GREEN BANK OBSERVATORY	***Title*:** LiFi Prototype	***Author*:** O'Neil, Creager	**GBT Memo #313** **RFI memo #156**

LiFi Prototype Results

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GBT Memo #313
RFI Memo #156

Change Record

VERSION	DATE	REASON
1.0	11 April, 2024	First draft
1.1	22 April, 2024	Minor editing changes and fixes

LiFi Prototype	*O'Neil, Creager*	*GBT Memo #313* *RFI memo #156*

CONTENTS

1 INTRODUCTION

In 2017 Green Bank Observatory (GBO) decided to install a LiFi system in one of the conference room (GB137) to test the feasibility of the system as a RF-quiet solution for network usage. Li-Fi is a wireless communication technology which uses light to transmit data and position between devices, rather than the traditional radio wavelength WiFi devices.

The system ultimately proved to not be a practical solution, and was turned off in March, 2024. Here we capture the reasons LiFi was not adopted by GBO nor recommended to the community.

2 PROJECT TIMESCALE

Late in 2017 Green Bank Observatory decided to install a test LiFi system in the smallest conference room (GB137). The decision as to which system to purchase consumed much of 2018, with the device first purchase for testing by the end of that (calendar) year. The device was tested in the anechoic chamber in February, 2019 and it failed the test, indicating mitigation would be needed (see Appendix A).

In 2019 an RFI enclosure was designed and re-tested (Appendix B & C), and passed the test. By February of 2020 the system was ready for installation.

Unfortunately, a combination of higher priority tasks and the COVID pandemic delayed installation of the system until December, 2022, when it was finally installed for use.

3 PROJECT COST

Unfortunately, a true cost for the project is not known, as the project was not tracked separately from other IPG work. The overall cost, though, was fairly high, and the work can be broken down as followed:

- Materials procurement: This took a few months of work and negotiation between the various companies which produce LiFi systems and the Green Bank IPG engineer and business manager
- Hardware: Total hardware cost was of order $35k for the one (partial) room (not including overhead).
- Anechoic chamber testing: The system went through three testing phases – initial tests, tests after the first round of mitigation, and tests after the second round of mitigation. In total, then, this is around a month of work for the IPG engineer.
- RF Mitigation work: This was by far the largest amount of work, and took around 3-5 FTE months of engineering work to design and test a working , mitigated, system.
- Shop time: All the parts required to mitigate RFI in the system had to be manufactured in the Green Bank machine shop, likely taking 1-2 FTE months of work by one of the machinists
- Installation and testing: This took significant work by the plant maintenance division (installation) and the computing division (testing). In all, about 1.5 FTE months of plant maintenance work and 2 months of systems administrators.

4 RF MITIGATION

In February, 2018, Carla Beaudet tested three different LiFi lamps manufactured by pureLiFi - LiFi ORES POE, LiFi ORES POE TEMPEST, and LiFi ORES POE TEMPEST ETH Filter. The results of the tests (given in Appendix A), clearly showed that the unintentional emissions of all the systems tested exceed the detection thresholds for both spectral line and total power observations.

During the year, Carla designed and had built an RFI enclosure for the system, which completely mitigated the issues, allowing for the system to be installed. Information on the RFI enclosure is in Appendix B, and the final RF mitigation tests are in Appendix C.

5 TECHNICAL FAILURES OF THE GBO LIFI SYSTEM

From a technical standpoint, the GBO LiFi-X system is not a viable system for the observatory to continue to maintain. Connecting this system and using this system both presented difficulties with few reasonable-to-implement solutions. The following are reasons why we do not recommend continuing to utilize this system:

- The units are not able to be daisy-chained;
- The units function only at 100 megabits per second (Mb/s) and provide even slower speeds to the user;
- The drivers are not properly maintained;
- The coverage of each unit is too small to roam around the table.

5.1 The Units are not Daisy-Chainable

One of the cost-saving ideas for this system was the way of connecting each of the units to the LAN. The original plan was to daisy chain the units together to use up only one switch port on the LAN switch side of this system. However, in practice, this setup did not work for the units. We could only get network on two or three of the units with this configuration and had to end run each individual unit back to the switch. This multiplied the ports necessary for this system from 1 to 6 for coverage over just the conference table. Switch ports are valuable real estate and this discovery severely limits the scalability of this connectivity option.

5.2 The Units Function only at 100 mb/s

In the planning and implementing of these devices, the RFI enclosures were created with a 100 Mb/s media converter inside. As of January 2023, the Computing division no longer supports fiber connections slower than 1 gigabit per second (Gb/s). Because of this, each unit will need to be opened to have their media converters updated to 1 Gb/s. This will take time and resources for little reward.
On top of this hurdle, using the units only gave users a speed of about 20Mb/s on average. This is a greater than 50% reduction in speed. Because of this, utilizing the system is slower than using standard 2.4GHz or

5GHz WiFi, and almost 50 times slower than utilizing a standard ethernet cable at the conference table (which currently function at 1Gb/s).

5.3 The Drivers are Not Maintained

The drivers to use the LiFi-X Dongles are not maintained well by the company and do not function on most operating systems. We tested the system on MacOS, RHEL7 Linux, and Windows.
On MacOS, the drivers could not even be installed, as they were flagged as malware. Because of this, Mac computers cannot connect to the LiFi. On RHEL7 Linux, the drivers also failed by creating a brand-new MAC address each time the LiFi-X dongle was plugged in. This meant that Linux users would never be able to connect to the internal network with this system due to our network security parameters. The Windows drivers were functional. This means that the only operating system that GBO employees could use for this system is Windows. However, with this system, Windows users had trouble getting their devices to detect and connect to the LiFi, even with drivers properly installed.

5.4 The Coverage is Too Small

The final major limitation to this system is that the coverage from each of the LiFi units was incredibly small. If a user's computer is too far to the left or the right of the coverage of the unit, they will not be able to connect. The coverage from 6 LiFi access points was not enough to allow roaming between access points and was only fully functional while a user is stationary. If a user wished to move around the table (even within the theoretical coverage), the connection would drop, and the user would have to go through the reconnection process. The coverage does not extend beyond the conference room table, and therefore did not offer any benefits not already offered by the ethernet cables already on the table.

6 CONCLUSION

While the LiFi-X system was a good test, it did prove to be a difficult and expensive system to use and maintain. The coverage was not wide enough to prove useful, the drivers were unmaintained, and the units took up a large amount of switch port real estate. The slow speeds provide a huge reduction in bandwidth from the standard ethernet connections on the table and did not give users the freedom to roam while connected to the system. Unfortunately, this system is not a good fit for the GBO or GBEMS and we have recommended it for decommissioning.

APPENDIX A – UNMITIGATED TESTS

Report written by C. Beaudet

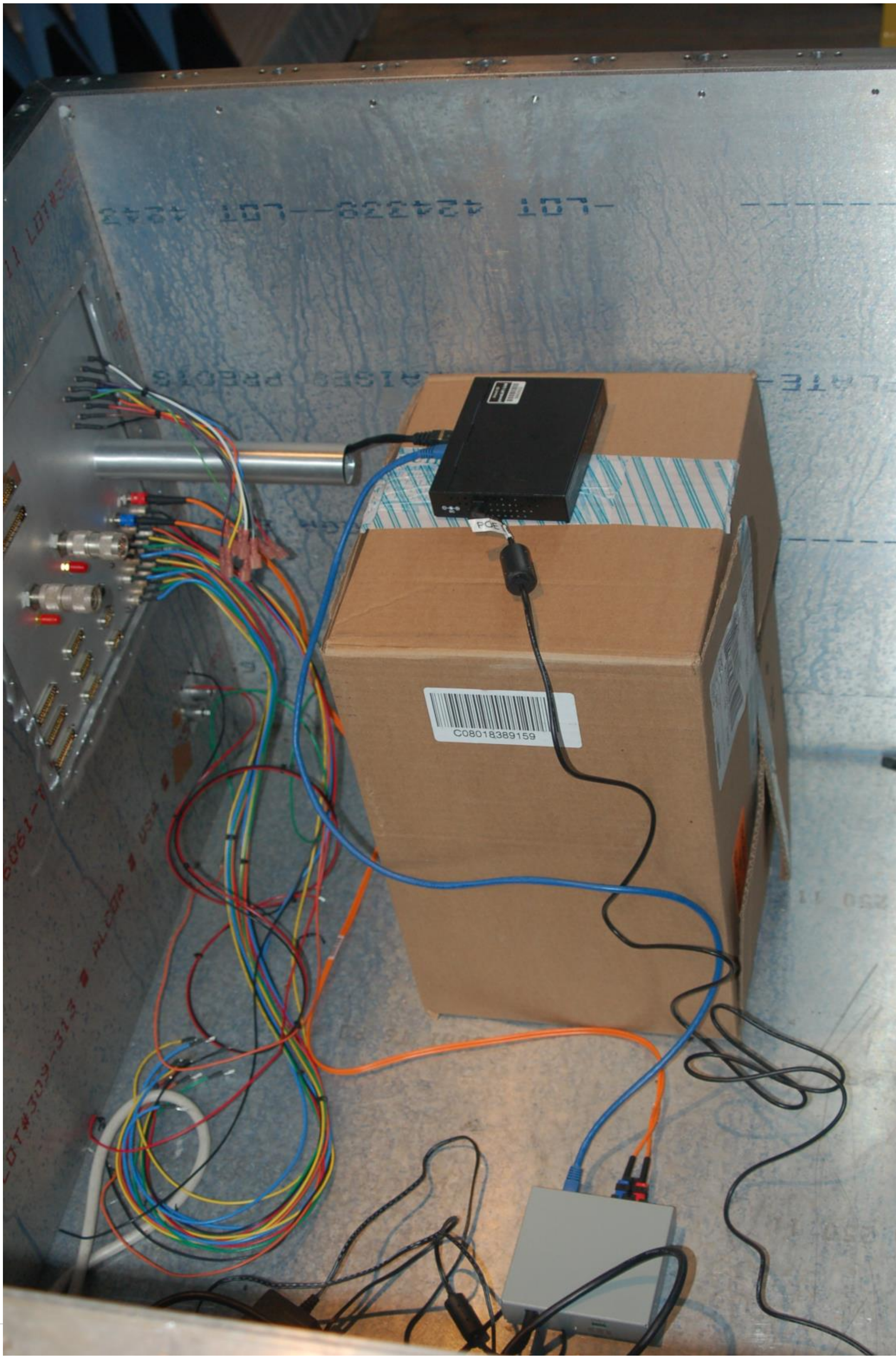
On Thursday, February 1 – Wednesday February 8, 2018, Carla Beaudet performed RF emissions tests on three configurations of LiFi, an optical wavelength wireless Ethernet system, provided by pureLiFi, a company based in Edinburgh, Scotland. In addition to testing the three configurations of LiFi access, the endpoint device, a Dell Laptop, was assessed with and without the LiFi dongle to see if the dongle contributes significantly to its emissions. The purpose of the testing is to assess the suitability of each of the three configurations for installation at the Green Bank Elementary School (GBEMS) which is seeking a wireless solution compatible with the GBO's mission of Radio Astronomy. The school is located at an approximate distance of 1460 m from the focal point GBT; 1460 m will be used as the reference distance for the purposes of this evaluation.

For testing the (3) LiFi lamps, a Test Bed was created by running an Ethernet fiber pair into the Quiet Box which contained a Fiber/Copper media converter. The media converter fed Ethernet to the provided Power over Ethernet switch. Power over Ethernet was routed out of the quiet box on a Cat 7 Ethernet cable via the Waveguide Beyond Cutoff tube usually used for routing fiber. This arrangement helped to minimize the noise of the Test Bed, but could not reduce it to levels beneath the noise floor of the test setup. For calibrated analysis of the EUT (Equipment Under Test) emissions, only peaks that exceed the Test Bed levels by 3dB or more were documented. Each of the (3) LiFi lamps was powered on and operation was verified via LiFi communication with the laptop, which was then removed from the chamber for the purposes of testing.

For evaluating the XC LiFi Dongle, the emissions of the Dell laptop PC served as the baseline, and only peaks that exceed those of the PC by 3dB or more were subjected to calibrated analysis.

The EUT was tested in the anechoic chamber at a distance of 7m from the receive antenna over the range 20 MHz to 1 GHz using the EM-6950 log periodic antenna, and at a distance of 5m from the receive antenna over the range from 1 GHz to 10 GHz using the EM-6961 Horn Antenna. The spectral plots reflect the raw data; all gains and losses of the test system including test distance, antenna gain, amplifier gain, cable loss, adapter loss, etc. are accounted for in the calibrated emissions tables. Calibrated measurements were performed on worst-case signals from the wideband spectral plot using a span of 10 MHz and a long (100 sweep) average. The resolution bandwidth used for all measurements was 10 kHz.

A qualitative description of the emissions of each EUT is followed by a table of calibrated measurements summarizing the worst-case measurements from that EUT. Overlaid spectral plots of the emissions of the 3 LiFi Lamps and the test bed are followed by overlaid spectral plots of the PC with and without the XC LiFi Dongle.



