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C-BAND AND K_u-BAND UAV LINE-OF-SIGHT DATA LINK EMC ANALYSIS FOR TWO OPERATIONAL SCENARIOS

Prepared for

OFFICE OF THE ASSISTANT SECRETARY OF DEFENSE (OASD)
Networks and Information Integration (NII) Spectrum Office
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PROJECT REPORT

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14. ABSTRACT
The Joint Spectrum Center conducted an electromagnetic compatibility analysis to determine the potential for electromagnetic interference (EMI) between the UAV Line-of-Sight Data Link Terminal and the communications-electronics (C-E) environment near Bisbee-Douglas International Airport and Whidbey Island Naval Air Station. This analysis included the 4400 – 4940, 5250 – 5850, and 14400 – 15350 MHz frequency bands. Each frequency band had a potential for EMI between the UAV terminals and various C-E systems in the environment. Environmental systems analyzed included, but were not limited to: radar systems (fixed and mobile), terrestrial microwave links, telemetry systems, satellite downlink systems, and radio astronomy telescopes. Where potential EMI was noted, mitigation techniques were recommended. The data presented in this report was current as of 8 September 2004.

15. SUBJECT TERMS
UAV, C-Band, K_u-Band, Data Link, Intersite, EMI

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PREFACE

The Joint Spectrum Center (JSC), a field activity of the Defense Information Systems Agency (DISA), was established to provide advice and assistance on all matters regarding the electromagnetic battlespace. Support is provided to the Secretary of Defense, the Joint Staff, the military departments, combatant commands, defense agencies, and other agencies of the US Government. The JSC works closely with the Joint Staff, Director for Command, Control, Communications, and Computer Systems, and the Assistant Secretary of Defense for Networks and Information Integration on spectrum matters. Direct support is provided to the Unified Commands and Joint Task Force Commanders on electromagnetic battlespace issues, including spectrum management and electronic warfare deconfliction. Support to Department of Defense (DoD) components and the US Government is provided through a sponsor-reimbursed, electromagnetic compatibility (EMC) program that provides EMC analyses for specific projects.

Comments regarding this report should be submitted to the Commander, JSC, 2004 Turbot Landing, Annapolis, MD 21402-5064

EXECUTIVE SUMMARY

The Office of the Assistant Secretary of Defense, Networks and Information Integration Spectrum Office requested that the DoD Joint Spectrum Center conduct an electromagnetic compatibility analysis to determine the potential for electromagnetic interference (EMI) between the unmanned aerial vehicle (UAV) line-of-sight (LOS) data link terminal and the communications-electronics (C-E) environment for two operational scenarios. The scenarios were derived from the Department of Homeland Security Analysis of Alternatives. The two operational scenarios were southern border vehicle intrusion (SBVI) near Bisbee-Douglas International Airport and northern maritime border security (NMBS) near Whidbey Island Naval Air Station. This analysis included the 4400 – 4940, 5250 – 5850, and 14400 – 15350-MHz frequency bands. These frequency bands were selected with the intent to utilize the existing Predator UAV. Where potential EMI was noted, mitigation techniques were recommended. These recommendations are limited by the specific scenarios chosen, and while they can be expected to be fairly representative, different scenarios may have additional issues.

All three frequency bands had a potential for bi-directional EMI between the terminals and various C-E systems in the environment. Eight main system types were analyzed: radars, terrestrial microwave links, RA telescopes, mobile systems, GDT return link, UAV command link, telemetry systems, and troposcatter systems.

This analysis provides insight into the magnitude of the spectrum management effort required for homeland security deployments. C-E equipment and resulting coordination challenges vary by region. Equipment tuning flexibility is critical to successful coordination in multiple regions. Flight path considerations within the regions of interest are also an important aspect of frequency coordination.

For the SBVI scenario, only the 5250 – 5850-MHz band is recommended. The recommended frequency bands for the NMBS scenario are the 5250 – 5850-MHz and 14400 – 15350-MHz bands. This is based on the number of issues and perceived frequency coordination difficulty.

SBVI issues included troposcatter systems that operate in the 4400 – 4940-MHz band, radars in the 5250 – 5850-MHz band, and radio astronomy and fixed microwave systems that operate in the 14400 –15350-MHz band.

NMBS issues included fixed microwave and troposcatter systems in the 4400 – 4940-MHz band, two radars in the 5250 – 5850-MHz band, and fixed microwave systems in the 14400 –15350-MHz band.

TABLE OF CONTENTS

FIGURES

TABLES

GLOSSARY

C/(I+N)	Carrier-to-Interference-Plus-Noise Power Ratio
C/N	Carrier-to-Noise Ratio
C-E	Communications-Electronics
DHS	Department of Homeland Security
DMS	Degrees Minutes Seconds
EME	Electromagnetic Environment
EMI	Electromagnetic Interference
FDR	Frequency Dependent Rejection
FDRCAL	Frequency Dependent Rejection Calculation
GCS	Ground Control Station
GDT	Ground Data Terminal
IF	Intermediate Frequency
I/N	Interference-to-Noise Power Ratio
JSC	Joint Spectrum Center
LNA	Low Noise Amplifier
LOS	Line-of-Sight
NAS	Naval Air Station
NMBS	Northern Maritime Border Security
RA	Radio Astronomy
RF	Radio Frequency
SBVI	Southern Border Vehicle Intrusion
S/I	Signal-to-Interference Ratio
S/N	Signal-to-Noise Ratio
STATGN	Statistical Antenna Gain
TCDL	Tactical Common Data Link
TIREM	Terrain Integrated Rough Earth Model
UAV	Unmanned Aerial Vehicle
VLBA	Very Long Baseline Array

SECTION 1 – INTRODUCTION

1.1 BACKGROUND

The Office of the Assistant Secretary of Defense, Networks and Information Integration Spectrum Office requested that the DoD Joint Spectrum Center (JSC) conduct an electromagnetic compatibility analysis to determine the potential for electromagnetic interference (EMI) between the unmanned aerial vehicle (UAV) line-of-sight (LOS) data link terminal and the communications-electronics (C-E) environment for two operational scenarios. This analysis included the 4400 – 4940, 5250 – 5850, and 14400 – 15350-MHz frequency bands. These frequency bands were selected with the intent to utilize the existing Predator UAV. The scenarios were derived from the Department of Homeland Security (DHS) Analysis of Alternatives. The two operational scenarios were southern border vehicle intrusion (SBVI) near Bisbee-Douglas International Airport and northern maritime border security (NMBS) near Whidbey Island Naval Air Station (NAS). Operations in the SBVI region monitor ground-based vehicles. Operations in the NMBS region monitor maritime vessels.

