National Radio Astronomy Observatory Student Cooperative Education Program

EVLA Radio Frequency Interference Survey From 1 – 8 GHz, Analysis of EMS System Noise Figure and VLA L-Band Feed Horns

VLA Interference
Memo # 23

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Co-op Period: August 1, 2001 through December 28, 2001

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Summary

This document covers the work done during my co-op employment at NRAO. Two major projects were accomplished: an RF interference survey from 1 – 8 GHz for the Expanded VLA, and digitizing the radiation patterns of the VLA L-band feed horns. Included in this document are examples of RF Engineering theory that I learned throughout my co-op experience. Perhaps this document this document will be of use for future co-op employees of NRAO.

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Part 1

Radio Frequency Interference Survey 1-8 GHz at the VLA

Abstract

The IPG group at the AOC has been assigned to determine characteristics of external RF interference that the expanded VLA should expect. The plan was to survey RFI from 1-50 GHz, covering each of the eight EVLA receiver bands. As of August, 2001, the survey has begun. Data is now available from 1-8 GHz, and preparations are being made to survey frequencies above 8 GHz. New sources of RFI have been observed and located. Plots of RFI power flux density (PFD) versus frequency are available for public viewing on the NRAO web page at:

http://www.aoc.nrao.edu/vla/interference/survey

The data sets for each of the PFD plots are also available from the above URL. Many of the RFI plots are also in this document along with frequency allocation information, and a description of some of the strongest interference signals.

Introduction

Radio Astronomy has always been very vulnerable to RF interference. Radar, wireless communication, mobile satellite service, and other radio technology continue to develop, causing more interference to radio astronomy and the EVLA. With the characteristics of interference known, one can compensate in EVLA development and design. Hopefully the data in the survey will also be useful to astronomers in observing. This document consists of four sections:

Section I describes the current Environmental Monitoring Station (EMS) used in the survey. The method of acquiring and processing the data is also discussed.

Section II contains power flux density (PFD) plots of RF interference from 1-8 GHz. Frequency allocation information and an RFI analysis accompany each plot. Section III contains an analysis of the EMS system noise figure. Section IV contains recommendations for acquiring RF interference data for frequencies above 8 GHz.

Section I: The Environmental Monitoring Station (EMS)

1.1 Introduction

The EMS was created by students in the NRAO co-op program. Each semester new improvements have been added. After many ups and downs, the system is now operating from 1-12 GHz. Some of the downs include periodic receiver failure, non-existent characterization data for antennas, and the collapse of the tower. Replacements, repairs, and adjustments have been made to get the system operational. Figure (1) is a block diagram of the system. The system is located at the southeast side of the VLA, near the dormitories. The antennas are located on a 50-foot Rohn Tower. The receiver and PC's are located in the RFI shelter, a metal building located near the tower.

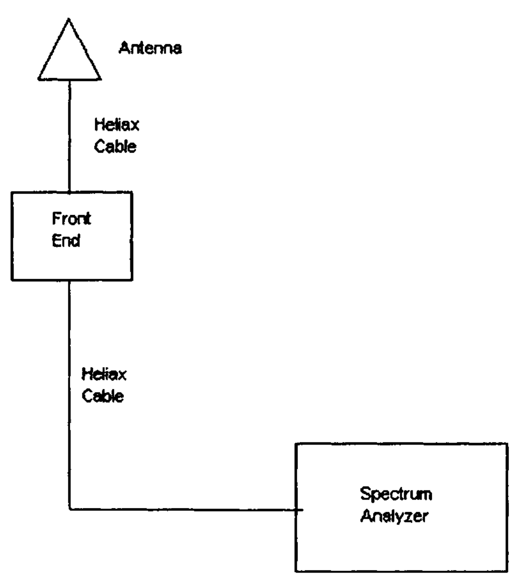


Figure 1: EMS System Block Diagram

1.2 Current EMS Components

In order of signal path, here is a brief description of each component in the EMS. See Appendix A for the EMS characterization data. Detailed characterization information on the components of EMS is available in the IPG office.

1.2.1 Antennas

For 1-8 GHz data, the antenna used was a Dome & Margolin1-8 GHz RCP omni-directional, conical log spiral. The antenna has right hand circular polarization. Its azimuth and elevation patterns have been professionally characterized at 2.1 GHz, 4 GHz, and 8 GHz. Raul Armendariz & Nathan Thomas from the IPG GROUP characterized its gain versus frequency. See Appendix A for a table of gain and effective aperture versus frequency. The effective aperture was used in calculating power flux density. An antenna was not available for measurements above 8 GHz. Two standard gain horns (8.2-12.4 and 12.4-18 GHz) have been ordered for survey use from 8-18 GHz. A dual ridged waveguide horn is available for monitoring from 18-40 GHz.

1.2.2 Cable "EMS-2" LDF2-50Ω

"EMS-2" is an 11 ft., 7 in. long 3/8" heliax cable that runs from the output of the 1-8 GHz omni antenna to the input of the front end.

1.2.3 Front End

The front end was designed by Kerry Shores and built by Raul Armendariz. It operates from 5 MHz to 13 GHz. It is remotely switchable from seven different bands starting with P-band and ending with X-band. Complete characterization data for the front end is available in the IPG office.

1.2.4 Cable "EMS-X"

"EMS-X" is a 62 ft. long 3/8" heliax cable that runs from the output of the front end to the input of the spectrum analyzer.

1.2.5 Receiver

The receiver is an HP 70001 spectrum analyzer. The internal preamplifier was used and the spectrum analyzer was in peak hold mode. As a whole, the receiver noise temperature at 2.5 GHz is approximately 2300 K.

1.3 Predicted System Noise Figure

Here is the calculation to predict the EMS system noise figure at 2500 MHz. This prediction is done assuming system settings identical to the system settings used to obtain one of the plots in Section II (see Figure 8, pg 15). This is the system setup:

1.3.1 System Setup for Noise Floor Prediction

EMS path	S-Band
Frequency Range	2 – 3 GHz
Resolution Bandwidth	215 kHz
Video Bandwidth	300 kHz
Spectrum Analyzer Attenuation	0 dB
Spectrum Analyzer Preamplifier	On
Spectrum Analyzer Mode	Peak Hold

Table 1: EMS setup for 2-3 GHz monitoring

1.3.2 Theoretical Noise Floor Calculation

The following equation was used to predict the system temperature (refer to Figure 1):

$$T_{SYS} = T_A + T_{C1} + \frac{T_{LNA}}{G_{C1}} + \frac{T_{C2}}{(G_{C1})(G_{LNA})} + \frac{T_{SA}}{(G_{C1})(G_{LNA})(G_{C2})}$$

Where:

$T_A \cong 150$ K (approximate noise temperature of the antenna)

$G_{LNA} = 38$ dB $= 6309$ (gain of the S-Band amplifier at 2.5 GHz)

$G_{C1} = -2$ dB $= 0.631$ (loss of cable "EMS-2" at 2.5 GHz)

$G_{C2} = -5$ dB $= 0.316$ (loss of cable "EMS-X" at 2.5 GHz)

$T_{LNA} = 260$ K (noise temp. of the S-Band low noise amplifier in the EMS front end)

$T_{C1} = (290/G_{C1}) - 290 = 169.59$ K (noise temperature of cable "EMS-2" at 2.5 GHz)

$T_{C2} = (290/G_{C2}) - 290 = 627.72$ K (noise temperature of cable "EMS-X" at 2.5 GHz)

$T_{SA} = 2290$ K (approximate noise temperature of the spectrum analyzer at 2.5 GHz)

Plugging in the parameters to the equation yields:

$$T_{SYS} = 150\text{K} + 169.59\text{K} + \frac{260\text{K}}{0.631} + \frac{627.72\text{K}}{(0.631)(6309)} + \frac{2290\text{K}}{(0.631)(6309)(0.316)}$$

$T_{SYS} = 734$ K

This is a prediction of what the system noise temperature will be at 2500 MHz. In Section III a comparison will be made between the above predicted noise temperature and the approximate actual noise temperature.

1.4 Data Acquisition

A serial connection from the spectrum analyzer to a PC transfers the data in ASCII text format. A program was written to display two columns: frequency bin (0-1023) and power (dBm). Knowing the frequency settings (span and center frequency) from the spectrum analyzer, each frequency bin can be associated with a frequency. The data is then calibrated, accounting for the net loss and gain and the antenna effective aperture, resulting with power flux density (W/m^2). The following equation was used:

$PFD * A_e = P_{Rx}$ The calibration was done manually in Microsoft Excel.

Appendix A contains the system losses and gains, and the antenna effective aperture.

Section II: Power Flux Density (PFD) Plots 1-8 GHz

2.1 PFD Plots, Allocation Information, RFI Analysis

This section contains RF interference plots obtained through the EMS system. Frequency allocation information is also provided. The plots are organized according to their associated band. There are plots for L-Band, S-Band, and C-Band. Low L-Band plots (1-1.2 GHz) have been given their own section because of the significant interest in DME radar interference. All of the following plots are taken with the spectrum analyzer in peak hold mode. The interference may look worse than it actually is because of intermittent signals detected in peak hold mode. A signal that occurs briefly will be recorded in peak hold mode. Above each plot is information on when and for how long the data was taken.

2.2 DME (1-1.2 GHz)

2.2.1 DME Frequency Allocations

Allocation Information	RFI Description, Characteristic
960 – 1215 MHz[1] • Aeronautical Radionavigation	Intermittent

Table 2: Frequency Allocations, 960 – 1215 MHz

2.2.2 RFI Summary, DME

DME (Distance Measuring Equipment) provides pilots with range in nautical miles. It also contributes a large amount of interference to the VLA. The interrogator signals are intermittent. The two transponder signals are at 1030 and 1090 MHz. The IPG group is working on a way to retrieve data at high resolution to study transient characteristics of DME and other interfering signals.

[1] All frequency allocations in bold letters indicate bands where RFI was detected. Allocations obtained from Spectrum Guide, by Bennett Z. Kobb. 3rd Edition, New Signals Press, 1996

