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DGPS Field Strength Measurements at a GWEN Site

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PREFACE

This report is provided by the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, to the Federal Highway Administration (FHWA), U.S. Department of Transportation, in fulfillment of Interagency Agreement Number DTFH61-93-Y-00110.

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The authors wish to acknowledge the following individuals from Institute for Telecommunication Sciences for their contributions to this report: M. Cotton for signal strength field measurements; R. DeBolt for DEM maps, three-dimensional topographical maps, and terrain profile plots; N. DeMinco for antenna modeling; Y. Lo for signal strength field measurements.

Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the technical aspects of the reported results. In no case does such identification imply that the material or equipment identified is the best available for the purpose.

The map in Figure 1 of this report was produced in part by using MapExpert^{TM} software from DeLorne Mapping.

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DGPS SIGNAL STRENGTH MEASUREMENTS AT A GWEN SITE

J. Randy Hoffman, John J. Lemmon, Ronald L. Ketchum [1]

Field strength measurements of a 300-kHz differential global positioning system signal transmitted at a Ground Wave Emergency Network site at Appleton, Washington were conducted. Data were acquired continually along five different routes and tagged with geographical position. Field strength along each individual route was plotted against distance from the transmitter and related to geological landmarks. Results were used as model inputs and to compare measured signal strengths with model predictions.

Key words: global positioning system (GPS); differential GPS (DGPS); signal strength measurements; Ground Wave Emergency Network (GWEN); propagation models

1. PURPOSE

The purpose of this study was to determine absolute differential global positioning system (DGPS) signal strengths at various distances from the Ground Wave Emergency Network (GWEN) site at Appleton, Washington. The transmitter, while owned and used by the U.S. Air Force Air Combat Command, has been temporarily reconfigured for DGPS transmissions on an experimental basis. Signal strength and background noise were measured along five different radial routes to compare the effects of different terrains. Results were used as model inputs and to compare measured signal strengths with model predictions.

2. STRATEGY

Measurements were conducted by driving five separate radial routes as shown in Figure 1. Data were only acquired during the daytime hours so that sky-wave effects were negligible. The first route started at Boise, Idaho (approximately 470 km southeast of the GWEN transmitter site) and followed Interstate 84 to Cascade Locks, Oregon (approximately 46 km west of the transmitter). All of the remaining routes started at Cascade Locks and ended at one of four locations: Bellingham, Washington; Medford, Oregon; Spokane, Washington; and Burley, Idaho (via Boise, Idaho). The route to Bellingham, Washington followed Interstate 84 east to Biggs, Oregon; Highway 97 north to Toppenish, Washington; Interstate 82 north to Ellensburg, Washington; Interstate 90 northwest to Seattle, Washington; and Interstate 5 north to Bellingham, Washington (approximately 330 km north of the GWEN transmitter site). The route to Medford, Oregon followed Interstate 84 west to Portland, Oregon, and Interstate 5 south to Medford, Oregon (approximately 400 km southwest of

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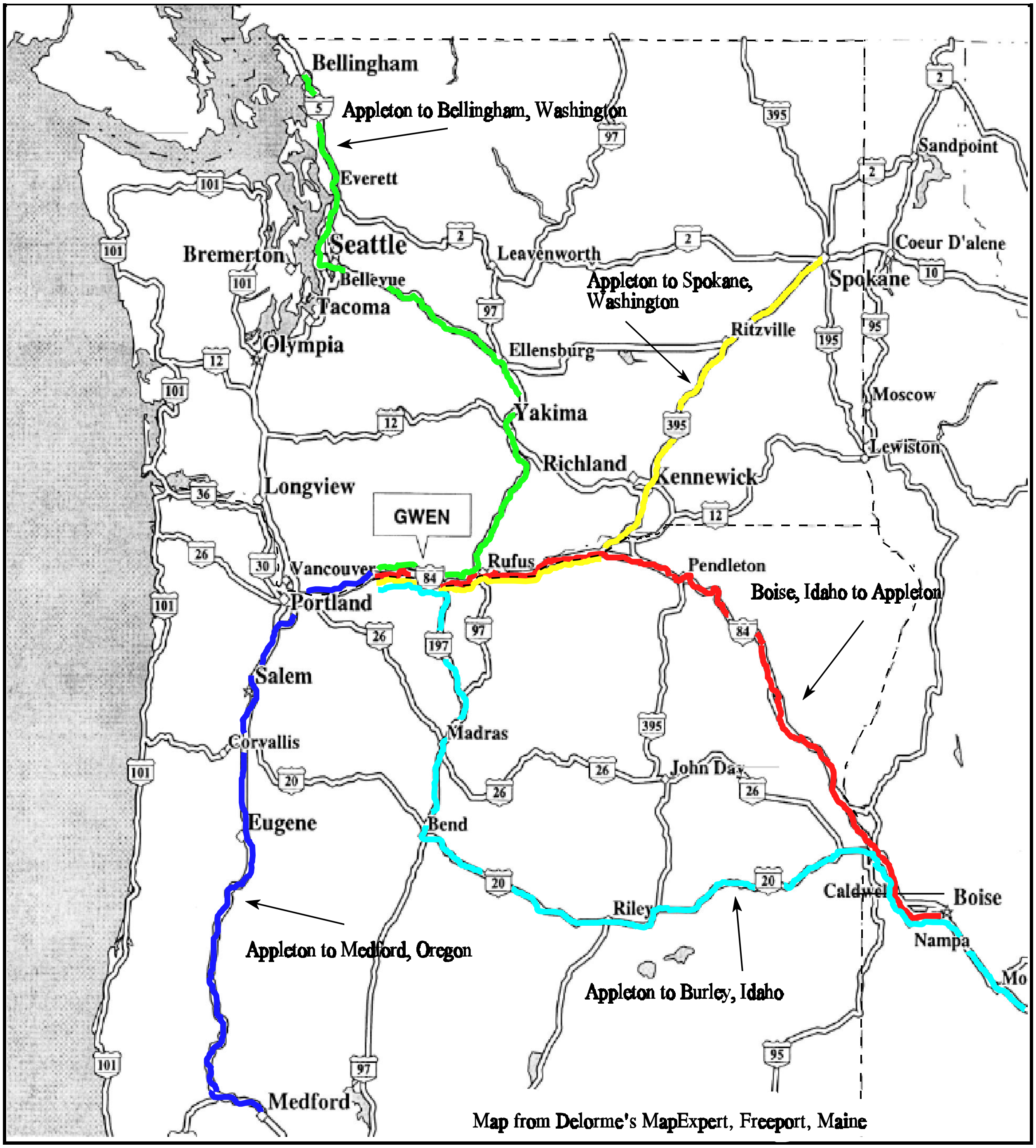