1.2 OBJECTIVES

The objectives of this task were to:

- Provide insight into the magnitude of the spectrum management effort required to support homeland security UAV efforts
- Assess the potential for EMI between the UAV and Ground Data Terminal (GDT) and the C-E environment identified by the SBVI and NMBS scenarios
- Identify mitigation techniques required to reduce or eliminate any potential interference

1.3 APPROACH

The scenarios were provided in a DHS Analysis of Alternatives presentation.[1-1] The flight paths were selected to place the largest portion of the orbit near the geographical surveillance region. The SBVI flight path is approximately 73.7 km north of the Mexican border. The NMBS flight path is near the Canadian border and crosses over it for a short distance. The entire flight path was assumed to be monitored for each flight. For each scenario, the nearest adequate and well-protected federal property near the center of the flight path with aviation facilities was selected for the GDT and associated launch/recovery activities in accordance with stated DHS preferences.

[1-1] "*BTS UAV Applications Analysis,*" AOA Briefing, Alexandria, VA: Center for Naval Analysis Corporation, 28 June 2004.

The 4400 – 4940, 5250 – 5850, and 14400 – 15350-MHz frequency bands were selected for this analysis based on potential Predator UAV operations. Air Combat Command is currently investigating operations using the 4400 – 4940-MHz frequency band as an alternate in Nevada. The Predator operating band is 5250 – 5850-MHz. The Predator communications roadmap identifies the 14400 – 15350-MHz frequency band for future Tactical Common Data Link (TCDL) use.

Operational characteristics were based on existing hardware. Current implementation of these data links utilizes a portion of the band for the command link and another portion of the band for the return link. Each band was analyzed as if the command link and return link operated over the entire band. The equipment operating characteristics for the 4400 – 4940 and 5250 –5850-MHz bands were based on the current Predator UAV datalink. The equipment operating characteristics for the 14400 – 15350-MHz band was based on the L-3 Communications TCDL.

The C-E environment for the bands was identified by accessing the Federal Communications Commission, Frequency Resource Record System, the Government Master File, Canadian Data File, and International Frequency List databases available at the JSC. Each fundamental frequency band included a 5% margin above and below the band. The specific frequency bands are listed in Table 1-1. The SBVI database selects were constrained to an area defined by the four points 360000N 1170000W, 360000N 1090000W, 280000N 1090000W, and 280000N 1170000W in degrees minutes seconds (DMS). The SBVI ground control station (GCS) is assumed to be located at Bisbee-Douglas International Airport at latitude 312809N and longitude 1093613W in DMS. The NMBS database selects were constrained to be within 600 km of 482000N 1230000W in DMS. The NMBS GCS is assumed to be located at Whidbey Island NAS at latitude 482107N and longitude 1223918W in DMS. Figures 1-1 and 1-2 show the shaded SBVI and NMBS geographical surveillance areas and UAV flight paths. The electromagnetic environment (EME) definition included equipment listed in the JSC databases.

Table 1-1. Database Select Frequency Criteria

	C-band, MHz		K_u-band, MHz
In-Band	4400 – 4940	5250 – 5850	14400 – 15350
In-Band (Including adjacent bands)	4180 – 5187	4988 – 6143	13680 – 16118

Because of the large number of systems in the environment, calculations of the potential for interference with UAV datalink terminals were based on successively more rigorous levels of analysis in order to eliminate systems from further consideration when a conservative analysis had shown that EMI was unlikely, thereby reducing the number of systems analyzed at each level. For the Level One analysis, a generic interference-to-noise power ratio (I/N) within the receiver -3 dB intermediate frequency (IF) amplifier (or filter) bandwidth was used. For the Level Two analysis, I/N thresholds applicable to the specific type of receiver under analysis were used. The Level Three analysis applied specific performance criteria for each type of environmental receiver, which included antenna coupling scenarios and receiver signal processing. For each system examined in the Level Three analysis, a degradation threshold related to C-E system function was used.