2.2.3 DME PFD Plots

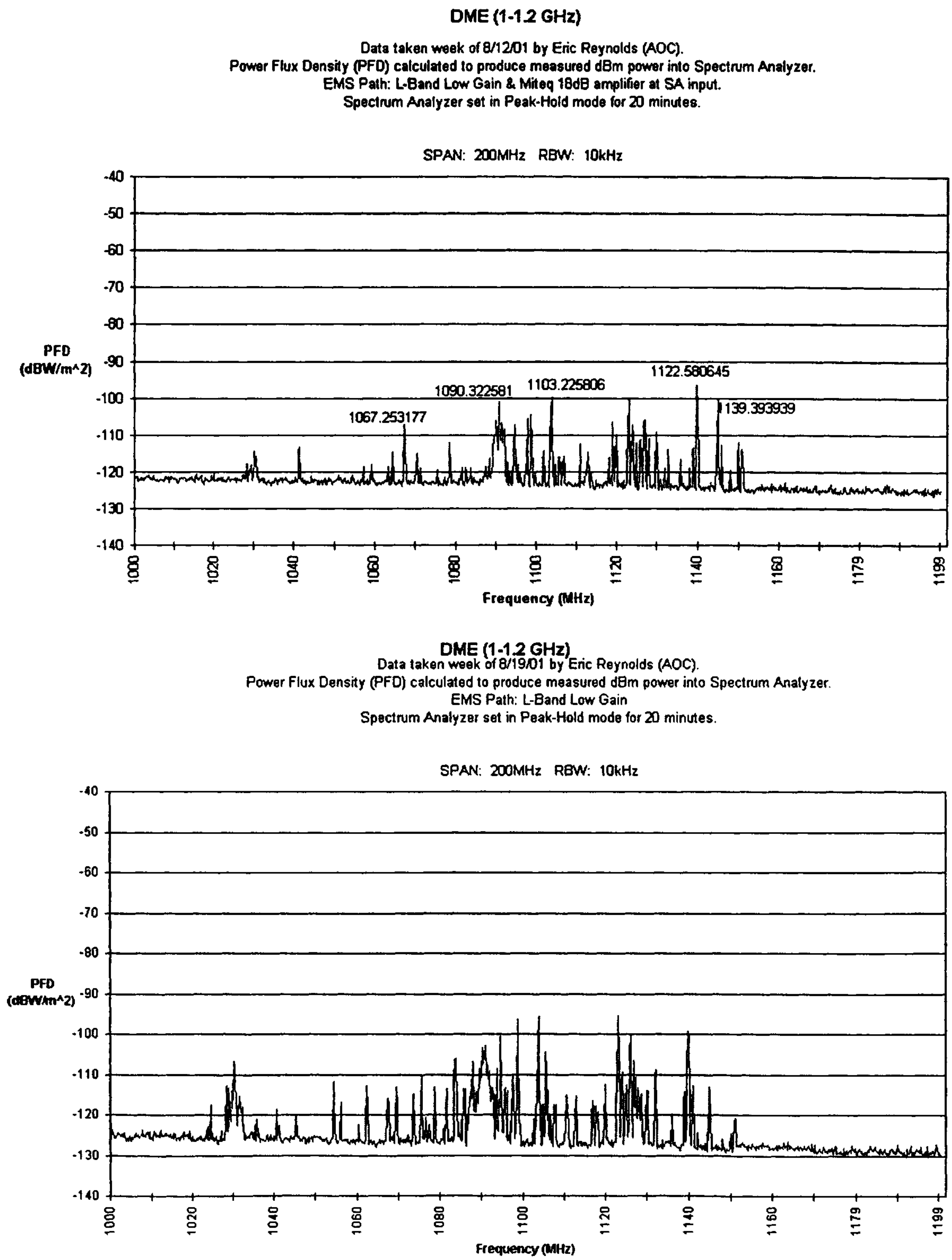


Figure 2: DME Peak Hold Plots

2.3 L-Band (1 – 2 GHz)

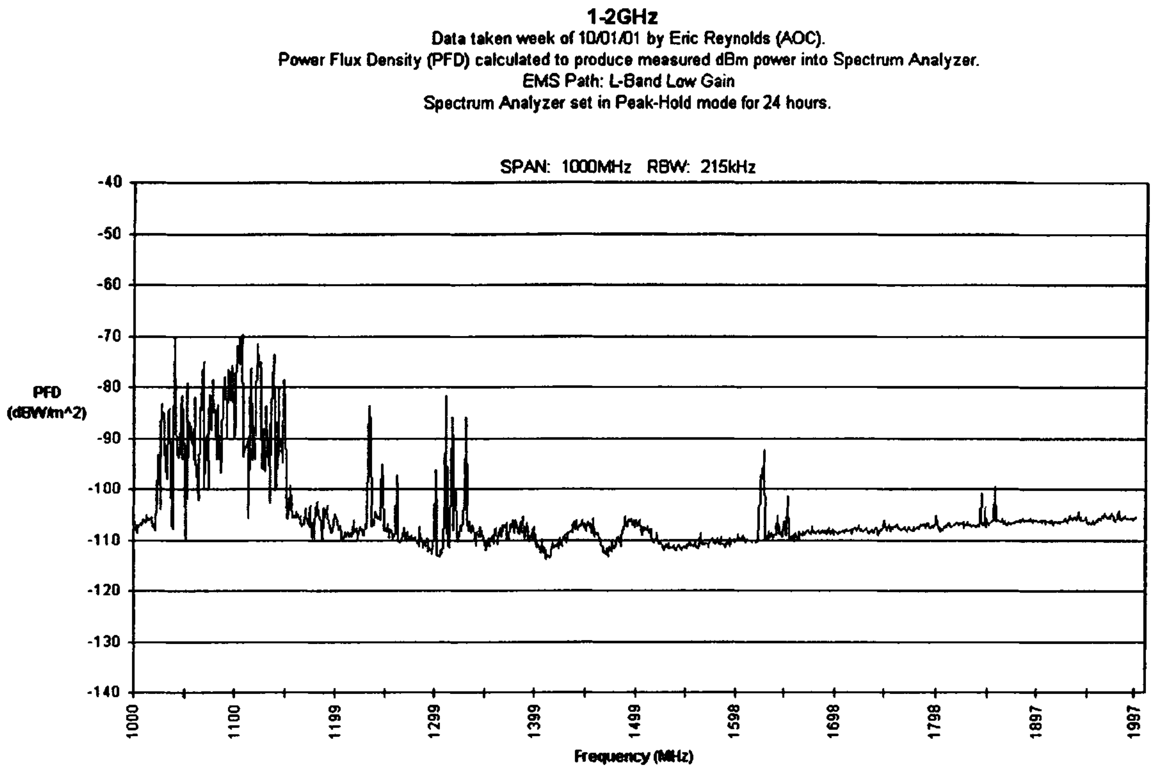


Figure 3: 24 Hour Peak Hold L-Band Plot

2.3.1 RFI Summary, L-Band

The most significant RFI in L-band is from the low frequencies (1000 – 1200 MHz). The low L-band signals are Distance Measuring Equipment (DME). Other sources of RFI in L-band are the Global Positioning System (GPS) from 1215 – 1240 MHz, aeronautical radionavigation from 1300 – 1350 MHz, and the Iridium satellite communications system from 1621.35 – 1626.5 MHz. Many studies have already been made with L-band RFI and can be found in the IPG office.

2.3.2 Frequency Allocations, 1.2 – 1.4 GHz

Allocation Information	RFI Description, Characteristic
960 – 1215 MHz • Aeronautical Radionavigation	Intermittent
1215 – 1240 MHz • Radionavigation Satellite • Global Positioning System (GPS)	Intermittent
1240 – 1300 MHz • Radiolocation • Amateur Radio	
1300 – 1350 MHz • Aeronautical Radionavigation • Radiolocation	Intermittent
1350 – 1400 MHz • Radiolocation • Fixed and Mobile services • FAA and Air Force JSS radar network	

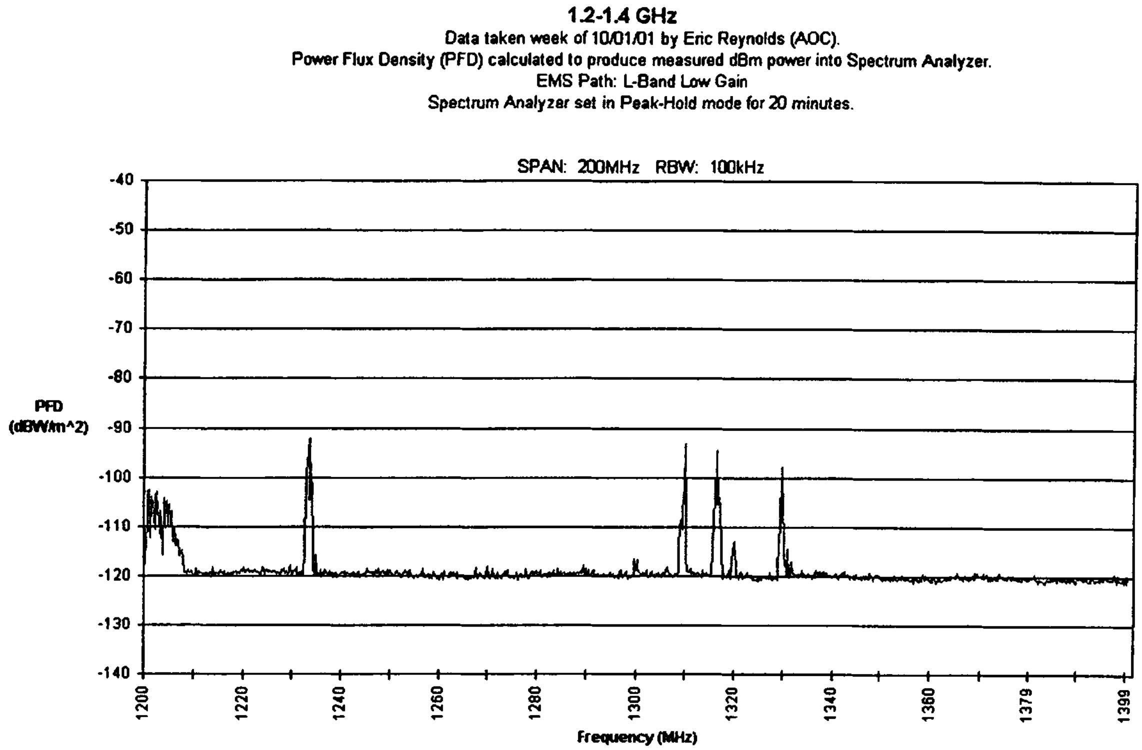
Table 3: Frequency Allocations, 960 – 1400 MHz

2.3.3 Frequency Allocations, 1.4 – 1.6 GHz

Allocation Information	RFI Description, Characteristic
1400 – 1427 MHz • Radio Astronomy	
1427 – 1429 MHz • Space Operation • Fixed and Mobile services • Private Land Mobile • Satellite Communications	
1429 – 1435 MHz • Fixed and Mobile services • Private Land Mobile	
1435 – 1525 MHZ • Mobile services	
1525 – 1530 MHz • Mobile services • Satellite Communications	

Table 4: Frequency Allocations, 1400 – 1530 MHz

2.3.4 PFD Plots, 1.2 – 1.6 GHz



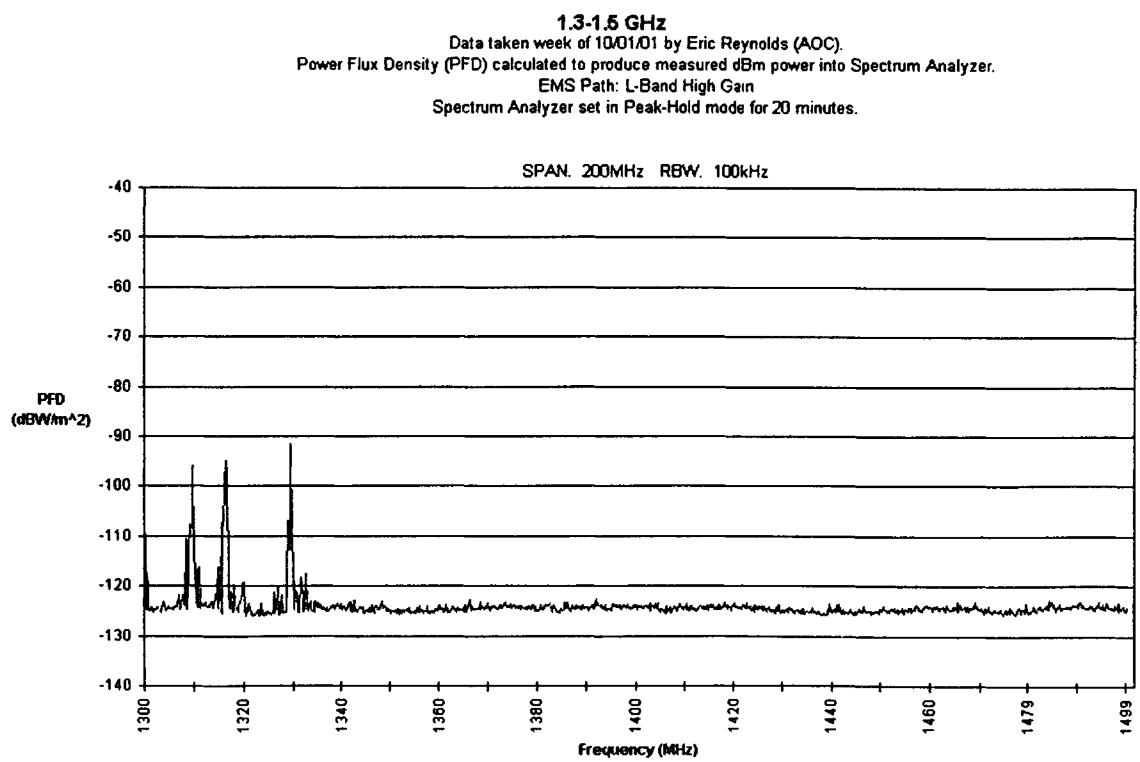


Figure 4: Peak Hold Plots, 1.2 – 1.5 GHz

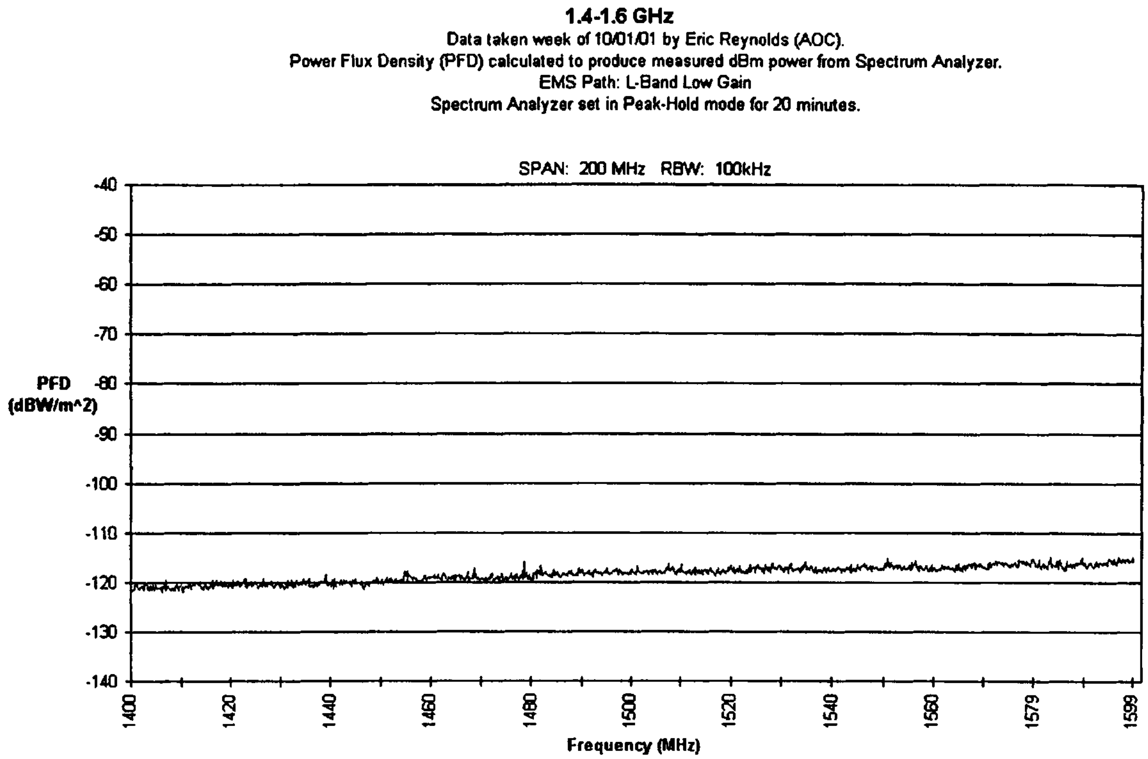


Figure 5: Peak Hold Plots, 1.4 – 1.6 GHz

2.3.5 RFI Summary, 1.2 – 1.6 GHz:

Most of the RFI from 1.2 – 1.4 GHz is caused by aeronautical radionavigation. The signals are intermittent and relatively strong. No RFI was detected from 1.4 – 1.6 GHz.

