Narrowband Propagation Statistics of Aeronautical Mobile-Ground Links in the L- and C-Bands

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Introduction

Integration of UAS into non-segregated airspace

- UAS in the NAS Project has addressed critical research issues
    - Aircraft and system certification
    - Detect and avoid techniques
    - Air traffic management procedures
    - Aircraft control human interfaces
    - Command and Control (C2) communications

Very high performance C2 communications is a key requirement

- Protected aviation spectrum, or functionally equivalent, required by ICAO
- Radio line-of-sight (LOS) using terrestrial systems (air-to-ground)
- Beyond radio line-of-sight (BLOS) using networked terrestrial stations and satellite communications

Allocations supporting UAS C2 (WRC-12 and WRC-15)

- LOS: L-Band (960-1164 MHz) and C-Band (5030-5091 MHz)
- BLOS: C-Band (5030-5091 MHz), Ku-Band (11/14 GHz), Ka-Band (20/30 GHz)

Introduction

For high performance C2 LOS communications, focus was on development of performance requirements & standards

To support standards, prototype radios were developed and flight tested

To support prototype radio development, characterization of the air-ground propagation channel was required

- L-Band, centered at 968 MHz
- C-Band, centered at 5060 MHz
- Narrowband data for both bands, wideband data for C-Band

Derive statistical channel characteristics, develop channel models

Make channel statistics generally available through ITU-R Study Group 3 Data Banks

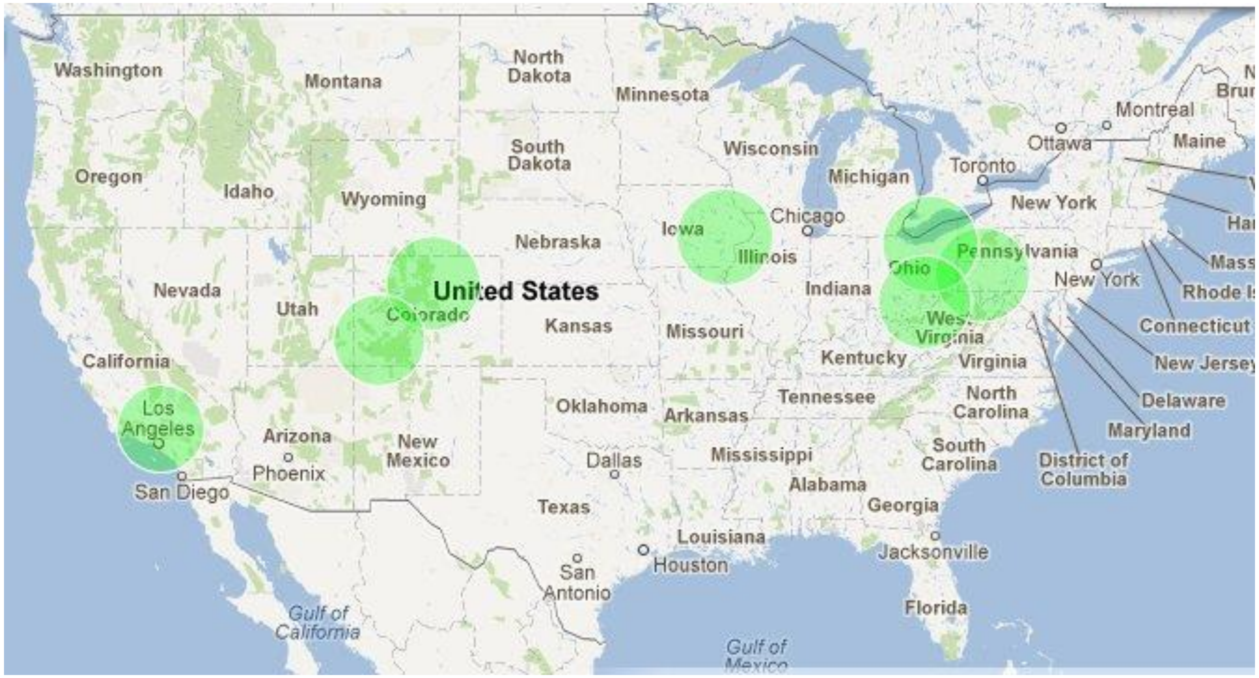
Air-Ground Channel Measurements

Measurement Campaign

Flight measurement campaigns were conducted to collect data on propagation characteristics of the AG channel, L- and C- bands