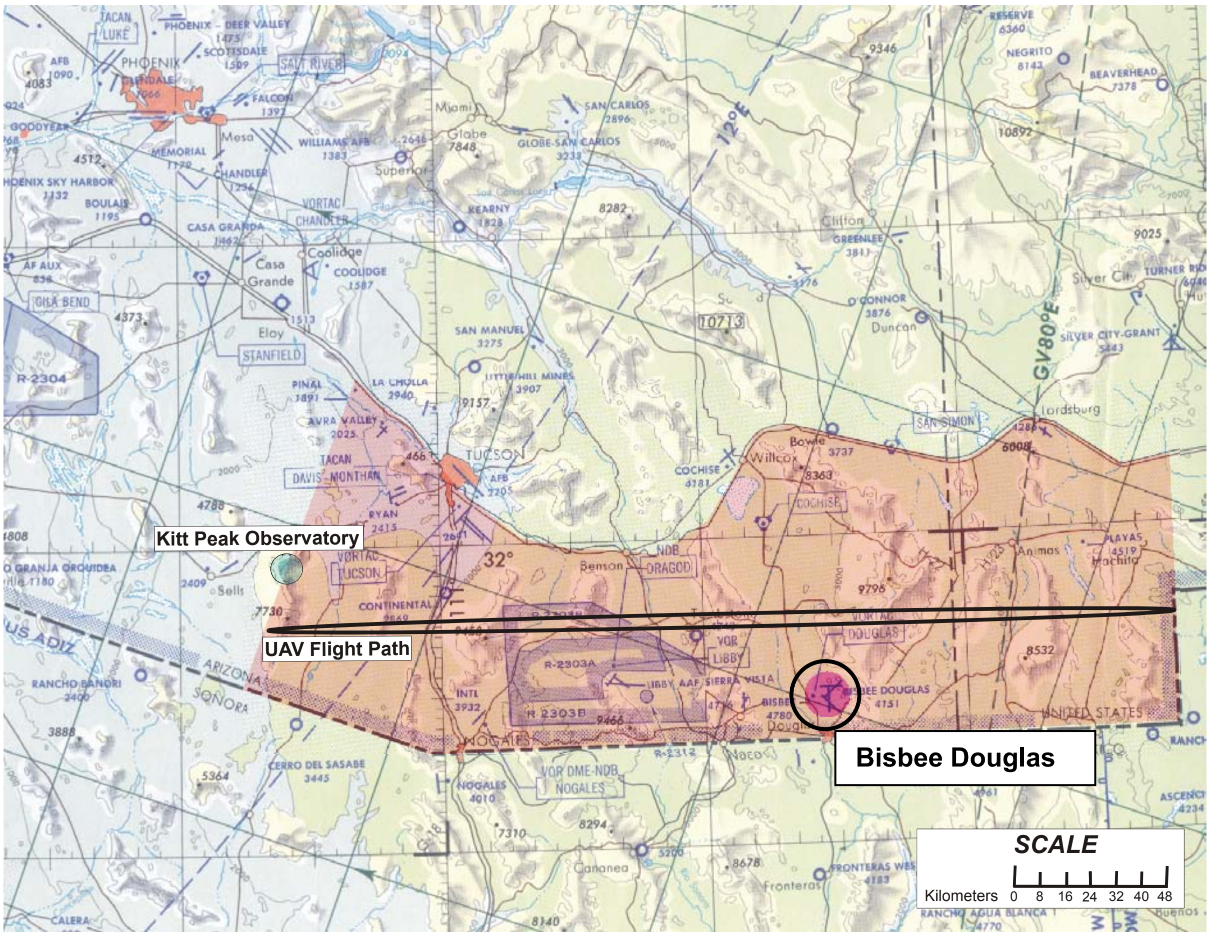

Figure 1-1. SBVI Scenario and Surrounding Geographical Area

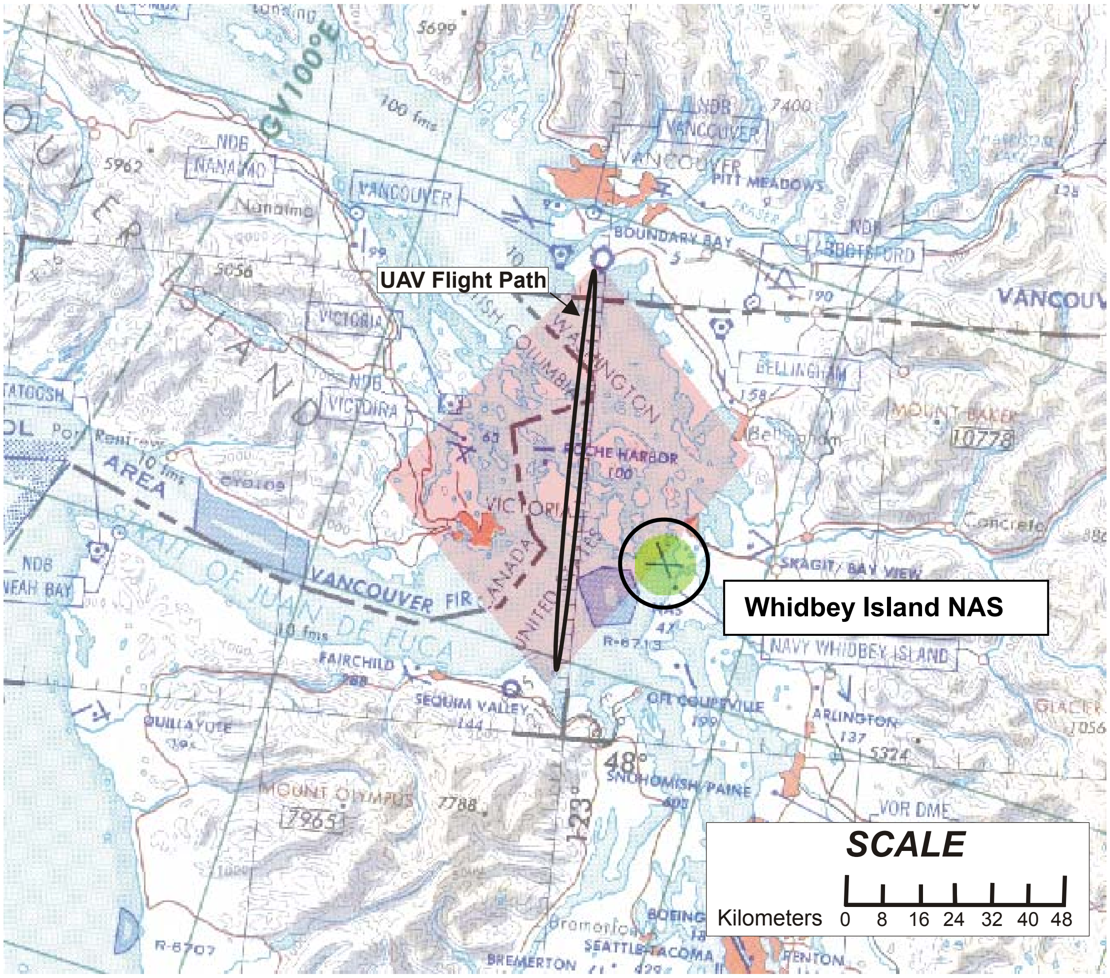

Figure 1-2. NMBS Scenario and Surrounding Geographical Area

For the Level One and Level Two analyses, received interference power at the input to the receiver was calculated for each receiver. The minimum distance between the environmental C-E system location and the UAV flight path was determined and used for path loss calculations. The JSC Terrain Integrated Rough Earth Model (TIREM) [1-2] was utilized to calculate propagation loss. The JSC Statistical Antenna Gain (STATGN) model[1-3] was utilized to estimate off-axis antenna gain. When not defined, the gain of the transmitter antenna in the direction of the receiver antenna, and the gain of the receiver antenna in

[1-2] D. Eppink, W. Kuebler, *TIREM/SEM Handbook*, ECAC-HDBK-93-076, Annapolis, MD: ECAC (now JSC), March 1994.

[1-3] W.R. Klocko, T. L. Strickland, *Environmental Analysis System (EASY) Statistical Gain Model for Fixed-Azimuth Antennas,* ECAC-TN-85-023, Annapolis, MD: DoD ECAC (now DoD JSC), April 1979.

the direction of the transmitter antenna, were calculated using the assumption that 90% of the time the antenna mainbeams would be off-axis to each other by more than 18 degrees. The receiver I/N was calculated and compared to the appropriate I/N threshold [$(I/N)_T$] to determine the potential for EMI for Level One and Level Two analyses.

Level Three radar calculations were based on I/N. The frequency-dependent rejection (FDR) and required frequency separation were calculated using the JSC frequency-dependent rejection calculation (FDRCAL) model.[1-4] Statistical antenna gain values were calculated using the STATGN program. Propagation loss was calculated using TIREM. The receiver I/N was compared to an $(I/N)_T$ of -6 dB to determine the potential for EMI.

The Level Three analysis of terrestrial microwave links entailed calculating desired carrier-to-noise ratio (C/N), fade margin, availability without interference, carrier-to-interference-plus-noise power ratio [C/(I+N)], and availability with interference. The reduction of availability was then calculated. Required frequency separation was determined to reduce interactions with greater than 0.1% availability reduction to less than 0.01% reduction. A C/N threshold [$(C/N)_T$] of 26.5 dB was used. For the Level Three analysis, the following conditions were assumed: maximum fade, mainbeam antenna coupling, no propagation blockage from structures.

The Level Three radio astronomy (RA) analysis involved calculations of interference power and noise at the antenna terminals and at the antenna location, respectively. The power level of the maximum tolerable interference at the antenna terminals, and maximum tolerable power density were determined. The interference power was compared to the maximum tolerable interference at the antenna terminals, and the noise power density was compared to the maximum tolerable power density to determine the potential for EMI.

