OHIO UNIVERSITY

School of Electrical Engineering & Computer Science

Wireless Channel Characterization: Modeling the 5 GHz Microwave Landing System Extension Band for Future Airport Surface Communications*

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Outline

- Introduction
- Measurement coordination
- Channel characterization & modeling
  - Overview
  - Mobile channel measurements
    - Tx @ ATCT, Rx in Mobile Van
    - Tx @ Ground Site, Rx in Mobile Van
  - Channel model construction
- Summary and future work

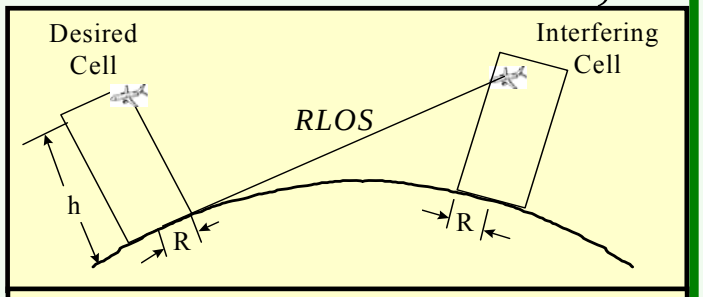
Introduction

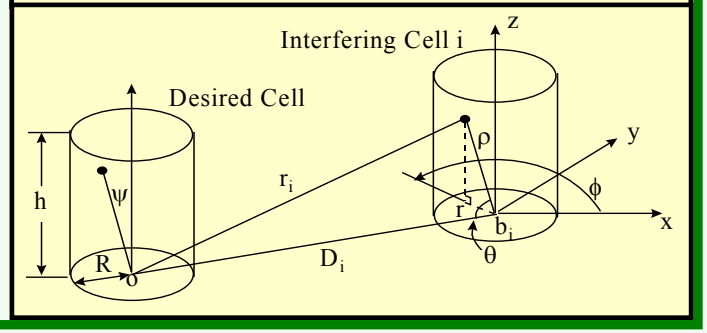
- Commercial aviation is growing
- In 2003, Congress & Executive Office formed the Joint Planning and Development Office (JPDO) for the Next Generation Air Transportation System (NGATS)
  - DoT, DHS, DoD, DoC, NASA, FAA
  - Now also more than 66 industry & private sector members

http://www.jpdo.aero

Introduction (2): NASA ACAST

- Motivation for work: in line with JPDO…civilian aviation has both near & long-term needs for new communications capabilities
  - VHF spectral "congestion" (118-137 MHz used for analog voice, very low-rate data (2.4 kbps))
  - New services desired, for mobile and "fixed" links, all "phases of flight"
    - En route
    - Takeoff/Landing
    - Taxiing and Parking





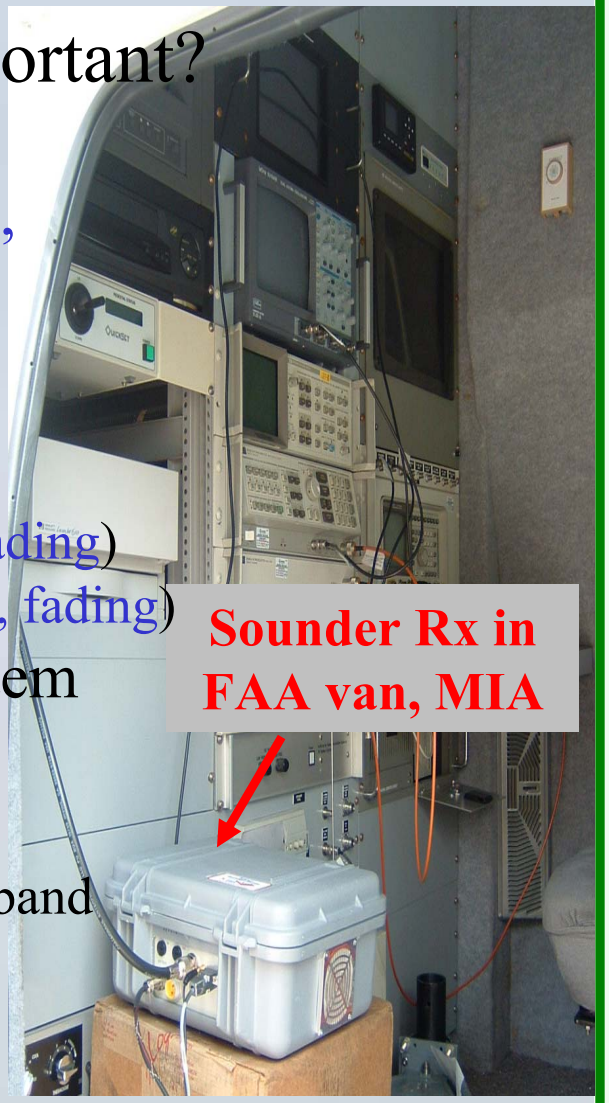
Introduction (3)

- Motivation (cont'd): frequency band selection
  - Easiest to quickly deploy system in "clean" spectrum
  - Deployment of new systems can "protect" reserved aeronautical spectrum ("use it or lose it")
    - International Civil Aviation Organization (ICAO) has delegation for International Telecommunications Union (ITU) World Radio Conference (WRC), next in 2007
  - Microwave landing system (MLS) extension band, 5.091-5.15 GHz, not widely used in many regions meets both the above criteria

Introduction (4)

- Why is channel characterization important?
  - If you don't know your channel, system performance will be suboptimal, possibly very poor, with
    - irreducible channel error rate that can preclude reliable message transfer (ISI)
    - spatial coverage "holes" where communication not possible (shadowing, fading)
    - severely limited data carrying capacity (ISI, fading)

    …all of which could require costly system additions to circumvent
  - Dearth of work for MLS band channel
    - Zero wideband experimental work for this band around airport surfaces



Measurement Coordination

- Measured at three major airports
  - Cleveland Hopkins International Airport (CLE)
  - Miami International Airport (MIA)
  - John F. Kennedy International Airport (JFK)

  and three small, general aviation (GA) airports
  - Ohio University Airport (OU)
  - Burke Lakefront Airport (BL)
  - Tamiami Airport (TA)

Measurement Coordination (2)

- Access to airport movement area has become more complicated in the post September 11 era
  - Strict security procedures must be followed to gain access to the airport surface area—requires careful coordination with airport management
- Principle objective when planning a measurement activity is to minimize impact to airport operations

Measurement Coordination (3)

- Before any measurements, FAA Spectrum Office conducted an RFI study (clean)
- NASA obtained a Special Temporary Authorization to transmit at the test frequency from NTIA

Selected "cat walk" at ATCT sub-junction level for Tx

- Good field of view
- Access to AC power

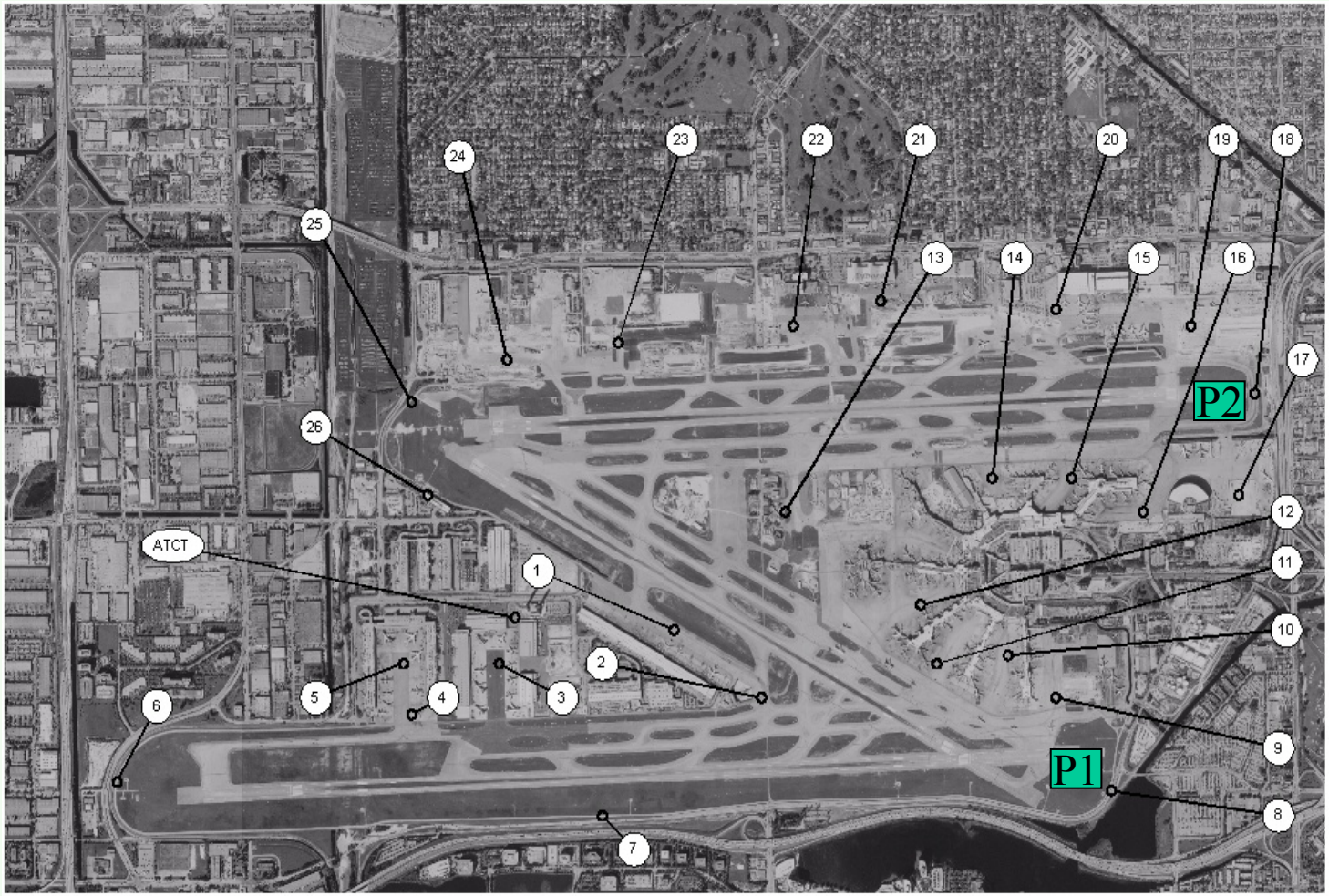
Measurement Coordination (4)

