NTIA Report TR-11-481

Improved Estimation of the Third-Order Harmonic Emissions of Land Mobile Radio Base Stations

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ABBREVIATIONS/ACRONYMS

AGL	Above Ground Level
dB	decibel
dBc	decibels relative to the carrier
dBm	decibels relative to a milliwatt
EIRP	Effective Isotropic Radiated Power
EMC	Electromagnetic Compatibility
GPS	Global Positioning System
ITS	Institute for Telecommunication Sciences
LMR	Land Mobile Radio
NEC	Numerical Electromagnetics Code
NTIA	National Telecommunications and Information Administration
OSM	Office of Spectrum Management
UHF	Ultrahigh Frequency

EXECUTIVE SUMMARY

The National Telecommunications and Information Administration (NTIA) is tasked with protecting the radiofrequency spectrum used by the Global Positioning System (GPS) through appropriate spectrum measurement practices. NTIA's Office of Spectrum Management (OSM) identified harmonic emissions from land mobile radio (LMR) systems as a potential source of interference into GPS and subsequently tasked ITS with measuring emissions from these sources. The task involved comparing predicted effective isotropic radiated power (EIRP) from an LMR base station to permitted limits under Federal Communications Commission (FCC) and NTIA guidelines.

This 2009 measurement effort was a sophisticated radiated emissions measurement requiring the use of an anechoic chamber. To restrict the number of test cases, the recommended test procedure prescribed the use of a "representative antenna" for the base station. The measured EIRP was used to perform an electromagnetic compatibility (EMC) analysis to predict interference. Such EMC analyses are often used to plan base station configuration and location based on the different separation distances and propagation losses typically encountered in practice.

Using a representative antenna for these calculations complicates subsequent EMC studies for base stations, because a representative antenna cannot accurately embody the wide variety of antennas used on LMR base stations. The analysis applied to the 2009 measurement effort also did not consider antenna directionality, forcing the assumption that the maximum received power occurred at the minimum separation distance. In addition, it used a free space pathloss model that does not consider interactions between the radiated field and the ground.

In this paper, we describe a study of LMR base station emissions performed using an alternative method for the EMC analysis that addresses all three of the limitations described above, yielding much more accurate EIRP estimates. This method does not require the use of the expensive anechoic chamber. Using parameters readily obtained from equipment datasheets, the revised method accurately models various base station antennas rather than using a single representative antenna. This reduces uncertainties in estimates of antenna gain and directivity. The method also integrates a proven propagation model that incorporates the interaction of ground conductivity and other factors to more accurately predict the received power in the proximity of an LMR base station. This facilitates a more detailed and accurate review of the proposed base station system's emissions.

We present detailed analyses for two common base station antennas and demonstrate the use of the model to examine the potential for interference from hypothetical LMR base stations into GPS receivers. Finally, we show how a simple modification to LMR base stations can mitigate the potential for interference in the GPS L2 band.

IMPROVED ESTIMATION OF THE THIRD-ORDER HARMONIC EMISSIONS OF LAND MOBILE RADIO BASE STATIONS

Eric D. Nelson and Nicholas DeMinco[1]

NTIA/ITS[2] has developed an improved electromagnetic compatibility (EMC) analysis method that can be applied to more accurately model real scenarios for evaluating interference. The methodology described in this report can be used to conduct EMC analyses for base stations that use a variety of antennas. The model can be used to determine the received power in the proximity of the base station at both the fundamental and harmonic frequencies. It uses accurate radio-wave propagation models and antenna models. The antenna models can be created for the fundamental and third harmonic frequencies of many antennas. Fields adjacent to the base station antenna are heavily influenced by interactions with ground, and the electromagnetic fields are dominated by the side lobe structure of the elevation pattern of the base station antenna. The described rigorous EMC analysis for a base station considers all of these factors to assess interference more accurately than previous methods.

Key words: undisturbed field method; electromagnetic compatibility; numerical electromagnetics code; land mobile radio; third order harmonics; received power; global positioning system; folded-dipole antenna.

1 INTRODUCTION

This report explores a new method for conducting electromagnetic compatibility analyses for base stations that use a variety of antennas. The method systematically determines the received power in the proximity of a base station system at both fundamental and harmonic frequencies. It is based on readily obtained equipment parameters and uses accurate antenna and propagation models which can readily accommodate new antenna types. The model is easily extended to new frequency ranges.

1.1 Background

In 2004 President Bush signed National Security Presidential Directive number 39 (NSPD-39) which dictated measures to protect the Global Positioning System (GPS). The directive tasked the National Telecommunications and Information Administration (NTIA) to take necessary measures to protect the radiofrequency spectrum used by the GPS through appropriate spectrum management practices. NTIA's Office of Spectrum Management (OSM) identified harmonic

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[2] The Institute for Telecommunication Sciences (ITS) is the research and engineering branch of the National Telecommunications and Information Administration (NTIA), a part of the U.S. Department of Commerce (DOC).

emissions from radio systems as a potential source of interference into GPS and subsequently tasked ITS with measuring emissions from these sources.

One set of measurements conducted in 2009 assessed the third-order emissions from a sample of UHF land mobile radio (LMR) transmitters operating at 409.2 MHz. These particular transmitters had the potential to generate third harmonic emissions in the GPS L2 band centered at 1227.6 MHz. LMR portable subscriber units and a base station transceiver were selected for testing. ITS performed the measurements using a customized measurement system and an anechoic chamber at the National Institute of Standards and Technology (NIST) in Boulder, CO. The measurements revealed low-level, but nonetheless observable, third-order harmonics from the LMRs in the GPS L2 band.

1.2 Prior Electromagnetic Compatibility Analysis Methodology

The test configuration used in 2009 for the portable LMRs included their standard whip antennas. The portables were manually operated by a technician within the chamber. The base station transceiver was operated remotely and a “representative antenna” mounted on a wooden tripod was used per standard practice.[3] In both cases, the emissions levels were measured using a reference antenna, and free space assumptions were used to compensate for propagation losses. This yielded power levels referenced to the output of the transmit antenna, i.e. the effective isotropic radiated power (EIRP).

Referencing emissions in EIRP facilitates subsequent electromagnetic compatibility analyses. For portable transmitters the EIRP is all that is required to evaluate a variety of meaningful interference scenarios. Such analyses can accommodate the different separation distances and propagation losses typically encountered in practice. Since LMR portables use integrated antennas, the choice of antenna types is limited and fewer test cases are required to characterize them. As a result, there is less uncertainty in the EIRP estimates and the subsequent analyses.

A much greater diversity of antenna types is used in base station applications. Actual antennas used in practice will vary widely from a representative antenna. For instance, a review of commercially available base station antennas designed for the UHF band yielded gains ranging anywhere from 5 to 12 dBi and designs ranging from stacked folded-dipole arrays to collinear omnidirectional antennas to directional yagis.

Use of a representative antenna for such a diverse array of antenna types introduces a significant uncertainty in the estimate of the base station’s EIRP. Moreover, the characteristics of base station antennas at their harmonic frequencies are not well understood, since these frequencies are typically outside their normal operating range. Antenna product literature is silent regarding the antennas’ directivity or gain at the third harmonic frequency. This further complicates the EIRP estimate.