Seven ground environments were tested:

- Over sea
- Over freshwater
- Hilly
- Mountainous
- Suburban
- Desert
- Near-urban



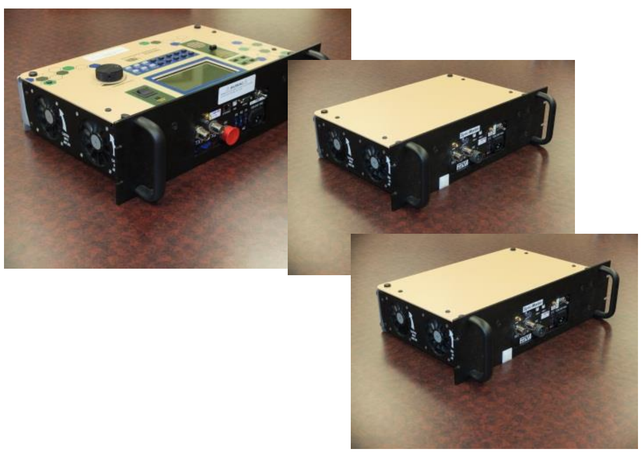
Flight test sites in the US

Air-Ground Channel Measurements

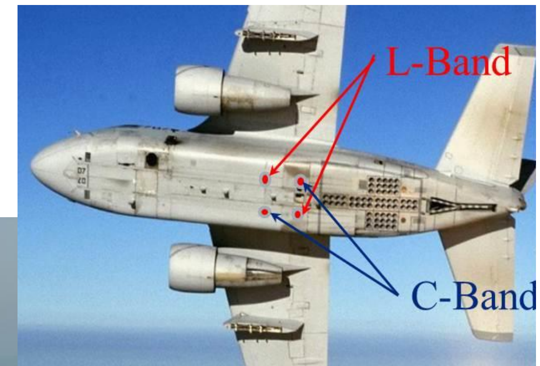
Measurement Campaign

A custom built AG channel measurement system was developed for these tests to collect data on the propagation characteristics of the AG channel, L- and C- bands

NASA Glenn Research Center's S-3B Viking was the test aircraft



Channel measurement system – one transmitter (left), two receivers



NASA GRC S-3B Flight Test Aircraft, and Receive Antenna Locations

Air-Ground Channel Measurements

Measurement Campaign

Flight measurement campaigns were conducted with a ground station transmitting signals to receivers on the test aircraft.

Two L-band antennas and two C-band antennas on the aircraft; two receiver sets collected received signals

Portable ground station was driven to the various test sites

Portable Ground Station Mounted on a Trailer.