- Prepared a measurement plan with desired
  - data recording locations
  - procedural approach
  - number of personnel involved
- Plan evaluated w/FAA for
  - accessibility
  - time of day
  - aircraft traffic activity
  - airport ingress/egress requirements
  - driving rules
- Final measurement plan evaluated & approved by FAA

View from MIA ATCT

Measurement Coordination (5)

- MIAMI aerial view, with numbered measurement locations

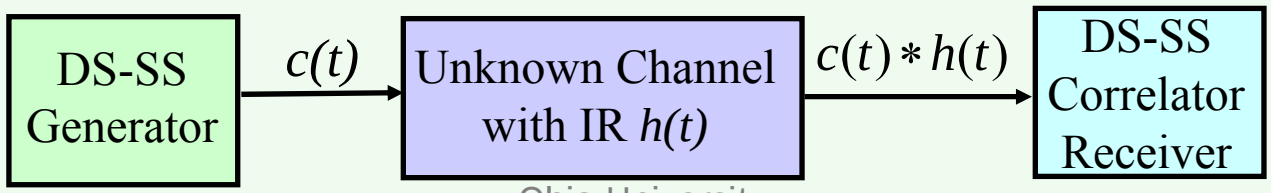


- Covered
  - Taxiways
  - Gates
  - Cargo areas
  - Access roads
- Both LOS and NLOS sites
- Also conducted mobile tests w/Tx at P2

- to #25, RMS-DS transitions
- (back to #34, field site meas)

Channel Characterization Overview

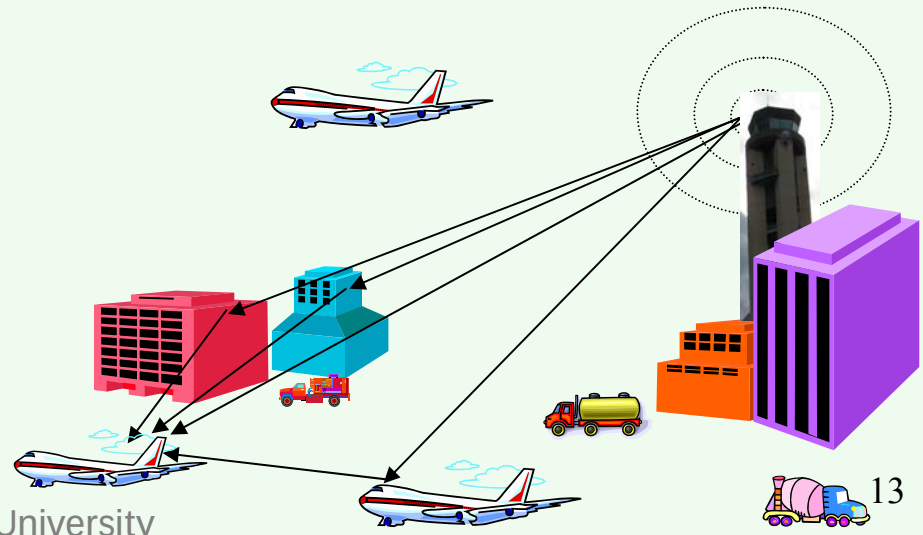
- Accurate, thorough channel characterization requires combination of 3 inter-related components:
  - *Analysis*: validate against theory, guide measurements
  - *Measurements*: data to build models, affirm theory, help classify, and identify unforeseen conditions
  - *Simulations*: create models for consistent evaluation of comparative system designs
- All results (analytical and measurement) we obtain are directly usable by engineers evaluating and/or designing communication systems for this application



Channel Characterization Method

- Channel "sounding" is transmission and subsequent reception of a test signal, from which we can infer channel characteristics: the <u>impulse</u> <u>response</u>
- Common test signal is a spread spectrum (direct sequence) signal, whose known correlation properties can be exploited to estimate channel's impulse response

What <u>is</u> the channel?
A wireless channel is the complete (set of) transmission path(s) taken by an electromagnetic signal from transmitter to receiver, in the band of interest, over the spatial region of interest.



Channel Impulse Response (CIR)

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

- $h(\tau;t)$= response of channel at time t, to impulse input at time t-τ ; model as *random* and *time-varying*
- Path amplitudes $\{\alpha_k\}$ depend upon
  - Path loss, shadowing loss
  - Reflection, diffraction, absorption losses
  - Amplitudes/phases of components within $\Delta\tau$ *(20 ns)*
- $z_k(t)$ = "persistence" process ($\in\{0,1\}$) to account for finite "lifetime" of multipath components
- Doppler: $\omega_{D,k}=2\pi f_{D,k}$; $f_{D,k}<<f_c$ except for very high velocity platforms (e.g., LEO satellites)
  - $2\pi f_c\tau_k$ can change rapidly, since f_c large

Airport Surface Environment

- Airport movement area is a dynamic environment
  - airline ramp activities such as baggage handling, fueling, catering taking place throughout the day
  - aircraft also taxiing, pushing into, and pulling out of gates
  - airport security vehicles, other ground vehicles moving about

Airport Surface Environment (2)

- Airport surface area classification: 3 regions
  - **LOS-O**: Open areas, e.g., runways, some taxiways
  - **NLOS-S**: mostly NLOS w/dominant Specular component plus low energy multipath components, e.g., near terminals
  - **NLOS**: obstructed LOS, largest DS, e.g., near gates

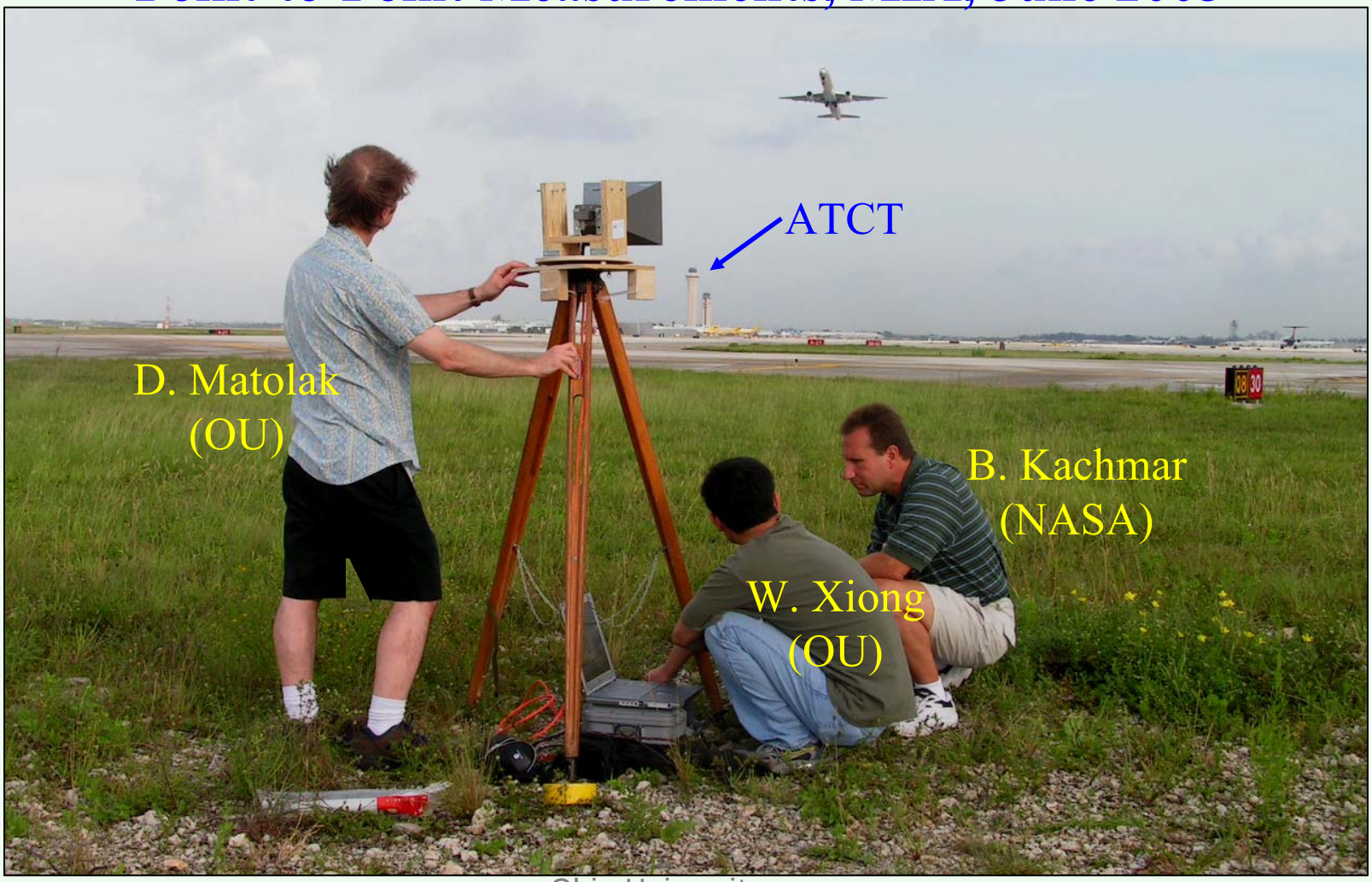
- Aircraft & ground vehicles generally inhabit all three regions; over long-enough durations, channel is statistically non-stationary
- Large buildings present persistent, long-delay multipath, in contrast to most terrestrial models

