UAS Modeling of the Communication Links Study Results

Document 1 of 2 (Main)

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UAS Modeling of the Communication Links
Study Results

Document 1 of 2 (Main)

UAS Fast-Time Control and Communication Modeling and Simulation

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LIST OF ACRONYMS

AGI	Analytical Graphics, Inc.
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Controller
ATCT	Air Traffic Control Tower
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Network
ATO	Air Traffic Organization
AVS	Aviation Safety
BER	Bit Error Rate
BLOS	Beyond Line of Sight
BW	Band Width
C&C / C2	Control and Communications
CASTS	Collision Avoidance Sensor Trade Simulation
CCI	Command and Control Interface
CCISM	Command and Control Interface Specific Module
CDMA	Code Division Multiple Access
COCR	Communication Operating Concept and Requirements
CPM	Continuous Phase Modulation
CSP	Communications Service Provider
CPDLC	Controller Pilot Data Link Communications
CS	Control Station
D	Distance
Data Comm	Data Communications

dB	Decibel
dBm	Decibel Millwatt
dBW	Decibel watt
CSP	Communication Service Provider
DIS	Distributed Interactive Simulation
DoD	Department of Defense
DSB–AM	Double Sideband Amplitude Modulation
DLI	Data Link Interface
DL	Downlink
DSP	Datalink Service Provided
Eb/N0	Energy Per Bit over Noise Power Spectral Density
EIRP	Equivalent Isotropically Radiated Power
ERAM	En Route Automation and Modernization
FAA	Federal Aviation Administration
FDMA	Frequency Division Multiple Access
FCS	Future Communications Study
FEC	Forward Error Correction
FIS-B	Flight Information Services - Broadcast
FM	Frequency Modulation
FMS	Flight Management System
GHz	Gigahertz
GEO	Geostationary Orbit Satellite
HITL	Hardware-in-the-Loop
HCI	Human Computer Interface

HD	High Density
HI/OTL	Human In/On the Loop
HLA	High Level Architecture
Hz	Hertz
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
ICV	Integrity Check Value
IFR	Instrument Flight Rules
IP	Internet Protocol
JAA	Joint Aviation Authority
JIPT	Joint Integrated Product Team
JPDO	Joint Planning and Development Office
kBps	Kilobytes per seconds
LD	Low Density
LOS	Line of Sight
L&R	Launch and Recovery
LVC-DE	Live Virtual Constructive – Distributed Environment
M&S	Modeling and Simulation
MASPS	Minimum Aviation System Performance Standards
MHR	Sacramento Mather Airport, CA
MHz	Megahertz
MS	Mission Support (Pilot)
NAS	National Airspace System
NASA	National Aeronautics and Space Administration

NASA KSC	NASA Kennedy Space Center
ND	Network on FAA side and Direct to CS
NextGen	Next Generation Air Transportation System
NM	Nautical Mile
NN	Network on FAA side and Network to CS
NTSB	National Transportation Safety Board
NVS	NAS Voice Switch
OSED	Operational Services and Environmental Definitions
PIC	Pilot in Command
QPS	Quadrature Phase Shift Key
RCP	Required Communications Performance
R&D	Research and Development
RF	Radio Frequency
RNP	Required Navigation Performance
RTCA	Radio Technical Commission for Aeronautics
SC203 CC WG2	Control and Communications Working Group 2
STK	Satellite Tool Kit
TX/RX	Transmitter/Receiver
UA	Unmanned Aircraft
UAPO	Unmanned Aircraft Program Office
UAS	Unmanned Aircraft Systems
UHF	Ultra High Frequency
UP	Sacramento Mather Airport
VFR	Visual Flight Rule
VHF	Very High Frequency

WG2	Working Group 2
WRC	World Radiocommunication Conference

EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) is the authority that grants access into, and operations within, the National Airspace System (NAS) for all aircraft, including Unmanned Aircraft Systems (UAS). The safe operation of UAS in the NAS must be assured if the full potential of UAS is to be realized and supported by the public and Congress.

This report analyzed the communication systems that are needed for the safe operations of UAS in the NAS. Safe operations can be defined as the availability of the required links to carry the information to control the UAS and the return links to allow controllers to know where the UAS is at any given moment as well as how it is performing.

This report is the end result of work performed jointly between the FAA and National Aeronautics and Space Administration (NASA)/Kennedy Space Center (NASA KSC). The work was done in support of the Radio Technical Commission for Aeronautics (RTCA) Special Committee 203 (SC-203) Control and Communications Working Group. The RTCA is a federal advisory committee to the FAA. Though the work was not under the direction of the working group, a large part of the specific values used in the simulations came from the working group. Specifically, all of the radio links were modeled based on the formulation completed by the working group.

This report analyzed three scenarios from RTCA SC-203 that represent how a UAS would operate in the NAS. Each scenario was created using the Satellite Tool Kit (STK) modeling and simulation tool. The flight paths of the UAS were generated and the UAS dynamics were likewise modeled. Then each communication asset such as transmitters, receivers, and antennas were modeled and placed on the appropriate UAS, satellite, or Control Station (CS). After that, the radio links were analyzed for signal strength and antenna blockage, and the overall link performance was analyzed in detail. The goal was to obtain 99.9% availability on all of the radio communication links. In order to ensure the 99.9% availability, certain values for the telemetry transmitter will have to be increased slightly from 1 watt up to about 4 watts which is reasonable.

The results of this analysis show that it is possible to send commands, during the airborne segment, to the Unmanned Aircraft (UA) and have the UA send back the system health and status with high availability of at least 99.9% of the time. This 99.9% availability included the condition of heavy rain at 90 mm/hr as well as interference from adjacent satellites. The link budget values used in this report were based on the work from the working group.

1 INTRODUCTION

There is today a growing imperative for permitting widespread integration of Unmanned Aircraft Systems (UAS) in both domestic and global air traffic operations. UAS are being used in great numbers by defense organizations in war efforts, while civil and commercial entities are inundating federal agencies with requests for UAS certifications. The future air transportation system is projected to have great increases in both the number of manned and unmanned aircraft operations; however, the currently designed air transportation system cannot support the projected demand. In 2003 the United States Congress directed the establishment of the Joint Planning and Development Office (JPDO) to address the future projected demands on the air transportation system. The JPDO is responsible for facilitating and coordinating the planning and implementation of the Next Generation Air Transportation System (NextGen).

NextGen is focused on implementing advanced system changes to the National Airspace System (NAS) to increase capacity, efficiency, safety, and security. Because there are differences between manned aircraft and UAS regarding operations, procedures, and system characteristics, UAS do not comply with current aviation procedures and policies. Nor are NAS air traffic systems designed to incorporate special use cases of UAS regarding Sense and Avoid and Control and Communications systems.

In 2004, the FAA requested that the Radio Technical Commission for Aeronautics (RTCA), a private non-profit corporation that develops consensus-based recommendations regarding aviation, address standards development for UAS integration in the NAS, specify how UAS will sense and avoid other aircraft as they navigate, and finally specify how UAS will navigate and communicate. The RTCA responded and established RTCA SC-203 Unmanned Aircraft Systems, a new special committee.

Today, the FAA and National Aeronautics and Space Administration (NASA) Kennedy Space Center (NASA KSC) are performing the modeling and simulation (M&S) efforts for the Control and Communications Working Group, which was chartered under RTCA SC-203. Key architectures and operational concepts are being modeled to assess concepts and quantify specific parameters to aid the working group in developing UAS control and communications standards. The results of the analysis will help the RTCA to mature the UAS Minimum Aviation System Performance Standards (MASPS) into guidance material for the FAA and UAS industry, while maintaining compatibility with international aviation standards.

1.1 BACKGROUND

In 2003, in order to address the future projected demands on the NAS, the United States Congress directed the establishment of the FAA-led JPDO, which is responsible for facilitating and coordinating the planning and implementation of NextGen. The JPDO is an inter-governmental cooperative effort which includes the FAA, NASA, the Departments of Transportation, Commerce, Defense, Homeland Security, and the White House Office of Science and Technology Policy. NextGen leverages existing and emerging technologies to transform the national air traffic system to meet the projected future demands on the NAS. The technologies include satellite-based navigation systems, digital communications, net-centric operations, advanced automation systems, and substantially improved weather forecasting capabilities. NextGen must be designed to support increased capacity, efficiency, flexibility, and interoperability of manned and unmanned aircraft and aerospace systems, while providing increased safety and security.

Within the aviation community, interest in using UAS for a broad range of purposes has been rapidly increasing, making UAS access to the NAS a priority. Current requests for access to the NAS are subject to technical and operational assessments of the specific UAS operation in question based on interim approval guidance. UAS operations are subject to operational limitations when there is any perceived risk to the public. It is a growing imperative within the UAS community, including public and civil users, to reduce these restrictions and support more routine access in order to improve and advance integration of UAS into the NAS. To reduce these restrictions and permit widespread integration of UAS in the NAS, the FAA will have to establish national UAS requirements to ensure that UAS are able to operate safely in NAS alongside conventional civilian and defense aircraft.

For UAS control and communications, there are many issues that need to be assessed:

- How is a UAS pilot to communicate with Air Traffic Control (ATC) – satellites, terrestrial network systems, FAA system?
- How will ATC receive UAS aircraft identification and position data?
- What frequency bands will be specified, what is the capacity of the frequency band per number of UAS?
- What communication protocols should be utilized?
- What secondary communications should be specified?
- What encryption standards should be incorporated?
- What requirements should be incorporated on the future FAA NAS Voice System?
- What control and communication systems should be certified?
- What latencies, availability, continuity values permit safe reliable transactions?

The M&S efforts being performed by the FAA and NASA KSC seek to assess and quantify these issues which have been raised by the RTCA SC-203 Control and Communications Working Group. The concept of operations under analysis includes satellite navigation and control of aircraft, advanced digital communications, advanced automation capabilities of aircraft control, and enhanced communication connectivity between all NAS components.

The aviation community shares a common challenge, specifically how to incorporate UAS into highly-complex dense airspaces while maintaining the current level of safety. The aviation community is working together to migrate to a new operational paradigm inclusive of UAS Control and Communications concepts which are central to this new operational paradigm.

As the operational concepts are developed, the aviation community is synergistically ensuring common international standards that support increased capacity and interoperable operational concepts that enable the unencumbered growth of the air transportation system. The RTCA SC-203 Control and Communications Working Group is expected to finalize the control and communications MASPS in 2013, after the ratification of frequency decisions at the World Radiocommunication Conference (WRC) in 2012.

1.2 PURPOSE

Today, the FAA and NASA KSC are performing the M&S efforts for the Control and Communications Working Group which was chartered under RTCA SC-203. Key architectures and operational concepts are being modeled to assess concepts and quantify specific parameters to aid the working group in developing UAS control and communications standards. The results of the analysis will help the RTCA to mature the UAS MASPS into guidance material for the FAA and UAS industry, while maintaining compatibility with international aviation standards.

The RTCA SC-203 Control and Communications (CC) Working Group (SC203 CC WG2) requires M&S efforts to assess concepts and quantify various approaches. The working group selects the results to be incorporated into white papers that summarize the concepts under review. SC203 CC WG2 cannot finalize MASPS until the spectrum analysis is complete and the amount of spectrum assigned to UAS operations have been agreed upon. This decision will occur at WRC 2012.

The RTCA document DO-264, Guidelines for Approval of the Provision and Use of Air Traffic Services supported by Data Communications, provides guidance material for stakeholders and approval authorities involved in the operational implementation of the provision and use of ATS supported by data communications. There are four major DO-264 Required Communications Performance Parameters that will be included in MASPS: Availability, Integrity, Continuity, and Availability. The white papers are focused on developing realistic and achievable performance parameters for the yet to be designed Control and Communications Links.

The SC203 CC WG2 is working with other SC203 and international CC working groups to incorporate concepts into the common M&S environment, such as:

- Actively working with the Sense and Avoid (SA) WG, Systems WG, and Safety WG to develop a better understanding of required CC performance to support SA function
- Working with EUROCAE WG73 to ensure a synergistic approach to CC requirements and performance

1.3 SCOPE

The work described in this document is based on the RTCA document entitled Operational Services and Environmental Definition (OSED), #224-09/SC203-036 and on the inputs provided by SC203 CC WG2 on UAS control and communications. The OSED provides the informational basis for assessing and establishing operational, safety, performance, and interoperability requirements for UAS operations in the NAS. The OSED is identified as an artifact of DO-264 and is part of the coordinated requirements capture process.

The scope of the work during this current project term is to model the communication links of three OSED scenarios that represent the two architectures referenced in document RTCA SC203 CC005_UAS Control and Communications Architectures[1].

The communication links that are modeled are the control links to the UAS as well as the telemetry links from the UAS. This project term does not include specific modeling of voice links so this report does not encompass specific voice link data.

The goal is to define the communication links for both Line of Sight (LOS) links as well as Beyond Line of Sight (BLOS) links. The results will show how well the links perform during the dynamics of a flight for various aircraft under varying conditions.

1.4 STAKEHOLDER DESCRIPTION

The primary stakeholders for this report are the FAA, NASA, and the RTCA SC-203 Control and Communications Working Group. The RTCA SC-203 will utilize this report to formulate recommended UAS standards. The community of civil and DoD government UAS users, as well as UAS users from the public, and commercial and educational institutions will be the benefactors of the national UAS standards that the FAA will establish based on recommendations from RTCA SC-203.

1.5 METHODOLOGY

The FAA and NASA KSC M&S approach was to develop all RTCA SC-203 Operational Services and Environmental Definitions (OSED) scenarios for communications link modeling utilizing a common environment, specifically the Analytical Graphics, Inc. (AGI) Satellite Tool Kit (STK) application. The models are used to validate performance parameters developed in CC papers by running multiple simulations with varying system characteristics and environmental conditions. Feedback from M&S is used to refine performance values for use in assessments and MASPS. The M&S approach was to:

- Determine UAS system level requirements (UAS characteristics) as it relates to M&S
- Develop UAS M&S scenarios
    - The initial goal is to develop a simple M&S UAS CC scenario
    - Establish/validate a baseline with the M&S tool(s)
    - Build upon the baseline with additional complexity from the other architectures

Modeling is tied to specific requirements, definitions, and industry standards.

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[1] RTCA SC203-CC005. UAS Control and Communications Architectures, Version, Date: December 23, 2008.

The M&S effort analyzes and develops constructive, Monte Carlo, and other modeling techniques to baseline STK scenarios from RTCA SC203 CC WG2 to determine specific requirements, criteria, and events for M&S activities.

Examples of analysis to consider as it pertains to control and communications, include, but are not limited to:

- Access Time Duration and Gap Periods analysis
- Dynamic/link performance analysis (Link Budget, BER, etc.)
- System-level interference analysis
- Sub-system analysis
- Interference analysis
- Sense and Avoid analysis (future study)
- Developed constructive Monte Carlo and other modeling techniques (future study)

This M&S report describes the modeling and simulation efforts associated with SC203 concept architectures that support UA Control and Pilot Controller voice and data communications. Provided is a general overview of modeling and simulation activities expected to be used for the architectures set forth in the RTCA SC203-CC005_UAS Control and Communications Architectures document [2] which is depicted in the following figure.

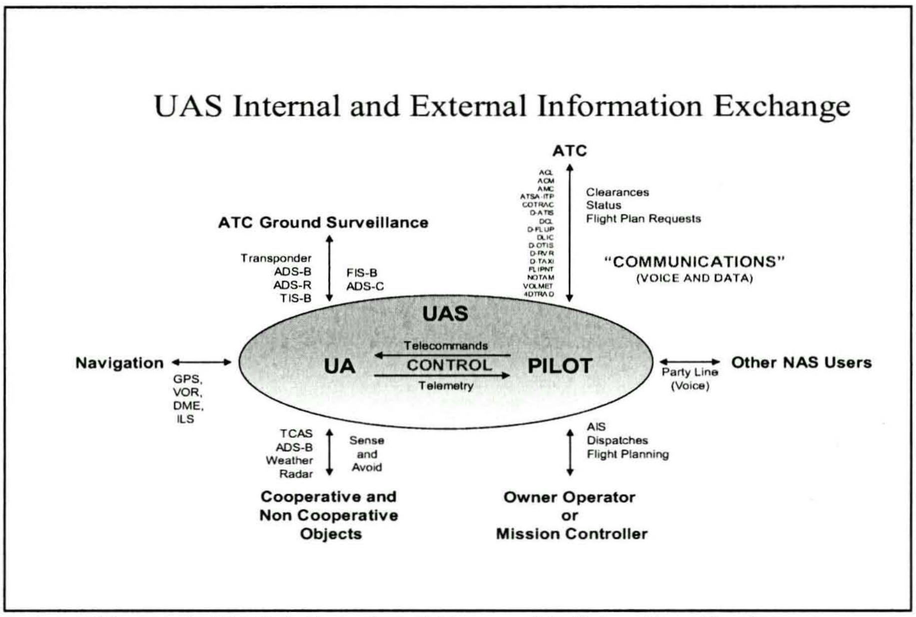

Figure 1: UAS Internal and External Information Exchange

Figure 1 is an overview of the Unmanned Aircraft System's (UAS) internal and external information exchanges that must be supported by any control and communications architecture. There are six external bi-directional interfaces as well as an internal interface between the UA and the UA pilot. The UA, UA CS, and the Control Link internal interface together comprise the UAS.

2 OVERVIEW OF UNMANNED AIRCRAFT SYSTEMS AND TYPES

This section is out of the Operational Services & Environment Definition (OSED) for Unmanned Aircraft System (UAS) document and bears repeating for readers not familiar with the contents[2].

Description/Abstract:

The OSED is a fundamental artifact of DO-264 that summarizes information collected under the Operational Services Environmental Information Capture (OSEIC) process. It provides a complete description of stakeholders, the operational characteristics of UAS, air traffic services associated with UAS operations, and the operational environment in which UAS operate. Because UAS designs and missions vary considerably, this OSED categorizes UAS on the basis of operational performance in order to aggregate, provide like characteristics and specificity as to the nature of UAS operations relative to NAS operational services and environments. The contents of the OSED are intended for reference in the development of DO-264 artifacts and may be modified or augmented based on the needs of those developing future artifacts and documents.

2.1 UAS DEFINITION

A UAS is comprised of the UA, its associated components, and the personnel required for operation. Two primary elements distinguish the UAS: 1) the operational system, or "UAS Element," comprises the aircraft, equipment, software, and persons involved in controlling and managing flight; and 2) the supporting system, or "Support Element," comprises the equipment, software, and persons involved in preparing, managing, and maintaining the system in pre- and post-operative phases. Descriptions of these elements and their respective segments are provided in subsections 2.2 and 2.3. Section 3 provides high-level descriptions illustrating the breadth and variation of UAS system architectures and UA types.

2.2 UAS ELEMENT

The UAS is comprised of three key segments (as follows and also illustrated in Figure 2):

- Aircraft Segment
- Control Segment
- Communications Segment

This report encompasses modeling the communication links between these three segments (i.e., modeling the control link to the UAS as well as the telemetry link from the aircraft). This report does not encompass specific modeling of the voice links.

[2] RTCA SC203 OSED Document No.: 224-09/SC203-036 Version 11, Date: October 23, 2009

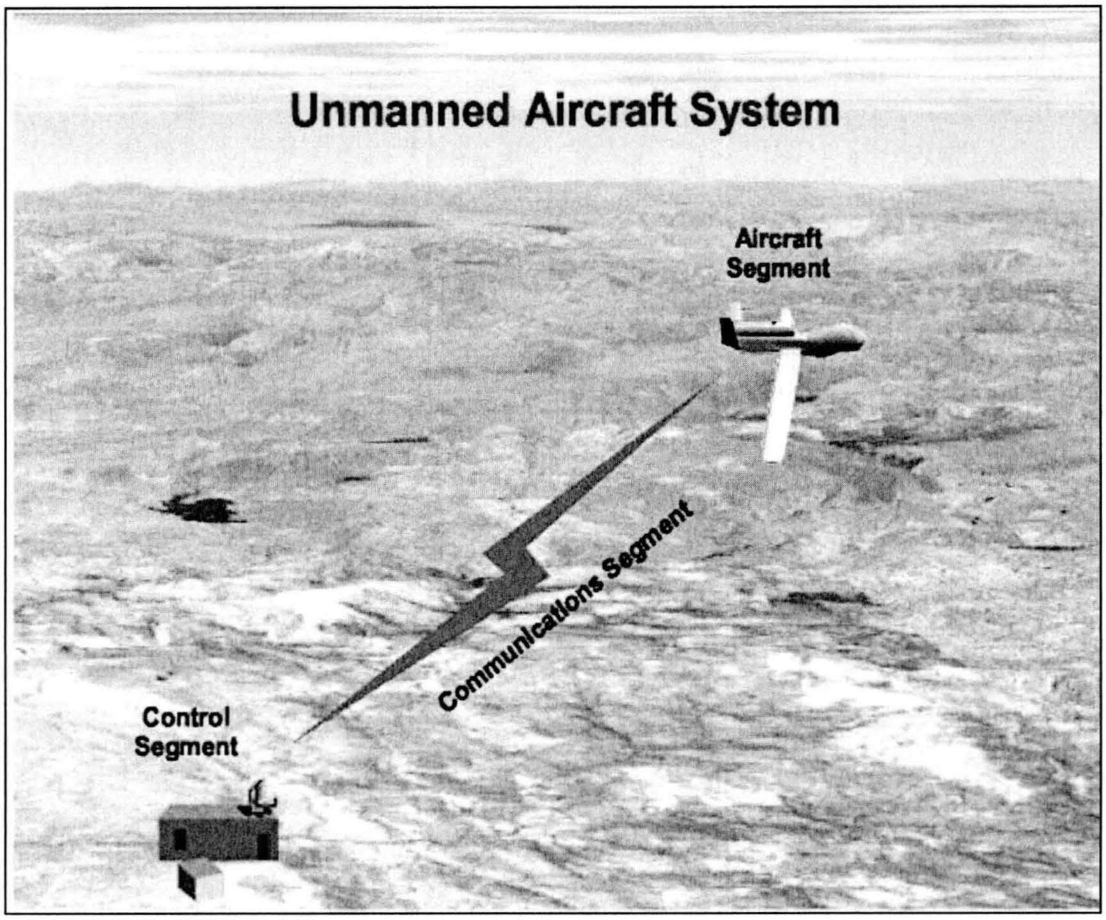

Figure 2: Unmanned Aircraft System

2.2.1 Aircraft Segment

The aircraft segment is referred to as the unmanned aircraft, or UA. A UA is defined in RTCA DO-304 as an aircraft operated without the possibility of direct human intervention from within or on the aircraft.

2.2.2 Control Segment

The Control Segment includes the components and persons necessary to control and manage UA operations in the air and at the launch/recovery sites.

2.2.3 Communication Segment

The Communication Segment is comprised of two primary communication links: 1) Telecommand & Telemetry and 2) Voice & Data. The telecommand communication uplinks flight control information to the UA and telemetry communication downlinks health and status information from the UA. The voice and data communications link refers to communications between and among the UAS, ATC, and other aircraft in the proximity of the UA.

2.3 SUPPORT ELEMENT

The Support Element, though not considered part of the three UAS segments, is a necessary component in initiating and terminating operations, and maintaining the UAS. The Support Element includes all persons, facilities, hardware, software, and equipment used to transport and prepare the UA for flight. Operational functions of the Support Element include preparation and communication of flight objectives and documents, training of personnel, maintaining UAS segments, and providing logistics support.

This report does not encompass specific modeling of the Support Element.

2.4 UAS TYPES

UAS features and capabilities vary widely. Current UA types range in size from several ounces to thousands of pounds. Many fly slowly and lack maneuverability.

The CS used to fly and monitor UA range from hand-held units to large conventional cockpit environments. These CS can be networked across multiple sites or can be placed aboard other aircraft.

Communication systems linking the CS to the UA range from simple electronic LOS to those capable of global reach using satellite relays.

This report encompasses three different types of unmanned aircraft the Raven, Cessna Caravan, and Predator.

2.5 SYSTEM ARCHITECTURES

Performance and functions of UAS can vary significantly based on their system architectures. These variations result from design tradeoffs among many variables such as operational need, cost, system integrity, technological maturity, risk tolerance, and environmental constraints. Understanding system architectures at both the system-level and subsystem-level provides insight as to how diverse UAS designs might interface with the external systems and operations in the NAS.

3 DESCRIPTION OF MODELED ARCHITECTURES

The RTCA SC203 CC WG2 proposed 10 architectures within the RTCA SC203-CC005_UAS Control and Communications Architectures document[2]. Since the 10 architectures had overlapping functionality, RTCA SC203 CC WG2 focused on architectures from each of the following categories: UA Control, UA Relay, and Non Relay. This report focuses on UA Control architectures. Scenario 1, 5, and 6 from the OSED document were selected for this report. Appendix A shows the mapping of all the OSED scenarios to the RTCA architectures. Sections 3.1 and 3.2 describe the two architectures selected for CC modeling.

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[2] RTCA SC203 OSED Document No.: 224-09/SC203-036 Version 11, Date: October 23, 2009

3.1 DIRECT CONTROL ARCHITECTURES LOS/BLOS

The Direct Control LOS architecture concept consists of a UA CS in direct communication using an LOS radio frequency (RF) radio link or a satellite link through a satellite system to a UA.

A typical radio linked flight would encompass a small UA, low altitude, short range operation (urban environment, surveillance, tracking, mapping etc.). Additional backup CS are considered for redundant RF links depending on the situation. A satellite link would extend the range of LOS to BLOS and provide redundancy to a LOS link.

3.2 NATIONWIDE NETWORK CONTROL

The Nationwide Network Control (C2N) architecture concept consists of a networked control architecture where the UA CS accesses a shared nationwide network maintained by a Communications Service Provider (CSP). The CSP, in turn, maintains an infrastructure of radio towers and (potentially) satellite earth stations which provide connectivity to the UA through a standardized protocol. The CSP network itself can be a combination of wired and wireless links as required. The LOS and satellite links can each be redundant or the LOS and satellite connections can be used together as a redundant pair, as required.

Section 3.3 provides a description of the three scenarios analyzed for this report.

3.3 SCENARIOS

Nine OSED scenarios were developed within STK and three scenarios (1, 5, and 6) were modeled with STK for in-depth analysis of the control communication systems. The LOS and BLOS links were analyzed within the three scenarios.

Sections 3.3.1 to 3.3.3 provide a description of the three scenarios. Scenario 1 uses LOS links only. Scenario 5 comprises LOS and BLOS links. There is one pilot that sends commands through two different CS connected by land lines. Scenario 6 is also comprised of LOS and BLOS links. There is only one CS and the LOS link is used primarily for takeoff and landing. Unplanned aerial operations are included within the scenario.

3.3.1 Scenario 1 - LOS Control

Scenario 1 consists of a direct control architecture between a mobile CS (stationary Police Cruiser) and a Raven UA within the Los Angeles (LA), California metropolitan area at 400 ft. MSL and a flight range approximately 19.5 miles (one way to intercept target).

The STK modeling tool, Terrain Model and Antenna Masking, was enabled to allow RF obstruction to occur, and to collect the subsequent data to analyze any RF degradation during the flight. The OSED document called for two control links (LOS) in this scenario to provide a level of redundancy. The placement of a backup CS was not specified so it was placed at the LA Police Department (LAPD) helicopter port, which includes an active Air Traffic Control Tower

(ATCT).Based on initial RF Access Gap Periods between the two links (Cruiser to UA and Command-2 to UA), an additional backup CS was added (Command-1) to close the Link.

Figure 3 provides a system level architecture/scenario overview. Note: The areas in yellow represent follow-on analysis.

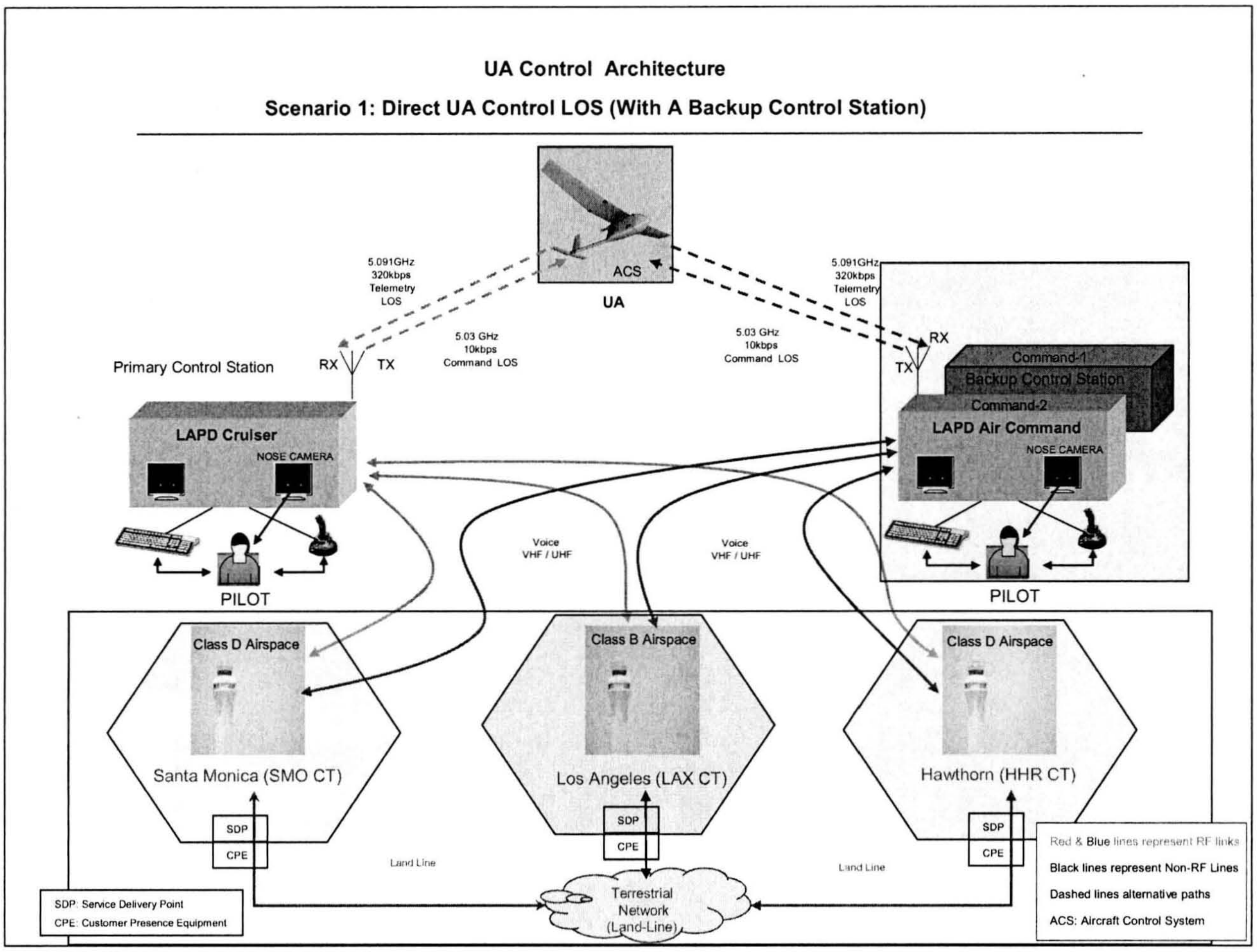

Figure 3: Scenario 1 - Direct UA Control LOS (Urban Surveillance)

3.3.2 Scenario 5 - LOS/BLOS Control

Scenario 5 depicted in Figure 4, examines the direct control architecture using a BLOS satellite link as the primary control between a Cessna Caravan air cargo delivery flight and the CS located in Bakersfield, CA. The scenario contains highly distributed operations and coordinative activities between ATC the PIC flying a traffic pattern at a non-towered airport.

The UAS in this scenario must comply with noise abatement procedures, lateral visual passing maneuvers, and perform a changeover from Visual Flight Rule (VFR) to Instrument Flight Rules (IFR). The most unique aspect of this scenario is that the primary CS makes use of a Mission

Support (MS) pilot who is not co-located in the same building. The flight is 440 nautical miles in length and the en route altitude is 7000 ft. MSL.

Figure 3 provides a system level architecture/scenario overview. Note: The areas in yellow in represent follow-on analysis.

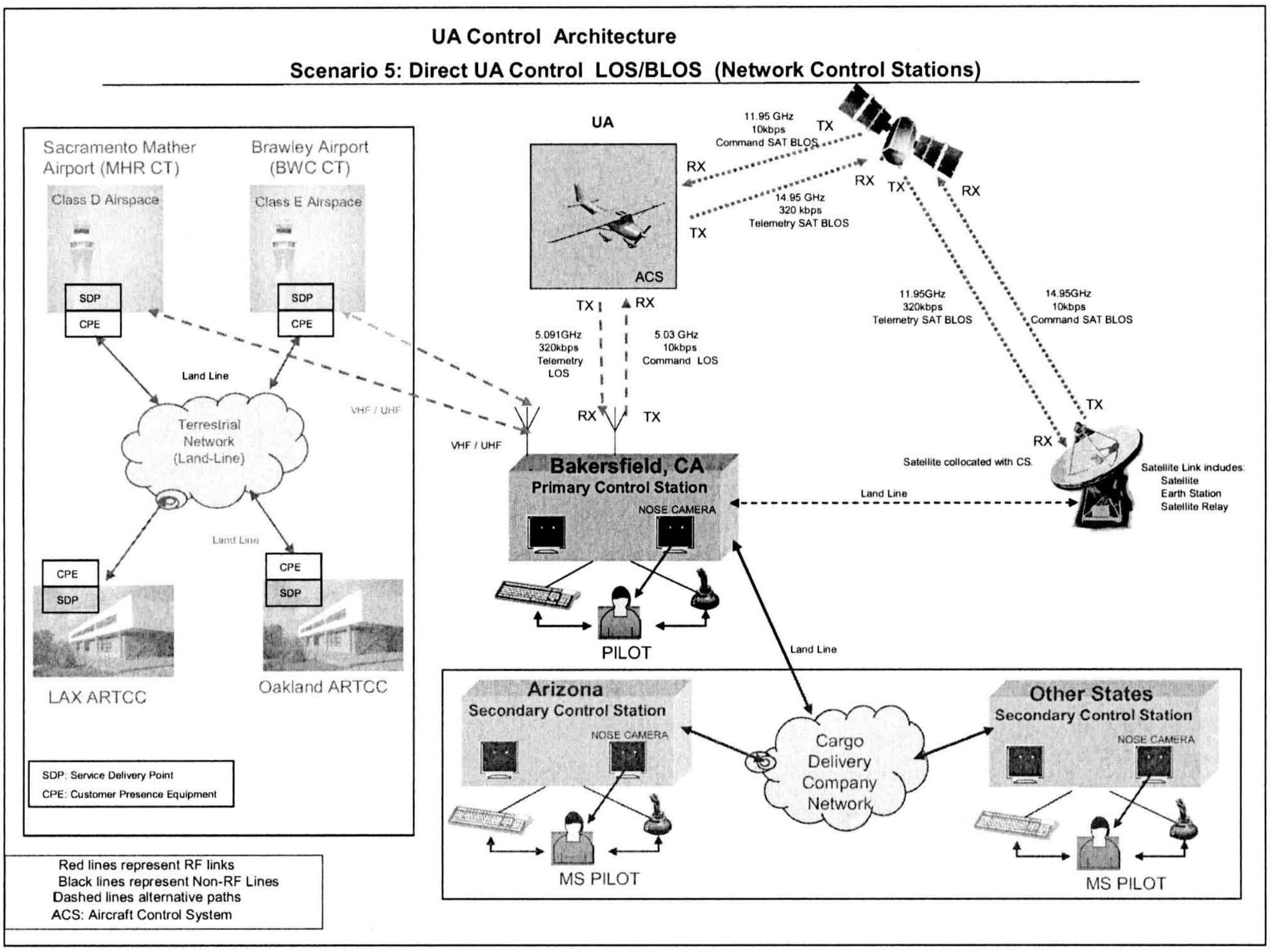

Figure 4: Scenario 5 - Direct UA Control LOS & BLOS (Cargo Delivery)

3.3.3 Scenario 6 - LOS/BLOS Control

Scenario 6 consists of both LOS and BLOS direct control architectures, as shown in Figure 5. The BLOS satellite link provides a redundant RF control link for the LOS between the UA CS and the Predator B. During this scenario the Predator B performs border surveillance and unplanned aerial work tracking border incursions on the northern border of the United States.

The STK Rain Model and Antenna Masking were configured within this scenario to allow RF obstruction to occur. Subsequently all RF degradation data was collected during the flight for use

during the analysis phase. The duration of the flight is approximately 10 hours at 20,000 ft. MSL, with lower altitudes for aerial maneuvers.
LOS links are used for takeoff, aerial work, and landing. BLOS links are active during the entire flight, however they are primarily used, as the name implies, when the UA is beyond LOS. Areas of interest covered by this scenario include IFR operations in controlled airspace, controlled airport operations, and unplanned aerial maneuvers in a dense en route air traffic environment.