Antenna Mast Extendable to 60 feet

Measurement Campaign

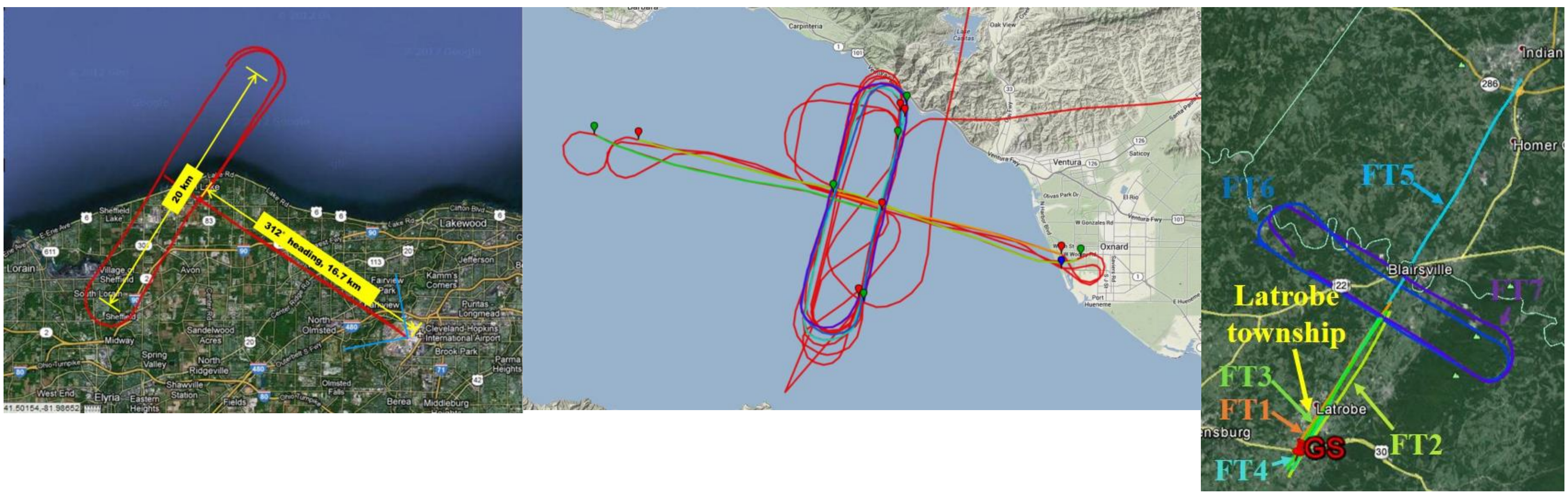
Other key measurement parameters

- The C-band chip rate was 50 Mchips/sec, providing single bandwidth of approximately 50 MHz
  - Delay resolution approximately 20 ns
- The L-band chip rate was 5 Mchips/sec, providing signal bandwidth of approximately 5 MHz for L-band
  - Delay resolution approximately 200 ns
- The C-band GS antenna gain is 6 dB with elevation/azimuth beamwidths of approximately 35º/180º
- The L-band GS antenna gain is gain 5 dB with elevation/azimuth beamwidths of approximately 60º/120º
- All antennas were vertically polarized, and for essentially all flight tests, the aircraft was within the GS antennas main beams
- Transmitter output power for both bands was 10 watts (40 dBm)

Measurement Campaign

Test Flights

- Flight path shapes included straight, (toward and away from GS) & oval
- Straight flight paths enable quantification of channel characteristics versus distance, & the oval flight paths varied aircraft antenna orientation
- Flight test planning had to account for limits on minimum altitude, proximity to populated areas, flying times, flight velocities, air traffic control requirements.



Example Flight Paths: Near Cleveland, Ohio; Near Oxnard, California; Near Latrobe, Pennsylvania

Data Processing

316 Million Channel Impulse Responses (CIRs) collected

CIRs - amplitudes and phases of all multipath components (MPCs)

For delay domain channel statistics these are converted to power delay profiles (PDPs) - the power output at time t vs. delay τ, when an impulse is input at time t-τ

From these CIRs, several channel characteristics were estimated

- attenuation or propagation path loss
- delay dispersion (delay spread)
- Doppler effects
- small-scale amplitude fading characteristics
- correlations among the signals received on the different antennas and in the two frequency bands

Air-Ground Channel Measurements

Data Processing

From the data, AG channel characteristics were estimated

1. Propagation path loss, or attenuation (dB)
2. Stationarity distance, SD (m)

   Spatial extent over which channel statistics are approximately constant
3. Ricean K-factor (dB)
4. Correlation coefficients (dimensionless)

   Between L-Band & C-Band, between the two L-Band antennas, and between the two C-band antennas
5. Airframe shadowing depths (dB) and durations (sec)
6. Multipath component statistics

   Amplitudes relative to the LOS component (in dB)

   Delays relative to the LOS component delay (in sec)

   MPC durations or “lifetimes” (in m)