Figure 1. Measurement routes (in color) for DGPS signal strength (red) Boise, Idaho to the GWEN transmitter, (yellow) GWEN transmitter to Spokane, Washington, (green) GWEN transmitter to Bellingham, Washington, (dark blue) GWEN transmitter to Medford, Oregon, (light blue) GWEN transmitter to Burley, Idaho.

the GWEN transmitter site). The route to Spokane, Washington followed Interstate 84 east to Hermiston, Oregon; Interstate 82 to Kennewick, Washington; and Highway 395 northeast to Spokane, Washington (approximately 350 km northeast of the GWEN transmitter site). The route to Burley, Idaho followed Interstate 84 east to The Dalles, Oregon; Highway 197 south to Bend, Oregon; Highway 20 east to Ontario, Oregon; and Interstate 84 through Boise, Idaho to Burley, Idaho (approximately 700 km southeast of the GWEN transmitter site).

3. MEASUREMENT SYSTEM

The measurement system (Figure 2) consists of a receiving antenna, low-pass filter, high-pass filter, amplifier, spectrum analyzer, global positioning system (GPS)/dead-reckoning (DR) receiver, and a computer. The low-pass filter attenuates signals at frequencies above 400 kHz, particularly the AM broadcast signals. The high-pass filter attenuates signals at frequencies below 285 kHz. The computer is used to control the spectrum analyzer, download raw data, gather GPS information, and perform various computations. The overall gain of the system between the output of the antenna and the measured output of the spectrum analyzer is 22 dB. The noise figure of the system is 10 dB, resulting in a sensitivity of 1 dBµV/m in a bandwidth of 300 Hz. The GPS receiver has a dead-reckoning system so that, if satellite lock is lost, the proper coordinate information is maintained.

4. TRANSMITTER

The antenna at the Appleton GWEN site is 91.1 m (299 ft) tall supported by 15 guy wires. The cross section is a triangle that is 0.609 m (2 ft) long on each side. It has 12 top-loading elements. A radial ground plane extending from the base of the tower contains approximately 100 copper wires, each 100 m (330 ft) long, and buried 30 cm underground [1]. The tuning coils were modified for a 300-kHz DGPS transmission and the power into the antenna was set at 1 kW. Based on theoretical considerations, the efficiency is expected to be 50%, giving a total radiated power of 500 W. The predicted directive gain for the ground wave (in the horizontal direction) is approximately 6 dB. Therefore, the expected field strength at 10 km is approximately 91 dBµV/m (see Appendix A).

5. MEASUREMENT PROCEDURE

A computer controlled the acquisition of data using GPIB and RS232 commands sent to the spectrum analyzer and GPS receiver, respectively. Data also were downloaded via GPIB and RS232. Both noise and DGPS signal strength data were acquired.

At the beginning of data acquisition and at approximately 20-min intervals, the spectrum between 285 kHz and 325 kHz was scanned for a frequency (f_{min}) where the noise was at a minimum. Prior to acquiring data on the DGPS signal, the noise power was measured at f_{min} (see Table 1). The noise power was measured to determine if the signal could be detected against the noise background. A single sweep was performed, after which, the mean, the standard deviation, and the peak noise power

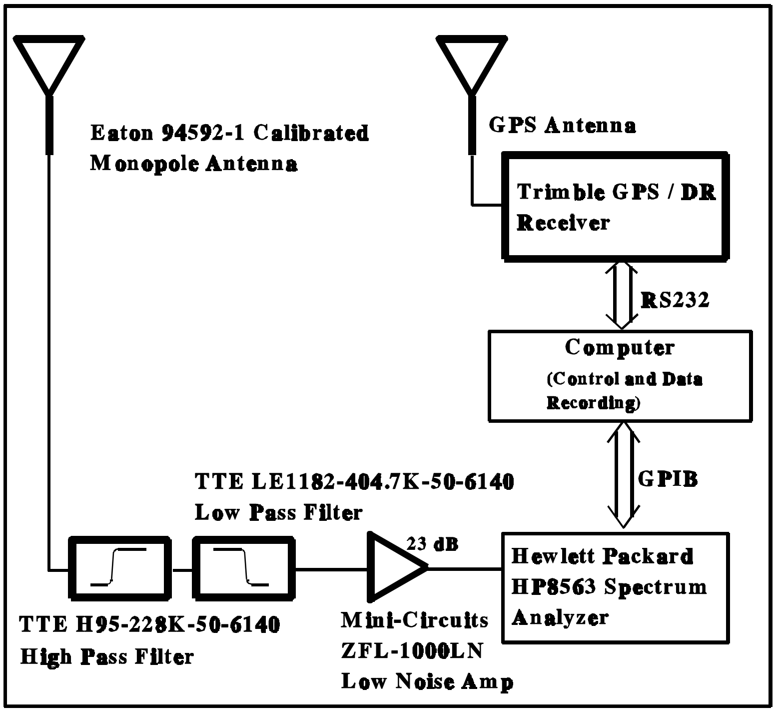

Figure 2. Block diagram of the measurement system.