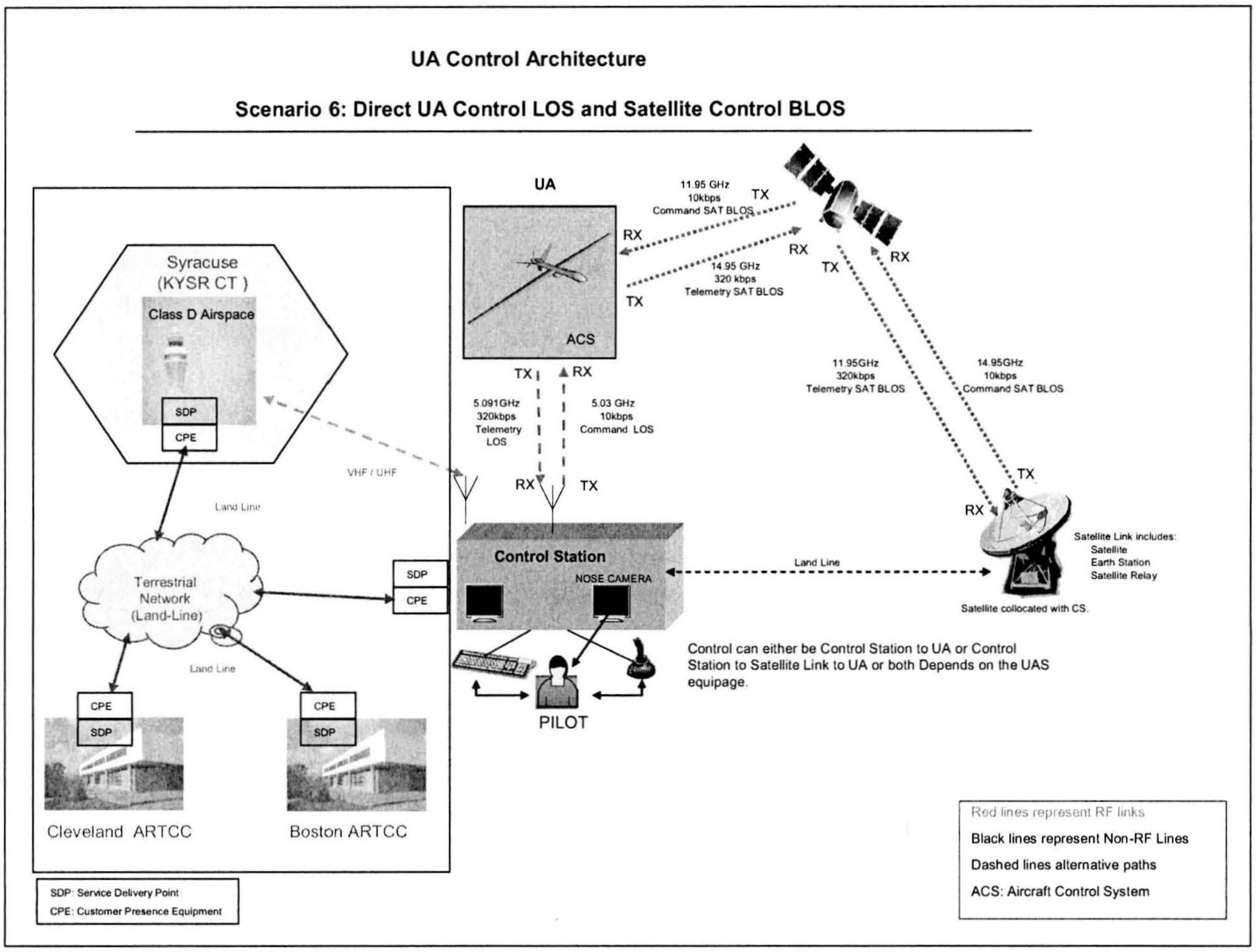

Figure 5: Scenario 6 - UA LOS & BLOS Border Patrol

4 OPERATIONAL CONCEPTS

Operational concepts for UAS are as varied as their systems. These variations result from a balance of considerations including mission needs, desired capabilities, risk tolerance, environmental conditions, economic costs/benefits, and rules governing operations.
Additional details can be found in the OSED document.

This report primarily focuses on modeling the UAS Control architectures associated with control and telemetry communication links between CS, UA, and satellites within the NAS.

4.1 COMMUNICATIONS SYSTEMS

UAS communication systems encompass LOS, BLOS, or terrestrial lines for Scenarios 1, 5, and 6. The ATC segments are not modeled in detail (TX/RX level) for this study but facilities were incorporated during the development of the models. Additional studies will account for ATC to UAS and other entities like Air Route Traffic Control Centers (ARTCC). Voice data as a hardware-in-the-loop element was not employed in this phase of simulation efforts.

The communication system modeled encompasses:

- Command Link
    - LOS: This is a 10 kBps link using a quadrature phase shift key (QPSK)
        - Two receive antennas on the UAS, top and bottom, configured in the middle of the plane. These are half hemispherical antennas
        - One Transmit antenna, directional to the UAS from the ground
    - BLOS
        - One UAS Directional Antenna up to a GEO Satellite
        - One Directional Receive Antenna on the GEO
        - One Directional Transmit Antenna on the GEO down to the UA
        - One Receive antenna on the UAS, top, configured in the middle of the plane. These are half hemispherical antennas
- Telemetry Link: This is a 320 kBps link using QPSK). This link uses the same antenna configuration as command but at different frequencies. The frequencies, power, and other link information is discussed in subsections of Section 6.5.

The communication system is made up of more than just the LOS and the BLOS links to and from the UA to the ground. Sections 4.1.1 to 4.1.4 describe additional elements to a communications system.

4.1.1 Telecommunications

This section requires future studies and will require in-depth investigation. Fast-Time modeling and simulation analysis will address current infrastructure terrestrial networks and future NextGen concepts specific to UAS voice, data, and video.

4.1.2 Mobile Communications

Mobile Communication is the CS within a mobile vehicle (e.g., Police Cruiser). A mobile unit can be stationary or moving. Scenario 1 provides an example of a stationary unit with an LAPD cruiser using mobile communications to control and receive telemetry between the UA, communicate to air traffic control, and provide backup communications to a control center in case of lost link on the primary control or telemetry link.

4.1.3 Satellite Communications

Satellite Communications provides the primary BLOS capability. Satellite communications for this report include:

- RF links between the satellite and satellite earth station
- A satellite relay link between the CS and satellite

4.1.4 Voice Communications

Voice communications are conducted between the CS and the ATC facility. There are different types of voice communications to consider:

- Direct RF link between CS to ATC
- A remote RF link between CS to ATC through the UA
- Terrestrial link (land-line)

Additional studies will address voice and data communications links between ATC to UAS.

5 FLIGHT PROFILES

A discussion of Flight Profiles is important because the three scenarios described in this report cover each one of the following flight profile descriptions. The following sections 5.1, 5.2 and 5.3 are excerpts from the OSED document.

Understanding how UAS intend to traverse the NAS is important in assessing compatibility with the Air Traffic Management (ATM) system and in characterizing UAS flights relative to other airspace users. This information is useful in developing collision encounter models and assessing safety risks associated with these flight profiles.

The flight profiles shown in this section represent generic operational behaviors of UA in the airborne environments. They are divided into three profiles: point-to-point, planned aerial work, and unplanned aerial work. Figures 6, 7, and 8 illustrate how each of the three UAS flight profiles must operate within the NAS.

5.1 POINT-TO-POINT

As illustrated in Figure 6, point-to-point UAS operations represent flights to an airfield or any other non-terminal area other than the departure airfield. Point-to-point operations are characterized by the direct nature of the flight and do not include aerial work or delays that may occur during the en route portion. For manned operations, point-to-point flights typically involve transport of passengers or cargo.

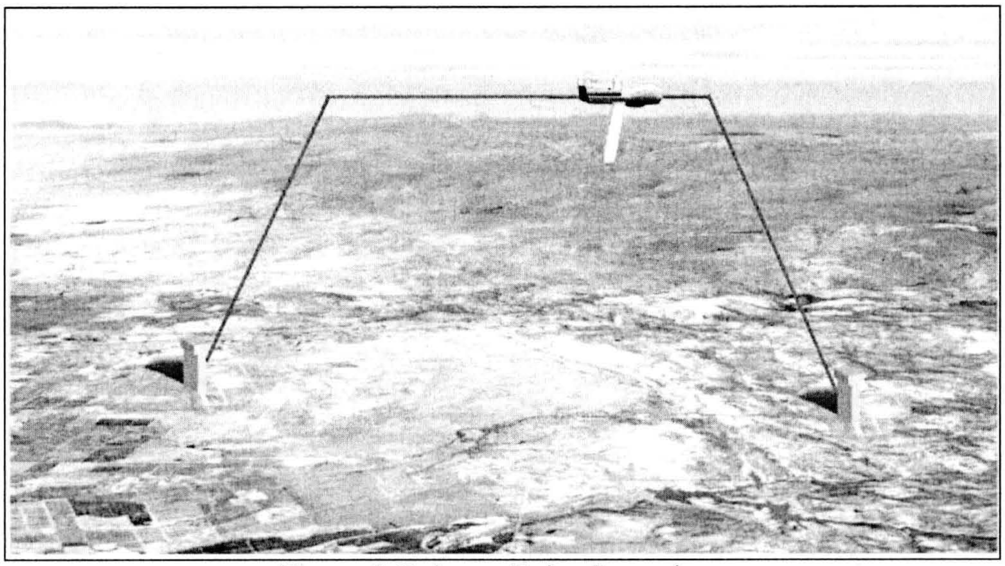

Figure 6: Point-to-Point Operations

5.2 PLANNED AERIAL WORK

As depicted in Figure 7, UAS planned aerial work operations generally refer to orbiting, surveillance, and tracking flights using pre-defined waypoints. Planned orbit operations, often referred to as "station keeping," are usually conducted for surveillance or communications relay. Planned tracking flights include surveillance of natural or political geographic features (such as shorelines, borders, buildings, roads, or pipelines). Orbiting and tracking operations occur using a range of UAS platforms within low, medium, and high altitude airspace and encompass VFR and IFR operations.

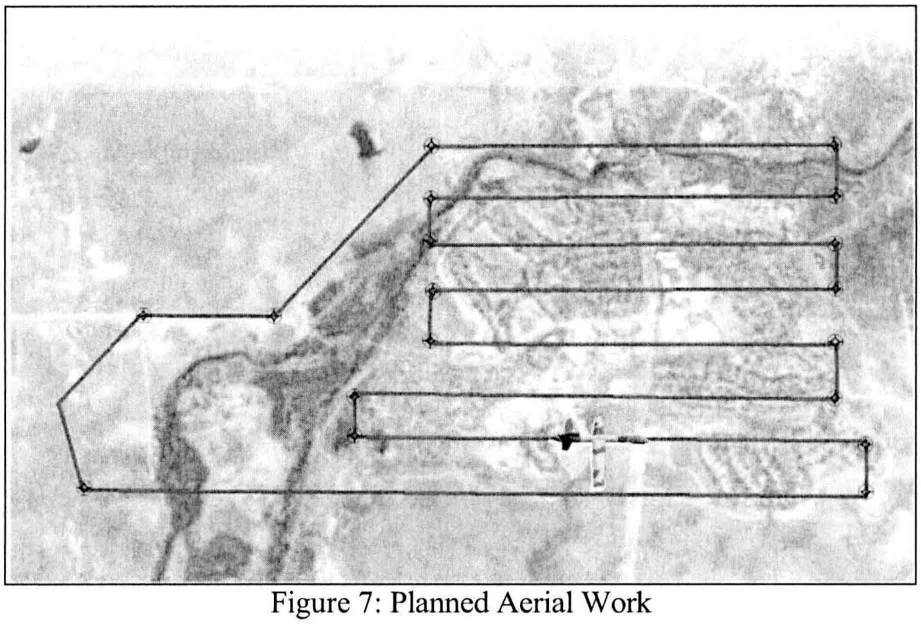

Figure 7: Planned Aerial Work

5.3 UNPLANNED AERIAL WORK

As depicted in Figure 8, unplanned aerial work operations are ad hoc in nature. Typical examples are tracking a ground vehicle or performing intermittent orbits to observe specific areas of interest. In such cases, UAS cannot predict their intended flight path but they can provide a general indication of their area of flight. For manned aircraft, these unplanned aerial work flights are usually conducted under VFR, though they can be accommodated in IFR depending on circumstances and a controller's workload ability to block airspace to allow these operations. ATC has the discretion to allow deviations for commercial activities but they may require cancellation of the IFR plan.

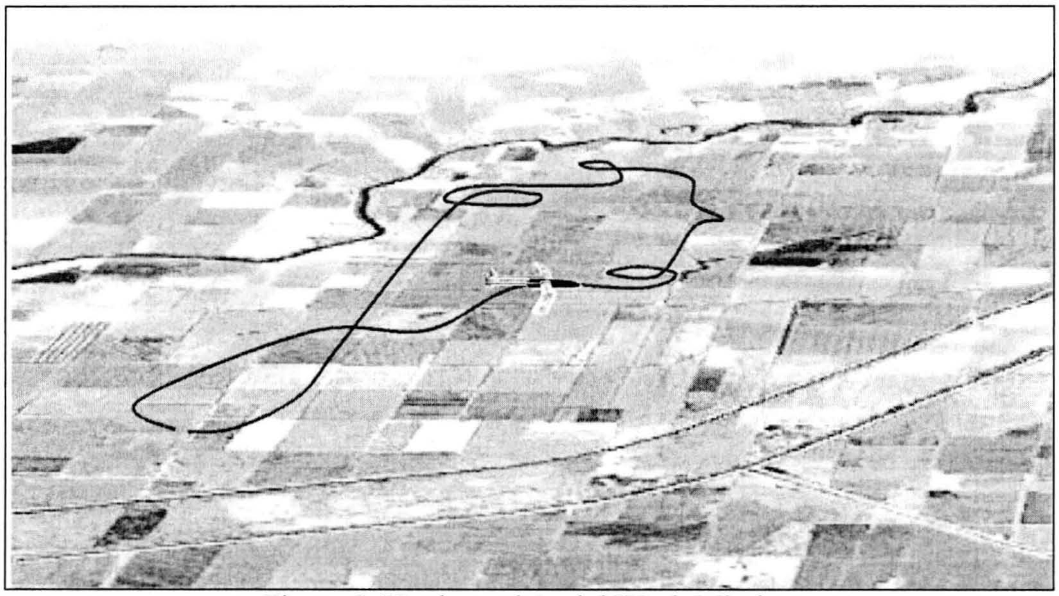

Figure 8: Unplanned Aerial Work Mission

6 MODELING AND SIMULATION

The FAA and NASA KSC M&S approach was to develop all RTCA SC-203 OSED scenarios for communications link modeling utilizing a common environment, namely the Analytical Graphics, Inc. (AGI) Satellite Tool Kit (STK) and Scalable Networks Technologies QualNet application. QualNet provided enhance network-modeling capabilities to STK.

The models are used to validate performance parameters developed in CC papers by running multiple simulations with varying system characteristics and environmental conditions. Feedback from M&S was used to refine performance values for use in assessments and MASPS. The next sections describe the M&S work effort which employed the two products as well as input from SC203 CC WG2 members.

6.1 APPROACH

Nine scenarios were modeled with STK's Mission Modeler. Three scenarios were modeled for in-depth analysis of the communication systems within this document including LOS links and BLOS Satellite links. After meeting with RTCA SC203, it was determined that the nine scenarios were more along the lines of how a UAS is to fly within the NAS, and only the control architectures were important for analyzing communications at the time. Thus only Scenarios 1, 5, and 6 were fully analyzed for the communication systems.

6.2 SCOPE

Within the three scenarios Link Budget, Access Time, Gap Period (LOST link), and Rain Attenuation on both LOS and BLOS links were fully analyzed.

Further analysis was conducted for interference from adjacent satellites in the BLOS scenarios 6. See Figure 58 for interference analysis for BLOS command link between the UA and GEO satellite.

6.3 SATELLITE TOOL KIT

STK is a high fidelity fast-time modeling and mission analysis application and software development kit for engineers and analysts. STK models complex systems and sub-components associated with (e.g., UAS, manned aircraft, satellites, ground vehicles, launch vehicles, and radar systems). STK includes extensive report and graph functions and the ability to export data to Excel.

STK is based on industry standard environmental models (e.g., Rain Model ITU-RP618-9, Terrain Integrated Rough Earth Model- TIREM 3.20) adds increase fidelity to the calculation and dynamic modeling of point-to-point and line-of-sight effects for link performance in STK/Communications. TIREM accounts for the effect of irregular terrain, sea water, and non-line-of-sight effects. TIREM also predicts radio frequency propagation loss over irregular terrain and seawater.

For this project, the following STK modules were utilized: Communications, Aircraft Mission Modeler, TIREM (Terrain), and Rain. The Communications and Aircraft Mission Modeler modules are described in further detail in the Sections 6.3.1 to 6.3.4 as well as antenna applications within the STK environment.

6.3.1 Communications

STK/Communications empowers users to define and analyze detailed communications systems; generate detailed link budget reports and graphs; visualize dynamic system performance in 2D and 3D windows; and incorporate detailed rain models, atmospheric losses, and RF interference sources in their analyses. This module uses TIREM, an industry standard for RF propagation, as well as Terrain.

6.3.2 Aircraft Mission Modeler

The Aircraft Mission Modeler propagator for the aircraft object is a premier tool for performing complex, highly accurate, time-based mission analysis for aircraft operations. Aircraft Mission Modeler features a rapid mission modeling tool that allows users to model specific mission requirements quickly and easily using either the step-by-step GUI interface or the 3D object editor. Utilizing aircraft specific characteristics, Aircraft Mission Modeler produces realistic flight paths based upon empirical, airframe-specific deterministic models. In addition to the default aircraft models included with the install, users can customize and add models as necessary to fulfill their needs. Table 1 contains the data used in each UA model.

Table 1: UA Performance Models

Basic UA Performance Model (3D Model File)					
Description	**Value**	**Description**	**Value**	**Description**	**Value**
Acceleration Built-In Model		***Climb Built-In Model***		***Landing Built-In Model***	
Basic		Ceiling Altitude	25,000 ft	Landing Speed	100 nm/hr
LEVEL TURNS		Airspeed	180 nm/hr	Sea Level Ground Roll	1 kft
Turn G	1.1547 G-Sea Level	Altitude Rate	2000 ft/min	Use Aero/ Propulsion Fuel Flow	Not Specified
Bank Angle	30 deg	Fuel Flow	500 lb/hr	Fuel Flow	500 lb/hr
Turn Acceleration	11.3237 m/sec^2	Initial Level Off for Acceleration	Not Specified	***TAKEOFF BUILT-IN MODEL***	
Turn Radius	Not Specified	Relative Airspeed Tolerance	Not Specified	Takeoff Speed	100 nm/hr
Turn Rate	Not Specified	***CRUISE BUILT-IN MODEL***		Sea Level Ground Roll	1 kft
CLIMB AND DESCENT TRANSACTIONS		Ceiling Altitude	25,000 ft	Departure Speed	150 nm/hr
Pull Up G	1.1547 G-Sea Level	Default Cruise Altitude	10,000 ft	Takeoff Climb Angle	3 deg
Pull Over G	0.75 G-Sea Level	Airspeed	Not Specified	Use Aero/ Propulsion Fuel Flow	
ATTITUDE TRANSACTION		Use Aero/ Propulsion Fuel Flow	Not Specified	Accel Fuel Flow	500 lb/h
Roll Rate	20 deg/sec	Minimum Airspeed	80 nm/hr	Departure Fuel Flow	500 lb/h
AOA/Pitch Rate	10 deg/sec	Minimum Flue Flow	600 lb/hr		
Sideslip/Yaw Rate	20 deg/sec	Maximum Airspeed	250 nm/hr		
AERODYNAMICS		Maximum Flue Flow	600 lb/hr		
Strategy	Not Specified	Maximum Endurance Airspeed	140 nm/hr		
Aircraft Operating Mode	Not Specified	Maximum Endurance Fuel Flow	400 lb/hr		
Lift Factor	1	Maximum Range Airspeed	180 nm/hr		
Drag Factor	1	Maximum Range Fuel Flow	500 lb/hr		
PROPULSION		***Descent Built-In Model***			
Strategy	Not Specified	Ceiling Altitude	25000 ft		
Speed Changes		Airspeed	180 nm/hr		
Max Thrust Acceleration	0.5 G-Sea Level	Altitude Rate	-2000 ft/min		

Max Thrust Deceleration	Not Specified	Use Aero/ Propulsion Fuel Flow	
Density Ratio Exponent	Not Specified	Fuel Flow	500 lb/hr
Thrust Factor	1	Initial Level Off for Acceleration	Not Specified
Fuel Factor	1	Relative Airspeed Tolerance	Not Specified

6.3.3 Antenna

Antennas are a key component of any communication system. Within STK, there is an ability to put antennas on aircraft and then model the masking of the airframe on the antenna. This was done for all three scenarios analyzed. The antenna used on the UA was a simple half hemispherical antenna. Two antennas were placed, one on top and one on the bottom, for LOS links. For BLOS links, a high gain antenna was used and was pointed toward the satellite. Likewise, the antenna placed on the satellite was a high gain antenna pointing to the UA. The CS also had a directional antenna pointing to the UA.

6.3.4 Antenna Mask

Antennas placed on any UA will be blocked due to the masking of the aircraft body on the antenna pattern. STK can calculate this masking and "block" out any communications from the antenna to the other end of the communication link. Figure 9 shows the mask of the top antenna (red) and the bottom antenna (yellow).

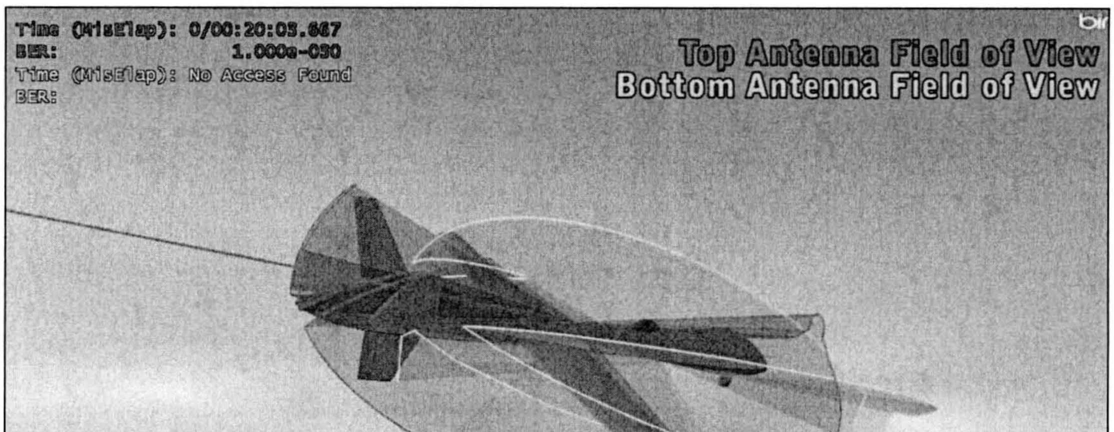

Figure 9: Top and Bottom Antenna Mask

6.4 QUALNET

QualNet is a network simulation tool that simulates wireless and wired packet mode communication networks. QualNet is used in the simulation of ground networks, satellite networks, and sensor networks among others. QualNet has models for common networks. Its primary use in this simulation was to determine data delays and packet dropouts. QualNet M&S was limit do to the extent of STK Air to Ground Analysis.

6.5 RADIO LINK BUDGET

Successful design of radio links involves many factors. A top level link budget analysis is a straightforward exercise and is the first step in determining the feasibility of any given radio system. A link budget calculation is a means to understand the various factors which can be traded off to realize a given cost and level of reliability for a particular communication system. The analysis was done for QPSK modulation with convolutional coding. Energy per bit over noise power spectral density (Eb/No) is how much energy is needed for a specific modulation at a specific BER. This is shown graphically in Figure 10 below. For the required BER of 10^{-5}, the Eb/No is 6.5 dB.

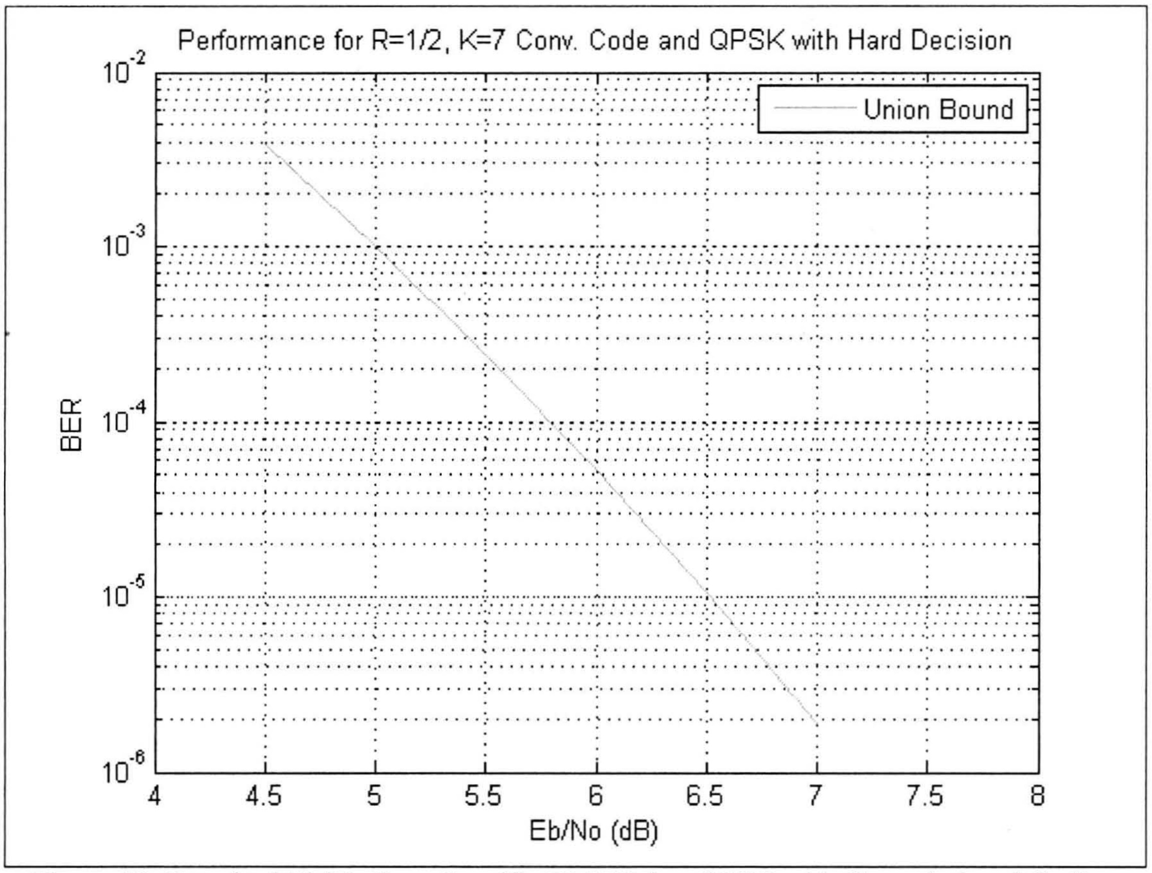

Figure 10: Required Eb/No for a Specific BER Using QPSK with Convolutional Coding

The LOS Link Margin, depicted in Table 2, is calculated for a 25 nm range. This value was used in the RTCA document on availability [3] and therefore was used in this analysis. The results of the link analysis below show a total excess margin of 18.5 dB for ground to UA and 6.5 dB for UA to ground.

Table 2: Link Margin for LOS

	Command	Telemetry
	Ground to UA	UA to Ground
Transmit Power (dBm)	30	32
Transmit Antenna Gain (dB)	28	-10
Transmit Cable Loss (dB)	-2	-2
Transmit EIRP	56	20
Path Loss (dB) (5 GHz, 25 NM)	-138	-138
Atmospheric Loss Margin (dB)	0	0
Multipath Loss Margin (dB)	-20	-20
Receiver Antenna Gain (dB)	-10	28
Receiver Cable Loss (dB)	-2	-2
Received Signal Power (dBm)	-94	-92
Thermal Noise @290 K	-174	-174
Receiver NF (dB)	2	2
Receiver BW (dBHz) (20khz &320Khz)	43	55
Receiver Noise Power (dBm)	-129	-117
Carrier-to-Noise Ratio (C/N)(dB)	35	23
Implemented Loss Margin	-4	-4
Safety Margin (dB0	6	6
Required C/N (dB) with Convolution Code	12.5	12.5
Excess Margin (dB)	18.5	6.5

Table 3 shows the link budget for the BLOS links. The BLOS link is different than the LOS link since it has two hops (subsequent steps along the satellite RF path from source to destination) for each of the links, command and telemetry, which are: CS to satellite, satellite to UA for command, and then the reverse path for telemetry. As to be expected, the link from the ground station, with a large antenna, is more robust than the link from the satellite to the UA. The excess margin is 21.2 dB for the ground to satellite and a -0.65 dB excess margin for the satellite to UA. This -0.65 dB would barely lower the BER of 10^{-5}.

Table 3: Link Margin for BLOS Command

	Command 14 GHz	Command 11GHz
	Ground to Satellite	Satellite to UA
Transmit Power (dBm)	21.5	9.2
Transmit Antenna Gain (dB)	59.1	38.2
Transmit Cable Loss (dB)	-2.14	-3.86
Transmit EIRP	78.46	43.54
Path Loss (dB) (5 GHz, 25 NM)	-208.46	-207.17
Atmospheric Loss Margin (dB) Rain	0	0
Receiver Antenna Gain (dB)	39.3	40.08
Receiver Cable Loss (dB)	-1	-0.5
Received Signal Power (dBm)	-91.7	-124.05
Thermal Noise @290 K	-174	-174
Receiver NF (dB)	11.6	1.1
Receiver BW (dBHz) (20khz & 320Khz)	43	43
Receiver Noise Power (dBm)	-119.4	-129.9
Carrier-to-Noise Ratio (C/N)(dB)	27.7	5.85
Implemented Loss Margin	0	0
Required C/N (dB) with Convolution Code	6.5	6.5
Excess Margin (dB)	21.2	-0.65

Table 4 is the link margin for the telemetry link of BLOS. The excess margin is 11.88 dB for the UA to satellite and 15.14 dB for the satellite to CS.

Table 4: Link Margin for BLOS Telemetry

	Telemetry 14GHz	Telemetry 11GHz
	UA to Satellite	Satellite to CS
Transmit Power (dBm)	38.9	17.62
Transmit Antenna Gain (dB)	39.67	38.2
Transmit Cable Loss (dB)	-4.17	-2.17
Transmit EIRP	74.4	53.65
Path Loss (dB) (5 GHz, 25 NM)	-209.55	-206.51

Atmospheric Loss Margin (dB) Rain	0	0
Receiver Antenna Gain (dB)	39.7	57.6
Receiver Cable Loss (dB)	-4.17	-1
Received Signal Power (dBm)	-99.62	-96.26
Thermal Noise @290 K	-174	-174
Receiver NF (dB)	1	1.1
Receiver BW (dBHz) (20khz &320Khz)	55	55
Receiver Noise Power (dBm)	-118	-117.9
Carrier-to-Noise Ratio (C/N)(dB)	18.38	21.64
Implemented Loss Margin	0	0
Required C/N (dB) with Convolution Code	6.5	6.5
Excess Margin (dB)	11.88	15.14

6.6 ASSUMPTIONS

This report details the communications links of UAS in the NAS. This is a complicated system. This report does not analyze the exact communication system as it is implemented today. Real world modeling is very complex and time consuming. This report spanned an effort of about six months, which is a short time for an effort of this magnitude. Thus, some details were assumed instead of fully modeled. An addendum to this report will be published as more detail analysis is conducted.

Assumptions for this report are as follows:

- Antenna Pattern was modeled as an ideal 3 dB gain antenna
- All antenna locations were placed on top and bottom center of the UA
- The link budgets were modeled with a -10 dB gain for worst case nulls. Further modeling will be using real work antenna patterns; this work has already been started
- All three planes were modeled with the same flight dynamics. This is a time-consuming process and for this report the authors did not think the flight dynamics would change the communications links
- Ground Networks were the hardest to model due to the tools not being available at first and then not being robust enough. Upgraded tools are being looked into in order to do a better job on the ground networks
- Voice Communication was not modeled at all. Voice Communication will be modeled in a future study.
- This report will take a high level discussion of delay
- For modeling the network data, a constant bit rate was assumed at 4.137 kBps
- The link budgets are based inputs from the RTCA SC203 CC Working Group-2 paper: "UAS Control and Communications Link Performance – Availability" [3]
- Rain rates used were none, 20 mm/hr, and 90 mm/hr.

[3] RTCA SC203 Doc. No.: CC203-CC016_UAS_Control and Communications Link Performance-Availability, Ver.: D, Date: April20, 2009

- Presence of interference from an adjacent satellite at different degrees away: 0.5 degrees, 1.0 degrees 1.5 degrees, and 2 degrees
- The placement of the antenna locations for this study does not reflect actual UA manufactures antenna locations, antenna specifications, radio configurations and UA performance characteristics. The study was to establish an initial baseline and validate inputs provided from the RTCA SC203-CC working group-2 for Fast-Time Modeling and Simulation (M&S) activities.

6.7 METRICS

This report is all about link margins; thus, we are measuring the ability of the pilot on the ground to send electronic commands to the UAS and the UAS to send back health and status to the pilot. What we "measure" is the ability of these electronic signals to get through in a timely manner.

The following metrics were utilized:

- Antenna Gains
- Transmit Power
- Receive Power
- Delays
- Modulation
- Data Rates
- Rain Rates
- Weather
- Interference
- Reliability

6.8 LIMITATIONS

Though modeling and simulation show very good results, modeling radio communications has many variables that are not being considered such as refraction of the UAS body and multipath, which are too complex to model in a timely manner. In most radio communications modeling, a link margin is added to compensate for these items that cannot be modeled very well. Thus, for land mobile communications, there is an additional 30 dB added to the link for margin. The following links have 20 dB for the ground to UAS links. Satellite to stationary ground links are very well understood and usually only have a margin of a couple of dB.

Another limitation is the handoff from LOS to BLOS or links between UA and multiple control stations. This report does not cover these types of situations. Handoffs are important because there are human in the loop delays that could influence the delivery of command and control signals to an UA. Example of this type of delays is the intentional had-off between two control station creating an actual lost link. (e.g., Time CS-1/PIC drops the control frequency to the time CS2/PIC acquires the link with both control stations using the same control frequency. It is possible to model this type of scenario within Fast-Time and include human delays within the results. Further investigation is required to determine the different types hand-off within the UAS, human delays and delay values.

7 REPRESENTATIVE SCENARIOS

OSED scenarios are summarized in this section. The M&S analysis for the communication links are depicted with accompanying analysis summaries.

7.1 SCENARIO 1 LAW ENFORCEMENT

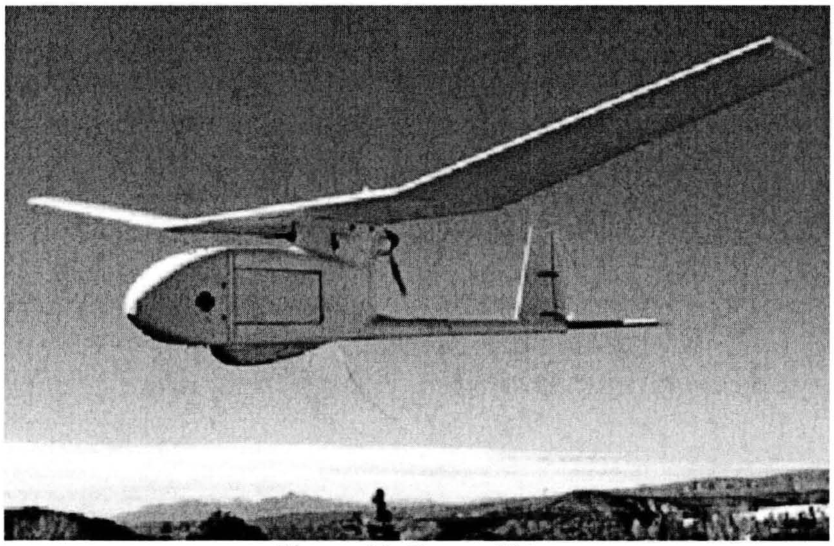

Figure 11: Raven UA

OSED Scenario 1 describes the application of a small, hand-launched Raven UA (Figure 11) to support a police operation in the Los Angeles area. The UA is integrated into a specially equipped UAS Air Unit police cruiser. The officers (pilot and support personnel) are trained in the UA launch, recovery, and operations, including communication with ATC. In this scenario, police in the Los Angeles area are called to investigate a suspect car observed leaving a crime scene. The car was last seen near Culver City heading toward the on ramp southbound on the 405 San Diego Freeway. Officers in a UAS Air Unit cruiser inform dispatchers that they will launch their UA to begin assisting in the search.

7.1.1 Flight Overview

Figure 12 shows the path of the Raven UA in the Los Angeles area.