Measurements: Example Photos

Mobile Measurements, MIA, June 2005

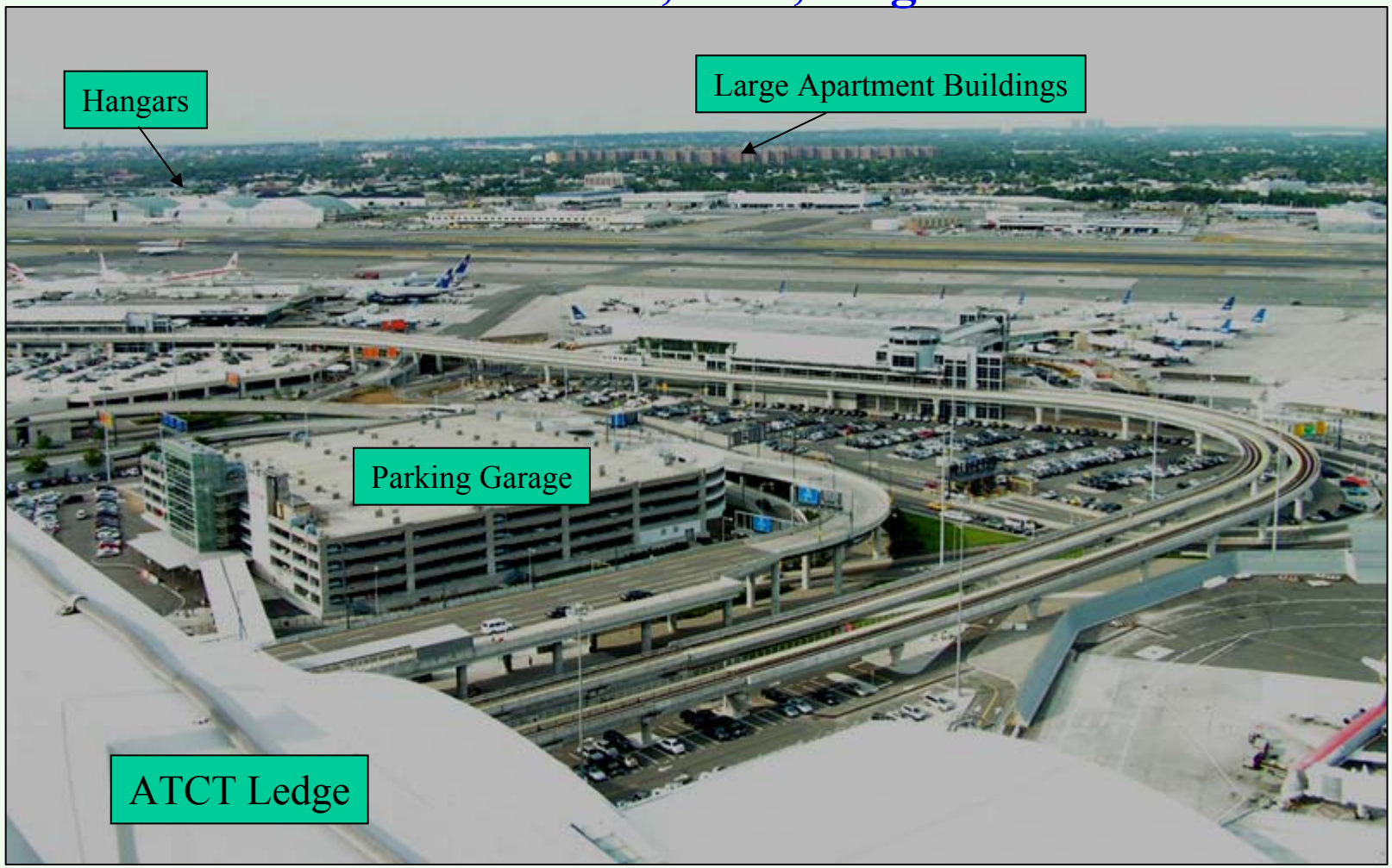
Measurements: Example Photos (2)

Point-to-Point Measurements, MIA, June 2005



Measurements: Example Photos (3)

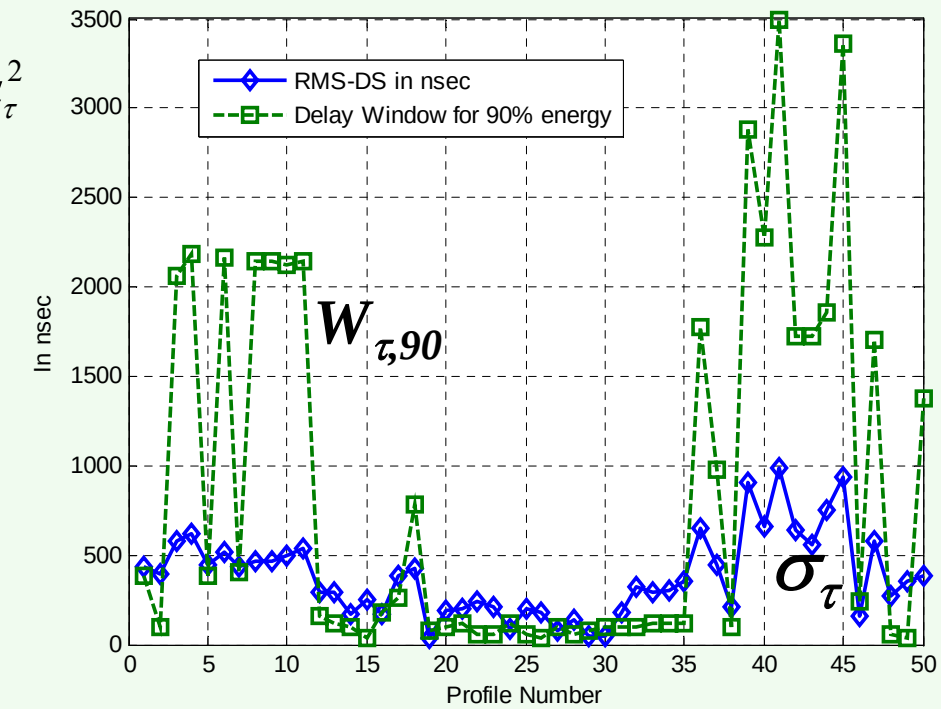
View from ATCT, JFK, August 2005



Channel Statistic Definitions

- **Delay Domain**
- RMS-DS: $\sigma_\tau = \sqrt{\dfrac{\sum_{k=0}^{L-1} \tau_k^2 \alpha_k^2}{\sum_{k=0}^{L-1} \alpha_k^2} - \mu_\tau^2}$
- Mean Energy Delay:

$$\mu_\tau = \frac{\sum_{k=0}^{L-1} \tau_k \alpha_k^2}{\sum_{k=0}^{L-1} \alpha_k^2}$$



- Delay Window $W_{\tau,x}$ = the length of the middle portion of the CIR containing x% of the total energy of the CIR

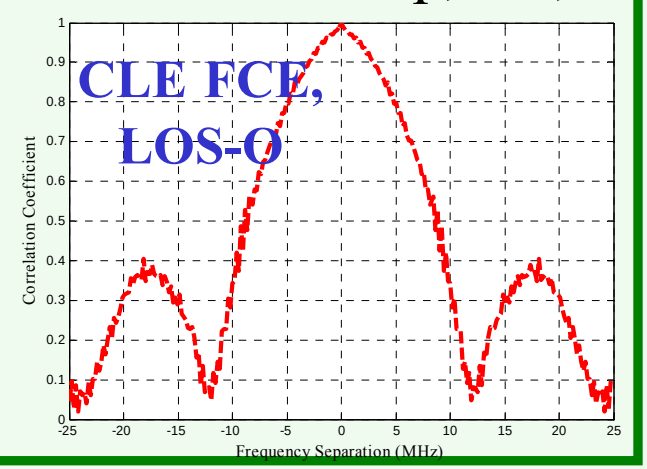
Channel Statistic Definitions (2)

- **Frequency Domain**
- Correlation (~coherence) bandwidth, defined as extent in frequency for which channel affects signal equally
- FCE: time variations of complex amplitudes of different "spectral lines" directly crosscorrelated w/time variations of reference spectral line
  - Crosscorrelation=$\gamma_H(a_{ref},a_i)$, where a_i is amplitude of spectral line at freq. index i, and a_{ref} is amplitude at the ref. freq., i.e.,

$$a_{ref,j} = |H(f,t)|_{f=f_{ref},t=t_j}$$

$$\gamma_H(a_{ref},a_i) = \frac{1}{N}\sum_{j=1}^{N} a_{ref,j} a^*_{i,j}$$

$$FCE = \frac{\gamma_H(a_{ref},a_i)}{\sqrt{\gamma_H(a_{ref},a_{ref})\gamma_H(a_i,a_i)}};$$



Mobile ATCT Measurements (1)

