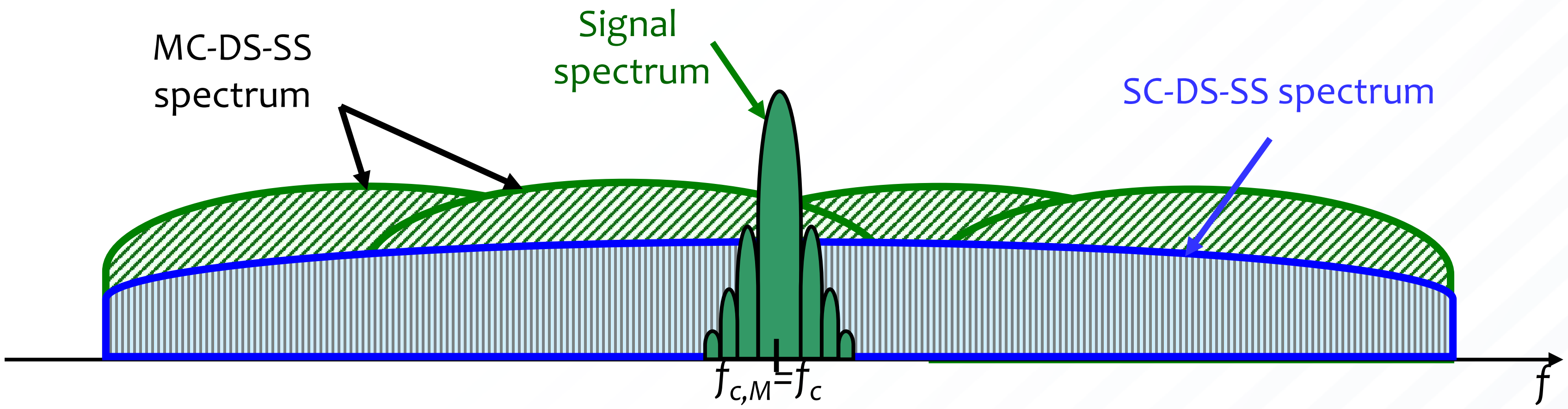
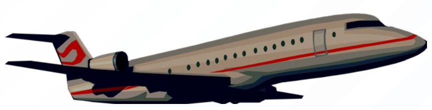
Jamming Mitigations