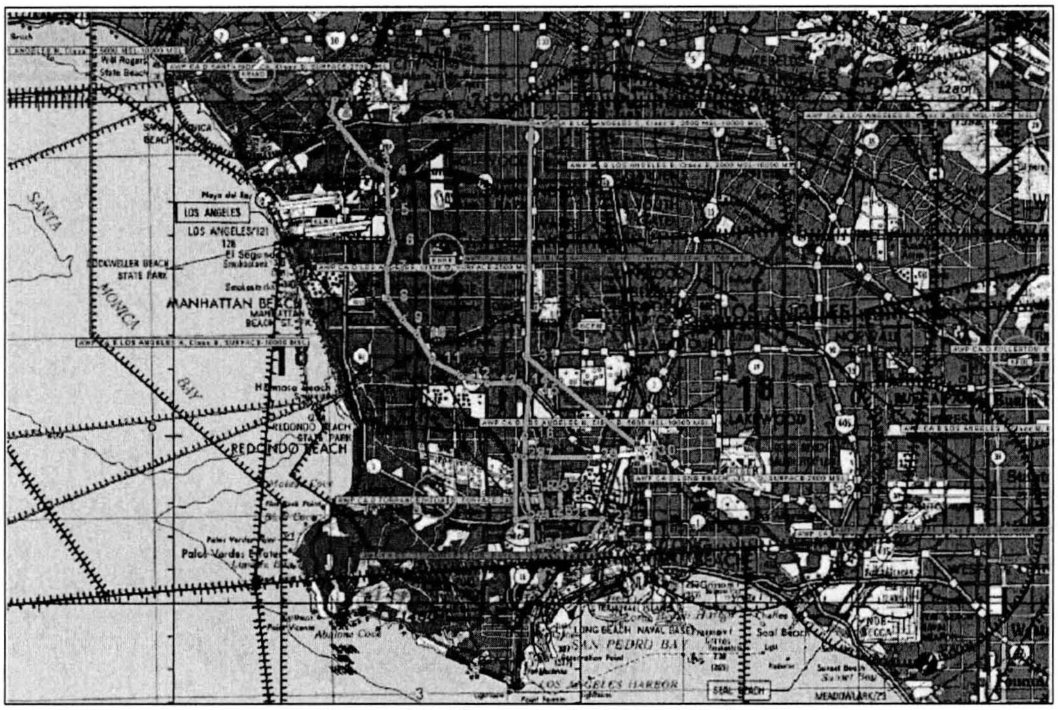

Figure 12: Scenario 1 - Flight Path

7.1.2 UA Description

The UA weighs 4.2 pounds, is electrically-powered, and operates at speeds between 30 and 70 knots. It is capable of 1.5 hours endurance. The aircraft is designed for GPS waypoint or manual flight path management and the autopilot provides continuous auto stabilization and prevention of exceeding all flight envelope limitations. The control station is integrated into the police cruiser and has a backup control station (at the central police station), if needed, for contingencies or more distant operations. A portable control unit is also stowed on the cruiser. The UA has geographic data encoded into the navigational system permitting the pilot to know the position of the UA at all times in relation to its surroundings to enhance situational awareness.

7.1.3 Scenario 1 - Setup

Figure 13 shows the Scenario 1 - UA Control Architecture. This is an LOS scenario only, and there is no BLOS link. The commands are to be sent from the Los Angeles Police Department cruiser and as the UA travels away from the cruiser a backup CS will be used. When running the scenario, it was found that there were large holes in the communication between the CS and the UA. A third CS was added and there was coverage during the whole scenario. The effect of rain on the link margin is determined with 0mm/hr rain, 20 mm/hr rain, and 90 mm/hr rain.

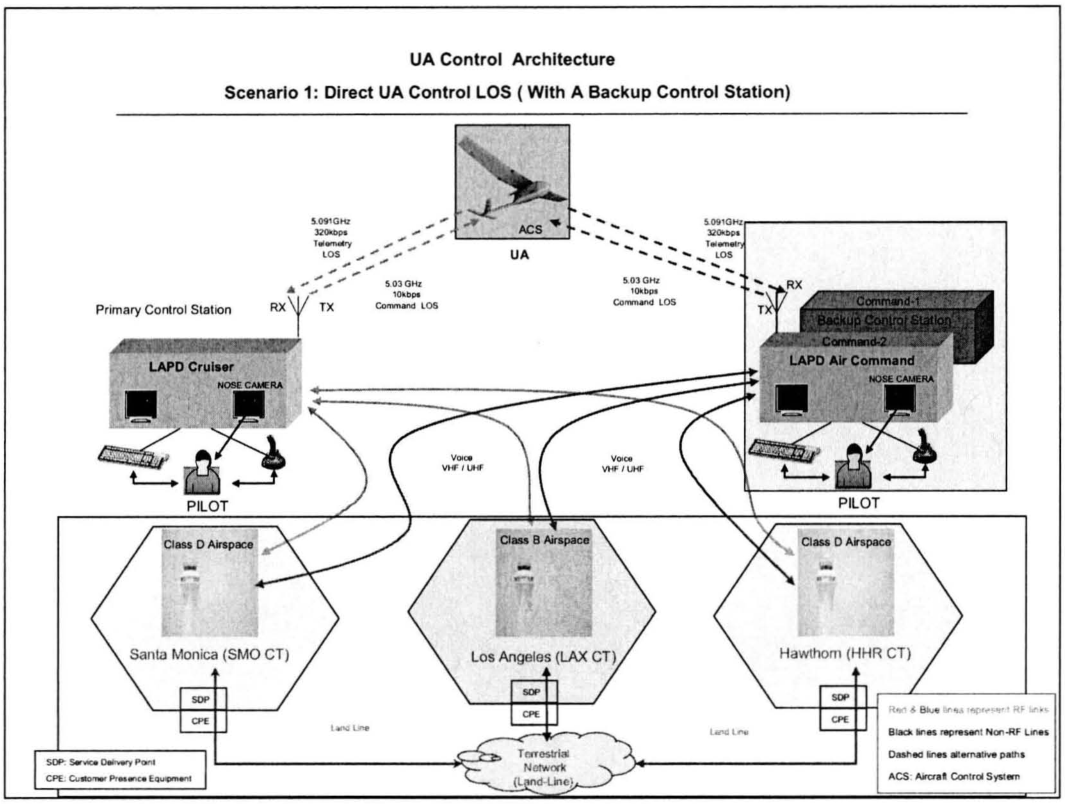

Figure 13: UA Control Architecture - Scenario 1 - Direct UA Control LOS (with Backup CS)

For LOS link margin needs to be 12.5 dB. This includes 6.5 dB for demodulation of the signal and another 6 dB for safety margin. The safety margin is needed to account for the various fluctuations of the RF link over time on a ground to aircraft link. The 6.5 dB for demodulation relates to a 10^{-5} bit error rate. As long as the Eb/No stays above 6.5, the signal will be properly demodulated.

For BLOS, the Eb/No needed is 6.5 dB without the safety margin. The safety margin is not needed from/to the GEO satellite since there are not as much fluctuations in the RF link along this path.

Scenario 1 has 22 graphs. The graphs are presented in the following:

- LOS command top antenna no rain, rain at 20mm/hr, and rain at 90 mm/hr.
- The rain was analyzed for 99.9% availability with rain rated of 0 mm, 2 mm and 90 mm at a height of 5 km.
- LOS command bottom antenna, then the combined antenna top and bottom for command and the combined antenna pattern for the Telemetry.

Note: All graphs have these rain values except the section on Interference.
Note: What is of interest for the reliability of the link for the combined antenna pattern but is how each antenna performed individually. The antennas were placed on each aircraft in the middle (top and bottom) locations on the plane.

7.1.4 Scenario 1 - LOS

The graphs shown in Figure 14, Figure 15, and Figure 16 show the command link from CS1 to the UA. Note: each graph title uses the word vehicle to reference the UA. The top antenna had a dropout as the UA was flying toward CS1 and the bottom antenna had a dropout as the UA was flying away from the CS1. This is due to three conditions between the UA and CS1, the geometry of the antenna placement, the configuration of the UA in flight, and the ground location of CS1. The combined antenna pattern shows no overall dropouts. The signal strength on this link overall was very high for the top and bottom antenna even for the three different rain rates.

This scenario is only 19 miles maximum LOS from when the UA takes off to its furthest point away from any CS. The graph below starts off with the UA 13 NM from the CS1 and flies closer to CS1 and then flies away from the CS1. In comparing these charts with the link budget calculated in Section 6.5, there is excess gain due to the UA flying closer to CS1 during flight. The link margins were calculated for 25 NM with a 20 dB multipath loss margin.
Note: The graphs below and in the next sections for the other scenario do not account for the 20 dB multipath loss margin. Thus, the graphs in general show higher signal strength except as noted.

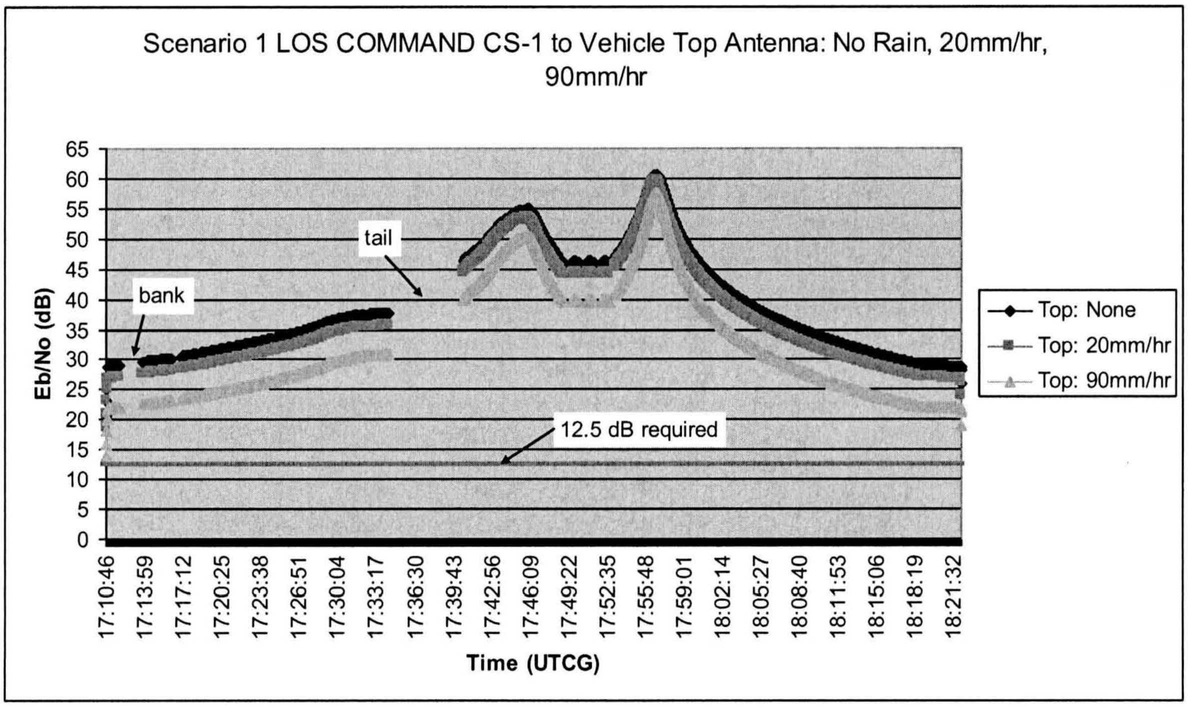

Figure 14: Scenario 1 - LOS COMMAND CS-1 to UA Top Antenna

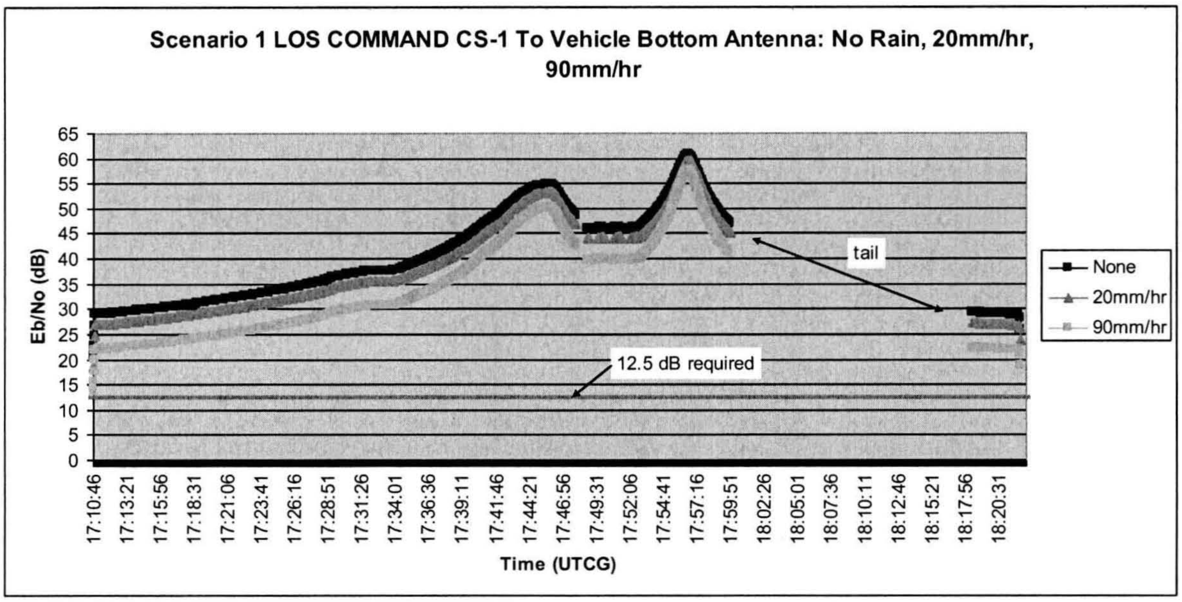

Figure 15: Scenario 1 - LOS COMMAND CS-1 to UA Bottom Antenna

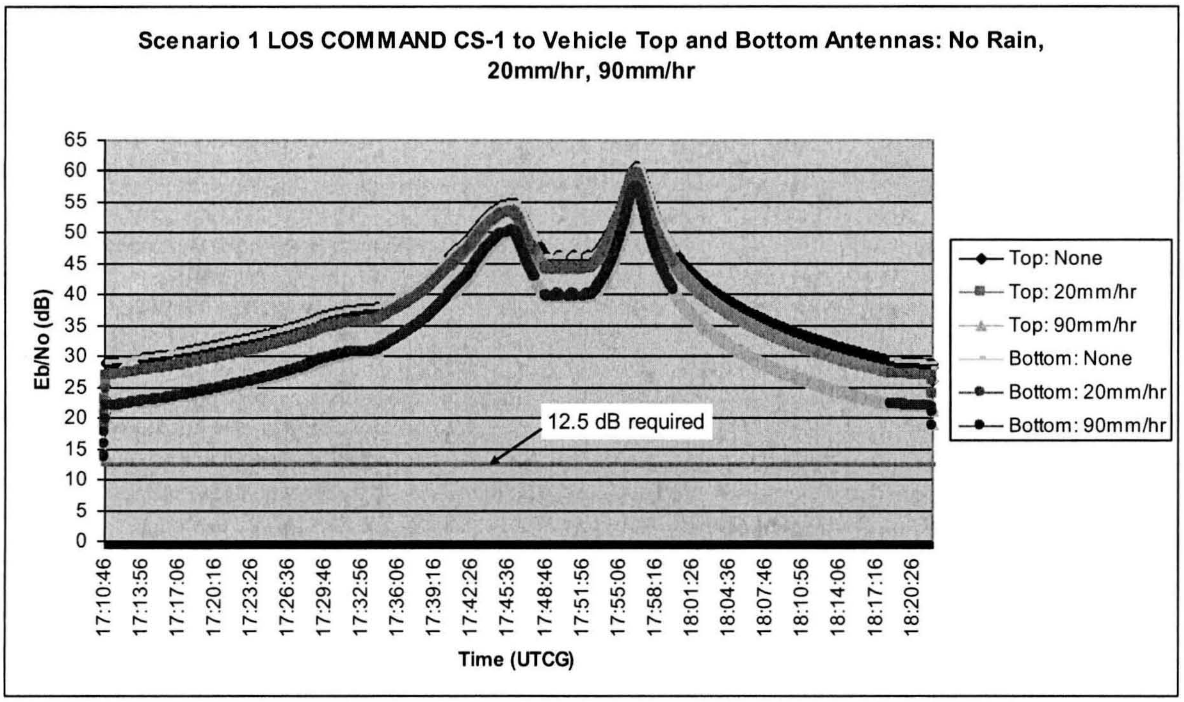

Figure 16: Scenario 1 - LOS COMMAND CS-1 to UA Top and Bottom Antennas

Figure 17, Figure 18, and Figure 19 show the return link or the telemetry link. This is a higher data rate link (320 kBps vs. 10 kBps). Thus the graphs show a lower signal strength across the scenario. The dropouts for both top and bottom antennas are the same as the command link again due to geometry of the antennas. The telemetry antenna and the command antenna are positioned in the approximate same location on the UA. Thus, the top is showing a dropout as it flies toward the CS1 and the bottom shows a dropout as it flies away from CS1. The signal strength goes below the required 12.5 dB at 10 miles range. For the 10^{-5} BER, the range is 14 miles.

Again, for the combined antennas there were no dropouts due to the geometry, but the lower signal has dropouts when the range is over 14 miles.

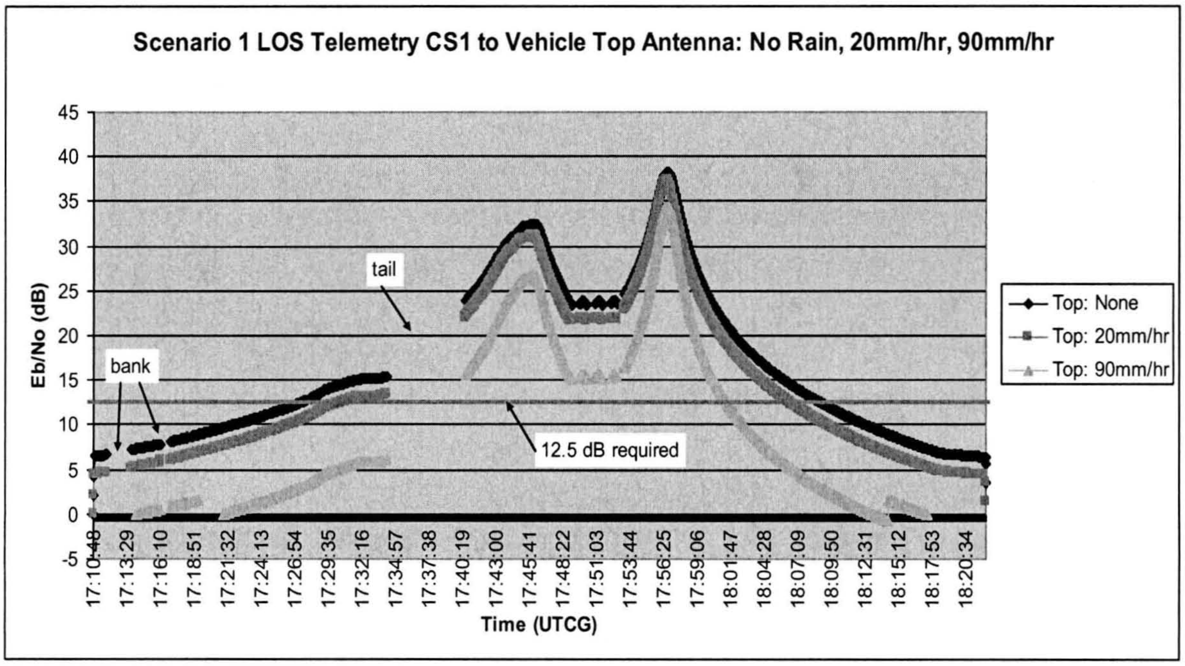

Figure 17: Scenario 1 - LOS Telemetry CS-1 to UA Top Antenna

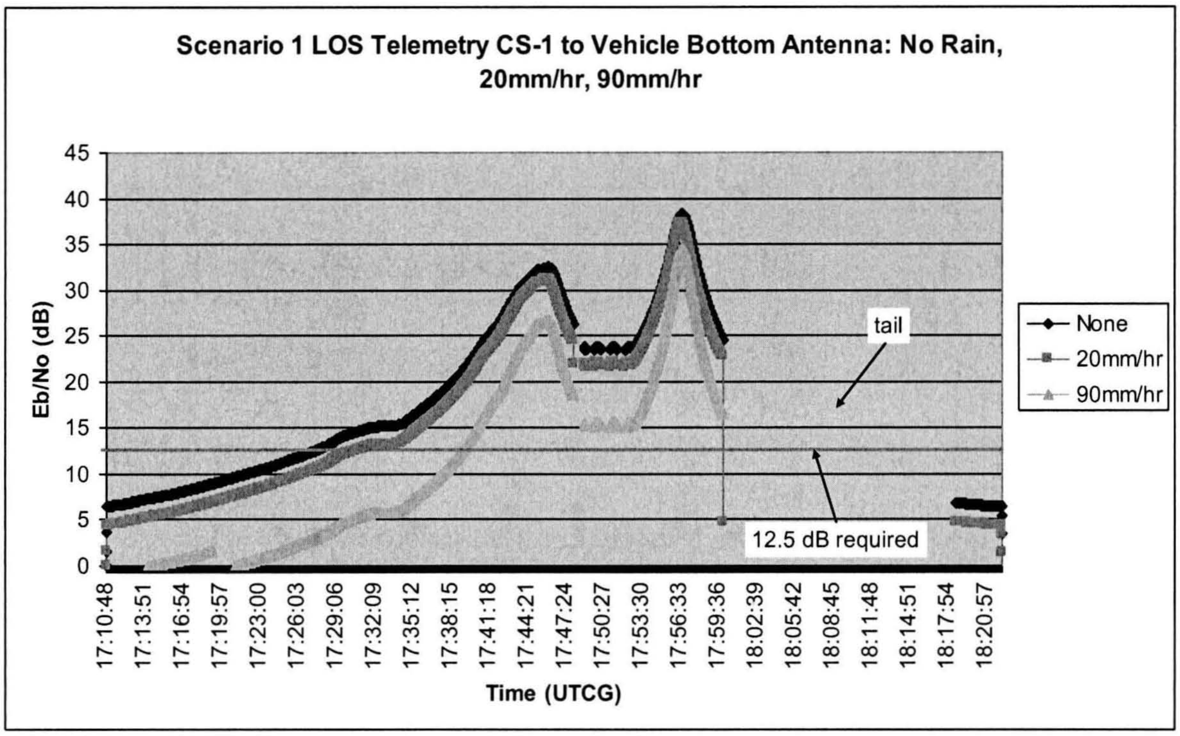

Figure 18: Scenario 1 - LOS Telemetry CS-1 to UA Bottom Antenna

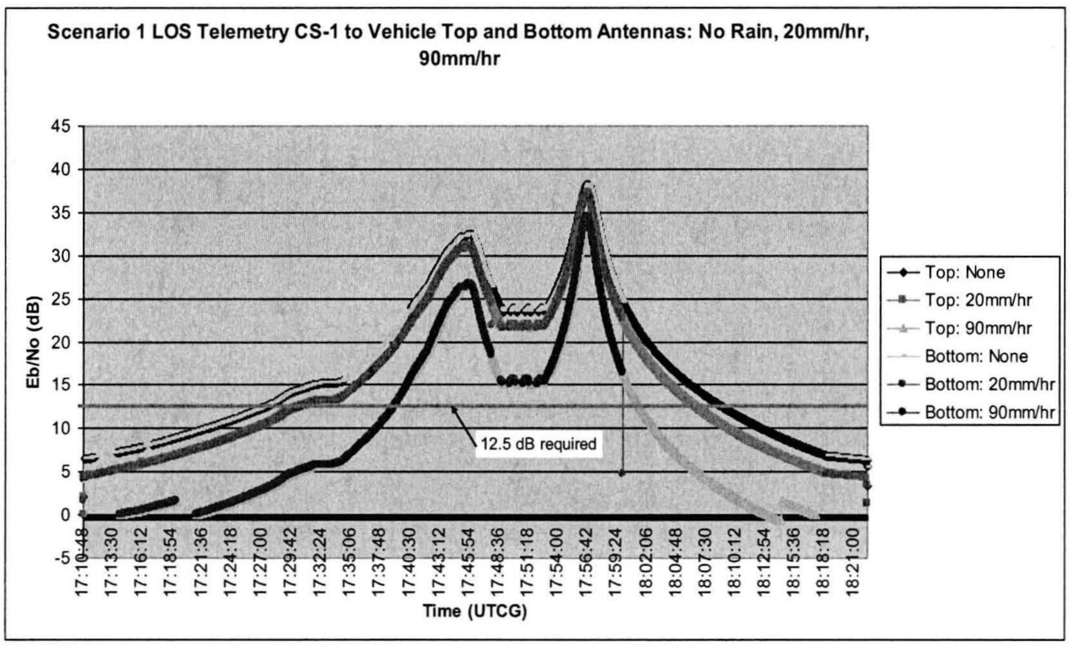

Figure 19: Scenario 1 - LOS Telemetry CS-1 to UA Top and Bottom Antennas

Figure 20, Figure 21, and Figure 22 are graphs of the command link between the UA to CS2. Figure 20 is a graph of the top command antenna. This figure shows dropouts due to flying away from CS2 or blocked by the tail. These same dropouts are longer for the bottom antenna and the bottom antenna has some dropouts due to the UA banking. The geometry is different for CS2 then CS1. CS1 was in a direct line from the UA, whereas the CS2 is off to the east. The combined antennas have minor dropouts of 1-2 seconds due to the UA banking. The signal strength was more than enough for all three rain rates.

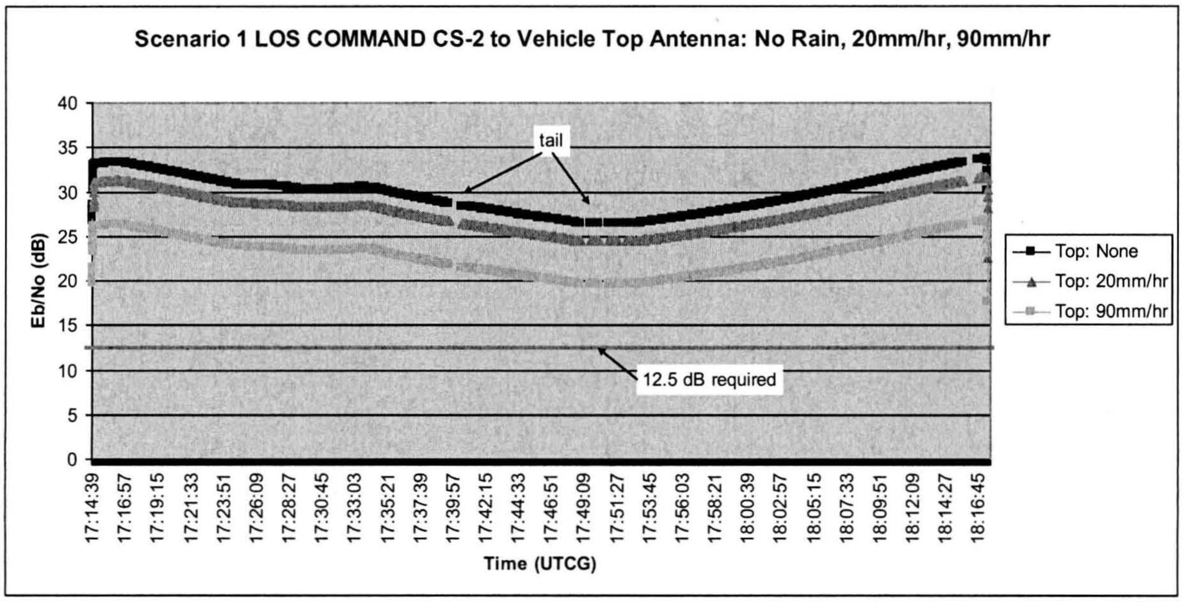

Figure 20: Scenario 1 - LOS COMMAND CS-2 to UA Top Antenna

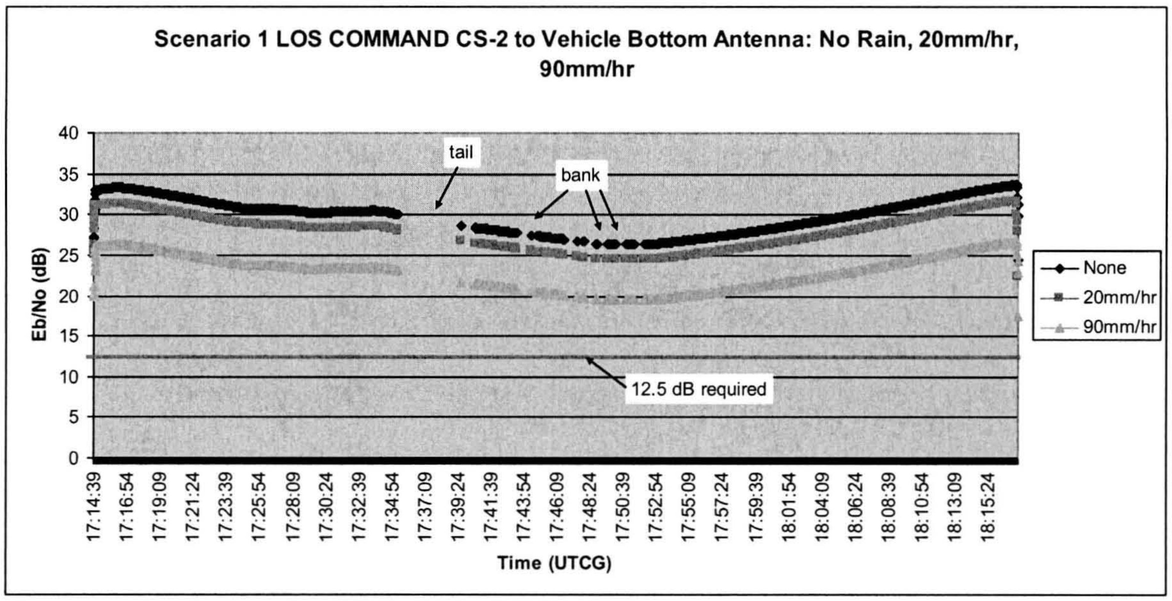

Figure 21: Scenario 1 - LOS COMMAND CS-2 to UA Bottom Antenna

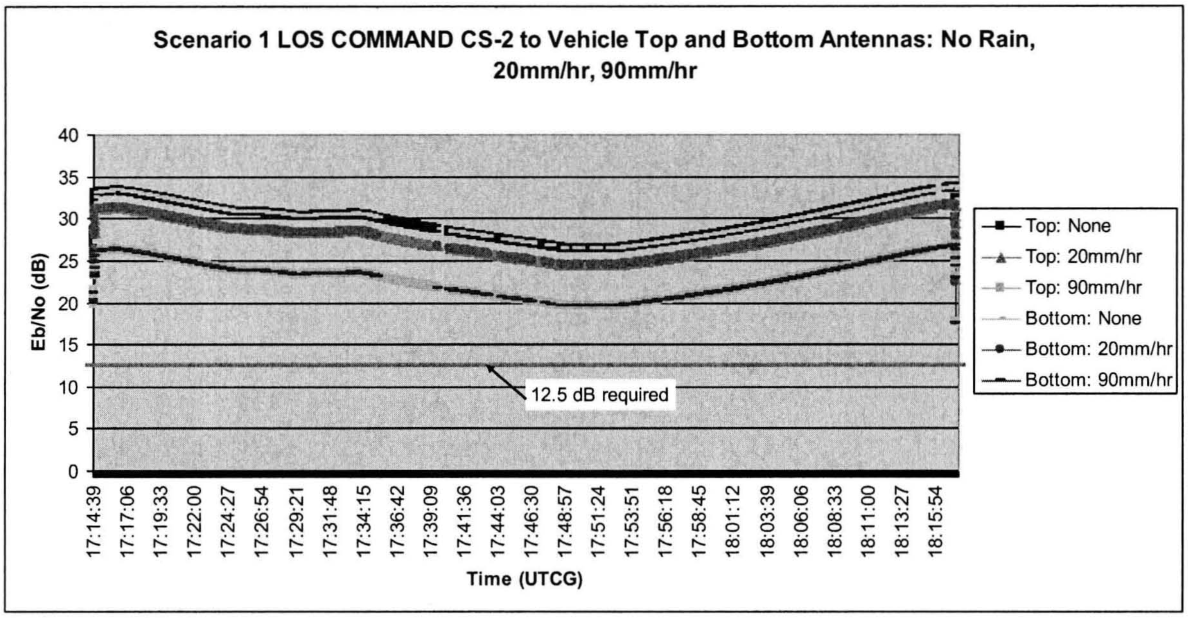

Figure 22: Scenario 1 - LOS COMMAND CS-2 to UA Top and Bottom Antennas

Figure 23, Figure 24, and Figure 25 are graphs of the telemetry between the UA to CS2. The first issue to note is the telemetry is all below the 12.5 dB required. The smallest range is 10 miles from the UA to CS2; this happens at 17:17:00 and again at 18:17:00. For the 10^{-5} BER, the range is 17.5 miles. The top antenna shows one dropout due to the blockage of the tail. The rain rates show even worse results, with the 20 mm/hr dropping below 6.5 dB at 13 miles and the 90 mm/hr never above 6.5 dB. The bottom antenna shows the same results except there is an added dropout due to the blockage of the tail. The combined graph (Figure 25) does not show any dropouts, just low signal strength.

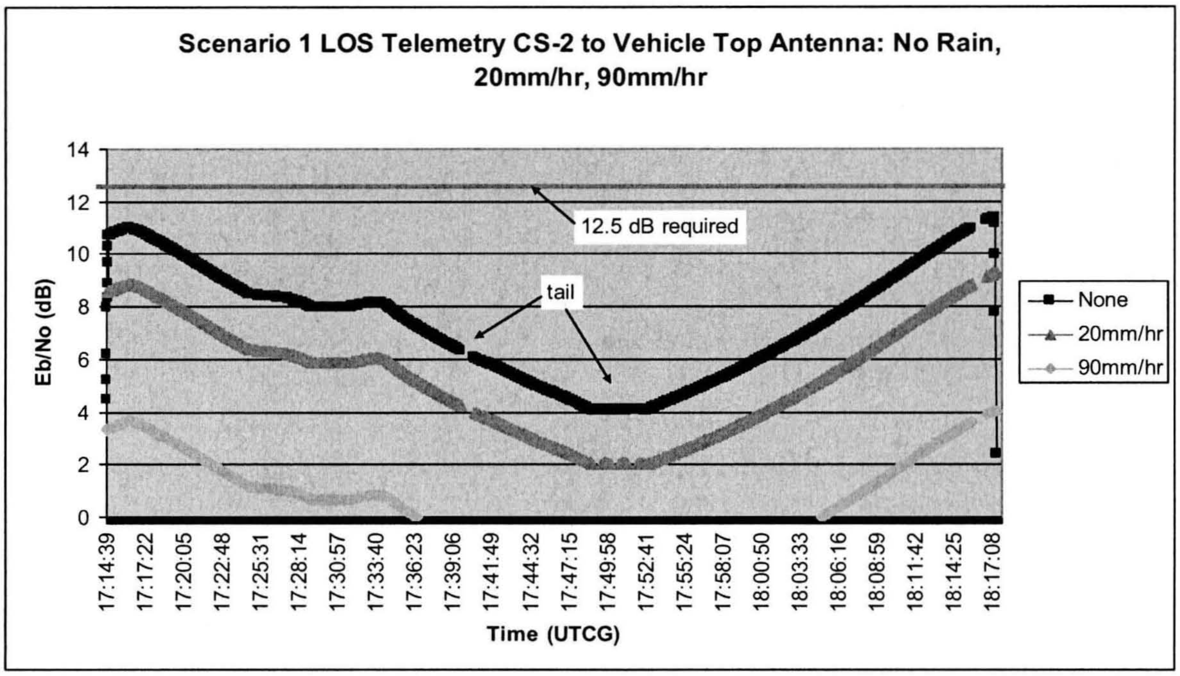

Figure 23: Scenario 1 - LOS Telemetry CS-2 to UA Top Antenna

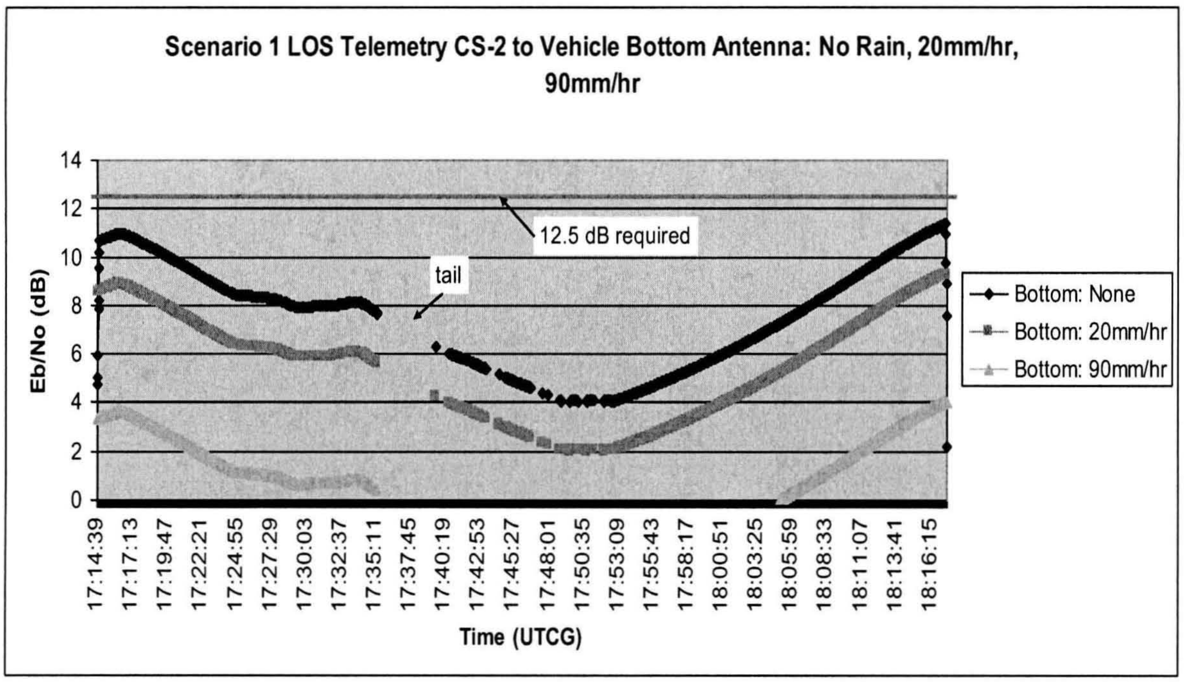

Figure 24: Scenario 1 - LOS Telemetry CS-2 to UA Bottom Antenna

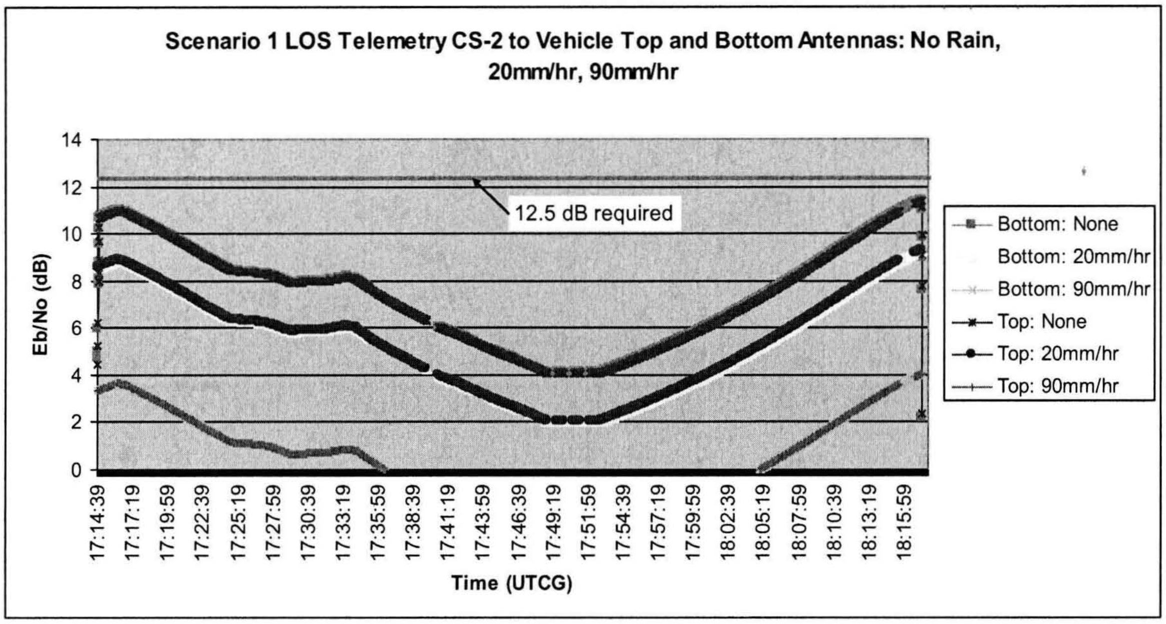

Figure 25: Scenario 1 - LOS Telemetry CS-2 to UA Top and Bottom Antennas

The next six graphs (Figure 26: Scenario 1 - LOS COMMAND Mobile Cruiser to UA Top Antenna

The blockage of the top telemetry antenna is from the UA flying directly over the Mobile Cruiser. The telemetry bottom antenna blockage is from when the UA is flying away from the Mobile Cruiser. The combined antennas again show no blockage except when the UA fly behind the hill.