The Level Three mobile, GDT return link, UAV command link, and telemetry systems analyses entailed calculating the desired received signal power, assuming free-space path loss. Signal-to-interference ratios (S/I) were then calculated. Interference power levels were calculated using TIREM and STATGN. S/Is were compared to S/I thresholds [$(S/I)_T$] of 12 dB to determine the potential for EMI.

A Level Three analysis of troposcatter was not performed since desired signal calculations require knowledge of transmitter and receiver system locations, and effective radiated power.

[1-4] Kenneth Clubb, et al., *Technology Transfer Programs for IBM-Compatible Personal Computers: User's Manual*, ECAC-UM-87-045, Annapolis, MD: ECAC (now DoD JSC), September 1987, Includes Change 1, September 1988.

Required frequency separation to preclude EMI was determined using FDRCAL for cases where EMI was predicted.

SECTION 2 – SYSTEM DESCRIPTION

Parameters used in the analysis were derived from the Predator C-band LOS data link and the K_u-band TCDL. When data was not available, parameter values were estimated based on operating characteristics of similar equipment and sound engineering assumptions. The data link component radio frequency (RF) characteristics are listed in Table 2-1.[2-1,2-2,2-3] The general data link RF configuration is shown in Figure 2-1.

Table 2-1. Datalink Technical Characteristics

Characteristic	Specifications					
Transmitter						
Tuning Range, MHz	4400 – 4940		5250 – 5850		14400 – 15350	
Tuning Increment, MHz	1					
Transmitter Power, dBm	40					
Link Type	Command	Return	Command	Return	Command	Return
Emission Bandwidth, MHz -3 dB -20 dB	 0.34 0.42	 8.5 18.0	 0.34 0.42	 8.5 18.0	 28 101	 9.4 57.4
Receiver						
Tuning Range, MHz	4400 – 4940		5250 – 5850		14400 – 15350	
Link Type	Command	Return	Command	Return	Command	Return
2nd IF Selectivity, MHz -3 dB -20 dB	 0.75 1.5	 20.0 22.5	 0.75 1.5	 20.0 22.5	 14.1* 64.0*	 4.7* 21.4*
Noise Figure (NF), dB	5.0*	2.0*	5.0*	2.0*	3.9	3.7
Noise Power (N), dBm[a]	-110.2	-99.0	-110.2	-99.0	-98.6	-103.6
SBVI Inteference Threshold (I_T), dBm[a]	-80.8		-83.8		-81.6	
NMBS I_T, dBm[a]	-74.5		-77.5		-75.3	
Antenna						
GDT Gain, dBi	30.5		29.0		40.0	
UAV Gain, dBi	15.0*		15.0		15.0*	
UAV Elevation -3 dB Beamwidth, degrees	30*		30		30*	
GDT Height, m	18.3*		18.3		18.3*	
UAV Height, m	7620*		7620		7620*	

* Estimated value

[a] These items were taken from values calculated in Section 3 and are listed to provide a complete picture of the system in the table.

[2-1] *Application for Equipment Frequency Allocation (DD Form 1494) for Predator C-Band MAE UAV Medium Altitude Endurance Unmanned Aerial Vehicle*, Stage 4 J/F 12/7253, Washington, DC: MCEB, 9 April 2003.

[2-2] *Application for Equipment Frequency Allocation (DD Form 1494) for L3 Communications Tactical Common Data Link (TCDL)*, Stage 3 J/F 12/7834/1, Washington, DC: MCEB, 18 February 1999.

[2-3] *Source Control Drawing for 4' Diameter, High Gain Antenna*, SCD00069, San Diego, CA: Aeronautical Systems Incorporated, Released 19 August 1999.

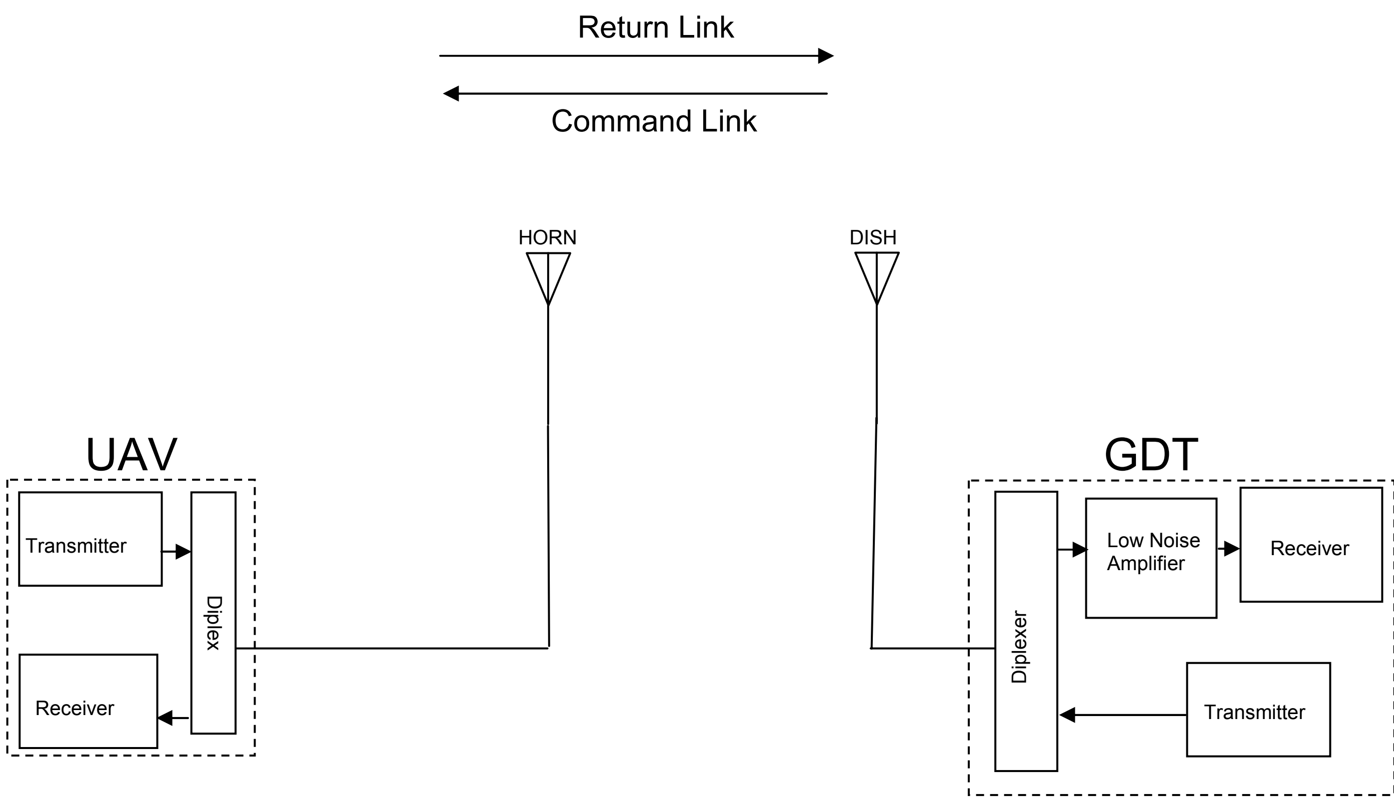

Figure 2-1. Datalink RF Configuration

SECTION 3 – ANALYSIS OVERVIEW

Due to the large number of systems in the environment, calculations of the potential for interference with the data link terminals were based on successively more rigorous levels of analysis in order to minimize the number of systems analyzed at each level.