Furthermore, the standard measurement procedure does not take into account the typical transmission path between a base station and antenna. Consideration of the numerous components used in actual base stations can dramatically alter the findings of an EMC analysis.

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[3] See 47 CFR 27.53 (e) and 47 CFR 90.543 (e)

For example, base stations typically use transmit filters. A worst-case analysis that omits filter effects can differ from one that includes them by more than 50 dB.

In addition, the propagation path adjacent to a real LMR base station is much more complex than the idealized environment of an anechoic chamber. The anechoic chamber is designed to absorb reflections, whereas the fields adjacent to a base station antenna are heavily influenced by interactions with the ground. Finally, radiated emissions measurements are performed at the boresight angle of the representative antenna while, in practice, radiated fields adjacent to a base station are dominated by the antenna’s lower sidelobes.

1.3 Improved Electromagnetic Compatibility Analysis Methodology

A rigorous EMC analysis for a base station transmitter should consider all of the factors described above. It should incorporate an accurate model for a variety of antenna types, frequency ranges, and geometries encountered in practice.

The purpose of this report is to present an improved method of EMC analysis that yields more accurate estimates of received power. We demonstrate the utility of this improved method by performing a detailed analysis of harmonic emissions of LMR base station systems in the GPS L2 band. The method uses analytic techniques based on first principles, is simple to implement, and has been validated through experimental methods. It incorporates a proven propagation model that is tailored to short-range propagation.

2 EMC ANALYSIS USING AN ISOTROPIC ANTENNA AND FREE SPACE PROPAGATION

As a baseline, we consider a typical LMR base station deployment with carefully selected characteristics representing a worst-case scenario. We then compare the results obtained using this simple model to our more sophisticated one and assess the possible improvements.

2.1 Determination of EIRP

Assume an LMR base station is operating at 409.2 MHz such that its third harmonic falls on the center of the GPS L2 band at 1227.6 MHz. Assume the base station system has a tower that supports an antenna with a center of radiation at 45 m above ground level (AGL). This is a typical base station height, since it can provide extensive coverage without triggering FAA height-based requirements for marking and lighting. To facilitate later intercomparisons we assume an EIRP of 100 W or 50 dBm at the fundamental frequency and an isotropic antenna. We assume the use of high performance coaxial cable at the base station. A typical 7/8" (22.2 mm) diameter cable has 2.5 dB/100 m attenuation at 400 MHz and 4.7 dB/100 m at 1250 MHz. Since the losses are low they will only differ slightly between the signal at the fundamental and third harmonic frequencies, so we neglect coax losses.

We can derive a rough order of magnitude estimate of third harmonic emissions by assuming that the transmitter generates the maximum allowable spurious emissions. LMR base station spurious emissions are specified to be less than -90 dBc, so the third harmonic would be at least 90 dB down from the fundamental at the output of the transmitter. For most antennas the gain and directivity at the third harmonic is not typically published information. For the sake of simplicity, assume they are the same as those at the fundamental. As a result, we estimate the EIRP of the third harmonic to be -40 dBm.

2.2 Estimation of the Received Power Level

Using the estimated EIRP of the third harmonic we can complete a simple worst-case EMC analysis. Assume a GPS receiver in the proximity of the base station at an elevation of 1.5 m. The closest this receiver can encroach upon the transmit antenna is 43.5 m, i.e. the difference in height between the two antennas. Assuming free space pathloss at 1227.6 MHz, there is 67.0 dB of attenuation over this distance. A GPS receiver using a 0 dBi antenna would see a received power level of -107.0 dBm.

Compare this receive power level to the recommended power limit for a jamming signal in the literature. The recommended minimum jammer to signal ratio for a carrier wave jammer is 21.9 dB for the L2 P(Y) code ([1], pg. 236) while the nominal received power level of a GPS L2 signal at ground level is -135.2 dBm. ([1], pg. 219). Therefore, received power in excess of -113.3 dBm is potentially harmful to a GPS receiver. This rough order of magnitude estimate indicates that the received power is 6.3 dB in excess of the recommended limit. This is true for a single channel LMR base station that has been properly engineered.

3 EMC ANALYSIS USING DIRECTIONAL ANTENNAS AND ADVANCED PROPAGATION MODEL

The preceding analysis predicted a receive power level from the LMR harmonic emissions in excess of the limits. It was derived from an EIRP estimate with an assumed isotropic antenna for a single channel transmitter site without transmit filters. A free space pathloss model was employed that neglects interactions between the radiated field and the ground. Assuming the antenna's directionality is not known, we found that the maximum received power occurred at the minimum separation distance.

It is well known that LMR base station antennas have nulls in their radiation patterns on their vertical axes—the point at which the separation distance is minimized—so a more complete consideration of antenna characteristics is needed. We present an improved EMC analysis methodology that considers this factor. The antenna modeling aspect of our method describes the vertical pattern of the antenna at both the fundamental and the harmonic frequency. It characterizes the sidelobes. The propagation model aspect treats ground interactions. The two facets comprise a method that predicts multiple peaks and nulls in the received power versus horizontal distance from the base station, which is a well-known phenomenon. Moreover, the method predicts that a simple free space model based on EIRP estimates and an isotropic antenna actually underestimates the received power by as much as 10 dB.

3.1 Antenna Modeling and the Undisturbed Field Propagation Model

The method selected for analyzing the antennas makes extensive use of method-of-moments calculations and is implemented in a computer program titled the Numerical Electromagnetics Code (NEC) [2]. It is an accurate method for analyzing antennas in the ultrahigh frequency (UHF) band. It is particularly suitable for wire antennas like those used in UHF base station applications where the radiating elements are modeled as wire segments in a geometry that represents the physical structure of the antenna. The method includes the effects of the mast support structure of the antenna.

The ITS undisturbed field model [3] was used to perform the propagation loss computations with the effects of antenna patterns factored into the model. The undisturbed field model is valid for short and long distances and both high and low antenna heights. The development of this model is discussed in an NTIA/ITS report [3]. The model involves the calculation of the undisturbed electric field and calculation of the loss based on the amplitude of the electric field as a function of distance, frequency, and the ground dielectric constants. The propagation was assumed to be located over average ground with $\sigma = 0.005$ S/m and $\varepsilon_r = 15.0$ as defined in Table 3 of [4].

The undisturbed field is the electric field produced by a transmit antenna at different distances and heights above ground in the absence of field-disturbing factors in the proximity of the receive antenna location. The presence of a receive antenna would disturb the electric field. The ITS report [3] provides a detailed investigation of the differences between the undisturbed and disturbed (mutual coupling) methods of field computation, and shows the differences between the results of propagation loss computed using both methods.

While the disturbed-field method is more exact, it is more computationally intensive and difficult to calculate than the relatively simple undisturbed field based computations. The ITS report shows via numerous examples that, for most scenarios, the difference between the propagation loss computed by undisturbed field method and the disturbed-field method is minimal. This is especially true for the distances involved in this current analysis.