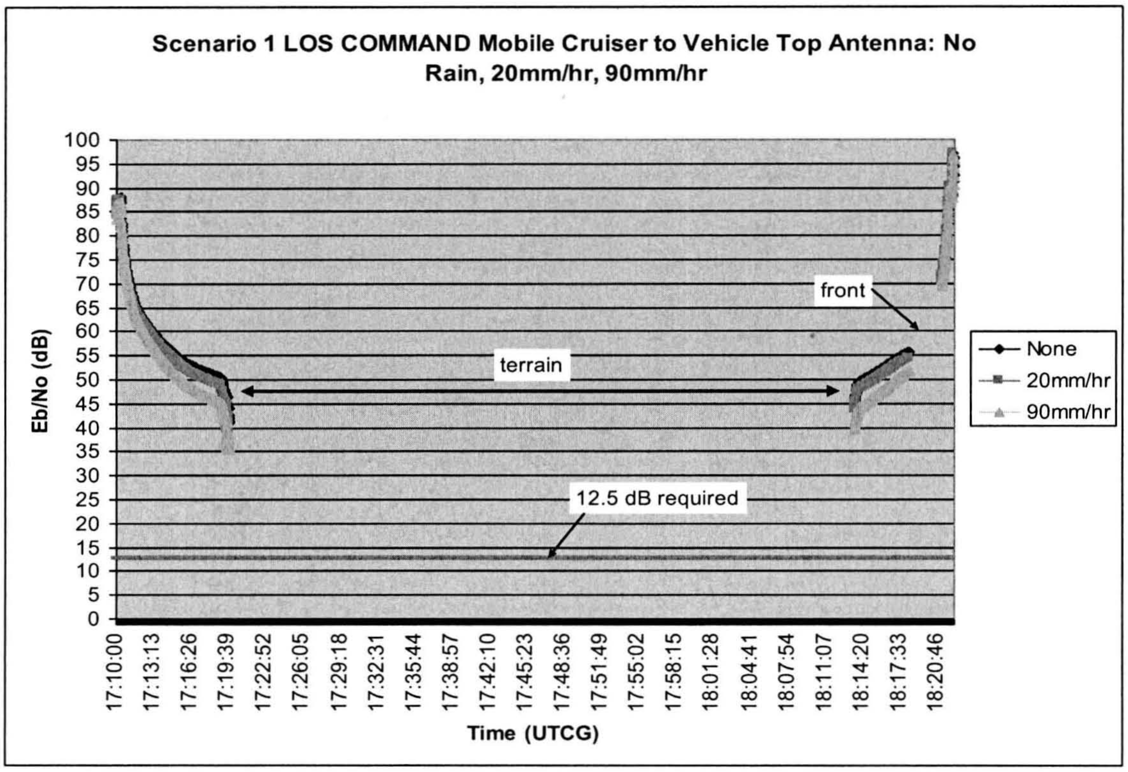

Figure 26: Scenario 1 - LOS COMMAND Mobile Cruiser to UA Top Antenna

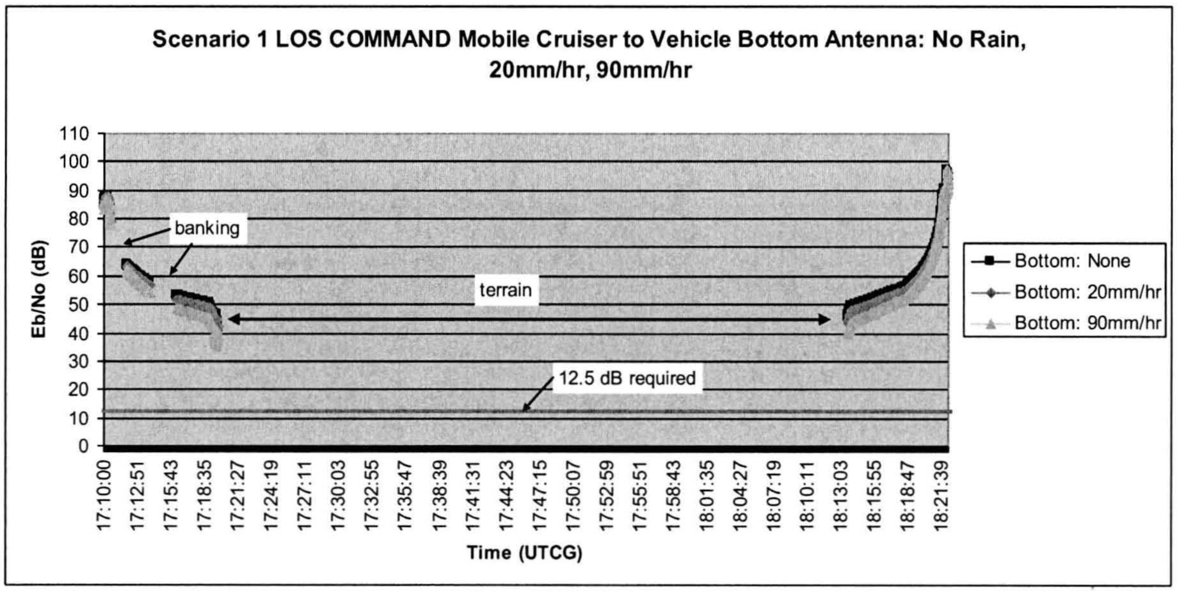

Figure 27: Scenario 1 - LOS COMMAND Mobile Cruiser to UA Bottom Antenna

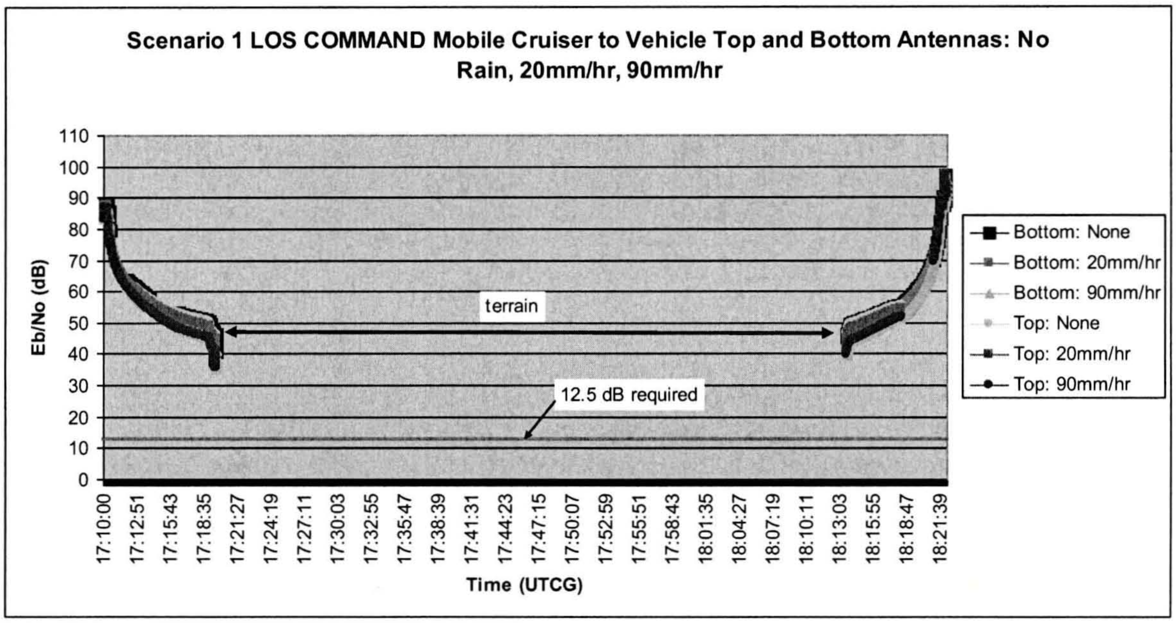

Figure 28: Scenario 1 - LOS COMMAND Mobile Cruiser to UA Top and Bottom Antennas

Figure 29, 30 and 31 shows the telemetry links. The blockage of the top telemetry antenna is from the UA flying directly over the Mobile Cruiser. The telemetry bottom antenna blockage is from when the UA is flying away from the Mobile Cruiser. The combined antennas again show no blockage except when the UA fly behind the hill. The signal strength for the Mobile Cruiser shows higher than either the CS1 or CS2. The reason for this is that the range is 0 miles as the UA starts flying and is only 3 miles as the UA goes behind the hill. All telemetry links had ample signal strength for all rain rates.

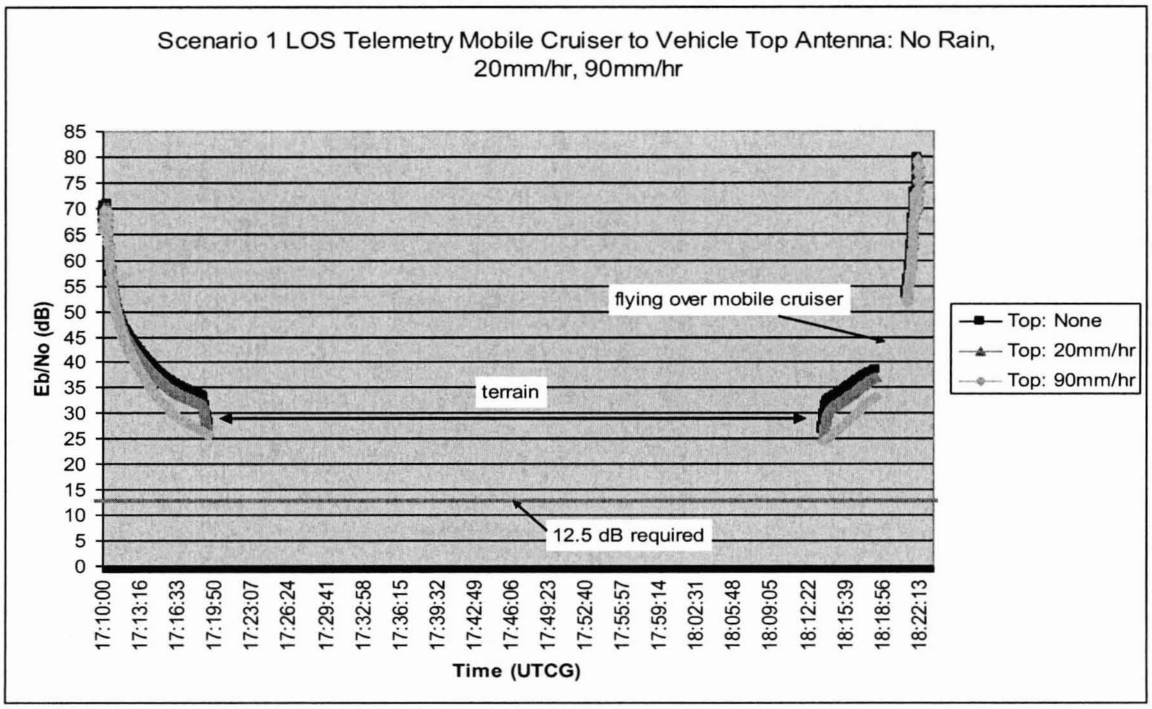

Figure 29: Scenario 1 - LOS Telemetry Mobile Cruiser to UA Top Antenna

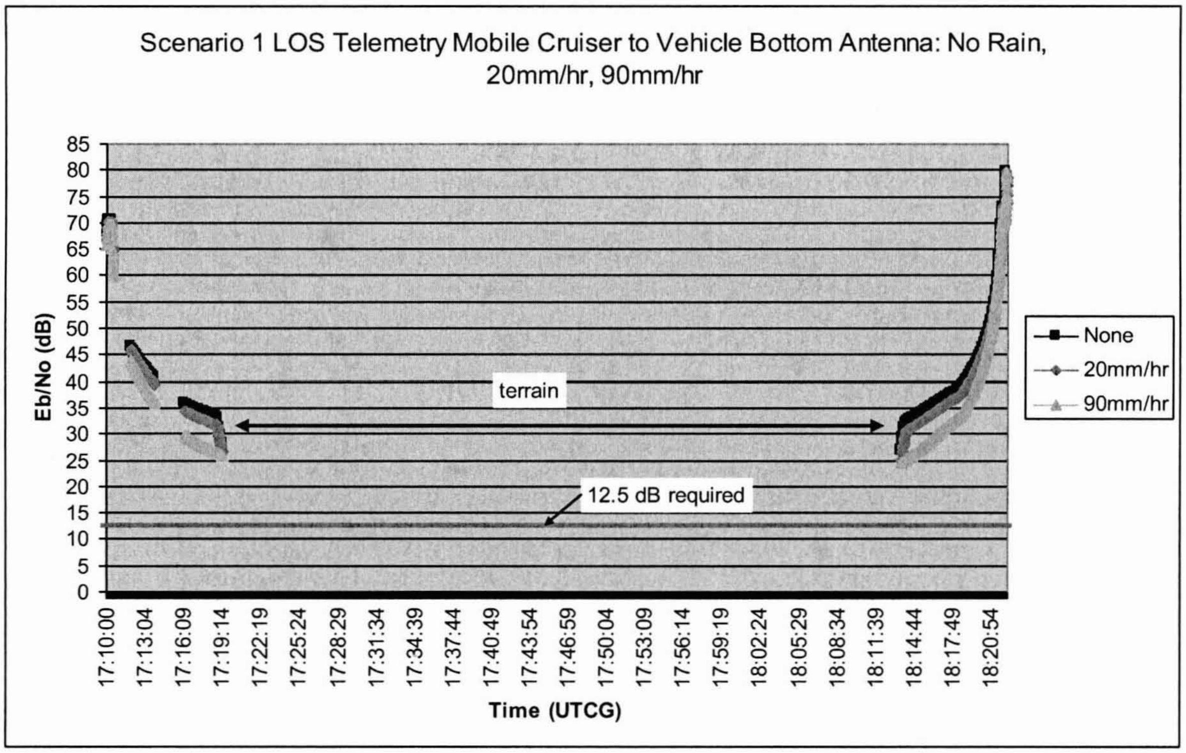

Figure 30: Scenario 1 - LOS Telemetry Mobile Cruiser to UA Bottom Antenna

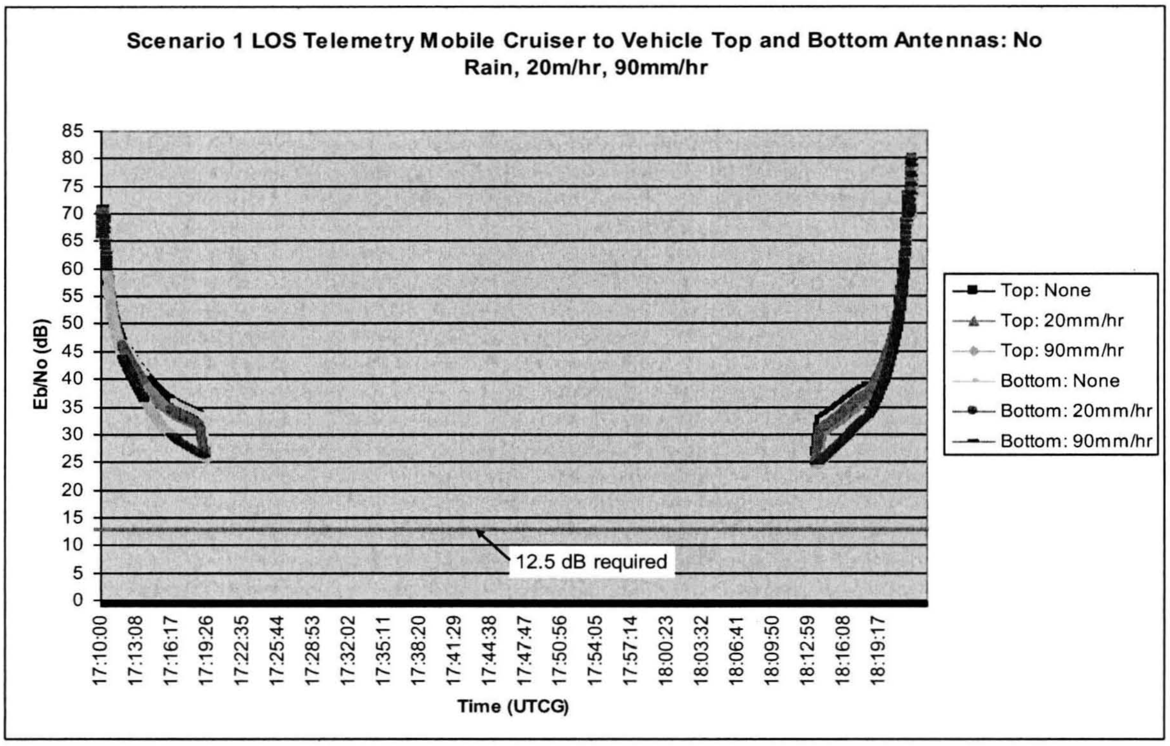

Figure 31: Scenario 1 - LOS Telemetry Mobile Cruiser to UA Top and Bottom Antennas

7.1.5 Scenario 1 - Gaps

Figure 32: Scenario 1 - Gaps for CS to UA Top and Bottom Antennas

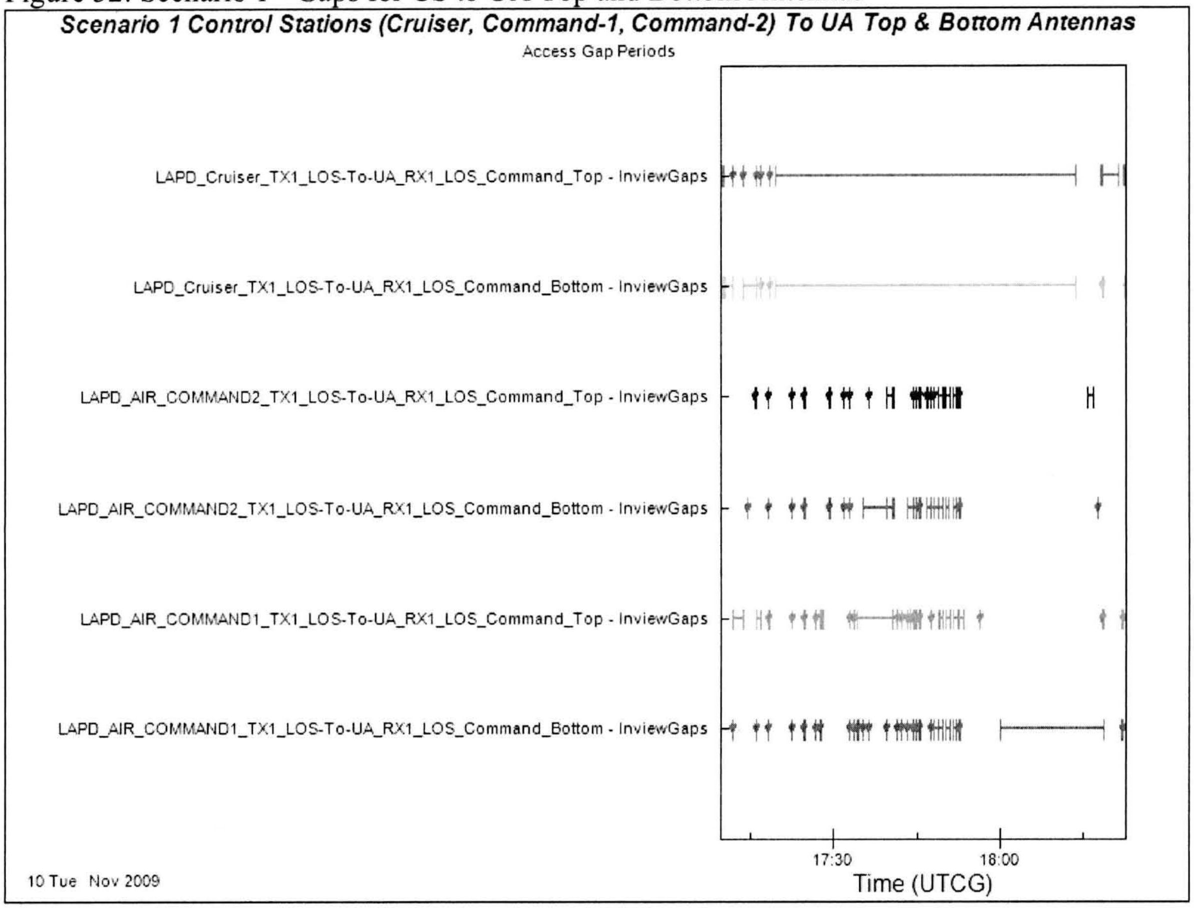

Figure 32: Scenario 1 - Gaps for CS to UA Top and Bottom Antennas

7.1.6 Scenario 1 – Combined Command and Telemetry Results

The results are shown graphically below. There were many links calculated for this and the other scenarios. The rain was analyzed for 99.9% availability with rain rated of 0 mm/hr, 20 mm/hr, and 90 mm/hr at a height of 5 km out to 25 NM.
The primary CS was unable to maintain a control RF Link during the flight. The largest access gap periods between object top and bottom UA antennas were caused by terrain (ridges and hills).

There were RF dropouts between the top and bottom UA antennas caused by aircraft obstructions (fuselage, wings, wheel assembles, etc.). Note that for this study, antenna locations were placed on top and bottom center of the UA body. Future studies should include actual UA antenna locations on the aircraft, providing manufacturers are willing to provide information.

The importance of CS location was demonstrated for primary or backup CS. With a second backup CS placed in a suitable location, the UA was able to maintain an overall RF link. The actual location of both backup CS required the antenna location to be placed 150 ft. above ground in order to establish an RF link between the UA and CS. The next two graphs show this result for command and telemetry.

Figure 33: Scenario 1 - Top and Bottom Antennas on UA to All Three Command Transmitters shows the combined command links with no dropouts and both links are above the 12.5 dB required. The command links held up under the criteria selected.

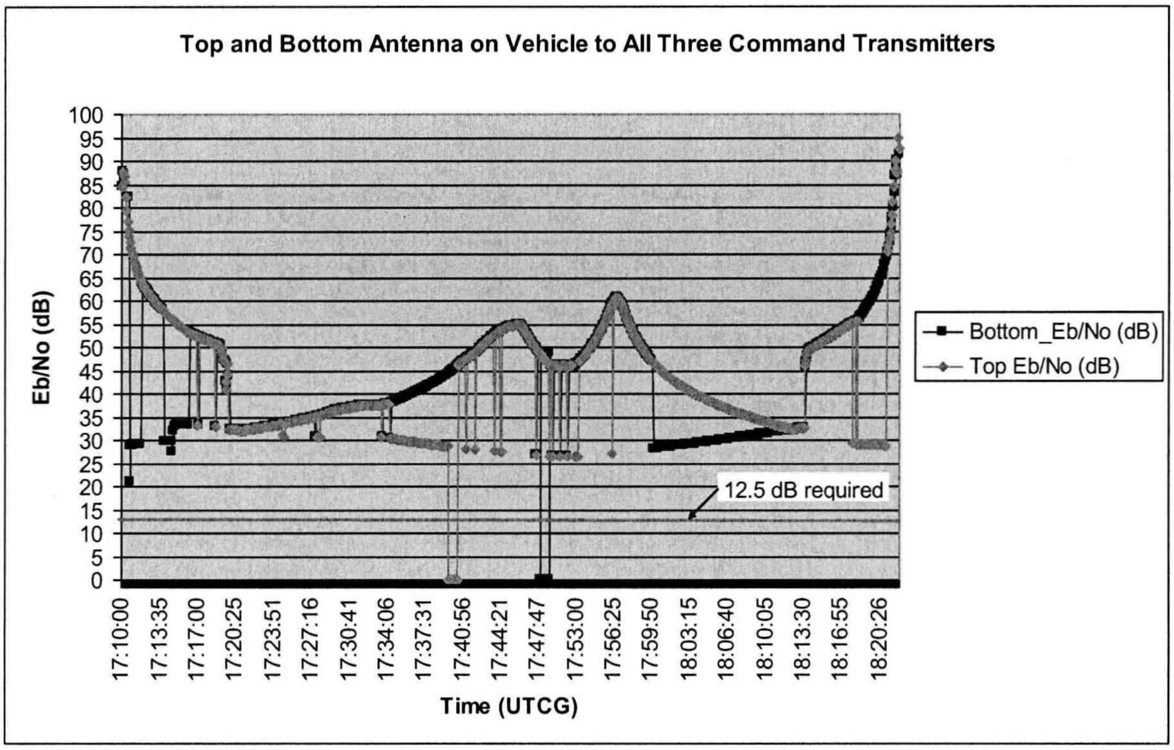

Figure 33: Scenario 1 - Top and Bottom Antennas on UA to All Three Command Transmitters

Figure 34: Scenario 1 - Top and Bottom Antennas on UA to All Three Telemetries Transmitters is the combined telemetry link for all three Control Stations. The results were not as good. The combined link is above the 12.5 dB (required) for most of the scenario. However at 17:19 the link drops down to 10 dB and does not go above 12.5 dB until 17:25. At 18:10 the scenario drops below 12.5 dB and picks up at 18:13. This was primarily due to the closer range of the Mobile Cruiser compared to CS1 and CS2 thus showing a higher signal strength. CS2 is the furthest CS from the UA showing the smallest signal strength. If the criterion of 6.5 dB is used for the 10^{-5} BER, the link holds up throughout the scenario.

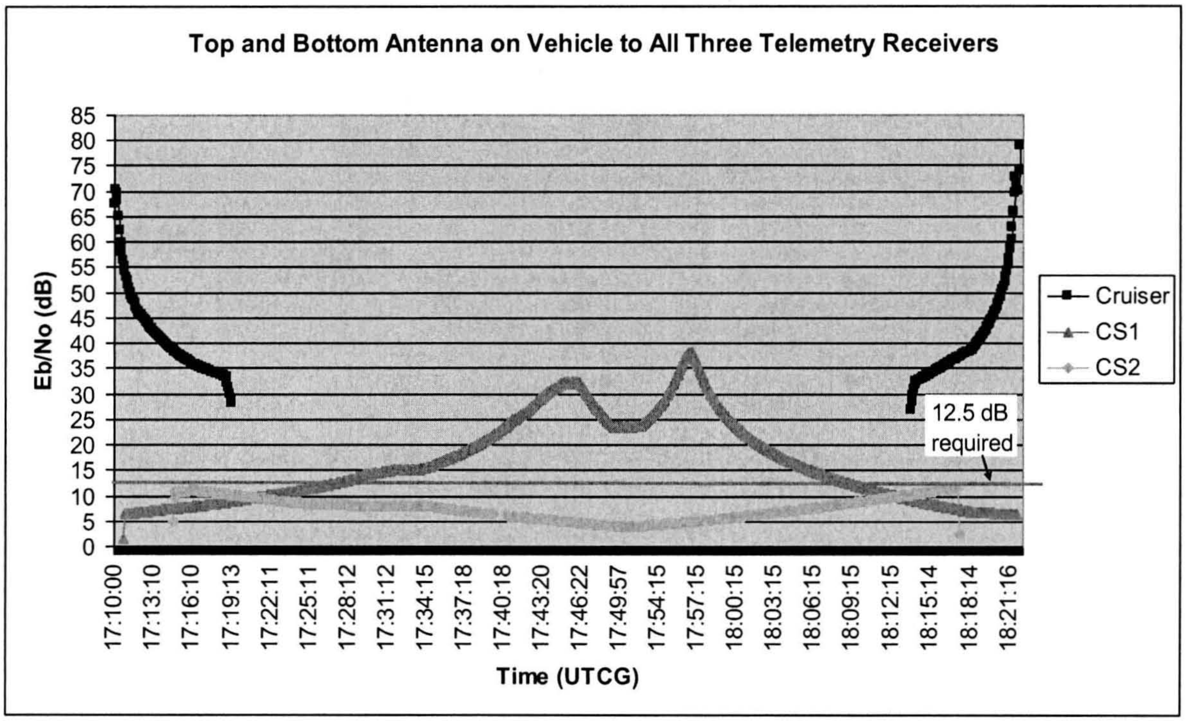

Figure 34: Scenario 1 - Top and Bottom Antennas on UA to All Three Telemetries Transmitters

Scenario 1 demonstrated the importance of CS locations for primary or backup CS. With a second backup CS placed in a suitable location, the UA maintained an RF link. The location of both backup CS required the antenna to be place 150' above ground in order to establish an RF link between the UA and CS.

7.1.7 Other Results - Terrain

This scenario involves a low flying UA at 400 feet. The other two scenarios have the UA flying at 20,000 feet. Since the UA was flying low and there is some terrain, this is the only scenario where TIREM was used. Figure 35 shows why there were dropouts from the LOS link due to the Ridge.

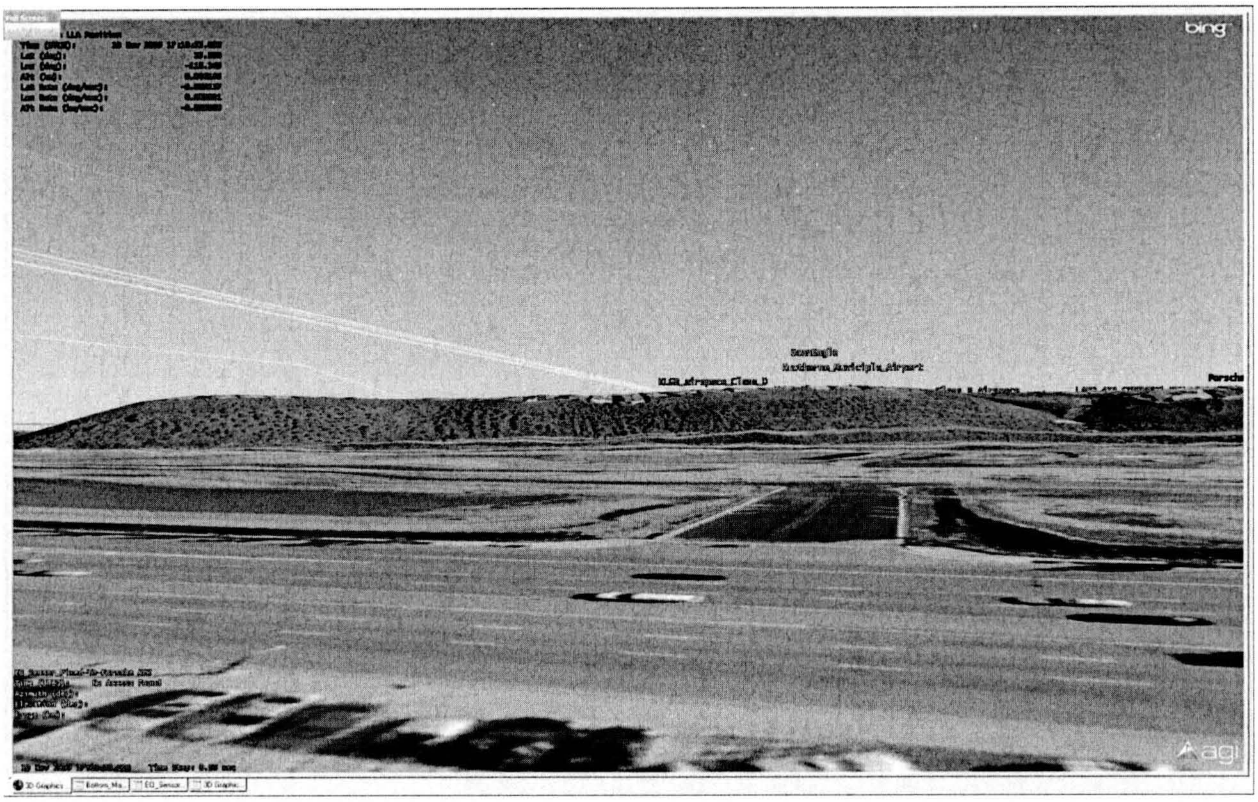

Figure 35: Scenario 1 - Blocking Ridge

7.2 SCENARIO 5 CARGO DELIVERY TURBOPROP CONVERSION

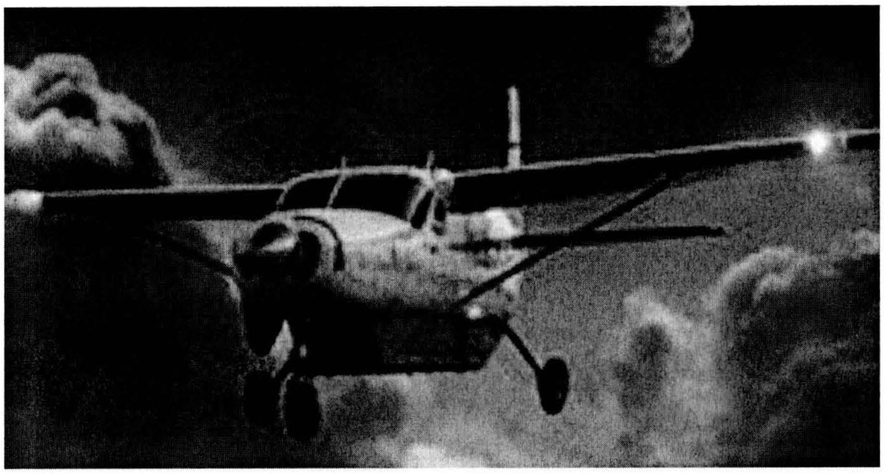

Figure 36: Cessna Caravan UA

OSED Scenario 5 depicts a Cessna Caravan UA (Figure 36) providing an air cargo delivery of natural gas replacement parts from a distributor in Sacramento, California, to an energy company located near the rural community of Brawley in southern California. The flight is 440 NM and 2 hours and 30 minutes flight time. The UA is operated by a major cargo delivery company and is supported by dispatchers, maintenance crew, ground operational crew, and communications specialists referred to as support element personnel. These personnel are both company and contract workers based throughout the U.S. The main operations center at Bakersfield, California including the pilot's CS, all control communications and dispatch facilities for the flight.

The UA and its ground support and maintenance crew are located at Sacramento Mather Airport (MHR). The UA is certified for single pilot operations, though company policy requires use of a copilot (either remotely located or co-located with the pilot-in-command) to monitor the entire flight. The MS copilot does not act in a traditional copilot role. The MS copilot monitors multiple flights during his or her duty time but can be dedicated to assisting the PIC in terminal flight operations at the request of the PIC during unusually heavy workload or contingencies.

7.2.1 Flight Overview

Figure 37 depicts the flight path for Scenario 5 of the Cessna Caravan UA.