were determined from 601 data points evenly spaced across the sweep. In addition, 50 samples evenly spaced across the 601 data points of the sweep were stored in the data file.

The DGPS signal strength was measured by performing 50 consecutive sweeps of a 500-Hz span. (see Table 1). After each sweep, the signal power at the DGPS center frequency was determined and recorded in the data file. Based on the antenna-correction factor and the known frequency, the signal field strength was calculated as described in Appendix B. With each sweep, a data string from the GPS was downloaded and placed in the file to mark the location of the acquisition. Each of the four parameters (frequency, power, field strength, and GPS coordinate string) was recorded for each of the 50 sweeps.

Two calibration procedures were conducted. The first procedure, performed immediately before measurements, was used to determine the total gain between the output of the antenna and the measured power determined by the spectrum analyzer. This gain was subtracted from the measured power to determine the power at the output of the antenna. The procedure amounted to putting a signal of known power into the cable which was normally connected to the antenna, and then measuring the power on the spectrum analyzer. The difference between the known power and the measured power is the gain of the system, which in this case is approximately 22 dB.

The second calibration procedure was used to determine any differences in antenna characteristics between those measured in a laboratory (during which the antenna-correction factor was determined)

Table 1. Spectrum Analyzer Settings

Parameters	Low Noise Scan	Signal Strength	Received Noise
Detection Mode	Normal	Normal	Sample
Resolution Bandwidth	300 Hz	300 Hz	300 Hz
Video Bandwidth	300 Hz	10 Hz	1 MHz
Span	40 kHz	500 Hz	zero
Reference Level	-30 dBm	-10 dBm	-40dBm
Attenuation	0 dB	0 dB	0 dB
Sweep Mode	10 Sweeps	Single	Single
Video Averaging	On	Off	Off
Sweep Time	2.0 s	5.0 s	6.0 s
Frequency	285-325 kHz	Center Frequency of Beacon	Quiet area between 285-325 kHz
Data Acquired	Determine quiet region of spectrum	Power at Center Frequency	601 data points

and the characteristics of the antenna when placed on the measurement van. First, the antenna was placed at the center of a 1.3-m round backplane which, in turn, was mounted on a tripod approximately one m above ground. This backplane configuration was used to simulate the measurement conditions in the laboratory. The power of a known transmitted signal (such as a DGPS signal) was measured. Then, the antenna was mounted on the measurement van and the power of the same signal was measured at eight different azimuth orientations of the van (approximately 45° apart). Results showed no significant difference between the two different antenna mounts and among the eight different azimuth orientations.

In addition to the aforementioned calibrations, the system was checked on successive days by placing the measurement van in the same physical location and measuring the DGPS signal. The purpose of this was to quickly determine if any changes had occurred in the system from one day to the next. Less than 1 dB variation was noted during the course of the measurements.

6. DATA PROCESSING

Data processing consisted of ordering the data and placing the results in an ASCII file for plotting. Since the distance between a specific transmitter and the receiver does not necessarily monotonically increase or decrease with each successive data point, the data were processed by ordering the data according to distance. This was performed for each of the five different routes. After ordering the data, three parameters were written to an ASCII file: distance, DGPS field strength, and noise field strength.

7. ANALYSIS

Results showing the signal strength as a function of distance from the transmitter for each of the five different routes are shown in Figures 3 through 7. The signal strength and noise as seen at the input to the antenna are plotted against the distance on the abscissa. The linear regression for signal strength as a function of the log base 10 of the distance was also determined for the first 100 km on each of the routes except the route to Medford, Oregon. Table 2 lists the field strength at 10 km and the slope for the different regression plots. These linear regressions are based on averages as opposed to the best possible signal strength that can be received at a specified distance. Therefore, the field strength at 10 km for the linear regression will show values less than those determined through theoretical predictions.

8. MEASUREMENT RESULTS

For each of the plots except the route to Medford, Oregon, there appears to be a bimodal distribution of points for the first 45 km. This is believed to be due to a difference in terrain between two approaches to and from the transmitter, one approach traveling 45 km west of the transmitter along Interstate 84, and the other approach traveling east of the transmitter along the same highway. For all routes except the one to Medford, Oregon, the data were collected starting on one side of the transmitter, passing it, and proceeding in the opposite side. On the first day, the data collection started east of the transmitter and ended at Cascade Locks, 46 km west of the Appleton site. All other routes started at Cascade Locks, three of which went past the GWEN site traveling east. Separation of the data for the two approaches shows greater signal power for routes traveling to the east of the transmitter. Figure 8 shows the three-dimensional topography of the of the two approaches (Interstate 84 highlighted in yellow).[2] One can see that the land west of the GWEN site at Appleton, Washington is characterized by rough terrain surrounding the gorge of the Columbia River. Figure 9 shows the terrain profile from the transmitter to Cascade Locks, Oregon. Figure 10 shows the terrain profile from the transmitter to Interstate 84, 45 km to the east. The land to the east is flatter except for a narrow gorge and a ridge along the north side of the river. It is interesting to note that the signal between the transmitter and Cascade Locks travels along the river gorge which

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[2] Digital elevation maps, terrain profile plots, and three-dimensional topographical maps were generated through the Telecommunications Analysis Service at ITS.