POE
C08018389159

Figure 1: Test Bed in Quiet Box

LiFi ORES POE

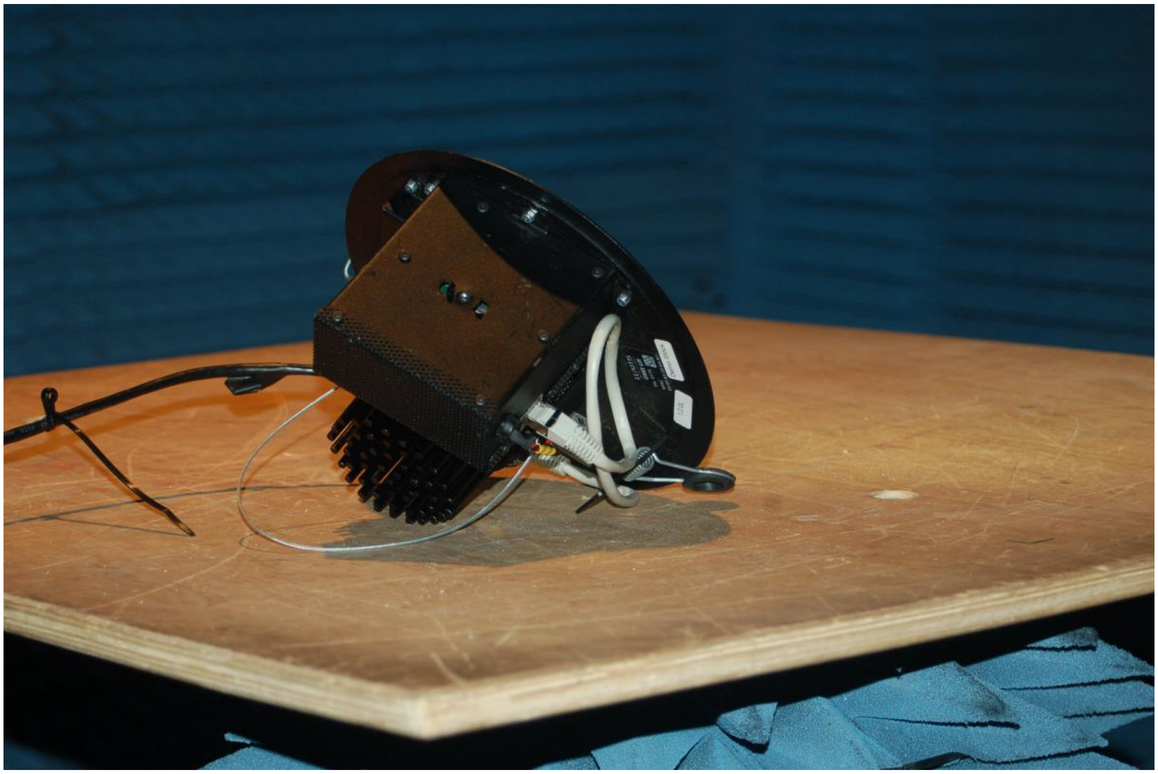


Figure 2: Lifi ORES with POE

This was the noisiest of the 3 LiFi lamps tested. Between 20 MHz and 7 GHz, many narrowband emissions were seen that could not be attributed to the test bed. The following table summarizes the calibrated worst-case emissions:

Worst Case Emissions Summary ORES							
Frequency (MHz)	Long Average Measurement (dBm)	Power Density @ GBT Reference Point (dBW/m2/Hz)	ITU-R RA.769 Continuum Limit (dBW/m2/Hz)	Emission Exceeds Continuum Limit by (dB)	ITU-R RA.769 Line Limit (dBW/m2/Hz)	Emission Exceeds Line Limit by (dB)	Emission Exceeds FCC Class B Limit[4] by (dBm, EIRP)
61.20	-39.70	-202.10	-255.65	53.54	-245.22	43.11	NA
106.20	-38.30	-199.67	-258.42	58.75	-245.01	45.34	NA
176.80	-42.24	-205.82	-258.85	53.03	-244.69	38.86	NA
249.30	-33.20	-196.43	-258.44	62.01	-244.36	47.93	-2.91
255.20	-36.10	-199.10	-258.40	59.30	-244.33	45.23	-5.58
382.60	-40.29	-199.71	-255.92	56.22	-243.75	44.04	-6.18
764.80	-37.10	-188.18	-253.38	65.20	-242.00	53.82	5.34
892.20	-40.32	-188.85	-253.70	64.85	-241.41	52.57	4.68
1002.00	-57.80	-204.05	-253.97	49.93	-240.91	36.87	-18.48
1025.00	-53.00	-199.41	-254.03	54.63	-240.81	41.40	-13.84
1127.00	-57.00	-203.60	-254.29	50.69	-240.34	36.74	-18.03
1153.00	-55.00	-201.43	-254.35	52.92	-240.22	38.79	-15.87
1282.00	-62.70	-208.70	-254.67	45.97	-239.63	30.93	-23.14
1408.00	-63.00	-208.39	-254.99	46.59	-239.05	30.66	-22.83
1537.00	-56.50	-201.13	-253.04	51.91	-238.39	37.26	-15.56
1665.00	-67.30	-210.99	-251.00	40.01	-237.00	26.01	-25.42
1792.00	-50.70	-193.63	-250.51	56.88	-236.72	43.09	-8.07
1920.00	-61.20	-202.92	-250.01	47.09	-236.44	33.52	-17.36
2047.00	-48.70	-190.17	-249.52	59.35	-236.16	45.99	-4.60
2177.00	-57.00	-197.99	-249.01	51.03	-235.87	37.88	-12.42
2303.00	-44.00	-184.74	-248.52	63.78	-235.59	50.84	0.82
2433.00	-62.50	-203.15	-248.02	44.87	-235.30	32.16	-17.58
2560.00	-55.80	-196.13	-247.52	51.39	-235.02	38.89	-10.57
2687.00	-65.50	-205.57	-247.03	41.46	-234.74	29.17	-20.01
2813.00	-57.30	-197.11	-246.69	49.58	-234.46	37.35	-11.54
2943.00	-61.80	-201.21	-246.35	45.14	-234.17	32.96	-15.65
3453.00	-58.80	-196.23	-245.02	48.79	-233.05	36.82	-10.67
3710.00	-60.30	-196.60	-244.35	47.75	-232.48	35.87	-11.04
4097.00	-70.70	-206.13	-243.34	37.22	-231.62	25.50	-20.56
4353.00	-72.50	-208.04	-242.67	34.63	-231.05	23.01	-22.48
4993.00	-64.80	-198.64	-241.01	42.36	-229.85	31.20	-13.08
5377.00	-74.80	-206.71	-240.93	34.23	-229.49	22.79	-21.14
5503.00	-74.80	-205.99	-240.91	34.92	-229.37	23.39	-20.42
5633.00	-74.80	-205.69	-240.89	35.20	-229.25	23.56	-20.13
6273.00	-78.20	-207.85	-240.77	32.92	-228.66	20.80	-22.29
6400.00	-78.30	-207.58	-240.75	33.17	-228.54	20.96	-22.02
6527.00	-78.17	-207.64	-240.73	33.09	-228.42	20.78	-22.08
6783.00	-74.80	-204.29	-240.68	36.39	-228.18	23.89	-18.73
6910.00	-75.33	-204.32	-240.66	36.34	-228.06	23.74	-18.75

Table 1: Worst-Case Emissions, LiFi ORES POE

*FCC Class B compliance not estimated[4] below 200 MHz due to lack of antenna calibration and chamber reflectivity

LIFI ORES POE TEMPEST

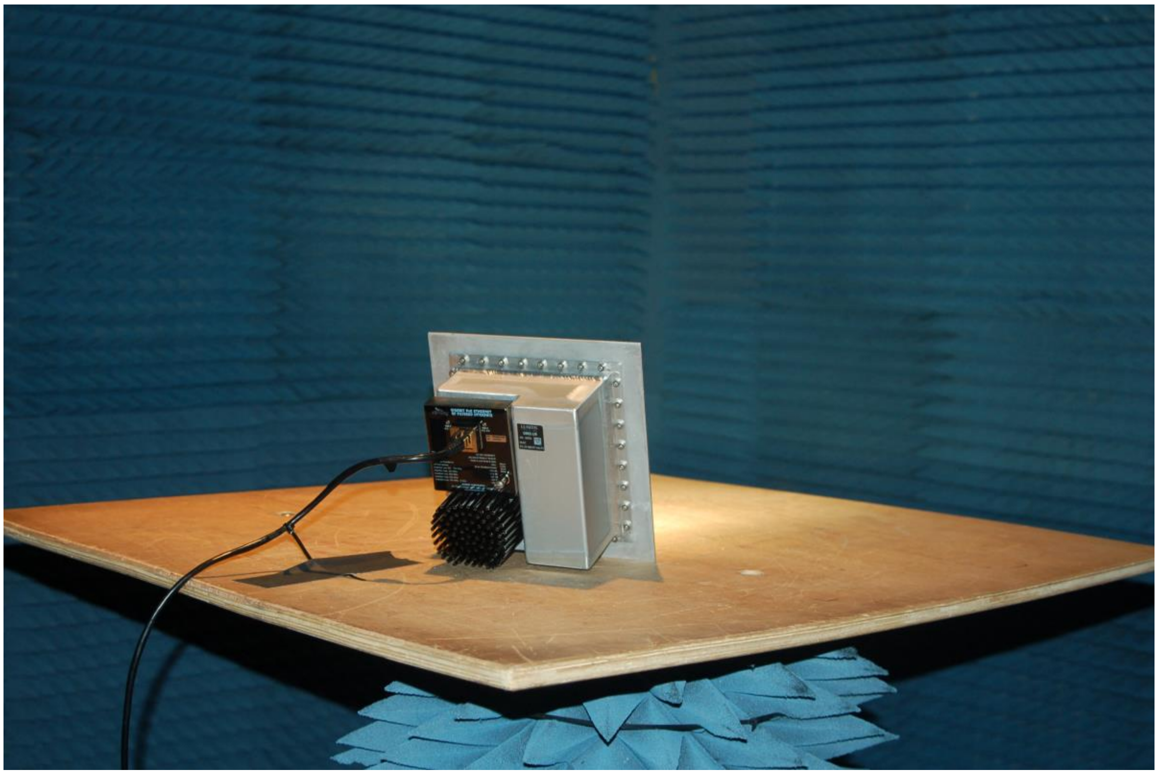


Figure 3: LiFi ORES POE TEMPEST

Figure 4: LiFi ORES POE TEMPEST ETH Filter

Unsurprisingly, this Faraday-enclosed version was the quietest of the 3 LiFi lamps tested. However, due to the low insertion loss of the Ethernet filter at frequencies below ~700MHz, (conveniently published on the exterior of the filter) there were still some measurable emissions that could not be attributed to the test bed. The following table summarizes these calibrated worst-case emissions:

Worst Case Emissions Summary ORES Tempest							
Frequency (MHz)	Long Average Measurement (dBm)	Power Density @ GBT Reference Point (dBW/m2/Hz)	ITU-R RA.769 Continuum Limit (dBW/m2/Hz)	Emission Exceeds Continuum Limit by (dB)	ITU-R RA.769 Line Limit (dBW/m2/Hz)	Emission Exceeds Line Limit by (dB)	Emission Exceeds FCC Class B Limit[4] by (dBm, EIRP)
25.90	-47.05	-213.98	-249.05	35.08	-245.38	31.40	NA
61.20	-37.77	-200.17	-255.65	55.48	-245.22	45.05	NA
82.70	-42.12	-203.70	-258.11	54.42	-245.12	41.42	NA
94.50	-49.63	-211.03	-258.27	47.24	-245.06	34.03	NA
106.20	-38.28	-199.64	-258.42	58.78	-245.01	45.37	NA
176.80	-39.36	-202.94	-258.85	55.92	-244.69	41.75	NA
249.30	-41.24	-204.46	-258.44	53.97	-244.36	39.89	-10.95
436.10	-56.70	-214.96	-254.72	39.77	-243.50	28.55	-21.44
535.90	-67.70	-223.41	-253.74	30.33	-243.04	19.63	-29.90
547.70	-67.10	-222.64	-253.62	30.99	-242.99	20.35	-29.12
747.40	-68.90	-220.44	-253.34	32.90	-242.08	21.63	-26.93

Table 2: Worst-Case Emissions, LiFi ORES POE TEMPEST

*FCC Class B compliance not estimated[4] below 200 MHz due to lack of antenna calibration and chamber reflectivity

LiFi XC Access Point with Lucibel Lucicup II Lamp:

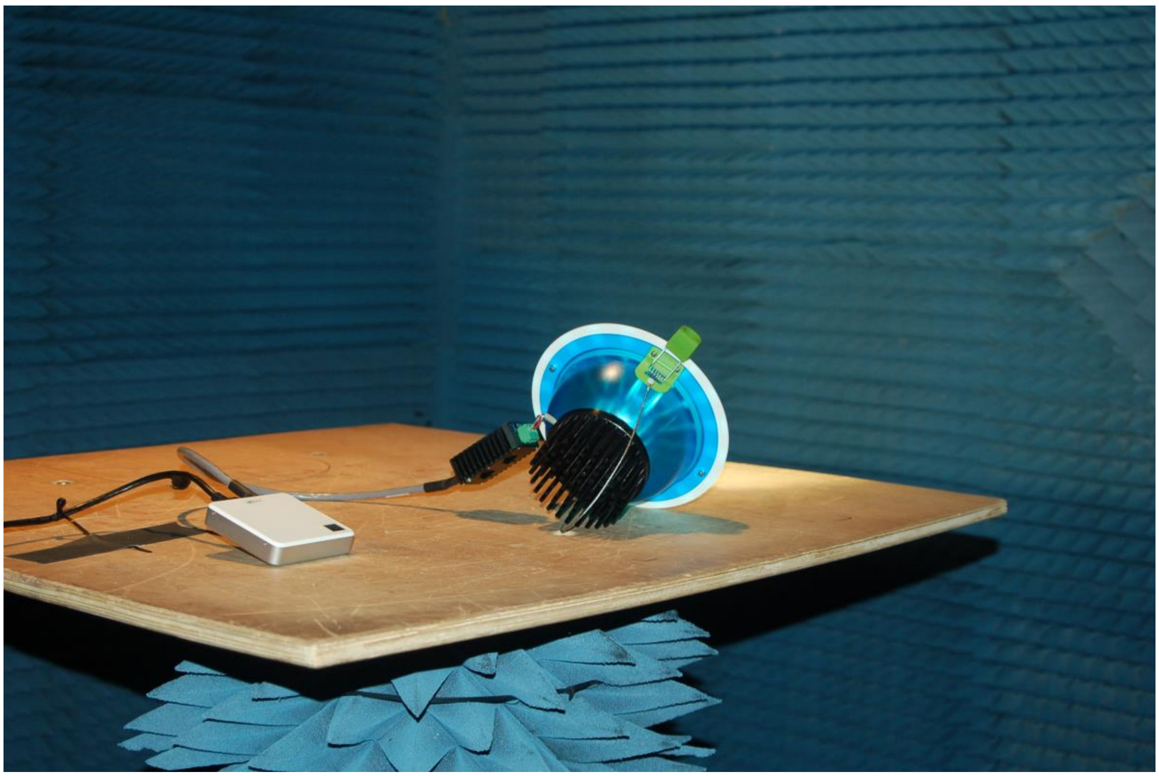


Figure 5: LiFi XC AP w/Lucicup

The Lifi XC Access point with the Lucicup II Lamp showed a fair number of narrow-band emissions between 20 MHz and ~2 GHz that could not be attributed to the test bed, but it was comparatively quieter than the ORES, which had measurable emissions up to roughly 6.9 GHz. The following table summarizes the calibrated worst-case emissions:

Worst Case Emissions Summary XC Access Point w/Lucicup							
Frequency (MHz)	Long Average Measurement (dBm)	Power Density @ GBT Reference Point (dBW/m2/Hz)	ITU-R RA.769 Continuum Limit (dBW/m2/Hz)	Emission Exceeds Continuum Limit by (dB)	ITU-R RA.769 Line Limit (dBW/m2/Hz)	Emission Exceeds Line Limit by (dB)	Emission Exceeds FCC Class B Limit[4] by (dBm, EIRP)
78.80	-44.30	-205.98	-258.06	52.09	-245.14	39.16	NA
106.20	-40.60	-201.97	-258.42	56.45	-245.01	43.04	NA
108.20	-40.90	-202.27	-258.44	56.17	-245.00	42.73	NA
172.90	-38.90	-202.28	-258.88	56.60	-244.70	42.42	NA
190.50	-45.70	-209.27	-258.78	49.50	-244.62	35.35	NA
249.30	-40.90	-204.13	-258.44	54.31	-244.36	40.23	-10.61
1127.00	-63.50	-210.10	-254.29	44.19	-240.34	30.24	-24.53
1252.00	-63.70	-209.85	-254.60	44.74	-239.77	29.91	-24.29
1282.00	-63.50	-209.50	-254.67	45.17	-239.63	30.13	-23.94
1377.00	-70.30	-215.91	-254.91	39.00	-239.20	23.29	-30.34
1665.00	-71.70	-215.39	-251.00	35.61	-237.00	21.61	-29.82
1793.00	-69.20	-212.13	-250.50	38.38	-236.72	24.59	-26.56
2047.00	-74.30	-215.77	-249.52	33.75	-236.16	20.39	-30.20

Table 3: Worst-Case Emissions, LiFi XC Access Point with Lucibel Lucicup II LED Fixture

*FCC Class B compliance not estimated[4] below 200 MHz due to lack of antenna calibration and chamber reflectivity

LiFi XC Station Dongle:

Figure 6: PC with LiFi XC Station Dongle

Figure 7: LiFi XC Station Dongle

The Lifi XC Station contributed just one rather wide-band emission to the emission profile of the Dell laptop PC, with a 3dB bandwidth of approximately 16 MHz around 719 MHz, as shown in the following summary table:

Worst Case Emissions Summary XC Dongle (ignoring PC noise)							
Frequency (MHz)	Long Average Measurement (dBm)	Power Density @ GBT Reference Point (dBW/m2/Hz)	ITU-R RA.769 Continuum Limit (dBW/m2/Hz)	Emission Exceeds Continuum Limit by (dB)	ITU-R RA.769 Line Limit (dBW/m2/Hz)	Emission Exceeds Line Limit by (dB)	Emission Exceeds FCC Class B Limit[4] by (dBm, EIRP)
719.00	-61.60	-213.81	-253.27	39.46	-242.21	28.40	-20.29

Table 4: Worst-Case Emissions, LiFi XC Station Dongle

*FCC Class B compliance not estimated[4] below 200 MHz due to lack of antenna calibration and chamber reflectivity