   MPC probabilities of occurrence

Narrowband Channel Statistical Results

Example Statistics

Fade depth

ITU: fade depth A is the attenuation in dB relative to the line-of-sight (LOS) component

$$A = L_{fs} - L_{meas}$$

L_{fs} is the free space path loss, L_{meas} is the measured path loss

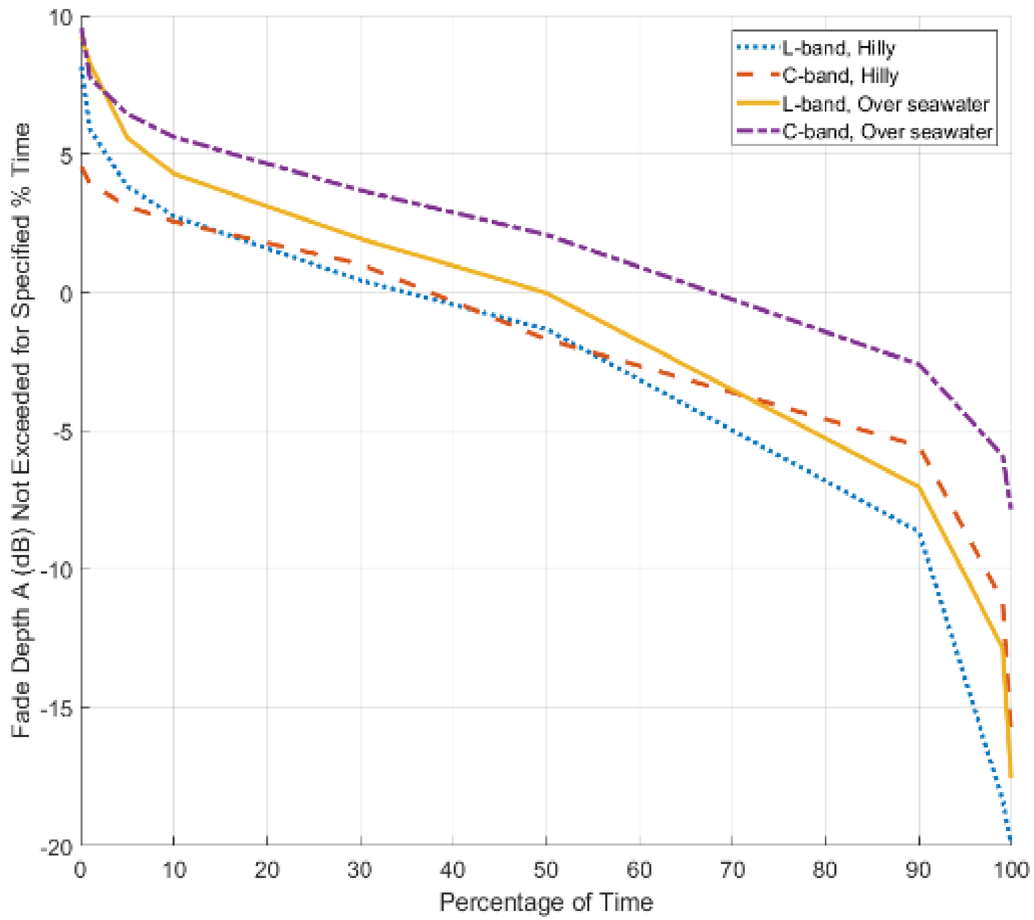
The case when A is larger than zero indicates that there is constructive interference and in general is uncommon - can be attributed to strong reflections in the environment.

