SECTION 5
IONOSPHERIC PROPAGATION AND AGGREGATION OF BPL EMISSIONS

5.1 INTRODUCTION

Thus far, NTIA's Phase 2 Study regarding BPL interference potential has focused on local interference due to a small quantity of co-frequency BPL devices. Of additional interest, however, is the potential effect of a large scale BPL deployment on aggregate noise levels over a national scale. An aggregate effect from BPL interference, if any, would occur due to ionospheric or "sky wave" propagation.

This sky wave phenomena, in which HF signals are refracted by charged particles in the ionosphere and returned to earth hundreds or thousands of miles away, is the same process through which short wave communications can be heard around the globe. Since current BPL systems make use of HF frequencies, and since modeling of BPL-energized power lines indicates much of the BPL emissions appear to radiate in an upward direction, these HF BPL emissions have the potential to travel many miles from their source. Moreover, because a given listening point may receive radiated BPL emissions from many sources, it is conceivable that an aggregation of signals could occur, raising the receiver noise floor level and rendering weak, desired signals unintelligible. In general, ionospheric propagation occurs for frequencies between 1.7 MHz and 30 MHz, as discussed in the NTIA Phase 1 Study.[59]

The analysis presented in this section expands upon and clarifies results presented in the NTIA Comments on the BPL NPRM.[60] These results have been augmented by additional modeling and application of the measurement guidelines released in the Commission's BPL Report and Order.

5.2 ANALYTICAL MODELING OF SKY WAVE PROPAGATION

5.2.1 Background

In its BPL comments, NTIA detailed a preliminary analysis of aggregation of BPL emissions via ionospheric propagation. That analysis employed the VOACAP HF statistical propagation prediction software and overhead power line models using the NEC software. The goal of that effort was to obtain a preliminary determination as to whether noise-like BPL emissions, propagated by ionospheric refraction and aggregated at a point, could present a viable interference concern.

NTIA's initial ionospheric aggregation analysis consisted of two parts: an effort to determine probable "worst-case" conditions for aggregation, and a set of simulations of widespread BPL deployments on overhead MV power lines and possible aggregation effects.

To estimate worst-case aggregation conditions, point-to-point VOACAP propagation calculations were used between several sites in North America over a wide range of times of day, months of the year and frequencies. NTIA then selected the conditions that produced the highest signal-to-noise levels at the various receive points to simulate widespread aggregation.

NTIA's aggregation simulation employed VOACAP in its "area" mode to calculate aggregate emissions received at multiple points from widespread BPL deployments. In the geographic center of every county in the United States, NTIA placed effective BPL emitters, each representing the total BPL emissions from its respective county. In the NTIA Comments, the power output of each effective BPL emitter was derived from NEC modeling of a simple overhead power line model described in the NTIA Phase 1 Study.[61] The model consisted of three 340-meter-long straight wires terminated together at the ends through impedances. In that report, NTIA calculated the radiated power output from the straight-wire power line model which would result in electric fields that met Part 15 limits, and the result was scaled by NTIA's deployment model and county population to arrive at the power output of each effective BPL emitter. The emitters were then given frequency-dependent, far-field radiation patterns based upon an elaborate overhead power line model developed using the NEC software.[62]

Propagation simulations were sequentially run for each emitter to a fixed grid of receive points covering CONUS, and the results were summed in the power domain. NTIA ran these simulations for the suspected worst-case sets of conditions derived from the point-to-point simulations described above.

This preliminary analysis led NTIA to conclude potential interference due to ionospheric aggregation of BPL signals was not a near-term challenge.

5.2.2 Approach

5.2.2.1 Power Line Models

For this report, NTIA determined new radiated power levels for each effective BPL emitter using the elaborate overhead power line model. Additionally, these power levels were calculated using the new measurement guidelines adopted in the BPL Report and Order.[63] Thus, the new simulations were based entirely upon the elaborate overhead power line model, rather than a combination of this model and the simplified power line model from NTIA's Phase I Study. This new approach resulted in different (but comparable) radiated power levels than those used in the NTIA Comments. Table 5-1 shows the values of radiated power as a function of frequency used in this study, along with the values previously presented in the Technical Appendix to the NTIA Comments.

NTIA created an additional NEC model of an underground BPL system (Figures 5-1 and 5-2). Similar propagation analyses were completed over a large sample of hours of the day, frequencies, months of the year and solar conditions (more than 1,300 sets of conditions), including the same conditions that resulted in the greatest aggregated interference-to-noise ratios using the overhead power line model as an emitter. As with the overhead model, NTIA used NEC to derive frequency-dependent directive-gain radiation patterns and radiated power necessary to meet Part 15 limits from the underground model. Radiated power calculations were again performed using the new BPL measurement guidelines in the BPL Report and Order.[64] The radiated power levels are listed in Table 5-1.

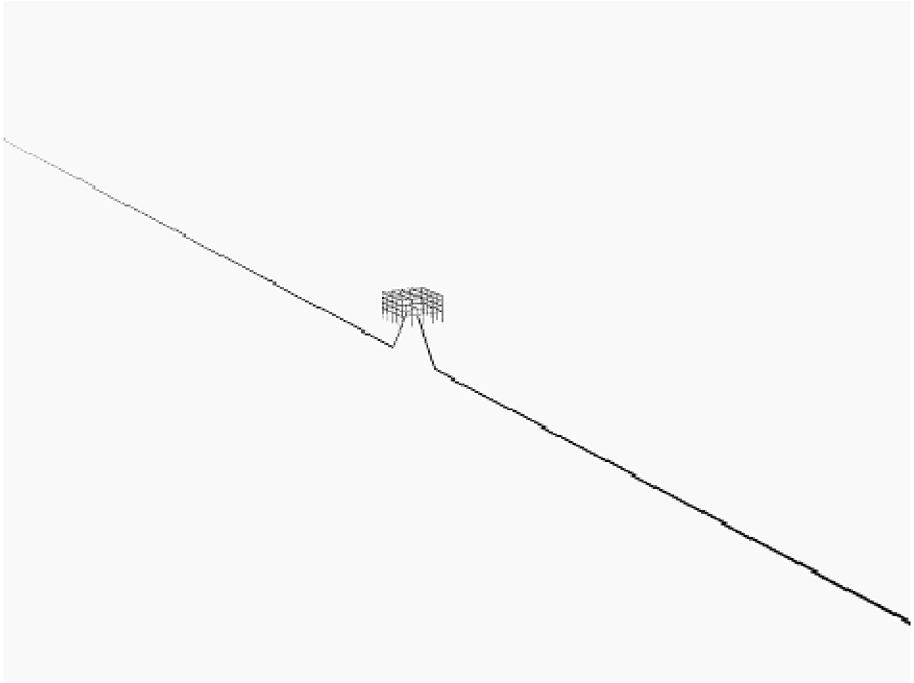

Figure 5-1: Underground power line model with ground removed. The underground line, comprised of three neutral wires surrounding a dielectric-insulated central wire, extends 340 meters end to end

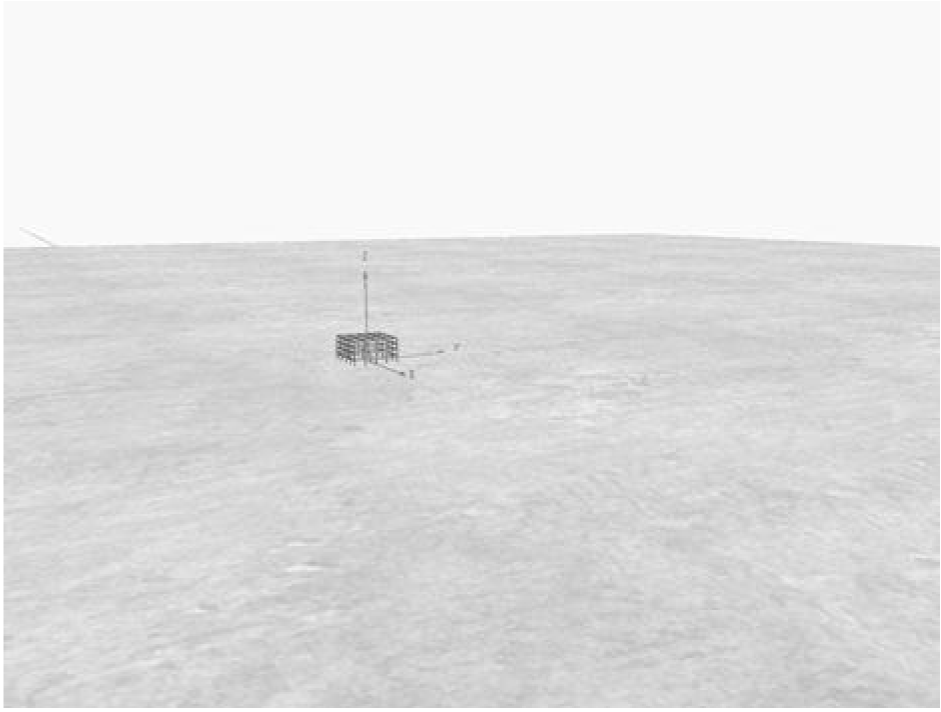

Figure 5-2: Underground power line model with ground included. The visible wireframe box represents a pad-mounted transformer, in which the BPL source is installed.