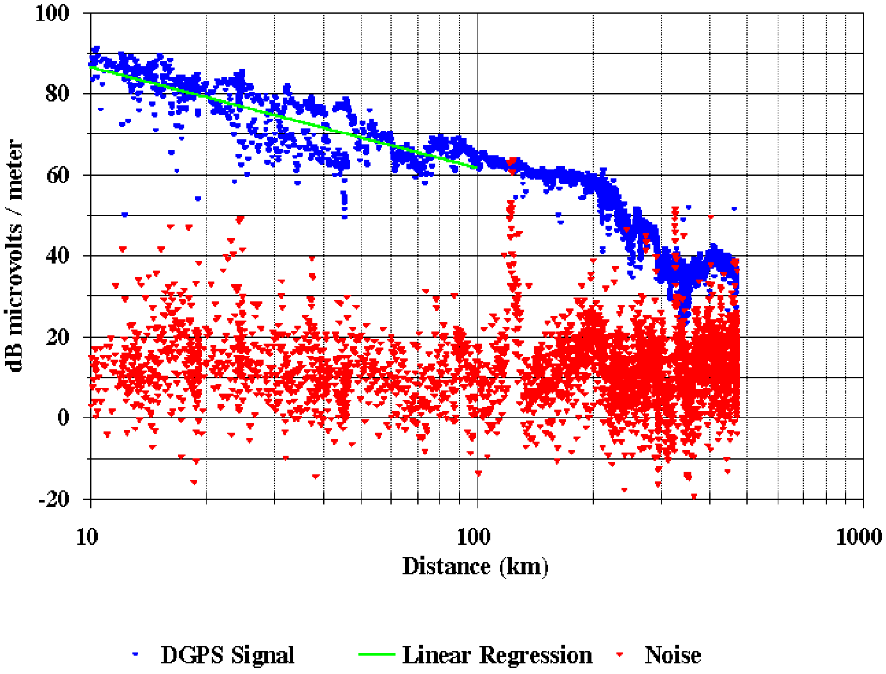

Figure 3. Signal strength vs. distance for the Appleton GWEN site coming from Boise, Idaho via Interstate 84.

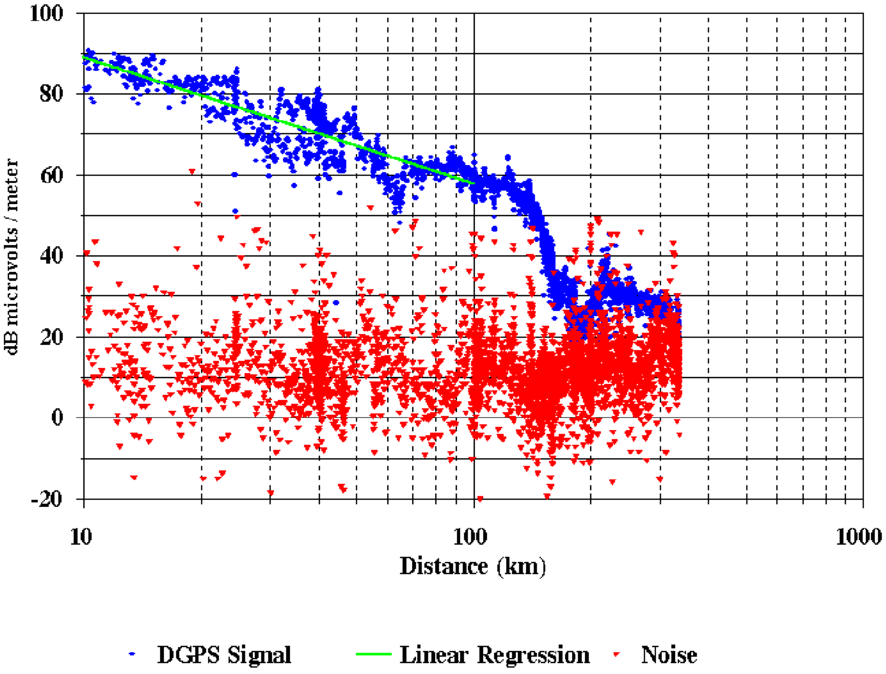

Figure 4. Signal strength vs. distance for the Appleton GWEN site going to Bellingham, Washington via Highways 97 and 5.