2.3.6 Frequency Allocations, 1.6 – 1.8 GHz

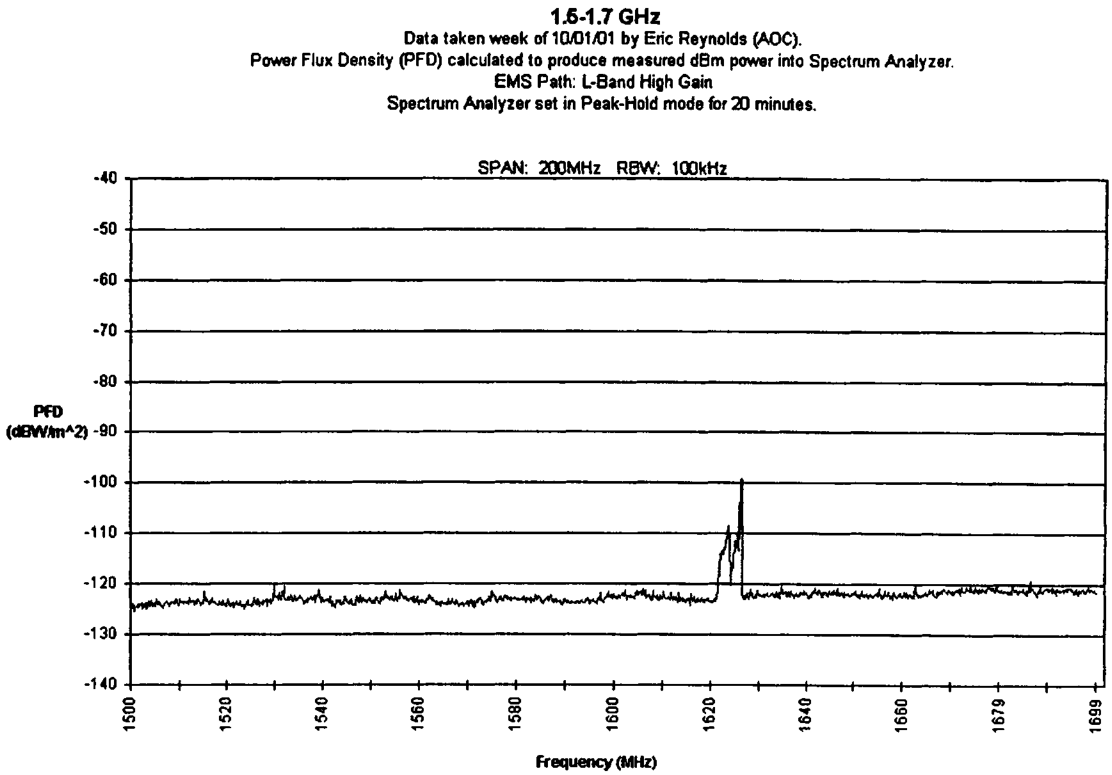
Allocation Information	RFI Description, Characteristic
1610 – 1626.5 MHz • Satellite Communication. Big LEO Spectrum (Iridium, Glonass) • Aeronautical Radionavigation	Continual
1626.5 – 1645.5 MHz • Maritime Mobile Satellite • Satellite Communication	
1645.5 – 1646.5 MHz • Mobile Satellite	
1646.5 – 1660 MHz • Aeronautical Mobile Satellite	
1660 – 1660.5 MHz • Aeronautical Mobile Satellite • Radio Astronomy	
1660.5 – 1668.4 MHz • Radio Astronomy • Space Research	
1668.4 – 1670 MHz • Radio Astronomy • Meteorological Aids (radiosonde)	
1670 – 1700 MHz • Meteorological Aids (radiosonde) • Meteorological Satellite	
1700 – 1710 MHz • Fixed Services • Meteorological Satellite	

Table 5: Frequency Allocations, 1610 – 1715 MHz

2.3.7 RFI Summary, 1.6 – 1.8 GHz:

The only RFI found in 1.6 – 1.8 GHz is from 1621.65 – 1626.5 GHz from the Iridium satellite communications system.

2.3.8 PFD Plots, 1.6 – 1.8 GHz



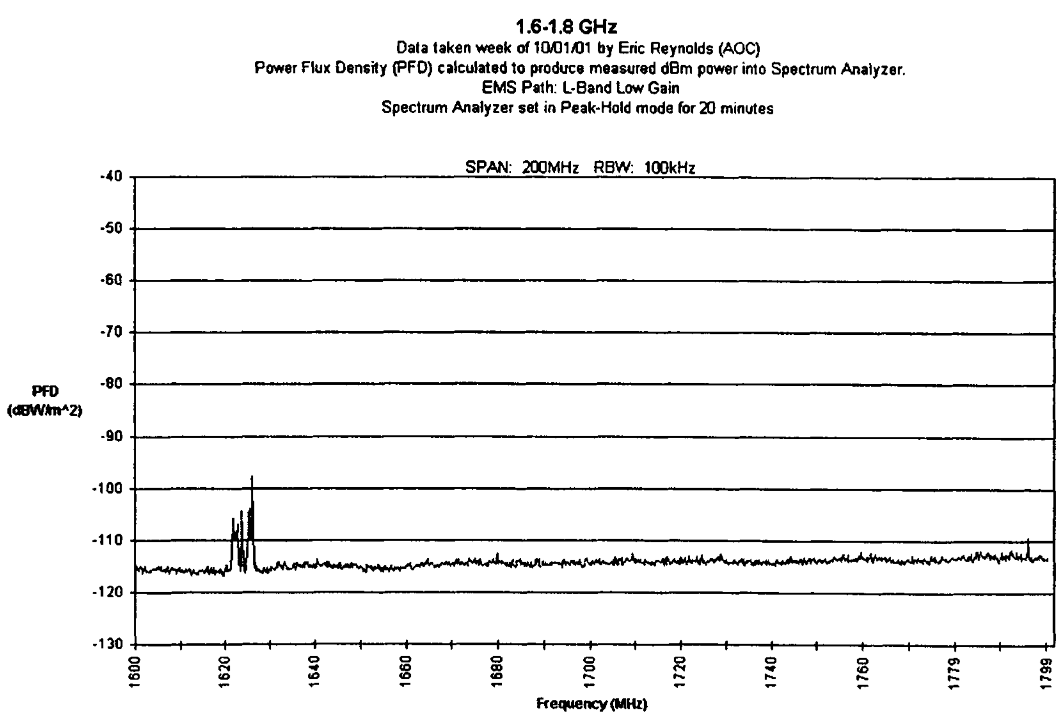


Figure 6: Peak Hold Plots, 1.5 – 1.8 GHz

2.3.9 Frequency Allocations, 1.8 – 2 GHz

Allocation Information	RFI Description,Characteristic
1710 – 1850 MHz • Fixed and Mobile services	Continual
1850 – 1990 MHz • Fixed and Mobile services • Personal Communications Services • Private Operational Fixed Services • RF Devices	
1990 – 2110 MHz • Fixed and Mobile services • Auxiliary Broadcast (74) Cable Television (78)	

Table 6: Frequency Allocations, 1710 – 2110 MHz

2.3.10 PFD Plots, 1.8 – 2 GHz

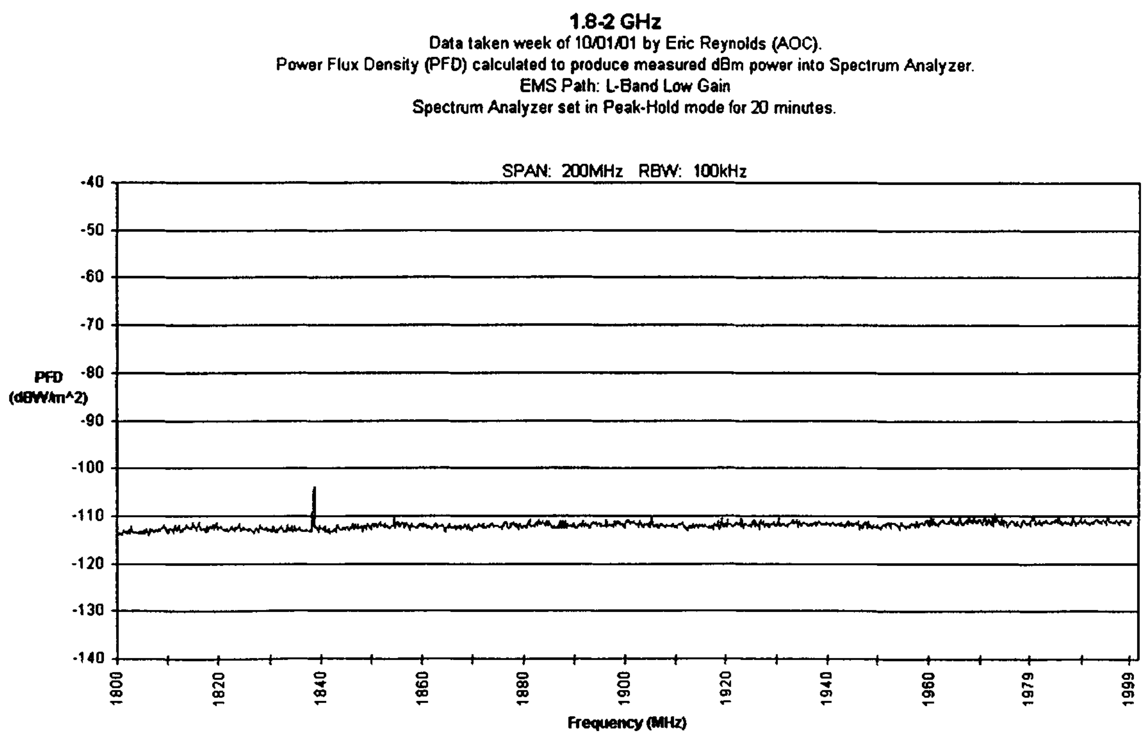
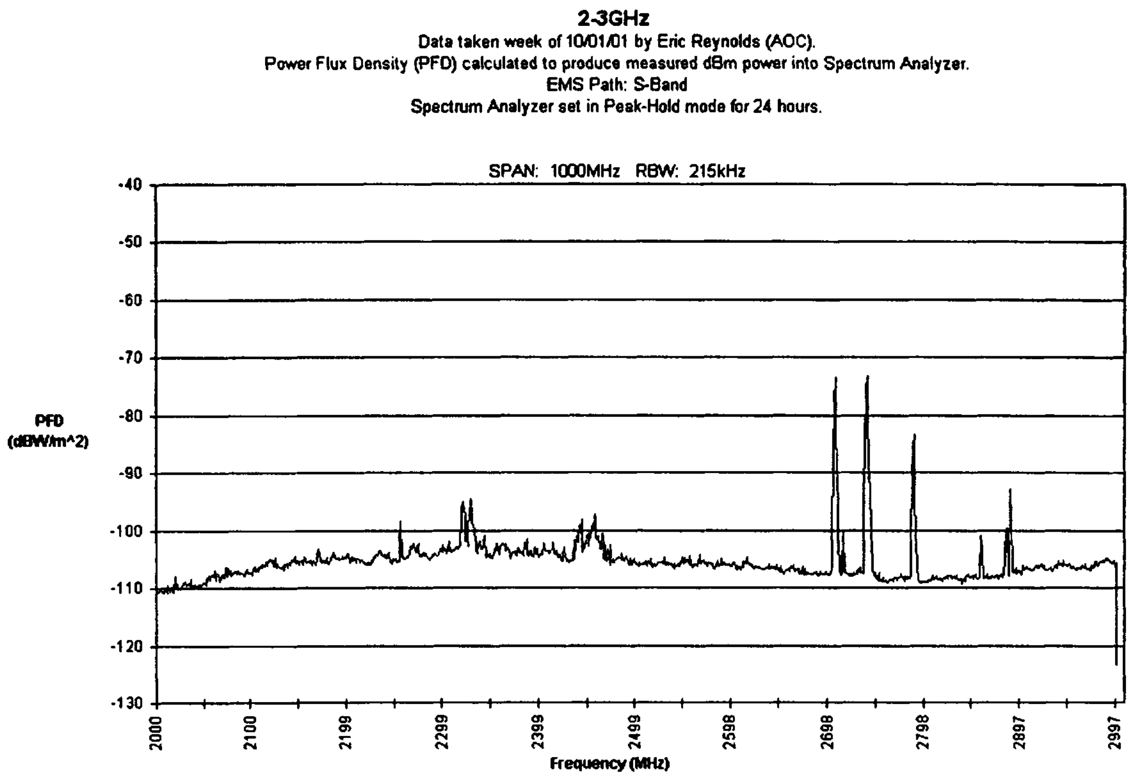