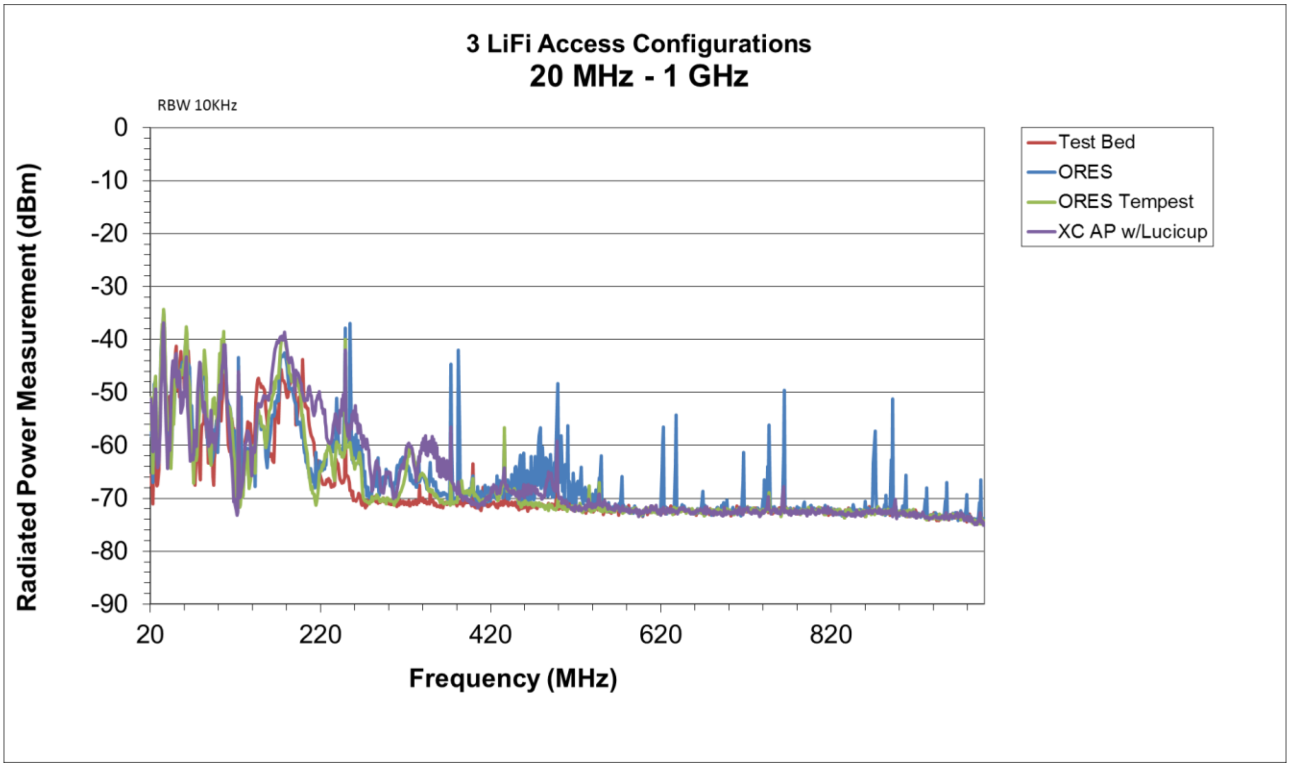


Figure 8: (3) LiFi Access Configurations 20 MHz – 1 GHz

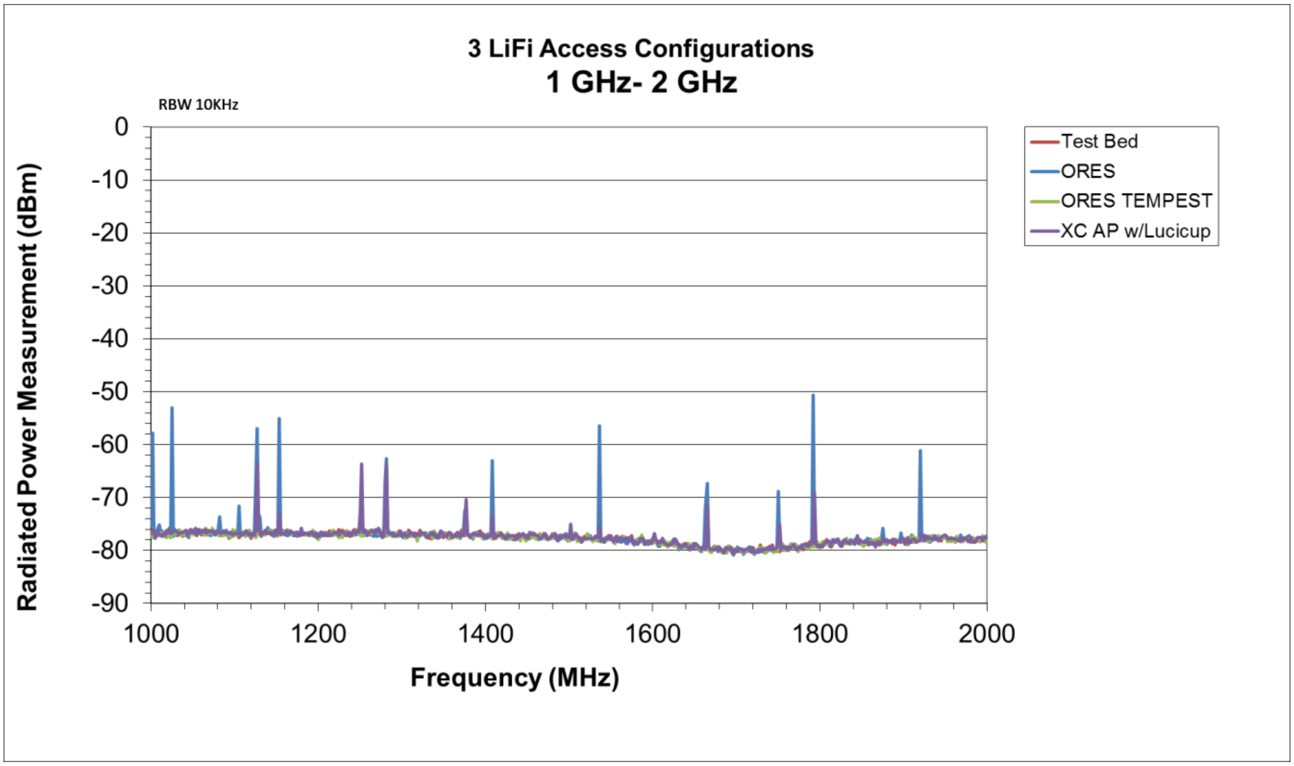


Figure 9: (3) LiFi Access Configurations 1 GHz – 2 GHz

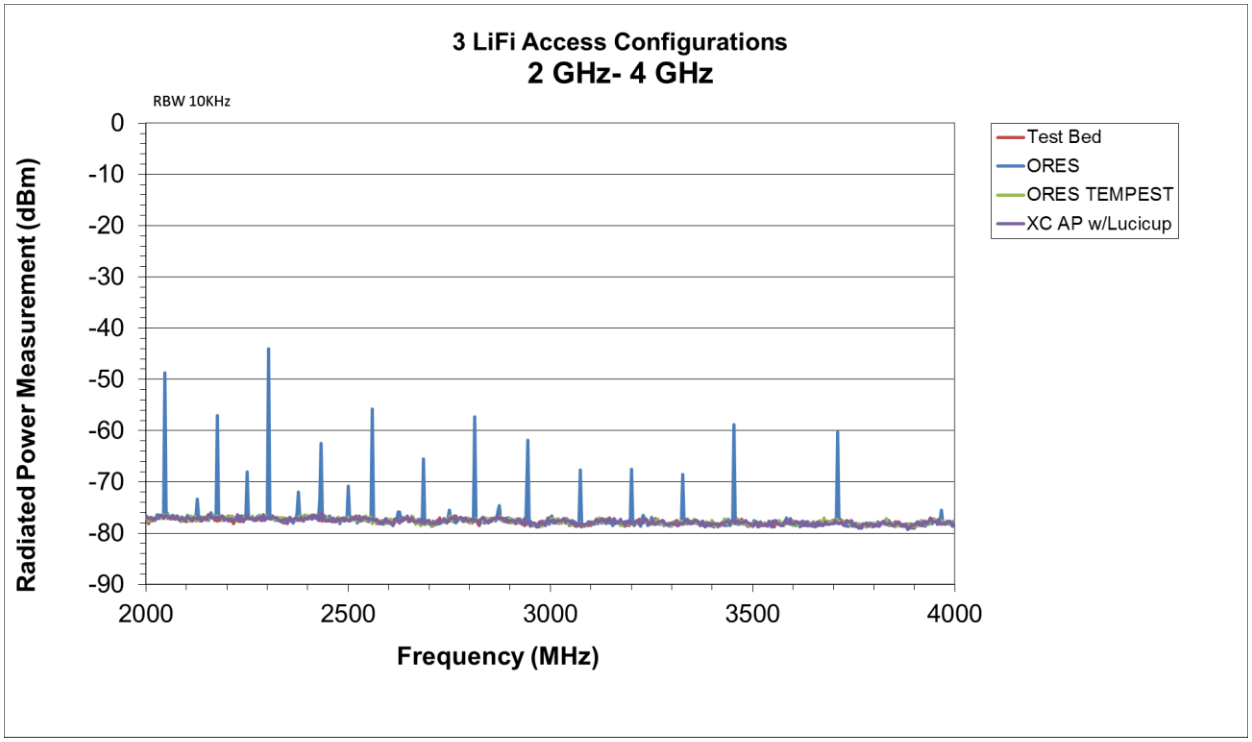


Figure 10: (3) LiFi Access Configurations 2 GHz – 4 GHz

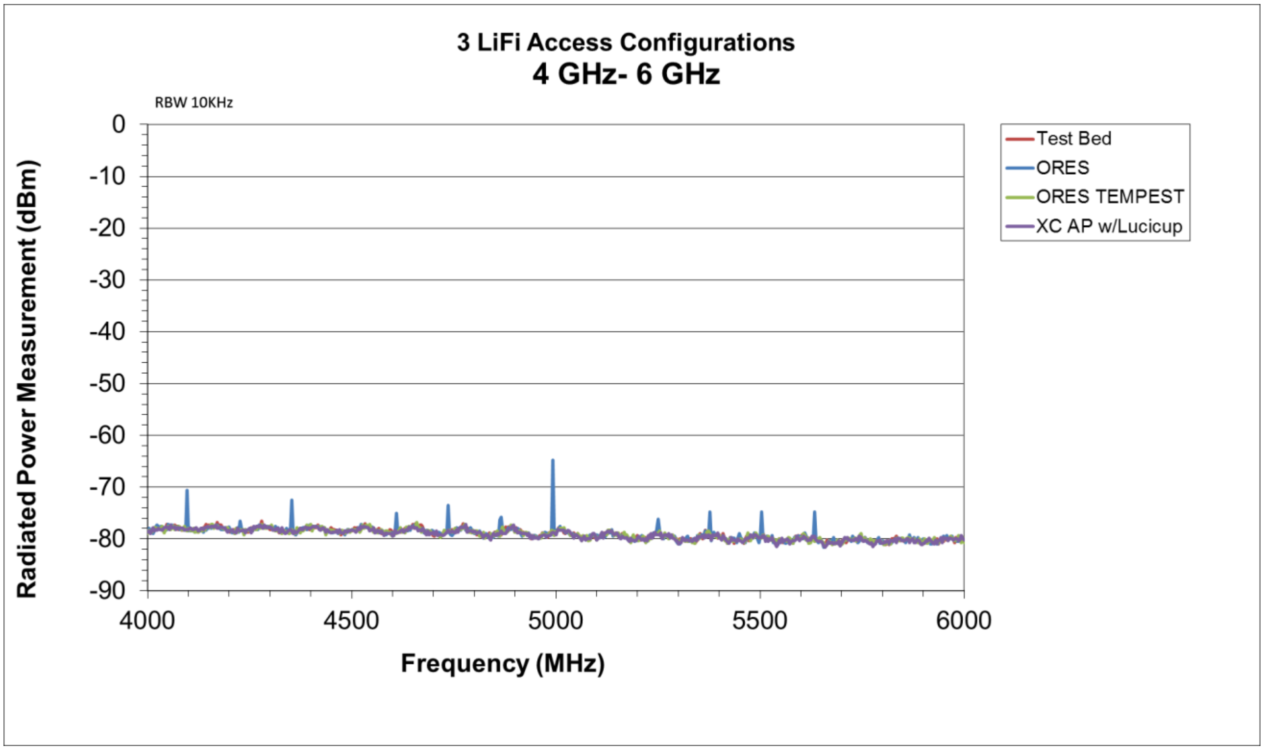


Figure 11: (3) LiFi Access Configurations 4 GHz – 6 GHz

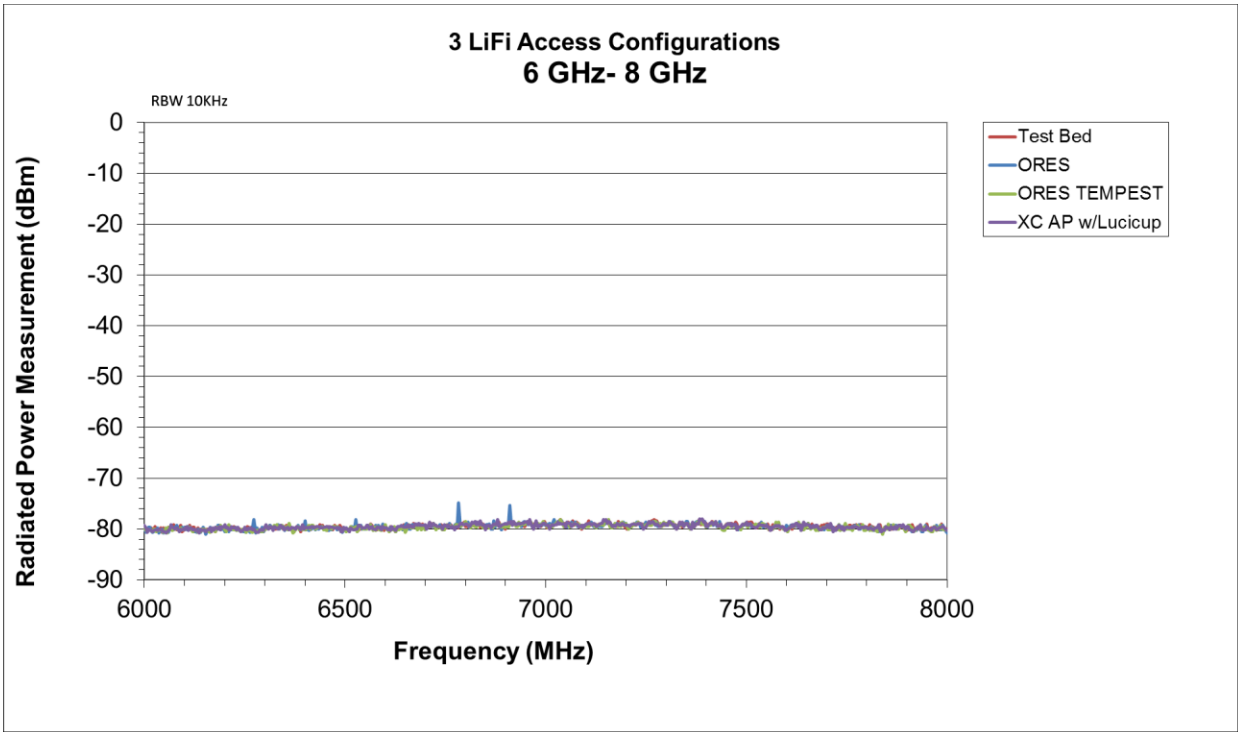


Figure 11: (3) LiFi Access Configurations 6 GHz – 8 GHz

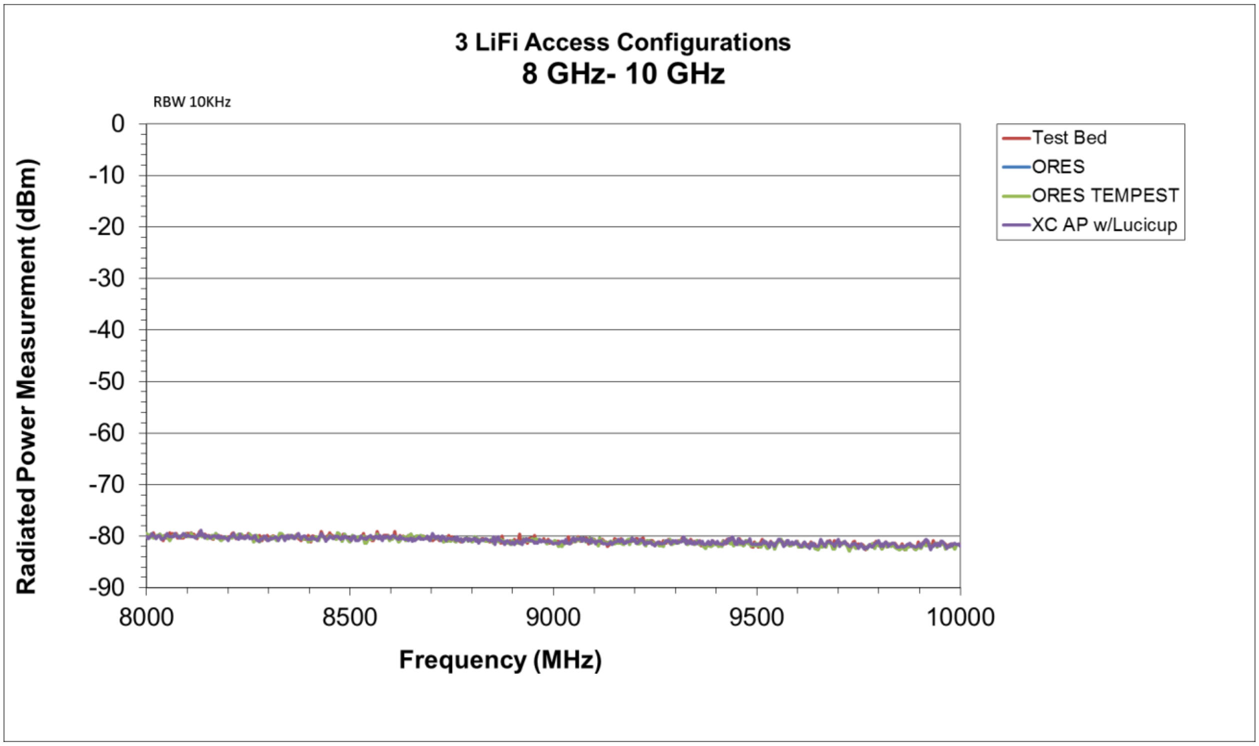


Figure 12: (3) LiFi Access Configurations 8 GHz – 10 GHz

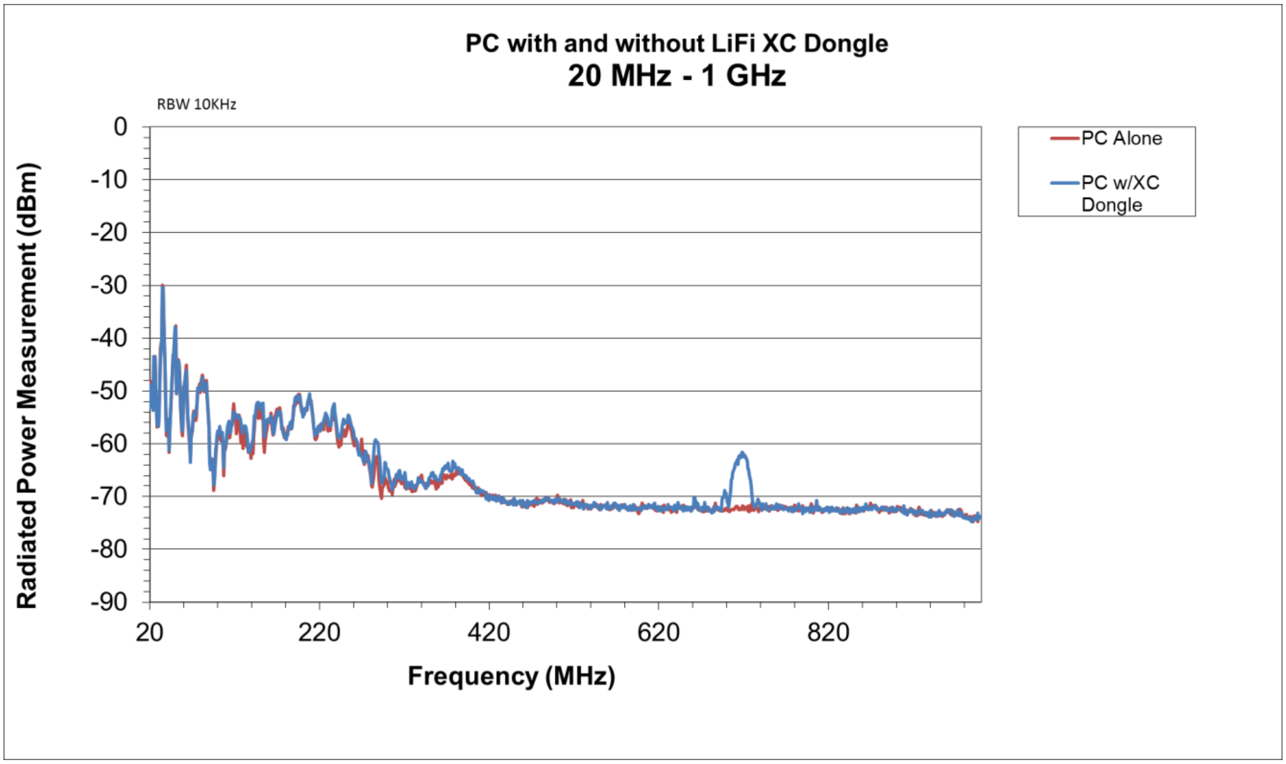


Figure 13: Dell Laptop with and without LiFi XC Dongle 20 MHz – 1 GHz

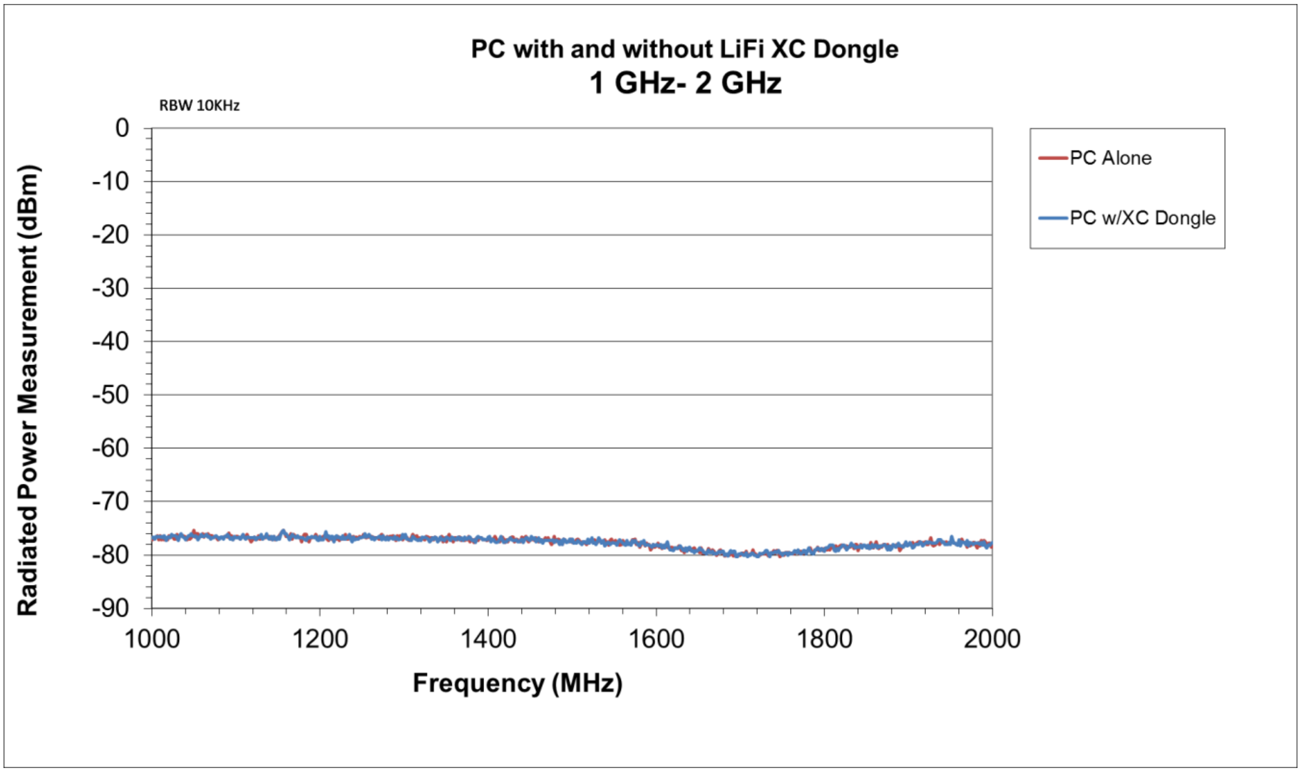


Figure 14: Dell Laptop with and without LiFi XC Dongle 1 GHz – 2 GHz

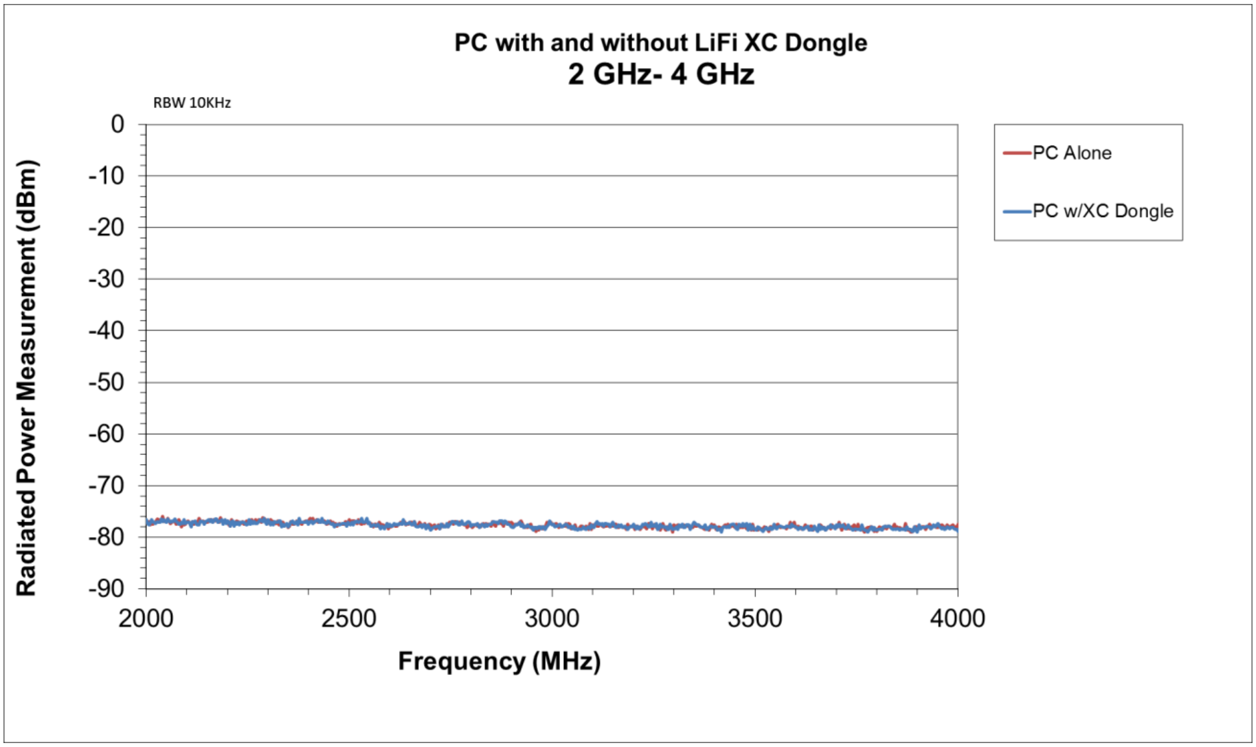


Figure 15: Dell Laptop with and without LiFi XC Dongle 2 GHz – 4 GHz

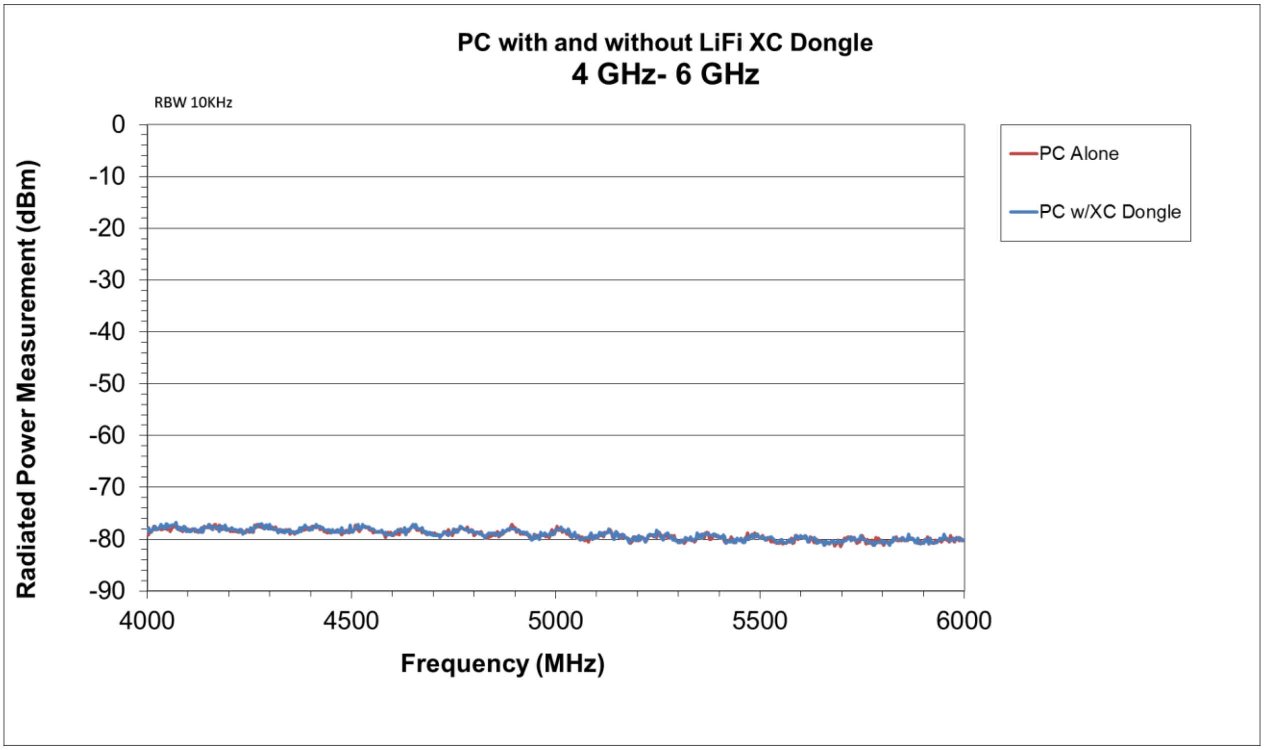


Figure 16: Dell Laptop with and without LiFi XC Dongle 4 GHz – 6 GHz

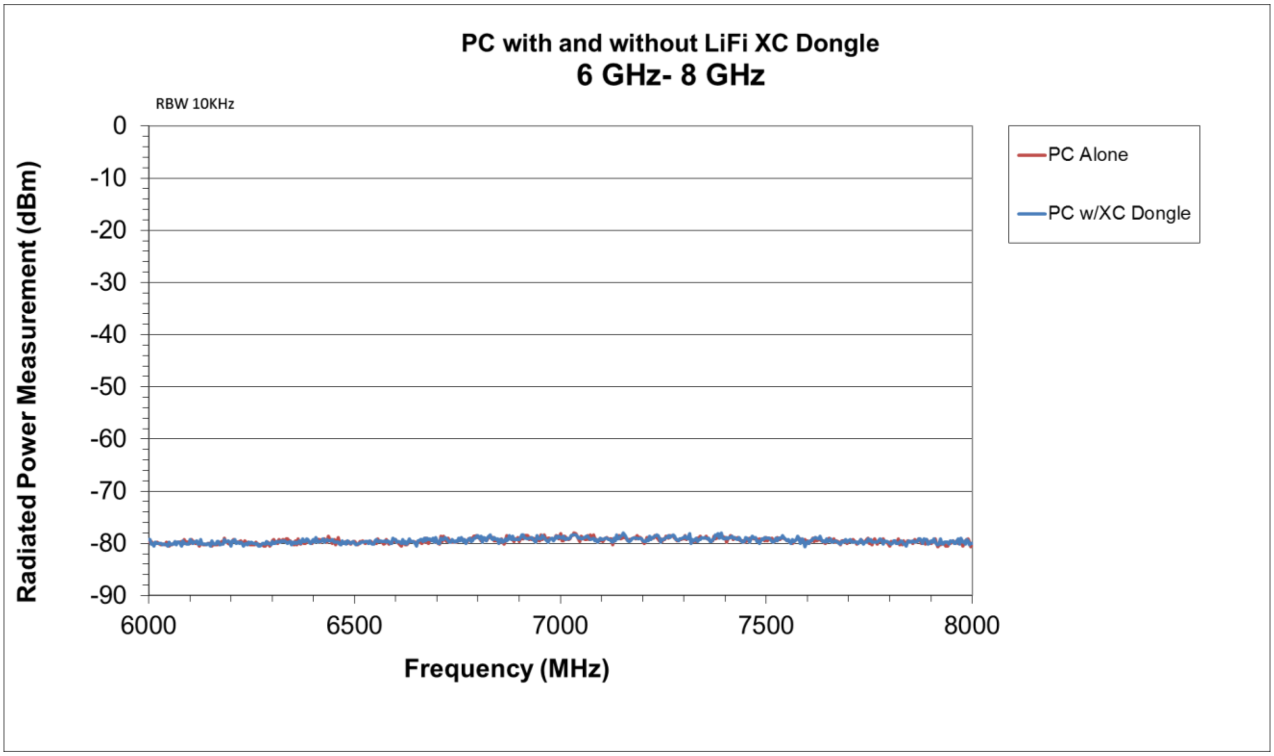