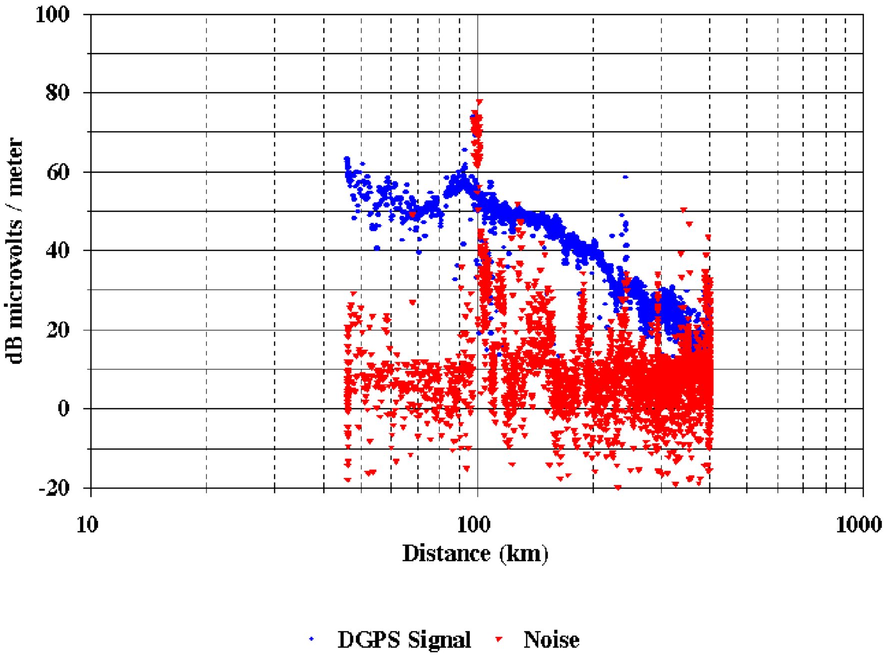

Figure 5. Signal strength vs. distance for the Appleton GWEN site going to Medford, Oregon via Interstate 5.

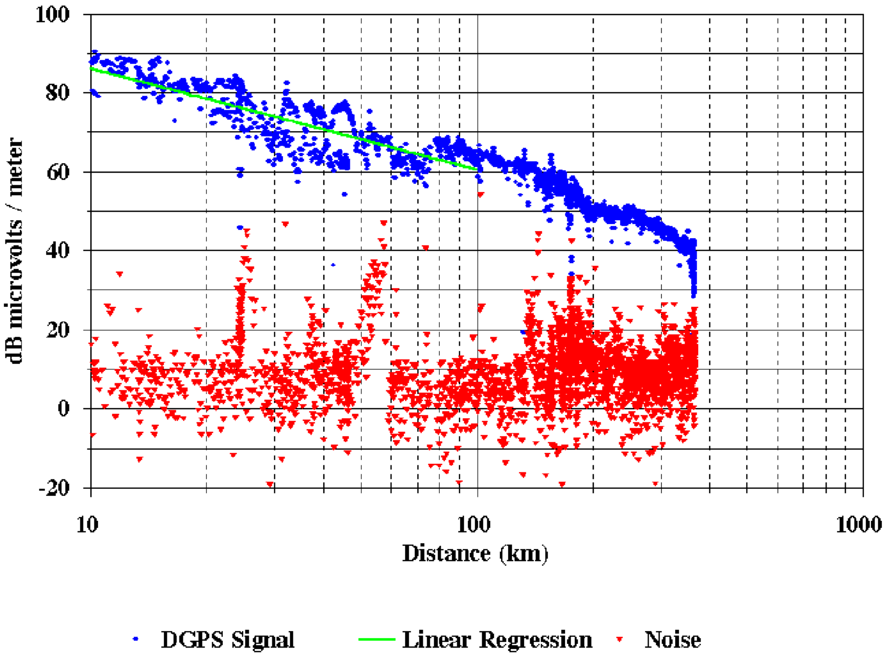

Figure 6. Signal strength vs. distance for the Appleton GWEN site going to Spokane, Washington via Highway 395.

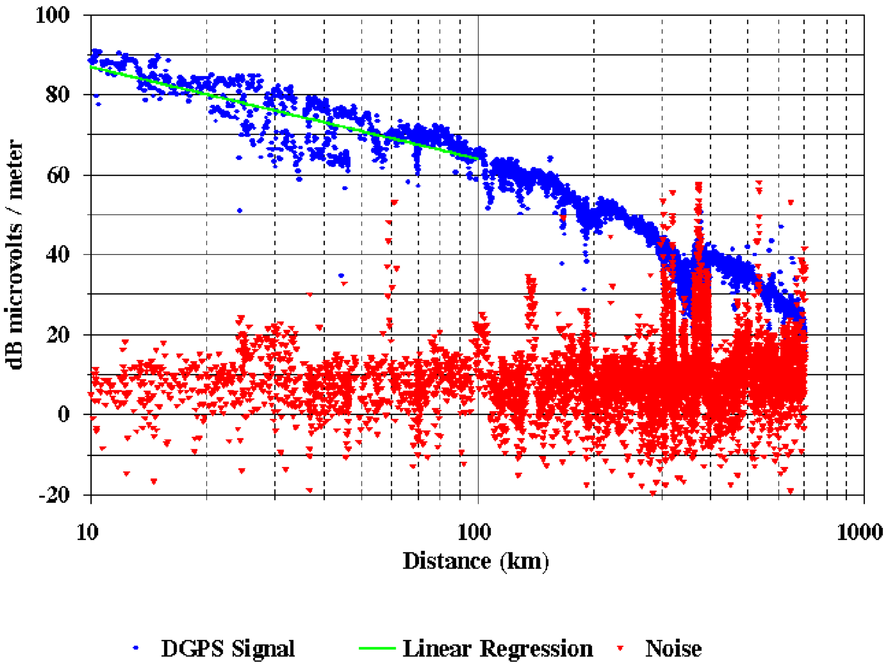

Figure 7. Signal strength vs. distance for the Appleton GWEN site going to Boise, Idaho via Highway 20.

is 2 km wide and surrounded by relatively steep hills on both sides (see Figure 11).