Figure 7: Peak Hold Plot, 1.8 – 2 GHz

2.4 S-Band (2 – 4 GHz)



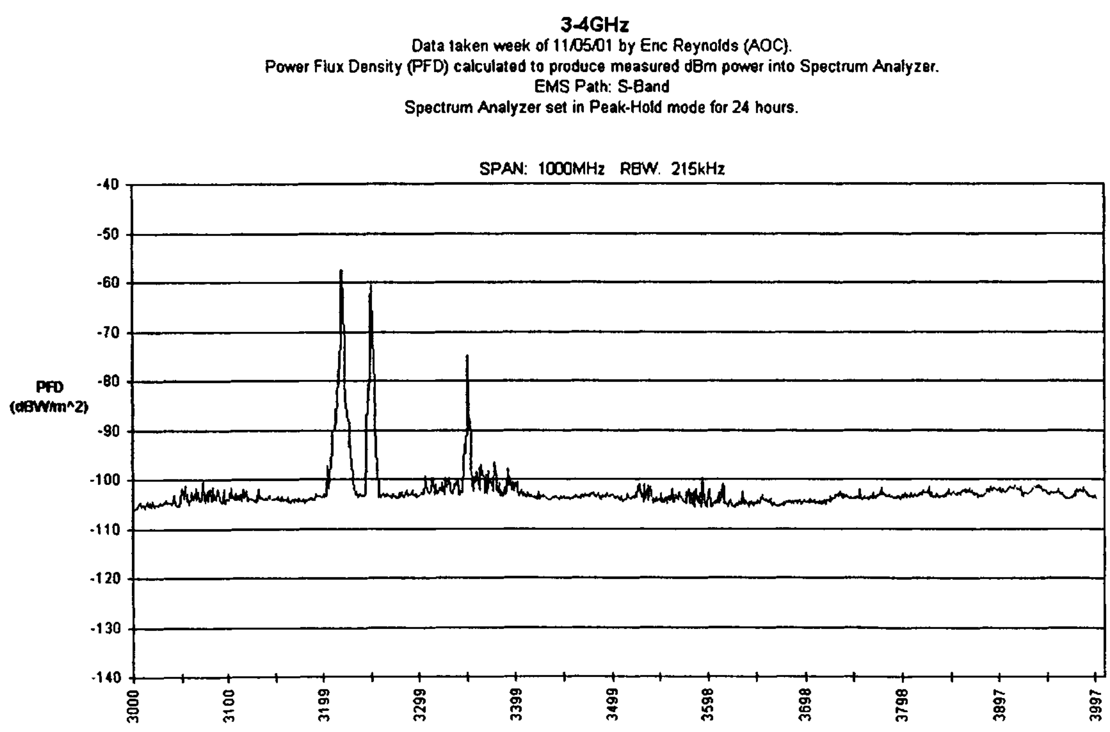


Figure 8: 24 Hour Peak Hold S-Band Plots

2.4.1 RFI Summary, S-Band

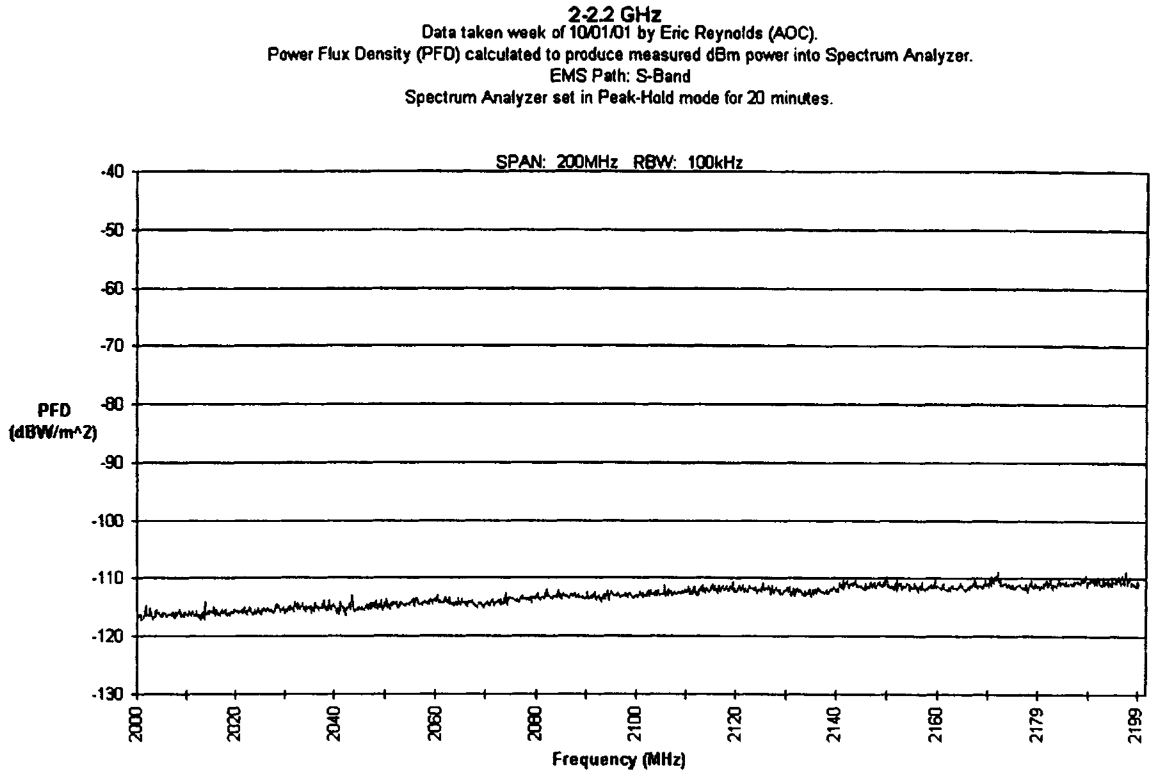
The major RFI in S-Band is from radars. NEXRAD Doppler Radar operates at 2740 and 2790 MHz, resulting in strong, intermittent RFI at the VLA. Defense radar signals were found from 3.1 - 3.6 GHz. They were strong, but seldom present.

2.4.2 Frequency Allocations, 2 – 2.4 GHz

Allocation Information	RFI Description,Characteristic
2110 – 2150 MHz • Fixed and Mobile services • Private Operational Fixed Services • Domestic Public Fixed Services • Public Mobile Services	
2150 – 2160 MHz • Fixed Services • Private Operational Fixed Services • Multipoint Distribution	
2160 – 2200 MHz • Fixed and Mobile services • Domestic Public Fixed Services • Private Operational Fixed Services • Public Mobile Services	
2200 – 2290 MHz • Fixed and Mobile services • Space Research and Operation • Earth Exploration Satellite	
2290 – 2300 MHz • Fixed and Mobile services • Space Research	
2300 – 2310 MHz • Amateur Radio	
2310 – 2360 MHz • Fixed and Mobile services • Radiolocation • Broadcasting-Satellite • Digital Audio Radio Services	Continual
2360 – 2390 MHz • Fixed and Mobile services • Radiolocation	
2390 – 2400 MHz • Amateur Radio	

Table 7: Frequency Allocations, 2110 – 2400 MHz

2.4.3 PFD Plots, 2 – 2.4 GHz



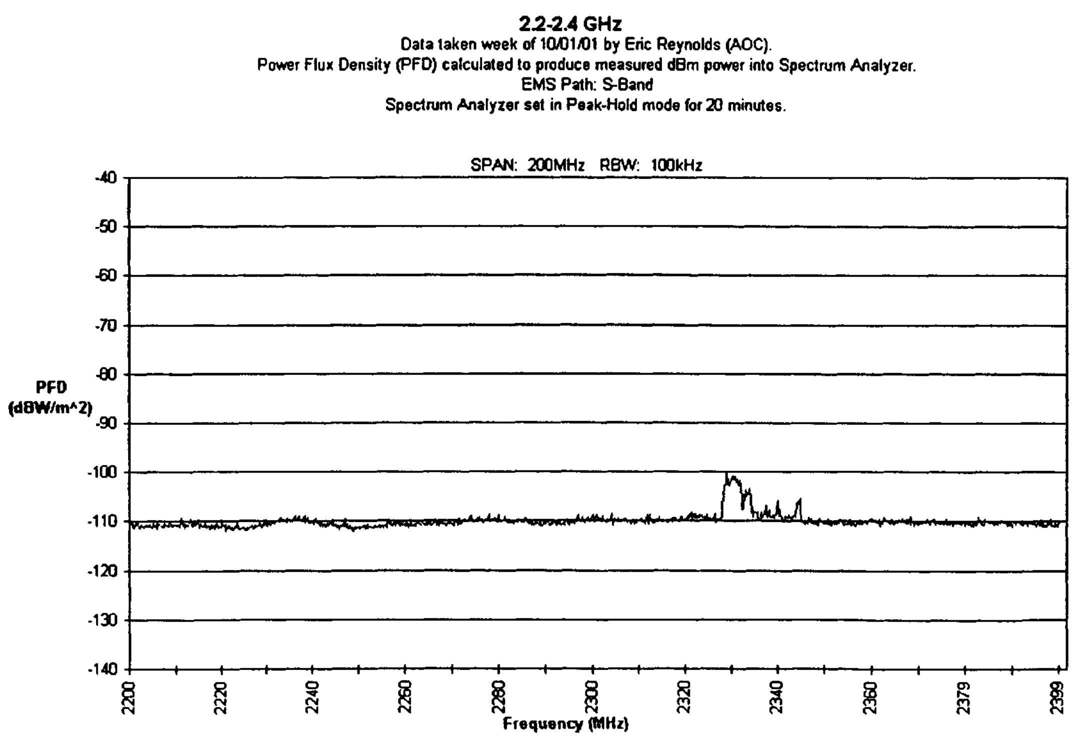


Figure 9: Peak Hold Plots, 2 – 2.4 GHz

2.4.4 Frequency Allocations, 2.4 – 2.6 GHz

Allocation Information	RFI Description,Characteristic
2400 – 2402 MHz • Amateur Radio	
2402 – 2417 MHz • Amateur Radio • Radiolocation	
2450 – 2483.5 MHz • Fixed and Mobile services • Radiolocation	
2483.5 – 2500 MHz • Radiodetermination Satellite • Mobile Satellite • Satellite Communication	
2500 – 2655 MHz • Fixed services • Broadcasting-Satellite • Auxiliary Broadcasting • Domestic Public Fixed Services	

Table 8: Frequency Allocations, 2400 – 2655 MHz

2.4.5 PFD Plots, 2.4 – 2.6 GHz

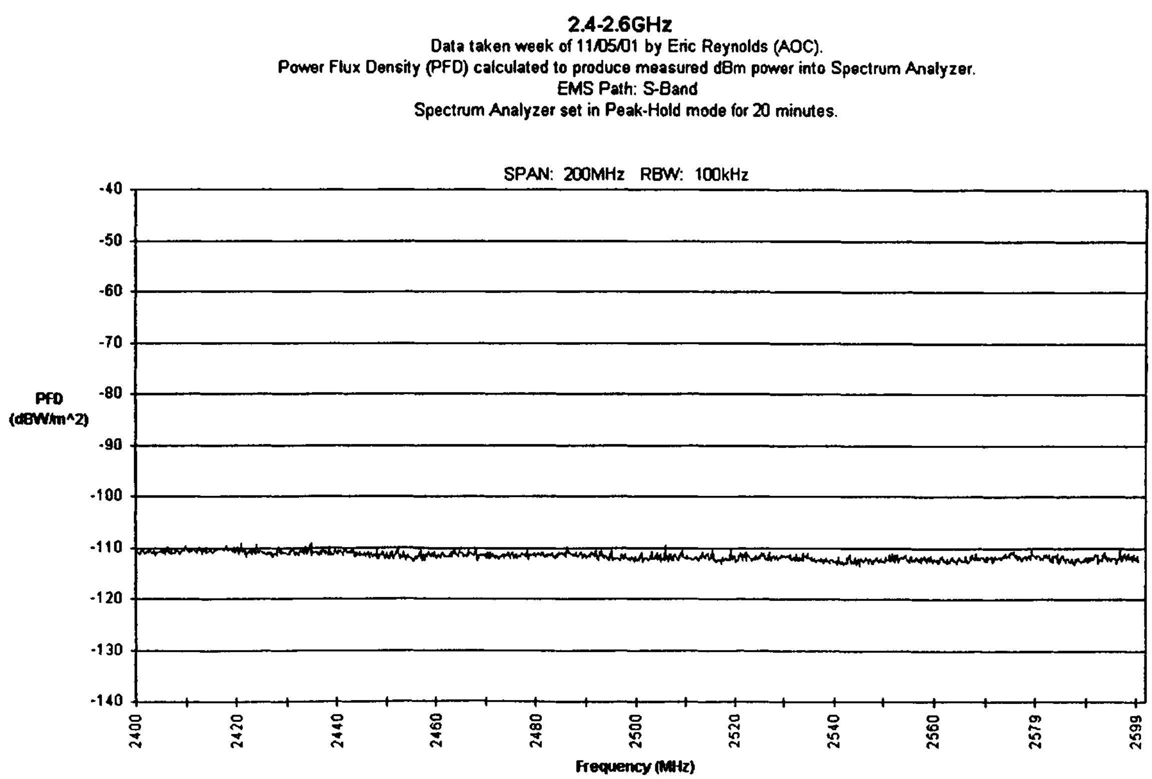


Figure 10: Peak Hold Plot 2.4 – 2.6 GHz

2.4.6 Frequency Allocations, 2.6 – 3 GHz

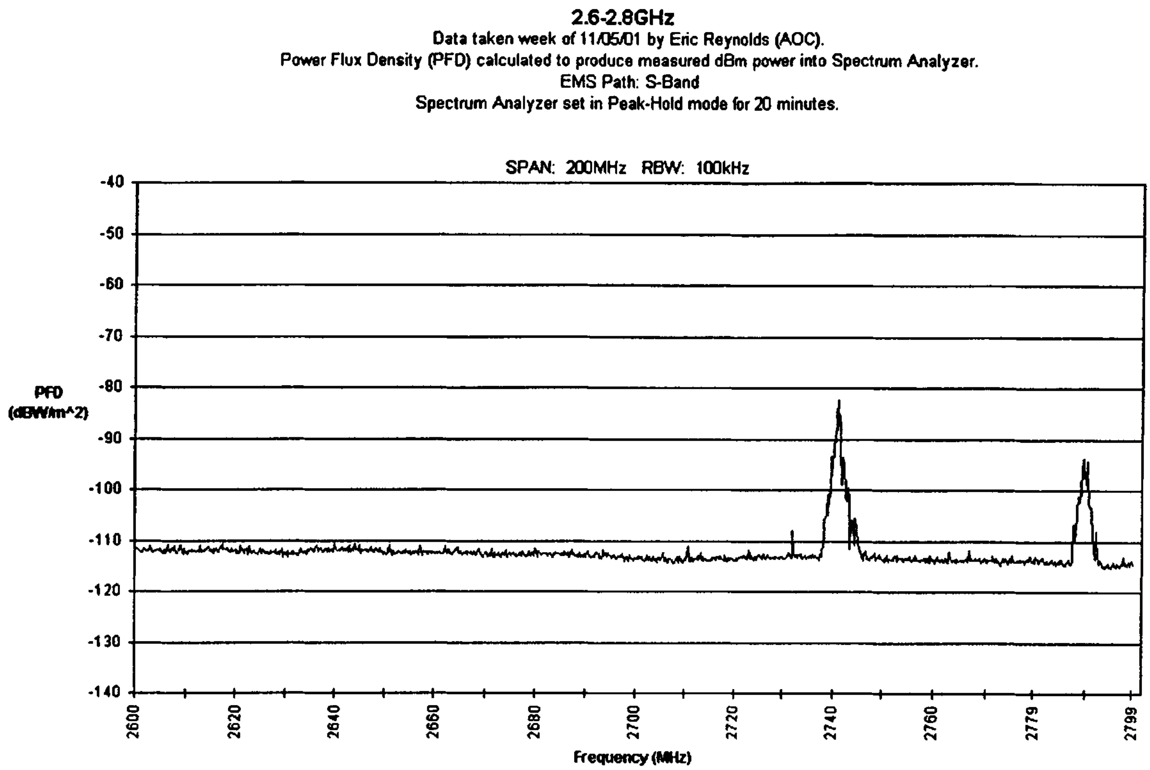
Allocation Information	RFI Description,Characteristic
2655 – 2690 MHz • Earth Exploration Satellite • Radio Astronomy • Space Research • Fixed services • Broadcasting-Satellite • Auxiliary Broadcasting • Private Operational Fixed Services	
2690 – 2700 MHz • Earth Exploration Satellite • Radio Astronomy • Space Research	
2700 – 2900 MHz • Aeronautical Radionavigation • Meteorological Aids • Radiolocation	Intermittent
2900 – 3100 MHz • Maritime Radionavigation • Radiolocation	

Table 9: Frequency Allocations, 2655 – 3100 MHz

2.4.7 RFI Summary, 2.6 – 3 GHz

The RFI in this band is from the next generation Doppler radar (NEXRAD) at 2740 and 2790 MHz. The signals are intermittent and relatively strong.