Narrowband Channel Statistical Results

Example Statistics

Fade depth

- Direct plot of what the ITU narrowband data tables contain
- Both frequency bands, for two distinct GS environments, over seawater and hilly
- Here, positive fade depth means measured path loss is **less** than free-space path loss – constructive interference



Fade depths not exceeded for given percentage of time for L-band and C-band over hilly and over seawater environments

Narrowband Channel Statistical Results

Example Statistics

Fade depth

- An alternative, plot fade as **positive** number in dB

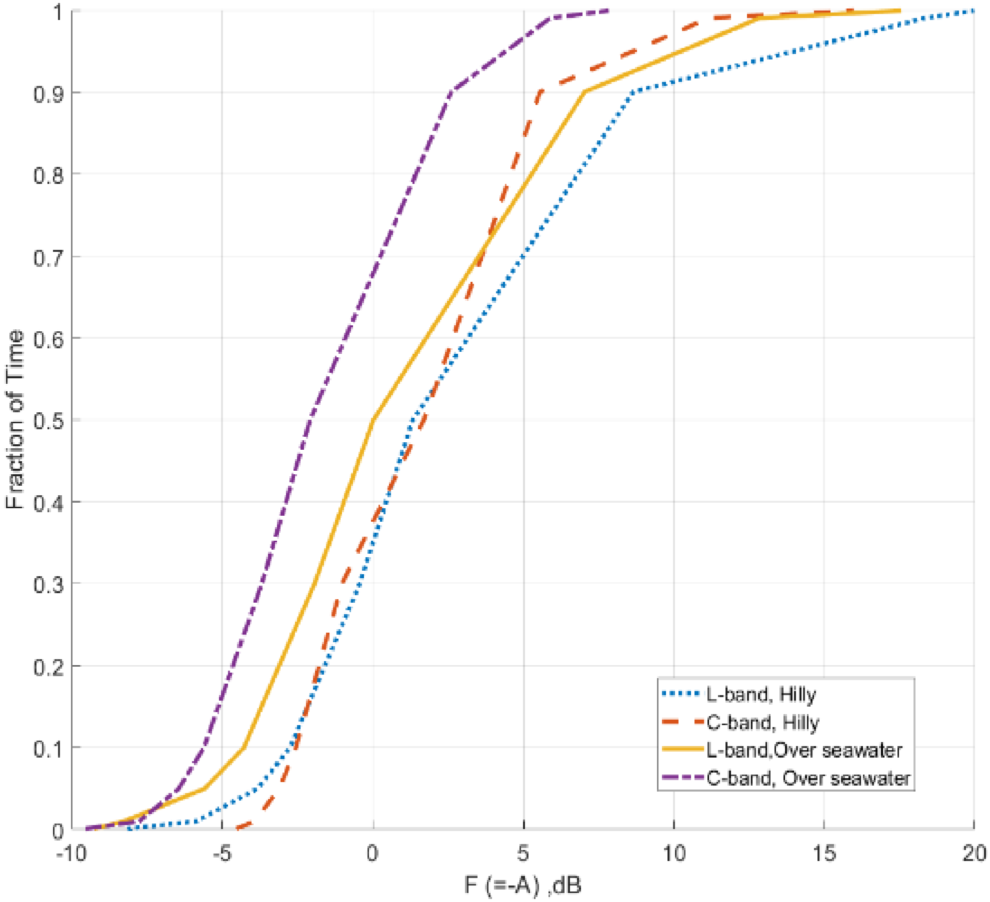
$$F = L_{meas} - L_{fs} = -A$$

to obtain conventional cumulative distribution function (cdf)

For example,

C-band over sea shows that for fraction of time ~0.7, path loss was less than that of free space, whereas for L-band hilly it was only 0.4