The undisturbed electric field technique includes near-field effects, the complex two-ray model, antenna near-field and far-field response and the surface wave. Since this is a line-of-sight model, the ground is assumed to be flat over the distance of the computations with no irregular terrain present. For distances of less than 7.5 kilometers, the curvature of the Earth has a negligible effect and can be assumed to be flat for frequencies less than 1300 MHz over a smooth Earth [3].

3.2 Folded-dipole Antennas

Folded-dipole antennas were selected for this analysis because they are used widely in UHF base station applications and have simple geometries that facilitate an NEC simulation. The folded-dipole antenna has a wider bandwidth than a typical straight wire half-wavelength dipole. Both a single-element folded-dipole antenna and a four-element collinear vertically-stacked folded-dipole array antenna were modeled. Figure 1 shows an example of a single-element antenna while Figure 2 shows a phased four-element model.

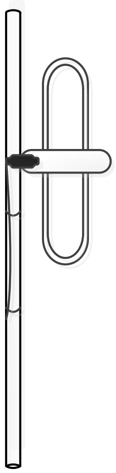

Figure 1. Single folded-dipole antenna on metal mast.

The single folded-dipole antenna consists of a single radiating element mounted with a one-quarter wavelength spacing from the mast and a one-half wavelength spacing from the top of the antenna. The model includes the effects of the support structure which is a 5 cm diameter metal mast. For the sake of simplicity our analysis assumes that the antenna, i.e. the radiating element and the 5 cm mast, are in turn mounted on a 5 cm diameter base station tower.

We also characterized a four-element collinear folded-dipole array antenna shown in Figure 2 modeled after a commercially available antenna. The center-to-center spacing between folded-dipoles for the model was three-fourths of a wavelength at 409.2 MHz. The elements are mounted at a quarter-wavelength offset from one side of the mast. Again, the antenna’s top element is centered one-half wavelength from the top of the antenna mast, and the antenna is itself mounted on an idealized 5 cm diameter tower. The antenna model created for these analyses was scaled to 409.2 MHz center frequency.

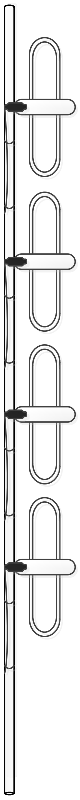

Figure 2. Four-element collinear folded-dipole collinear array antenna on metal mast.

The close proximity of the radiating elements to the antenna mast is modeled using NEC by representing the physical structure of the mast with numerous wire segments. The NEC program calculates the antenna patterns and the input impedance of the antenna. The mutual impedance effects between the folded-dipole antenna elements are also taken into consideration in this calculation.

For both the single folded-dipole antenna and the four-element collinear folded-dipole array antenna models, each folded-dipole is slightly shorter than one-half wavelength to cancel the reactive component of the input impedance. Full cancellation of the reactive part is not completely achieved due to the coupling between the mast and folded-dipoles. The real part of the input impedance is approximately 300 ohms, which can be conveniently matched to a 300 Ω transmission line.

The model predicted that the antennas would have a mismatch loss of less than 1 dB at both the fundamental frequency of 409.2 MHz and the third harmonic of 1227.6 MHz. This is because the antenna exhibits an input impedance resonance at the third harmonic similar to the resonance at the fundamental frequency. This is a characteristic of dipole antennas. The input impedance would vary more at non-harmonic frequencies, and the resultant mismatch would be greater.

To gain an understanding of the antennas themselves, we model them separately in a free space environment using NEC. Later, we will incorporate them into the undisturbed field model, which considers that the antennas' interaction with the earth produces a reflected wave off the ground.

The elevation patterns for the single folded-dipole are shown in Figure 4 for both the fundamental frequency of 409.2 MHz and the third harmonic frequency of 1227.6 MHz. Figure 3 illustrates the geometry used for determination of the vertical elevation angle, which is measured in degrees below the horizon. The angle φ in the figure is given by: $\varphi = \arctan(h/d)$.

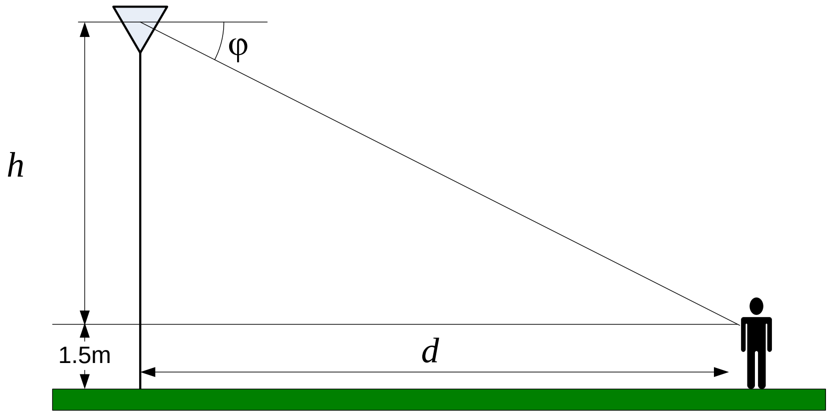

Figure 3. Geometry used for determination of vertical elevation angle at a given distance.