The route going from Boise, Idaho to Cascade Locks, Oregon shows a dip in the signal power at a distance between 200 and 400 km from the transmitter (see Figure 3). Figure 12 is a digital elevation map (DEM) showing the topography of the area. Higher elevations are represented by lighter shades of gray. High mountain peaks are white. The route from Boise, Idaho to the transmitter is shown as a thick yellow line, and the route from the transmitter to Boise is shown as a thick red line. One can see that when traveling between 400 km and 200 km from the transmitter along Highway 84

Table 2. Field Strength at 10 km and Slope for Least Squares Fit

Route	**Field Strength at 10 km** dBμV/m	**Slope** (dBμV/m) / log(km)
Boise, Idaho to GWEN via Interstate 84	86.5	-24.9
GWEN to Seattle, Washington via Highway 97	88.9	-31.1
GWEN to Spokane, Washington via Highway 395	86.2	-25.6
GWEN to Boise, Idaho via highway 20	86.9	-23.0

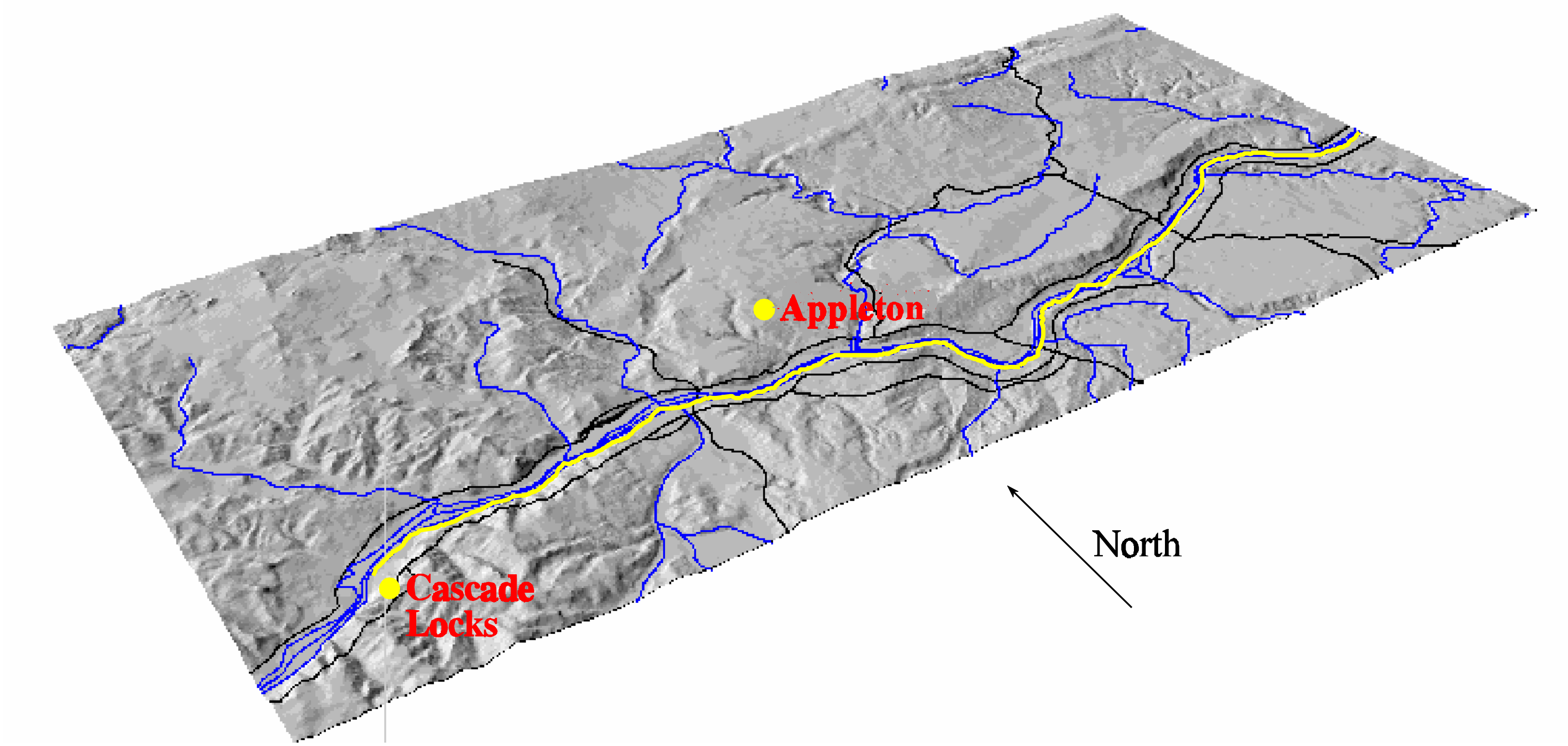

Figure 8. Topography of routes 45 km east and west of the Appleton GWEN site (routes shown in yellow).