For the Level One and Level Two analyses, the undesired power level at the input to the receiver was calculated for each receiver, considering the FDR provided by the IF filter. For ground-to-ground interactions, the distance between the systems under analysis were calculated based on longitude and latitude. These distances were used in propagation loss calculations. For air-to-ground and ground-to-air interactions, a slant range distance of 29.4 km was calculated based on the intersection of the bottom edge of the mainbeam with the ground, given a typical UAV altitude of 7620 m and the bottom edge of the mainbeam is 15 degrees below the horizon. This slant range distance was then used to calculate the terrain-dependent propagation loss. The STATGN model was utilized to estimate off-axis antenna gain. When not defined, the gain of the data link terminal transmitter antenna in the direction of the receiver antenna, and the gain of the receiver antenna in the direction of the data link terminal, were calculated using the assumption that 10% of the time there would be mainbeam coupling. The noise power in the receiver -3-dB IF bandwidth was calculated. The calculated I/N was compared to the appropriate $(I/N)_T$ to determine the potential for EMI. For the Level One analysis, a generic I/N within the receiver -3-dB IF-amplifier (or filter) bandwidth was used. For the Level Two analysis, I/N thresholds applicable to the specific type of receiver under analysis were used.

The Level Three analysis applied specific performance criteria for each type of environmental receiver, which included antenna coupling scenarios and receiver signal processing. For each system examined in the Level Three analysis, a degradation threshold related to C-E system function was used.

For all levels of analysis, the potential for interference between the UAV datalink and in-band/adjacent-band systems was determined by first calculating I/N within the IF amplifier bandwidth as shown in Equation 3-1.

$$I/N = P_T + G_T - L_P + G_R - L_S - FDR - N \tag{3-1}$$

where I/N = interference-to-noise power ratio, in dB

P_T = interfering transmitter peak power, in dBm

G_T = gain of the transmitting antenna in the direction of the receiving antenna, in dBi

L_P	=	propagation loss between the transmitting antenna and the receiving antenna, in dB
G_R	=	gain of the receiving antenna in the direction of the transmitting antenna, in dBi
L_S	=	total system losses (transmitter and receiver) for the undesired path, in dB
FDR	=	frequency-dependent rejection, in dB
N	=	noise power in the receiver IF bandwidth, in dBm

In Equation 3-1, FDR is defined as the average power-input-to-average-power-output ratio.

The noise power was calculated as follows:

$$N = -114 + 10 \, \text{Log}\,(BW) + NF \tag{3-2}$$

where N = receiver noise power, in dBm
BW = -3-dB bandwidth, in MHz
NF = receiver noise figure, in dB

When the -3-dB IF bandwidth was not available, it was calculated based on the necessary bandwidth of the C-E system as denoted in the emission designator.

$$BW = \frac{B_N}{2x10^{\frac{17}{40}}} \tag{3-3}$$

where B_N = necessary bandwidth as denoted in the emission designator

and all other terms are as previously defined.

The bandwidth slope was assumed to be 40-dB/decade for both receivers and transmitters.

3.1 LEVEL ONE ANALYSIS

The I/N was calculated within the IF amplifier (or filter) bandwidth. The propagation loss term was calculated using TIREM. The receiving antenna gain in the direction of the UAV data link was calculated based on a statistical gain model. The total system losses were assumed to be 3 dB. For land mobile systems in the environment, the radius of mobility and maximum range was assumed to be 1 km. For telemetry systems the radius of mobility and maximum range was assumed to be 50 km.

The noise figure for all environmental systems was assumed to be 5 dB. The calculated I/N was compared to an $(I/N)_T$ of -9 dB.[3-1] This $(I/N)_T$ corresponds to an increase in the receiver noise floor of 0.5 dB. For those systems exceeding the -9 dB $(I/N)_T$, a Level Two analysis was performed.

3.2 LEVEL TWO ANALYSIS

The Level Two analysis applied specific $(I/N)_T$ degradation thresholds based on the type of C-E systems remaining in the environment. Eight main system types required Level Two analyses: radar systems, terrestrial microwave links, radio astronomy telescopes, mobile systems, GDT return link, UAV command link, telemetry, and troposcatter systems.

An $(I/N)_T$ of -6 dB was established for all radar systems in this analysis. The analysis assumed all radar systems had either narrowband receiver/processors (e.g., pulse-Doppler processing), or adaptive constant false alarm rates. This threshold is equivalent to a 1-dB increase in the system noise level, or approximately a 5%-decrease in detection range.

For terrestrial microwave, mobile, GDT return link, UAV command link, telemetry, and troposcatter systems operating in the environment, an $(I/N)_T$ of 0 dB was established as a threshold for this analysis.[3-2]

For single dish radio telescope antennas, the equations used to establish threshold levels for interference considered harmful to radio astronomy observations are specified in ITU-R RA.769-2.[3-3] The thresholds specified in this report are explained in more detail in Section 3.3.3.

The C-E systems operating in the adjacent bands above or below the UAV data link bands were identified and the FDR for each was calculated accounting for off-tuned rejection due to frequency separation between the environmental systems and the UAV datalink systems.

[3-1] M. Coleman-Ragland, L. McIntyre, et al., *EMC Analysis Handbook*, JSC-CR-97-010, Annapolis, MD: DoD Joint Spectrum Center, March 1997.

[3-2] T. Keech, M. O'Hehir, and T. Hensler, *$JSMS_W$ Interference Analysis Algorithms*, JSC-CR-96-016B, Annapolis, MD: DoD Joint Spectrum Center, April 1998.

[3-3] *Protection Criteria used for Radio Astronomical Measurements*, ITU-R RA.769-2, Geneva: ITU, 2003.

3.3 LEVEL THREE ANALYSIS

For those systems that exceeded the I/N thresholds established in Level One and Level Two analyses, a more detailed analysis (Level Three) was conducted. The Level Three analyses applied specific performance criteria for each type of environmental receiver including antenna coupling scenarios and receiver signal processing.