Table 5-1: BPL structural radiated power at Part 15 limit

Frequency (MHz)	Radiated Power (dBW/Hz) Overhead (from Technical Appendix)	Radiated Power (dBW/Hz) Overhead	Radiated Power (dBW/Hz) Underground
2	-105.49	-103.04	-94.26
4	-104.87	-106.71	-87.84
6	-104.27	-104.38	-84.66
8	-103.68	-102.99	-82.73
10	-103.11	-102.89	-83.29
12	-102.55	-102.93	-79.38
14	-102.01	-104.06	-78.43
16	-101.49	-106.32	-74.75
18	-100.98	-97.48	-75.16
20	-100.49	-103.48	-79.52
22	-100.01	-104.29	-81.67
24	-99.55	-101.04	-82.24
26	-99.11	-105.71	-82.45
28	-98.68	-100.98	-83.47
30	-98.27	-98.04	-84.28

Greater NEC-calculated radiated power from underground structures is not unexpected, as ground losses subsequently attenuate this power significantly. Thus, it is to be expected that NTIA's underground model radiated significantly more power than overhead systems while meeting Part 15 limits. With both the overhead and underground models, increased variability of radiated power with frequency is largely due to the vast increase in complexity of the model used over previous work.

The BPL Report and Order specified that compliance measurements should take place at ¼ wavelength intervals down the power line from the BPL device, to a distance of one wavelength of the mid-band frequency, at a measurement height of one meter.[65] To derive the original Part 15 values used in the analysis presented in the NTIA Comments, field strength values were calculated at 0.5 meter intervals along the entire length of the power line. Thus, the new methodology makes use of far fewer points to find peak field strength values around the power line. Nonetheless, the derived radiated power is in remarkable agreement with the previously derived values reported in the Technical Appendix to the NTIA Comments.

The radiated power levels were derived by exciting the NEC models in question using a unit voltage source, finding the magnetic or electric field values through NEC simulation at appropriate points around the models as specified in the BPL measurement guidelines, and scaling all subsequent electric field values by the dividend of calculated electric field divided by the Part 15 limit. To translate the scaling to the power domain, NEC-calculated radiated power levels were scaled by the square of this factor.

5.2.2.2 Use of Voice of America Coverage Analysis Program

As in the NTIA Comments, NTIA calculated BPL interference and man made noise power values using VOACAP's area mode in a fixed 31×31-point grid of receiving points covering CONUS and centered on Kansas City, Missouri.[66] NTIA again assumed BPL deployment densities based in part on U.S. Census data to simulate effective BPL emitters in the geographic center of each county in the United States (including Alaska and Hawaii).[67] As before, these emitters were given frequency-dependent directive-gain radiation patterns calculated using the elaborate NEC overhead power line model and located in the geographic center of each county. The radiation patterns used were arithmetically averaged in azimuth to simulate the random orientation of multiple BPL-energized power lines represented by each effective emitter.

In this study, NTIA ran full ionospheric aggregation simulations over a comprehensive set of more than 8,500 sets of conditions (including all months of the year, hours of the day, low and high levels of solar activity and frequencies from 2 to 30 MHz in 2 MHz increments). NTIA used these simulations to calculate the Interference-plus-Noise-to-Noise ratio, or (I+N)/N, conditions due to large numbers of deployed BPL devices.[68] The results presented here were examined in terms of sets of conditions producing worst-case increases to the local receiver noise floor.

VOACAP reports results of propagation in terms of signal-to-noise ratio (SNR). Table 5-2 indicates how the SNR values reported by VOACAP translate into noise floor increases.

Table 5-2: Noise floor increase [(I+N)/N] as a fuction of Signal-to-Noise Ratio

Noise floor increase, (I+N)/N (dB)	SNR (dB)
3	0
1	-5.868
0.5	-9.135
0.1	-16.327
0.05	-19.363
0.01	-26.373
0.005	-29.386

5.3 SIMULATION CHARACTERISTICS

NTIA ran simulations both with the Smoothed Sunspot Number (SSN) parameter set to a high value (150) to simulate excellent propagation characteristics during the peak of the 11-year solar cycle, and to a low value (25) to simulate depressed propagation characteristics at the low point in the solar cycle. Because of software design, all receive points used VOACAP's quarter-wave vertical monopole antenna (type 22) over ground with dielectric constant ε_r=15 and conductivity σ set to 0.005 S/m.[69] In reality, ground characteristics vary in the United States, ranging from very poor (ε_r=3 and σ= 0.001 S/m) to excellent (ε_r=20 and σ=0.030 S/m).

The manmade noise level was set to remote or quiet rural levels (-164 dBW/Hz at 3 MHz) at all receive points, to best address receiving conditions at many federal sites.[70] As with receive-point antennas, software design allows one manmade noise level to be assigned to all receive points in VOAAREA's calculation grid. Actual manmade noise levels in the United States can vary from quiet rural conditions to the very high noise levels that can be found in industrial areas. Furthermore, some preliminary studies now indicate that actual background noise levels at HF frequencies may have increased since benchmark noise studies were completed several decades ago.[71]

NTIA individually scaled the NEC-calculated radiated power levels by the number of active BPL devices expected to serve the urban households in each county in the United States. Urban households were used in this analysis as they present greater deployment densities than rural households, and as such, are more likely to be the bulk of early deployments of Access BPL service. As in the earlier analysis, NTIA assumed that a BPL injector had the data handling capacity to support an average of 30 customers, and 1 of 4 urban households was a BPL customer. In other words, one BPL injector was assumed per 120 urban households. With nearly 85 million urban households in the United States, this assumption resulted in a total of over 705,000 modeled BPL devices in this analysis.[72]

Several other factors were taken into consideration when predicting the receiver noise floor increase. First, NTIA considered that not all BPL devices will operate at the Part 15 limit; therefore, the average radiated signal was assumed to be 4 dB below the Part 15 limit. Second, the analysis was based on root-mean-square (RMS) values; therefore an adjustment was made to convert the quasi-peak BPL signal level to an RMS level.[73] Third, since the devices in the system do not all operate at the same frequency, an allowance of 6 dB was given (*i.e.*, 1 in 4 BPL injectors are assumed to be co-frequency). Finally, the assumed duty cycle of BPL devices was set at a mean of 55 percent. These adjustments to the BPL radiated power levels are listed in Table 5-3.

Table 5-3: Adjustment Factors for Access BPL Devices

Factor	Adjustment (dB)
Devices operating at levels below Part 15 limits	4
Quasi-Peak to RMS Conversion	3
Co-frequency distribution factor	6
Duty Cycle	2.6
Total	15.6

The receive points in the VOAAREA calculation grid used 1 Hz bandwidths (set by adjusting the radiated interfering BPL signal power of each transmitting point to the power in dBW/Hz). The noise power levels provided by VOAAREA were in dBW/Hz. The received signal power from all effective BPL emitters at a given receive point was summed in the power domain independent of the noise power level, and the resulting summed BPL interfering power and the noise power at that point were used to calculate interference-to-noise. Thus, the aggregate interference-to-noise ratio at a point was into a 1Hz bandwidth.

Simulations were run across frequencies from 2 to 28 MHz (in 2 MHz increments), for all months of the year and for all hours of the day (approximately 4300 simulations). Table 5-4 summarizes the assumptions listed above as they were applied to this simulation.