2.4.8 PFD Plots, 2.6 – 3 GHz



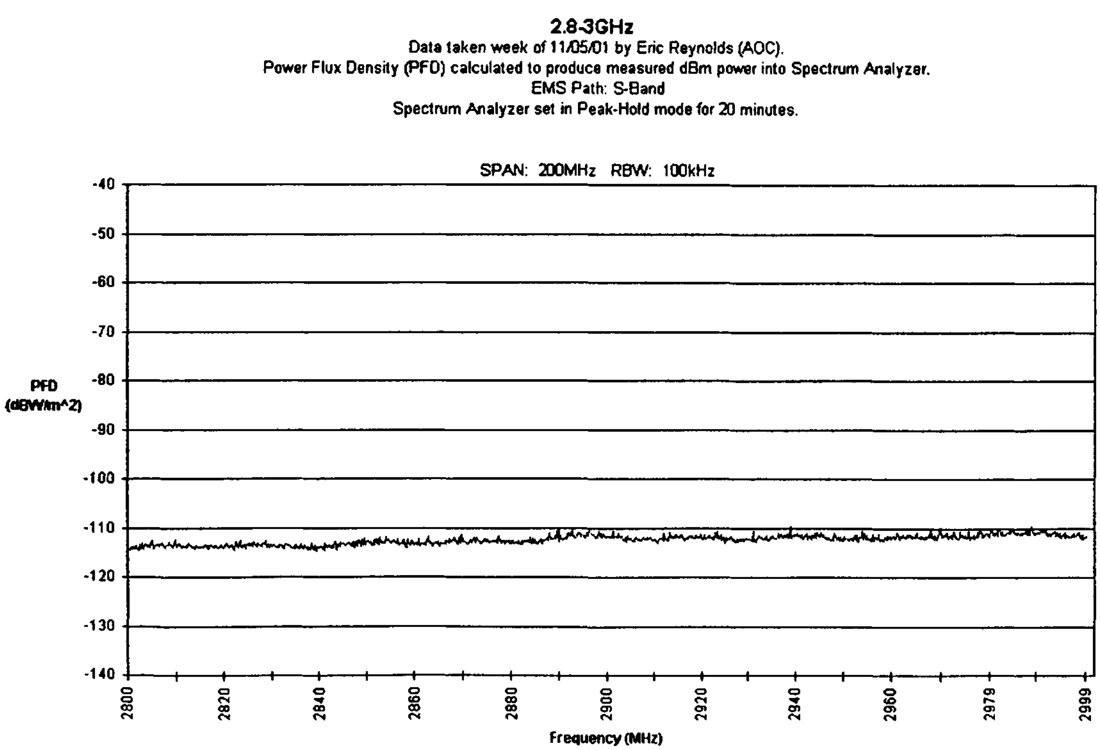


Figure 11: Peak Hold Plots, 2.6 – 3 GHz

2.4.9 Frequency Allocations, 3 – 4 GHz

Allocation Information	RFI Description,Characteristic
3.1 – 3.3 GHz • Radiolocation	Seldom Present
3.3 – 3.5 GHz • Radiolocation • Amateur Radio	Seldom Present
3.5 – 3.6 GHz • Aeronautical Radionavigation • Radiolocation	
3.6 – 3.7 GHz • Aeronautical Radionavigation • Radiolocation • Fixed Satellite	
3.7 – 4.2 GHz • Fixed Services • Fixed Satellite • Domestic Public Fixed Services • Satellite Communications • Private Operational Fixed Services	

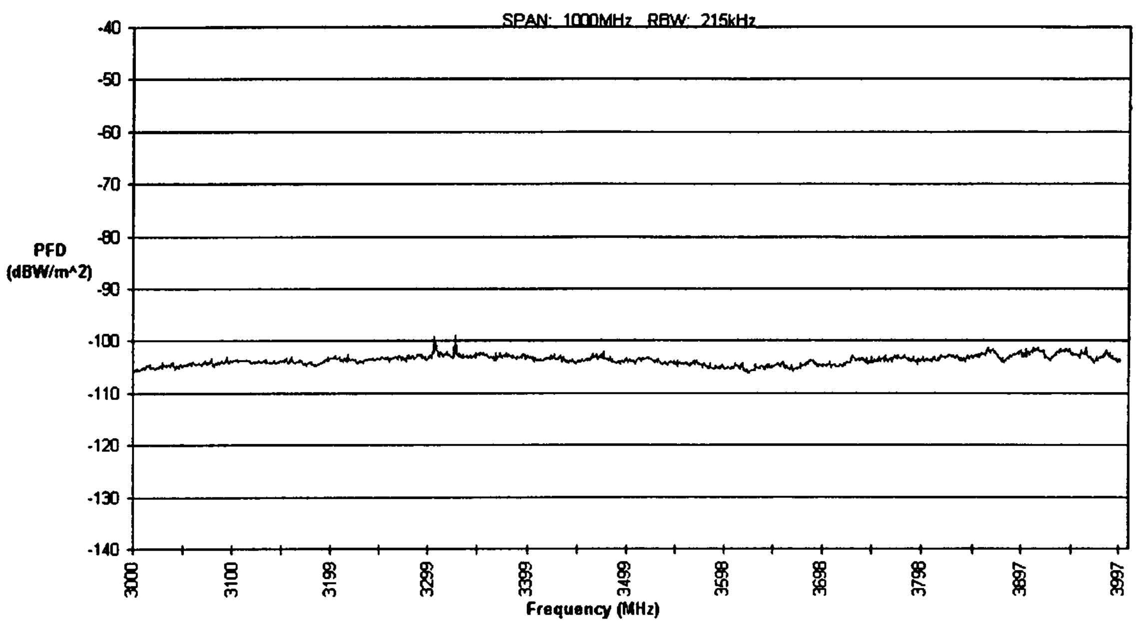
Table 10: Frequency Allocations, 3.1 – 4.2 GHz

2.4.10 RFI Summary, 3 – 4 GHz

The RFI (3.1 – 3.3 GHz) in this band is from defense radar. The signals are detected only when the monitoring system is set in peak hold mode for 24 hours.

2.4.11 PFD Plots, 3 – 4 GHz

3-4GHz
Data taken week of 10/01/01 by Eric Reynolds (AOC).
Power Flux Density (PFD) calculated to produce measured dBm power into Spectrum Analyzer.
EMS Path: S-Band
Spectrum Analyzer set in Peak-Hold mode for 24 hours.



3-4GHz
Data taken week of 11/05/01 by Eric Reynolds (AOC).
Power Flux Density (PFD) calculated to produce measured dBm power into Spectrum Analyzer.
EMS Path: S-Band
Spectrum Analyzer set in Peak-Hold mode for 24 hours.

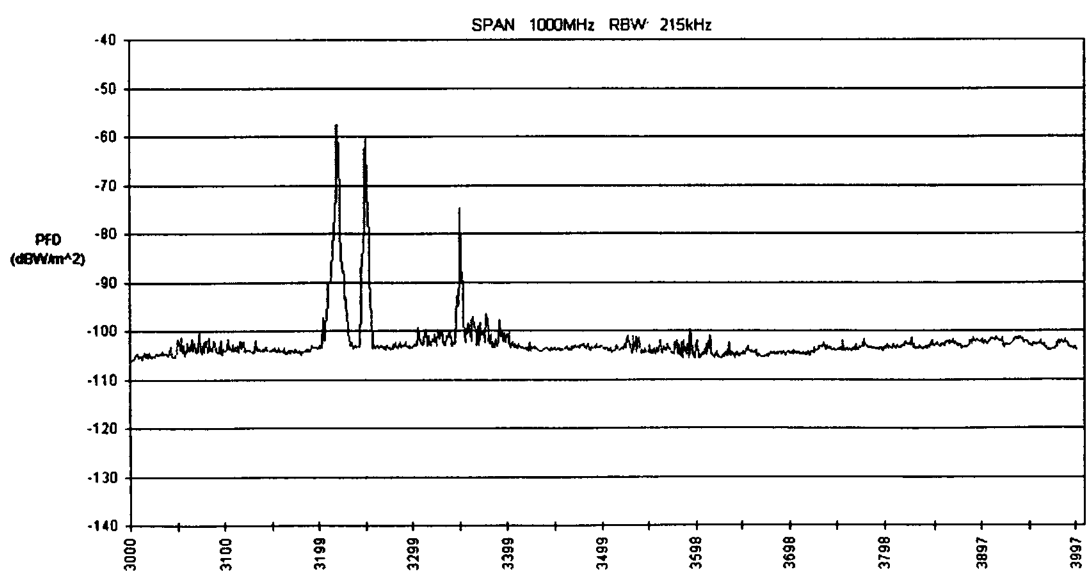


Figure 12: 24 Hour Peak Hold Plots, 3 –4 GHz

2.5 C-Band (4– 8 GHz)

2.5.1 Frequency Allocations, 4 – 5 GHz

Allocation Information	RFI Description,Characteristic
4.2 – 4.4 GHz • Aeronautical Radionavigation • Aviation	Continual
4.4 – 4.5 GHz • Fixed and Mobile Services	
4.5 – 4.66 GHz • Fixed and Mobile Services • Fixed-Satellite	
4.66 – 4.8 GHz • Fixed and Mobile Services • Fixed-Satellite	
4.8 – 4.99 GHz • Fixed and Mobile Services	Intermittent
4.99 – 5 GHz • Radio Astronomy • Space Research	

Table 11: Frequency Allocations, 4.2 – 5 GHz

2.5.2 RFI Summary, 4 – 5 GHz:

Interference in the 4.2 – 4.4 GHz band is caused by aeronautical radionavigation. The 4.8 – 4.99 GHz band sees interference from communication services from the Departments of Defense, Energy, and the Treasury.

2.5.3 PFD Plots, 4 – 5 GHz

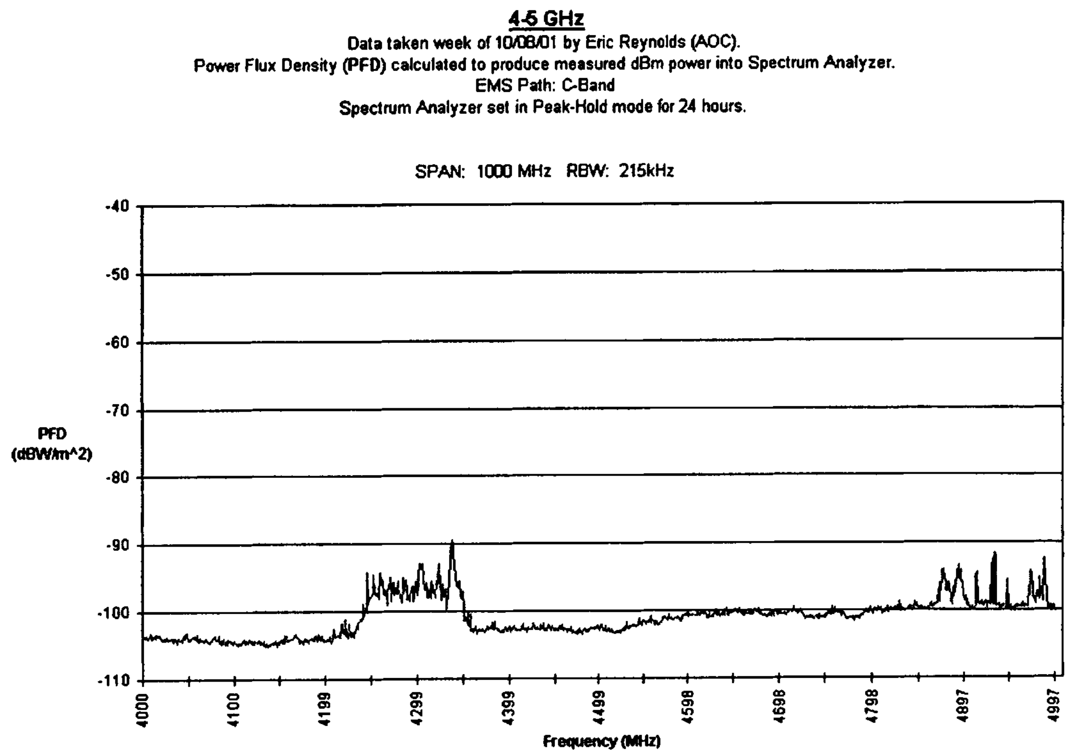


Figure 13: 24 Hour Peak Hold Plot, 4 – 5 GHz

2.5.4 Frequency Allocations, 5 – 6 GHz

Allocation Information	RFI Description,Characteristic
5 - 5.25 GHz • Aeronautical Radionavigation • Aviation	Seldom Present
5.25 – 5.35 GHZ • Radiolocation	
5.35 – 5.46 GHz • Aeronautical Radionavigation • Aviation • Radiolocation	Seldom Present
5.46 – 5.47 GHz • Radionavigation • Radiolocation	Seldom Present
5.47 – 5.6 GHz • Maritime Radionavigation • Radiolocation	Seldom Present
5.6 – 5.65 GHz • Maritime Radionavigation • Radiolocation • Meteorological Aids	Seldom Present
5.65 – 5.85 GHz • Radiolocation • Amateur Radio	Seldom Present
5.85 – 5.925 GHz • Radiolocation • Amateur Radio • Fixed-Satellite	

Table 12: Frequency Allocations, 5 – 5.925 GHz

2.5.5 RFI Summary, 5 – 6 GHz

The RFI from 5 – 6 GHz is only detected when the system is in peak hold mode for 24 hours.