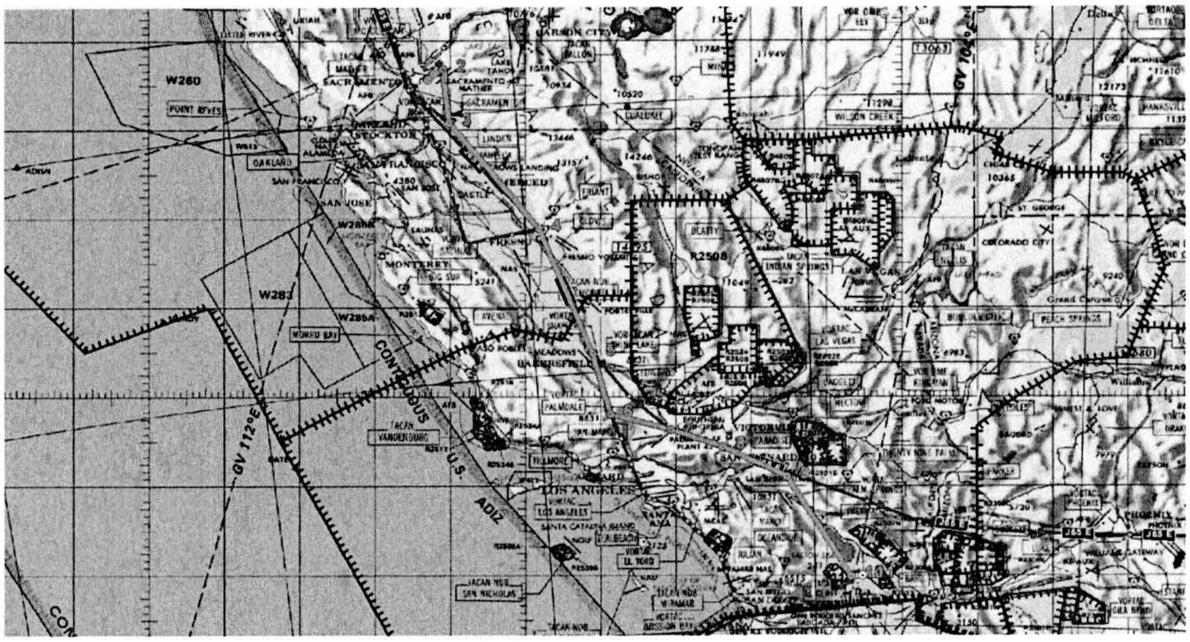

Figure 37: Scenario 5 - Flight Path

<u>7.2.2 UA Description</u>

The UA is a Cessna Caravan (fixed-wing, single-engine turboprop) converted for cargo operations in a manned or unmanned mode. It is CAT 1 all-weather capable and well suited for operations into and out of small rural airports. The UA is typically flown autonomously but can also be manually flown when conditions exist. The CS is located in a secure office building and is identical to 20 other CS located in the same facility. Additional control stations are located at remote sites in five other states. These remote CS are used primarily for mission pilot support and to act as a backup in case of primary CS problems but can also be use as the primary CS. Communications used for aircraft control and operational communications are networked from various locations in the U.S. Figure 38: Antenna Patterns for Top and Bottom Telemetry and Command

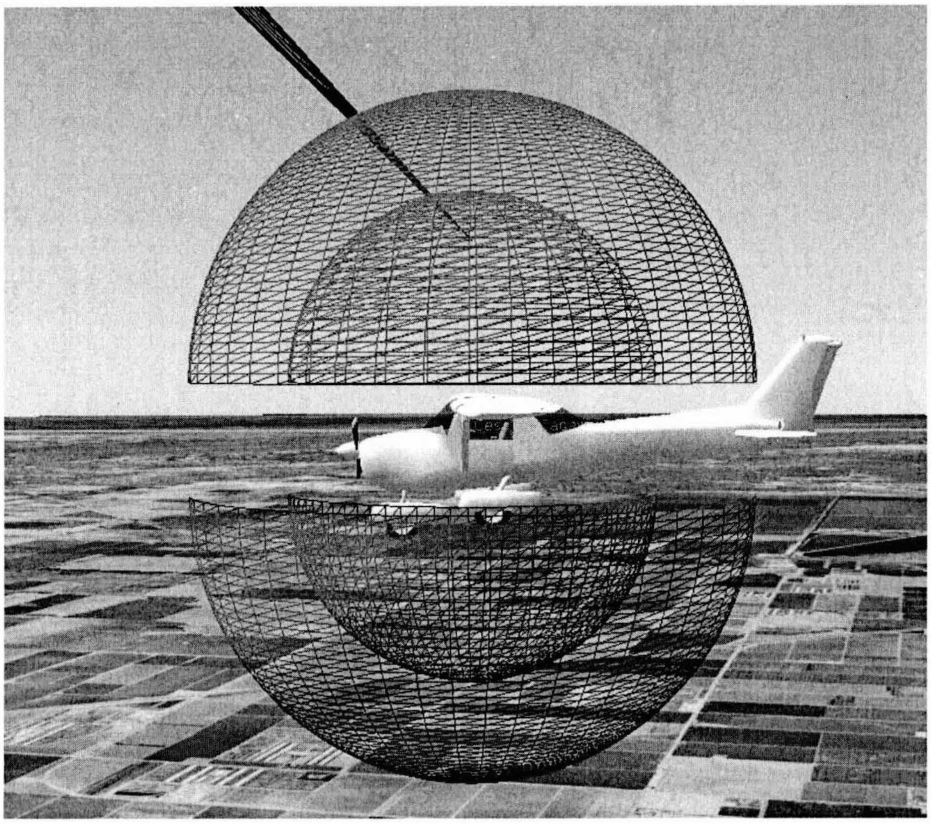

Figure 38: Antenna Patterns for Top and Bottom Telemetry and Command

7.2.3 Scenario 5 - Set Up

Scenario 5 is shown in shown in

QualNet was used in this scenario to analyze the packet delays. The effect of rain on the link margin is determined with 0 mm/hr. rain, 20 mm/hr rain, and 90 mm/hr rain. Interference by an adjacent GEO satellite was also analyzed in all BLOS links. The adjacent satellite was placed 2 degrees away from the GEO satellite and then moved one half of a degree until it was only 0.5 degrees away from the GEO. The interference was analyzed for the command link from the GEO down to the UA.

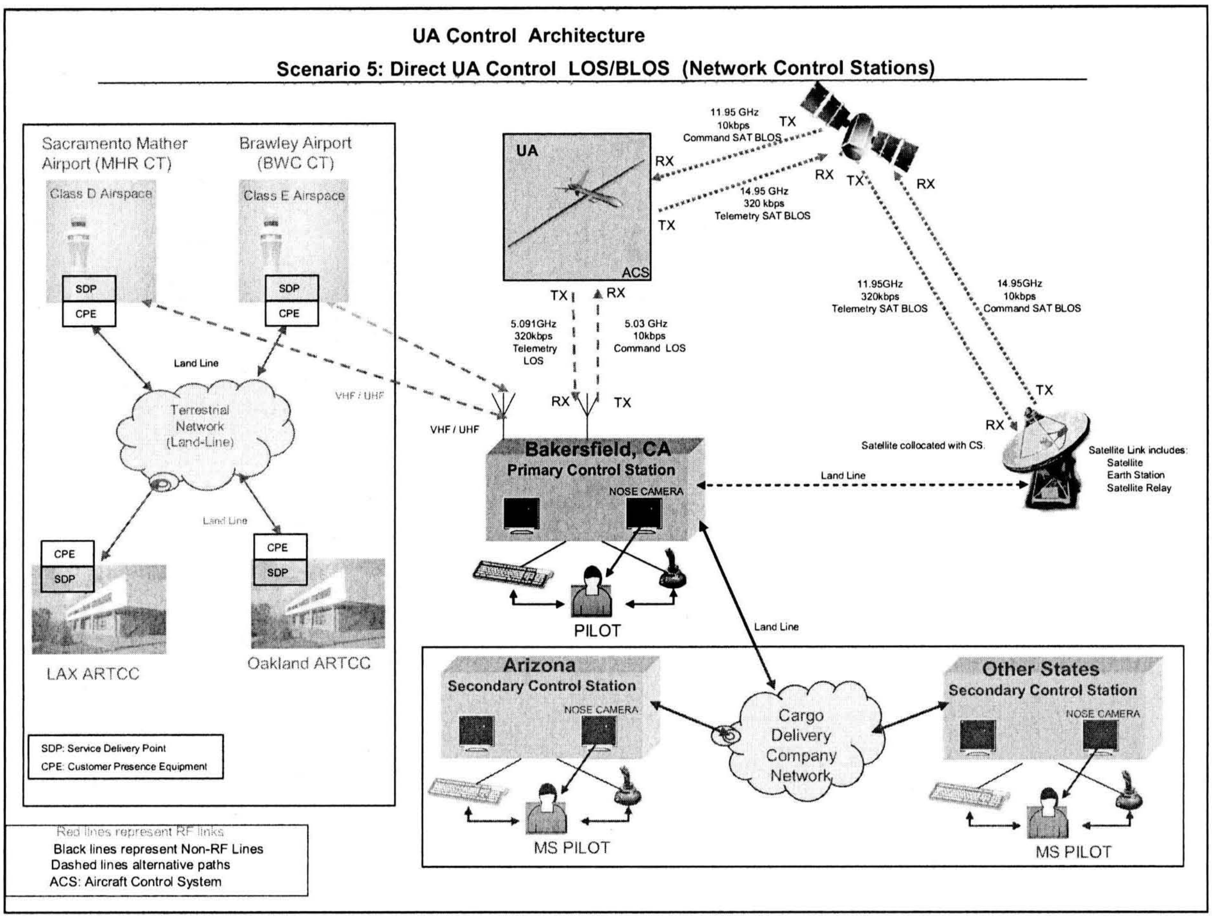

Figure 39: UA Control Architecture – Scenario 5 - Direct UA Control LOS/BLOS

7.2.4 Scenario 5 - LOS

Scenario 5 differs from Scenario 1 in that Scenario 1 had 3 CS and no BLOS, while Scenario 5 had two CS and a BLOS link up to a GEO satellite. Thus, in these types of scenarios the LOS link is used primarily for takeoff and landing and the BLOS is used for the mission. The UA flies over 500 miles from Sacramento, California, down to Bakersfield, California, and landing at Brawley Airport to the south. Sacramento and Bakersfield are the primary CS.

The first six charts Figure 40 to 45) are Sacramento LOS to the UA. The first graph, Figure 40, shows the UA picks up the CS with a strong signal since it's less than a mile away. As the UA flies away from the CS there is top and bottom antenna blockage by the tail. The top antenna shows more blockage as the UA climbs. This is due to the geometry of the antenna placement. Figure 41 shows the 25 NM line that was placed there as a comparison of the link margins that was calculated earlier in the report in Section 6.5 Radio Link Budget. These link margins were calculated for 25 NM. As can be seen for the command link the margin over the 12.5 dB required is 25 dB. As stated previously, the 20 dB multipath loss margin is not included on these graphs. Thus, at 25 NM, there is an excess margin of 25 dB. If we subtract the 20 dB multipath margin, we are left with a 5 dB margin over that which is required. The third graph Figure 42, is the combination of the top and bottom antenna. The combined antennas do not show any dropouts as seen in Figures 40 and 41. The LOS links graphs have different start times would be associated with data selection.

As the UA flies down range, the effect of rain is more pronounced. This is because the rain is modeled as a constant value over the whole scenario. The radio waves have to transverse more of the rain as the UA moves away from the CS. There is about a 5 dB difference in the 90 mm/hr over the 45 minutes of the graph of the bottom antenna.

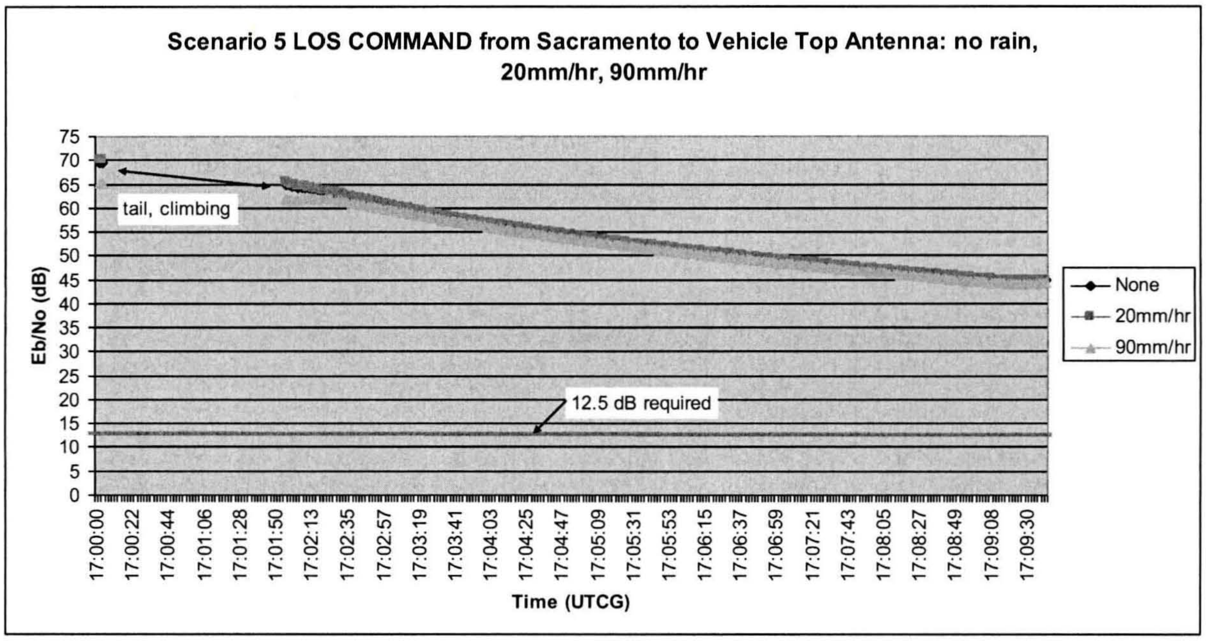

Figure 40 : Scenario 5 - LOS COMMAND from Sacramento to UA Top Antenna

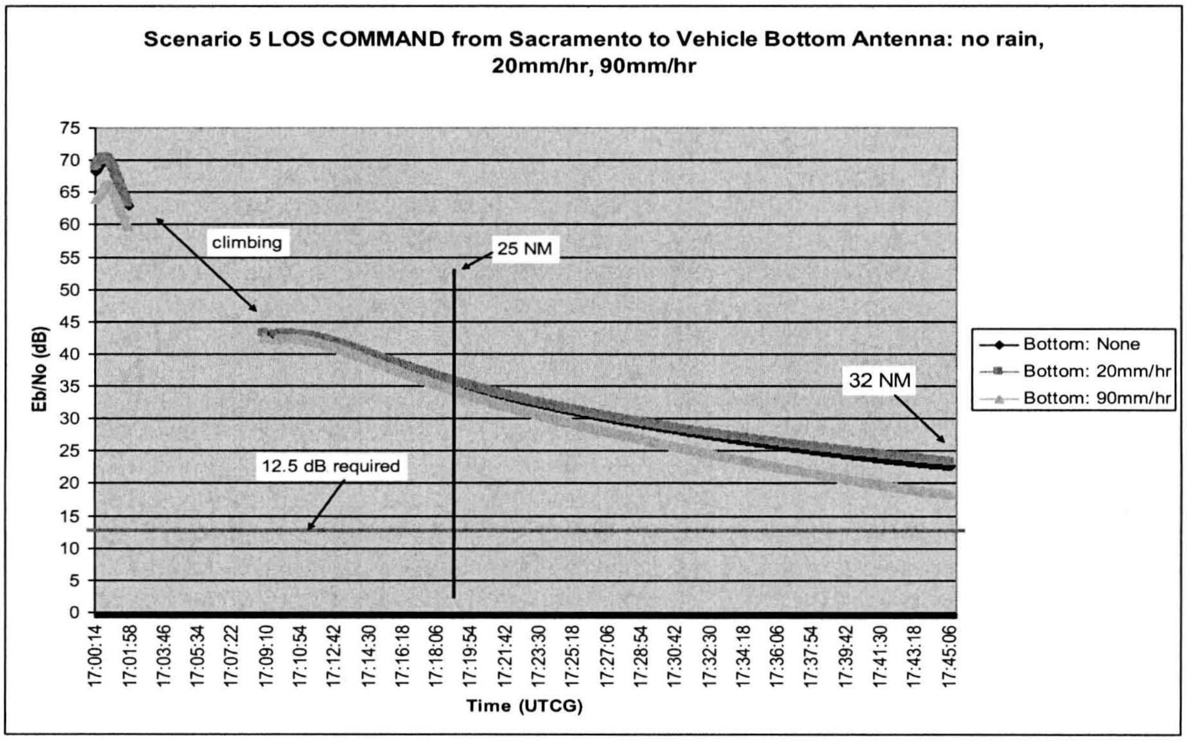

Figure 41: Scenario 5 - LOS COMMAND from Sacramento to UA Bottom Antennas

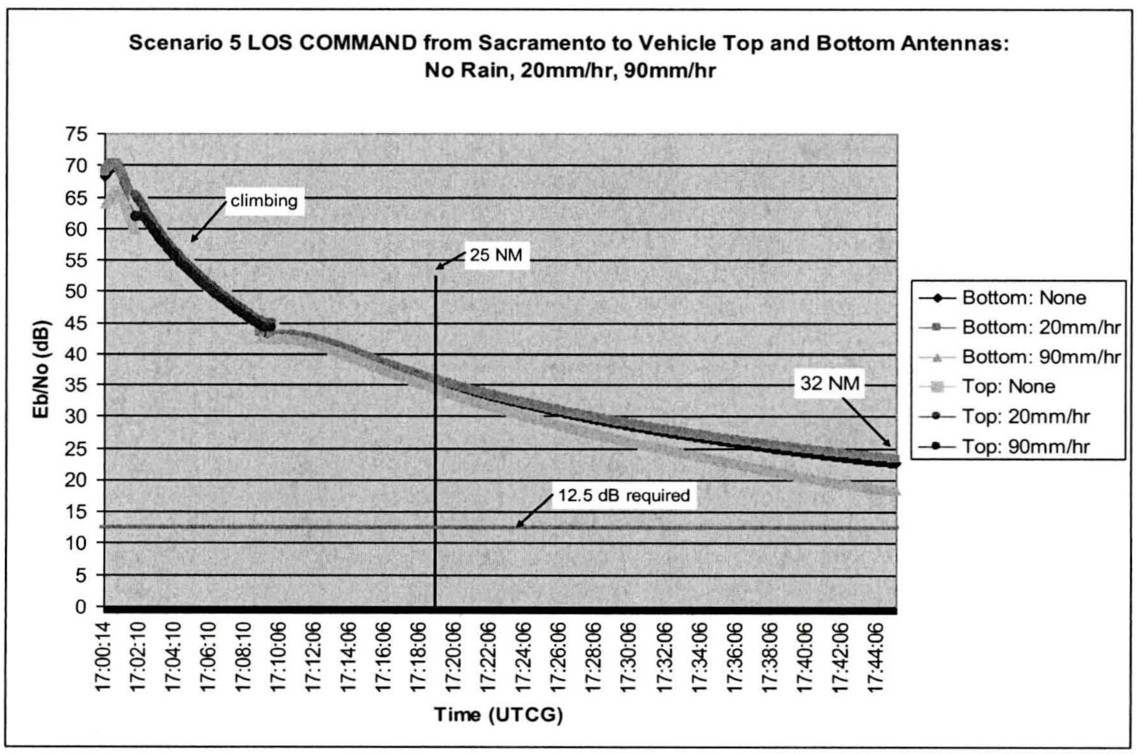

Figure 42: Scenario 5 - LOS COMMAND from Sacramento to UA Top and Bottom Antennas

Telemetry is the return data to the CS. More bandwidth is required for the UA which is sending data back to the CS Ex: video feed, UA performance data, may include system health status also. The two telemetry links are associated with the top and bottom Antenna locations that are being compared in the analysis. (RF Diversity). Figure 45 shows the combined telemetry links with no dropouts using both top and bottom antennas. The two telemetry links are associated with the top and bottom Antenna locations that are being compared in the analysis.

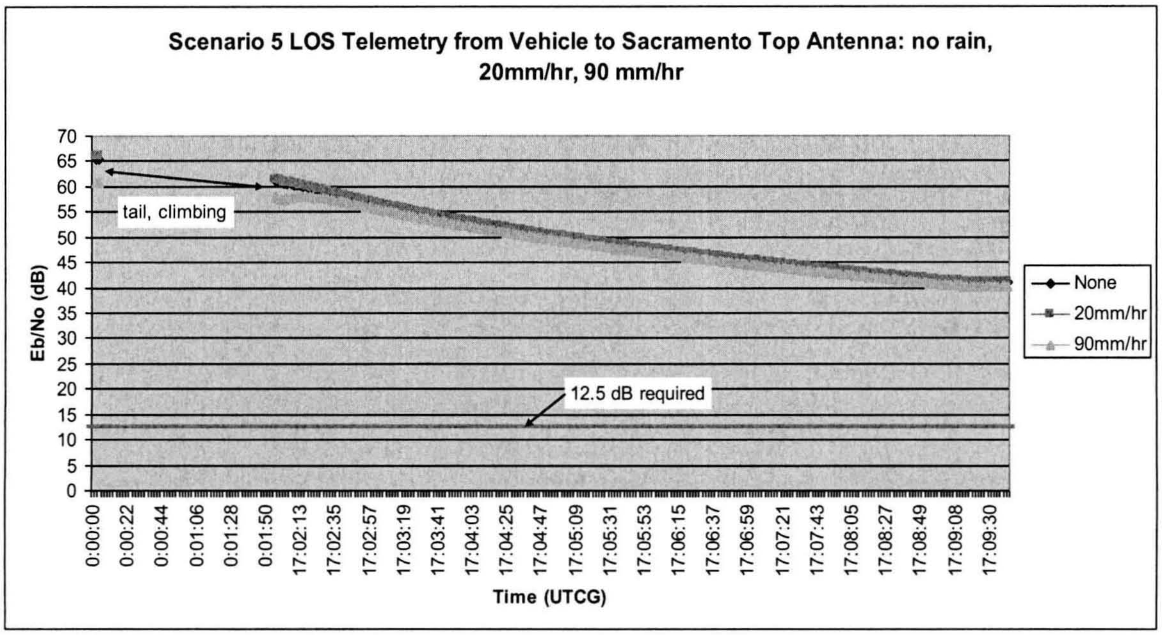

Figure 43: Scenario 5 - LOS Telemetry from UA to Sacramento Top Antenna

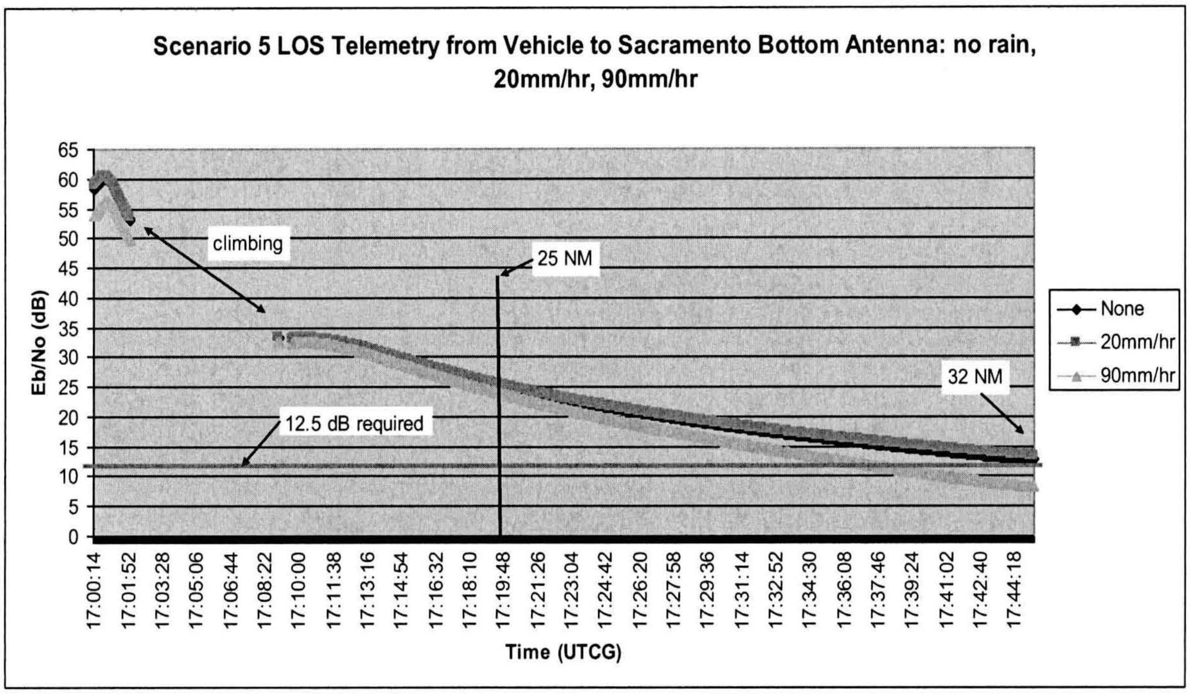

Figure 44: Scenario 5 - LOS Telemetry from UA to Sacramento Bottom Antenna

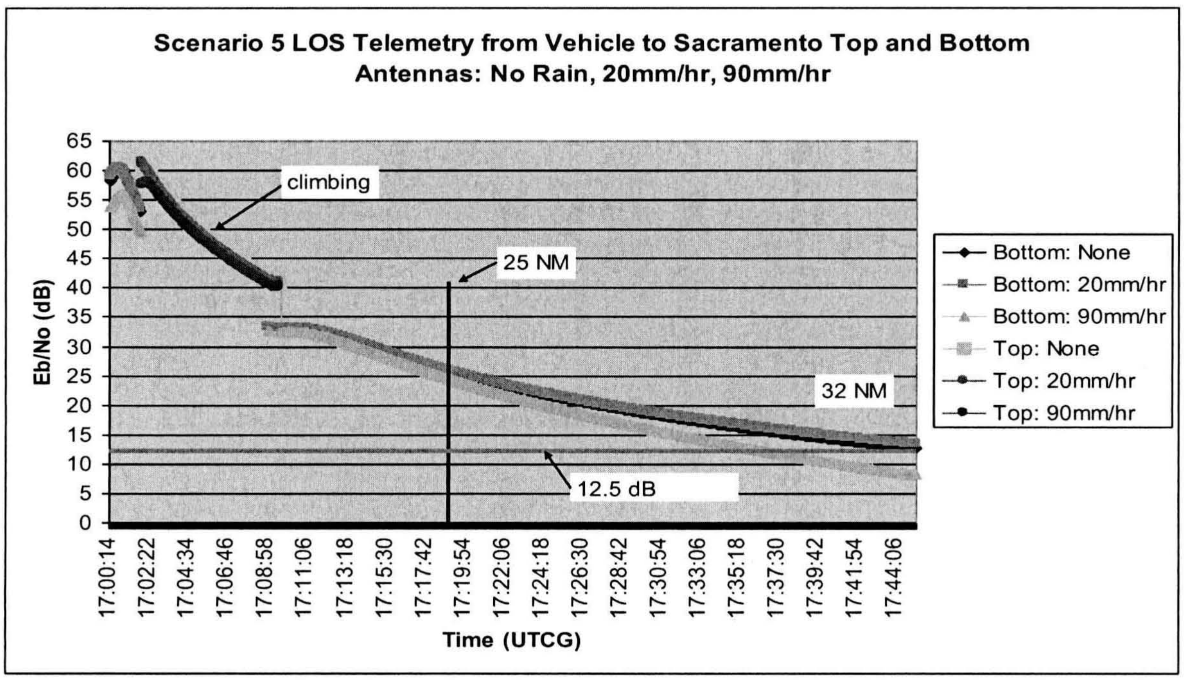

Figure 45: Scenario 5 - LOS Telemetry from UA to Sacramento Top and Bottom Antennas

Figures 46, 47, and 48 shows Bakersfield command to the UA. As the UA flies down range the second CS, Bakersfield picks up the UA on a LOS link. Figure 46 shows that the top antenna only connects when the UA banks left. Whereas Figure 47 Bakersfield, California shows the bottom antenna doesn't experience that dropout. The signal strength getting stronger and weaker is due to the UA approaching Bakersfield CS and then flying past the CS. The combined pattern in Figure 48 does not have any dropouts.

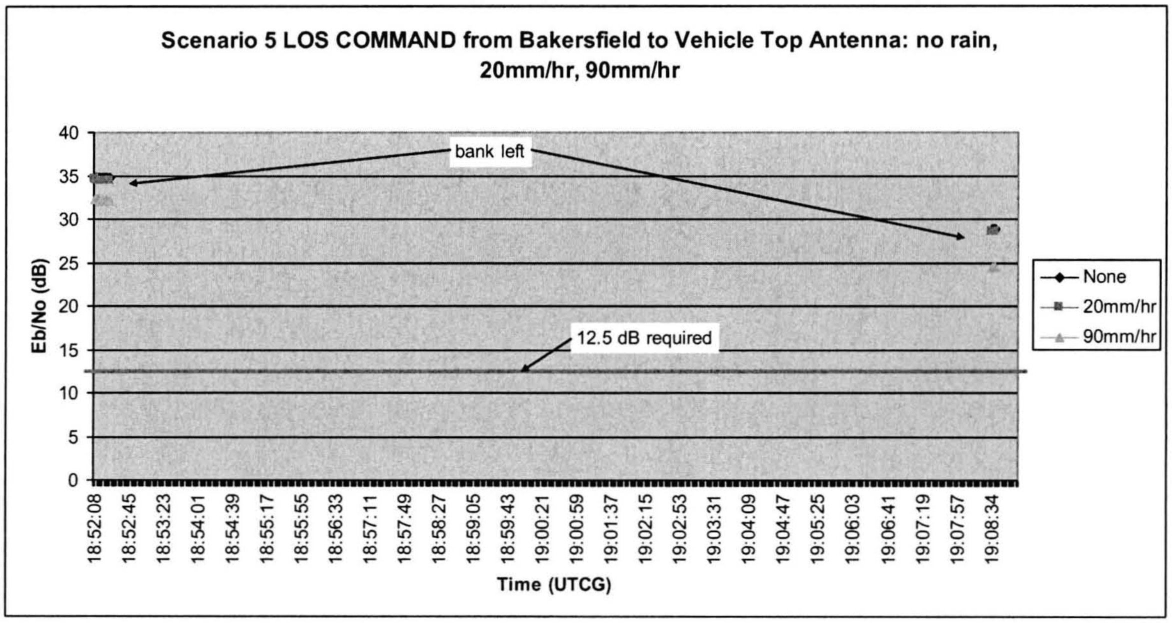

Figure 46: Scenario 5 - LOS COMMAND from Bakersfield to UA Top Antenna

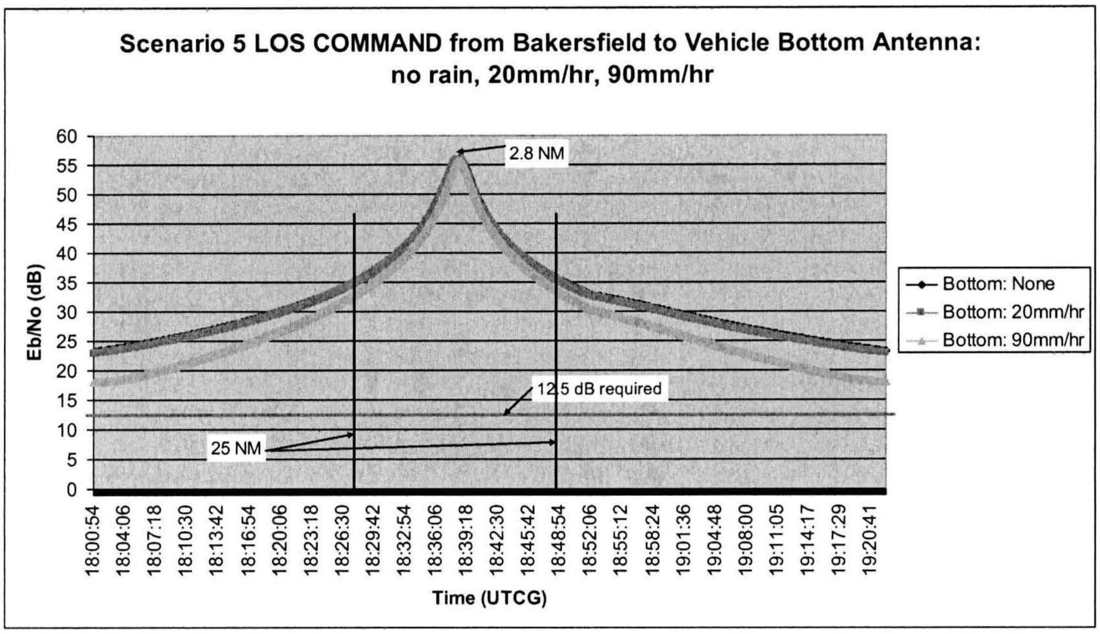

Figure 47: Scenario 5 - LOS COMMAND from Bakersfield to UA Bottom Antenna

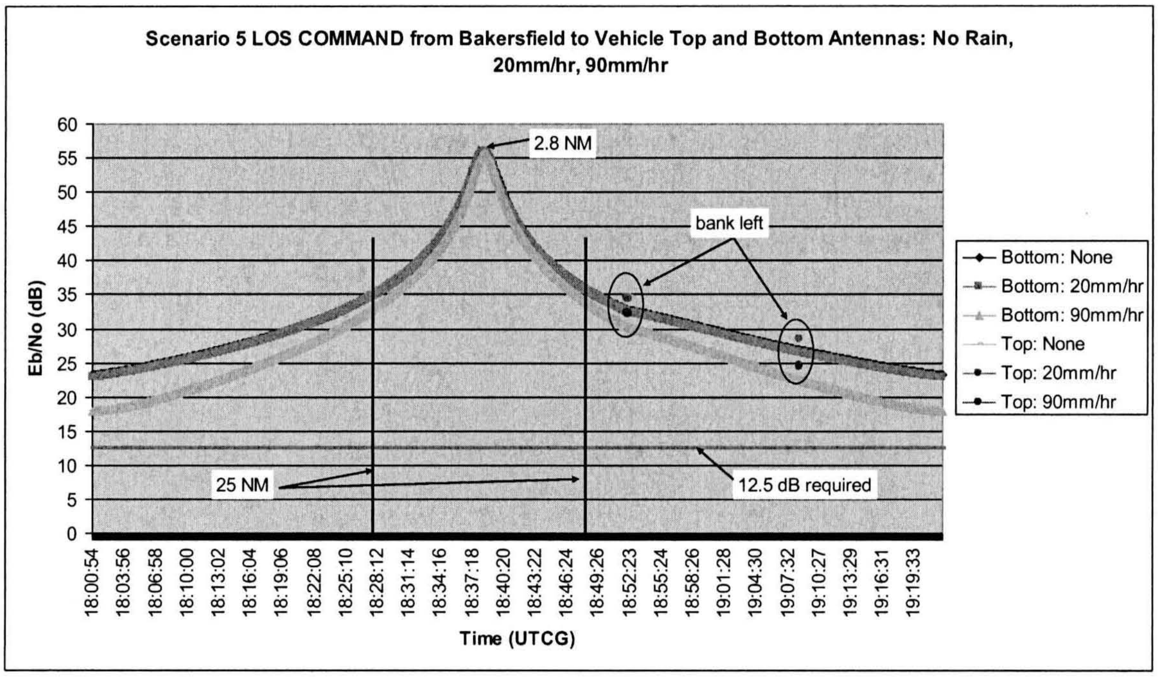

Figure 48: Scenario 5 - LOS COMMAND from Bakersfield to UA Top and Bottom Antennas

Figure 49: Scenario 5 - LOS Telemetry from UA to Bakersfield Top Antenna Figure 49, 50, and 51 are the telemetry link between the UA and Bakersfield CS. The Telemetry link follows very close to that of the command link except the signal strength is lower due to the higher data rate. The results are similar to those discussed in the previous paragraph.