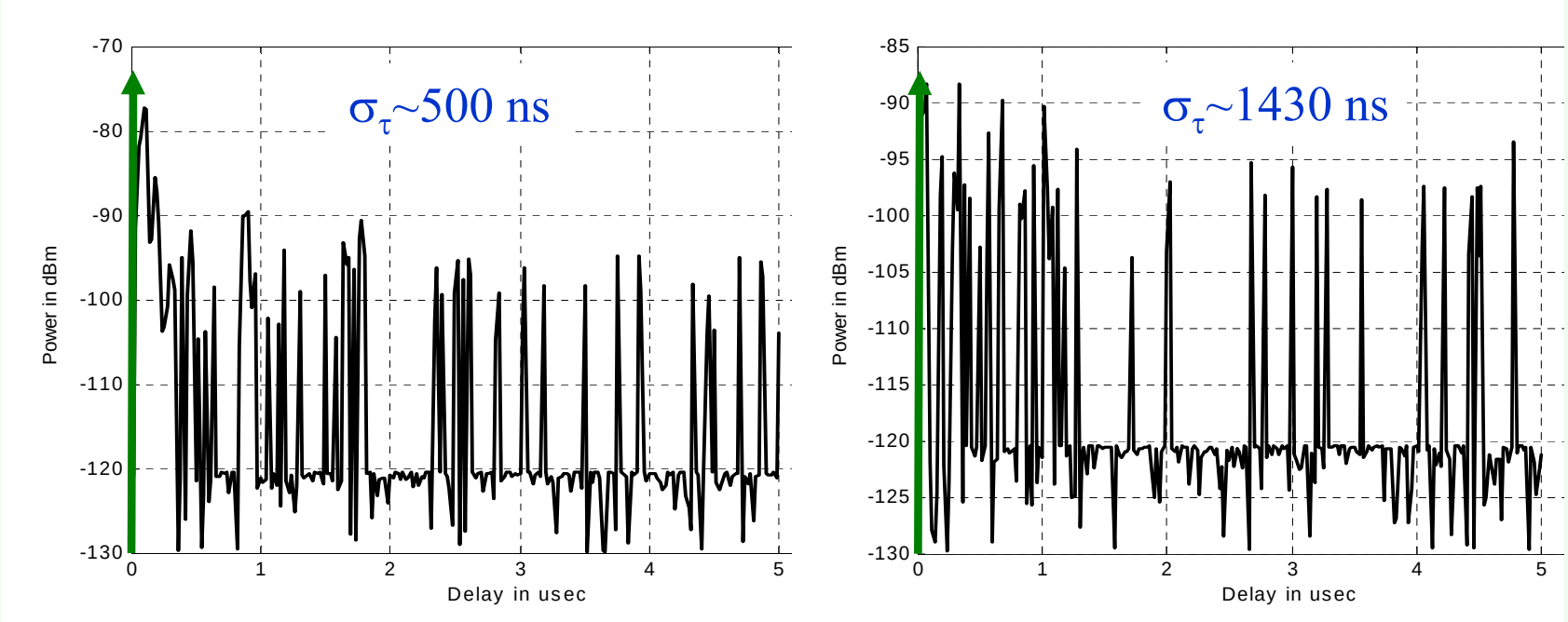
Measured RMS-DS [min; mean; max] (ns), Three Settings						
Airport	**Mobile**			**Point -Point**	**Field Site Transmit**	
	NLOS	**NLOS-S**	**LOS-O**	**LOS-O**	**NLOS**	**NLOS-S**
JFK	[800; 1,469; 2,456]	[21.4; 311; 798.7]	—	—	[802; 1,475; 2,433]	[5.8; 317.3; 799.5]
MIA	[1,000; 1,513; 2,415]	[23.1; 459; 999.9]	—	[5.6; 163; 249]	[1,000; 1,625; 2,451]	[8; 443; 997]
CLE	[500; **1,206**; 2,472]	[125; **295**; 499]	[14; **65**; 124]	[1; 18.12; 202]	—	— —
OU	—	[14; 293; 2,416]	—			
BL	—	[126; 429; 2,427]	[5; 44; 124]			
TA	[502; 1,390; 2,404]	[15; 256; 499]	—			

Over 51,000 total PDPs collected in 6 airports:

- ~ 35,000 for mobile setting
- ~ 5,000 for point-to-point setting
- ~ 11,800 for airport field site

Mobile ATCT Measurements (2)

- Power delay profiles—PDPs (received power vs. delay), after noise thresholding, for 50 MHz bandwidth



CLE, NLOS-S case

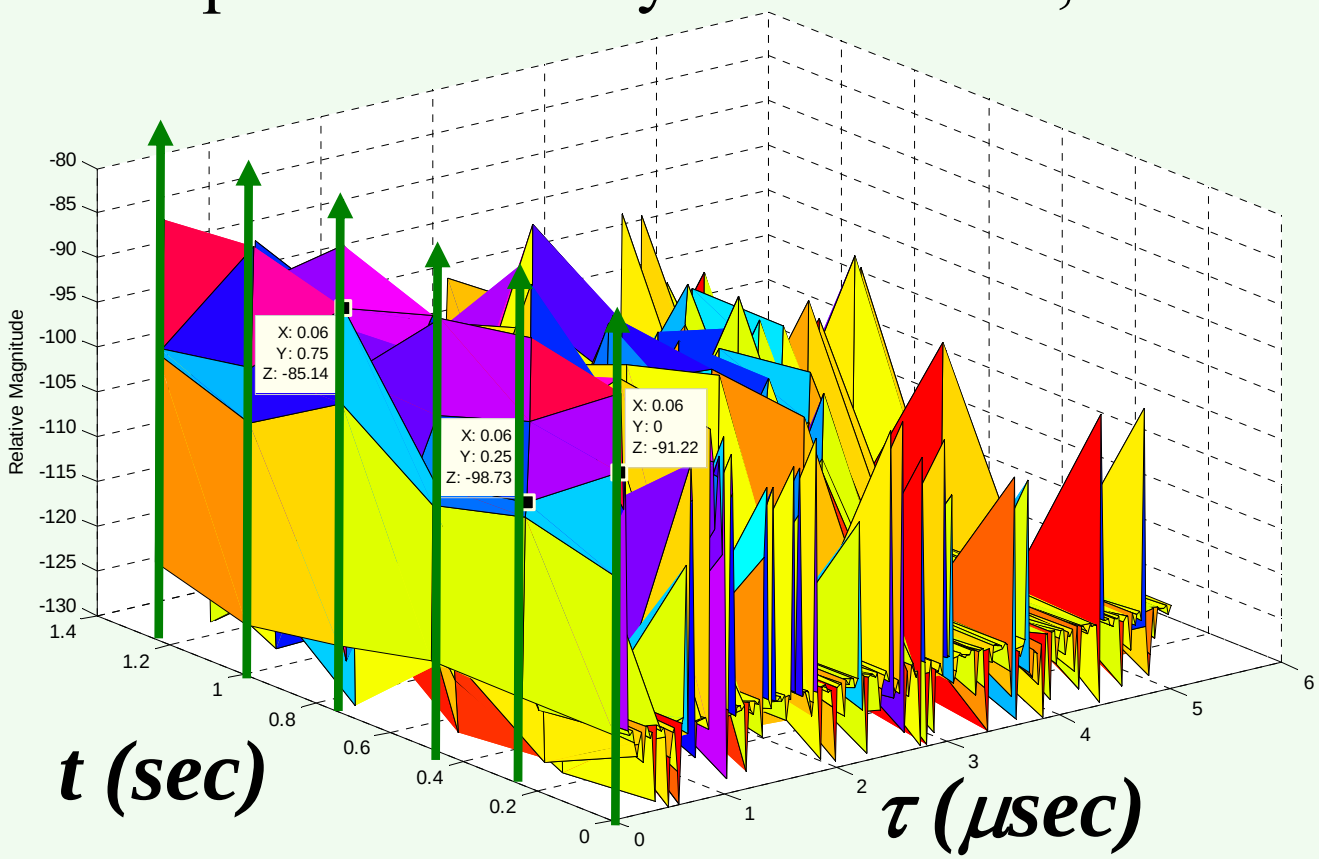
Significant multipath (~ 9 dB) up to $3T_c$ (0.06 μsec) + numerous weaker components

MIA, NLOS case

Significant multipath (~ 0 dB) up to $15T_c$ (0.3 μsec)

Mobile ATCT Measurements (3)

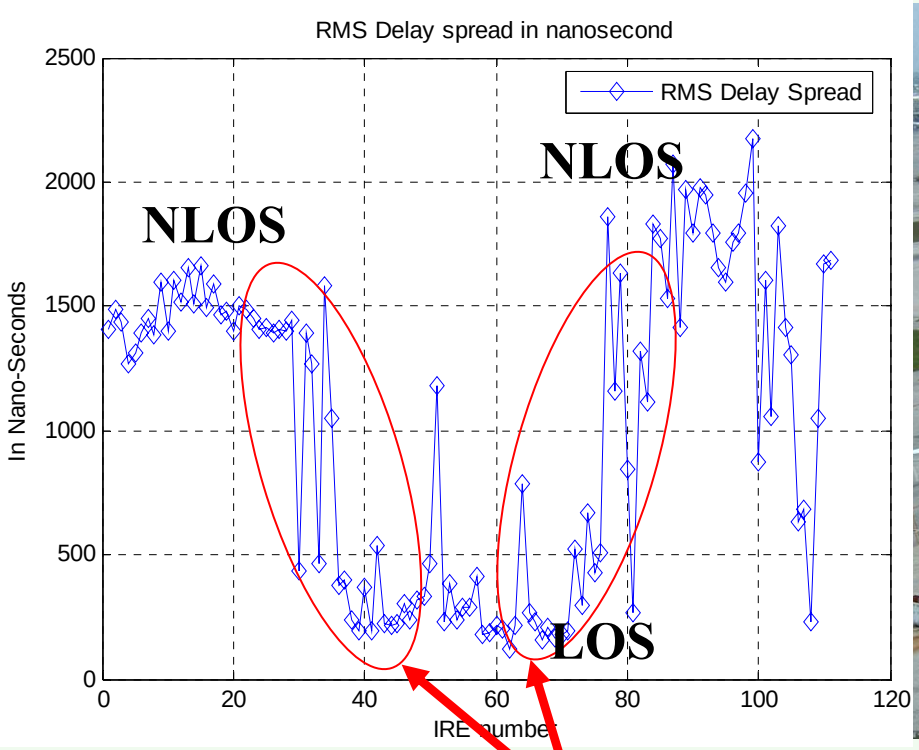
- MIA PDP: power vs. delay and vs. time, NLOS



Fades of approximately 14 dB on main tap

Mobile ATCT Measurements (4)