Direct result of strong 2-ray effect



CDFs for L-band and C-band over hilly and over seawater environments

Narrowband Channel Statistical Results

Example Statistics

Fade duration

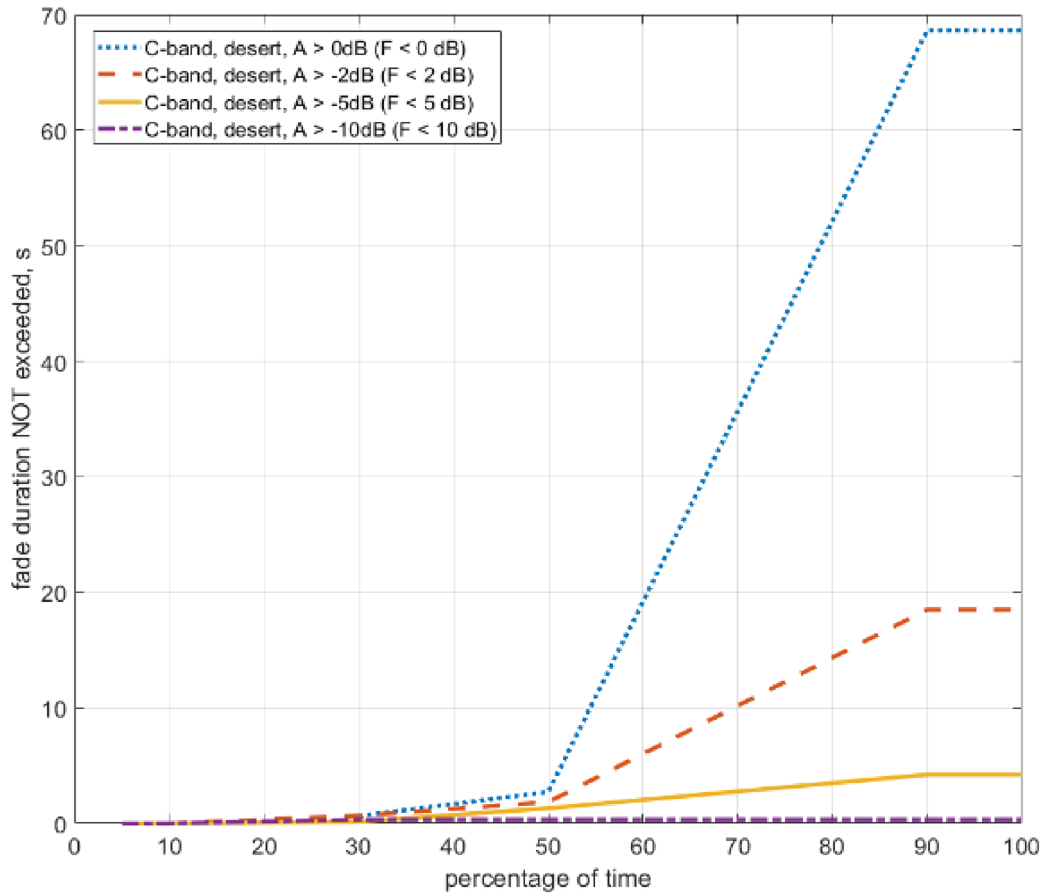
- Length of fade durations for a given percentage of time, at a selected fade level