Table 5-4: Simulation conditions

Effective BPL emitters	Overhead	Underground
Excitation	Voltage source on single line, centrally located	Voltage source in pad-mounted transformer, centrally located
Far field pattern		
Source	NEC-4.1 overhead model	NEC-4.1 underground model
Variability	Averaged over azimuth, variable by elevation and frequency	
Type	Directive gain	
Power level		
Source	NEC-4.1 overhead model	NEC-4.1 underground model
Structure emissions limits	Limited by Part 15 limits, as measured using BPL measurement guidelines	
County-level scaling	Scaled by urban households in county	
Parameter used	NEC-4.1 “radiated power” value (specified as output power after	

	structure losses, but not ground losses, are considered)
Placement	Geographic centers of all counties in the United States
Receive antennas	
Antenna type	Quarter-wave monopole (VOACAP type 22)
Ground conditions	"Average" ground
Conductivity	0.005 S/m
Relative permittivity	15
Placement	31x31 grid of receive points throughout CONUS
Noise	"Quiet rural" noise conditions (-164 dBW/Hz)
Simulation	
Frequencies	From 2 to 30 MHz in 2 MHz steps
Times of day	From 0 to 23 hours UTC in 1-hour increments
Months of year	From January to December
Solar conditions	Smoothed Sunspot Numbers (SSN) 25 and 150
Primary path geometry	Short path
Calculation methodology	Short/long path smoothing
Calculated parameters	Received signal strength (SDBW), received noise (NDBW)
Power Adjustment Factor	-15.6 dB (detailed in Table 5-3)

5.4 SIMULATION RESULTS

In order to gauge whether a given aggregated BPL signal level presents a risk of harmful interference to a radiocommunication receiver, NTIA considered two threshold values of (I+N)/N, or receiver noise floor increase.[74] The lower threshold, a 1 dB increase in the noise floor (corresponding to a BPL interference-to-noise ratio of approximately -5.9 dB), was chosen as the level at which some harmful interference might occur. The higher threshold, increasing the noise floor by 3 dB (a BPL interference-to-noise ratio of 0 dB), was selected as a level at which harmful interference was considered to be a significant risk.

Analysis of the impact of BPL aggregation was done by combining the BPL signal levels of the modeled overhead and underground BPL systems with the background noise levels, such that the combination met the noise floor increase thresholds listed above. This analysis enabled NTIA to examine the ionospheric aggregation effects while varying the relative numbers of overhead and underground systems.

5.4.1 Comparison of Overhead and Underground Analysis Results

The simulations found overhead systems produced aggregated signal levels greatly in excess of underground systems, even when both classes of systems were adjusted to meet Part 15 limits. The median value for overhead aggregated BPL signal level was approximately 20 dB higher than that of an equal number of underground systems, given the same ionospheric propagation characteristics, over all the conditions modeled. This finding suggests that, where feasible, installation of BPL devices operating in the 1.7 to 30 MHz frequency range on underground wiring could have significant advantages over the same devices operating on overhead systems, from the standpoint of signal aggregation due to ionospheric propagation.

The relative impact of overhead and underground BPL aggregation can be seen graphically in the following results. Figures 5-3 and 5-4 illustrate the number of overhead plus underground devices needed to cause a worst-case 1 or 3 dB increase in the noise floor at any geographic location in the United States under best propagation and lowest local noise floor conditions.

For these graphs, ionospheric aggregation modeling was used to derive sets of conditions for both low and high solar activity during which the greatest ratios of signal-to-noise level due to aggregated BPL was produced. For all other sets of conditions and geographic locations, calculated aggregation resulted in less impact to the noise floor. Thus, for most calculated conditions, more BPL devices would be required to produce the same impact on the local noise floor as that illustrated in Figures 5-3 and 5-4.

Calculations for periods of high solar activity indicated that maximum aggregated BPL signal levels occur primarily at higher frequencies in the HF band (18-30 MHz) during mid-to-late afternoon hours in the fall and winter. Calculations using low solar activity conditions found maximum aggregated BPL signal levels primarily at lower frequencies in the HF band (4-8 MHz). As was indicated by calculations assuming high solar activity conditions, maximum aggregated BPL signal levels were found during late afternoon hours during the fall and winter.

Figure 5-3 depicts combinations of underground and above-ground BPL devices that produce increases in the noise floor of 1dB (lower curve) and 3 dB (upper curve). This figure is generated for the combination of ionospheric propagation and noise conditions (15:00 UTC during November at 30 MHz, with high-level solar activity) that produce the highest aggregate BPL signal relative to the local noise floor at any geographic point. Under these conditions, more than 1.35 million overhead BPL devices alone could be deployed before realizing a 1 dB increase in the noise floor at any geographic location. This number increases to 5.23 million overhead BPL devices for a 3 dB aggregate noise floor increase. By reducing the number of overhead devices and adding underground BPL devices, the total number of deployed BPL devices can be greatly increased, while meeting the same levels of noise floor increase.

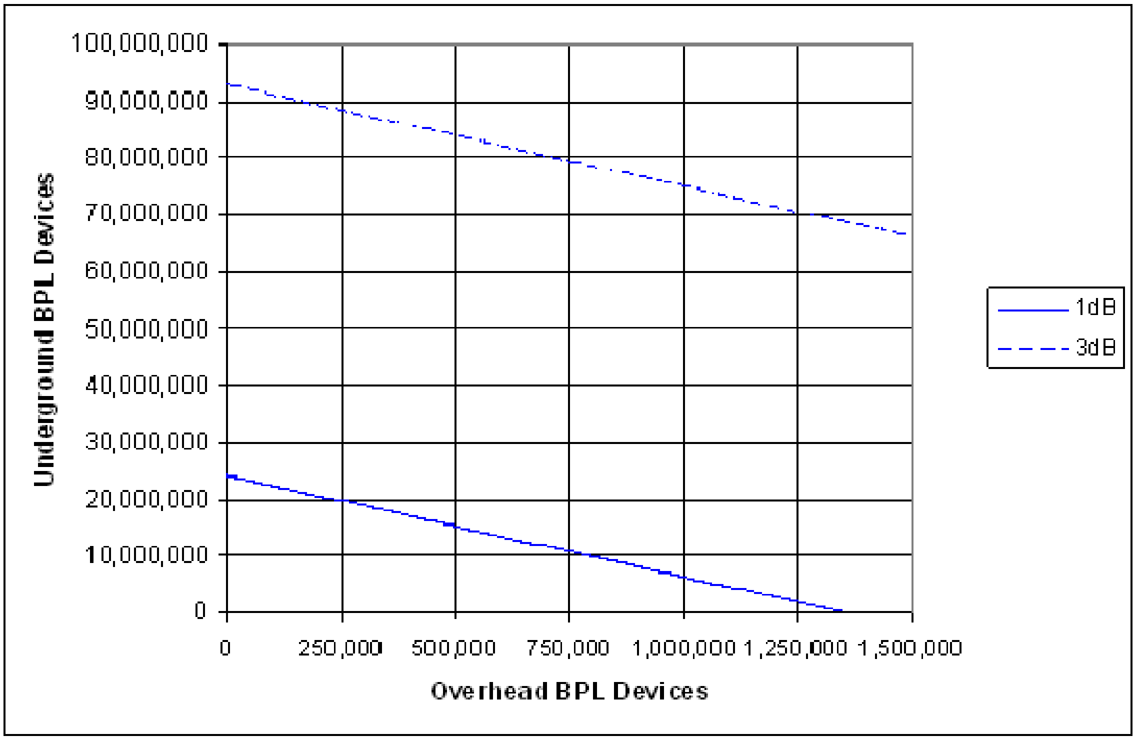

Figure 5-3: Number of underground BPL devices compared to the number of overhead BPL devices required to meet specified increase in noise floor under high SSN conditions

Figure 5-4 depicts numbers of overhead BPL devices compared to the number of underground BPL devices necessary to realize a 1 dB and 3 dB increase in the receiver noise floor under low solar cycle conditions. As with solar cycle maxima results, the fewest overall BPL devices necessary to meet the thresholds occurs when overhead BPL devices are used exclusively. For these conditions, approximately 916,000 overhead BPL devices would be required to raise the noise floor by 1 dB. By contrast, the exclusive use of underground BPL devices in the 1.7 to 30 MHz frequency range would allow nearly 10 million BPL devices to be deployed before producing a 1 dB noise floor increase.