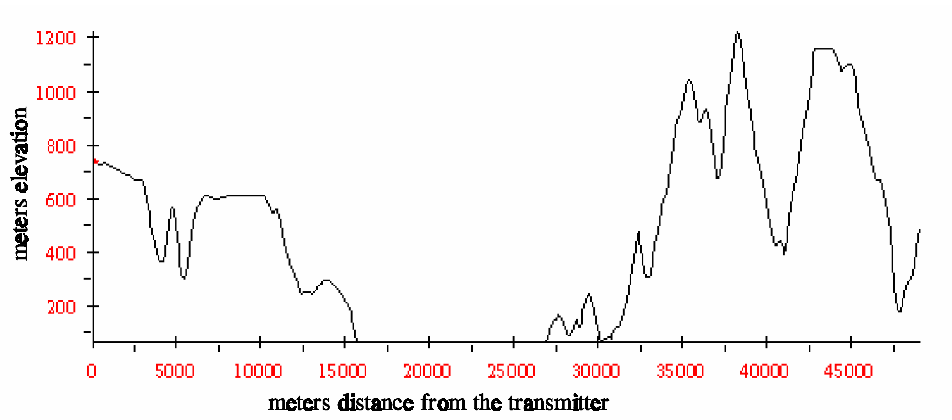

Figure 9. **Terrain profile from the transmitter west 45 km to Cascade Locks, Oregon.**

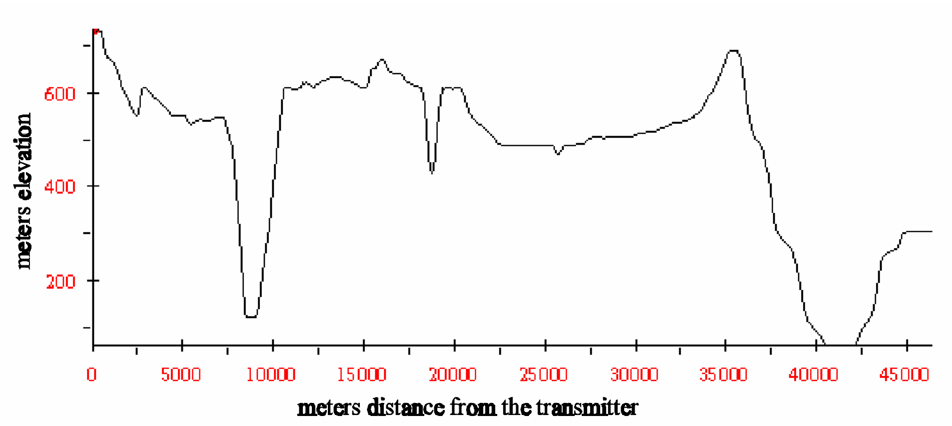

Figure 10. **Terrain profile from the transmitter east 45 km to Interstate 84.**

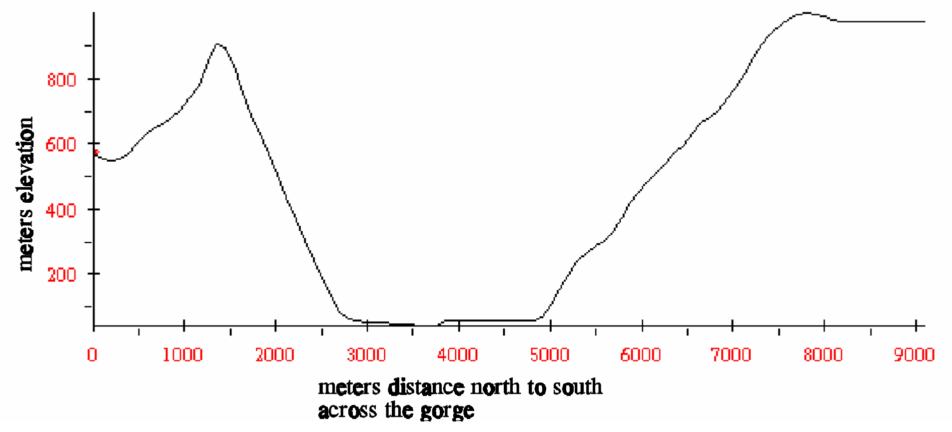

Figure 11. **Terrain profile from north to south across the Columbia River Gorge approximately 32 km east of the transmitter.**