Figure 17: Dell Laptop with and without LiFi XC Dongle 6 GHz – 8 GHz

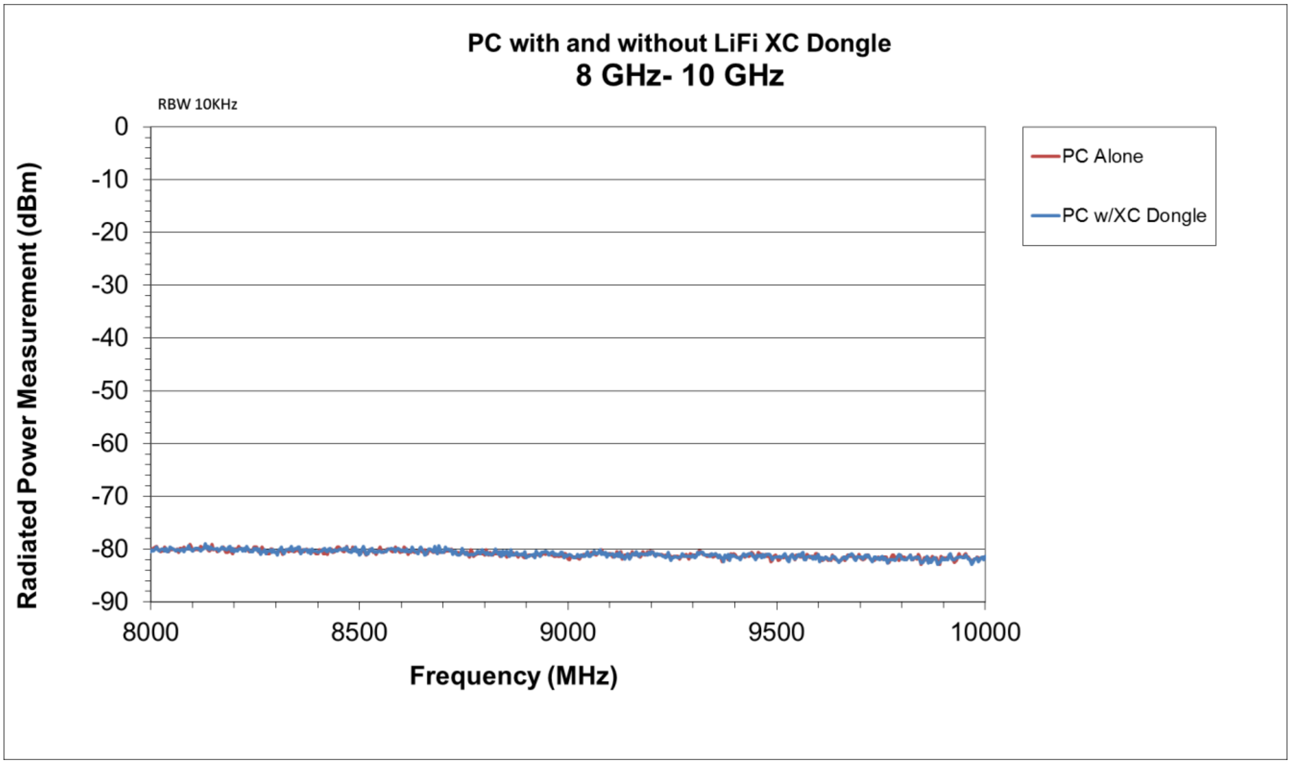


Figure 18: Dell Laptop with and without LiFi XC Dongle 8 GHz – 10 GHz

Discussion:

While any of the LiFi systems tested would be a much more preferable solution to wireless communication at GBEMS than WIFI, it is clear from the tabulated worst-case emissions that the unintentional emissions of all the systems tested exceed the detection thresholds for Line and Continuum observations. (This is what we find for practically any digital electronics at typical on-site or near-site distances.) While the ORES TEMPEST solution would protect observations at frequencies above ~750 MHz, it would be in the GBO's interest to take advantage of the fiber Ethernet infrastructure we previously installed at GBEMS by designing an enclosure for the ORES or the XC Access Point w/Lamp that integrates a media converter into a Faraday enclosure. This solution would offer an exciting possibility for the Green Bank site as well as for the GBEMS.

Note #1: No allowance was made for shielding from incidental structure.