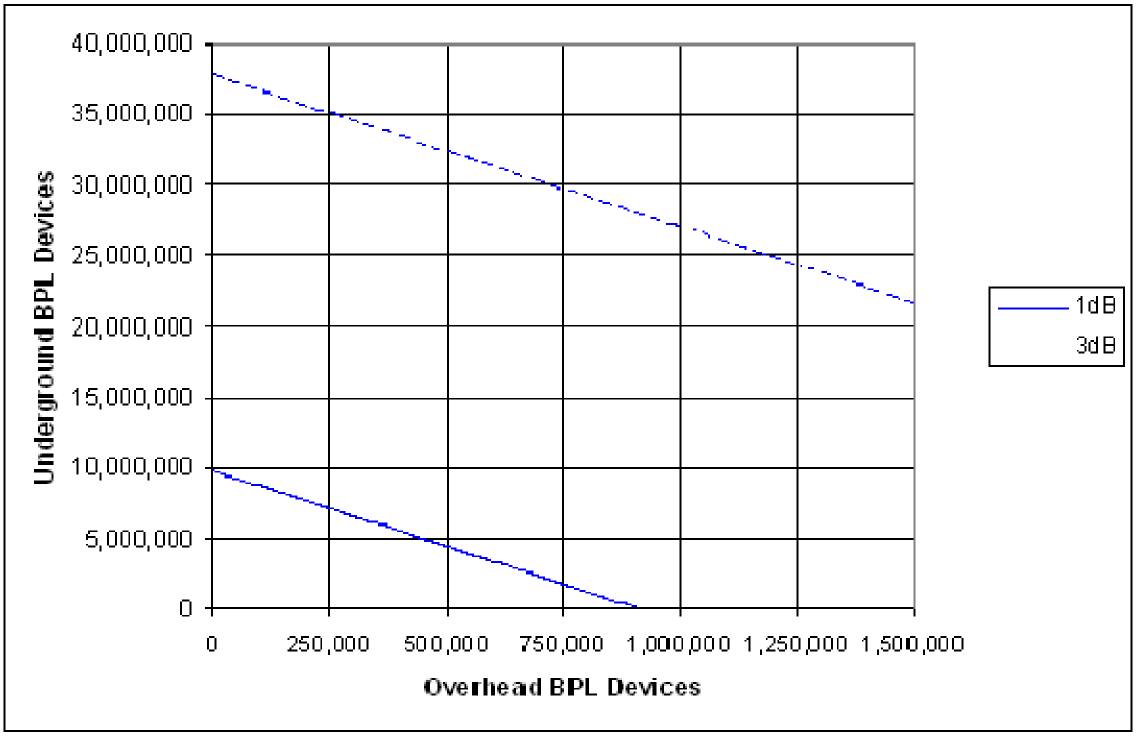

Figure 5-4: Number of underground BPL devices compared to the number of overhead BPL devices required to meet specified increase in noise floor under low SSN conditions

5.4.2 Maps of Ionospheric Aggregation

Figures 5-6 through 5-17 depict aggregated BPL interference-to-noise ratio (labeled as “Signal-to-Noise”) contour maps across CONUS for a number of BPL deployment cases. These maps combine the aggregate power contributions of overhead and underground BPL devices distributed by population throughout the United States in various ratios such that the maximum aggregate BPL SNR encountered at any geographic point produces an approximate 1 dB or 3 dB increase in the noise floor.

Because of the way VOACAP produces output, only signal-to-noise ratios are indicated in the legends of the contour maps. To aid in interpreting Figures 5-6 through 5-17, a sample contour map is provided in Figure 5-5. Figure 5-5 illustrates the translation of the values in these legends to the respective increases in the noise floor. The lighter shaded regions correspond to greater levels of noise floor increase due aggregation of BPL emissions. The peak location or locations are identified on the contour maps by a circular symbol having a cross inside it.

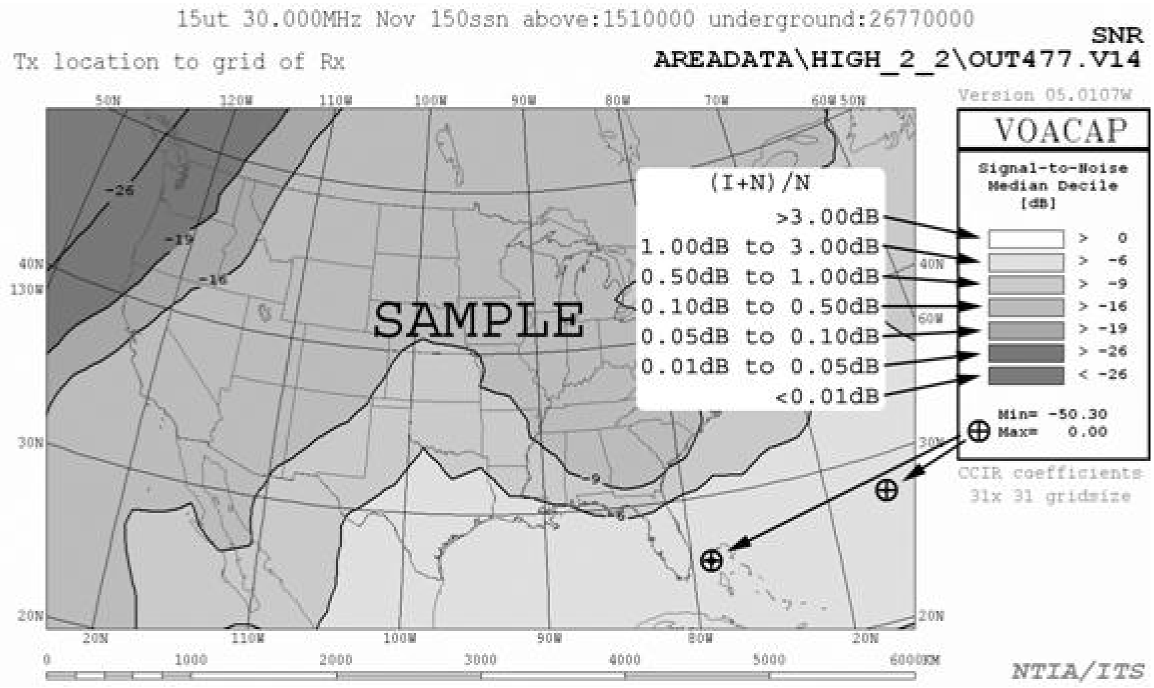

Figure 5-5: Sample VOAAREA output map detailing the increase in the noise floor for each signal-to-noise value in the map legend.

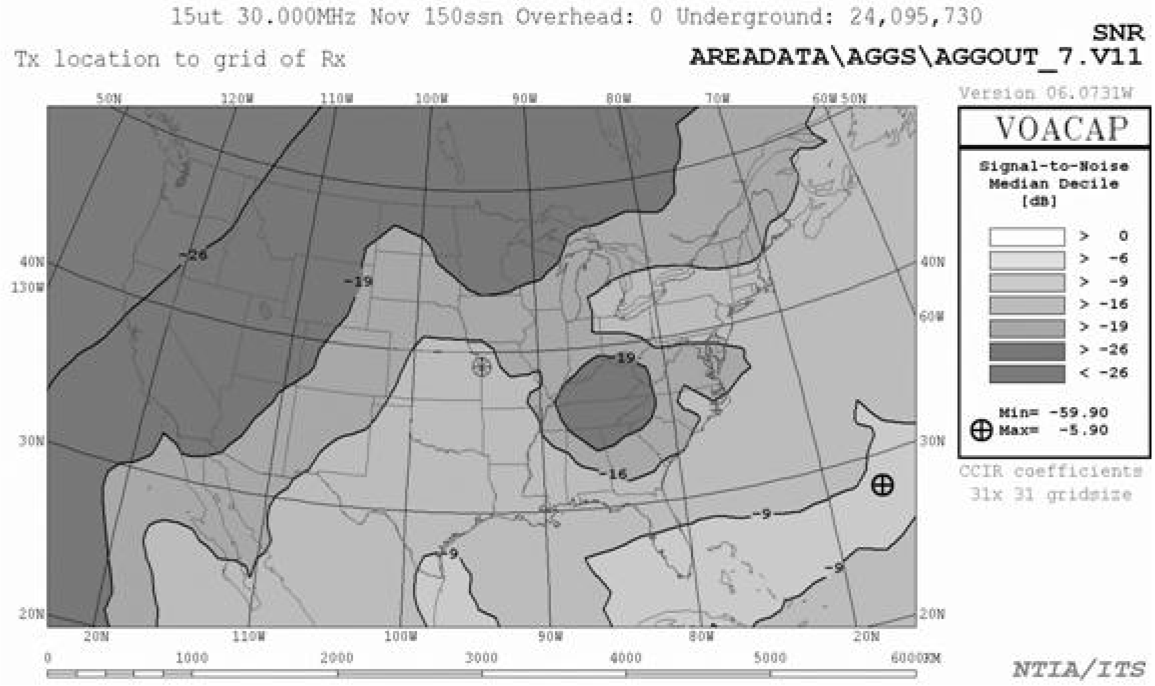

Figure 5-6: Aggregation under high SSN conditions due to 24,095,730 underground devices and no overhead devices with maximum noise floor increase of 1 dB