3.3.1 Radar Systems

The potential for interference from the GDT command link and UAV return link transmitters to in-band and adjacent-band radar systems was calculated based on the I/N within the -3 dB IF amplifier (or filter) bandwidth. Equation 3-1 was used to calculate the I/N. I/N was compared to an $(I/N)_T$ of -6 dB to predict the level of compatibility between the UAV and radar systems. The statistical antenna gain values were calculated using the STATGN program. Propagation loss was calculated using TIREM. Required frequency separation was determined using FDRCAL.

3.3.2 Terrestrial Microwave Links

The potential for interference from the GDT command link and UAV return link transmitters to the in-band and adjacent-band terrestrial microwave links was analyzed by calculating the C/N of the existing link design. The C/N was calculated as:

$$C/N = EIRP - L_{PF} + G_R - N \tag{3-4}$$

where C/N = carrier-to-noise power ratio, in dB

EIRP = effective isotropic radiated power, in dBm

L_{PF} = free-space propagation loss between the transmitting antenna and the receiving antenna, in dB

and all other terms are as previously defined.

Free-space propagation loss was calculated as:

$$L_{PF} = 20 \text{ Log}(F) + 20 \text{ Log}(D) + 32.45 \tag{3-5}$$

where L_{PF} = free-space path loss, in dB
F = transmit frequency of the carrier, in MHz
D = link distance, in km

and all other terms are as previously defined.

The calculated C/N was compared to the performance threshold $(C/N)_T$ to determine the available fade margin. The maximum available fade margin of the existing link was determined by:

$$FM1 = C/N - (C/N)_T \tag{3-6}$$

where FM1 = maximum available fade margin of existing link without interference, in dB

and all other terms are as previously defined.

The availability for the existing link design was calculated. The path availability[3-4] when the UAV data link is not transmitting, was determined by:

$$A = 1 - (16 \times 10^{-7} \times F \times D^2 \times 10^{-FM1/10}) \tag{3-7}$$

where A = availability, unitless

and all other terms are as previously defined.

To assess the effect of interference from the data link, the C/(I+N) was calculated as:

$$C/(I+N) = C - 10 \, Log(10^{I/10} + 10^{N/10}) \tag{3-8}$$

[3-4] Roger L Freeman, *Radio System Design for Telecommunications*, New York, NY: John Wiley & Sons, Inc, 1987.

where $C/(I+N)$ = carrier-to-interference-plus-noise-power ratio, in dB
C = carrier power, in dB

and all other terms are as previously defined.

$$I = P_T + G_{T2} + G_{R2} - L_P - L_S - FDR \tag{3-9}$$

G_{T2} = transmitter antenna gain in the direction of the victim receiver antenna, in dBi
G_{R2} = receiver antenna gain in the direction of the interfering transmitting antenna, in dBi

and all other terms are as previously defined.

The G_{T2} and G_{R2} terms in Equation 3-9 were calculated using a statistical gain model based on antenna directionality. The terrain propagation loss was calculated using TIREM for the GDT command link and UAV return link transmitters to the terrestrial microwave link interactions. The FDR term was calculated using FDRCAL.

To assess the effect of interference on the existing link, the C/(I+N) was compared to the $(C/N)_T$ to determine the remaining fade margin. The fade margin for the links with interference present was calculated as:

$$FM2 = C/(I+N) - (C/N)_T \tag{3-10}$$

where FM2 = maximum available fade margin of existing link with interference present, in dB

and all other terms are as previously defined.

The availability in the presence of interference from the datalink was then calculated. The availability was based on the percentage of time that the datalink would be transmitting annually at a given location. The path availability was calculated as:

$$A = 1 - (16 \times 10^{-7} \times F \times D^2 \times 10^{-FM2/10}) \tag{3-11}$$

and all terms are as previously defined.

The Level Three analysis of the terrestrial microwave links entailed calculating desired carrier-to-noise ratio (C/N), fade margin availability without interference, C/(I+N), and availability with interference. The reduction of availability was then calculated. Typically, 0.99999 availability is used as a general threshold. For those systems in the environment that did not have an availability of 0.99999 in the desired link (without interference from the UAV), a threshold of 0.99975 was used.[3-5] However, many microwave links did not meet 0.99975 availability without interference from the UAV. Therefore, a percentage of availability reduction approach was used.

Required frequency separation was determined to reduce interactions with greater than 0.1% availability reduction to less than 0.01% reduction. The required FDR was determined by adjusting the FDR value until the availability reduction due EMI was less than 0.01%. From the required FDR, the minimum frequency separation was then determined by using the FDRCAL program.

3.3.3 Radio Astronomy Telescopes

The interference from the GDT command link and UAV return link transmitters to single-dish RA telescopes in the environment was assessed using the equations specified in ITU-R RA.769-2 (Reference 3-3). From Reference 3-3, the receiver sensitivity can be expressed as:

$$\Delta T = \frac{Ts}{\sqrt{\Delta f(t)}} \tag{3-12}$$

where ΔT = smallest detectable change in equivalent temperature of the output terminal of the antenna, in K
Ts = system temperature, in K
Δf = noise bandwidth, in Hz
t = integration time, in sec

The smallest power level change at the radiometer input which can be detected and measured by the radiometer is ΔP. The sensitivity equation can be used to relate ΔP to the total system sensitivity (noise fluctuations) expressed in temperature units through the Boltzmann's constant as:

[3-5] *DCS Digital Line of Sight Link Design*, Engineering Publication 1-90, Reston VA: Defense Communications Engineering Center, April 1990.

$$\Delta P = k\Delta T_S$$

(3-13)

where k = Boltzmann's constant (1.38×10^{-23} Joules/°k)

and all other terms are as previously defined.

Assuming an introduced error of 10% in the measurement of ΔP, the power level of maximum tolerable interference, ΔP_H, at the antenna terminals is as follows:

$$\Delta P_H = 0.1\Delta P\Delta f$$

(3-14)

where ΔP_H = the new power level of maximum interference, in dBW

and all other terms are as previously defined.

The Reference 3-3 also identifies calculations for interference expressed in terms of power flux-density incident at the antenna. For convenience, the equation is given for an antenna having a gain, in the direction of arrival of the interference, equal to that of an isotropic antenna:

$$PD_I = 10Log(\Delta P_H) + 20Log(F) - 38.6$$

(3-15)

where PD_I = maximum tolerable power density (average power density), in dBW/m^2

and all other terms are as previously defined.

Since Reference 3-3 identifies calculations for both power flux-density and received power at the RA telescopes, the interference from the datalink was assessed by calculating both. However, the received power levels at the RA telescopes (P_R) are more indicative of the estimated degradation of the telescopes.

To evaluate the effects of the datalink signal on the RA telescopes in the environment, the interference power levels (peak and average) at the RA telescopes were calculated as follows:

$$P_R = P_T + G_T - FDR - L_P - L_S - L_{PR} - L_B - 30 \quad (3\text{-}16)$$

where P_R = received power at the RA telescope, in dBW
L_B = attenuation due to building blockage, as appropriate, in dB
L_{PR} = receiver processing loss, as appropriate, in dB

and all other terms are as previously defined.