2.5.6 PFD Plots, 5 – 6 GHz

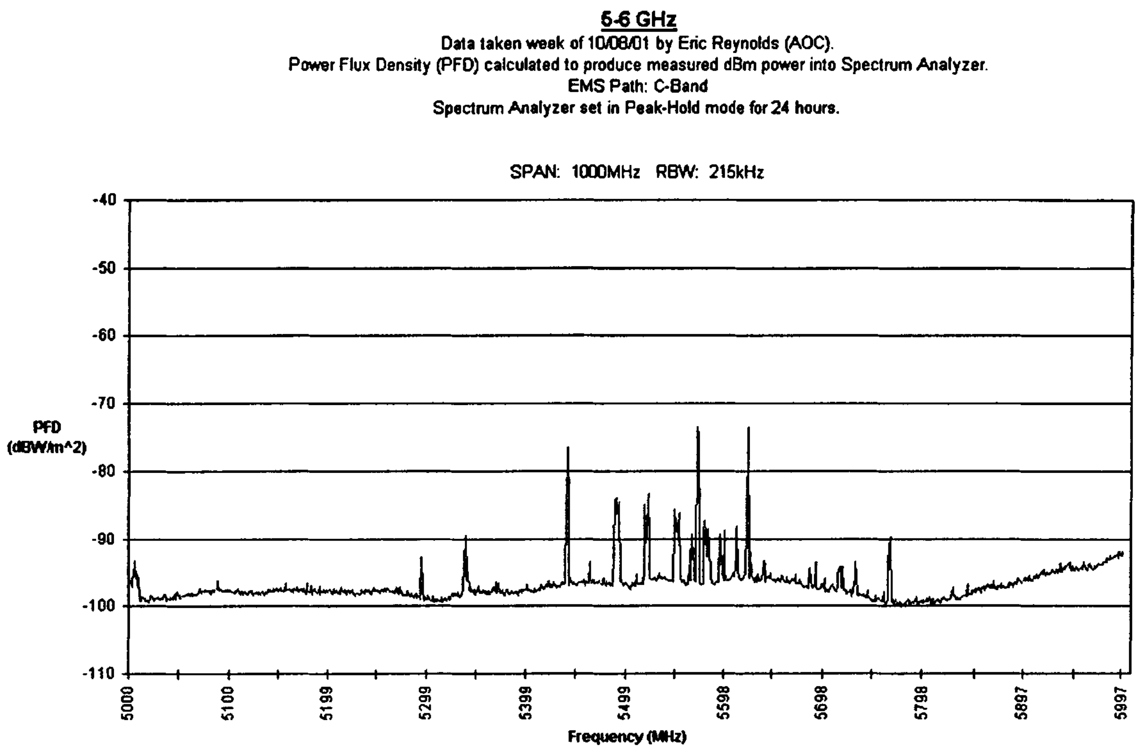


Figure 14: 24 Hour Peak Hold Plot, 5 – 6 GHz

2.5.7 Frequency Allocations, 6 – 7 GHz

Allocation Information	RFI Description,Characteristic
5.925 – 6.425 GHz • Fixed Services • Fixed-Satellite • Domestic Public Fixed Services • Satellite Communications • Private Operational Fixed Services	
6.425 – 6.525 GHz • Fixed-Satellite • Mobile Services • Domestic Public Fixed Services • Auxiliary Broadcast Cable Television • Private Operational Fixed Services	Seldom Present
6.525 – 6.875 GHz • Fixed Services • Fixed-Satellite • Domestic Public Fixed Services • Satellite Communications • Private Operational Fixed Services	
6.875 – 7.075 GHz • Fixed and Mobile Services • Fixed-Satellite • Domestic Public Fixed Services • Auxiliary Broadcast Cable Television	

Table 13: Frequency Allocations, 5.925 – 7.075 GHz

2.5.8 RFI Summary, 6 – 7 GHz

The RFI from 6 – 7 GHz is only detected when the system is in peak hold mode for 24 hours. The source is unknown.

2.5.9 PFD Plots, 6 – 7 GHz

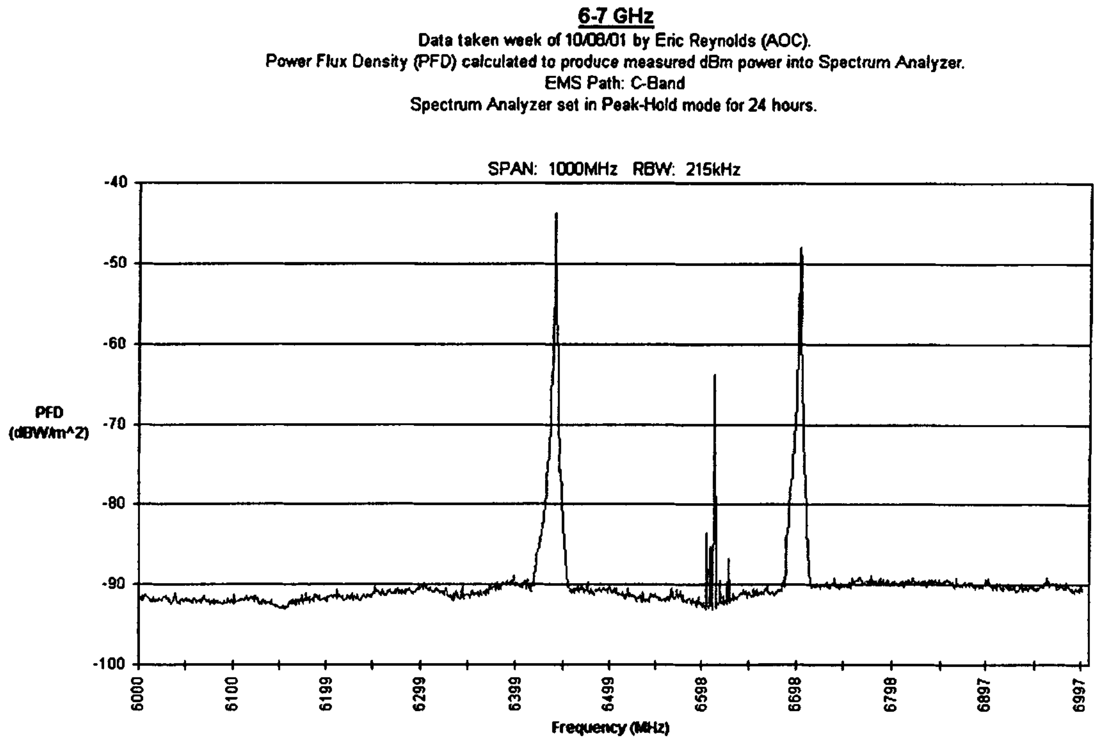


Figure 15: 24 Hour Peak Hold Plot, 6 – 7 GHz

2.5.10 Frequency Allocations, 7 – 8 GHz

Allocation Information	RFI Description,Characteristic
7.075 – 7.125 GHz • Fixed and Mobile Services • Domestic Public Fixed Services • Auxiliary Broadcast Cable Television	
7.125 – 7.19 GHz • Fixed Services	
7.19 – 7.235 GHz • Fixed Services • Space Research	
7.235 – 7.25 GHz • Fixed Services	
7.25 – 7.3 GHz • Fixed-Satellite • Mobile-Satellite	
7.3 – 7.45 GHz • Fixed Services • Fixed-Satellite • Mobile-Satellite	
7.45 – 7.55 GHz • Fixed Services • Fixed-Satellite • Meteorological-Satellite • Mobile-Satellite	
7.55 – 7.75 GHz • Fixed Services • Fixed-Satellite • Mobile-Satellite	
7.75 – 7.9 GHz • Fixed Services	
7.9 – 8.025 GHz • Fixed Services • Fixed-Satellite • Mobile-Satellite	

Table 14: Frequency Allocations, 7.9 – 8.025 GHz

2.5.11 PFD Plots, 7 – 8 GHz

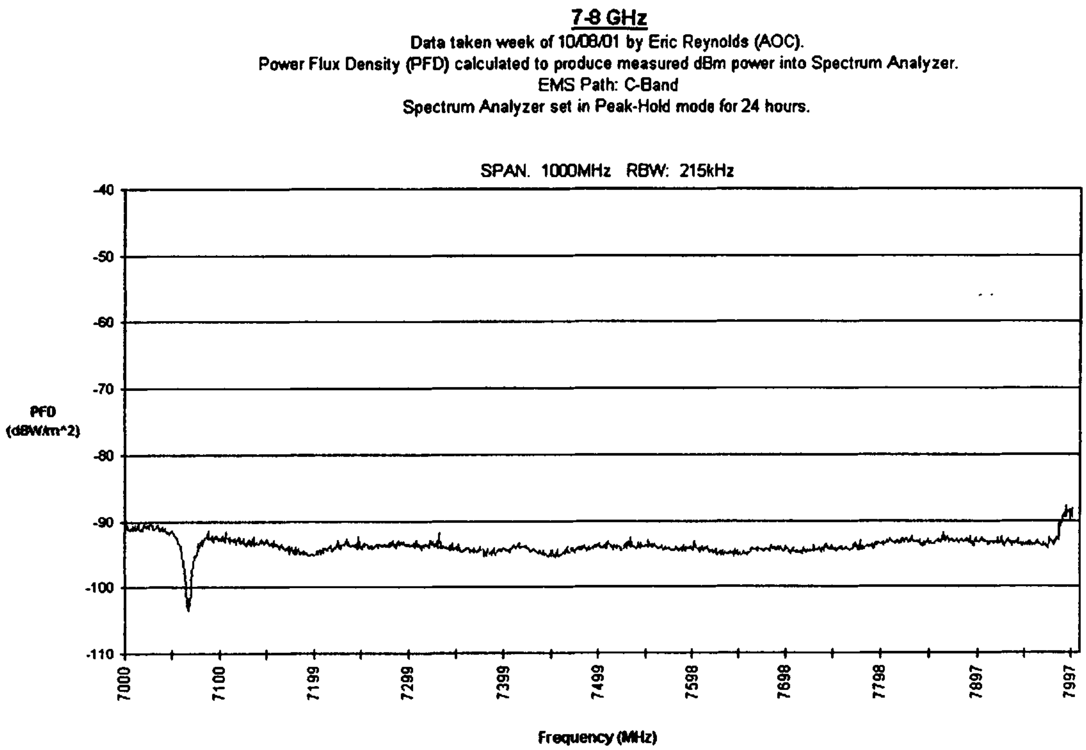


Figure 16: 24 Hour Peak Hold Plot, 7 – 8 GHz

2.6 RFI Summary, 1 – 8 GHz

The following table summarizes the RFI found in the survey. For each band that had RFI, the frequency and power flux density of the strongest peaks are recorded in the table below.

Band (MHz)	Frequency (MHz)	PFD (dBW/m^2)	Signal Characteristic	Source
960 - 1215	1030.1	-107	intermittent	DME
960 - 1215	1103.4	-96	intermittent	DME
960 - 1215	1090.5	-103	intermittent	DME
960 - 1215	1202.5	-103	intermittent	GPS
1215 - 1240	1233.2	-92	intermittent	GPS
1240 - 1300	-------	-------	-------	-------
1300 - 1350	1309.5	-93	intermittent	aeronautical radionavigation
1300 - 1350	1329.5	-91	intermittent	aeronautical radionavigation
1350 - 1610	-------	-------	-------	-------
1610 - 1626.5	1626	-99	continual	Iridium
1626 - 1710	-------	-------	-------	-------
1710 - 1850	1838.5	-104	continual	Unknown
1850 - 2310	-------	-------	-------	-------
2310 - 2360	2328.6	-100	continual	unknown
2360 - 2700	-------	-------	-------	-------
2700 - 2900	2740..6	-82	intermittent	NEXRAD Doppler Radar, aeronautical radionavigation
2700 - 2900	2789.1	-94	intermittent	NEXRAD Doppler Radar, aeronautical radionavigation
2900 - 3100	-------	-------	-------	-------
3100 -3500	3218.9	-57	intermittent	radiolocation, amateur
3700 - 4200	-------	-------	-------	-------
4200 - 4400	4337.2	-90	continual	aeronautical radionavigation
4400 - 4800	-------	-------	-------	-------
4800 - 4990	4932.6	-92	intermittent	Fixed & Mobile Services
4990 - 5250	-------	-------	-------	-------
5250 - 5850	5338	-90	intermittent	airborne weather radar
5250 - 5850	5622.7	-74	intermittent	airborne weather radar
5850 - 6425	-------	-------	-------	-------
6425 - 6875	6439.9	-44	seldom present	unknown
6425 - 6875	6699.9	-48	seldom present	unknown
6875 - 7900	-------	-------	-------	-------
7900 - 8025	7991.2	-88	seldom present	FAA

Table 15: RFI Summary, 1 – 8 GHz

Section III: Analysis of the EMS System Noise Temperature

3.1 Introduction

This section contains an approximate calculation of the EMS system noise temperature at selected frequencies based on some of the PFD plots from Section II. These values will be compared to the predicted noise temperature calculations from Section I. The method of approximating the noise temperature will be shown using the same frequency and system settings from the calculation of Section I (pg. 4). The system settings produced the plot in Figure 8.

3.2 Actual Noise Figure Calculation

The following equations were used for frequency 2500 MHz:

(1) $P_{noise} = PFD * Ae$

(2) $P_{noise} = k*Tpk*B$, $Tpk = \dfrac{P_{noise}}{(k*B)}$

where:

Tpk = noise temperature with the spectrum analyzer in peak hold.