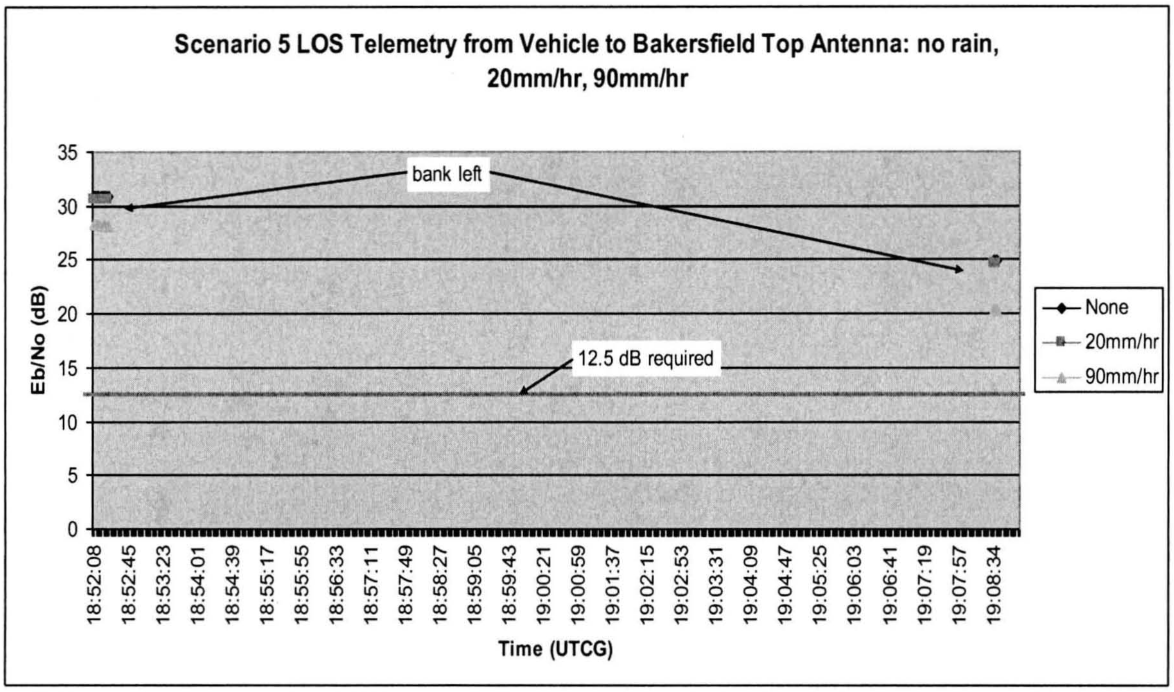

Figure 49: Scenario 5 - LOS Telemetry from UA to Bakersfield Top Antenna

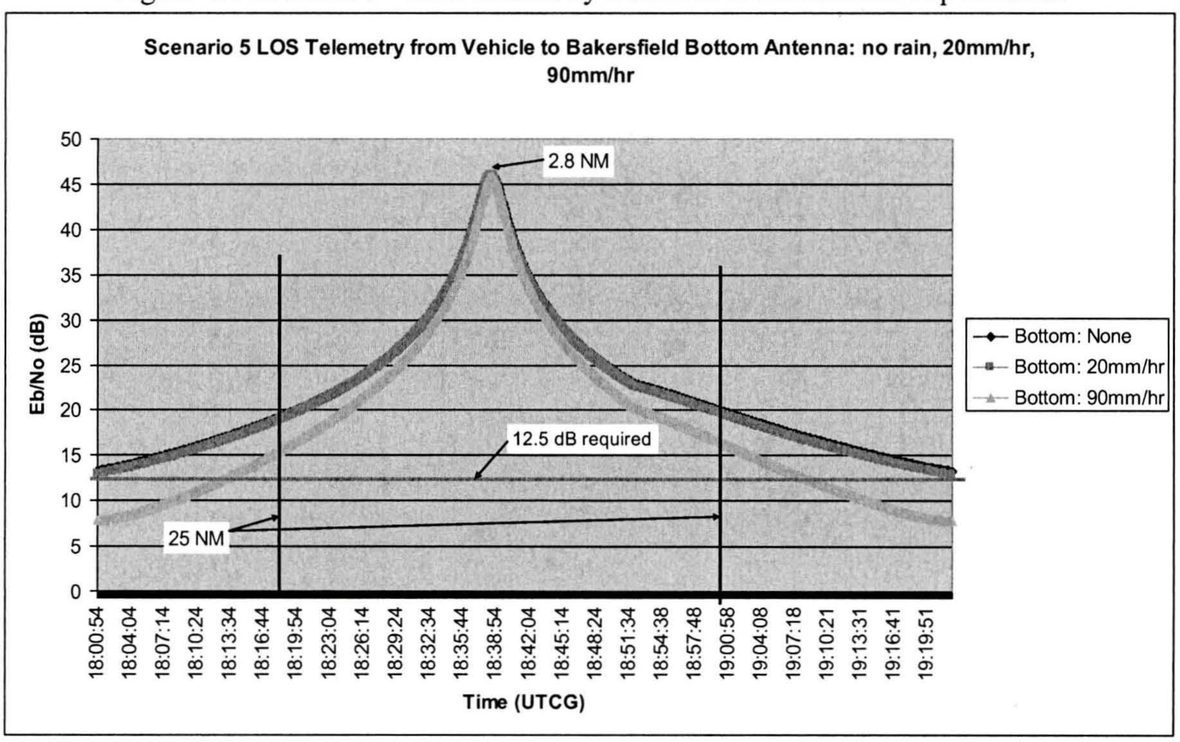

Figure 50: Scenario 5 - LOS Telemetry from UA to Bakersfield Bottom Antenna

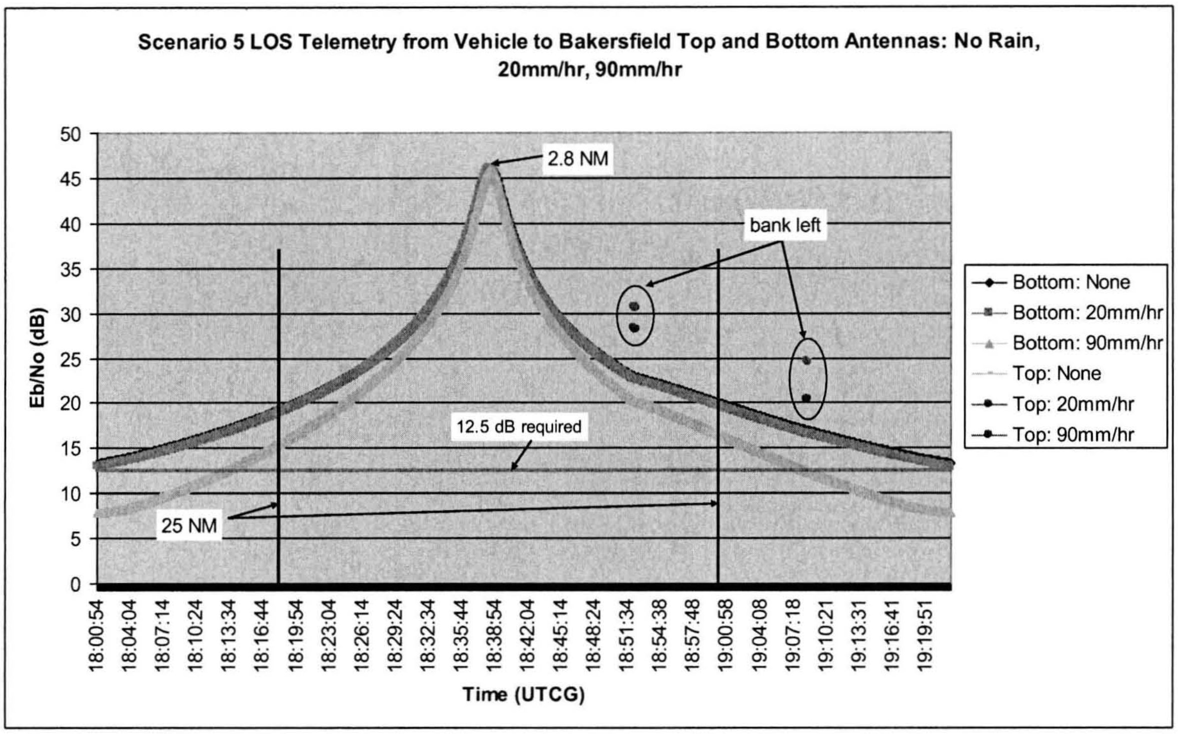

Figure 51: Scenario 5 - LOS Telemetry from UA to Bakersfield Top and Bottom Antennas

7.2.5 Scenario 5 - BLOS

The BLOS link is usually an easier link to model because it is a direct link going from either the UA or CS up to a GEO satellite. Multipath is usually not an issue and therefore the 6 dB safety margin is not required. Terrain is not a factor because of the link going up to the satellite.

There are actually four links for the BLOS:

- The command links; CS to GEO; GEO to UA.
- The telemetry links, UA to GEO and GEO to CS.
- The CS has the largest antennas with a gain of 59 dB whereas the UA antenna gain is only 38.2 dB, for a 1 meter dish on the UA. The GEO antenna gain is 38.2 dB.

For the command link budget calculation there was a 21.2 dB excess margin for the CS to the GEO Figure 52 and
Figure 53 GEO to UA. Unlike the LOS that was calculated for 25 NM, the BLOS link is calculated for a GEO satellite at an altitude of 22,000 miles. These graphs will have more of a straight line over time since the range does not change that much as the UA flies its flight path.

Figure 54 for this command link (CS to GEO) shows about 20 dB, which is inline with the link budget for command link. For the other part of the command link (GEO to UA) there is a -0.65 excess margin in the link calculation from Section 6.5 Radio Link Budget. The graph is showing a 4 dB excess margin and for the 90mm/rain only about a 0.5 dB excess gain.

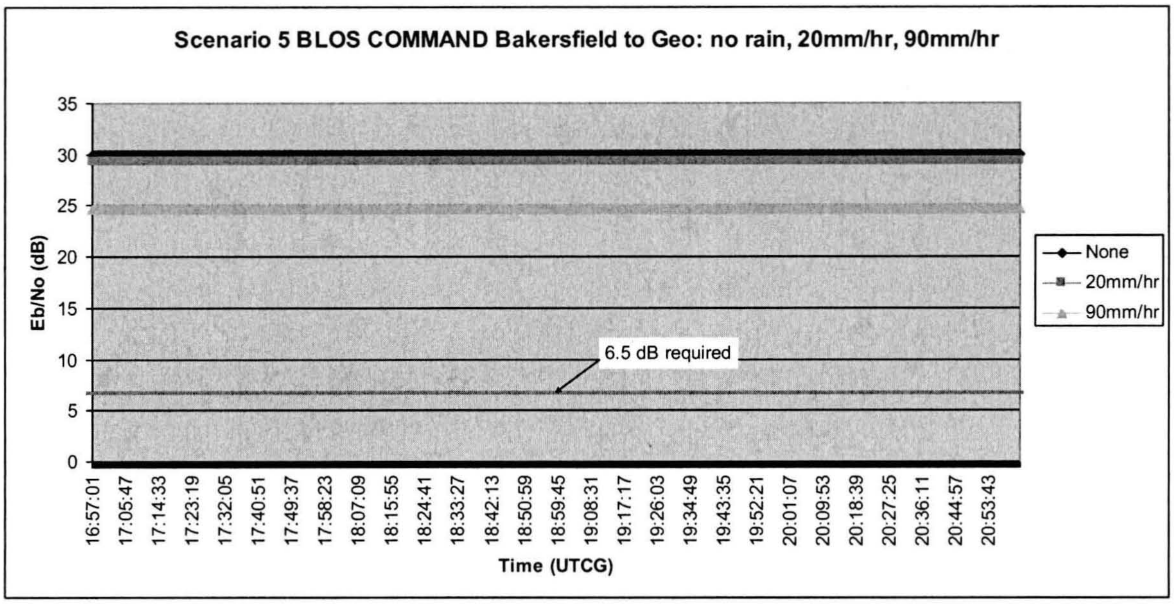

Figure 52 : Scenario 5 - BLOS COMMAND Bakersfield to GEO

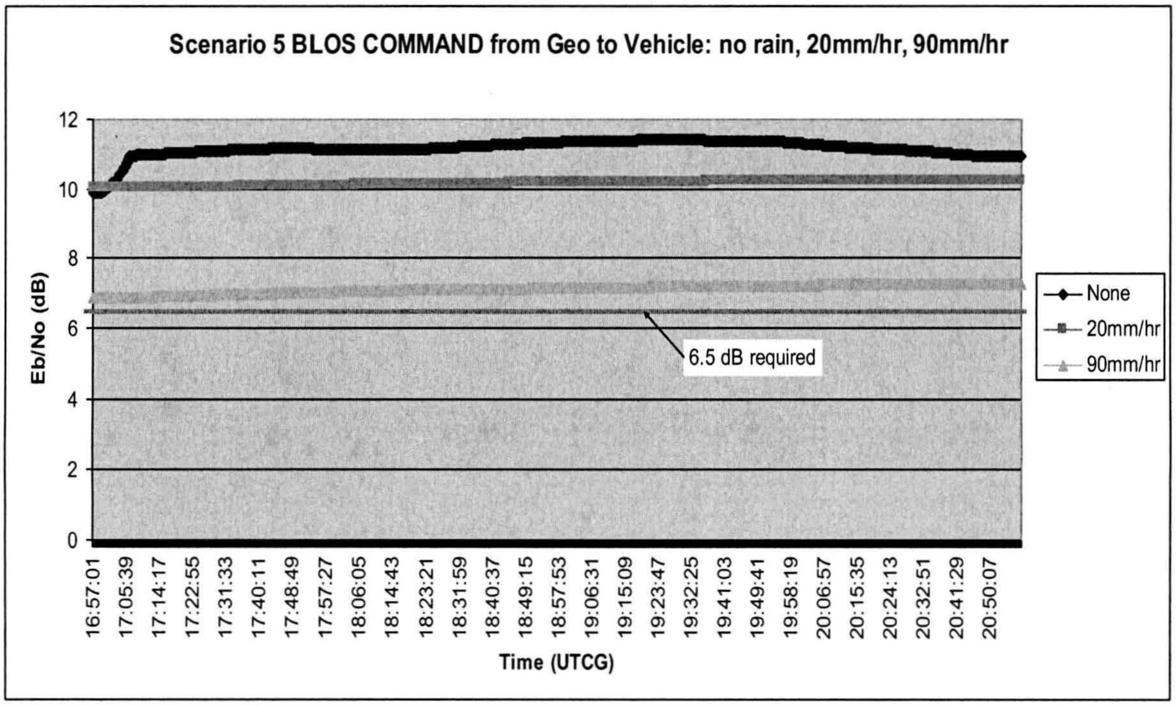

Figure 53: Scenario 5 - BLOS COMMAND from GEO to UA

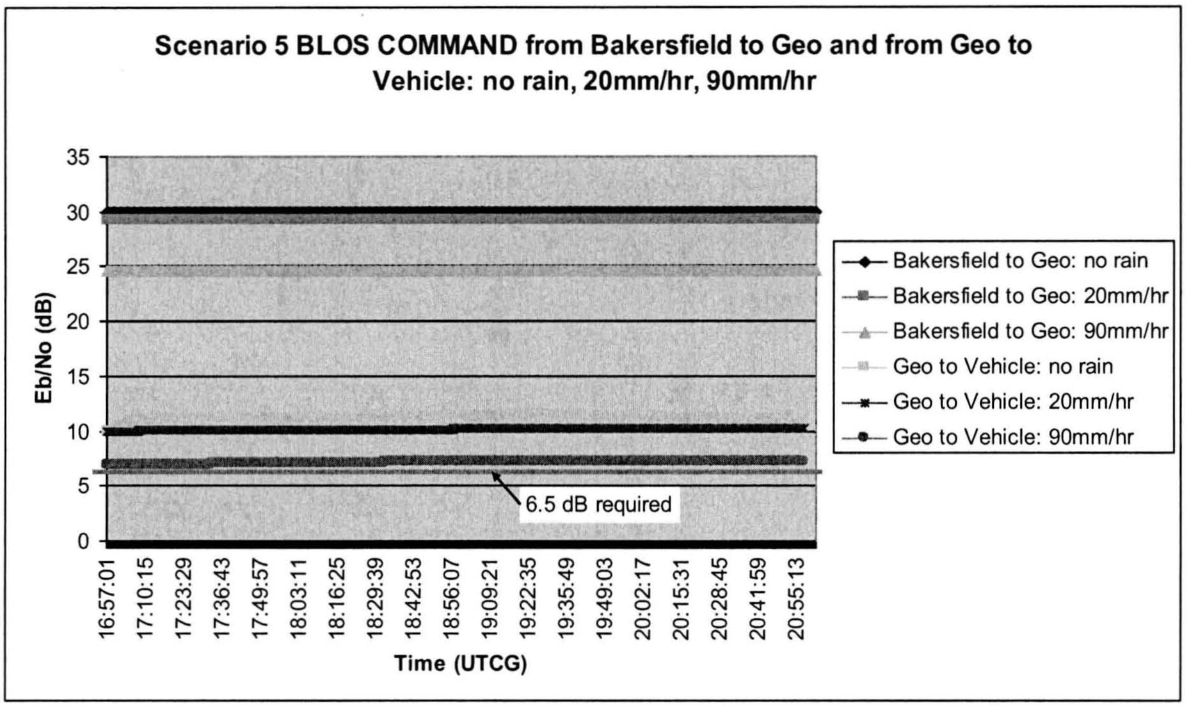

Figure 54: Scenario 5 - BLOS COMMAND from Bakersfield to GEO and from Geo to UA

Figure 56: Scenario 5 - BLOS Telemetry from UA to GEO 55 and Figure 56 show the telemetry link from the UA to the GEO and the GEO to the CS at Bakersfield. The link margin calculations show an excess margin of 11.88 dB, whereas the graph below shows an excess margin of about 2 dB and no excess for either the 20 mm/hr or 90 mm/hr rain rate. Figure 55: Scenario 5 - BLOS Telemetry from GEO to Bakersfield shows the GEO to the CS at Bakersfield. The calculated excess margin was 15.1363 dB. The graph for this link shows an excess margin of 15 dB, whereas for the 90 mm/hr rain rate the excess margin is about 10 dB.

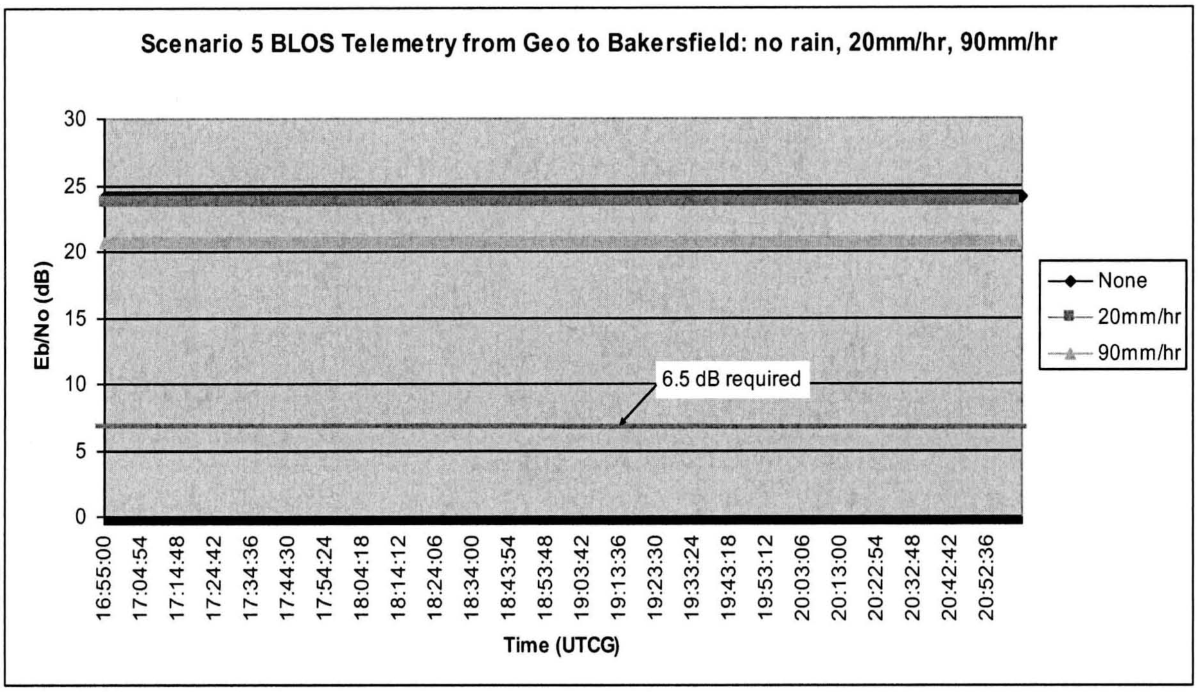

Figure 55: Scenario 5 - BLOS Telemetry from GEO to Bakersfield

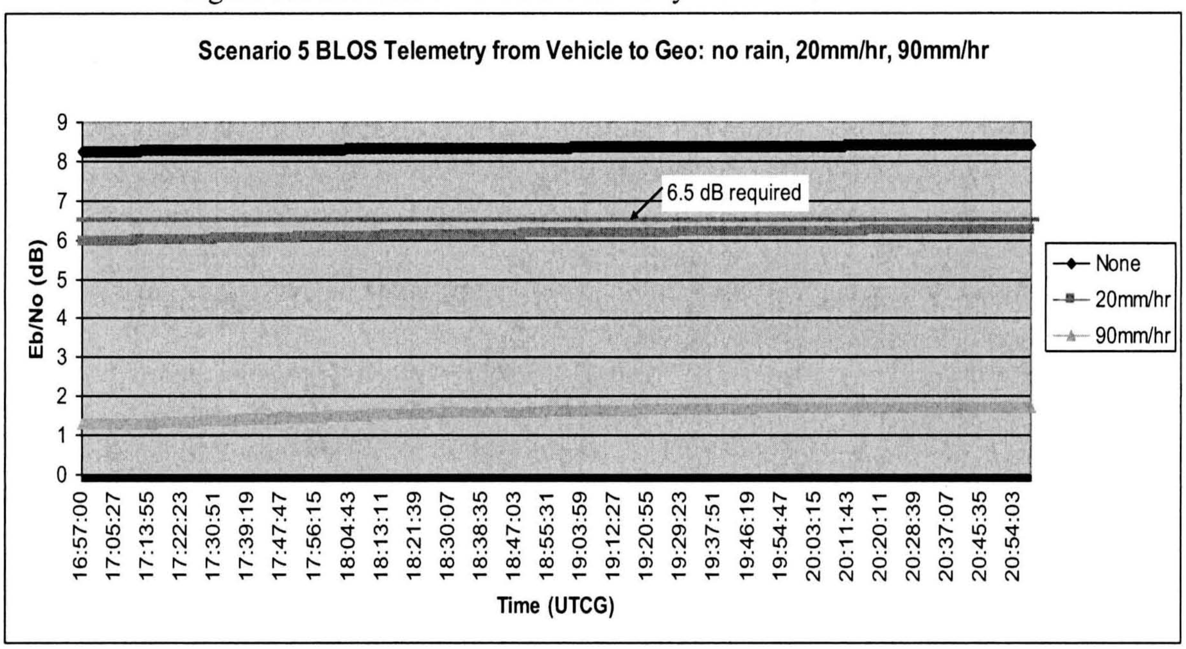

Figure 56: Scenario 5 - BLOS Telemetry from UA to GEO

For the telemetry links, the only links that did not meet the required 6.5 dB were the UA to the GEO for both rain rates (20 mm/hr and 90 mm/hr).

7.2.6 Scenario 5 – BLOS Interference

This scenario analyzed the effects of interference on the command link from the GEO to the UA from an adjacent satellite. An adjacent satellite was placed 2 degrees away from the GEO and then moved toward the GEO in 0.5 degree steps. There was no noticeable interference until the second GEO was 1.5 degrees and no adverse effect until the second GEO was 1 degree apart. This would degrade the performance down to about a 10^{-3} BER, which is unacceptable.

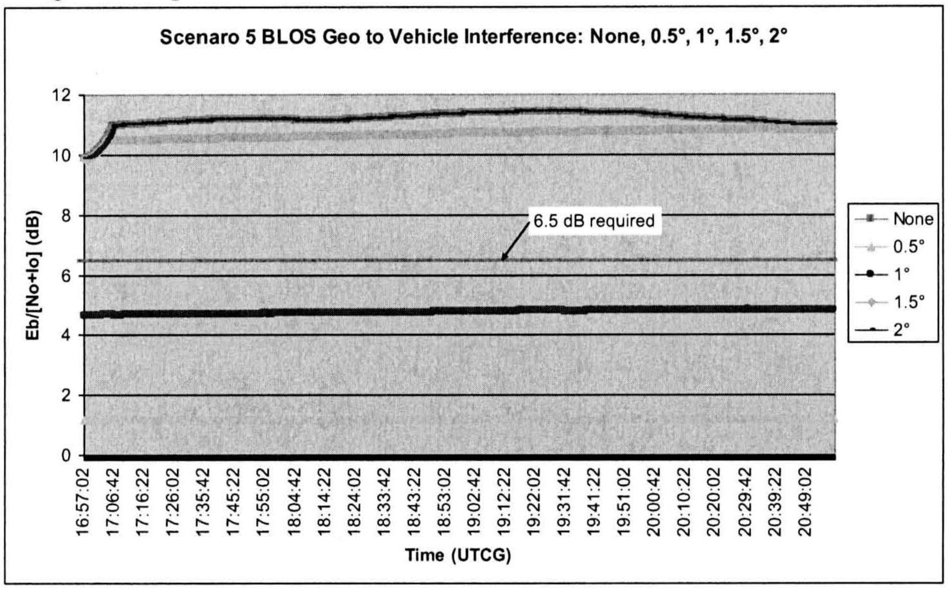

Figure 57: Scenario 5 - BLOS COMMAND from Geo to UA Interference

7.2.7 Scenario 5 - Gaps

Figure 58 graphically depicts the dropouts or gaps in the link. The gap analysis shows many small gaps of 1-2 seconds as well as the larger gaps covered in detail in the graphs above.

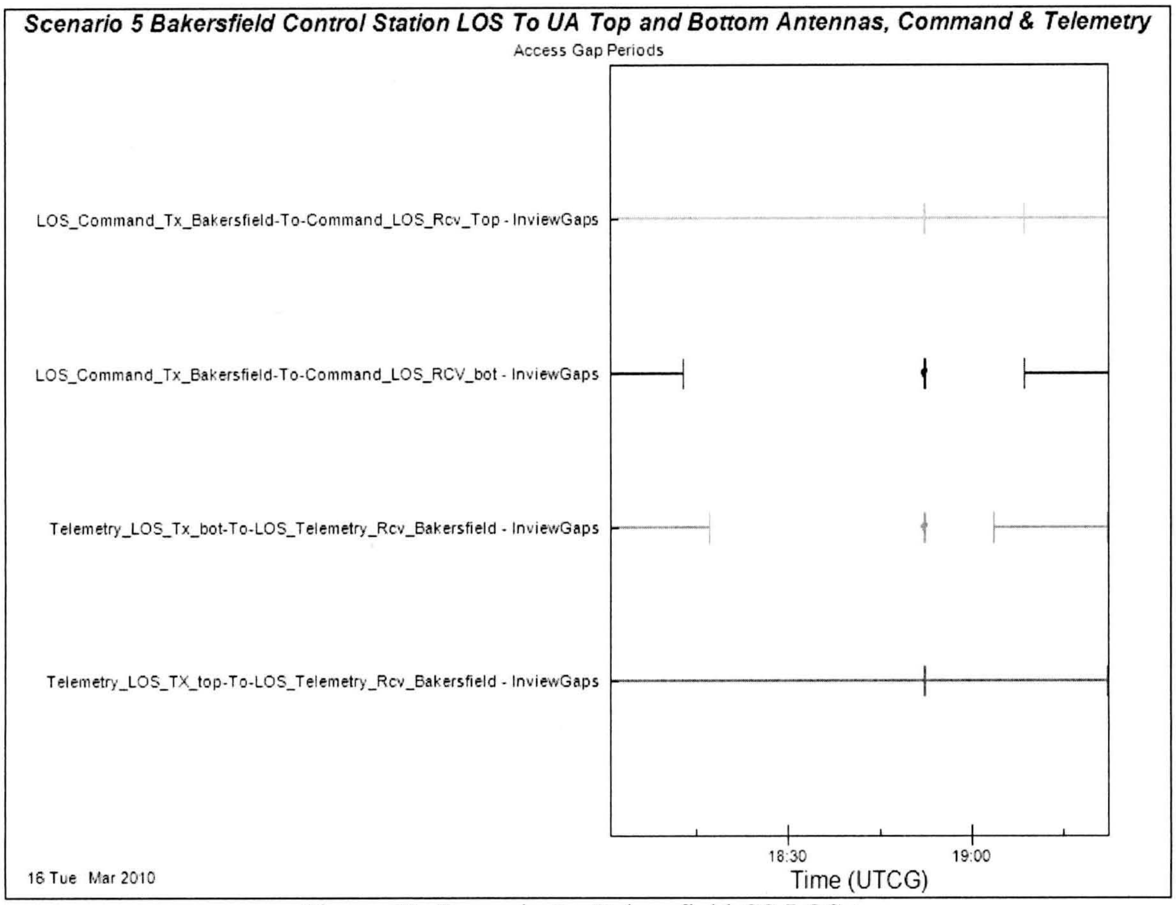

Figure 58: Scenario 5 - Bakersfield CS LOS to UA Top and Bottom Antennas, Command and Telemetry

7.2.8 Scenario 5 - QualNet

QualNet was used in this scenario to analyze if there was any dropped packets and what the delay would be. Results are illustrated in Table 5. This was a very high level approach to this analysis and will be further explored in follow-on M&S activities.

The RF propagation delay to the GEO for this scenario was .128 seconds compared to a known RF propagation delay link to a GEO satellite of .125 seconds. It was determined that the delay difference of a known RF propagation delay to the GEO and this scenario RF propagation delay of .003 sec is within reason for the delays through the avionics. Further work needs to be done in QualNet for the links as well as the land lines between the CS.

The GEO to UA had a high jitter that resulted in a 1 packet loss. It will take more detailed analysis to determine why this was so since the signal strength was about the same for the UA to GEO.

Table 5: QualNet Network Results

	BLOS			
	Command		Telemetry	
	CS to GEO	GEO to UA	UA to GEO	GEO to CS
Average Delay	0.13298	2.30570	0.13638	0.13298
Jitter	0.00260	0.20400	0.00343	0.00260
Maximum Delay	0.13041	0.40470	0.47267	0.38816
Packets Dropped	0	1	0	0

7.2.9 Scenario 5 - Results

The BLOS control link between the CS and UA was closed during the entire flight. The graphs followed fairly close to link calculations as compared to the LOS calculations at 25 NM. For the LOS, at 25 NM, there is an excess margin of 25 dB. If we minus off the 20 dB multipath margin, we are left with a 5 dB margin over that which is required. There is about a 5 dB difference in the 90 mm/hr over the 45 minutes of the graph on the bottom telemetry antenna.

Again, as with Scenario 1, the combined LOS antennas do not show any dropouts.

For the BLOS command link budget calculation there was a 21.2 dB excess margin. Unlike the LOS that was calculated for 25 NM, the BLOS link is calculated for a GEO satellite at an altitude of 22,000 miles. These graphs will have more of a straight line over time since the range does not change that much as the UA flies its flight path. The graph for the command link shows about 20 dB, which is inline with the link budget for command link.

This scenario analyzed the effects of interference on the command link from the GEO to the UA from an adjacent satellite. An adjacent satellite was placed 2 degrees away from the GEO and then moved toward the GEO in 0.5 degree steps. There was no noticeable interference until the second GEO was 1.5 degrees away from the primary GEO and no adverse effect until the second GEO was 1 degree apart causing the performance to degrade to about a 10^{-3} BER, which is unacceptable.

7.3 SCENARIO 6: BORDER SURVEILLANCE AND TRACKING TURBOPROP

OSED Scenario 6 involves a Predator B turboprop UA performing border surveillance tracking border incursions on the northern border of the U.S. The flight is a routine operation, taking place at night, but with the expectation of some unplanned aerial work if and when any border incursions or smuggling operations are witnessed. Areas of interest covered by this scenario include IFR operations in controlled airspace, controlled airport operations, and unplanned aerial maneuvers in a dense en route air traffic environment.

Figure 59: Predator B UA

7.3.1 Flight Overview

Figure 60: Scenario 6 Flight Path60 shows the path of the Predator B UA on the northern border U.S.

Figure 60: Scenario 6 Flight Path

7.3.2 UA Description

According to the RTCA OSED, the Predator B is a turboprop, long-endurance UA whose performance is characterized by modest climb rates and flight speeds. It is flown with the pilot-in-the-loop (manual control) during takeoff and landing. During planned or unplanned aerial work it's flown with a combination of semi-autonomous pilot-in-the-loop and manual pilot-in-the-loop. The CS is designed specifically for the Predator B and is not shared with other UA. The pilot's planning rooms and CS are located within a secure access area located on the periphery of the airport, near the National Guard buildings, as are the ground support crew and aircraft hangars.

7.3.3 Scenario 6 - Set Up

The architecture for scenario 6 is shown in

This scenario starts and ends with LOS links for takeoff and landing from Syracuse, NY. BLOS (SATCOM) is used when out of range for LOS. The majority of the time for command and telemetry RF links occurred during BLOS. The UA monitors the US and Canada northeast border for approximately twelve hours. The unplanned aerial work consist of flying figure eight patterns in an area approximately 10 by 20 nautical miles during LOS, then the UA goes to BLOS. There is only one CS in this scenario. The effect of rain on the link margin is determined with 0 mm/hr. rain, 20 mm/hr. rain, and 90 mm/hr. rain.

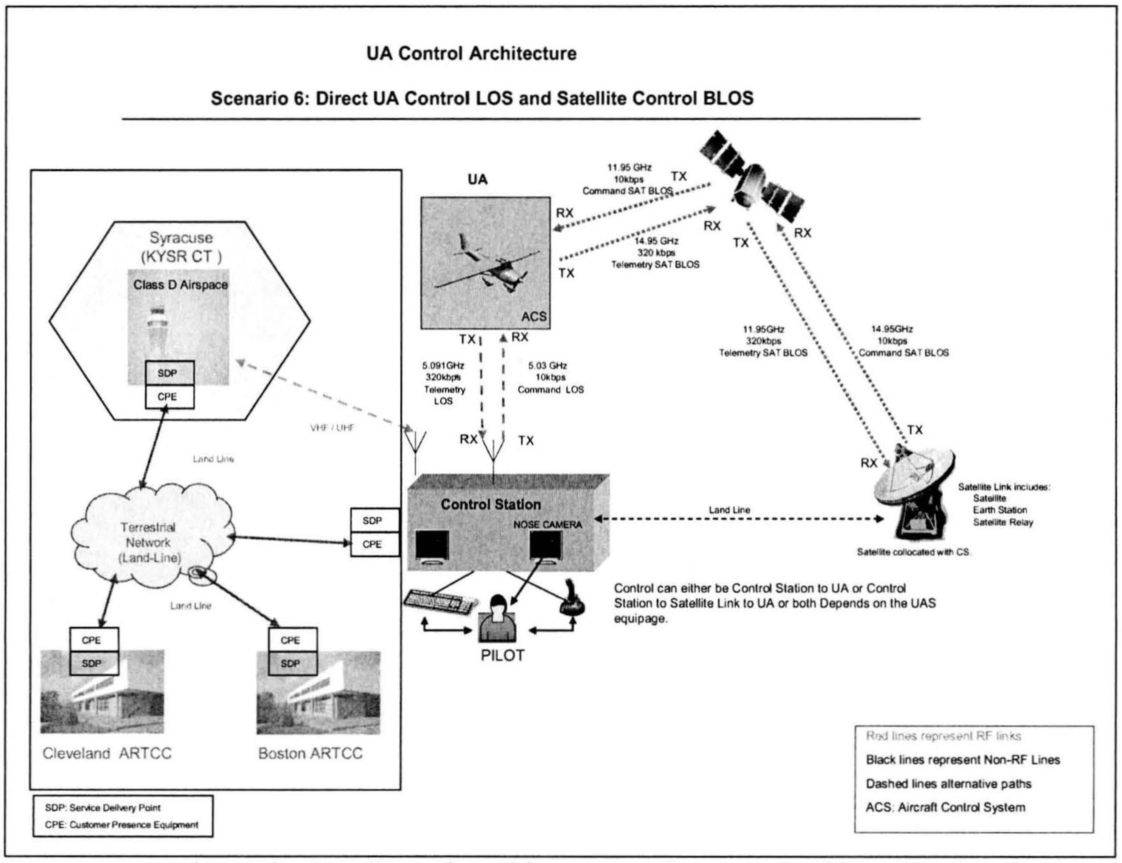

Figure 61: UA Control Architecture — Scenario 6 - Direct UA Control LOS and Satellite Control BLOS

Figure 62: Scenario 6 Eb/No shows the BLOS and LOS links. The BLOS links CS to satellite and the satellite to UA is shown in green. The LOS link CS to UA top antenna is in red, and the LOS CS to bottom antenna is in yellow. The gaps occur on the during both LOS links.

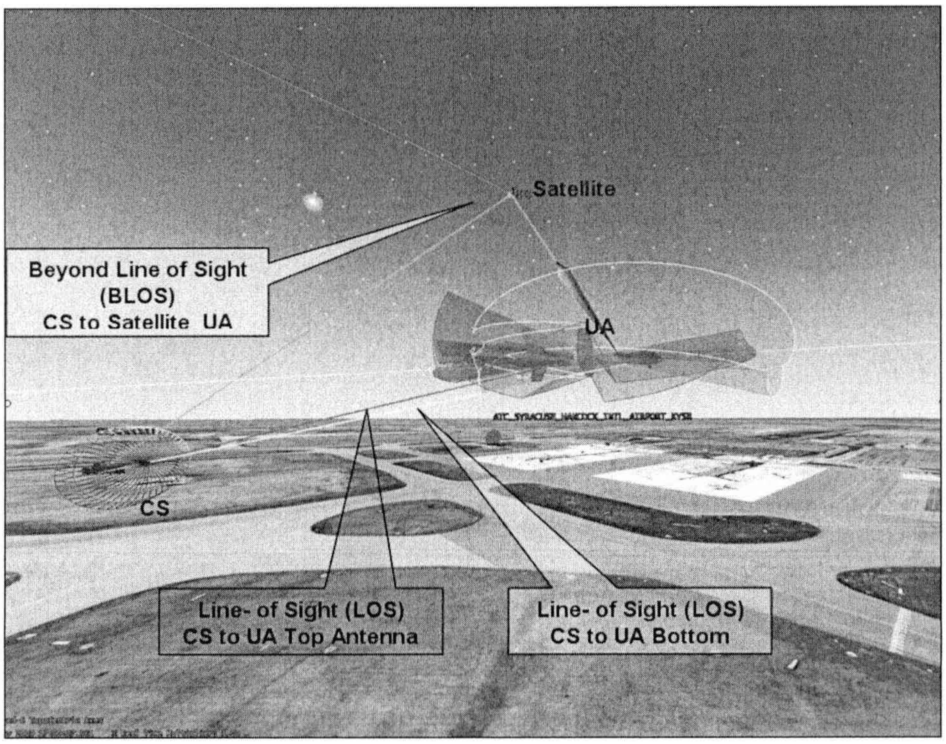

Figure 62: Scenario 6 Eb/No (Link Gaps)

7.3.4 Scenario 6 - LOS

The next six graphs Figure 63: Scenario 6 - LOS COMMAND from Syracuse to UA Top Antenna

The first part of the flight, LOS, showed various dropouts due to the wing, front of the plane and the tail. After the BLOS part of the flight the UA flies back into the LOS range but there are no more dropouts as the UA flies toward the CS.