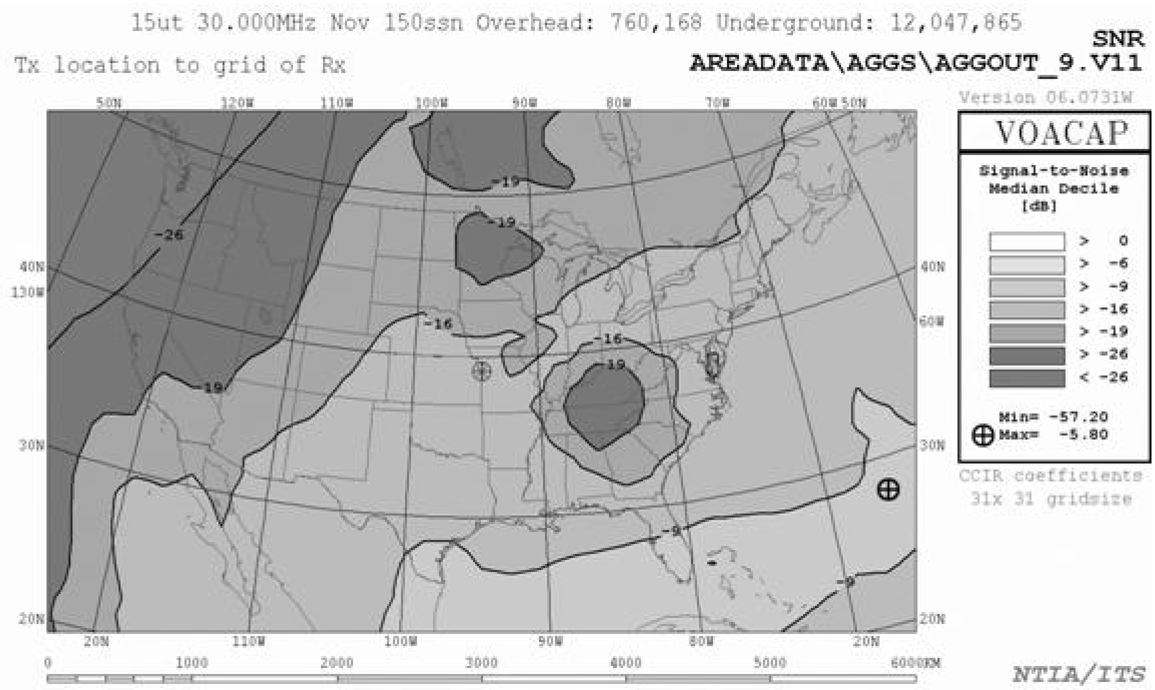

Figure 5-7: Aggregation under high SSN conditions due to 12,047,865 underground devices and 760,168 overhead devices with maximum noise floor increase of 1 dB

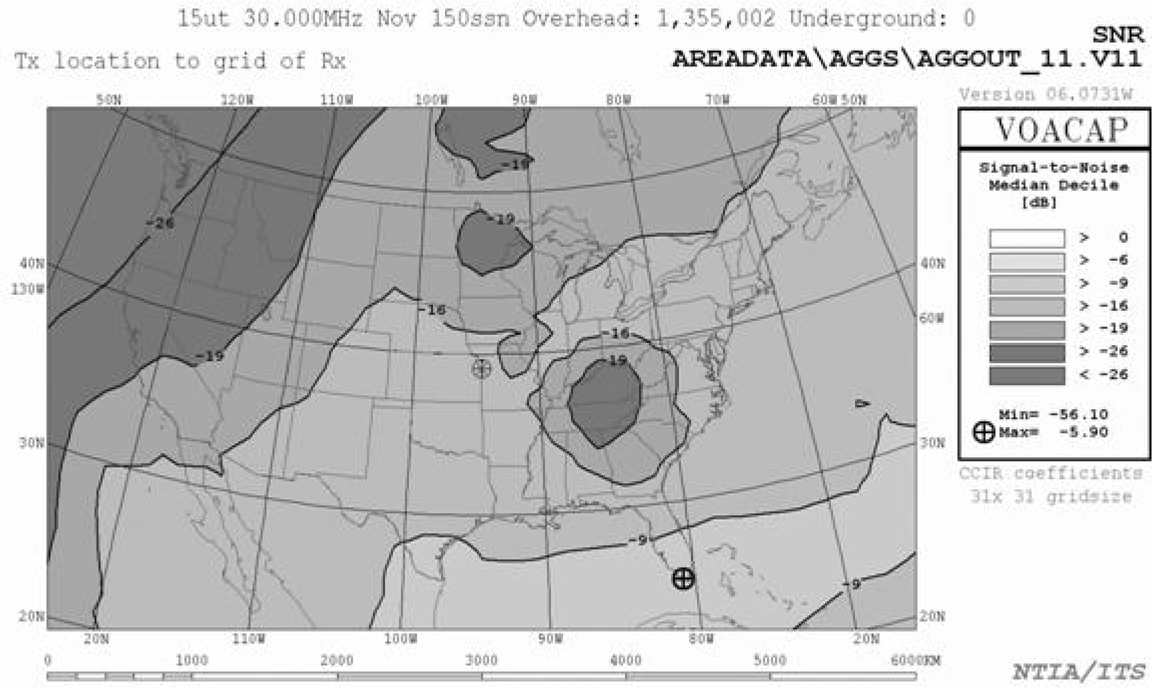

Figure 5-8: Aggregation example under high SSN conditions due to no underground devices and 1,355,002 overhead devices with maximum noise floor increase of 1 dB

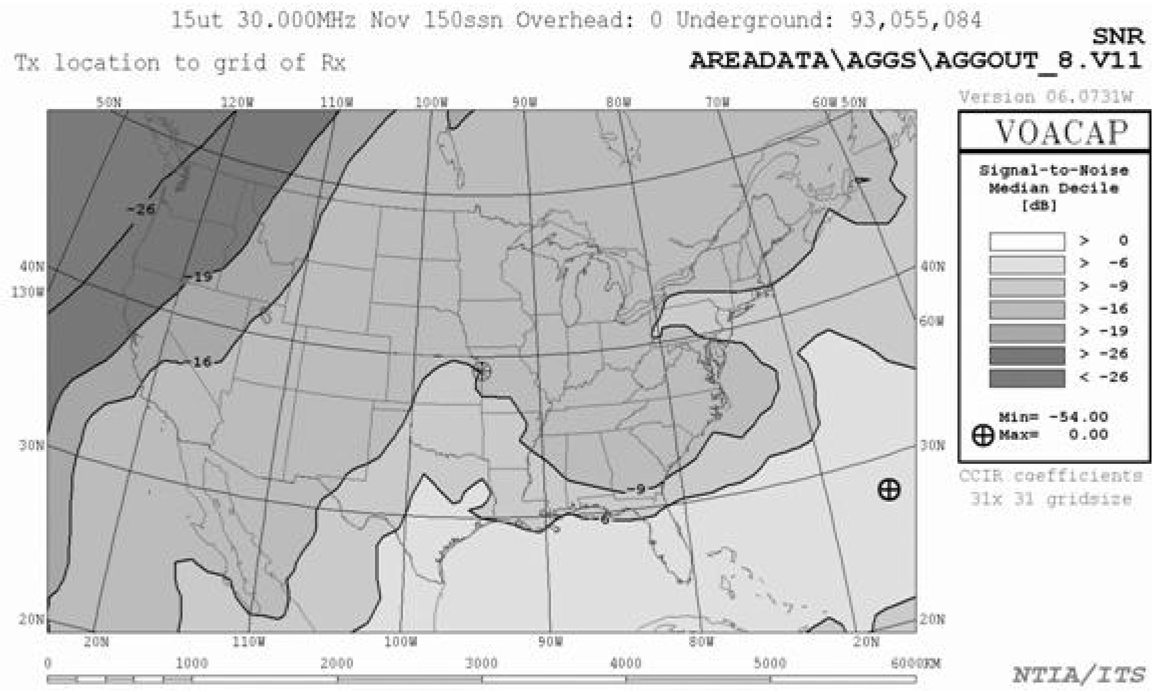

Figure 5-9: Aggregation example under high SSN conditions due to 93,055,084 underground devices and no overhead devices with maximum noise floor increase of 3 dB