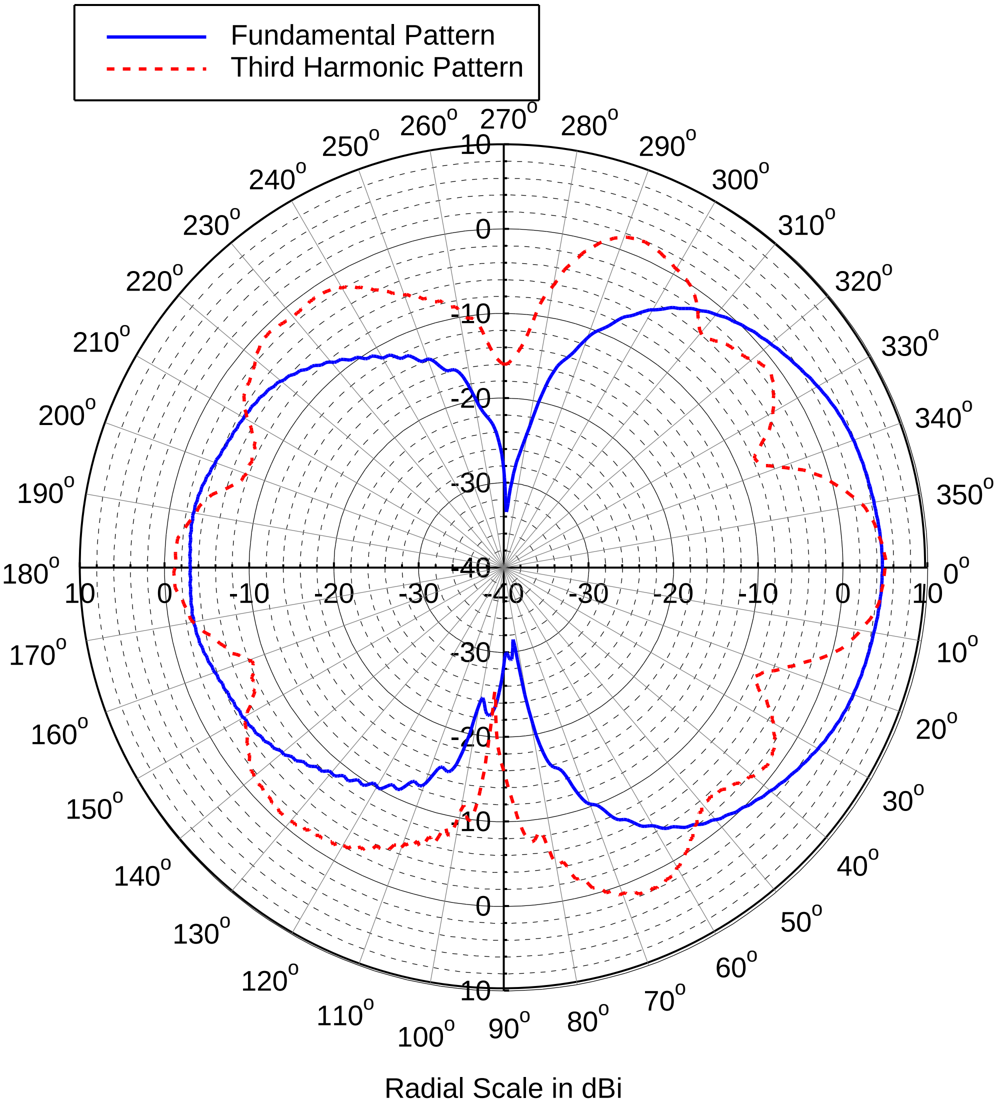

Figure 4. Fundamental and third harmonic elevation pattern plot of single folded-dipole antenna on metal mast.

At the fundamental frequency the radiation pattern possesses a single lobe, resulting in more uniform coverage in elevation than what is predicted at the third harmonic frequency where there are multiple lobes. This is a result of the different current distributions on the antenna for each frequency. The peak gains are similar at both the fundamental and the third harmonic frequencies, but the antenna's coverage at shorter ranges will differ due to the lower sidelobes.

The elevation patterns for the vertically-stacked four-element collinear folded-dipole array antenna are shown in Figure 5 for both the fundamental frequency of 409.2 MHz and the third harmonic frequency of 1227.6 MHz. The maximum gain at the boresight angle is similar for both the fundamental and the third harmonic frequencies. At the fundamental frequency the antenna has a main lobe and multiple sidelobes with the first upper and lower sidelobes about 13 dB down from the main lobe. This is typical for a uniformly excited array antenna. The remaining sidelobes are more than 13 dB down from the main lobe. The antenna pattern at the third harmonic frequency has larger sidelobes, two of which are only approximately 3 dB down from the main beam. There are also many more sidelobes in the antenna pattern at the third harmonic frequency than there are at the fundamental frequency. This is due to the different current distributions and relative phasing on the array antenna at the shorter wavelengths at the third harmonic frequency.

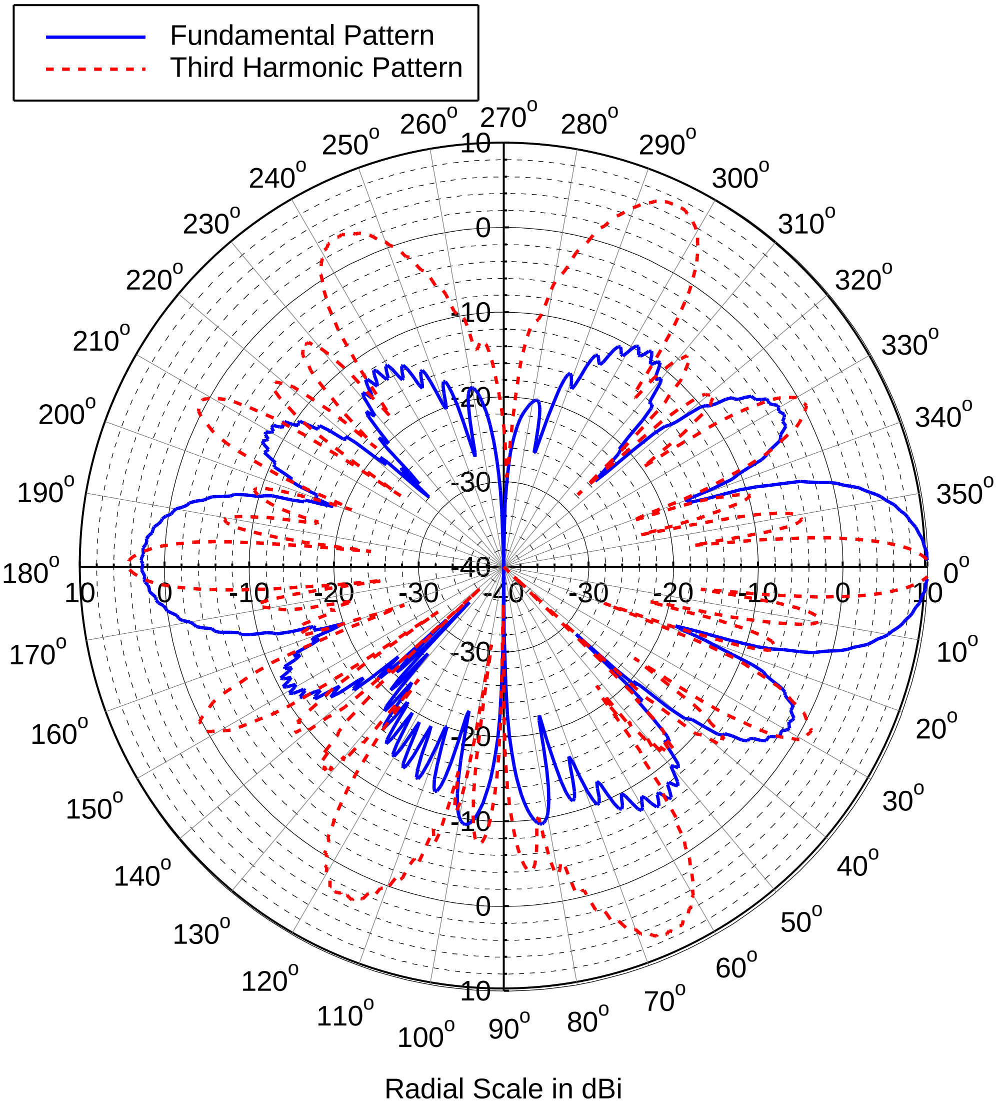

Figure 5. Fundamental and third harmonic elevation pattern of four-element collinear folded-dipole array antenna on metal mast.