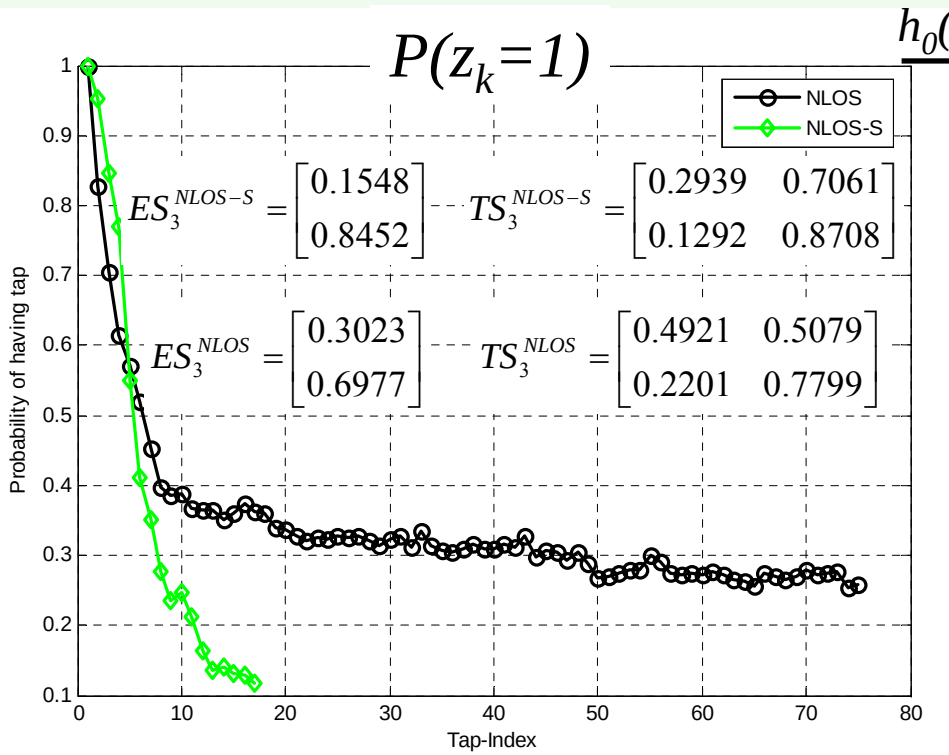
- Plots of RMS-DS vs. profile index (time)

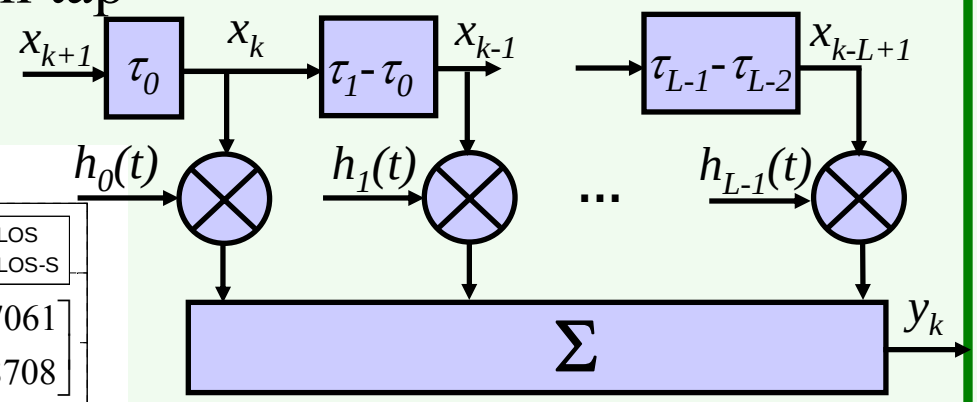


MIA: Multiple transitions to/from NLOS/LOS/NLOS

Mobile ATCT Measurements (5)

- Tap probability of occurrence (fraction of time), 50 MHz BW
- Threshold = 25 dB from main tap



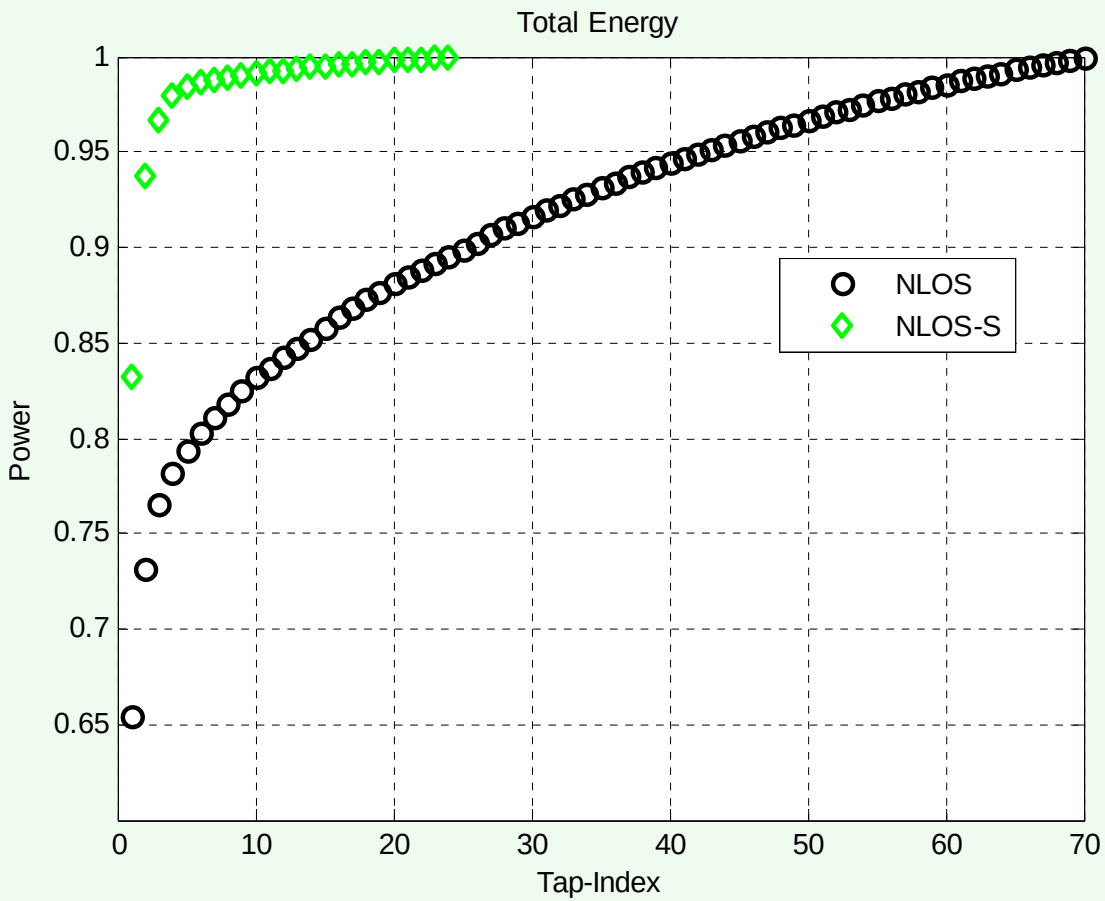


- NLOS-S: # taps L=18
- NLOS: # taps L=**75**

$$h_k(t) = z_k(t)\alpha_k(t)e^{j\phi_k(t)}$$

Mobile ATCT Measurements (6)

- Cumulative energy versus tap index for 50 MHz BW

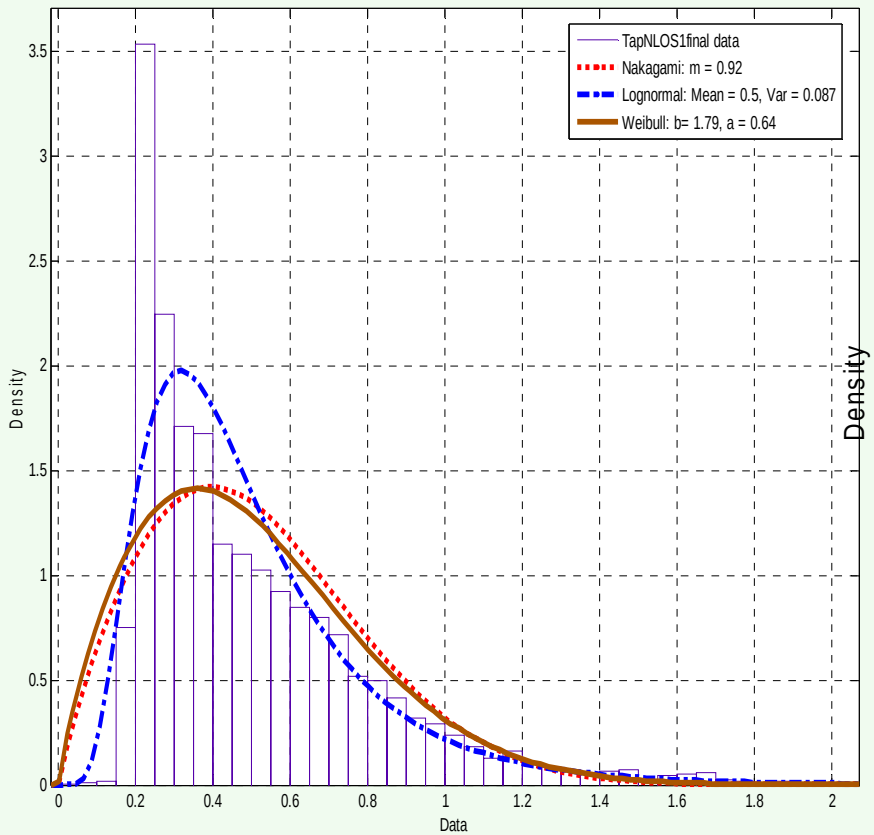


Tap Index	% Energy
NLOS-S	
4	98
9	**99**
NLOS	
10	83
15	85.8
20	88.1
25	90
30	91.6
35	93.2
40	**94.5**