For the datalink radiating toward the RA telescopes, the expected power density levels incident on the RA telescopes were calculated as follows:

$$PD = P_T + G_T - FDR - L_p + 20\ Log(F) - 68.5 \quad (3\text{-}17)$$

where PD = average power density, in dBW/m^2

and all other terms are as previously defined.

For cases where additional isolation is required, FDRCAL was used to determine required frequency separation to preclude EMI.

3.3.4 Mobile, GDT Return Link, UAV Command Link, and Telemetry

The potential for interference from the UAV return link and GDT command link transmitters to the mobile and telemetry systems, and from the C-E transmitters to the GDT return link and UAV command link receivers were analyzed by first calculating the desired signal level, using Equation 3-18.

$$S = P_{T2} + G_T - L_{PF} + G_R - L_{S2} \quad (3\text{-}18)$$

where S = desired received power, in dBm
P_{T2} = desired transmitter peak power, in dBm
L_{S2} = total (transmitter and receiver) system losses for the desired path, in dB

and all other terms are as previously defined.

The interference threshold was determined by subtracting $(S/I)_T$ from the calculated desired signal power. The interference power was calculated using Equation 3-9. Receiver mainbeam antenna gain was used for G_T and G_R. The G_{R2} term was calculated using the STATGN model based on receiver antenna directionality. The free-space propagation loss was calculated using Equation 3-5. The terrain propagation loss used in Equation 3-9 was calculated using TIREM.

The calculated I was compared to the interference threshold (I_T) to evaluate system performance. For the Level Three analysis, the $(S/I)_T$ was 12 dB.[3-6]

3.3.5 Troposcatter

Determination of the potential for interference from the GDT command link and UAV return link transmitters to troposcatter systems was based on the I/N within the -3 dB IF amplifier (or filter) bandwidth. Equation 3-1 was used to calculate the I/N. I/N was compared to an $(I/N)_T$ of 0 dB to predict the level of compatibility between the UAV and troposcatter systems. The statistical antenna gain values were calculated using the STATGN program. Propagation loss was calculated using TIREM. Required frequency separation was determined using FDRCAL.

[3-6] R. H. Haines, *An EMC Analysis of the GPS Ground Antenna and Monitor Station at Kwajalein Island*, ECAC-CR-82-113, Annapolis, MD: DoD ECAC (now DoD Joint Spectrum Center), March 1983.

SECTION 4 – RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

4.1 RESULTS

The SBVI in-band/adjacent-band environment within the geographic areas is defined by the four points 36° N 117° W, 36° N 109° W, 28° N 109° W, and 28°N 117°W. The SBVI GCS is assumed to be located at Bisbee-Douglas International Airport at latitude 312809N and longitude1093613W in DMS. The NMBS database selects were constrained to within 600 km of 482000N 1230000W in DMS. The NMBS GCS is assumed to be located at Whidbey Island NAS at latitude 482107N and longitude 1223918W in DMS. For those systems not culled out in the Level One and Level Two analyses, a Level Three analysis was performed.

For the two scenarios, eight main system types were analyzed: radars, terrestrial microwave links, RA telescopes, mobile systems, GDT return link, UAV command link, telemetry systems, and troposcatter systems.

4.1.1 Radar Victim Analysis

There were 105 potential interactions involving radar systems in the environment that required a Level Three analysis. The nomenclatures included AN/FPS-16, AN/FPS-16(V), AN/TPQ-39, AN/TPQ-39(V), AN/TPS-76, MOTSST171, MOTSST171C, TDWR, VARIAN69006, VEG161C-2, and VEG626C.

There were 39 SBVI UAV return link, 28 NMBS UAV return link, and 2 NMBS GDT command link source interactions requiring 5-MHz or less frequency separation in the 5450 – 5825-MHz frequency band. There were no potential interactions with radar systems in the 4400 – 4940 and 14400 – 15350-MHz frequency bands requiring Level 3 analysis. It should be noted that the UAV return link source interaction calculations are worst case since minimum slant range based on the scenario flight path was used.

4.1.2 Terrestrial Microwave Link Victim Analysis

A Level Three analysis for the UAV datalink was performed for 120 microwave links as a victim of interference from the UAV datalinks operating in the SBVI and NMBS scenario regions. Four microwave links were predicted to have more than 0.1% decrease in system availability. Pertinent information concerning the four victim systems is provided in Table 4-1 along with frequency separation requirements to mitigate the potential EMI.

Table 4-1. Terrestrial Microwave Links With Greater Than 0.1% Availabiliy Reduction

Agency Number	Receiver Latitude, DMS	Receiver Longitude, DMS	Availability without Interference, unitless	Availability with Interference, unitless	Link Distance, km	Frequency, MHz	Required Frequency Separation, MHz
SVBI Scenario, UAV Source							
AF 871686	325245N	1124358W	0.99958	0.99799	53	4810	1
NMBS Scenario, UAV Source							
CAN 911730	490652N	1215407W	0.0.99744	0.99167	45	4645	5
CAN 911731	490652N	1215407W	0.99872	0.99744	41	4645	1
CAN 911732	490605N	1204525W	0.99083	0.98169	67	4645	4

4.1.3 Radio Astronomy Telescope Victim Analysis

A Level Three analysis was required for the very-long baseline array (VLBA) RA telescopes listed in Table 4-2. The results presented in Table 4-2 indicate that while no EMI is predicted to the Brewster site, severe EMI is predicted to the Kitt Peak site.

4.1.4 Mobile Victim Analysis

A Level Three analysis for the UAV return link transmitter to mobile receivers was performed for 25 mobile systems as a victim of interference from the datalink operating in the SBVI and NMBS scenario regions. No EMI interactions were predicted.

4.1.5 GDT Return Link Victim Analysis

A Level Three analysis for environmental C-E systems interfering with the GDT return link was performed for 38 systems operating in the SBVI and NMBS scenario regions. Marginal EMI was predicted from a MOSS171C operating at 5460 MHz and located at Fort Huachuca.

4.1.6 UAV Command Link Victim Analysis

A Level Three analysis for environmental C-E systems interfering with the UAV command link was performed for 926 systems operating in the SBVI and NMBS scenario regions. EMI was predicted for 124 assignments involving 13 different nomenclatures. Table 4-3 lists the nomenclatures and worst-case frequency separation. Most of the predicted interference cases to the UAV command link involve the SBVI scenario.