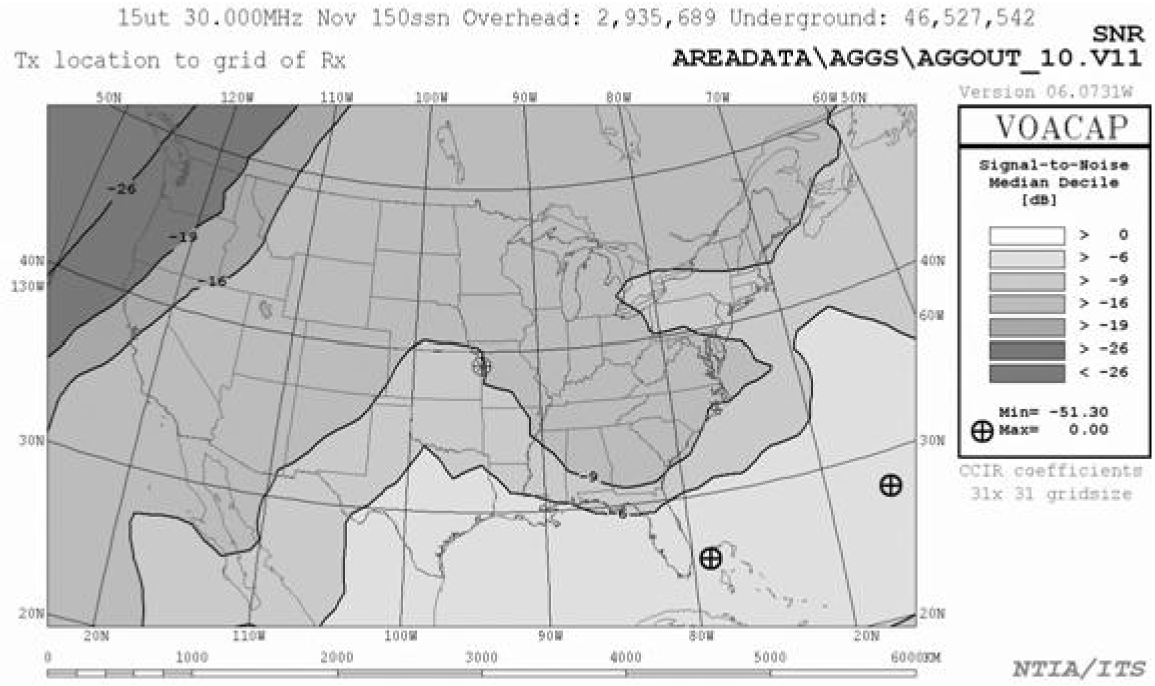

Figure 5-10: Aggregation example under high SSN conditions due to 46,527,542 underground devices and 2,935,689 overhead devices with maximum noise floor increase of 3 dB

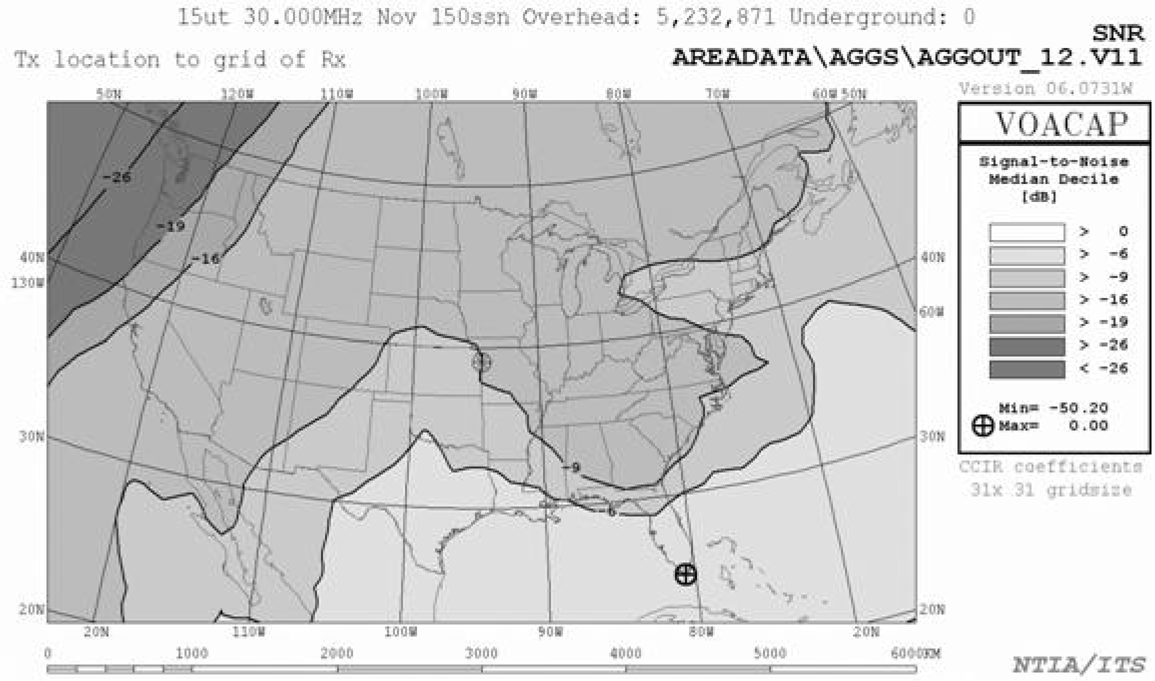

Figure 5-11: Aggregation example under high SSN conditions due to no underground devices and 5,232,871 overhead devices with maximum noise floor increase of 3 dB

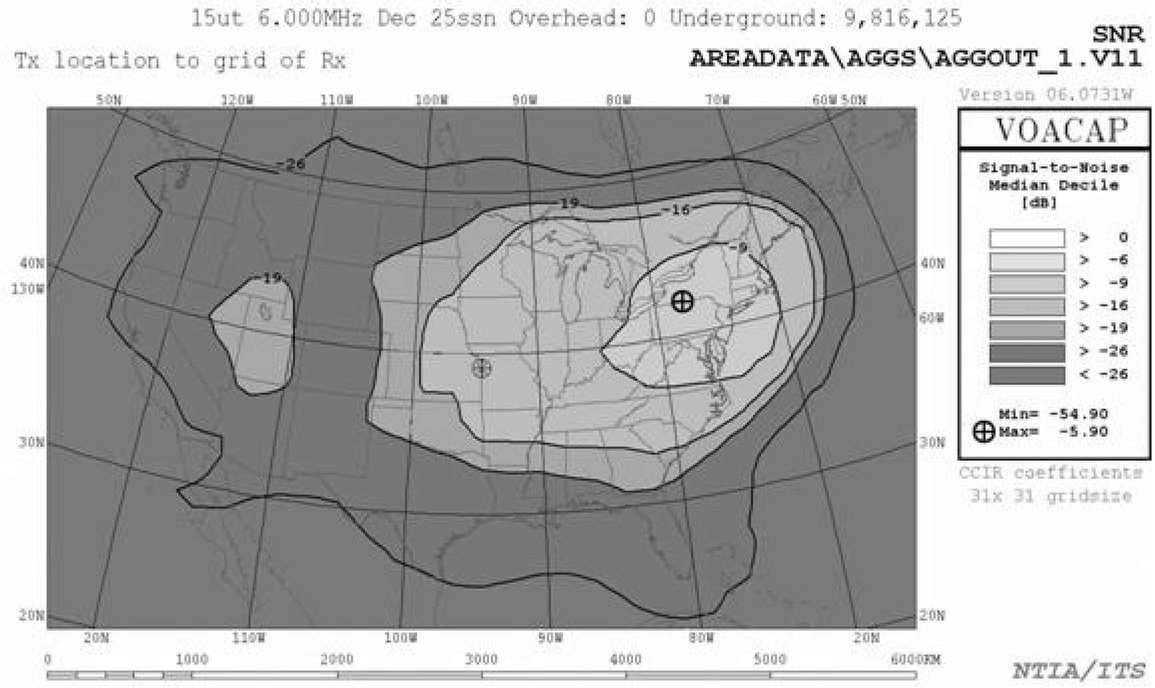

Figure 5-12: Aggregation example under low SSN conditions due to 9,816,125 underground devices and no overhead devices with maximum noise floor increase of 1 dB