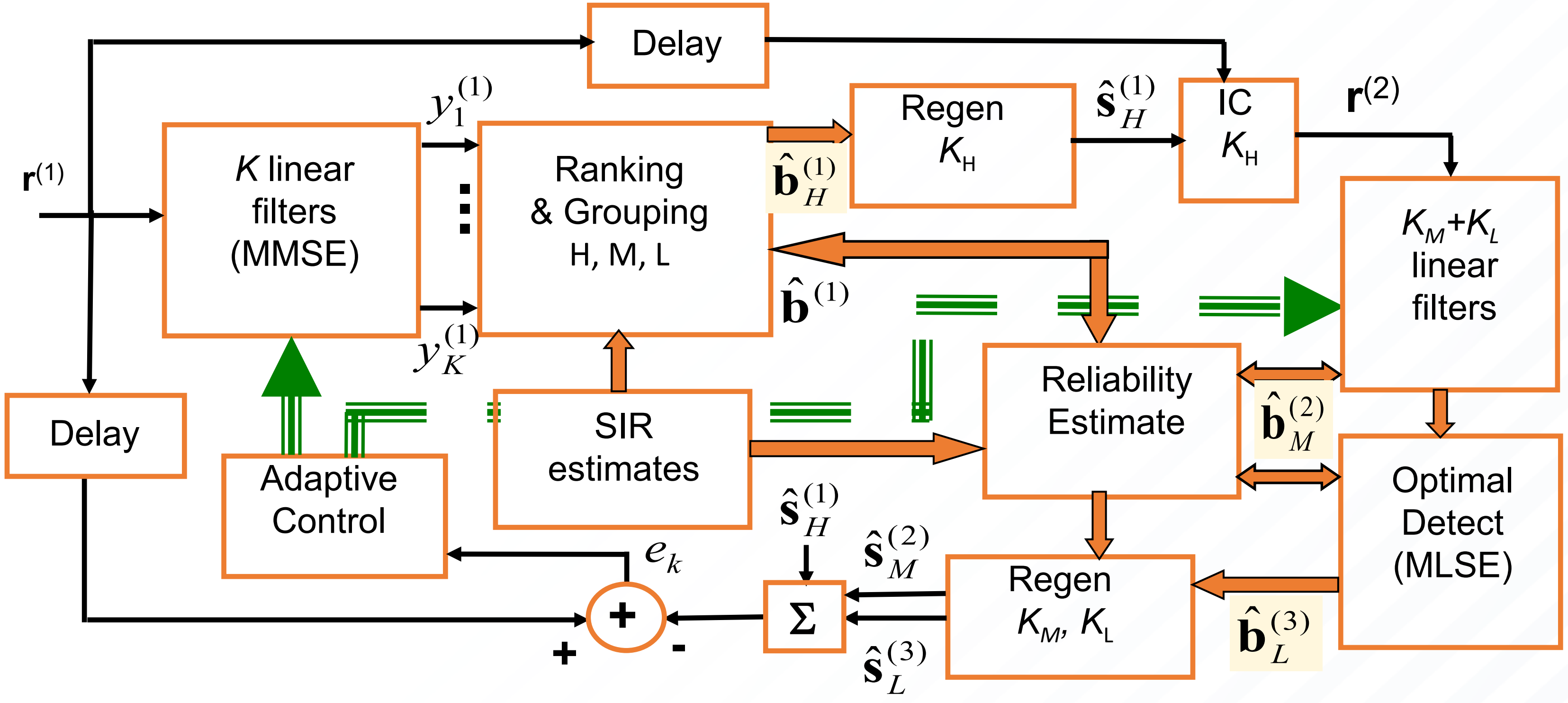
- **Spread Spectrum**
  - By far most effective signaling technique to mitigate jamming
  - Two main types: Direct sequence & Frequency hopped (+UWB, hybrids)
- Strong FEC coding + Interleaving
- Spatial (nulling, beam steering)
- MAC & above (routing, adaptive learning)



Jamming Mitigations (2)

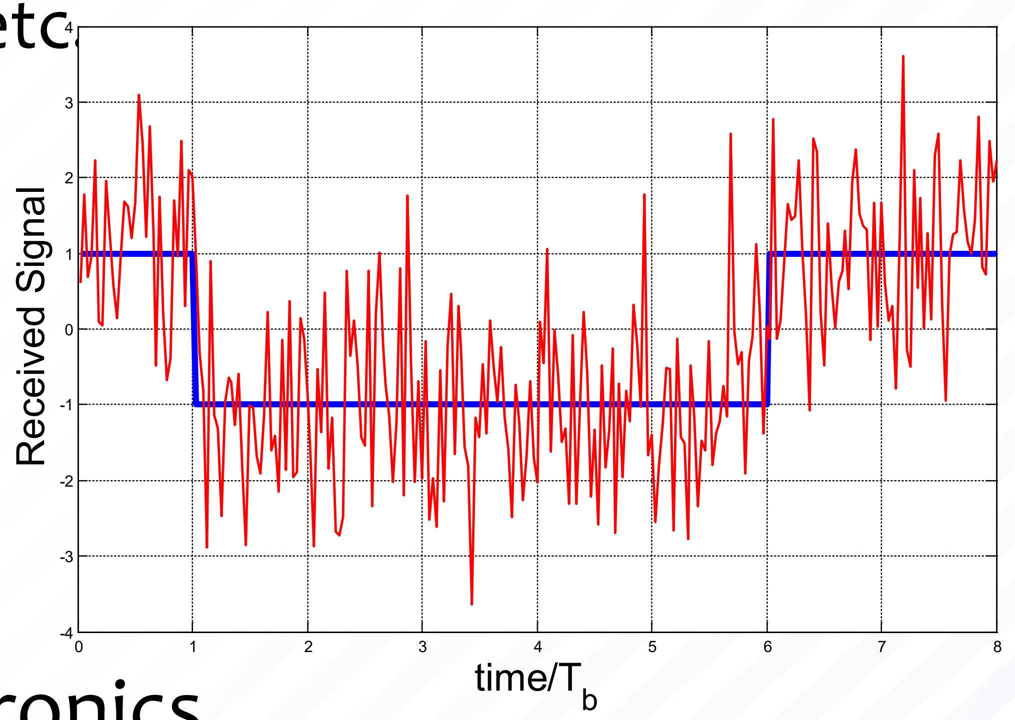


- Active Interference Cancellation (IC)
  - Detect & subtract Jammer signal
  - Easiest if Jammer continuous, deterministic
    - If not (e.g., pulsed, random) challenging adaptive SP!