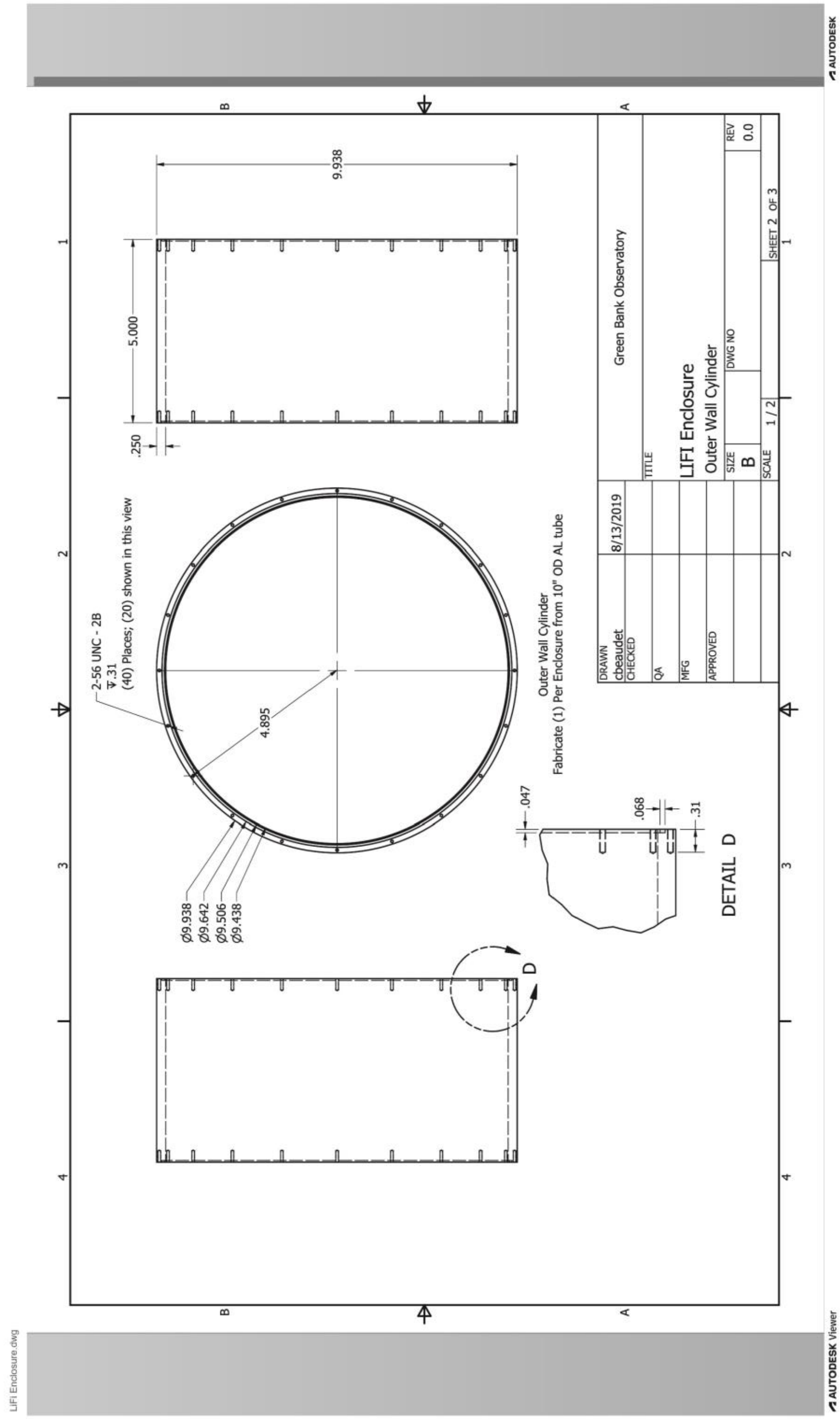
Note #2: RFI limits to radio astronomy are found J. R. Fisher's report "RFI Radiation Limits in the Vicinity of the GBT" dated May 9, 1997.

Note #3: Methods & calculations used for RFI tests are established by J. R. Fisher's report of August 1994, "Evaluation of Electrical Device Interference Potential to Radio Astronomy Observations."

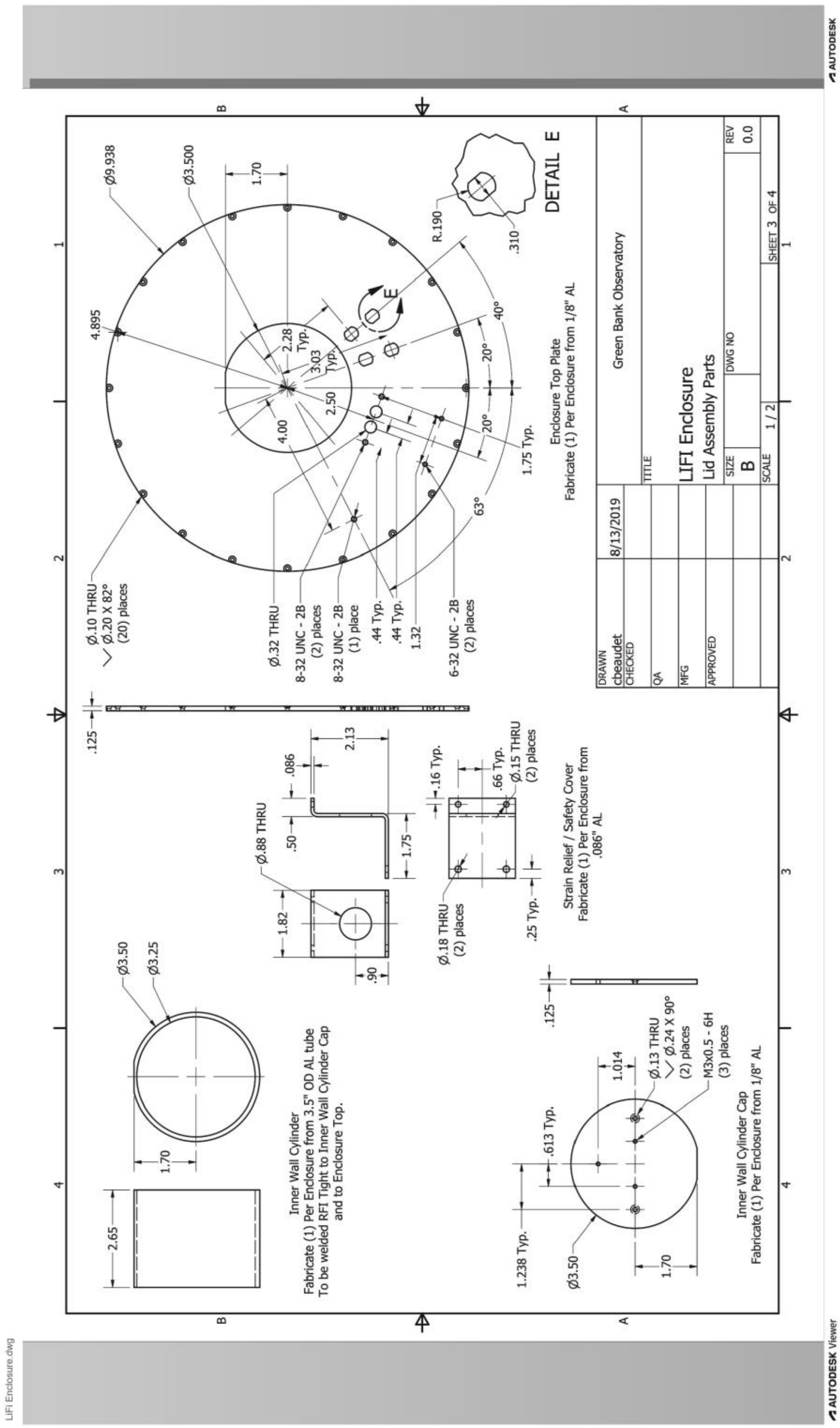
Note #4: FCC Class B compliance is estimated, not assessed, since we do not use the requisite quasi-peak detector in our measurements, we do not use a turntable, and we have a somewhat reflective chamber at frequencies below 2 GHz, and use an antenna for which calibration is extrapolated at frequencies below 200 MHz.

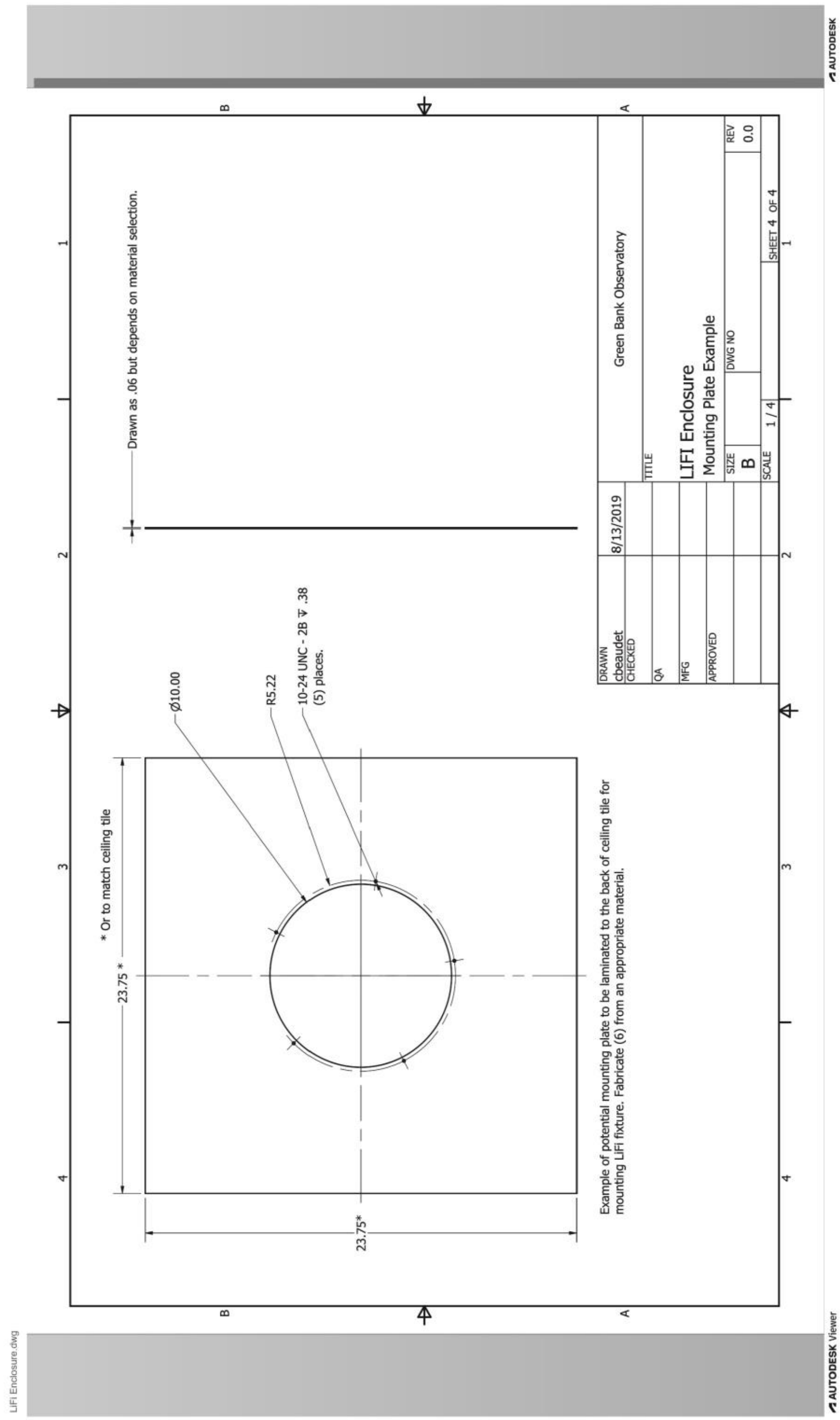
APPENDIX B – LIFI RF ENCLOSURE

Designed by C. Beaudet



AUTODESK
Green Bank Observatory
LIFI Enclosure
Outer Wall Cylinder
TITLE
SIZE
B
SCALE
1 / 2
DWG NO
SHEET 2 OF 3
REV
0.0
DRAWN
cbeaudet
8/13/2019
CHECKED
QA
MFG
APPROVED
9.938
5.000
.250
2-56 UNC - 2B
↧.31
(40) Places; (20) shown in this view
4.895
Outer Wall Cylinder
Fabricate (1) Per Enclosure from 10" OD AL tube
Ø9.938
Ø9.642
Ø9.506
Ø9.438
.047
.068
.31
DETAIL D
D
LiFi Enclosure.dwg
AUTODESK Viewer


Enclosure Top Plate
Fabricate (1) Per Enclosure from 1/8" AL
DETAIL E
Green Bank Observatory
LIFI Enclosure
Lid Assembly Parts
DRAWN
cbeaudet
8/13/2019
SIZE
B
SCALE
1 / 2
SHEET 3 OF 4
REV
0.0
Inner Wall Cylinder
Fabricate (1) Per Enclosure from 3.5" OD AL tube
To be welded RFI Tight to Inner Wall Cylinder Cap
and to Enclosure Top.
Strain Relief / Safety Cover
Fabricate (1) Per Enclosure from
.086" AL
Inner Wall Cylinder Cap
Fabricate (1) Per Enclosure from 1/8" AL
AUTODESK Viewer
LiFi Enclosure.dwg



Drawn as .06 but depends on material selection.
* Or to match ceiling tile
23.75 *
23.75*
Ø10.00
R5.22
10-24 UNC - 2B ⊽ .38
(5) places.
Example of potential mounting plate to be laminated to the back of ceiling tile for mounting LiFi fixture. Fabricate (6) from an appropriate material.
Green Bank Observatory
DRAWN
cbeaudet
8/13/2019
CHECKED
QA
MFG
APPROVED
TITLE
LIFI Enclosure
Mounting Plate Example
SIZE
B
DWG NO
REV
0.0
SCALE 1 / 4
SHEET 4 OF 4
AUTODESK Viewer
LiFi Enclosure.dwg

APPENDIX C – MITIGATED RF TESTS

Report written by C. Beaudet

On Wednesday November 27, 2019, Carla Beaudet performed RFI tests on a LiFi ORES system packaged together with a MeanWell IRM-60-48 power supply, and a AD-Net AN-102-X3X1 media converter, all in a RFI enclosure. The media converter features two optical ports; this allows the installer the option to daisy chain a group of LiFi units together from a single 1GB optical network port (bandwidth is, of course, shared in this configuration). The LiFi ORES was tested individually on February 8, 2018, and shown to have overlimit emissions up to 6.9 GHz. A somewhat mitigated version of the system, the ORES Tempest, with a copper Ethernet port, was shown to have overlimit emissions up to ~540 MHz. An unpackaged assemblage of the same equipment:

- LiFi ORES
- MeanWell IRM-60-48 power supply
- AD-Net AN-102-X3X1 media converter

will henceforth be referred to as the EUT, (Equipment Under Test), and the packaged assemblage will be referred to as EUTmit (Equipment Under Test mitigated). The EUTmit is intended for installation in Jansky Lab Conference Room 137 in Zone 2, at a distance of 1801 m from the focal point GBT, which will be used as the reference distance for the purposes of this evaluation.