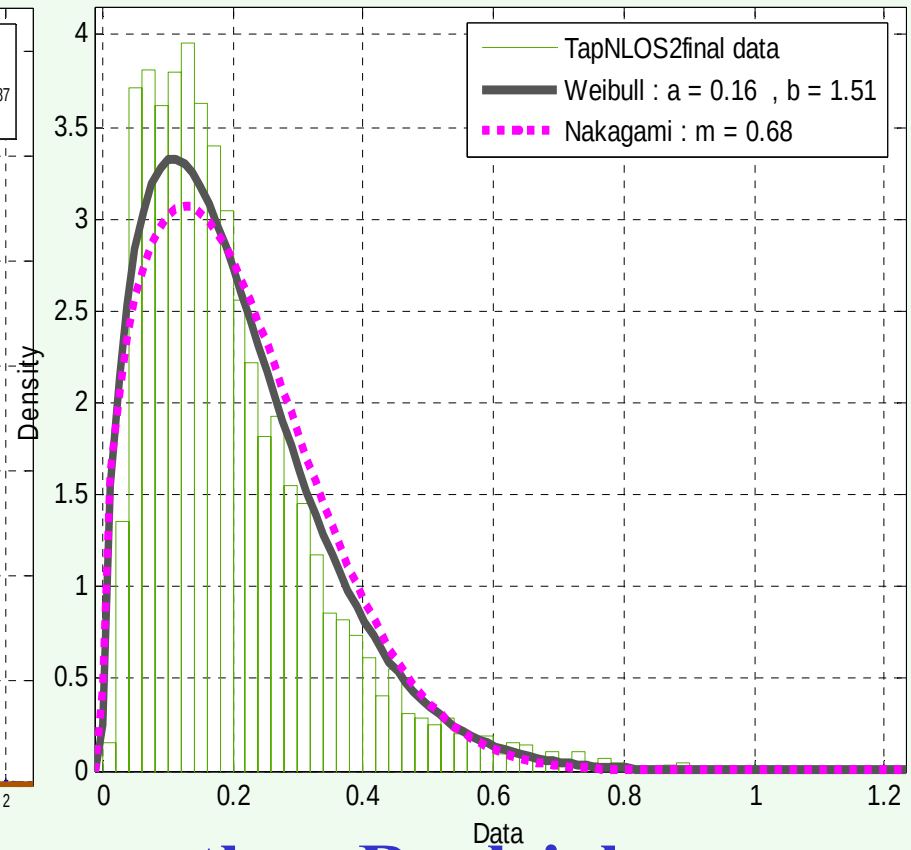
Mobile ATCT Measurements (7)

- Amplitude distribution, MIA, NLOS

Tap #1



Tap #2



- **Both NLOS taps 1 & 2 worse than Rayleigh**

Mobile ATCT Measurements (8)

- Amplitude statistics for NLOS-S, 50 MHz bandwidth

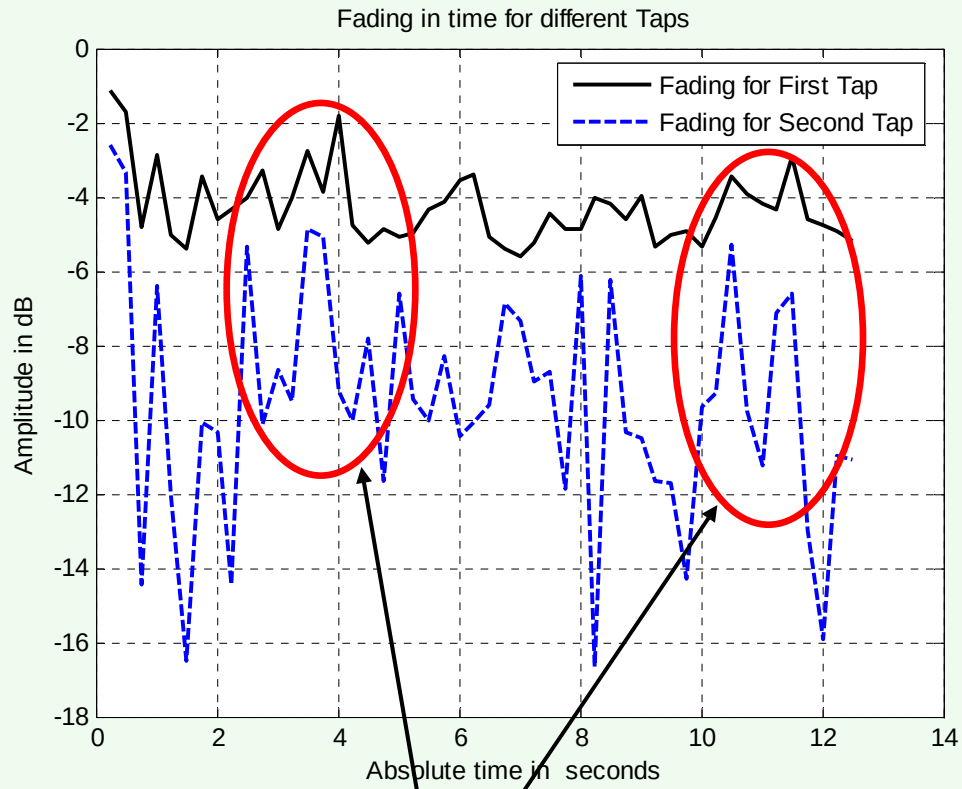
Tap Index	Fractional Energy	Shape Parameter (*b*)	Alternate Distribution Parameter
1	0.7666	3.81	K = 6.8 dB
2	0.1042	1.66	***m* = 0.78**
3	0.0310	1.86	m=0.98
4	0.0167	1.91	m=1.09
5	0.0084	1.97	m=1.16
6	0.0069	1.86	m=1.04
7	0.0049	2.04	m=1.21
8	0.0045	1.89	m=1.01
9	0.0043	1.90	m=1.05

- Weibull probability density
  - $f_w(x) = \frac{b}{a^b} x^{b-1} e^{-\left(\frac{x}{a}\right)^b}$
  - b = shape factor, determines fading severity
  - a = scale parameter

$$= \sqrt{\frac{E(x^2)}{\Gamma\left(\frac{2}{b}+1\right)}}$$

Mobile ATCT Measurements (9)

- Time series of Taps 1 and 2, NLOS-S, 50 MHz BW



Highly correlated taps

- Tap correlations for NLOS-S, 50 MHz BW

Taps	(Min, Max)
(1,2)	(-0.33,**0.706**)
(1,3)	(-0.34,**0.43**)
(1,4)	(-0.39,0.31)
(1,5)	(-0.38,**0.74**)
(1,6)	(-0.42,0.13)
(1,7)	(-0.42,0.11)
(1,8)	(-0.38,0.0078)
(1,9)	(-0.43,0.18)

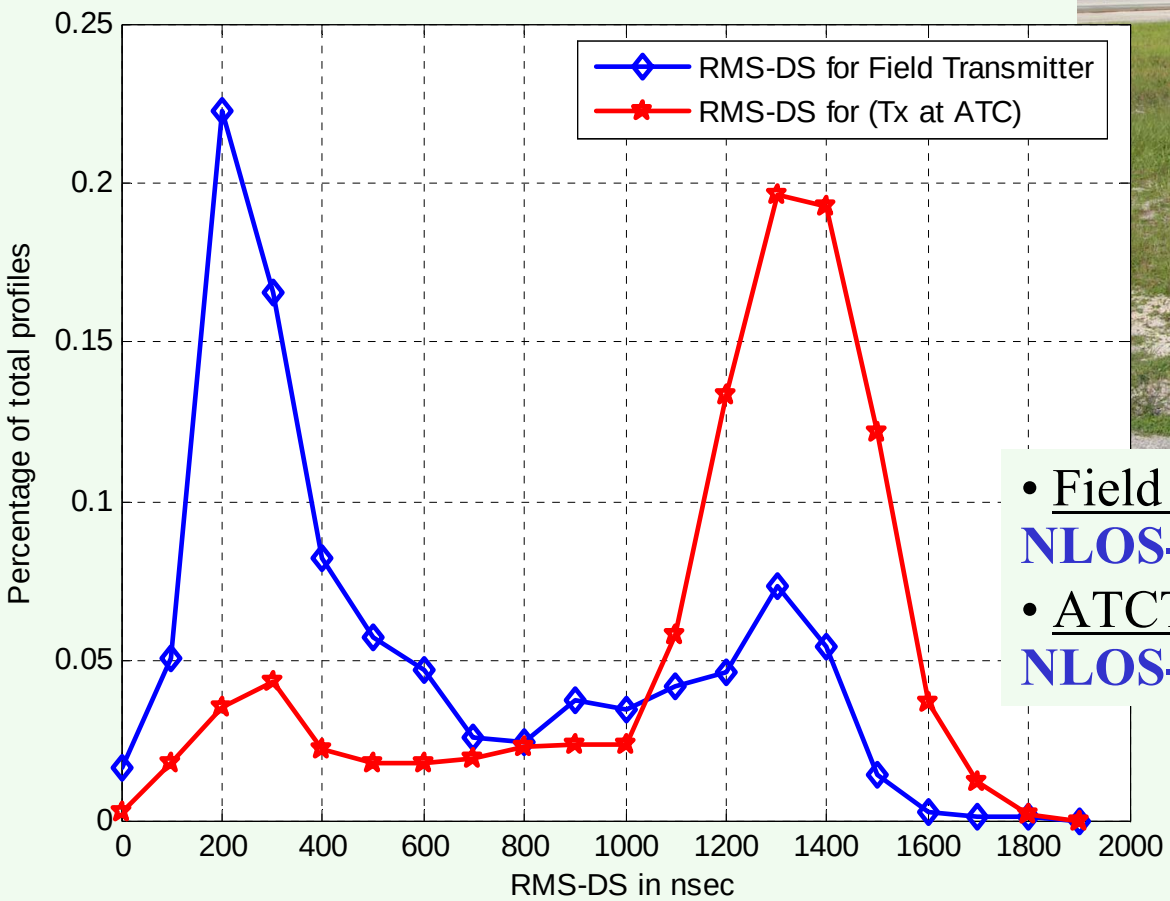
Mobile Field Site Measurements (1)