An example in plot form for C-band in desert environment

For this case, for 50% of the time, fades of up to 5 dB last ~1 second or less

For 50% of the time, fades of up to 0 dB last ~3 seconds or less

For 90% of the time, fades of up to 5 dB below LOS last for less than ~5 seconds



Fade durations (s) not exceeded for given percentage of time

Narrowband Channel Statistical Results

Example Statistics

Fade duration

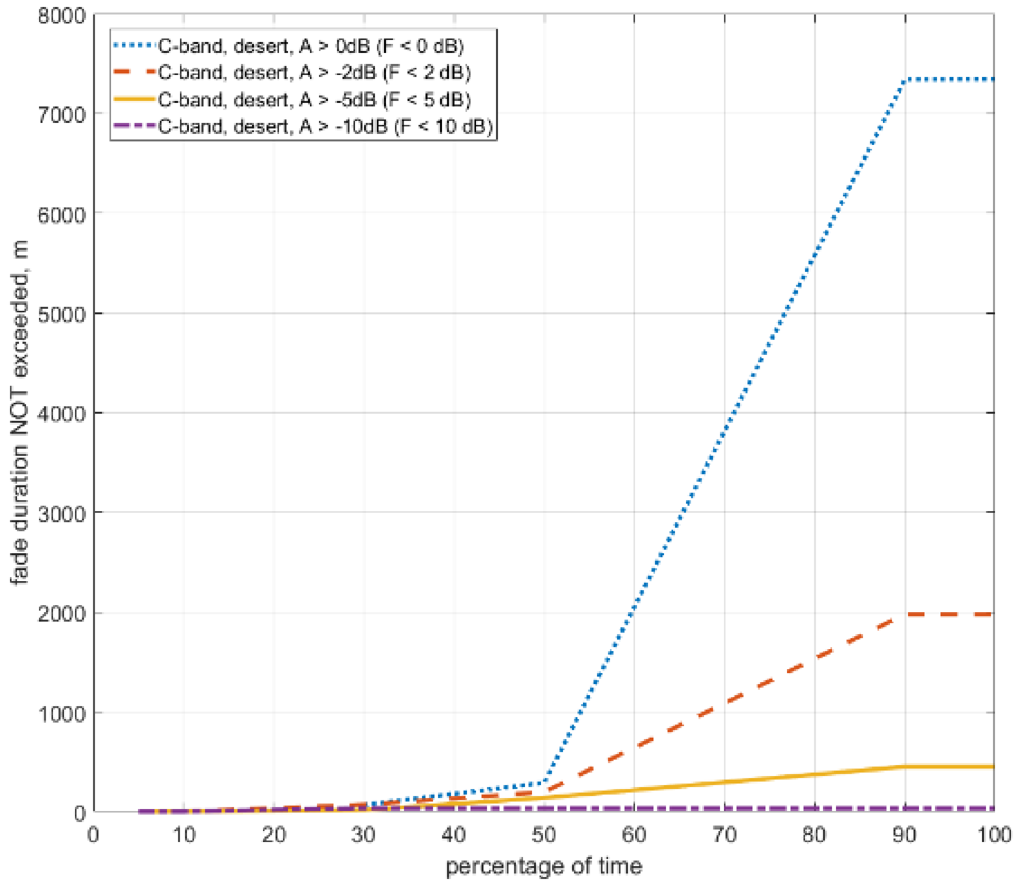
- Length of fade durations is a direct function of the flight velocity

Alternatively, represent fades spatially – faded lengths in meters rather than in seconds

For this case, for 50% of the time, fades of up to 5 dB last ~150 meters or less

For 90% of the time, fades of up to 5 dB last ~500 meters or less

For 90% of the time, fades of up to 5 dB below LOS last for less than ~2000 meters



Fade durations (m) not exceeded for given percentage of time

Narrowband Channel Statistical Results

Example Statistics

Summary of Statistical Results

For ITU-R Study Group 3 Data Tables,

We provided:

Test conditions

Fade duration, time

Fade duration, distance

Frequency *f* (GHz)	5060MHz
Polarization (L/C)	Linear (vertical)
Polarization tilt angle φ_p (degrees)	NA
Signal source	
Ground Station latitude (–90…+90) (degrees)	34.1770°
Ground Station longitude (–90…+90) (degrees)	-119.2354°
TX antenna gain towards mobile (dBi)	6
TX 3 dB beamwidth θ_r (degrees, azimuth)	180
TX 3 dB beamwidth θ_r (degrees, elevation)	35
Local ground site characteristics [5]	70
TX antenna height ag h_t (m)	23.4696m
Aeronautical mobile station	
RX Aircraft Type	Lockheed S-3B Viking
RX country[1]	USA
RX Path Type (linear, oval, etc.)[2]	Linear
RX start latitude (–90…+90) (degrees)	34.2456°
RX start longitude (0..360) (degrees) E	240.516°E
RX end latitude (–90…+90) (degrees)	34.19475°
RX end longitude (0…360) (degrees) E	240.748°E
RX average altitude amsl h_{gr} (m)	797.619m
RX antenna type	quarter-wavelength monopole
RX 3 dB beamwidth θ_r (degrees, azimuth)	NA
RX antenna gain (dBi)	5
RX multipath reduction? (Y/N)	N
RX dynamic range (dB)	60
RX integration time (s)	variable
Data sampling interval (s)	0.000333
Data resolution (dB)	0.5