For testing purposes, the EUT (followed by the EUTmit) was powered on and operation was verified via LiFi communication with a laptop, which was then removed for the test. The EUT and EUTmit were tested individually in the anechoic chamber at a distance of 7m from the receive antenna over the range 20 MHz to 1 GHz using the EM-6950 log periodic antenna, and from 1 GHz to 10 GHz using the EM-6961 Horn Antenna. Between 20 MHz and 4.7 GHz, strong broadband and narrowband emissions were seen from the EUT, but the enclosure has mitigated all emissions below the detection threshold. Calibrated measurements were performed on worst-case signals from the wideband spectral plots using a span of 10 MHz and a long (100 sweep) average. The resolution bandwidth used for all measurements was 10 kHz. Spectral plots of the emissions follow summaries of the calibrated worst-case measurements:

Worst Case Emissions Summary						
Frequency (MHz)	Long Average Measurement (dBm)	Power Density @ GBT Reference Point (dBW/m2/Hz)	ITU-R RA.769 Continuum Limit (dBW/m2/Hz)	Emission Exceeds Continuum Limit by (dB)	ITU-R RA.769 Line Limit (dBW/m2/Hz)	Emission Exceeds Line Limit by (dB)
126.71	-30.70	-194.06	-258.68	64.62	-244.92	50.86
383.22	-31.06	-192.26	-255.90	63.64	-243.74	51.49
1438.33	-52.16	-196.22	-254.61	58.39	-238.90	42.69
373.43	-42.15	-203.42	-256.26	52.83	-243.79	40.36
1563.33	-56.66	-199.98	-252.62	52.63	-238.25	38.27
53.29	-37.11	-201.88	-254.17	52.29	-245.25	43.38
3373.33	-57.33	-193.92	-245.23	51.31	-233.22	39.30
1025.00	-57.50	-202.80	-254.03	51.23	-240.81	38.01
1815.00	-57.50	-199.27	-250.42	51.15	-236.67	37.40
3250.00	-57.66	-194.83	-245.55	50.72	-233.49	38.66
1501.67	-59.33	-203.18	-253.60	50.42	-238.57	35.39
2046.67	-58.83	-199.19	-249.52	50.33	-236.16	36.96
169.79	-43.76	-208.99	-258.89	49.91	-244.72	35.73
167.83	-43.95	-209.20	-258.91	49.70	-244.73	35.52
65.03	-42.70	-206.71	-256.36	49.65	-245.20	38.48
2566.67	-58.66	-197.86	-247.50	49.64	-235.01	37.15
2563.33	-58.66	-197.87	-247.51	49.64	-235.01	37.14
3500.00	-59.33	-195.39	-244.90	49.51	-232.94	37.55
3436.67	-59.50	-195.88	-245.07	49.18	-233.08	37.20
1063.33	-60.50	-205.82	-254.13	48.31	-240.63	34.81
1126.67	-60.66	-206.15	-254.29	48.13	-240.34	34.19
1065.00	-61.00	-206.32	-254.13	47.81	-240.62	34.30
1690.00	-60.83	-203.19	-250.90	47.72	-236.94	33.76
3123.33	-61.33	-199.06	-245.88	46.82	-233.77	34.71
3310.00	-61.83	-198.69	-245.40	46.71	-233.36	34.68
55.24	-43.73	-208.34	-254.53	46.19	-245.24	36.90
4003.33	-66.83	-201.21	-243.59	42.37	-231.83	30.62
4066.67	-70.50	-204.79	-243.42	38.63	-231.69	26.90
4063.33	-70.66	-204.94	-243.43	38.49	-231.70	26.76
4313.33	-70.66	-205.16	-242.78	37.62	-231.14	25.98
4253.33	-72.00	-206.50	-242.93	36.43	-231.28	24.77
4190.00	-72.33	-206.79	-243.10	36.31	-231.42	24.63
24.90	-43.93	-212.94	-248.94	36.00	-245.38	32.44
4126.67	-74.00	-208.38	-243.27	34.89	-231.56	23.18
4376.67	-73.66	-208.20	-242.61	34.42	-231.00	22.80
4316.67	-74.66	-209.16	-242.77	33.61	-231.14	21.97