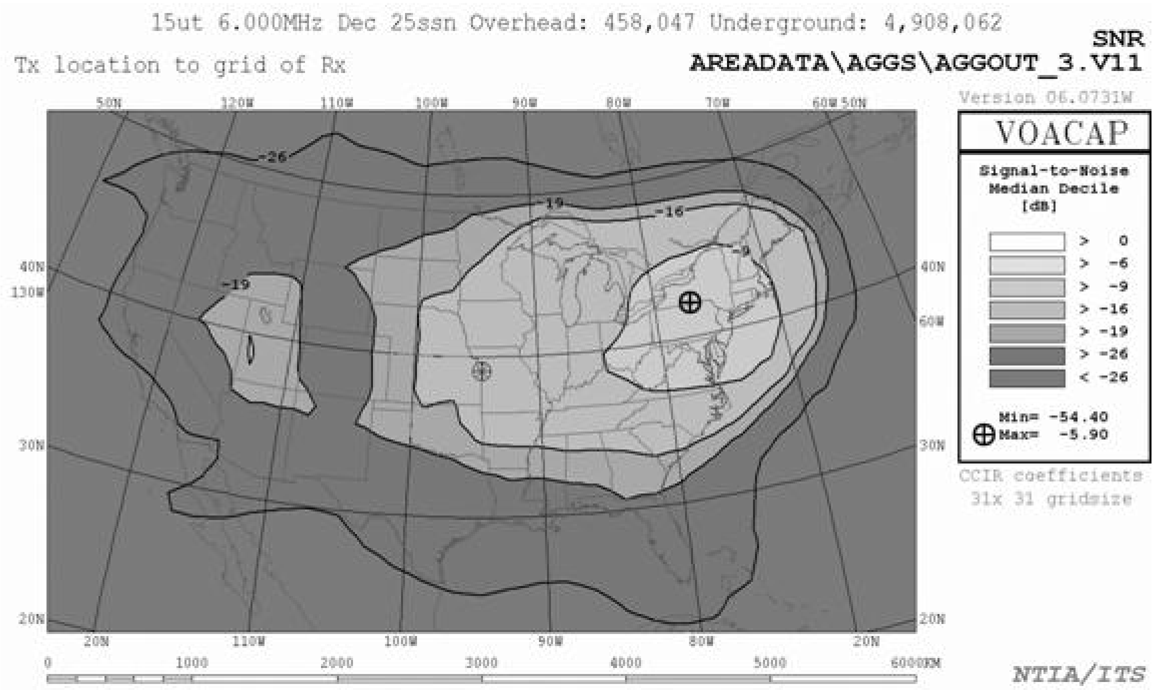

Figure 5-13: Aggregation example under low SSN conditions due to 4,908,062 underground devices and 458,047 overhead devices with maximum noise floor increase of 1 dB

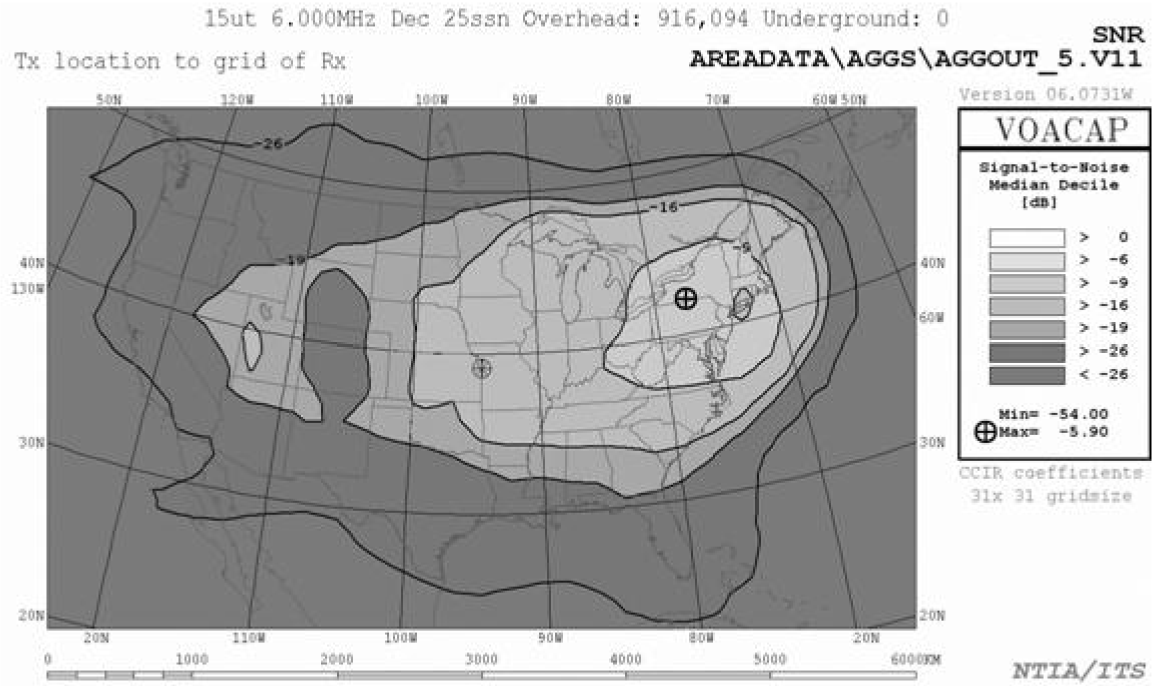

Figure 5-14: Aggregation example under low SSN conditions due to no underground devices and 916,094 overhead devices with maximum noise floor increase of 1 dB

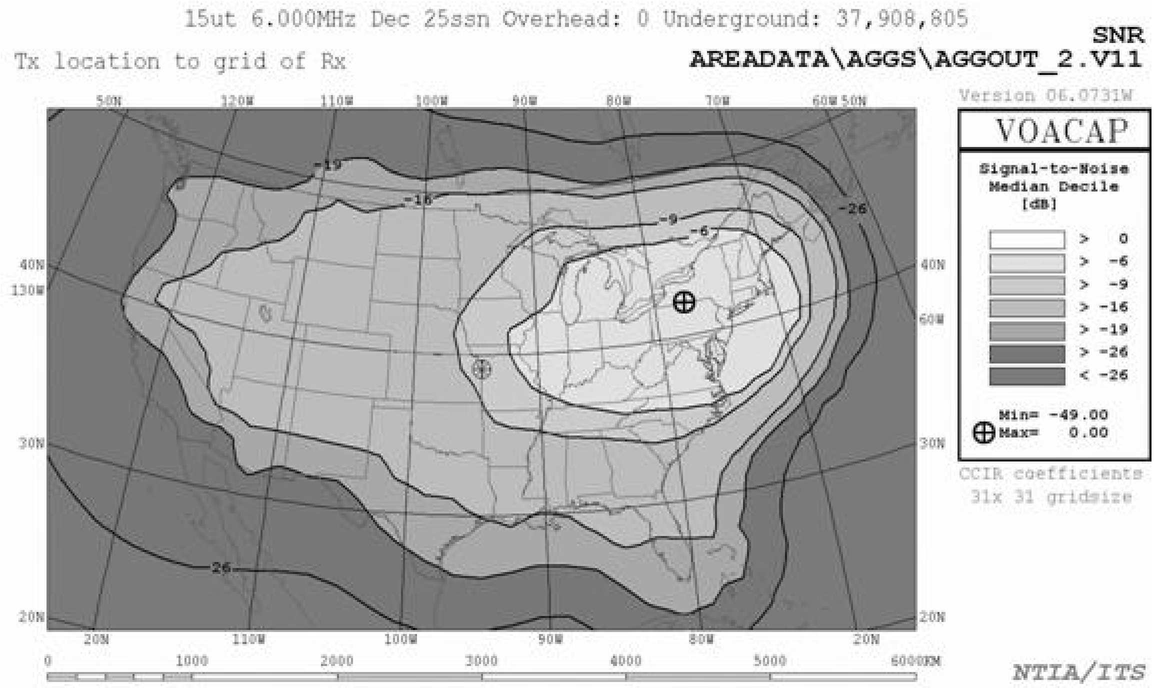

Figure 5-15: Aggregation example under low SSN conditions due to 37,908,805 underground devices and no overhead devices with maximum noise floor increase of 3 dB