Figure 68 shows the combined antennas top and bottom. There are still dropouts as compared to Scenario 1, where all three CS are combined with top and bottom antennas there are no dropouts at all. This is a problem of only having one CS to one UA even with two antennas there are still dropouts depending on flight path and placement of antennas on the UA.

This is critical and is one of the most important results of this paper. The success of an RF link depends on many factures, the conditions of the link (e.g., signal strength), the environment the UAS is operating (rain levels, type of terrain, urban) the geometry of the UA during flight, the location of the antennas on an UA, and the number of transmitters / receivers / CS(s) required to complete a mission.

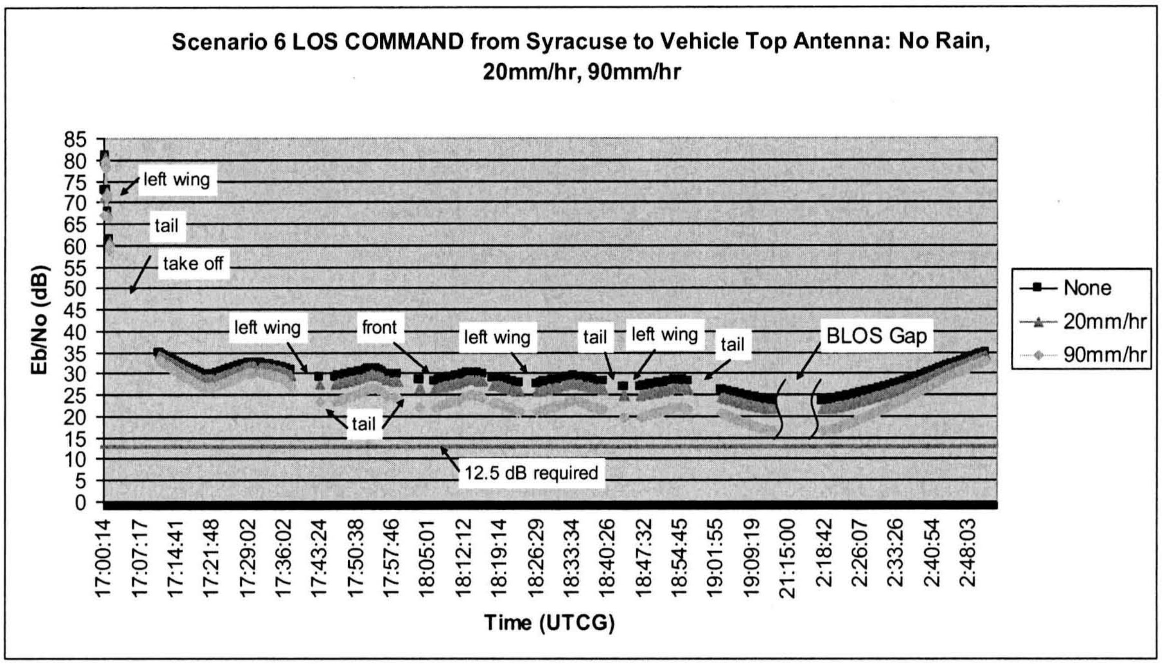

Figure 63: Scenario 6 - LOS COMMAND from Syracuse to UA Top Antenna

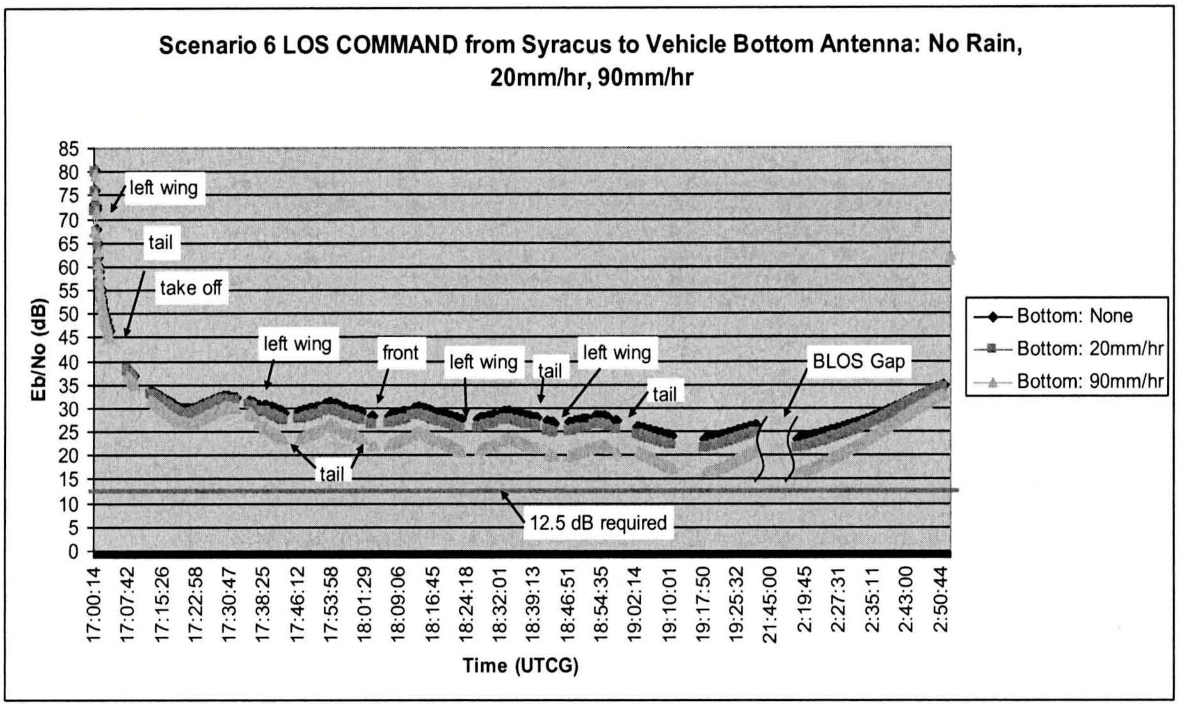

Figure 64: Scenario 6 - LOS COMMAND from Syracuse to UA Bottom Antenna

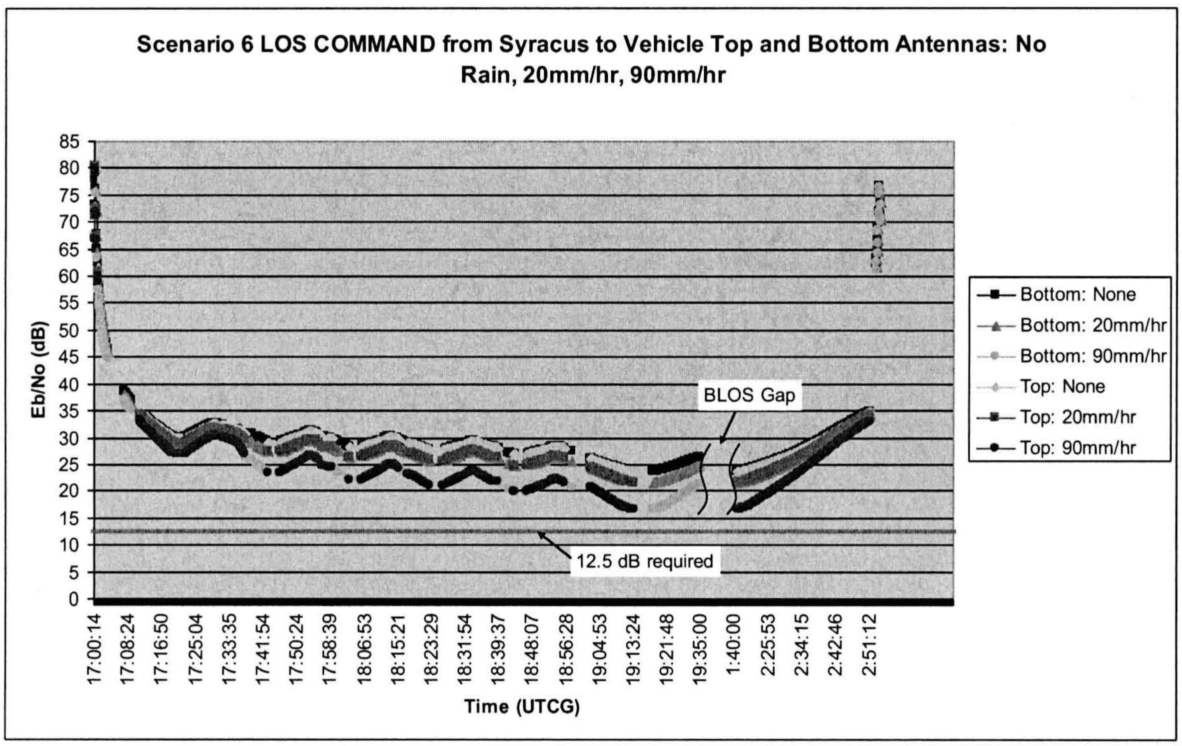

Figure 65: Scenario 6 - LOS COMMAND from Syracuse to UA Top and Bottom Antennas

The telemetry LOS shows that again there are various dropouts due to the wing, front of the plane, and the tail. After the BLOS gap, the UA flies back in the LOS range but there are no more dropouts. The results follow the same trend as the command but at lower signal strength due to the higher data rate taking more RF power.

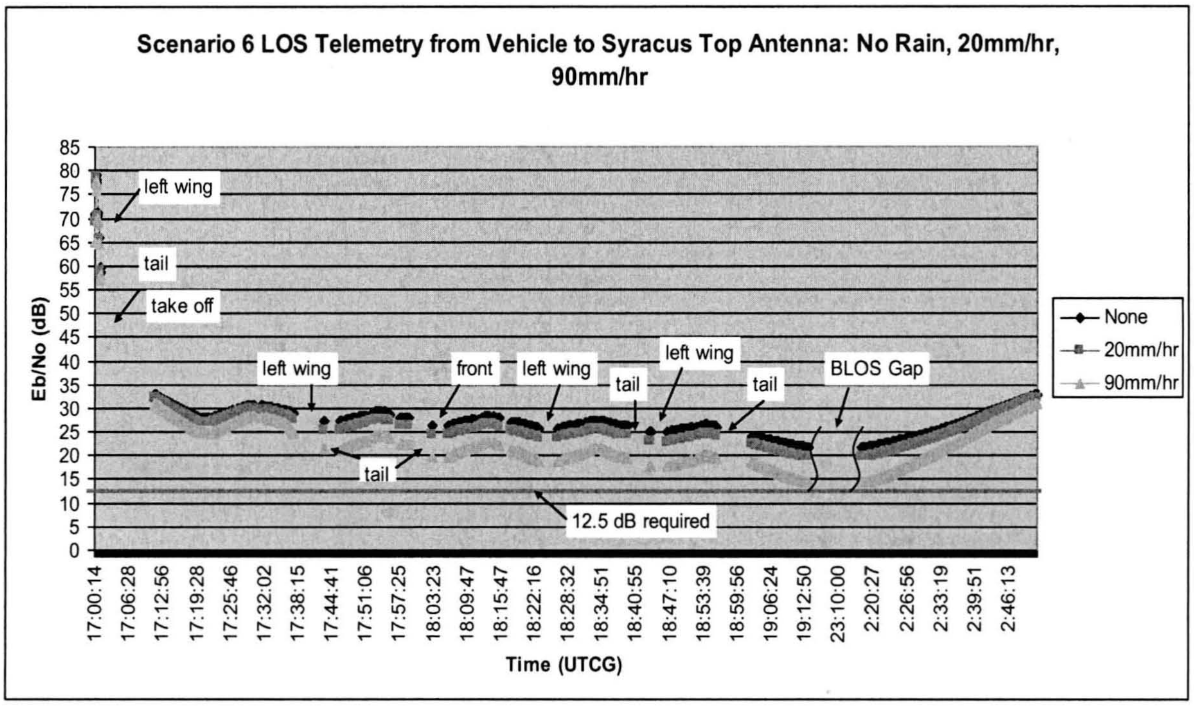

Figure 66: Scenario 6 - LOS Telemetry from UA to Syracuse Top Antenna

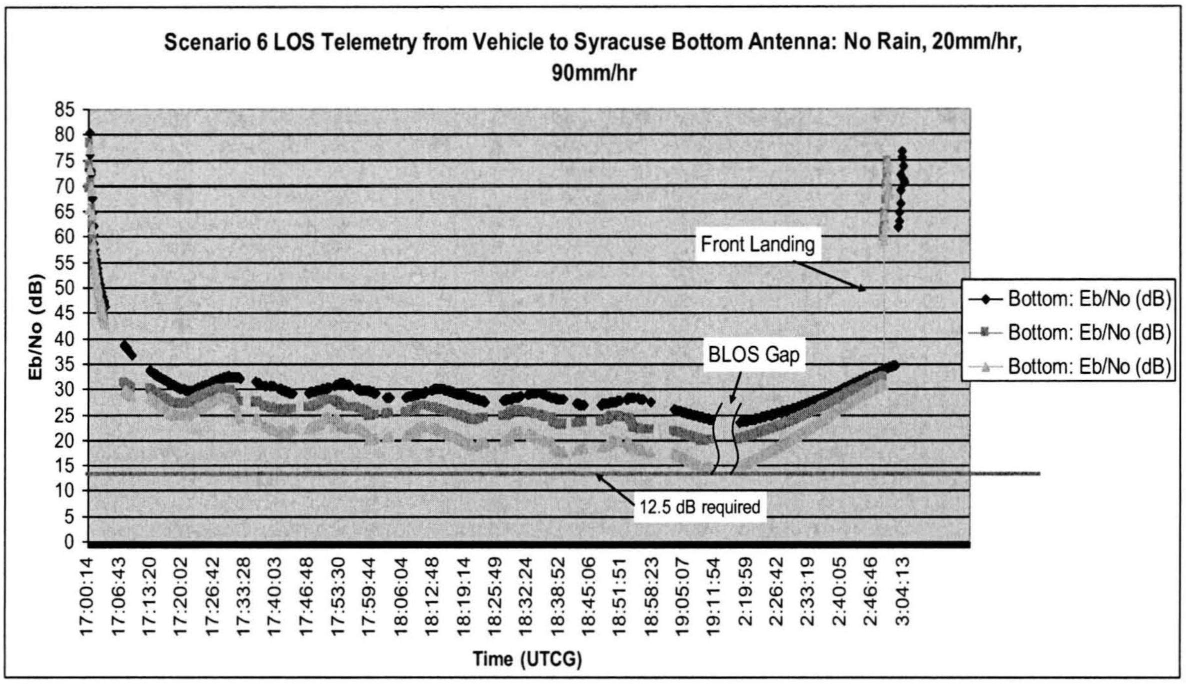

Figure 67: Scenario 6 - LOS Telemetry from UA to Syracuse Bottom Antenna

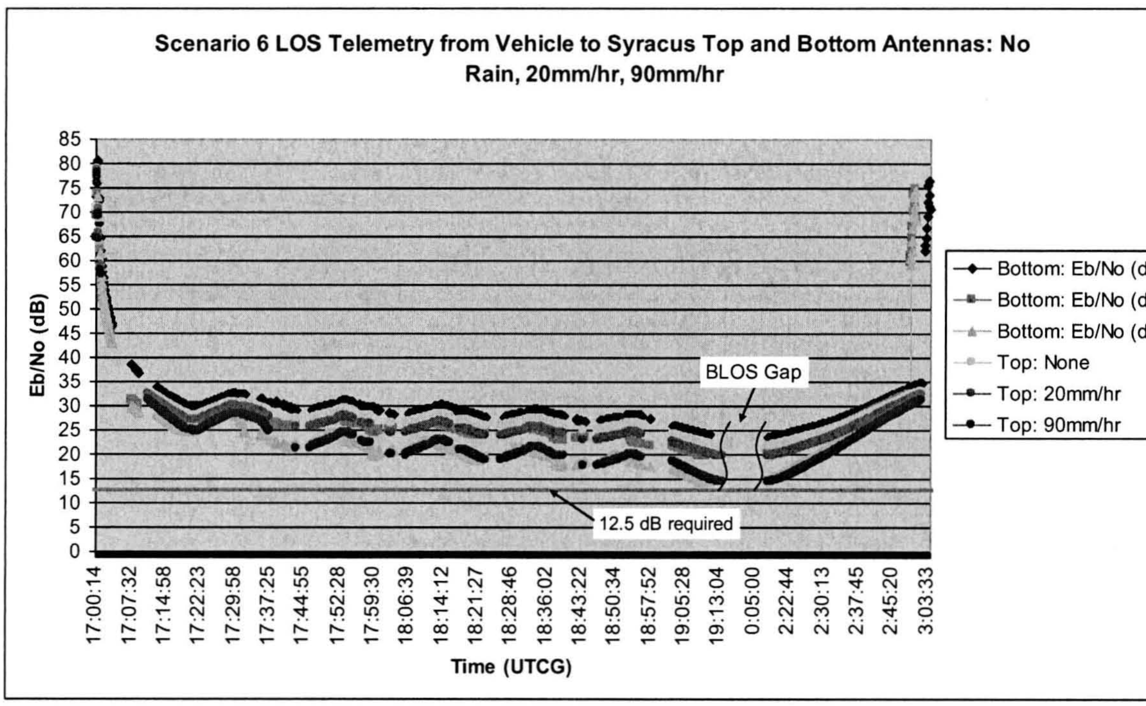

Figure 68: Scenario 6 - LOS Telemetry from UA to Syracuse Top and Bottom Antennas

7.3.5 Scenario 6 – BLOS

The next four graphs Figure 63: Scenario 6 - LOS COMMAND from Syracuse to UA Top Antenna
Figure 69: Scenario 6 - BLOS COMMAND from Syracuse to GEO is the CS up to the GEO has a calculated excess margin of 21.2 dB and the graph shows 25 dB for no rain and 17 dB for the 90 mm/hr. rain.

Figure 70: Scenario 6 - BLOS COMMAND from GEO to UA
is the command from GEO to the UA has a calculated excess of -0.65 and the graph shows an excess of gain of about 5 for no rain and about 0.5 dB for the 90 mm/hr. rain.

Figure 71: Scenario 6 - BLOS Telemetry from UA to GEO 71 is the telemetry for the UA up to the GEO. The calculated excess margin is 11.88 dB, whereas the graph shows about 2 dB for no rain and a -1 dB for 20 mm/hr. and down to 0 for 90 mm/hr. This link would fail during a heavy downpour and be of about 10-4 BER for moderate rain of 20 mm/hr.

Figure 72: is the telemetry from the GEO to the CS at Syracuse. The calculated excess link margin is 15.13 dB, whereas the graph shows about 18.5 dB, and the heavy rain is about 5 dB less or 13.5 dB.

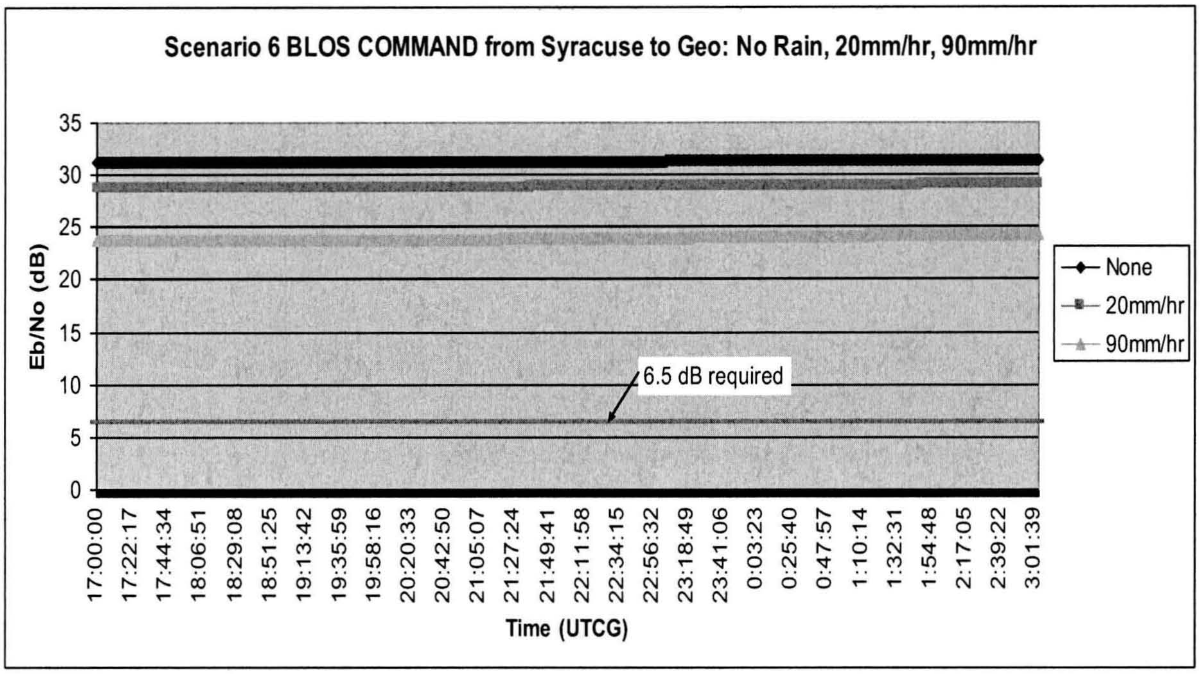

Figure 69: Scenario 6 - BLOS COMMAND from Syracuse to GEO

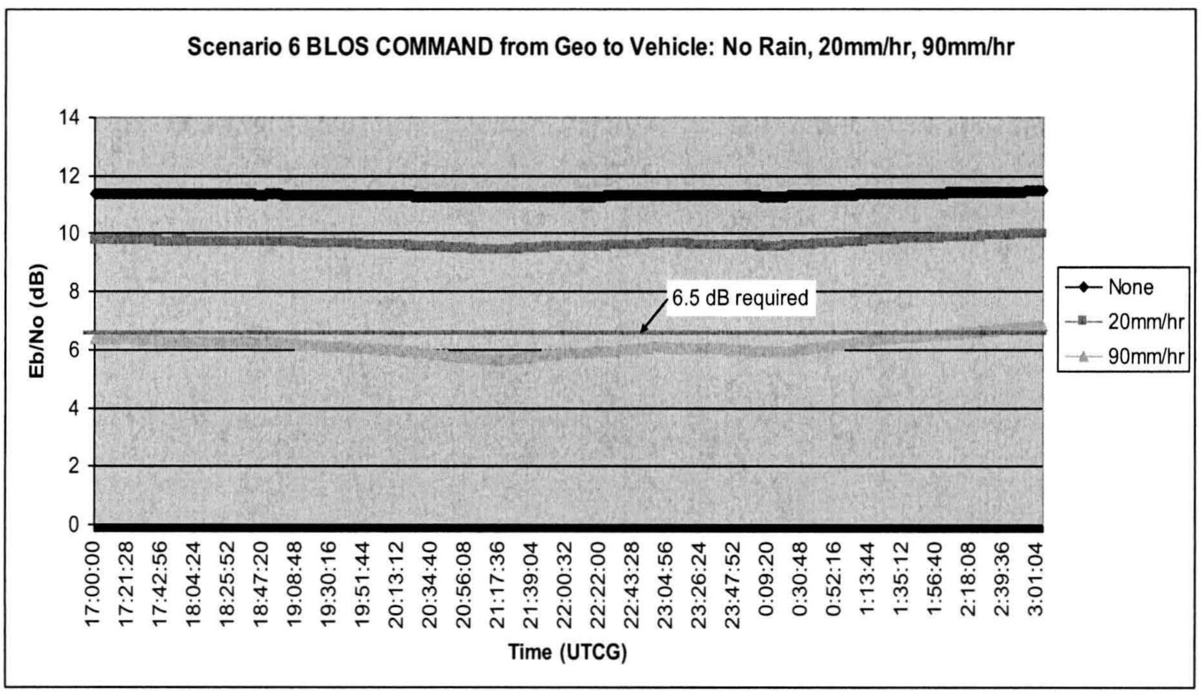

Figure 70: Scenario 6 - BLOS COMMAND from GEO to UA

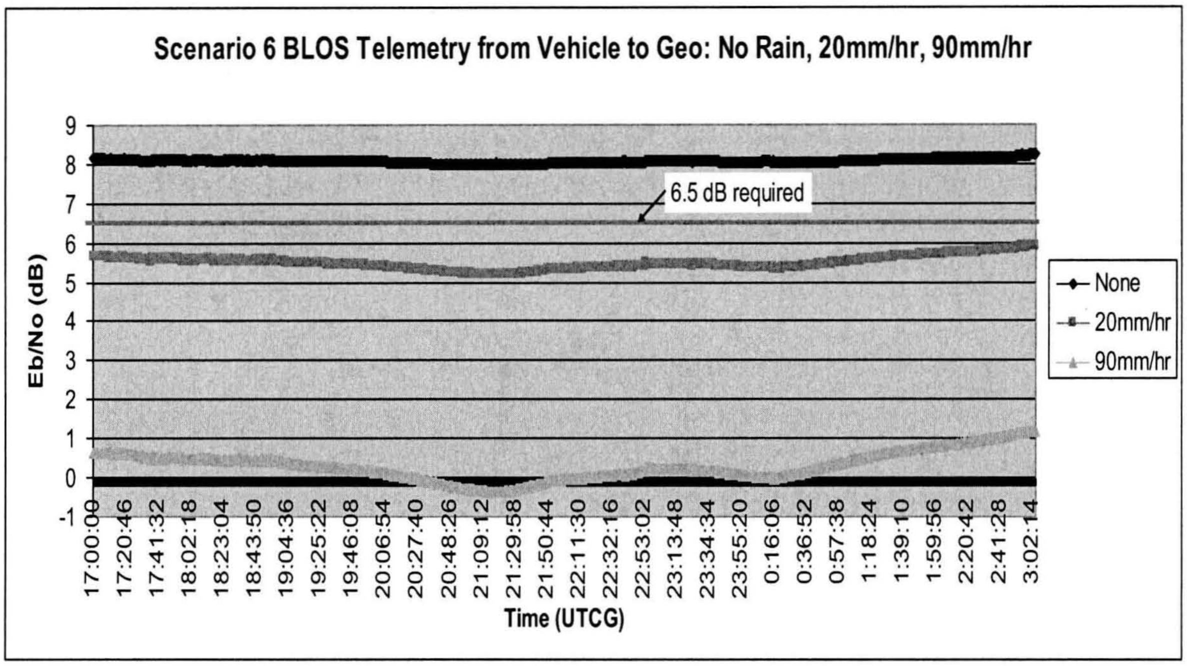

Figure 71: Scenario 6 - BLOS Telemetry from UA to GEO

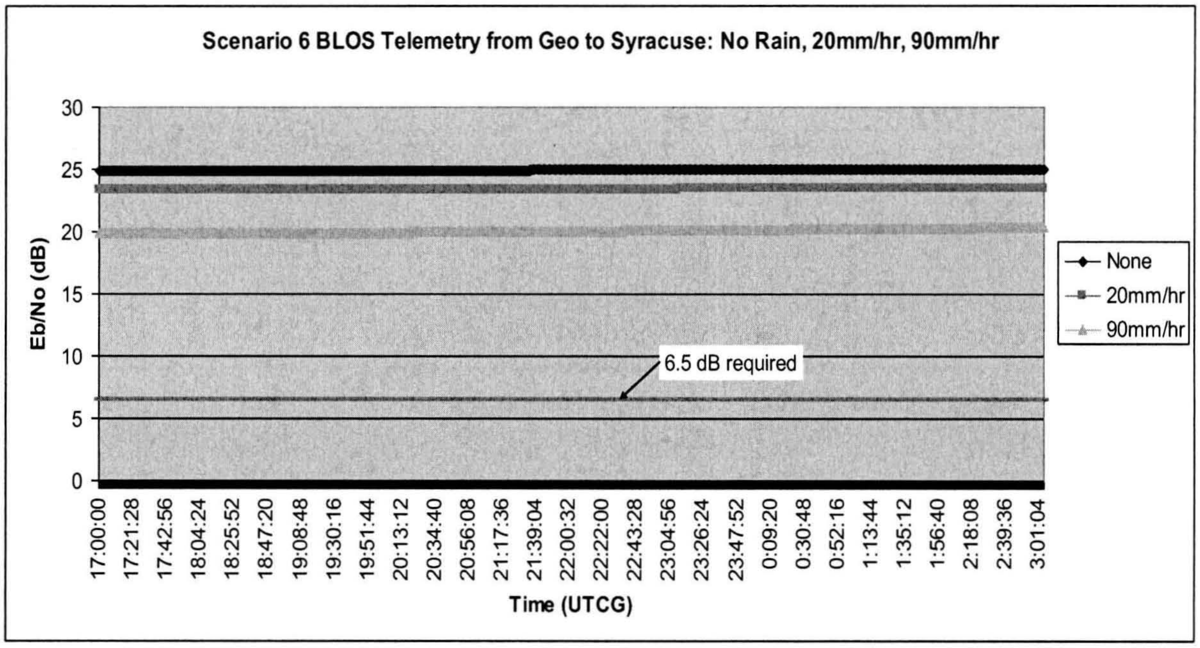

Figure 72: Scenario 6 - BLOS Telemetry from GEO to Syracuse

7.3.6 Scenario 6 - Gaps

The figure 73: below shows graphically depicts the dropouts or gaps in the link. The gap analysis shows many small gaps of 1-2 seconds as well as the larger gaps covered in detail in the above graphs.

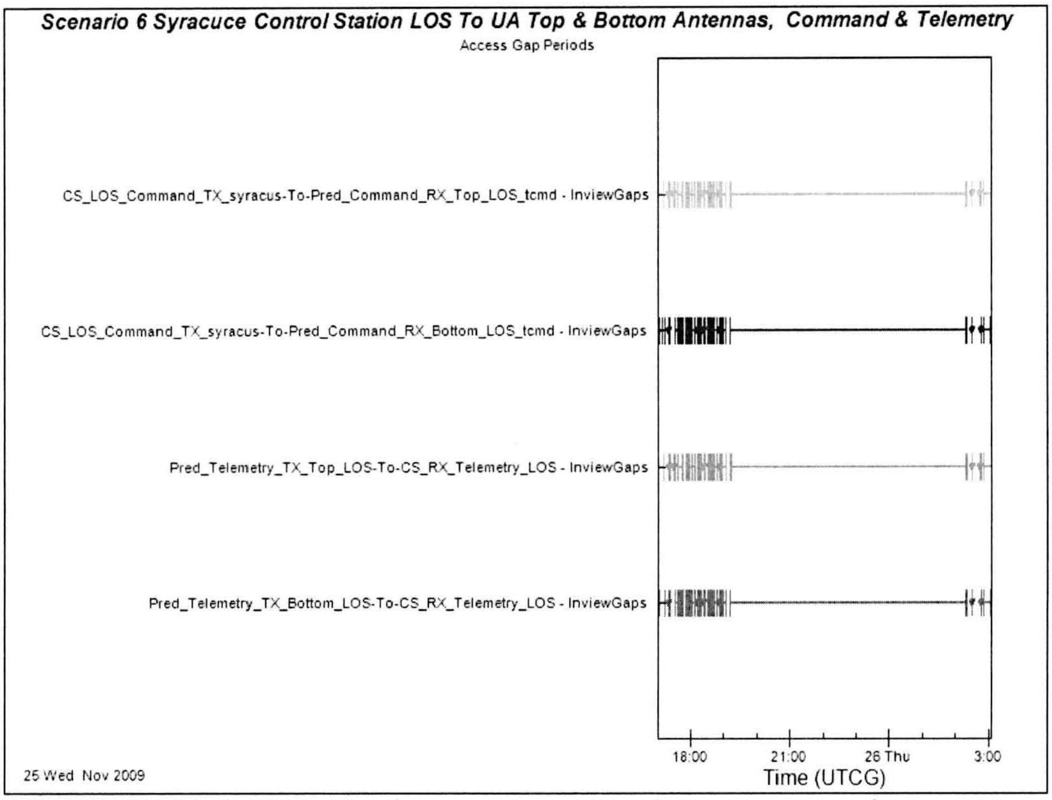

Figure 73: Scenario 6 - Syracuse CS LOS to UA Top and Bottom Antennas, Command and Telemetry

7.3.7 Scenario 6 - Results

The LOS control link between the CS and UA dropped out during takeoff, landing, and aerial maneuvers. The RF link dropout occurred for both the top and bottom UA antennas were the results of aircraft obstructions (fuselage, wings, wheel assembles, etc.).

Scenario 6 shows that a single CS with LOS and BLOS links to the UA can be combined (using the top and bottom antennas) can have the same overall results of no RF dropout during the duration of the flight. This can be compared to Scenario 1 where three combined CS RF links (LOS) was required to close the control and telemetry links. This is critical and is one of the most important results of the paper. Scenario 6 BLOS follows along the same results as Scenario 5.

Figure: 69 graph is the CS up to the GEO. The calculated excess margin was 21.2 dB and the graph shows 25 for no rain and 17 dB for 90 mm/hr rain.

Figure: 70 graph is the command from GEO to the UA. It has a calculated excess of -0.65 and the graph shows an excess gain of about 5 for no rain and about 0.5 dB for the 90 mm/hr rain.

Figure: 71 graph is the telemetry for the UA up to the GEO. The calculated excess margin is 11.88 dB, whereas the graph shows about 2 dB for no rain and -1 dB for 20 mm/hr and down to

0 for 90 mm/hr. This link would fail during a heavy downpour and be of about 10^{-4} BER for moderate rain of 20 mm/hr.

Figure: 72 graph is the telemetry for GEO Satellite to the CS at Syracuse. The calculated excess margin is 15.13 dB, whereas the graph shows about 18.5 dB, and the heavy rain is about 5 dB less or 13.5 dB.

7.4 SCENARIO 1 - LOS CS (MT. WILSON) UPDATES AND RESULTS

7.4.1 Flight Overview Mt. Wilson Location

After the results above were presented to the SC203 CC WG2 it was decided that a single high elevation location was needed for the communications link instead of three separate ground locations. For comparison the three ground stations located in the Valley are shown in red and Mt Wilson, located in the mountains above Los Angeles, is shown in green in Figure 74. Also shown in Figure 74 are the difference air spaces that the UA utilizes. Mt Wilson has an observatory as well as other communication towers, thus it would be an ideal place to locate a UA Control Antenna. The following results were obtained after the control station was moved to Mt Wilson. The UA is at 400 feet altitude. What this simulation did not model was blockage due to buildings. There would have been a great deal of blockage due to buildings if the UA was flying at 400 feet in such a dense metropolitan area.

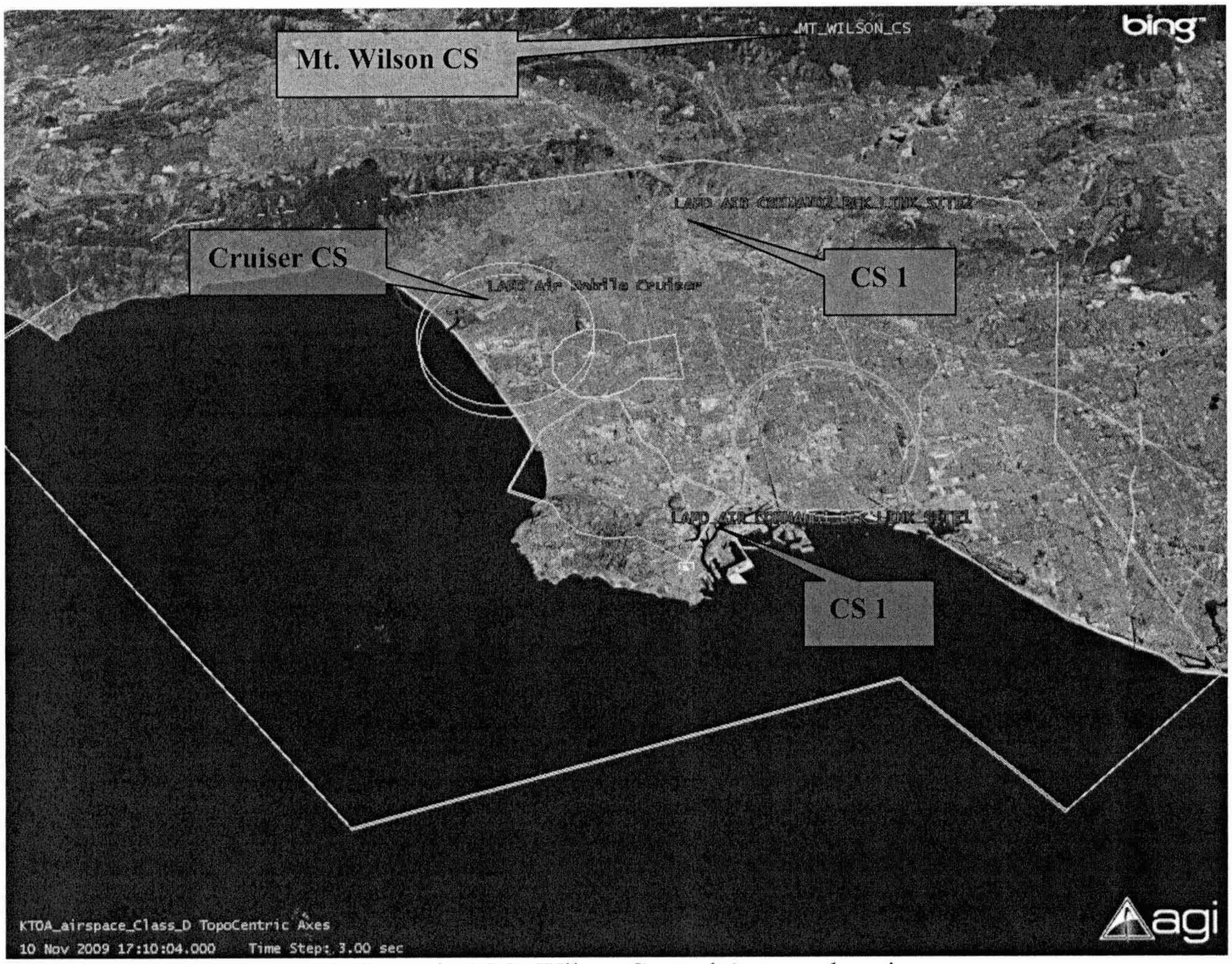

Figure 74: Scenario 1 Mt. Wilson Control Antenna location

The placement of the control station on Mt. Wilson instead of three separate ground stations proved to be very beneficial as will be shown in the next pages.