Table 4-2. RA Telescopes Requiring Level Three Analysis

System	Frequency Band, MHz	Latitude, DMS	Longitude, DMS	Location		RA Frequency, MHz	Threshold		Calculated		Frequency Separation Required, MHz	FDR Resulting from Frequency Separation, dB
				City	Sate		Power, dBW	Power Density, dBW/m^2	Received Power from UAV, dBW	Power Density from UAV, dBW/m^2		
VLBA	4400 – 4940	315736N	1113636W	Kitt Peak	AZ	4600 – 5100	-206.9	-172.3	-115.1	-80.2	a	90.5
VLBA	14400 – 15350	315736N	1113636W	Kitt Peak	AZ	14400 – 15400	-204.1	-159.5	-125.1	-80.3	a	77.7
VLBA	4400 – 4940	480748N	1194048W	Brewster	WA	4600 – 5100	-206.9	-172.3	-223.9	-179.7	0	0
VLBA	14400 – 15350	480748N	1194048W	Brewster	WA	14400 – 15400	-204.1	-159.5	-234.8	-190.0	0	0

[a] Frequency separation will not provide required FDR.

Table 4-3. C-E Source to UAV Command Link Analysis Results

Nomenclature	Scenario	Frequency, MHz	Frequency Separation, MHz
AN/FPS-16	SBVI	5450 – 5825	5
AN/MPS-25	SBVI	5565, 5665	6
AN/MPS-36	SBVI	5450 – 5825	5
AN/TPQ-39	SBVI	5450 – 5825	3
AN/TPS-76	SBVI	5600, 5684	3
AN/TRC-170	SBVI and NMBS	4400 – 4940	3
MOTSST171C	SBVI	5450 – 5825	2
RIEWXR700C	SBVI	5440	2
TDWR	SBVI	5610	2
VEG161C-2	SBVI	5525	2
VEG626C	SBVI	5405, 5500	1
Weather Radar	NMBS	5450 – 5600	2
Weather Radar	NMBS	5500 – 5650	7

4.1.7 Telemetry System Victim Analysis

A Level Three analysis for the UAV return link transmitter interfering with telemetry receivers was completed for 67 telemetry systems operating in the SBVI and NMBS scenario regions. EMI was not predicted.

4.1.8 Troposcatter System Victim Analysis

A Level Two analysis for the UAV return link transmitter interfering with the 4400 – 4940-MHz AN/TRC-132A and AN/TRC-170 troposcatter receivers was completed for 40 troposcatter systems operating in the SBVI and NMBS scenario regions. EMI was predicted for 38 cases with 3-MHz or less frequency separation required to prevent potential EMI.

4.2 CONCLUSIONS

4.2.1 SBVI Scenario

The results show that the 4400 – 4940-MHz band is used extensively in Mexico for fixed microwave. Although only marginal EMI problems were predicted to the microwave systems, EMI may be severe if the SBVI flight path were moved closer than the analyzed distance of 73.7 km to the Mexican border.

Severe EMI is predicted from the UAV return link transmitter to the Kitt Peak VLBA in both the 4400 – 4940 and 14400 – 15400-MHz frequency bands. Therefore, frequency coordination may not be possible in the SBVI scenario region for these frequency bands.

Troposcatter sets in the SBVI scenario region may be sources of EMI to the UAV command link receiver and victims of EMI from the UAV return link transmitter in the 4400 – 4940-MHz frequency band.

The results show that numerous radar systems operate in the 5450 – 5825-MHz portion of the 5250 – 5850-MHz band. The UAV return link may interfere with the radar and the radar may interfere with the UAV command link. Frequency coordination for 5250 – 5850 MHz in the region may be difficult.

The database selects show that several 14000 – 14500-MHz satellite communications Earth-to-space links operate in the 14400 – 15350-MHz band. Although the links were not predicted to be EMI issues, there may be a coordination and EMI issue if the flight path is modified from the presented flight path. This issue could be minimized by moving the flight path closer to the Mexican border.

4.2.2 NMBS Scenario

The results show that the 4400 – 4940-MHz band is used extensively in Canada for fixed microwave. Although only marginal EMI problems were predicted to the microwave systems, more EMI cases may be identified if the NMBS flight path were modified.

Troposcatter sets in the NMBS scenario region may be sources of EMI to the UAV command link receiver and victims of EMI from the UAV return link transmitter in the 4400 – 4940-MHz frequency band.

The UAV return link may interfere with two weather radars, and the two weather radars may interfere with the UAV command link. Frequency management to avoid weather radars in the 5400 – 5650 MHz should not be an issue.

The database selects show that numerous 14000 – 14500-MHz satellite communications Earth-to-space links operate in the 14400 – 15350-MHz band. Although the links were not predicted to be EMI issues, there may be coordination and EMI issues if the flight path is modified from the present flight path.

There are also numerous Canadian 15000-MHz microwave links in the region. The microwave links may also be a coordination issue and EMI issue if the flight path is modified to be closer to the Canadian border.

4.3 RECOMMENDATIONS

This analysis was intended to provide insight into the magnitude of the spectrum management effort required for homeland security deployments. C-E equipment and resulting coordination challenges vary by region. Equipment tuning flexibility is critical to successful coordination in multiple regions. Flight path considerations within the regions of interest are also an important aspect of frequency coordination. These recommendations are limited by the specific scenarios chosen, and while they can be expected to be fairly representative, different scenarios may have additional issues.

The recommended frequency band for both scenarios is the 5250 – 5850-MHz band, and 14400 – 15350 MHz for the NMBS scenario. This is based on the number of issues and perceived frequency coordination difficulty.

4.3.1 SBVI Scenario

- The selected flight path should not pose problems with the numerous Mexican fixed microwave links but if flight paths are selected that are closer than 74 km from the Mexican border, the 4400 – 4940 MHz operations should be re-analyzed to ensure compatibility is maintained with those microwave links.

- If UAV operations are needed near the National Science Foundation's radio astronomy observatory operating in the 4600 – 5100 and 14400 – 15400-MHz bands, coordination to use those frequencies may be very difficult.

- Frequency coordination is suggested with the numerous 4400 – 4940-MHz troposcatter set operators.

- There are some predicted issues with the UAV return link to a few radars. The currently used 5250 – 5475-MHz return link band should only result in restrictions or a requirement for close coordination within the upper 25 MHz of that band. Frequency coordination for use of the 5450 – 5825-MHz band may be difficult to achieve due to the incompatibility of the UAV return links with radar systems.

- Satellite communications Earth-to-space links exist in the 14000 – 14500-MHz band. Moving the flight path further to the south or maintaining operating frequencies above 14500 MHz would reduce potential coordination issues.

4.3.2 NMBS Scenario

- If flight paths are moved closer to the Canadian border, 4400 – 4940 and 14400 – 15350-MHz operations should be re-analyzed to ensure compatibility with Canadian fixed microwave links.

- Frequency coordination with 4400 – 4940-MHz troposcatter set operators will be required.

- Frequency coordination with two weather radars in the 5400 – 5650-MHz band will be required.

- Satellite communications Earth-to-space links exist in the 14000 – 14500-MHz band. Moving the flight path further north or maintaining operating frequencies above 14500 MHz should reduce potential coordination issues.

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