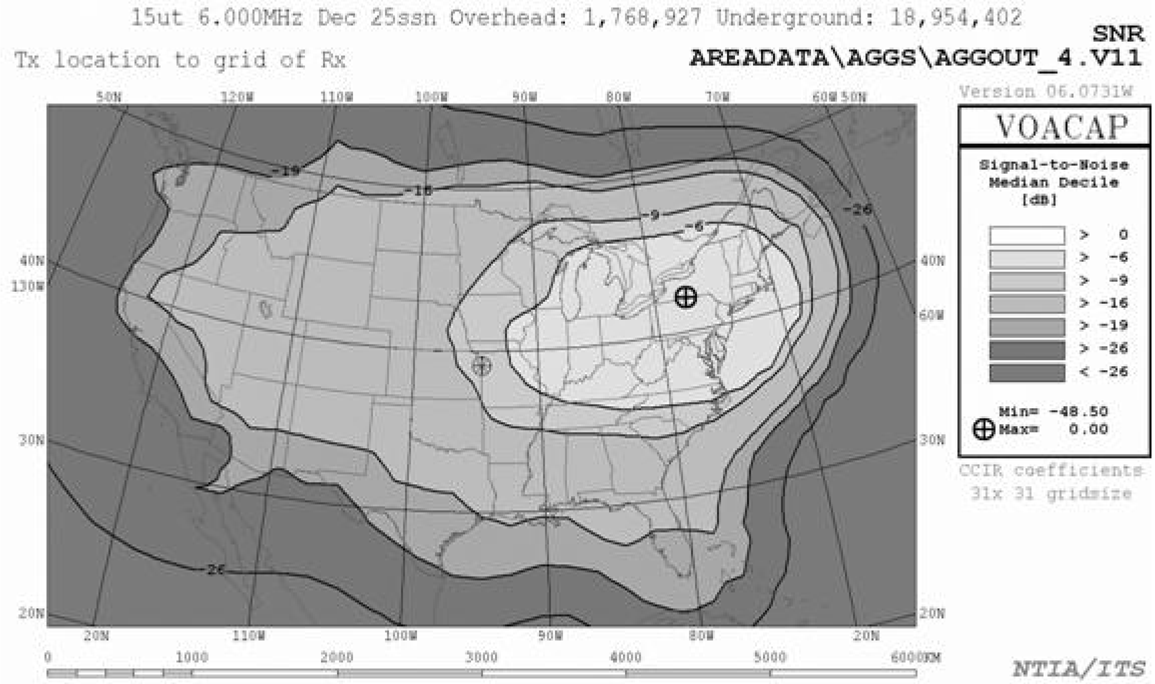

Figure 5-16: Aggregation example under low SSN conditions due to 18,954,402 underground devices and 1,768,927 overhead devices with maximum noise floor increase of 3 dB

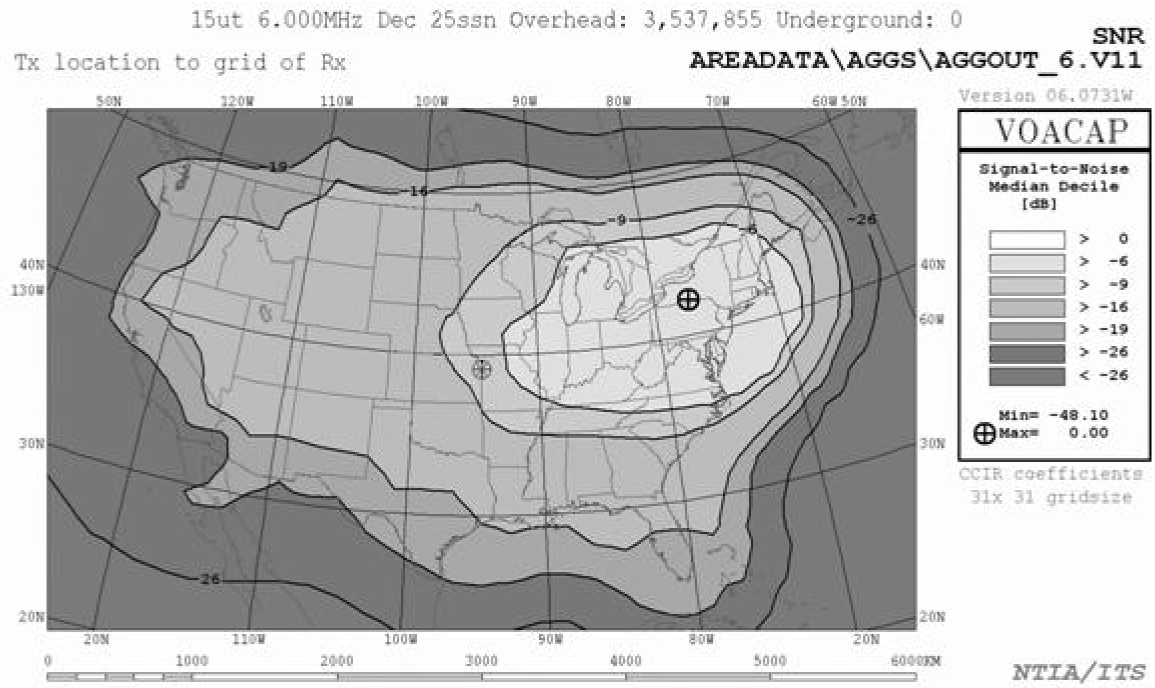

Figure 5-17: Aggregation example under low SSN conditions due to no underground devices and 3,537,855 overhead devices with maximum noise floor increase of 3 dB

The aggregation examples of Figures 5-6 through 5-17 depict the two circumstances (one for low solar cycle activity and one for high) in which the fewest devices are needed to reach the thresholds indicated at any geographic point and across all conditions of time and frequency simulated. As can be seen from the figures, under these conditions of best propagation/lowest noise and using the assumptions developed in this study, more than 916,000 overhead BPL devices deployed nationwide would be necessary to produce increases in the noise floor of 1 dB at any geographic point—well above the 705,000 BPL devices expected in NTIA's deployment model for passing 100 percent of the urban households in the United States. Far more devices could be deployed without reaching either 1 dB or 3 dB thresholds if a significant percentage are deployed on underground power lines.

In the vast majority of cases modeled (other times of day, months of the year and frequencies), many more devices, both underground and above ground, were required to produce the stipulated increases in the noise floor.

5.5 SUMMARY

NTIA modeled two power line structures and conducted comprehensive aggregation studies using VOAAREA propagation software to determine the potential for harmful interference to federal radiocommunication systems in the 1.7 to 30 MHz frequency range due to BPL signals propagated via the ionosphere. This analysis made use of several factors that differed from those used previously in the Technical Appendix to the NTIA Comments. These factors included BPL transmitter characteristics based entirely on an elaborate power line model, the use of the Part 15 measurement methodology in the BPL Report and Order, a more comprehensive set of ionospheric aggregation simulations, and the use of an underground power line model to further characterize aggregated interference potential.

The simulation results for the deployment of Access BPL on MV overhead power lines operating in the 1.7 to 30 MHz band show that, for a wide scale deployment of overhead BPL devices (such that BPL services passes 100 percent of the urban households in the United States), the noise floor increase is expected to be less than 1 dB for the worst case propagation conditions. In reality, approximately 20 percent of the MV power lines are underground and many BPL systems operate in the VHF band. From these results, a widespread deployment of Access BPL systems in the United States is not expected to pose a problem for federal radiocommunication systems operating in the 1.7 to 30 MHz band.