3.3 Estimation of the Received Power Level

The antenna patterns for the two simulated antennas were integrated into the undisturbed field model. The undisturbed field model uses these patterns to predict the amplitudes of the direct and reflected waves emitted from the antenna at the various angles of incidence. Equation (1) was used to compute the received power at the fundamental frequency of 409.2 MHz using the propagation loss computed with the undisturbed field model.

$$\mathrm{P}_r(dBm) = P_t(dBm) + G_t(dBi) + G_r(dBi) - L_{proploss}(dB) - L_{spurious}(dB) - L_{filter(dB)} \qquad (1)$$

where

P_r(dBm) = the received signal power in dBm at the fundamental frequency of 409.2 MHz
P_t(dBm) = the transmitted power in dBm into the antenna terminals
G_t(dBi) = transmitter antenna gain in decibels referenced to an isotropic antenna as a function of elevation angle, φ
G_r(dBi) = receiver antenna gain in decibels referenced to an isotropic antenna
$L_{proploss}$ (dB) = propagation loss in dB computed by the undisturbed field model
$L_{spurious}$ (dB) = spurious response rejection in dB
L_{filter} (dB) = filter isolation in dB

The EIRP was normalized to 100 W peak by offsetting the transmitter power by the peak gain of the antenna. The undisturbed field model can be used to model the receive antenna, but for the sake of simplicity, a 0 dBi isotropic receive antenna was assumed. The loss terms for spurious response rejection and filter isolation are 0 dB at the fundamental frequency. As noted in Section 2.1, the difference between coaxial cable losses at the fundamental and third harmonic frequencies is negligible, so they were not considered.

The received power level for the third harmonic frequency of 1227.6 MHz can be computed using (1) with the appropriate substitutions for the antenna characteristics, spurious response rejection, and the filter loss at this frequency. The emissions at the third harmonic are assumed to be a worst-case value of -90 dBc, i.e., $L_{spurious}$ = 90 dB. Filter losses are considered later; presently they are assumed to be 0 dB.

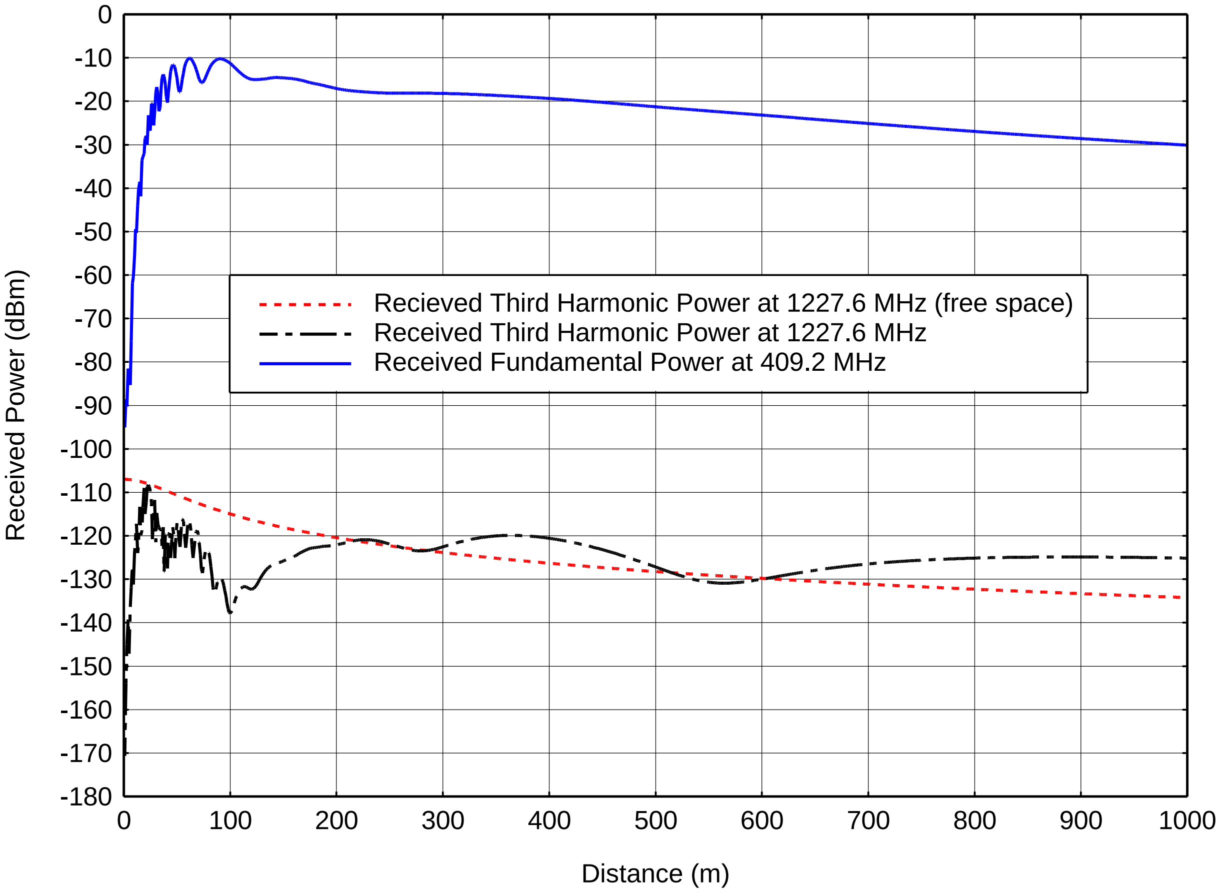

Figure 6. Received power from a single folded-dipole transmitter antenna, 100 W EIRP, antenna center height of 45 m AGL, 0 dBi receive antenna, ground constants: $\sigma = 0.005$ S/m and $\varepsilon_r = 15.0$.

Figure 6 shows the predicted received power level versus distance using the undisturbed field method for a single folded-dipole transmitter antenna at 45 m AGL and 100 W EIRP and an isotropic receiver antenna at a height of 1.5 m. The transmit antenna operates at the fundamental frequency of 409.2 MHz and is mounted on a two-inch diameter metal mast. Also shown in this figure is the system's response at 1227.6 MHz, assuming that spurious emissions were 90 dB below the power at the fundamental frequency. For reference, the third harmonic response is compared to the predicted received power assuming an isotropic transmitter antenna and free space pathloss. The free space curve intersects the vertical axis at -107.0 dBm. This matches our previous estimate of received power that we obtained in Section 2.2. The undisturbed field method predicts a spike in the power at horizontal distance of ~20 m from the base. At this distance, the free space and undisturbed field methods are in close agreement. However, the two curves diverge by more than 20 dB at 100 m, and the free space model consistently underestimates the received power at distances greater than 300 m. We gain a more detailed understanding of the environment surrounding the tower using the undisturbed field method because the free space model does not consider constructive interference due to ground reflections and exaggerates the gain at the antenna's nadir.