Figure 1: Worst-Case Emissions, Pre-Mitigation

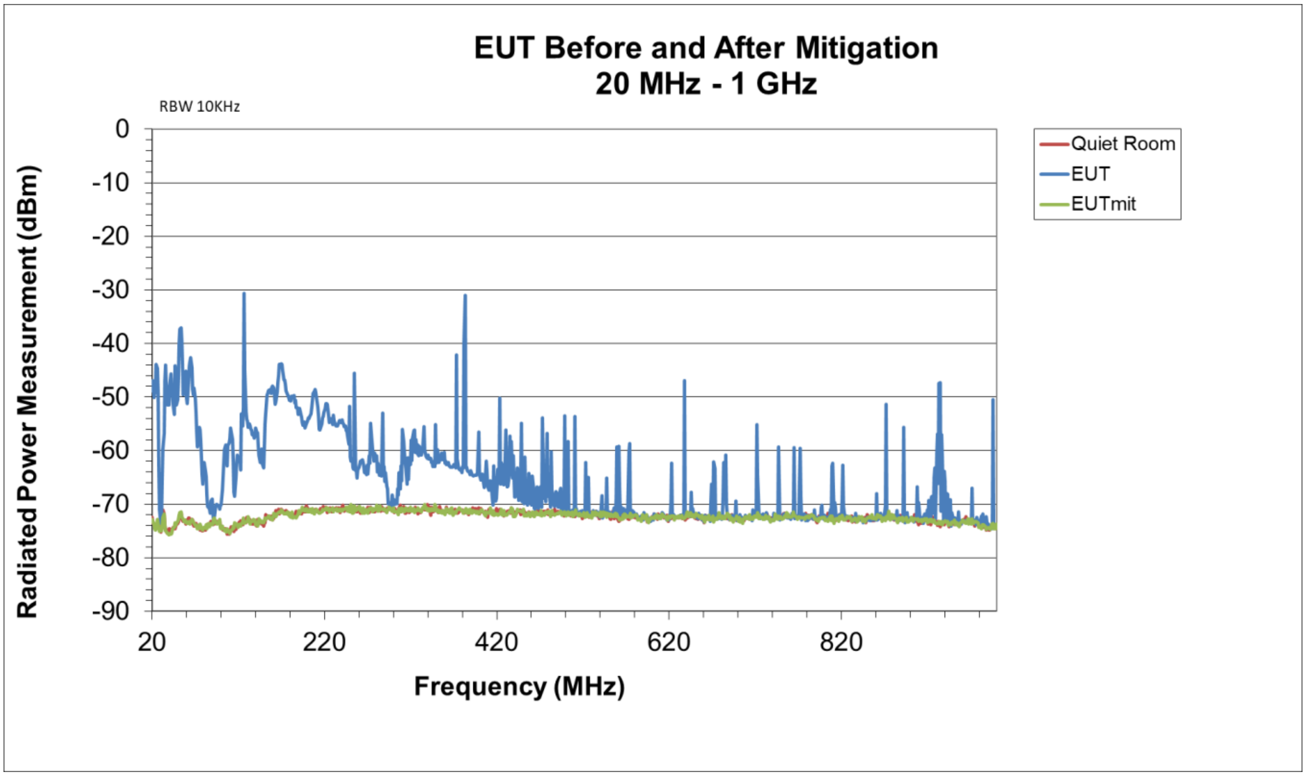


Figure 2: 20 MHz – 1 GHz

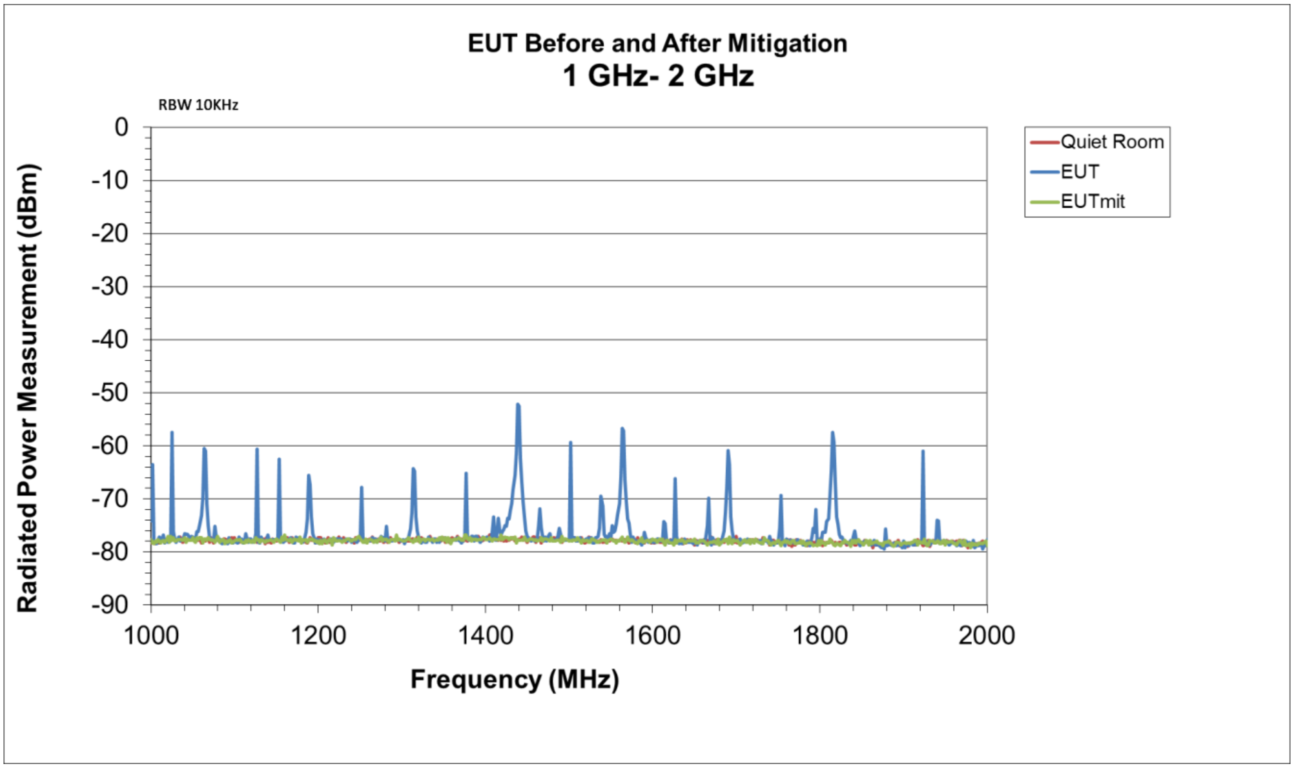


Figure 3: 1 GHz – 2 GHz

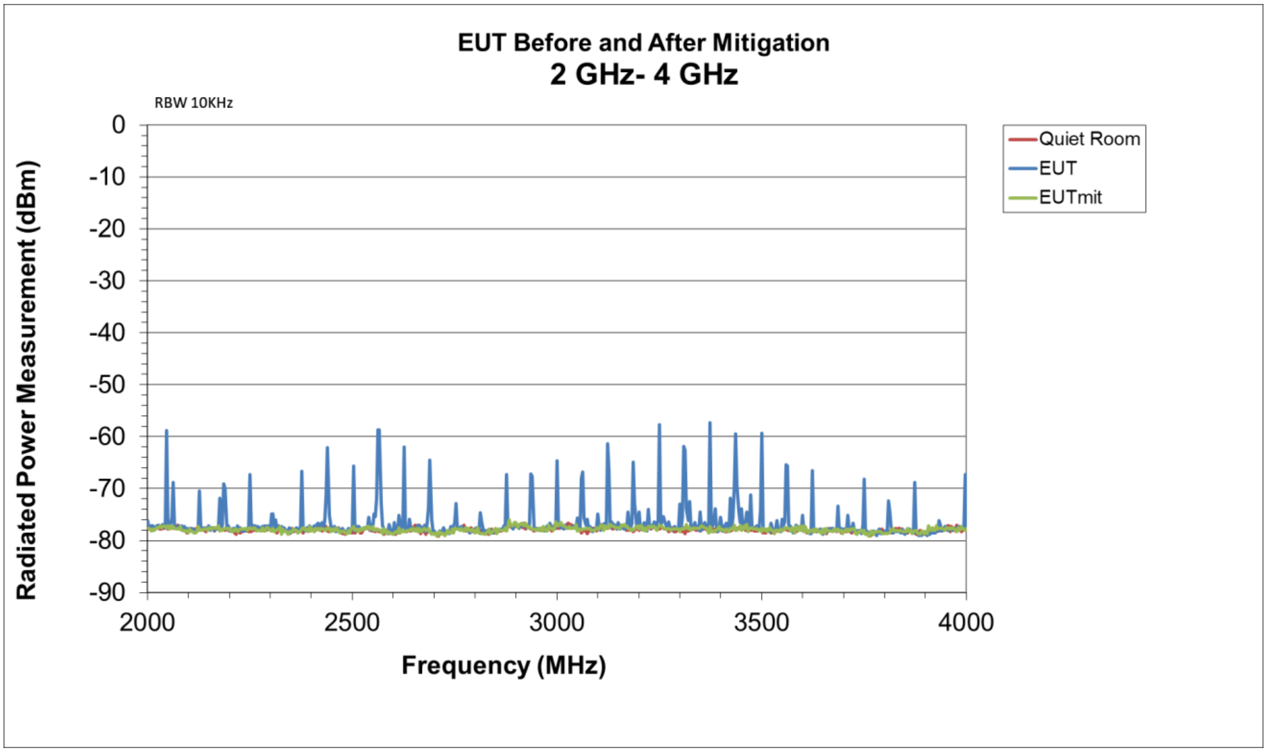


Figure 4: 2 GHz – 4 GHz

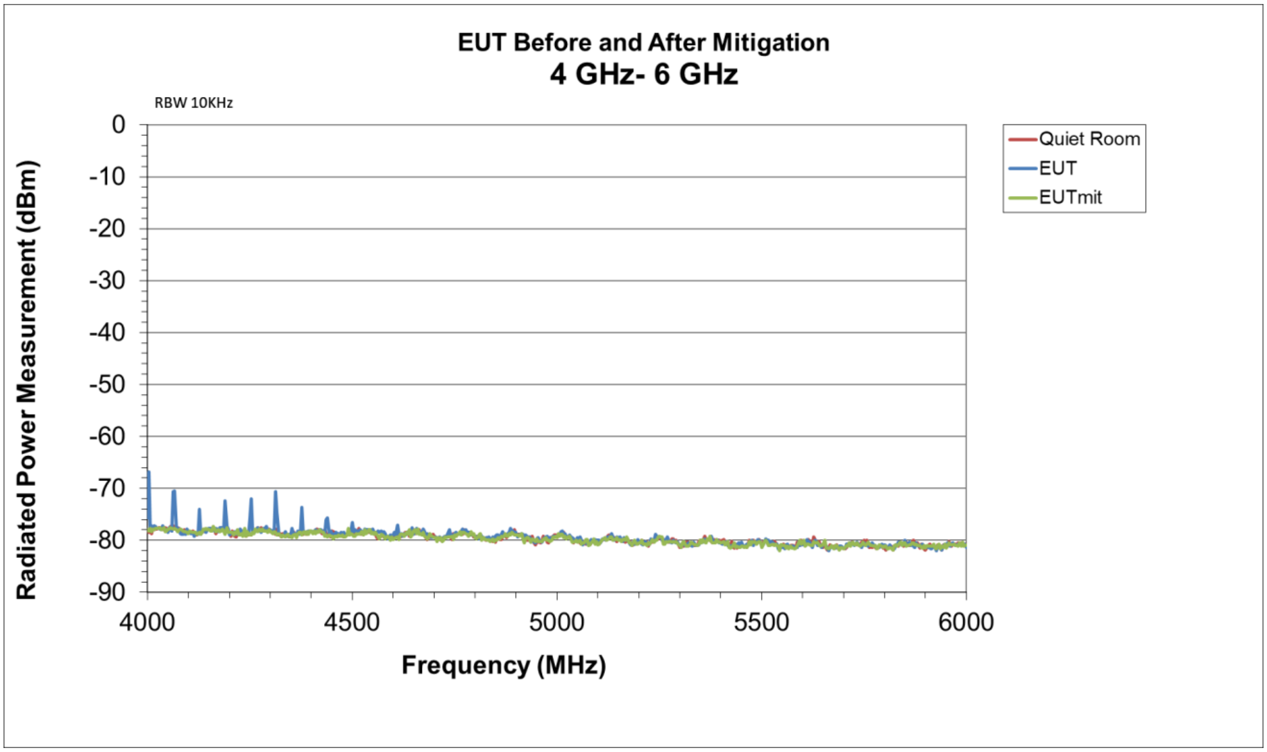


Figure 5: 4 GHz – 6 GHz

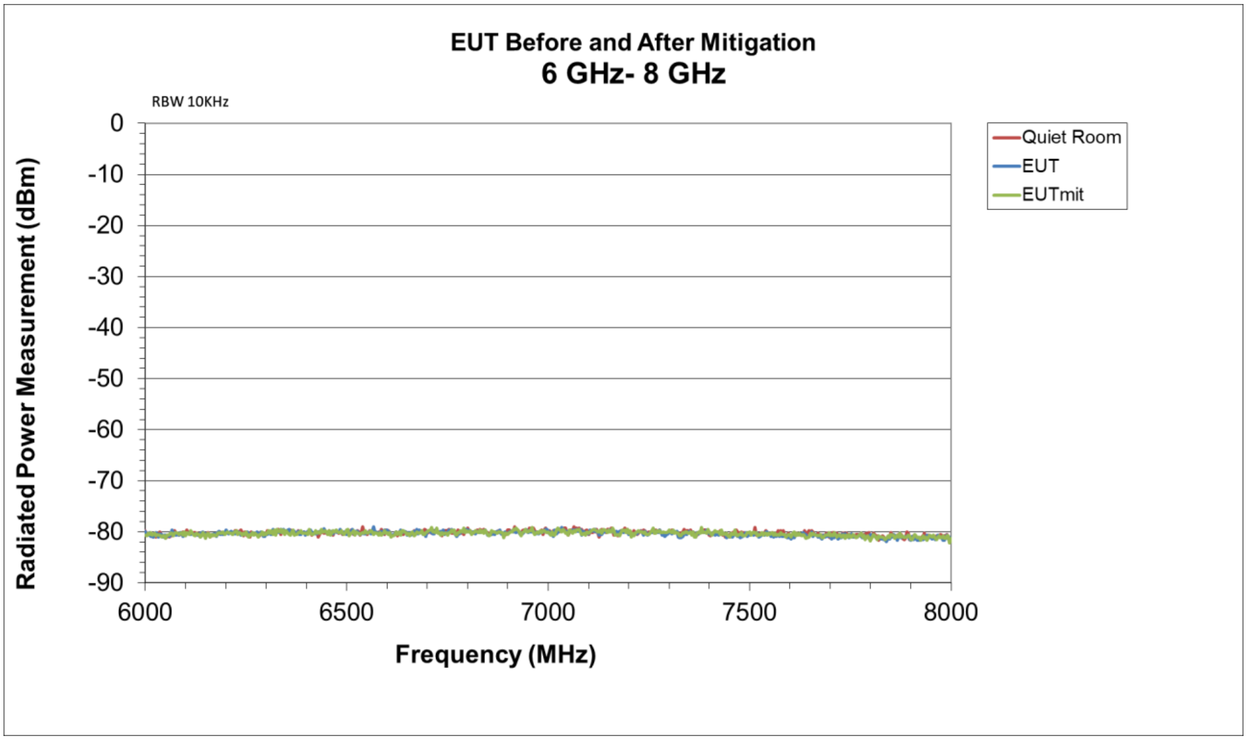


Figure 6: 6 GHz – 8 GHz

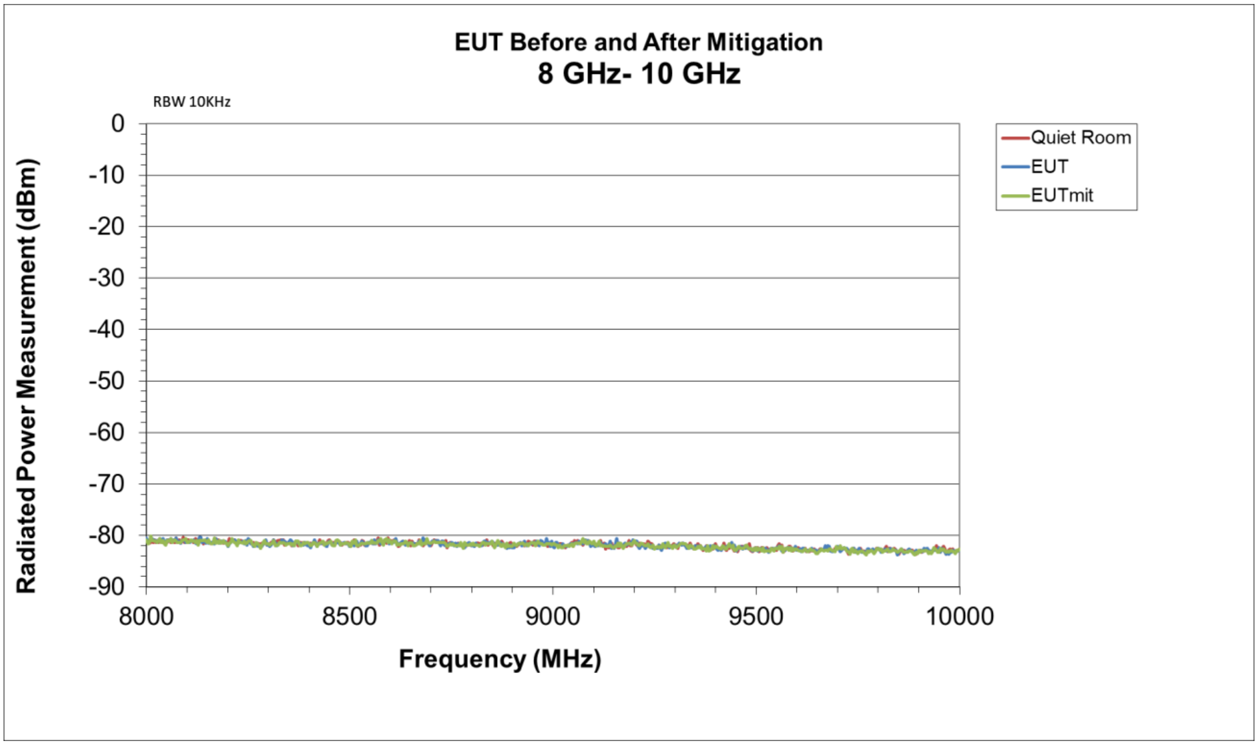


Figure 7: 8 GHz – 10 GHz

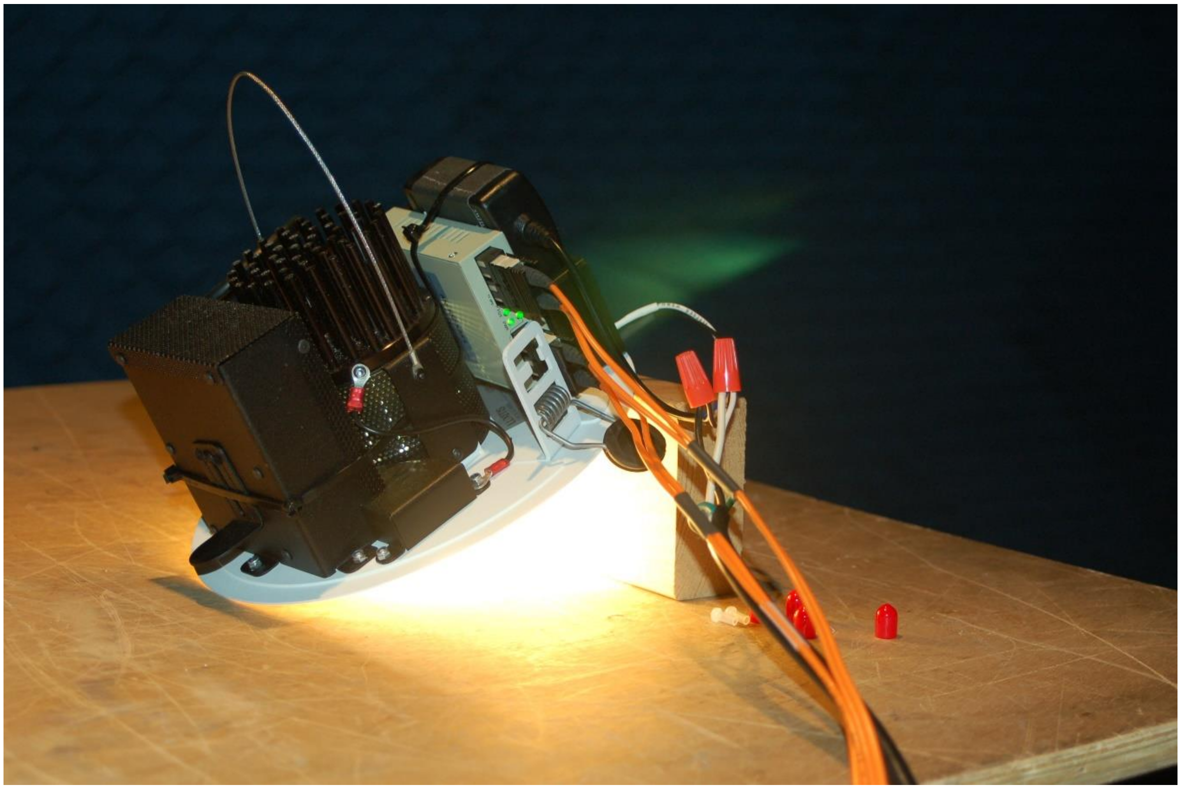


Figure 8: Test Photo EUT

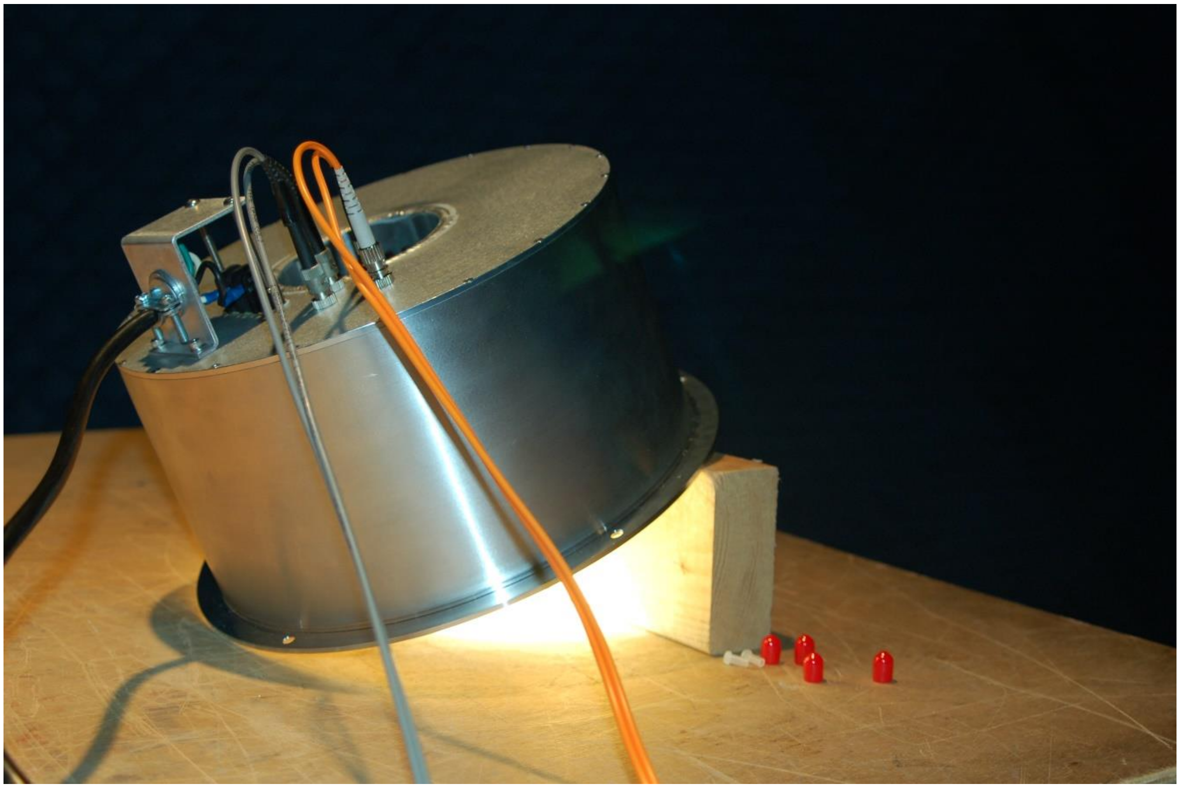


Figure 9: Test Photo EUT Mitigated

EUT as mitigated is recommended for installation in the Jansky Lab.

Note #1: No allowance was made for shielding from incidental structure.

Note #2: RFI limits to radio astronomy are found J. R. Fisher's report "RFI Radiation Limits in the Vicinity of the GBT" dated May 9, 1997.

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