Jamming Impacts

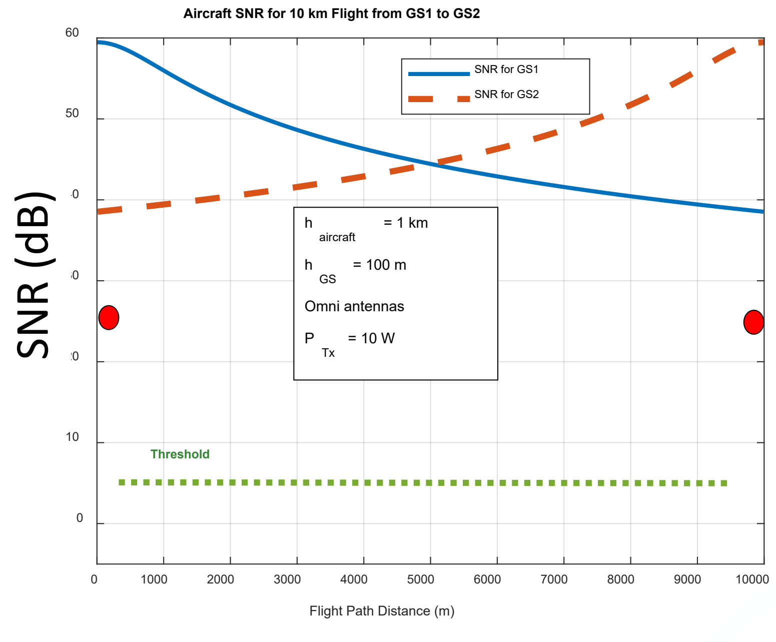
- Degraded performance
  - Lower $SN(I)R \Rightarrow$ larger BER
  - Reduced image quality, garbled voice, etc.
- No link or lost link
  - Inability to synchronize



- In extreme case, damage to RF electronics

Simple Jamming Example

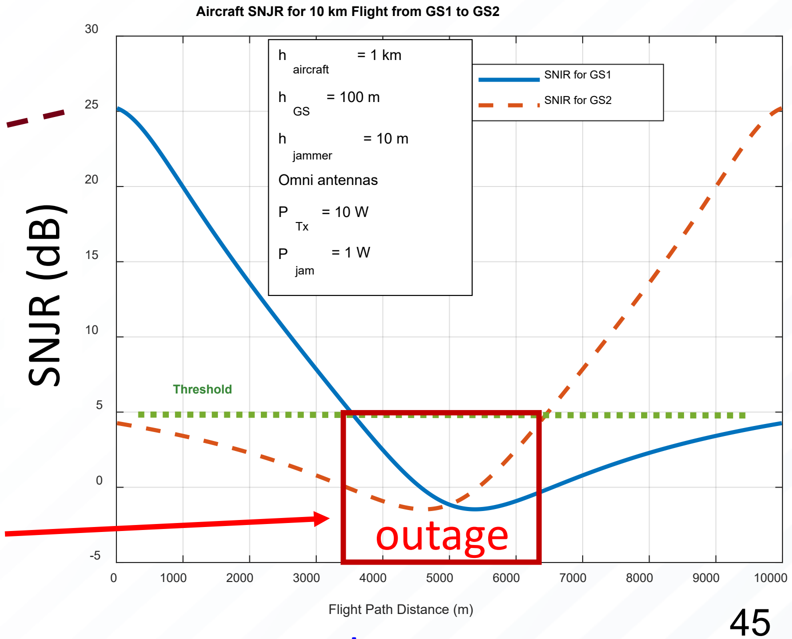
- Assume a 10 km flight, altitude 1 km
  - P_{Tx}= 10 W, NF= 3 dB, B=1 MHz, GS height 100 m
- Jammer at 5 km, 1 km GC distance from flight path
  - P_J= 1 W, Jammer height 10 m
- Omni antennas, LOS channels, SNR_{min}=5 dB