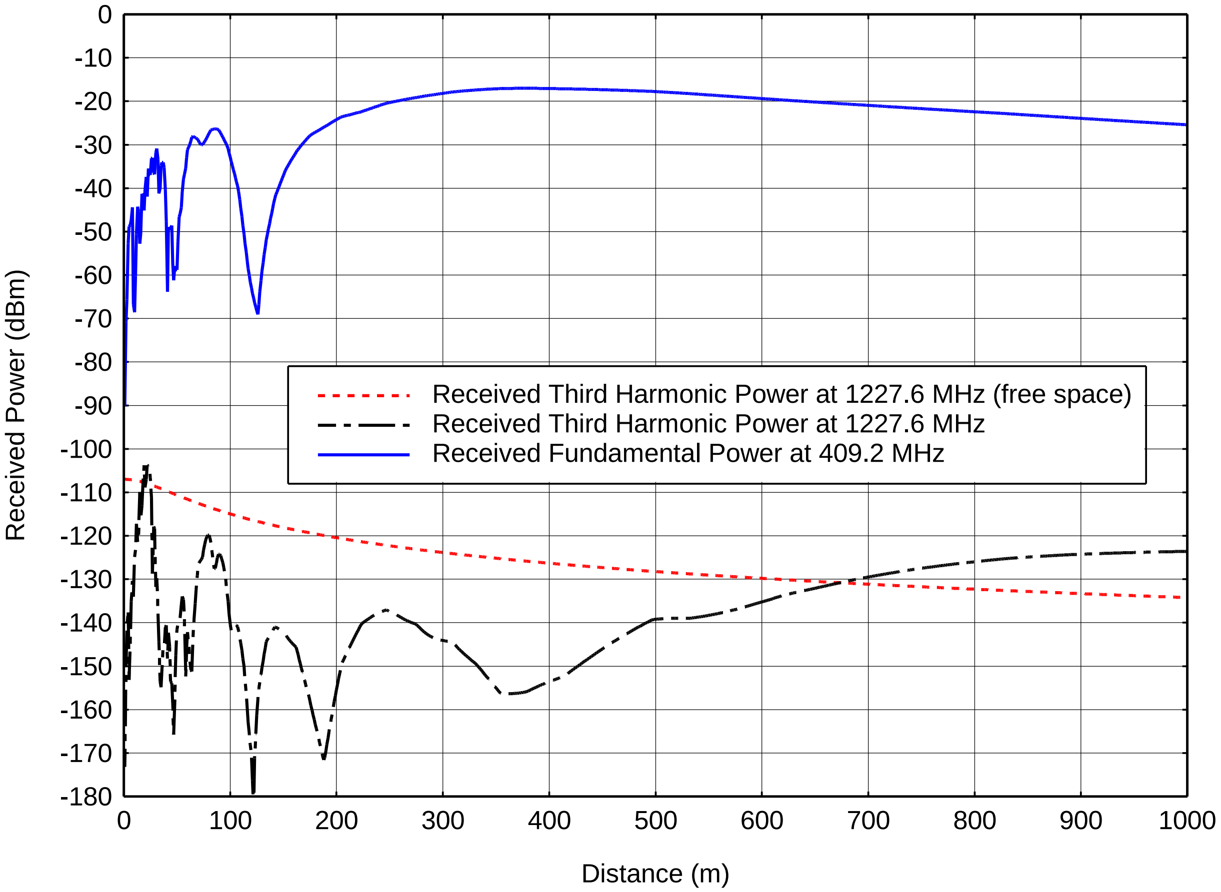

Figure 7. Received power from a four-element collinear folded-dipole array transmitter antenna, 100 W EIRP, antenna center height of 45 m AGL, 0 dBi receive antenna, ground constants: σ = 0.005 S/m and ε_r = 15.0.

Similarly, Figure 7 shows the received power for the same system except with a four-element collinear folded-dipole array antenna. This is a more common antenna type for base station applications, since it provides an additional 5 dB of gain on the horizon. Again, the transmit power is adjusted to achieve a normalized EIRP of 100 W. This plot exhibits greater lobe structure than that of the single-element antenna case.

Nulls in the received power are most easily mapped to nulls in the vertical antenna pattern by working backwards from maximum to minimum distances as the vertical pattern angle φ ranges from 0 to 90 degrees. Consider the fundamental frequency first. The main beam covers distances from the horizon down to the null at approximately 120 m. The first lower lobe covers from 120 m to 45 m. The null at 45 m corresponds to a vertical angle of approximately 45 degrees below the horizon, since the change in height from the transmit to receive antennas is 45 – 1.5 = 43.5 m. The last lobe on the plot from 10 to 45 m corresponds to the second lower sidelobe. Note also the substantial null at the antenna's nadir.

Consider the received power curve for the third harmonic shown in black in Figure 7. The various peaks illustrated in the plot occur at the following antenna elevation angles:

Table 1. Received Power Plot Features as a Function of Antenna Elevation Angle

Range (m)	Elevation angle, φ	Notes
1000	2.6º	main beam
250	10º	1st lower sidelobe peak
140	18º	2nd lower sidelobe peak
80	29º	3rd lower sidelobe peak
55	39º	4th lower sidelobe peak
20	66º	6th lower sidelobe peak

Note that the maximum received power of -105 dBm occurs on the 6th lower sidelobe at 66 degrees below the horizon. This sidelobe is only 2 dB down from the antenna's peak gain at the boresight angle shown in Figure 5. This predicted received power level is 2 dB stronger than the estimate of -107.0 dBm from Section 2.2. The undisturbed field method demonstrates that these stronger power levels are restricted to a very limited range of distances spanning approximately 20 m. At all other distances, the received power is below -120 dBm. This scenario shows substantial divergence between the undisturbed field method and a free space method both at closer ranges where the free space method dramatically overestimates and at greater distances where it underestimates the received power by more than 10 dB.

The preceding analyses assumed a tower height of 45 m, which is a common LMR base station height. For the sake of completeness, an analysis was prepared for both antenna types at a lower antenna height. A height of 15 m served as a reasonable lower bound. Figure 8 and Figure 9 show the results of this analysis for the single-element and four-element collinear folded-dipole antennas, respectively.