PFD ≅ -106 dBW/m^2 = 2.5E-11 W/m^2 (approximate average value from plot, Fig. 8)

Ae = 1.4E-3 m^2 (Measured value for 1-8GHz omni conical spiral. Used in calibrating PFD data at 2.5GHz)

k = 1.38E-23 W*s/K (Boltzmann's constant)

B = 215 kHz (Resolution bandwidth used)

Plugging in to equation (1), Pnoise = PFD * Ae:

Pnoise = (2.5E-11 W/m^2)*(1.4E-3 m^2)

Pnoise = 3.57E-14 W

Plugging into equation (2), $Tpk = \frac{Pnoise}{(k*B)}$

$$Tpk = \frac{(3.57E\text{-}14\ W)}{[(1.38E\text{-}23\ W*s/K)*(215000Hz)]}$$

Tpk = 12,032 K

This is for peak hold data. In order to estimate the average system noise temperature, an approximate ratio of peak/average data for the same spectrum analyzer settings was obtained at 2500 MHz:

peak/avg. = 12dB = 16

Now an approximation for the average system noise temperature can be made:

T_{SYS} = Tpk/16

$T_{SYS} = \frac{12{,}032\ K}{16}$

T_{SYS}= 752 K

This is an approximation of the system noise temperature at 2500 MHz based on the measurements in Figure 8. This value is fairly close to the predicted value of 734 K obtained in Section I. Table 16 is a comparison of predicted and actual noise temperature approximations at selected frequencies in other EMS bands.

3.3 Comparison of Theoretical and Actual Noise Figures

EMS Band	Plot (Figure #)	Frequency	Theoretical Noise Figure	Actual Noise Figure
L-Band Low Gain (1 – 2 GHz)	Fig. 3	1500 MHz	9.7 dB = 2400 K	11.9 dB = 4183 K
L-Band High Gain (1.265 – 1.835 GHz)	Fig. 5	1500 MHz	4.9 dB = 609 K	3.2 dB = 318 K
S-Band (2 – 4 GHz)	Fig. 8	2500 MHz	5.5 dB = 734 K	5.6 dB = 752 K
C-Band (4 – 10 GHz)	Fig. 15	6000 MHz	6.9 dB = 1141 K	8.6 dB = 1830 K

Table 16: Comparison of Theoretical and Actual Noise Figures

The second column in the above table refers to the plot used to calculate the noise figure. The noise temperature in the L-Band Low Gain path is very high. This is because the amplifier in this path has a very small gain ($\cong$ 8 dB) and a fairly high noise temperature ($\cong$ 750 K). The gain of the LNA is not high enough to contribute in lowering the noise floor of the spectrum analyzer. The actual noise floor was higher than the predicted noise floor for a number of reasons. Some noise was unaccounted for and could not be predicted. Also, the existence of RF interference will raise the noise floor of the system.

Section IV: Recommendations for Monitoring Above 8 GHz

4.1 Introduction

Due to the current setup of the Environmental Monitoring System, RF interference data could not be taken for frequencies higher than 8 GHz. This section contains suggestions for surveying these higher frequencies.

4.2 RFI Monitoring 8 – 12 GHz:

An RFI survey from 8 – 12 GHz can be accomplished in the near future. The only two items needed are a low noise amplifier (LNA) and an antenna.

A Miteq 35 dB amplifier is available in the IPG lab that operates from 6 – 18 GHz. It has a noise figure close to 1.2 dB (92 K). A path has been included in the current EMS front end for an amplifier to operate from 10 – 12 GHz. This amplifier simply needs to be installed in the current front end.

Two standard gain horn antennas have been purchased and are expected to arrive some time in January 2002. One of the antennas operate from 8 – 12.4 GHz and will be used for RFI monitoring.

4.3 RFI Monitoring 12 – 18 GHz:

The Miteq 6 – 18 GHz amplifier described above can be used in the front end. The other standard gain horn that was purchased operates from 12.4 – 18 GHz, and will arrive in January. Two significant changes will need to be done for monitoring above 12 GHz. The two parts of EMS that will need to be replaced are the RF coaxial switches in the front end and the heliax cables.

The RF switches in the front end operate up to 12.4 GHz. These will need to be replaced with switches that can operate at higher frequencies.

There are two heliax cables in EMS. EMS-2 is the 3/8" cable from the antenna to the front end and EMS-X is the 3/8" cable from the front end to the spectrum analyzer. These cables operate up to 13 GHz. The cables can be replaced with ¼" heliax, which generally operates up to 20 GHz.

4.4 RFI Monitoring 18 – 40 GHz

The spectrum analyzer operates up to 22 GHz. Spectrum analyzers are very expensive, so it is impractical to purchase a new spectrum analyzer that operates up to 40 GHz. Perhaps IPG can borrow one or find one in government surplus. A better solution is down converting. This will require a mixer and a local oscillator (LO) between the antenna and the front end. The signals would need to be down converted to a maximum of 20 GHz in order to use the EMS front end, ¼" heliax cables, and spectrum analyzer. This means that an LO of 20 GHz would be required. Kerry Shores and Nathan Thomas are currently working on the design of a renovated EMS system.

An antenna is available that operates from 18 – 40 GHz. The antenna is an EMCO double-ridged waveguide horn that was purchased by IPG in June 2001.

Part 2

Analysis of the Pattern Characteristics in the L-Band Feed Horns

Introduction

A small project I did as a co-op was digitize the antenna radiation patterns of three of the L-Band feed horns currently used in the VLA. Sri Srikanth, the designer of the new L-Band feed horns for the EVLA, requested this. The radiation patterns of the VLA L-band feed horns were measured in the 1970's. These patterns are just analog plots. Sri wanted discrete data points to put in the software he uses. I took samples of 1° for H-plane and E-plane cuts at three frequencies for three different feed horns. This helped in the design of the EVLA L-band feed horns. Here is an example of what one of the patterns looks like:

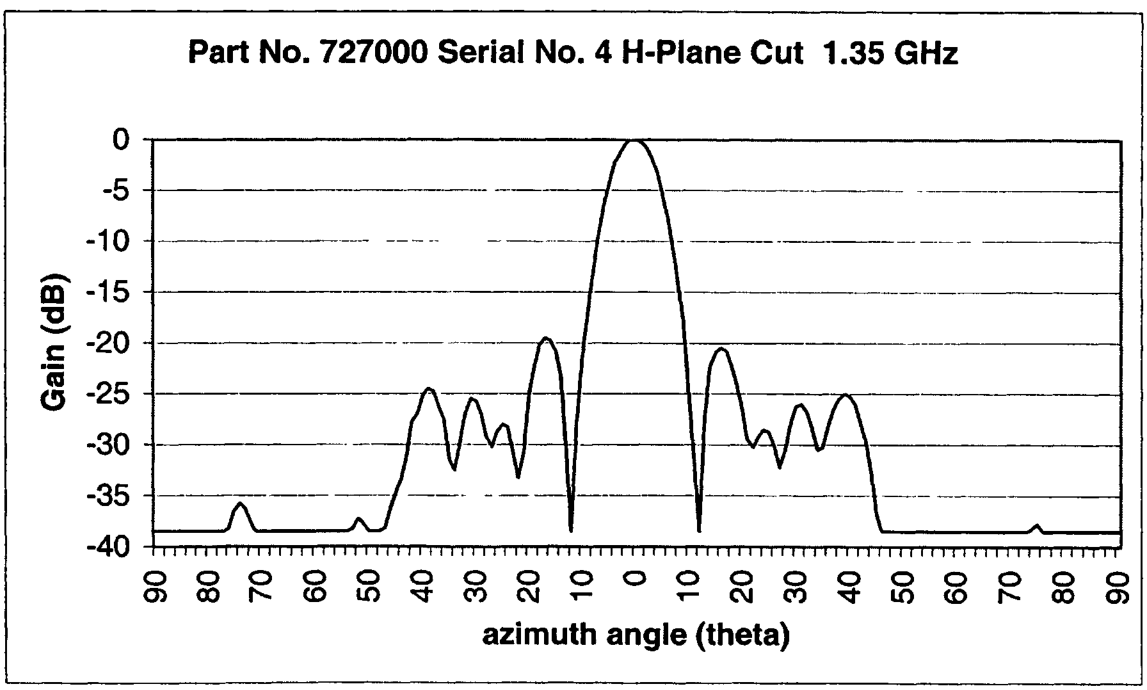


Figure 17: Example Radiation Pattern of a VLA L-Band Feed Horn

Section I: Method for Directivity and Beam Efficiency Calculations

With the normalized power radiation patterns digitized, there is now a way to approximate the directivity and beam efficiency of the VLA L-band feed horns. The directivity is the value of the directive gain in the direction of its maximum value. The following equation was used to calculate the directivity[2]:

$$D = \frac{4\pi}{\Omega_A} = \frac{4\pi}{\iint P_n(\theta, \phi)\sin\theta d\theta d\phi} \qquad (1)$$

where: $\Omega_A = \iint P_n(\theta, \phi)\sin\theta d\theta d\phi$ = beam area

$P_n(\theta, \phi)$ = normalized power radiation pattern

$d\theta$ = change in θ from 0 to π

$d\phi$ = change in ϕ from 0 to 2π

The patterns that were digitized were 2-dimensional cuts in E-plane and H-plane. Assuming that the patterns are symmetrical and there is no variation in ϕ, the integral with respect to ϕ is 2π. Equation (1) reduces to:

$$D = \frac{4\pi}{2\pi \int P_n(\theta)\sin\theta d\theta}$$

where θ is from 0 to π (0° to 180°)

$P_n(\theta)$ has been digitized, and the integral of a discrete function is the sum of each discrete value. Discrete samples were taken every 1° from 0° to 90°. For points between 90° and 180°, an average value of –40dB, -50dB, or -60dB was assumed. The approximate directivity can then be given by:

$$\frac{4\pi}{\quad}$$

[2] Antennas, by John D. Kraus 2nd Edition, McGraw-Hill 1988, pg.101 - 102

$$D \cong \qquad 2\pi(\pi/180) \sum_{m=0}^{m=180} P_n(\theta_m)\sin\theta_m$$

This is an approximation using discrete samples from half (0° to 180°) of a radiation pattern similar to the one in Figure 17. This approximation was done on the other half of the radiation pattern as well, and similar values were obtained. The same method was used for H-plane and E-plane cuts, and similar values were obtained. Due to the dynamic range of the pattern measurement, data that had a value less than -40 dB could not be recorded. For this data, an approximate average value of –40, -50, or -60 dB was assumed.

Beam efficiency can also be approximated. Beam efficiency is the ratio of the main beam area to the total beam area. The following equation was used:

$$\varepsilon_M = \frac{\Omega_M}{\Omega_A}$$

Where:

$$\Omega_A = 2\pi(\pi/180) \sum_{m=0}^{m=180} P_n(\theta_m)\sin\theta_m = \text{The total beam area from } 0° \text{ to } 180°.$$

$$\Omega_M = 2\pi(\pi/9) \sum_{m=0}^{m=9} P_n(\theta_m)\sin\theta_m = \text{The main beam area from } 0° \text{ to } 9°.$$

<u>Section II: Summary of Directivity and Beam Efficiency Approximations</u>

On the next page is a summary of the directivity and beam efficiency calculations for one of the L-band feed horns. The directivity and beam efficiency are approximated from radiation patterns from three L-band frequencies; 1.35, 1.53, and 1.72 GHz. For each frequency, there is an H-Plane cut and an E-Plane cut. For both E-Plane and H-

Plane cuts, an approximation of directivity is made using the right and left hand half of the pattern.

Part No. 727000 Serial No. 4

Explanations

-40 dB:	Condition where the approximate average value assumed for gains less than -40 dB was -4(
-50 dB:	Condition where the approximate average value assumed for gains less than -40 dB was -5(
-60 dB:	Condition where the approximate average value assumed for gains less than -40 dB was -6(
+ :	Condition where the total beam area was approximated using 1 degree samples from 0 to 1٤ degrees on the right hand half of the pattern.
- :	Condition where the total beam area was approximated using 1 degree samples from 0 to 1٤ degrees on the left hand half of the pattern.
avg:	The average of right and left hand values

Table 17: Explanations of the Assumed Conditions for Directivity Calculations

Directivity and Beam Efficiency Approximations

1.35 GHz

Table 18

Condition	Directivity Approximation	Directivity Approximation (dB)	Beam Efficiency Approximation
E-Plane Cut			
-40 dB +	455.14	26.58145005	0.766
-40 dB -	434.69	26.38179649	0.739
-40 dB avg	444.915	26.48277048	0.7525
-50 dB +	464.74	26.67210054	0.783
-50 dB -	443.75	26.47138366	0.755
-50 dB avg	454.245	26.57290156	0.769
-60 dB +	465.73	26.68134214	0.784
-60 dB -	444.67	26.4803783	0.757
-60 dB avg	455.2	26.58202253	0.7705
H-Plane Cut			
-40 dB +	451.45	26.54609657	0.818
-40 dB -	505.54	27.03755524	0.829
-40 dB avg	478.495	26.79877404	0.8235
-50 dB +	463.54	26.66087216	0.839
-50 dB -	522.34	27.17953285	0.857
-50 dB avg	492.94	26.92794061	0.848
-60 dB +	464.78	26.67247432	0.842
-60 dB -	524.08	27.19397586	0.86
-60 dB avg	494.43	26.94104814	0.851

1.53 GHz

Condition	Directivity Approximation	Directivity Approximation (dB)	Beam Efficiency Approximation
E-Plane Cut			
-40 dB +	518.79	27.14991596	0.797
-40 dB -	456.92	26.59840168	0.802
-40 dB avg	487.855	26.8829076	0.7995
-50 dB +	539.81	27.32240926	0.829
-50 dB -	471.71	26.73675083	0.828
-50 dB avg	505.76	27.03944478	0.8285
-60 dB +	542	27.33999287	0.832
-60 dB -	473.24	26.75081446	0.83
-60 dB avg	507.62	27.05538725	0.831
H-Plane Cut			
-40 dB +	502.03	27.0072967	0.859
-40 dB -	598.19	27.76839149	0.838
-40 dB avg	550.11	27.4044954	0.8485
-50 dB +	519.25	27.15376505	0.889
-50 dB -	623.05	27.945229	0.873
-50 dB avg	571.15	27.56750181	0.881
-60 dB +	521.03	27.1686273	0.892
-60 dB -	625.66	27.9633839	0.876
-60 dB avg	573.345	27.58416029	0.884

Table 19: Summary of Directivity Calculations, 1.53 GHz

1.72 GHz

Condition	Directivity Approximation	Directivity Approximation (dB)	Beam Efficiency Approximation
E-Plane Cut			
-40 dB +	610.88	27.85955907	0.853
-40 dB -	573.62	27.58624285	0.858
-40 dB avg	592.25	27.72505069	0.8555
-50 dB +	640.14	28.06274966	0.894
-50 dB -	599.67	27.77912323	0.897
-50 dB avg	619.905	27.92325139	0.8955
-60 dB +	643.23	28.08366292	0.898
-60 dB -	602.41	27.79892173	0.901
-60 dB avg	622.82	27.9436255	0.8995
H-Plane Cut			
-40 dB +	635.16	28.0288314	0.794
-40 dB -	659.01	28.18892005	0.769
-40 dB avg	647.085	28.10961333	0.7815
-50 dB +	661.29	28.20391955	0.826
-50 dB -	687.18	28.37070511	0.802
-50 dB avg	674.235	28.28811293	0.814
-60 dB +	664.03	28.22187701	0.829
-60 dB -	690.14	28.389372	0.806
-60 dB avg	677.085	28.30643193	0.8175

Table 20: Summary of Directivity Calculations, 1.72 GHz

In most of the approximations, the directivity stayed close to 27 dB, and the beam efficiency stayed close to 80%. The efficiency could be much better if the side lobes were not as big. Part of the design of the EVLA feed horns is to reduce the side lobes and maintain a narrow main beam. There is a trade off between half power beam width of the main beam and the strength of the side lobes. Hopefully the digitized samples and the directivity approximations will be helpful in the design of the EVLA L-band feed horns.