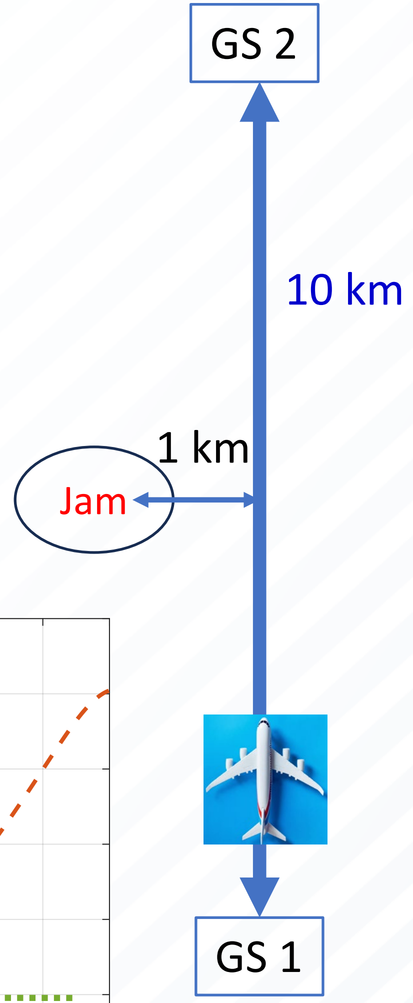
No Jammer

Minimum SNR reduction from Jamming = 15 dB

Jammer causes > 2 km outage



Jammer



Transmission Security

- TRANSEC: protect transmissions from interception & exploitation by means other than cryptanalysis
  - Spatial, temporal, & frequency domain techniques
  - Spread spectrum
  - Low probability of detection (LPD) signaling
  - Anti-jam signaling

- AAM transmissions need not be LPD
- Exploitation can be geolocation, estimation of movement/intent, etc., not necessarily critical for AAM

Navigation & Surveillance Reliability

- Both N & S employ wireless signaling, so the **same** principles & techniques as used in communications apply
  - GPS jamming is common
- Commercial aircraft today use ADS-B for surveillance, which works in a known frequency band, 1 MHz bandwidth
  - AAM will likely use, but may need more spectrum
  - New air-air links for surveillance?

How Might We Effectively Disrupt?

1. From public info, find…
   a. ce … signal
      du
   b. lik
2. Strat
   a. Ob
   b. Fo … on, so
      co
   c. Ea

Countermeasures

For channel effects

1. Multipath: frequency diversity & equalization, power control, spatial diversity (some complexity, cost, but mature technology)
2. Shadowing: time-diversity, site diversity (latency, capacity, cost)

For jamming (complexity, cost)

1. Spread spectrum & power control
2. Multi-band communication
   - Of lesser value is "standard" time & frequency diversity
3. More complex/costly: adaptive antennas, interference cancelling

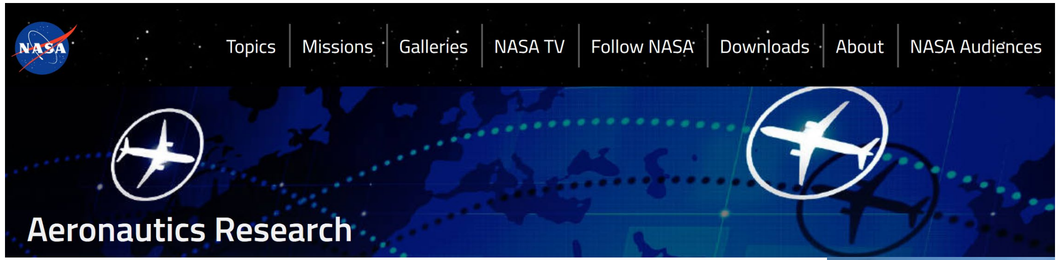
Future Work

- Quantify link disruption “costs;” risk analysis
- Quantify multiband link establishment & operational costs
- Quantify spread spectrum benefits, operation
- Radio air interface augmentation, testing
- Red team testing!