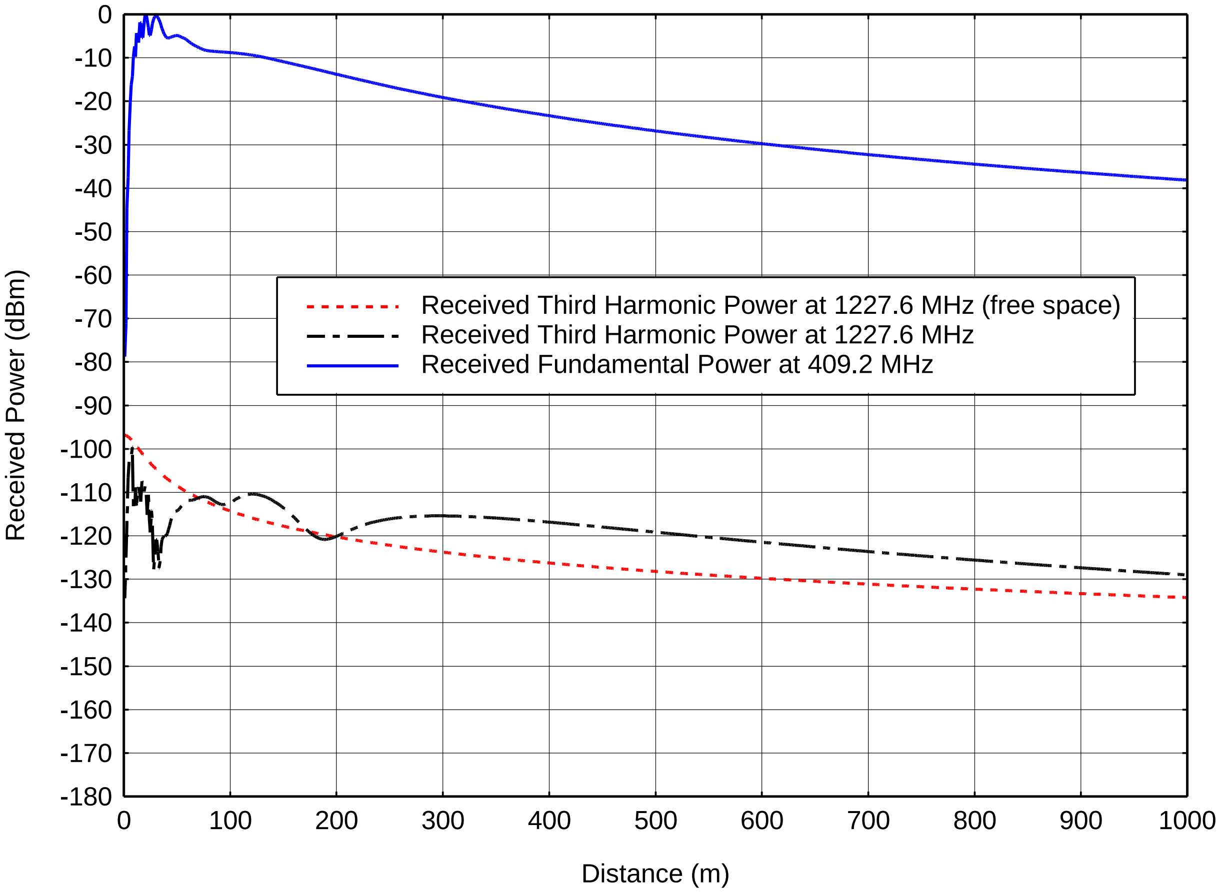

Figure 8. Received power from a single folded-dipole transmitter antenna, 100 W EIRP, antenna center height of 15 m AGL, 0 dBi receive antenna, ground constants: σ = 0.005 S/m and ε_r = 15.0.

Note that the lower antenna height effectively compresses the lower vertical sidelobes into a narrower range adjacent to the base station. For example, compare the position of the null between the main beam and the first lobe as depicted in Figure 7 to that depicted in Figure 9. The null occurs at ~120 m for the antenna mounted at 45 m AGL and at ~45 m for the antenna mounted at 15 m AGL. The lower tower height also results in higher received power levels for a given horizontal distance. The maximum received power is ~10 dB stronger for both antenna types.

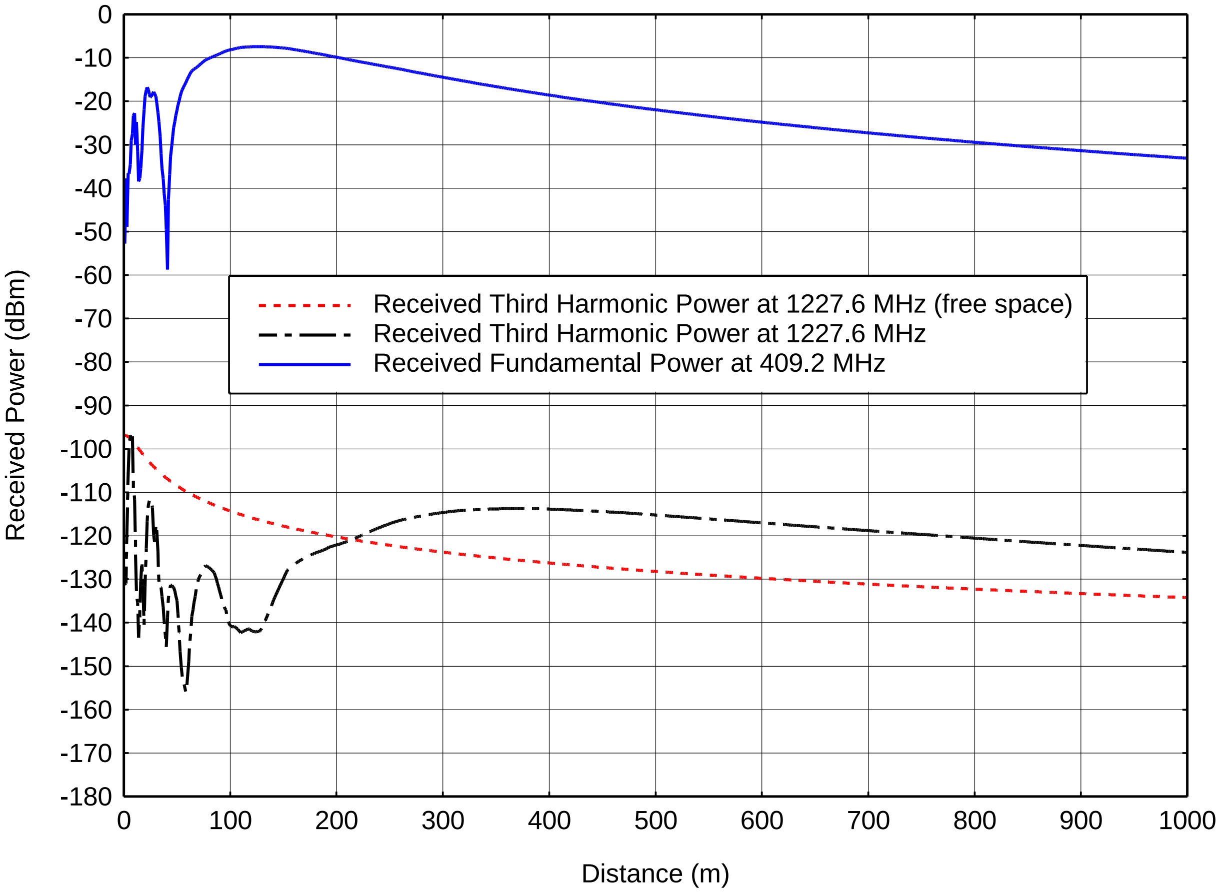

Figure 9. Received power from a four-element collinear folded-dipole array transmitter antenna, 100 W EIRP, antenna center height of 15 m AGL, 0 dBi receive antenna, ground constants: σ = 0.005 S/m and ε_r = 15.0.

3.4 Refinement of the EMC analysis

The preceding analyses predicted received power levels incumbent upon a hypothetical GPS receiver in close proximity to LMR base stations in excess of the maximum jammer signal level of -113.3 dBm. The model illustrates that the affected regions are restricted to narrow ranges within tens of meters from the base station.