- Airport Field Sites useful in network to
  - Provide adequate signal strength in areas shadowed and distant from ATCT
  - Reduce channel dispersion
- Video clip of measurement in MIA
- Points 13-17, Tx at "P2" site
- (to aerial photo)
- Video Clip 0038
- PDP Animation

Tamiami, Kendall, FL

Mobile Field Site Measurements (2)

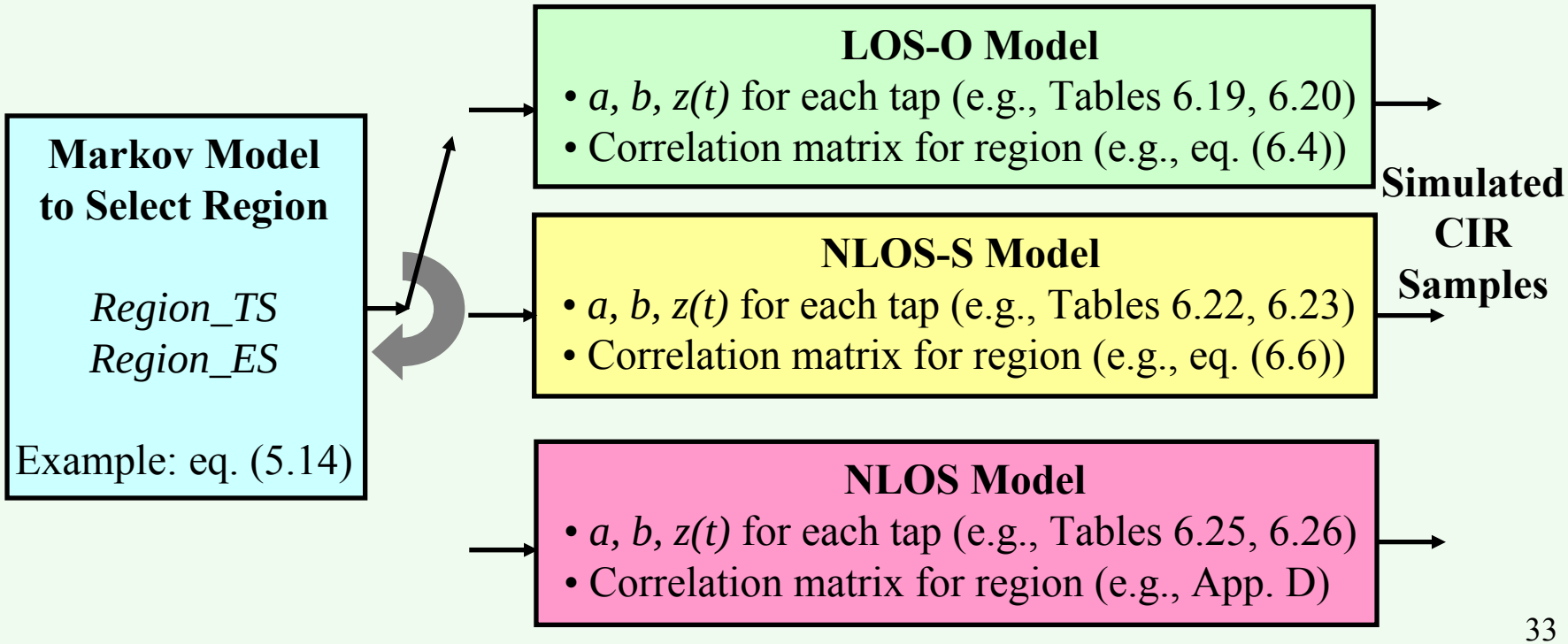
- Distribution of RMS-DS for Field Site and ATCT Tx



- Field Site Tx: **75% profiles in NLOS-S and 25% in NLOS**
- ATCT Tx: **23% profiles in NLOS-S and 77% in NLOS**

Channel Model Construction

- 3-state Markov chain to model transitions between propagation regions
- 2-state Markov chain for tap persistence processes
- Correlated Weibull amplitude fading



Channel Model Construction (2)

- Select channel BW (20 MHz), airport size (Lg)
- Using mean RMS-DS, # NLOS taps is 32
  - Reduce to ***L*=25**, account for 95% energy
- Select tap correlation matrix (worst-case, avg.,...)
- Obtain tap amplitude statistics →
- Obtain tap persistence process parameters ↓

Tap Persistence Process Parameters

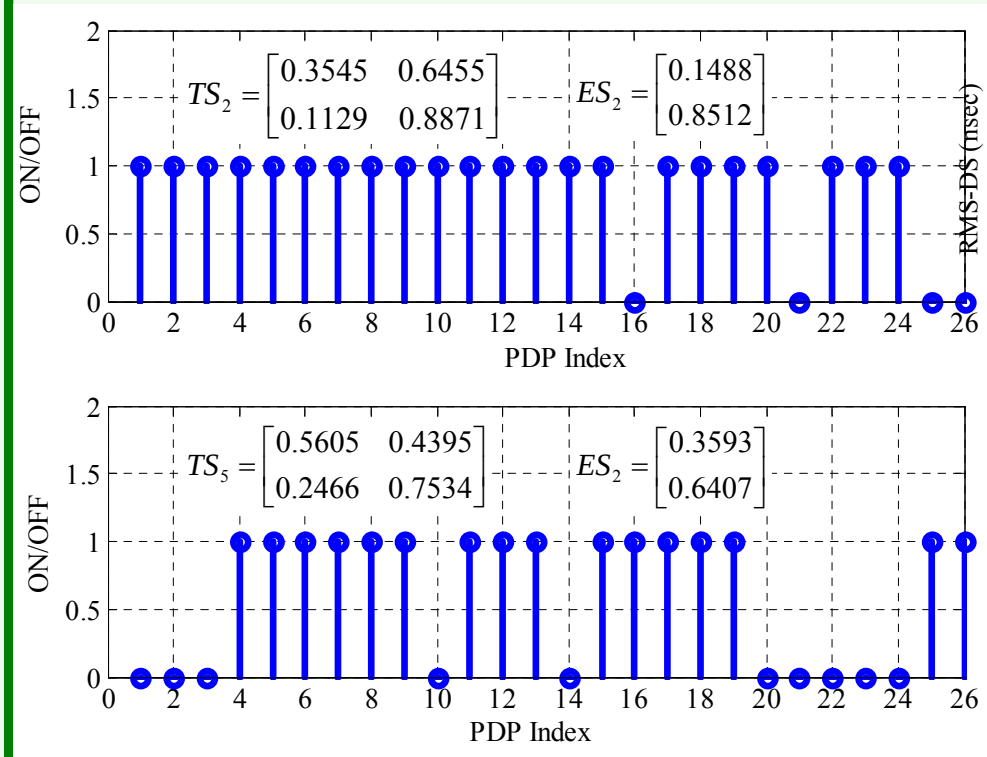
Tap Index	Probability State 1	Probability State 0	P_{00}	P_{01}	P_{10}	P_{11}
1	1.0000	0	*n/a*	*n/a*	0	1.0000
2	0.8540	0.1460	0.2409	0.7591	0.1298	0.8702
3	0.7168	0.2832	0.3772	0.6228	0.2462	0.7538
4	0.6563	0.3437	0.4535	0.5465	0.2863	0.7137
5	0.6321	0.3679	0.4875	0.5125	0.2981	0.7019
6	0.6065	0.3935	0.5119	0.4881	0.3168	0.6832
…	…	…	…	…	…	…

Tap Amplitude Statistics

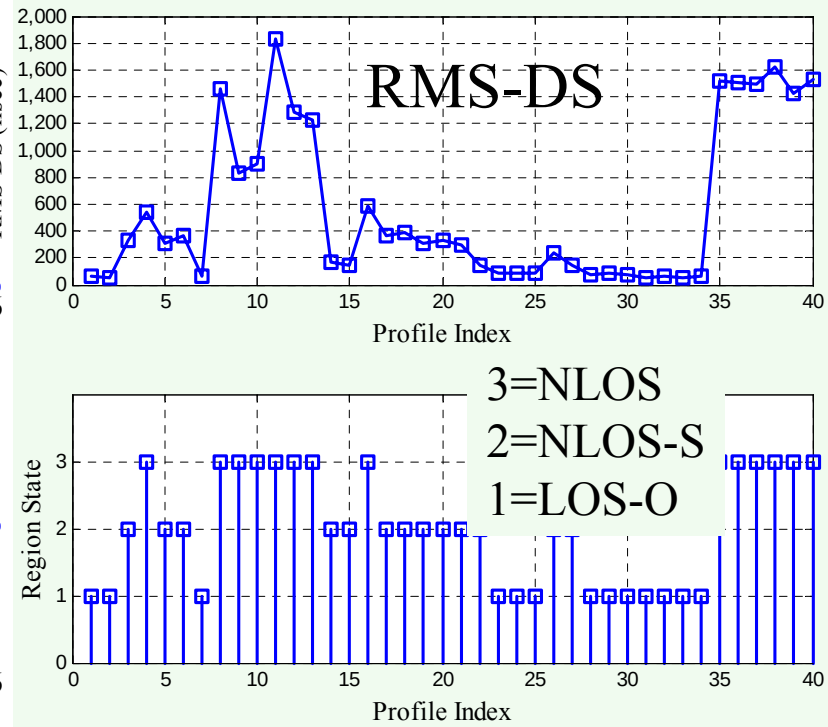
Tap Index	Weibull Factor (*b*)	Tap Energy
1	1.98	0.4953
2	1.5	0.0587
3	1.6	0.0261
4	1.6	0.0223
5	1.6	0.0191
6	1.55	0.0193
7	1.66	0.0174
8	1.65	0.0164
9	1.67	0.0155
10	1.65	0.0159
11	1.56	0.0168
12	1.59	0.0164
13	1.61	0.0154
14	1.61	0.0151
…	…	…