Summary

- Aviation growing, particularly for UAS, AAM
  - Multiple programs, worldwide
  - ATM requires *reliable* AG/AA comm. (CNNS)
  - Link availability underlies reliability
- Reliable signaling underlies reliable networking
  - URLLC may offer some tools
  - Reliable signaling requires PHY channel knowledge, adversary characterization
  - Example results: channel impairments, jamming

Summary (2)



- AG/AA channels can yield
  - Small scale fading: usually ~Ricean, maybe Rayleigh, or worse
  - Obstruction: highly frequency & environment dependent
  - Rapid time variation: IMPCs, large Doppler
- Interference/jamming can yield
  - **Reduced SNR**: packet loss, frame/message errors
  - **Link outage**: **zero** availability for some duration!
- All of which make always-available, reliable CNS for AAM challenging
- Investigate new designs w/multiple bands, antennas, SS…

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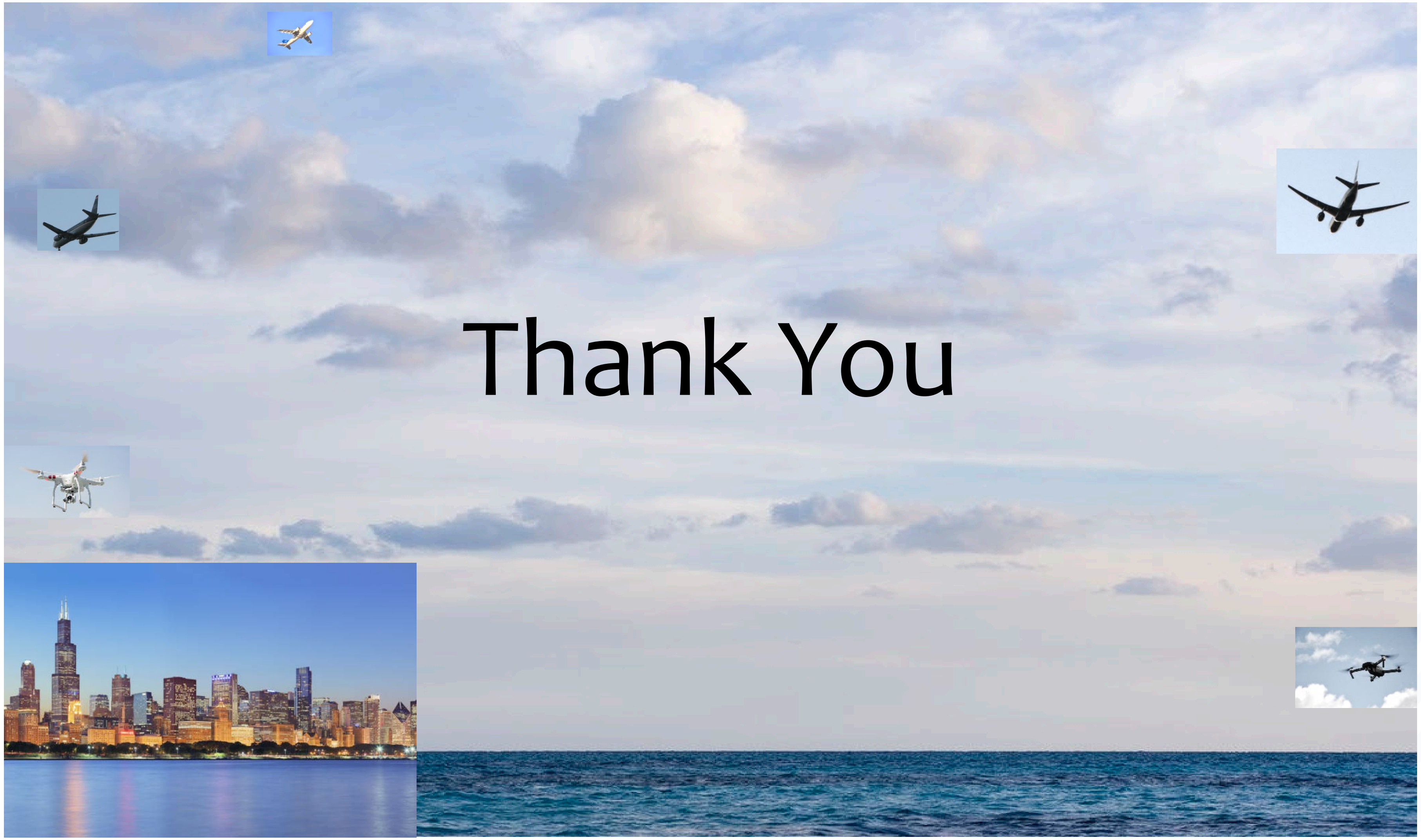
Questions?