The model can be refined in a number of ways to yield a better estimate of received power and to suggest design changes that would satisfy GPS compatibility requirements. First, adjustments to account for different EIRPs can be readily derived from the above plots by offsetting the received power levels in reference to the normalized EIRP of 100 W. Another possibility is to model the receive antenna’s gain and directivity. In addition, measured conducted third harmonic emission levels could be used rather than applying a worst-case assumption of -90 dBc from the spurious response rejection specification. In fact, according to [1], in some scenarios, modest decreases (on the order or 5-10 dB) in third harmonic emissions beyond our -90 dBc assumption would yield acceptable emission levels in the GPS L2 band.

Another refinement to this analysis, one that is a common best practice in LMR base station design and would provide the most substantial effect, is to use a transmit filter. Transmit filters prevent emissions from adjacent collocated transmitters from feeding back into a transmitter and mixing to create third-order products. In this application, a filter would have the added benefit of suppressing harmonic emissions in the GPS L2 band. Use of a reflective lowpass filter in the transmission path would reduce the harmonic emissions to levels below the thermal noise floor. For example, our product research identified a commercially available filter for the 406–512 MHz band with 0.3 dB of passband insertion loss, a 50 W power rating, and more than 50 dB of rejection at the third harmonic. Unit cost in low quantities was approximately $350. Filters with higher power ratings and similar performance were available for under $850.

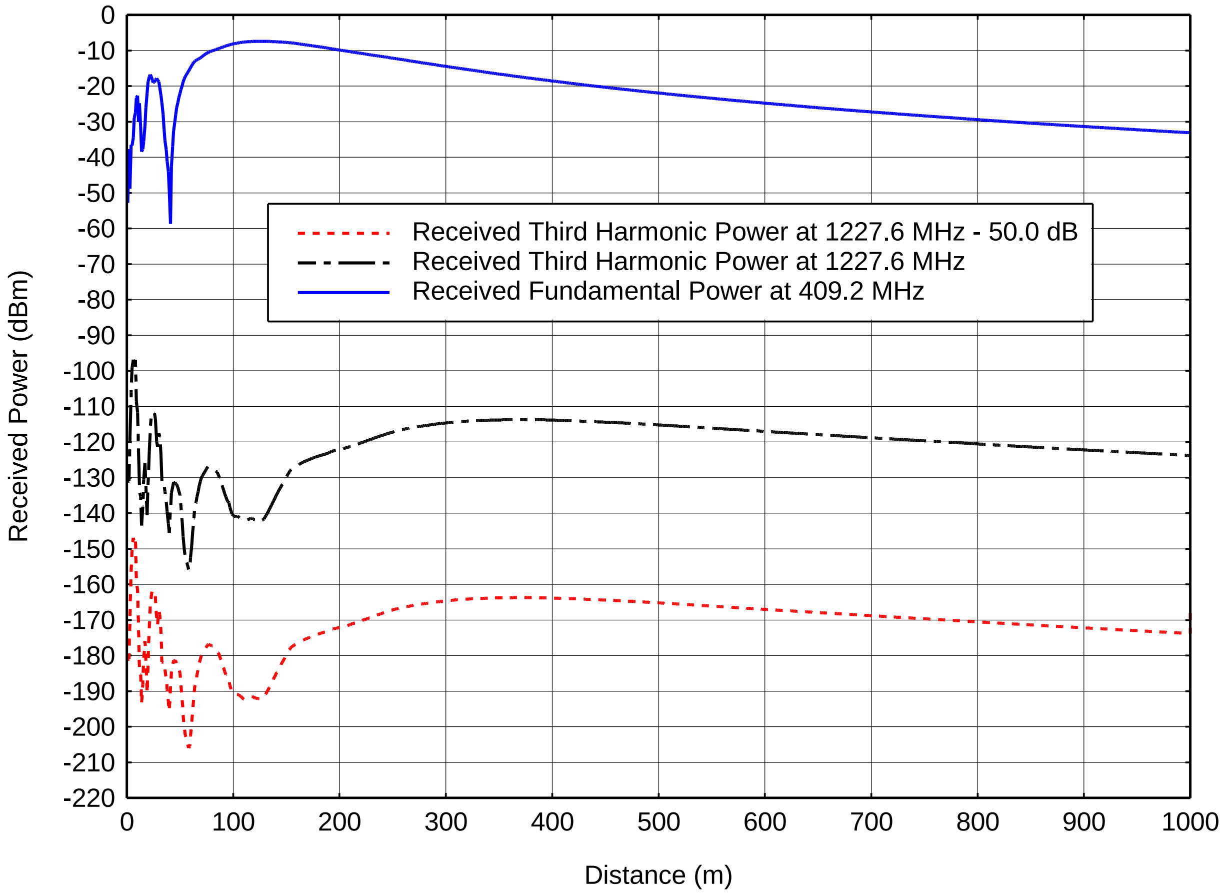

Figure 10. Received power from a four-element collinear folded-dipole array transmitter antenna, 100 W EIRP, antenna center height of 15 m AGL, 50 dB of out of band rejection, 0 dBi receive antenna, ground constants: σ = 0.005 S/m and ε_r = 15.0.

Consider the worst case of the four preceding analyses—that is, the four-element collinear folded-dipole array antenna mounted 15 m AGL. In Figure 10 we reproduce its received power plot and add a curve that represents the received power with a lowpass filter installed in the transmit path. Observe that the predicted received power never exceeds -147 dBm—much lower than the -113.3 dBm interference threshold determined in Section 2.2 and even lower than the nominal GPS L2 signal level of -135.2 dBm.

4 CONCLUSION

The use of the undisturbed field method to assess the potential for harmful emissions from LMR base station transmitters provided greater insight into an EMC analysis than a simple analysis based on an isotropic antenna and free space pathloss. The model treated ground interactions and accounted for the directivity of various antenna types at both fundamental and third harmonics. The undisturbed field method can easily be adapted to treat a variety of antenna types and operating frequencies.

Adjacent to the base station, it provided finer detail and showed that the peak power is concentrated in a narrow range of distances. At greater distances, the undisturbed field method showed that the simpler isotropic antenna and free space pathloss method actually under-predicted the received power by more than 10 dB in some cases. Finally, we demonstrated that the use of bandpass filters would reduce UHF LMR base station emissions in the GPS L2 band to levels well below the nominal GPS L2 signal level.

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15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

NTIA/ITS has developed an improved electromagnetic compatibility (EMC) analysis method that can be applied to more accurately model real scenarios for evaluating interference. The methodology described in this report can be used to conduct EMC analyses for base stations that use a variety of antennas. The model can be used to determine the received power in the proximity of the base station at both the fundamental and harmonic frequencies. It uses accurate radio-wave propagation models and antenna models. The antenna models can be created for the fundamental and third harmonic frequencies of many antennas. Fields adjacent to the base station antenna are heavily influenced by interactions with ground, and the electromagnetic fields are dominated by the side lobe structure of the elevation pattern of the base station antenna. The described rigorous EMC analysis for a base station considers all of these factors to assess interference more accurately than previous methods.

16. Key Words (Alphabetical order, separated by semicolons)

undisturbed field method; electromagnetic compatibility; numerical electromagnetics code; land mobile radio; third order harmonics; received power; global positioning system; folded-dipole antenna.

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