APPENDIX A: EMS Path and Antenna Characteristics

Injected Signal Power: -60 dBm

Data obtained by Eric Reynolds and Raul Armendariz, 8/14/01

Band (in FE)	**Injected Signal** (frequency)	**Measured Output** (dBm)	**Measured Net Gain** (dB)	**Theoretical Net Gain** (1) - (2) - (3)	**Difference** THE - MEA
Band 1	20 MHz	-51	9	11 - .3 - .05 = **10.7**	1.7
	200 MHz	-50	10	11 - 1.0 - .17 = **9.8**	-0.2
P-Band	400 MHz	-51	9	11 - 1.5 - .24 = **9.3**	0.3
Low	600 MHz	-51	9	11 - 1.8 - .29 = **8.9**	-0.1
Gain	800 MHz	-51	9	11 - 2.1 - .35 = **8.6**	-0.4
	1000 MHz	-51	9	11 - 2.4 - .39 = **8.2**	-0.8
Band 2	100 MHz	-27	33	34 - .3 - .05 = **33.7**	0.7
	200 MHz	-27	33	34 - 1.0 - .17 = **32.8**	-0.2
P-Band	400 MHz	-28	32	34 - 1.5 - .24 = **32.3**	0.3
High	600 MHz	-28	32	34 - 1.8 - .29 = **31.9**	-0.1
Gain	800 MHz	-28	32	34 - 2.1 - .35 = **31.6**	-0.4
	1000 MHz	-28	32	34 - 2.4 - .39 = **31.2**	-0.8
Band 3	1 GHz	-59	1	3.8 - 2.4 - .39 = **1.0**	0
	1.2 GHz	-55	5	7.2 - 2.7 - .44 = **4.1**	-0.9
L-Band	1.4 GHz	-55	5	7.2 - 2.9 - .47 = **3.8**	-1.2
Low	1.6 GHz	-57	3	7.2 - 3.1 - .51 = **3.6**	0.6
Gain	1.8 GHz	-58	2	7.2 - 3.3 - .55 = **3.4**	1.4
	2 GHz	-59	1	5.1 - 3.5 - .57 = **3.1**	2.1
Band 4	1 GHz	-64	-4	-2.4 - 2.4 - .39 = **-5.2**	-1.2
	1.2 GHz	-45	15	20 - 2.7 - .44 = **16.9**	1.9
L-Band	1.4 GHz	-28	32	34 - 2.9 - .47 = **30.6**	-1.4
High	1.6 GHz	-30	30	34 - 3.1 - .51 = **30.4**	0.4
Gain	1.8 GHz	-31	29	34 - 3.3 - .55 = **30.2**	1.2
	2 GHz	-71	-11	-6.7 - 3.5 - .57 = **-10.8**	0.2
Band 5	2 GHz	-34	26	30 - 3.5 - .57 = **25.9**	-0.1
	2.2 GHz	-35	25	30 - 3.6 - .61 = **25.8**	0.8
	2.4 GHz	-35	25	30 - 3.8 - .63 = **25.6**	0.6
S-Band	2.6 GHz	-35	25	30 - 3.9 - .66 = **25.4**	0.4
	2.8 GHz	-34	26	30 - 4.1 - .69 = **25.2**	-0.8
	3 GHz	-36	24	30 - 4.4 - .72 = **24.9**	0.9
	3.2 GHz	-37	23	30 - 4.5 - .75 = **24.8**	1.8
	3.4 GHz	-36	24	30 - 4.7 - .77 = **24.5**	0.5
	3.6 GHz	-36	24	30 - 4.8 - .80 = **24.4**	0.4
	3.8 GHz	-37	23	30 - 4.9 - .83 = **24.3**	1.3
	4 GHz	-38	22	30 - 5.2 - .85 = **23.9**	1.9

Band 6	4 GHz	-32	28	35 – 5.2 - .85 = 28.9	0.9
C-Band	4.5 GHz	-33	27	35 – 5.6 - .91 = 28.5	1.5
	5 GHz	-33	27	35 – 5.9 - .97 = 28.1	1.1
	5.5 GHz	-35	25	35 - 6.3 - 1.03 = 27.7	2.7
	6 GHz	-36	24	33 - 6.6 - 1.08 = 25.3	1.3
	6.5 GHz	-36	24	33 - 6.9 - 1.14 = 24.9	0.9
	7 GHz	-37	23	33 - 7.3 - 1.19 = 24.5	1.5
	7.5 GHz	-37	23	33 - 7.6 - 1.25 = 24.2	1.2
	8 GHz	-37	23	35 - 7.9 - 1.29 = 25.8	2.8
	8.5 GHz	-37	23	33 - 8.2 - 1.34 = 23.5	0.5
	9 GHz	-38	22	32 - 8.5 - 1.39 = 22.1	0.1
	9.5 GHz	-39	21	32 - 8.8 - 1.44 = 21.8	0.8
	10 GHz	-41	19	32 - 9.1 - 1.49 = 21.4	2.4
Band 7	10 GHz	-77	-17	0 - 9.1 - 1.49 = -10.6	6.4
X-Band	11 GHz	-78	-18	0 - 9.6 - 1.57 = -11.2	5.8
	12 GHz	-78	-18	0 - 10.2 - 1.67 = -11.9	6.1
	13 GHz	-80	-20	0 - 10.7 - 1.75 = -12.5	7.5
	14 GHz	-79	-19		
	15 GHz	-80	-20		
	16 GHz	-85	-25		
	17 GHz	-85	-25		
	18 GHz	-86	-26		

Effective Aperture Calculations

For 1-8 GHz RCP Omnidirectional Discone. Dorne & Margolin S/N 032 antenna.

Data obtained and calculated by Nathan Thomas & Raul Armendariz, 8/2001

Frequency (GHz)	Power SA	Transmitted Power dBm	Line Loss Tx Ant. dB	Gain Tx Ant. dB	Loss EMS dB	P5 Power dBm	Received Power dBm	Polarization mismatch dB	Loss Free Space dB	P4 Linear w/m^2	P5 Linear w	Effective Aperture 1/m^2	Effective Aperture dB/m^2	Antenna Gain
1	-75	0	-2	11.55	-3.9	-68.1	-49.08	-3	-58.63	1.2E-05	1.55E-07	0.01253141	-19.02	1.7497151
1.2	-74.3	0	-2.5	12.7	-4.1	-67.2	-48.43	-3	-58.63	1.4E-05	1.91E-07	0.01327394	-18.77	2.6688849
1.4	-72.5	0	-3	13.8	-4.25	-65.25	-47.83	-3	-58.63	1.6E-05	2.99E-07	0.0181134	-17.42	4.9570514
1.6	-75	0	-3	14.7	-4.45	-67.55	-46.93	-3	-58.63	2E-05	1.76E-07	0.00866962	-20.62	3.0988982
1.8	-76.5	0	-3	15.45	-4.75	-68.75	-46.18	-3	-58.63	2.4E-05	1.33E-07	0.0055335	-22.57	2.5032969
2	-77.17	0	-3	16.1	-5.19	-68.98	-45.53	-3	-58.63	2.8E-05	1.26E-07	0.00451856	-23.45	2.5236396
2.2	-81.2	0	-3	17.35	-5.51	-72.69	-44.28	-3	-58.63	3.7E-05	5.38E-08	0.00144212	-28.41	0.9745692
2.4	-82.5	0	-3	17.35	-5.83	-73.67	-44.28	-3	-58.63	3.7E-05	4.3E-08	0.0011508	-29.39	0.9255285
2.6	-81.2	0	-3.25	17.35	-6.15	-72.05	-44.53	-3	-58.63	3.5E-05	6.24E-08	0.00177011	-27.52	1.6707599
2.8	-79.7	0	-3.25	17.35	-6.47	-70.23	-44.53	-3	-58.63	3.5E-05	9.48E-08	0.00269153	-25.7	2.9463437
3	-82.3	0	-3.5	17.35	-6.78	-72.52	-44.78	-3	-58.63	3.3E-05	5.6E-08	0.00168267	-27.74	2.1145105
3.2	-85.2	0	-3.5	17.35	-7.56	-74.64	-44.78	-3	-58.63	3.3E-05	3.44E-08	0.00103276	-29.86	1.4766151
3.4	-87	0	-3.75	17.35	-8.34	-75.66	-45.03	-3	-58.63	3.1E-05	2.72E-08	0.00086497	-30.63	1.3961278
3.6	-85.8	0	-4	17.35	-9.12	-73.68	-45.28	-3	-58.63	3E-05	4.29E-08	0.00144544	-28.4	2.6156061
3.8	-87	0	-4	17.35	-9.91	-74.09	-45.28	-3	-58.63	3E-05	3.9E-08	0.00131522	-28.81	2.6517620
4	-88.2	0	-4.25	17.35	-10.67	-74.53	-45.53	-3	-58.63	2.8E-05	3.52E-08	0.00125893	-29	2.8124663
4.2	-88.5	0	-4.25	17.35	-11.28	-74.22	-45.53	-3	-58.63	2.8E-05	3.78E-08	0.00135207	-28.69	3.3301664
4.4	-90.7	0	-4.5	17.35	-11.89	-75.81	-45.78	-3	-58.63	2.6E-05	2.62E-08	0.00099312	-30.03	2.6845574
4.6	-93	0	-4.5	17.35	-12.5	-77.5	-45.78	-3	-58.63	2.6E-05	1.78E-08	0.00067298	-31.72	1.9883050
4.8	-95.2	0	-4.5	17.35	-13.11	-79.09	-45.78	-3	-58.63	2.6E-05	1.23E-08	0.00046666	-33.31	1.5012389
5	-96.8	0	-4.75	17.35	-13.72	-80.08	-46.03	-3	-58.63	2.5E-05	9.82E-09	0.00039355	-34.05	1.3737489
5.2	-96.3	10	-5	8	-13.47	-79.83	-45.63	-3	-58.63	2.7E-05	1.04E-08	0.00038019	-34.2	1.4354036
5.4	-97.5	10	-5.25	8	-13.22	-81.28	-45.88	-3	-58.63	2.6E-05	7.45E-09	0.0002884	-35.4	1.1742346
5.6	-99.2	10	-5.5	8	-12.97	-83.23	-46.13	-3	-58.63	2.4E-05	4.75E-09	0.00019498	-37.1	0.8537749
5.8	-95.2	10	-5.75	8	-12.72	-79.48	-46.38	-3	-58.63	2.3E-05	1.13E-08	0.00048978	-33.1	2.3005058
6	-101.7	10	-6	8	-12.46	-86.24	-46.63	-3	-58.63	2.2E-05	2.38E-09	0.0001094	-39.61	0.5498824
6.2	-102.5	10	-6	8	-12.91	-86.59	-46.63	-3	-58.63	2.2E-05	2.19E-09	0.00010093	-39.96	0.5416898
6.4	-104.8	10	-6	8	-13.36	-88.44	-46.63	-3	-58.63	2.2E-05	1.43E-09	6.5917E-05	-41.81	0.3769878
6.6	-102.7	10	-6	8	-13.81	-85.89	-46.63	-3	-58.63	2.2E-05	2.58E-09	0.00011858	-39.26	0.7211991

6.8	-105.7	10	-6	8	-14.26	-88.44	-46.63	-3	-58.63	2.2E-05	1.43E-09	6.5917E-05	-41.81	0.4255838
7	-105.8	10	-6.5	8	-14.72	-88.08	-47.13	-3	-58.63	1.9E-05	1.56E-09	8.0353E-05	-40.95	0.5497477
7.2	-103.2	10	-6.5	8	-14.76	-85.44	-47.13	-3	-58.63	1.9E-05	2.86E-09	0.00014757	-38.31	1.0681502
7.4	-103.2	10	-6.75	8	-14.8	-85.4	-47.38	-3	-58.63	1.8E-05	2.88E-09	0.00015776	-38.02	1.2062318
7.6	-102.3	10	-7	8	-14.84	-84.46	-47.63	-3	-58.63	1.7E-05	3.58E-09	0.00020749	-36.83	1.6733798
7.8	-103.5	10	-7	8	-14.88	-85.62	-47.63	-3	-58.63	1.7E-05	2.74E-09	0.00015885	-37.99	1.3494492
8	-104.2	10	-7.25	8	-14.91	-86.29	-47.88	-3	-58.63	1.6E-05	2.35E-09	0.00014421	-38.41	1.2886866

APPENDIX B: List of References and Sources

Spectrum Guide, Frequency Allocations in the United States, 30 MHz – 300GHz
Bennet Z. Kobb
Third Edition, New Signals Press, 1996

Antennas
John D. Kraus
2nd Edition, McGraw-Hill, 1988

Measuring the Radio Frequency Environment
E. Skomal & A. Smith
Von Nonstrand Reinhold Company, 1985

Spectrum Monitoring Handbook
International Telecommunications Union, 1995