Measurement: Experiment No.	Aggregate
Start date (yyyy.mm.dd)	2013.06.11
End date (yyyy.mm.dd)	2013.06.11
Duration *d* (days) [3]	6424.91sec=.07436d
Average elevation angle (degrees)	3.1589 °
Range of elevation angles (degrees)	0.69172° to 20.5002°
Average velocity of aircraft (m/s)	90.7912m/s
Environment	
Over Sea	
Weather conditions[4]	
Ground temperature range at TX	
Land mobile terrain type[5]	70
Land mobile building type[5]	70
Land mobile vegetation type[5]	70
Land mobile surface shape[6]	overwater
Sea state	WMO Sea State Code 2
80% CDF of basic transmission loss, L80 (dB)	137.57
90% CDF of basic transmission loss, L90 (dB)	138.82

Narrowband Channel Statistical Results

Example Statistics

C-band and L-band example *cdf* values for the 7 GS environments

Table 2. C-band environment fade depths, *F* in dB

Environment	1% of time Fade depth, F	50% of time Fade depth, F	99% of time Fade depth, F
Over Seawater	-7.76	-2.08	5.90
Over Freshwater	-6.99	-1.14	7.03
Hilly	-3.93	1.70	11.16
Mountainous	-5.17	0.58	12.29
Suburban	-6.97	-0.42	9.61
Desert	-8.71	-2.24	5.54
Near-Urban	-6.82	-0.37	6.18

Table 3. L-band environment fade depths, *F* in dB

Environment	1% of time Fade depth, F	50% of time Fade depth, F	99% of time Fade depth, F
Over Seawater	-8.27	0.02	12.85
Over Freshwater	-5.11	2.96	12.44
Hilly	-5.89	1.33	18.34
Mountainous	-5.70	2.93	13.12
Suburban	-5.84	2.02	10.80
Desert	-6.20	0.84	11.05
Near-Urban	-3.47	1.85	9.17

Narrowband Channel Statistical Results

Example Statistics

Example of submitted data tables

C-band over seawater statistics

Note that fade duration in meters is something new for ITU-R

Fade depth relative to LOS (dB) exceeded for percentage of time

Percentage of time	0.1	1	5	10	30	50	90	99	99.9
Fade depth A (dB)	9.55	7.76	6.44	5.61	3.68	2.08	-2.61	-5.90	-7.84

Fade duration (s) NOT exceeded for percentage of time at given fade levels

Percentage of time	0.1	1	5	10	30	50	90	99	99.9
0 dB	–	–	–	–	1.4001	3.3430	66.6908	66.6954	66.6958
2 dB	–	–	–	0.0243	0.8718	2.6406	13.0563	22.5271	22.5273
5 dB	–	–	0.0015	0.0054	0.5074	1.1421	3.2973	3.5692	3.5692
10 dB	–	–	–	–	–	–	–	–	–

Fade Duration in meters

Percentage of time	0.1	1	5	10	30	50	90	99	99.9
0 dB	-	-	-	-	124.25362	306.74454	5854.4283	5854.8473	5854.8892
2 dB	-	-	-	2.4251109	79.427671	241.9133	1242.269	1979.7795	1979.799
5 dB	-	-	0.124276	0.4435302	47.191287	99.844811	313.07495	313.89079	313.89391
10 dB	-	-	-	-	-	-	-	-	-

Conclusion

- Described UAS in the NAS project & its importance in collecting data useful for evaluation & design of high-reliability UAS C2 links
- Large amount of this data was AG flight test data, and this enabled us to gather statistics on fade depths relative to free-space path loss
  - Propagation models developed
  - Statistics developed for general use
- An important goal for NASA was to make this information available
  - ITU-R Study Group 3 has created the repository for such information and reviews and approves statistics placed into its Databanks
- Table formats were proposed to and accepted by IT-R Study Group 3
- The data was organized and presented to the ITU-R for inclusion in the Study Group 3 Databanks, accepted August 2017
- Wideband statistics are similarly being organized and prepared for submittal to ITU-R Study Group 3

Thank you!

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