Channel Model Construction (3)

- Example persistence process and propagation region Markov chain outputs



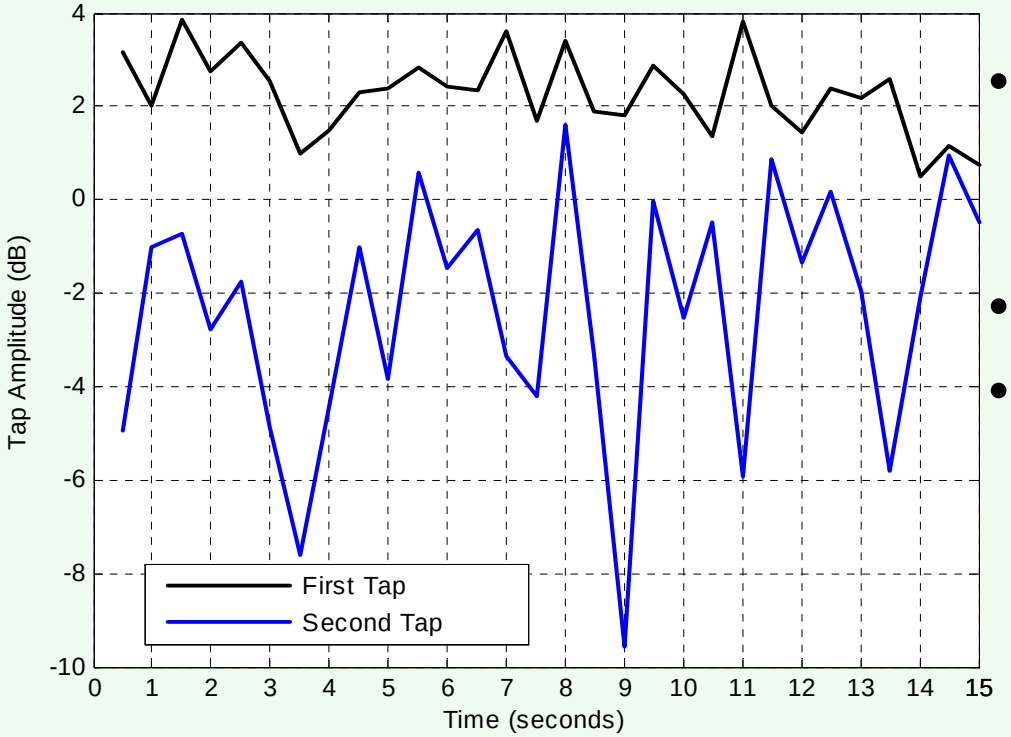
Tap Persistence, Taps 2, 5



Propagation Region

Channel Model Construction (4)

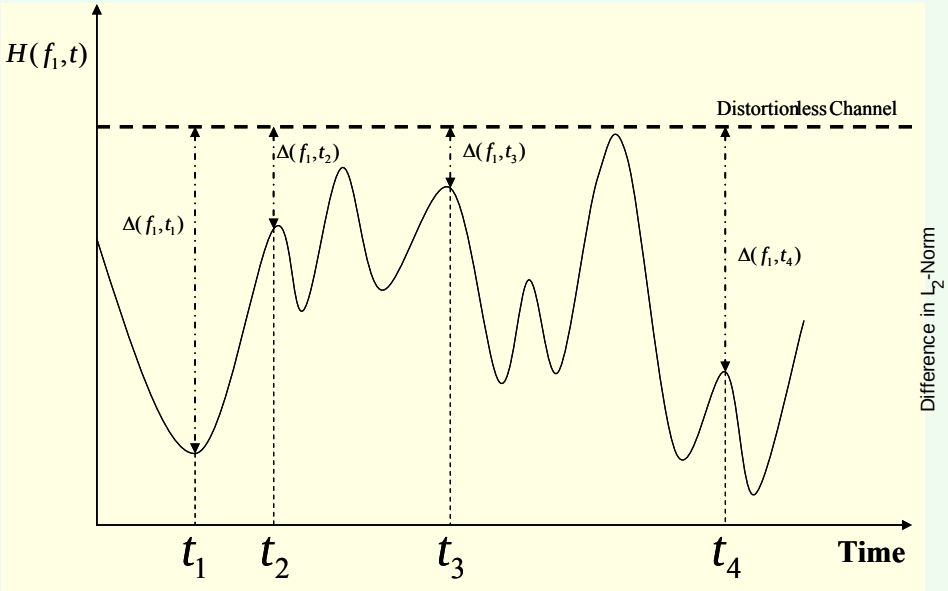
- Example tap fading amplitudes, Large Airport, NLOS-S

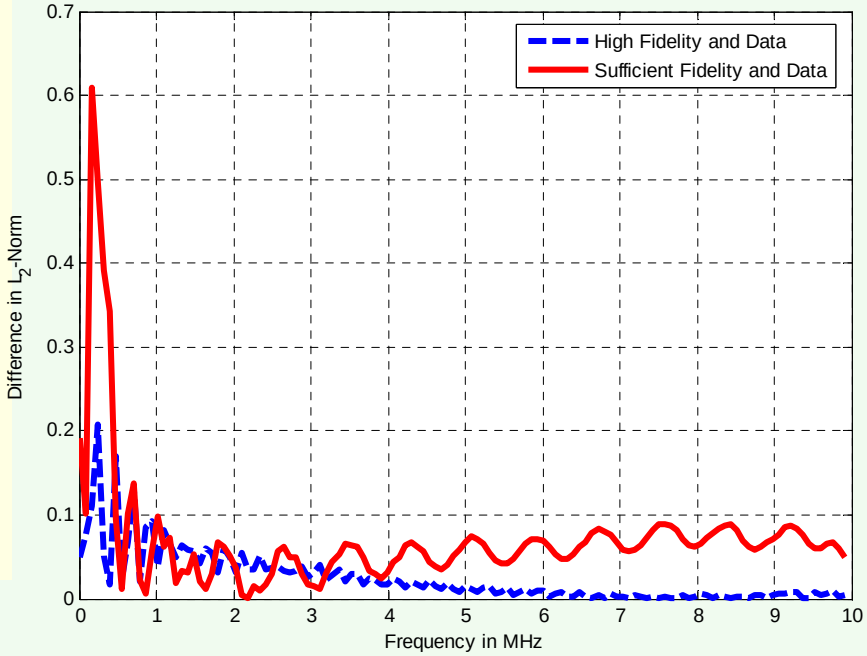


- Weibull Fading Parameters
  - Tap 1: $E(\alpha^2)$=0.79, b=4.8
  - Tap 2: $E(\alpha^2)$=0.1 , b=1.7
- $r_{12} = 0.79$
- Developed algorithm to generate multivariate, correlated Weibulls with arbitrary $E(\alpha^2)$, b

Channel Model Evaluation

- Model comparison: SF & HF vs. Measured Data





$$\Delta_M(f,t) = 1 - H_M(f,t)$$

$$L_2 - norm_{(t)} = \left\| \Delta_M(f_j,t) \right\|_2 = \sqrt{\int_{\{t\}} \Delta_M^2(f_j,t)\,dt} \cong \sqrt{\sum_{i=1}^{N_M} \Delta_M^2(f_j,t_i)}$$

Summary (1)

National Aeronautics and Space Administration

Federal Aviation Administration

- Provided motivation to characterize the 5 GHz MLS extension band channel around airport surface areas
  - Need for effort from the point of view of efficient communication link design, and band protection

- Recent measurement campaign multiple airports described, including
  - Coordination w/local authorities required for successful tests
  - Description of equipment, measurement process
  - Example measured results
  - Example modeling results

Summary (2)

- Correlated scattering in all regions of airport
- Amplitude statistics for some taps worse than Rayleigh
- Statistical non-stationarity
- Both high-fidelity and sufficient fidelity channel models developed

$$\mathbf{R}_{\alpha}^{\mathrm{NLOS-S}} = \begin{bmatrix} 1 & 0.7881 & 0.2940 & 0.3485 & 0.4782 & 0.4581 & 0.8969 & 0.5644 \\ 0.7881 & 1 & 0.3134 & 0.6588 & 0.4255 & 0.8239 & 0.7768 & 0.6160 \\ 0.2940 & 0.3134 & 1 & 0.5758 & 0.8606 & 0.6958 & 0.4222 & 0.9695 \\ 0.3485 & 0.6588 & 0.5758 & 1 & 0.6939 & 0.6605 & 0.9513 & 0.7965 \\ 0.4782 & 0.4255 & 0.8606 & 0.6939 & 1 & 0.9181 & 0.4653 & 0.8869 \\ 0.4581 & 0.8239 & 0.6958 & 0.6605 & 0.9181 & 1 & 0.6528 & 0.6052 \\ 0.8969 & 0.7768 & 0.4222 & 0.9513 & 0.4653 & 0.6528 & 1 & 0.7502 \\ 0.5644 & 0.6160 & 0.9695 & 0.7965 & 0.8869 & 0.6052 & 0.7502 & 1 \end{bmatrix}$$

Field Site Measurement Summary

- Can reach areas that are “hard-to-reach” from ATCT Tx
- Comparatively, channel is less dispersive than ATCT Tx mobile channel
- A very high-fidelity channel model can be implemented with lower complexity than for the ATCT mobile measurement model

Future Work

1. Refine channel models for VTV applications

- *<u>Goal</u>: Develop high-fidelity, non-WSSUS models for Vehicle-to-Vehicle channels, for Intelligent Transportation Systems (ITS)*

2. Wideband air-ground channel characterization in 960-1024 MHz aeronautical spectrum, for future air-ground communications

- *<u>Goal</u>: Develop wideband statistical channel models applicable to the 960-1024 MHz aeronautical (DME) band*

3. Evaluation of candidate communication system (IEEE 802.16, cellular) performance on airport surface in MLS extension band

- *<u>Goal</u>: Determine expected performance of best technology candidate(s) for airport surface communications deployment*

Questions??