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Hyper-Spectral Communications & Networking for ATM:

Air-ground & **airport** communications to increase _safety_, _efficiency_

Why: Civil aviation comm. networks must expand to meet ↑ demand, improve safety

How: Design, test adaptive *dual*-band radios w/ robust spectrally-efficient mod. (FBMC)

- Quantify airport network mmWave channel characteristics

Accomplishments

- Dual-band radios attain higher reliability & throughput in terrestrial tests: Successful flight tests, April 2022—TRL 5
  - Interest from industry, ICAO standards group
- Many contributions to mmWave channel models; tools for airport network coverage planners
- Successful drone detection tests: foundation for new airport detection systems

Team

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- North Carolina State University, Prof. Ismail Guvenc
- Boise State University, Prof. Hani Mehrpouyan
- Architecture Technology Corp., Gregory Carr

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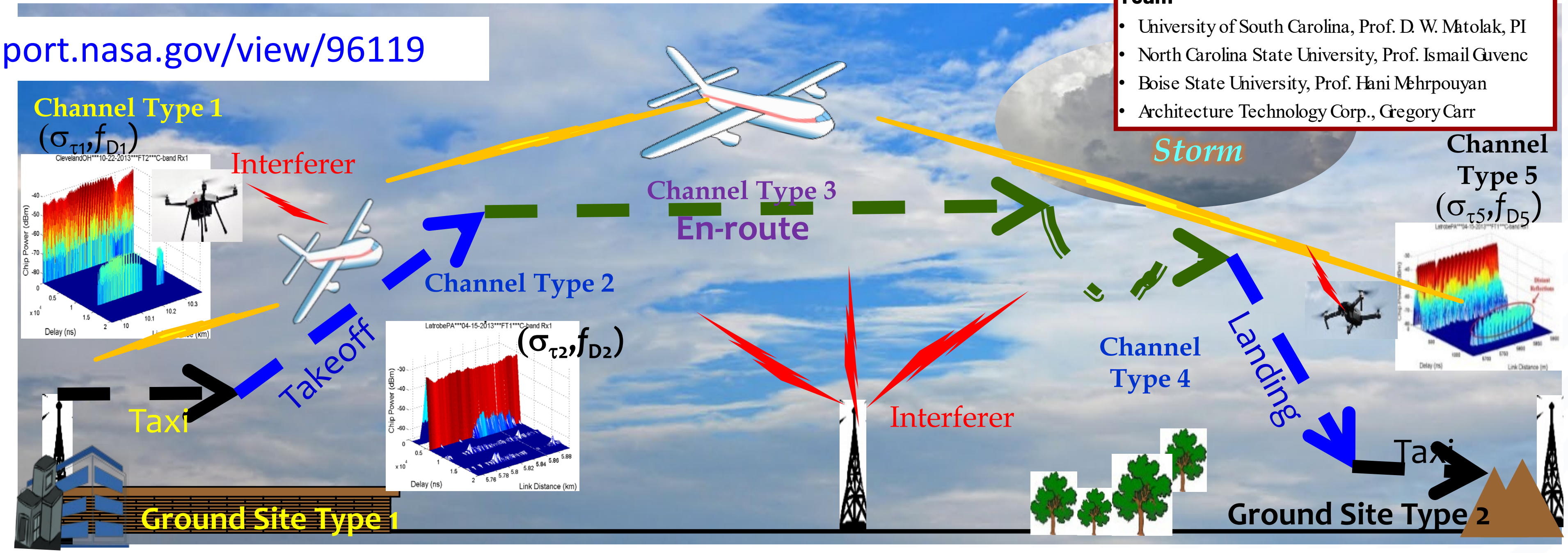

Air-ground communication links encounter varied channel & interference conditions over typical flight phases