7.4.2 Antenna Patterns

In addition to the moving of the ground station to Mt. Wilson, the antenna pattern was changed from a 3 dB ideal Omni antenna to a more realistic antenna. The patterns of these two antennas are shown below (Figure 75, Figure 76). Figure 75 shows a polar plot of a typical 3 dB antenna and Figure 76 shows the same antenna as a STK graphic, depicting the top and bottom antenna pattern surrounding the UA. The Omni has a uniform 3 dB gain, whereas the realistic antenna has a peak gain of 4 dB and nominal gain of about 0 dB with deep nulls in the middle.

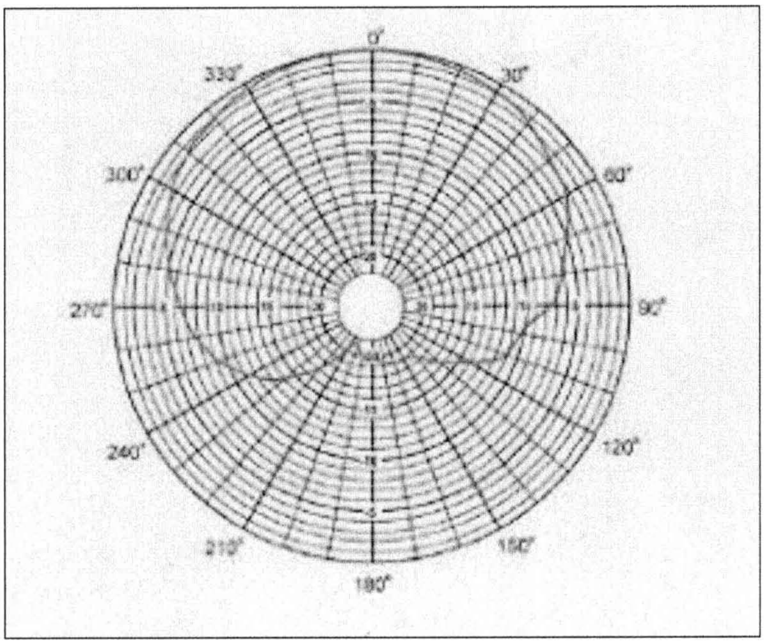

Figure 75: Polar Plot of a Typical 3 dB Antenna

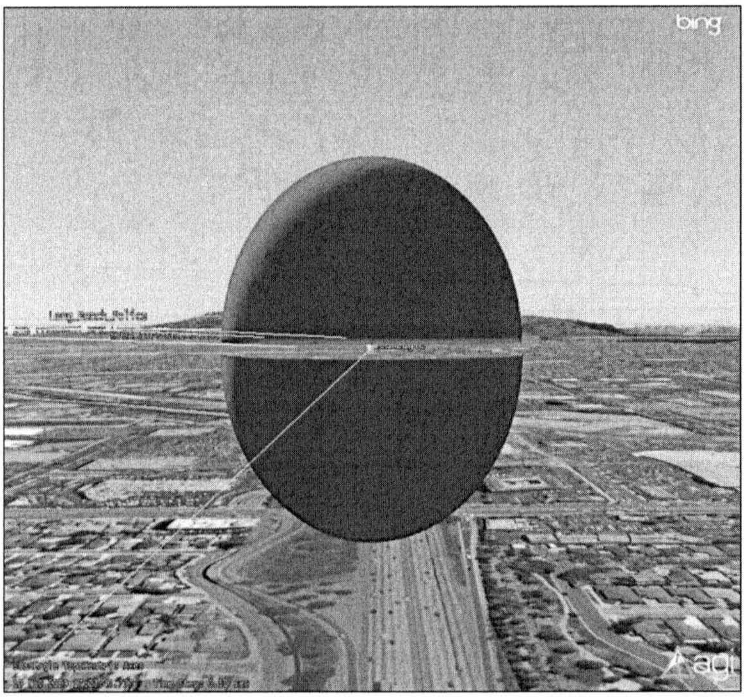

Figure 76: STK graphic of an Omni Antenna Pattern surrounding the UA

The following two figures show the realistic antenna plots, Figure 77 is a polar plot looking at a vertical cut of the antenna pattern. Figure 78 is a polar plot looking at a vertical cut of the antenna pattern.

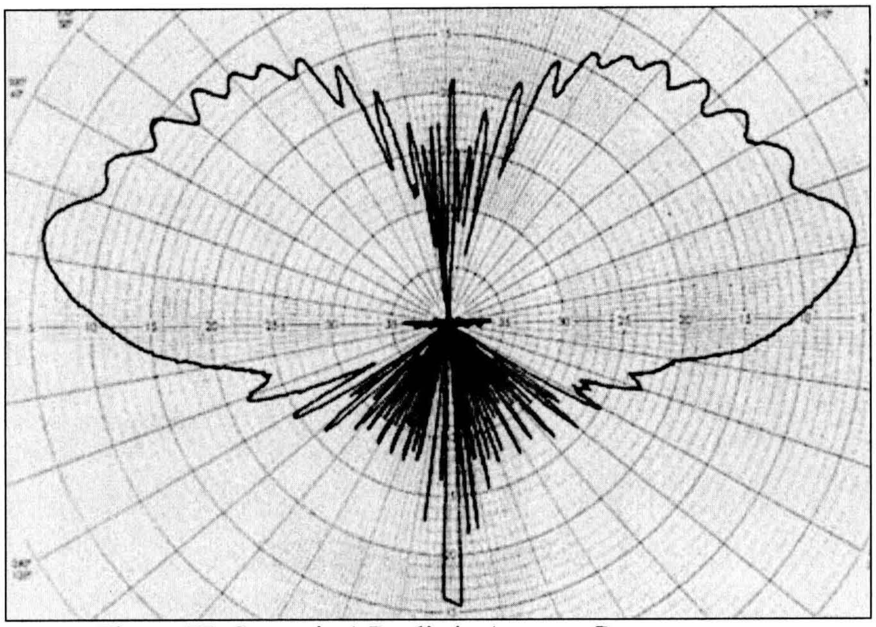

Figure 77: Scenario 1 Realistic Antenna Pattern

Figure 78 is a chart of gain as a function of elevation angle. In this chart straight up is 0 degrees, which shows a -14 dB gain. As the UA flies level the elevation angle to the CS is about a 2 degrees elevation, which references the chart antenna pattern to be 88 degrees giving an antenna gain of about 0 dB. As the UA changes attitude, the gain relative to the Mt Wilson CS will vary and thus the link margin will vary. This is discussed in the next section

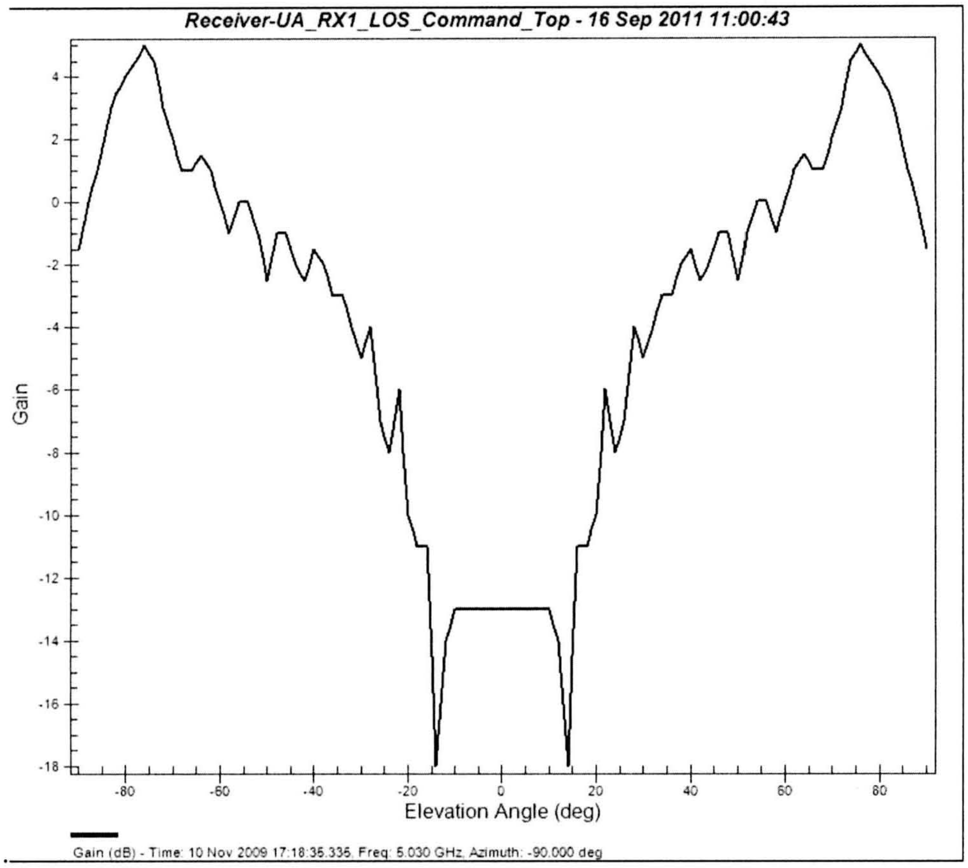

Figure 78: Scenario 1 Realistic Antenna Pattern - a chart of gain as a function of elevation angle

7.4.3 Command Link

A 12.5 dB Eb/No is needed to ensure the Command link. The rain attenuation was recalculated for worst case. Worst case rain rate of 90 mm/hr only contributed 2.4 dB of attenuation for this scenario. Thus there were no drop outs on any of the following command links (Figure 79 and Figure 80) due to rain attenuation and the telemetry links graphs (Figure 81 and 82) below are for no rain scenarios. Both the top and bottom antenna had links well above the 12.5 dB required. The spikes both up and down are due to the peak or null of the UA antenna pointing to the Mt Wilson fixed antenna. As an example, at the start of the scenario the Eb/No is about 20 dB then goes up to 50 dB. At the 20 dB Eb/No mark, the UA is banking toward the Mt Wilson CS. Then when the UA is at about a 10 degree bank, the peak antenna pattern is facing Mt Wilson CS, thus the Eb/No at this point is 50 dB which correlates to an antenna gain of 4 dB.

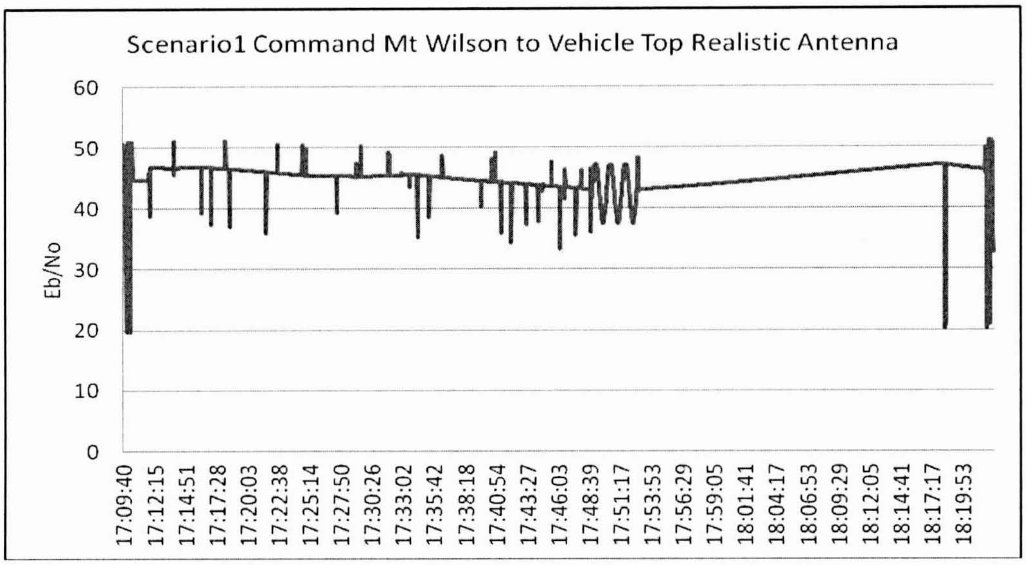

Figure 79: Command Top Realistic Antenna

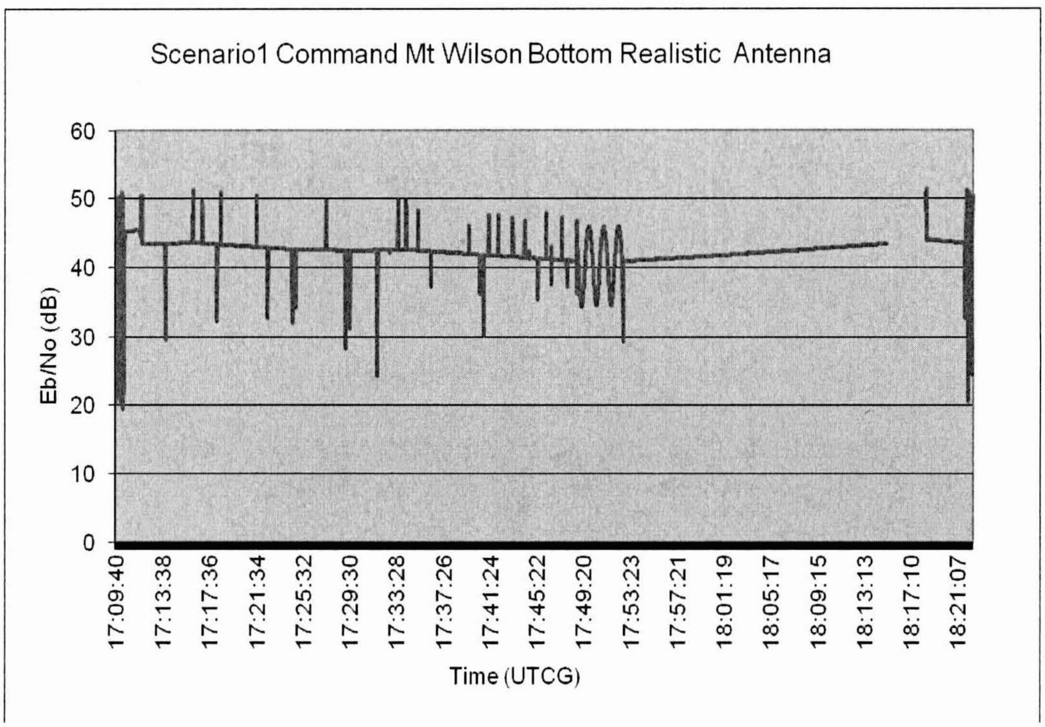

Figure 80: Command Bottom Realistic Antenna

7.4.4 Command Links Gaps

For the Control Link from Mt. Wilson to the top Command antenna there were drop outs. The scenario was run with the rain rate of 90 mm and it was determined for the command link that dropouts were not due to rain attenuation but to blockage of the antenna from the UA. Again the rain attenuation was about 2.5 dB for a 90 mm/hr rain rate.

The following chart shows the statistic for the gaps.

Table 6: Command Top Antenna

Minimum	0.04 seconds
Maximum	4.251 seconds
Average	1.809 seconds
Total	23.809 seconds
Gap over 4 seconds	1
Gap 3-4 seconds	3
Gap 2-3 seconds	0
Gap 1-2 seconds	3
Gap less than 1 second	6
total	13

Table 7: Command Bottom Antenna

Minimum	0.036 seconds
Maximum	198.55 seconds
Average	30.7
Total	2159 seconds
Gap over 4 seconds	3
Gap 3-4 seconds	1
Gap 2-3 seconds	1
Gap 1-2 seconds	1
Gap less than 1 second	1
total	7

As to be expected the bottom antenna has the largest gap, due to the blockage of the UA between the antenna and the fixed Mt. Wilson antenna. Otherwise the UA blockage is due to banking. When flying south the top antenna is on the right and has more blockage since Mt. Wilson is on the opposite side of the UA. When the UA is flying north bottom antenna is on the left and has more blockage. Below is a chart (Table 8) showing the blockage and what contributed to the blockage. What should be noted is that there is no blockage when both antennas are used. If one antenna is blocked the other is not. The top antenna is in black and the bottom antenna is in red. All gaps are due to body masking from the on-board antenna to the Mt. Wilson antenna.

A very important point is when using a top and bottom antenna located at the wing tips, there is no blockage at all, therefore, all messages would get through. The antennas are model as follows: one on one winglet on the top and the other antenna on the winglet on the bottom on the opposite wing. This gives maximum space diversity.

Table 8: Blockage during Command Link

Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Blockage
17:09:40	17:09:42	2.341	slow bank away
17:09:48	17:09:48	0.416	slow bank away
17:09:50	17:09:50	0.04	tip of nose
17:11:51	17:11:55	3.849	slow bank away
17:16:11	17:16:14	3.6	slow bank away
17:17:00	17:17:02	1.663	fast bank away
17:18:34	17:18:35	0.986	fast bank away
17:21:37	17:21:37	0.561	fast bank away
17:27:30	17:27:32	1.964	fast bank away
17:33:35	17:33:39	3.835	slow bank away
17:34:17	17:34:21	4.251	slow bank away
17:41:19	17:41:20	0.807	fast bank away
17:42:07	17:42:09	1.635	fast bank away
17:52:44	17:52:50	5.717	slow bank away
18:15:06	18:18:25	198.55	Blockage by fuselage
18:21:48	18:21:52	4.316	slow bank away
18:21:52	18:21:52	0.036	same bank
18:22:04	18:22:07	3.086	slow bank away
18:22:16	18:22:16	0.202	slow bank away

7.4.5 Telemetry Link

The biggest difference of the Command Link and the Telemetry Link is the data rate. The Command Link is 10 kBps and the Telemetry Link is 320 kBps. The Links were modeled with the antennas at the same location as that of the command antennas. The Eb/No is less due to the higher data rate and power transmitted from the UA instead of the Mt Wilson fixed site. The Mt. Wilson transmitter had a EIRP of 26.6 dB and a EIRP of between -26 dBW up to about 4 dBW This change is due to the Realistic antenna pattern as the UA maneuvers.

Figure 81 shows the link between the UA top realistic transmit antenna to the fixed Mt. Wilson antenna. The envelope follows the command link, but with lower Eb/No of about 10-12 dB. All Eb/No were above the required 12.5 dB. Figure 82 shows the bottom telemetry antenna.

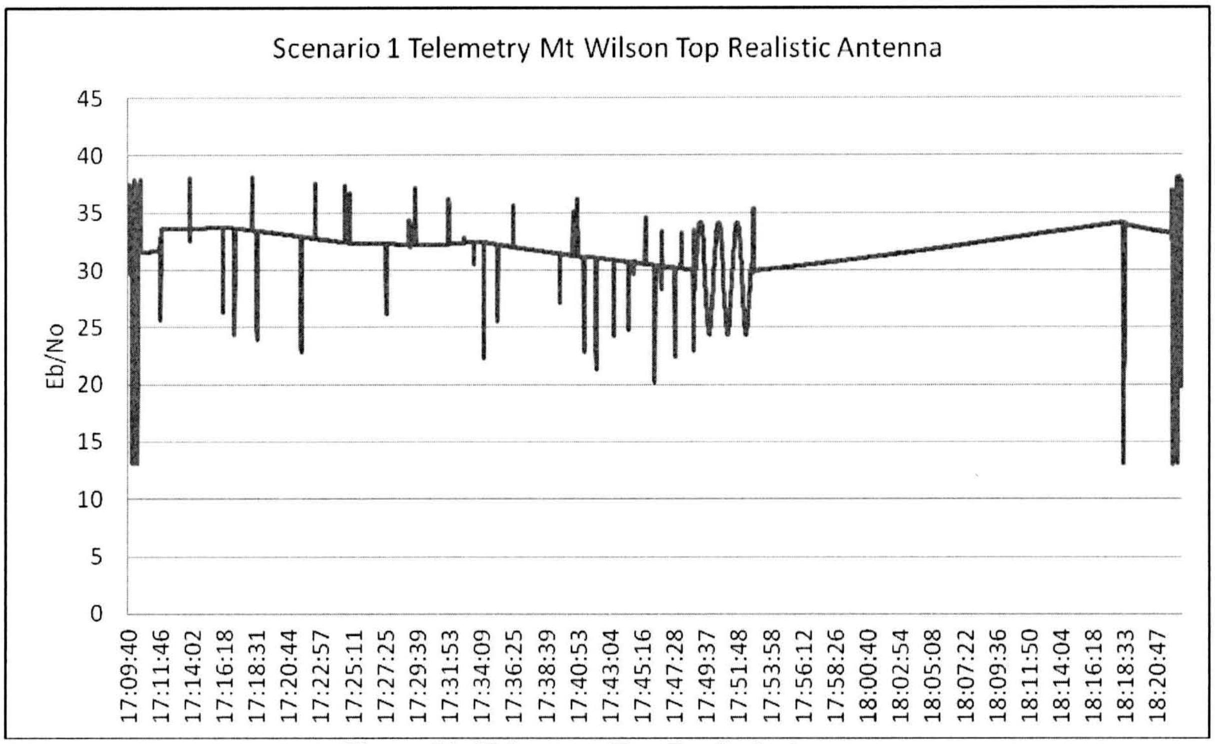

Figure 81: Telemetry Top Realistic Antenna

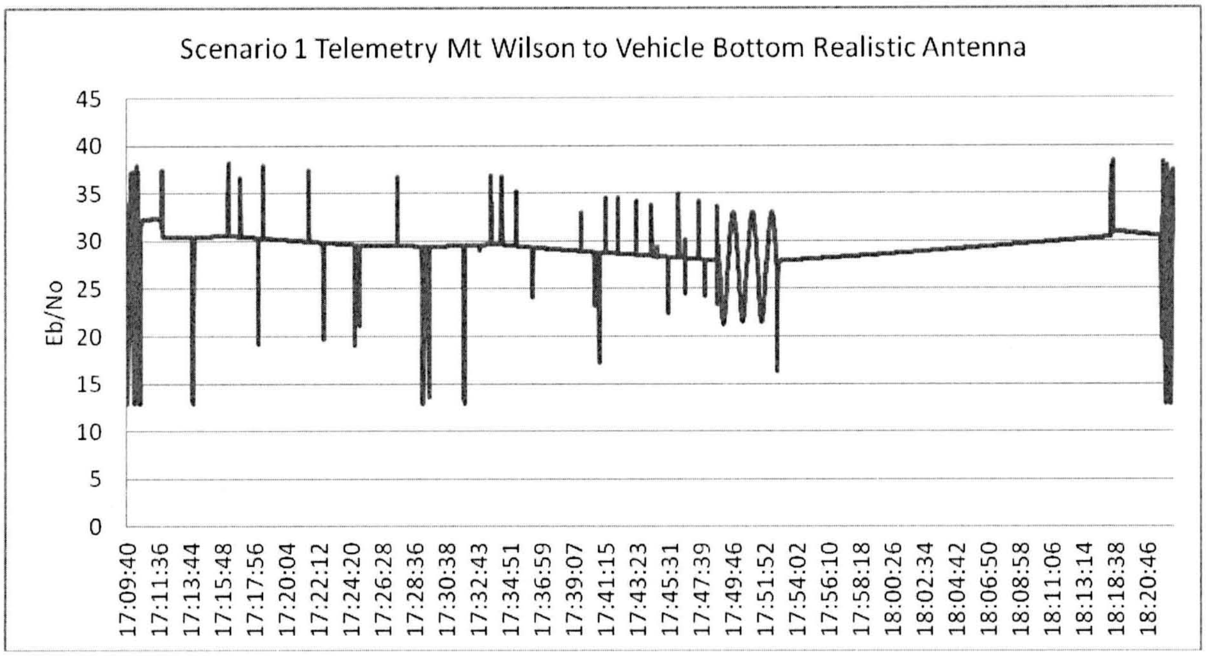

Figure 82: Telemetry Bottom Realistic Antenna

7.4.6 Telemetry Link Gaps

The antenna on the UA did not change. They are the same antenna used for command as well as telemetry. The only difference is the data rate. The command link is 10 kBps where as the telemetry link is 320 kBps.

Again, when one antenna is blocked the other is not. The top antenna is in black and the bottom antenna is in red. All gaps are due to body masking from the on board antenna to the Mt. Wilson antenna. The following chart shows the statistic for the gaps.

Table 9: Top Telemetry Antenna Gaps

Minimum	0.04 seconds
Maximum	4.26 seconds
Average	1.805 seconds
Total	27.809 seconds
Gap over 4 seconds	1
Gap 3-4 seconds	3
Gap 2-3 seconds	0
Gap 1-2 seconds	3
Gap less than 1 second	18
total	25

Table 10: Bottom Telemetry Antenna Gaps

Minimum	0.035seconds
Maximum	198seconds
Average	17.8 seconds
Total	214 seconds
Gap over 4 seconds	3
Gap 3-4 seconds	1
Gap 2-3 seconds	1
Gap 1-2 seconds	1
Gap less than 1 second	7
total	13

A very important point is when using a top and bottom antenna located at the wing tips, there is no blockage at all, therefore, all messages would get through. Commands are in black, telemetry is in red.

Table 11: Blockage during Telemetry Link

Start Time	Stop Time	Duration (sec)
17:09:48	17:09:48	0.414
17:09:50	17:09:50	0.041
17:09:53	17:09:53	17:09:53
17:10:02	17:10:02	0.114
17:10:10	17:10:10	0.114
17:10:19	17:10:19	0.114
17:11:51	17:11:55	3.854
17:16:11	17:16:14	3.609
17:17:00	17:17:02	1.669
17:18:34	17:18:35	0.99
17:21:37	17:21:37	0.568
17:27:30	17:27:32	1.972
17:33:35	17:33:39	3.838
17:34:17	17:34:21	4.26
17:41:19	17:41:20	0.815
17:42:07	17:42:09	1.641
17:44:46	17:44:46	0.103

17:46:37	17:46:38	0.114
17:47:56	17:47:57	0.674
17:48:48	17:48:48	0.132
17:48:54	17:48:55	0.413
17:49:31	17:49:31	0.425
17:50:09	17:50:09	0.426
17:50:46	17:50:46	0.425
17:51:24	17:51:25	0.428
17:52:01	17:52:02	0.423
17:52:40	17:52:40	0.428
17:52:42	17:52:42	0.103
17:52:44	17:52:50	5.717
18:15:06	18:18:25	198.553
18:21:48	18:21:52	4.316
18:21:52	18:21:52	0.035
18:22:04	18:22:07	3.085
18:22:16	18:22:16	0.293
18:22:23	18:22:24	1.177
18:22:24	18:22:25	0.114

7.4.7 Summary for Mt. Wilson

The above section described the change in scenario 1 from using three ground stations at street heights to one ground station elevated at 5554.07 ft on top of a mountain looking down into the LA basin. In addition a realistic antenna pattern was used instead of a uniform 3-dB gain antenna pattern. The realistic antenna pattern had a nominal gain of 0 dB and deep lobes as the elevation angle neared zero.

Also moving the antenna to the winglet location instead of under or above the wing was a vast improvement.

So after all the changes the results were that even with a rain rate of 90 mm /hr and hour the link margin was meet and with the use of two antennas there are no gaps during this flight.

8 SUMMARY

Section 7 discussed the results of each scenario that were analyzed. This section is a summary of the results as well as the overall modeling and simulation work that was done.

This report is the end result of over a year of work conducted jointly between the FAA and NASA KSC. The work was done in support of the RTCA SC-203 Control and Communications Working Group. A large part of the specific values used in the simulation came from the working group. All of the radio links were modeled based on the formulation completed by the working group. STK was selected as the tool of choice due to demonstrated NASA KSC experience utilizing this tool for past communication systems development. During those development periods, the STK communication models were found to be in line with real data collected during live test flights on various aircraft. As seen in Section 7, the STK results were close to the static link margins that were calculated in Section 6.5.

The use of QualNet was introduced due to a discussion during a RTCA SC-203 Control and Communications Working Group on the modeling and simulation being done for this report. It was noted that the communication delays were not being modeled. At that time, it was decided to purchase QualNet for the terrestrial communications link portion, since STK's latest release permits QualNet to work inside the STK environment. Unfortunately, there was a steep learning curve and some confusion on how well QualNet modeled land lines. During the course of the year, there was not enough time to work out the issues with STK/QualNet and only recently have these issues been resolved. Section 9 discusses future work. The STK/QualNet analysis is a predominant portion of the future work that will answer the communications delay issue, packet drops, and completion of the whole communication chain, not just the radio links.

The three scenarios modeled that utilized two RTCA architectures were: Scenario 1, LOS only (direct control to UA only) with multiple CS; Scenario 5, LOS with two CS (nationwide network and BLOS); and Scenario 6, LOS with one CS and BLOS.

It was found that when only an LOS link is used for a low elevation UA, at least three CS are needed. With a top and bottom antenna and only two CS within the flight path, there will be dropouts. Once a CS was added perpendicular to the flight path, there were no dropouts. However, on some of the telemetry links the signal strength went below the required 12.5 dB. This alludes to the fact that either more transmit power is needed or larger antennas are needed.

LOS rain effects on the link were a concern on the longer traversed aircraft routes. As the UA traveled this route the heavy rain rate of 90 mm/hr. resulted in higher attenuation at 5.03 GHz. At one NM, the rain attenuation was 2 dB, and at 25 NM the rain attenuation was 5 dB. The results demonstrated that the longer the UA flies through continuous rain the higher the link attenuation becomes.

For the BLOS links, there were no dropouts on either the command or the telemetry links. Even at heavy rain rates, the command link was above the 6.5 dB required for Scenario 5 and for Scenario 6. But, the telemetry link fell below the 6.5 dB required when rain attenuated the signal in Scenarios 5 and 6.

With the proper use of modeling and simulation, it is possible to analyze the effects of different requirements as well as the effects of natural conditions such as rain, fog, or snow. This report addressed the availability of radio links for UAS as they fly in the NAS. This requirements development effort is a primary step needed to establish UAS standards designed to permit safe operation of UAS in the NAS.

Overall, the STK simulations performed accurately as compared to the link budget calculated in section 6.5.

9 FUTURE WORK

The following delineates planned future M&S work.

Additional information for the scenarios:

- Localized weather conditions
- Detailed antenna information size antenna pattern location height power sensitivity
- Antenna pointing algorithms
- Satellite Systems: Low Earth Orbit (LEO) and Medium Earth Orbit MEO
- Radar
- Antenna patterns
- Terrestrial communication
- Collision avoidance
- Interference analysis of combined frequencies and other sensors
- Electromagnetic Interference EMI
- Increase transmitter power
- Real weather data
- Transmitters and receivers
- Terminal
- Post-flight data from FAA UAS Demonstration
- Hardware-in-the-loop

A real-time communication simulator like QualNet is a very powerful technology for getting the most out of a simulation, since it allows the combination of real and simulated entities, giving the realism of actual hardware with the inexpensive scalability of simulated entities. QualNet has this ability through the use of the emulator EXATA. The scenario can be set up and real time network traffic can be added to the scenario.

Hardware-in-the-Loop is the ability to utilize real flight hardware in a simulated flight environment. Figure 83 illustrates the concept of placing real hardware within a simulation environment.

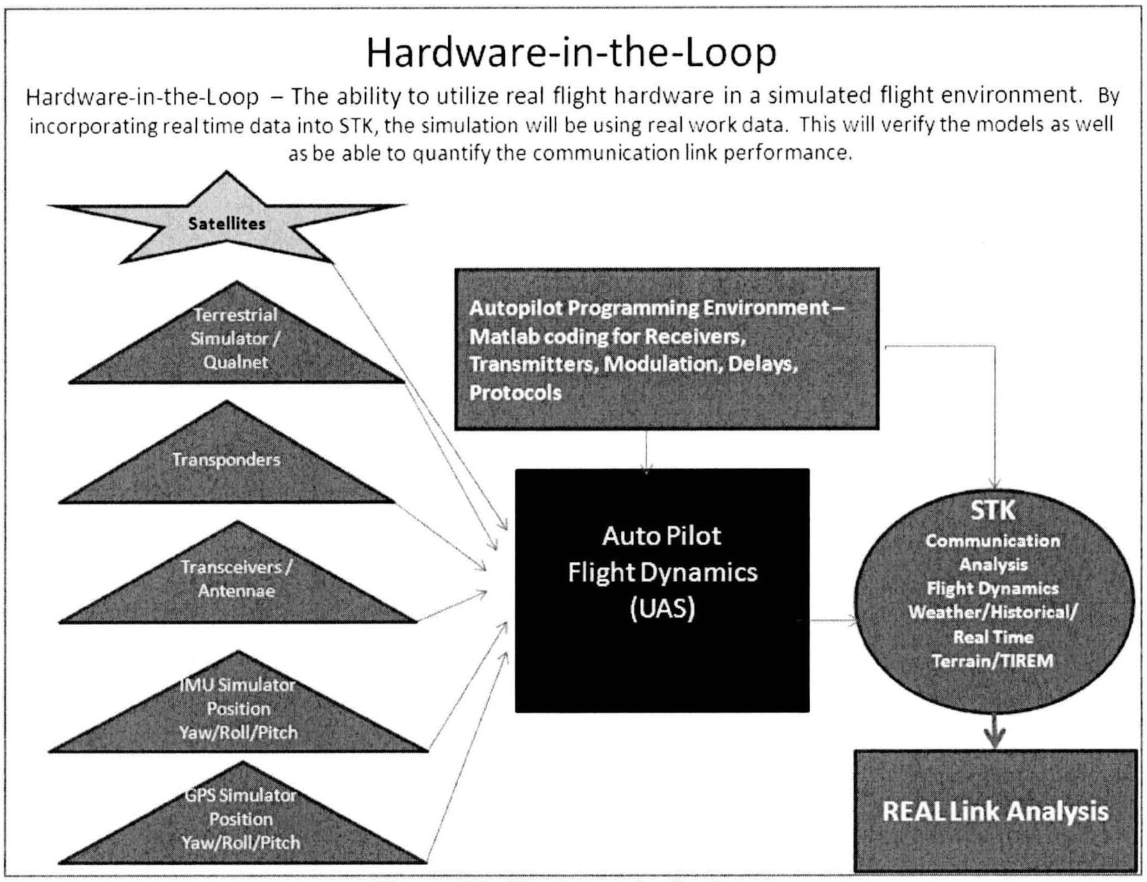

Figure 83: Hardware in the Loop

Hardware-in-the-Loop is a form of real-time simulation. It differs from pure real-time simulation through the addition of a real component in the loop. This hardware component may be a controller (autopilot system), antennas, transceivers, GPS, engines, any control surfaces, sensors, etc. The purpose of a Hardware-in-the-Loop system is to provide all of the electrical/mechanical stimuli needed to fully exercise the simulation. By interfacing a GPS simulator with an autopilot system the autopilot system will interpret the GPS simulated coordinates during the flight as designated GPS locations. When communication transceivers are added to the autopilot system, real communications data can be analyzed and collected for an end-to-end link analysis. The data will be fed back into the STK environment for further communications analysis. Hardware-in-the-loop enables comprehensive test and training activities without actual flights of a UAS, while "carrying" the transmitters or receivers under test.

Hardware-in-the-loop enables component-level and system-level testing and verification, both in the laboratory and in the field. Key applications include:

- Flight system and ground system testing for satellite, UAS, and sensor applications
- Telemetry tracking system verification for test ranges
- Reference signal and interference signal generation on-air or in the laboratory
- Compliance testing

- Performance testing
- Diversity combining testing
- Training and education
- Realistic loop-back testing
- A great deal can be learned by including critical parts of the communication system.
- Hardware intrinsically adds delays to a communication link — these values have to be considered.

To perform the dynamic link analysis (transmitter/receiver/antenna), Hardware-in-the-Loop will be added to provide real data in a real-time environment.

The UAS autopilot (i.e., the Flight Management System) is used as part of the Hardware-in-the-Loop. By incorporating real time data into STK, the simulation will be using real work data. This will verify the models as well as be able to quantify the communication link performance. Time delay is one criterion on the command link that needs to be analyzed; this Hardware-in-the-Loop will quantify what types of delays are to be expected during flights as well as determine how long delays are tolerable on a control link.