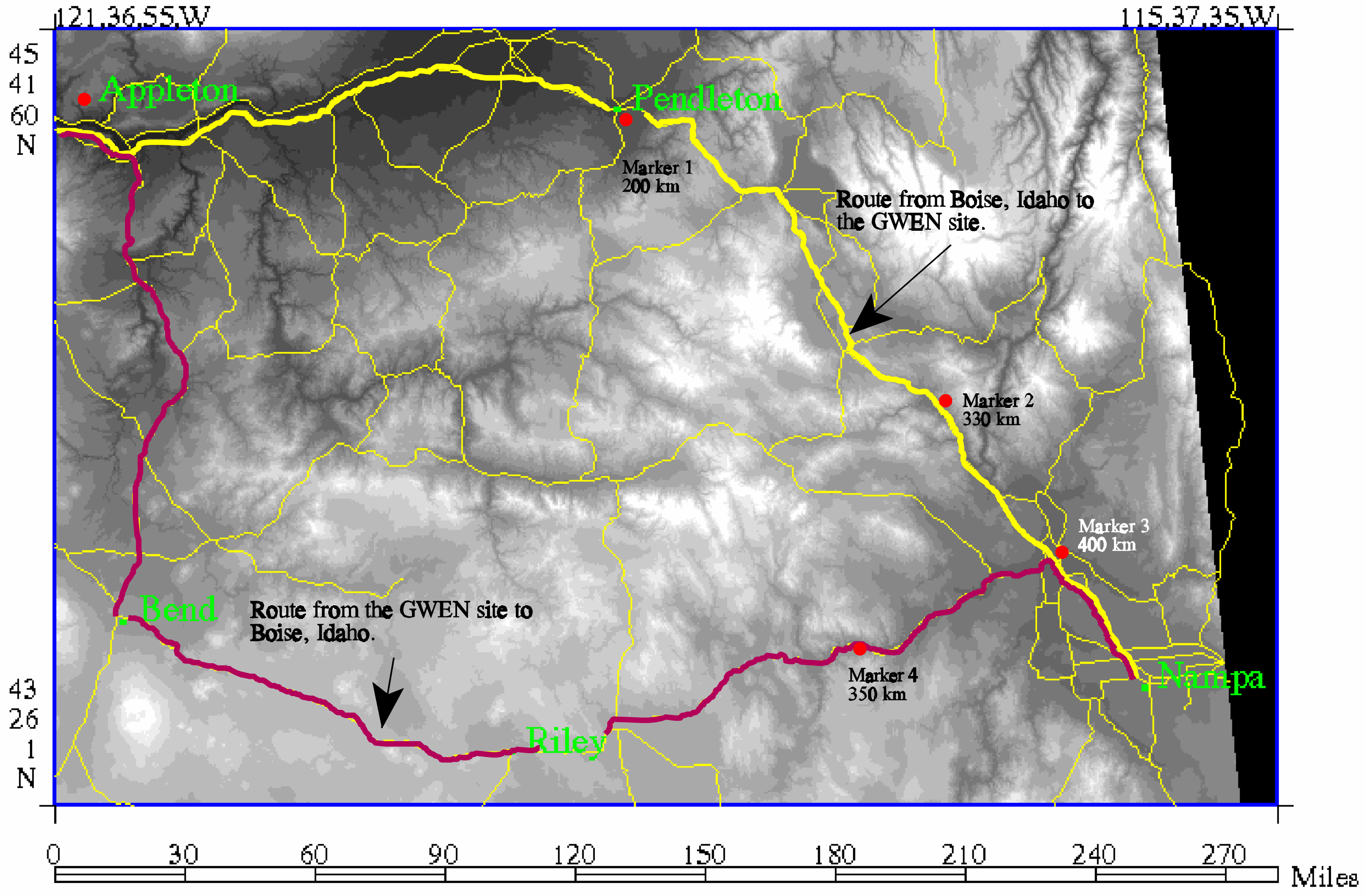

Figure 12. Topography for both routes between Boise, Idaho and the Appleton GWEN site, (yellow) route between Boise, Idaho and the GWEN transmitter, (red) route between the GWEN transmitter and Burley, Idaho.

(marker 3 and marker 1, respectively) the signal path is obstructed by a range of mountains in the Wallowa Whitman National Forest west of the interstate. The greatest dip in the signal power occurs at 330 km from the transmitter on Interstate 84 (marker 2) where the highest point in the mountain range (Rock Creek Butte - 2773 m (9097 ft)) is in direct line with the transmitter. Two areas of significant noise elevation can be seen at approximately 120 and 320 km from the transmitter.

Traveling east to Boise, Idaho along Highways 197 and 20, one can see a different scenario. The signal power (Figure 7) shows a more gradual roll off with distances extending to 700 km from the transmitter. There is, however, a sharp dip at 350 km which then rises shortly thereafter. Figure 12 shows the terrain along this route to be flatter with less prominent obstructions. A smaller mountain range in the Malheur National Forest, lies approximately 80 km north of Highway 20. Within this mountain range is an isolated peak (Strawberry Mountain - 2757 m (9044 ft)) which is in direct line between the transmitter and marker 4 (coinciding with a distance of 350 km from the Appleton site and the dip in signal power noted above).

Data collected along the route to Bellingham, Washington show a small dip in the signal power at 63 km and a large dip between 140 km and 200 km (see Figure 4). Figure 13 shows the topography of the area with the route marked by a thick yellow line. Approaching marker 1, 63 km from the transmitter, the measurement vehicle passed over a mountain ridge and then dipped into a valley. Between marker 2 (140 km from the transmitter) and marker 3 (200 km from the transmitter) the measurement vehicle traveled over a mountain pass with the Cascade Mountains located between the receiver and the transmitter. At 200 km, when the measurement vehicle was lined up with two large mountain peaks (Mt. Rainer - 4392 m (14410 ft) and Mt. Adams - 3751 m (12307 ft)) and the transmitter, the greatest dip in the signal power occurs. It is interesting to note, however, that as the measurement vehicle continued north to Bellingham, Washington, the signal power showed a sharp rise and then a gradual roll off, notwithstanding the fact that Mt. Rainer and Mt. Adams continued to lie directly in the path.

Signal power on the route between the transmitter and Medford, Oregon (see Figure 5) shows an initial dip followed by a marked rise and then a gradual roll off. Topography of the area is shown in Figure 14 with the route marked by a thick red line. The initial dip in signal power coincides with the route along the Columbia River Gorge between Cascade Locks and the entrance to the gorge, 90 km west of the transmitter. Of the five routes, the one to Medford, Oregon shows the greatest overall attenuation over the entire distance. From Portland, Oregon to Medford, regions of the Cascade Mountains always lie between the transmitter and the receiver. Many of the mountains in this area are between 3048 and 3353 m (10,000 and 11,000 ft) high. One can also see that at Portland, located 100 km from the transmitter, the noise power was as much as 60 dB higher than the average. Measurement notes also describe power lines paralleling Interstate 5 for most of the distance between Portland and Salem, Oregon.

As can be seen in Figure 6, the signal power between the transmitter and Spokane, Washington is relatively linear without any significant areas of attenuation. Figure 15 shows the topography for the area, which is very flat with few if any remarkable geological landmarks. A few areas of elevated noise can be seen.

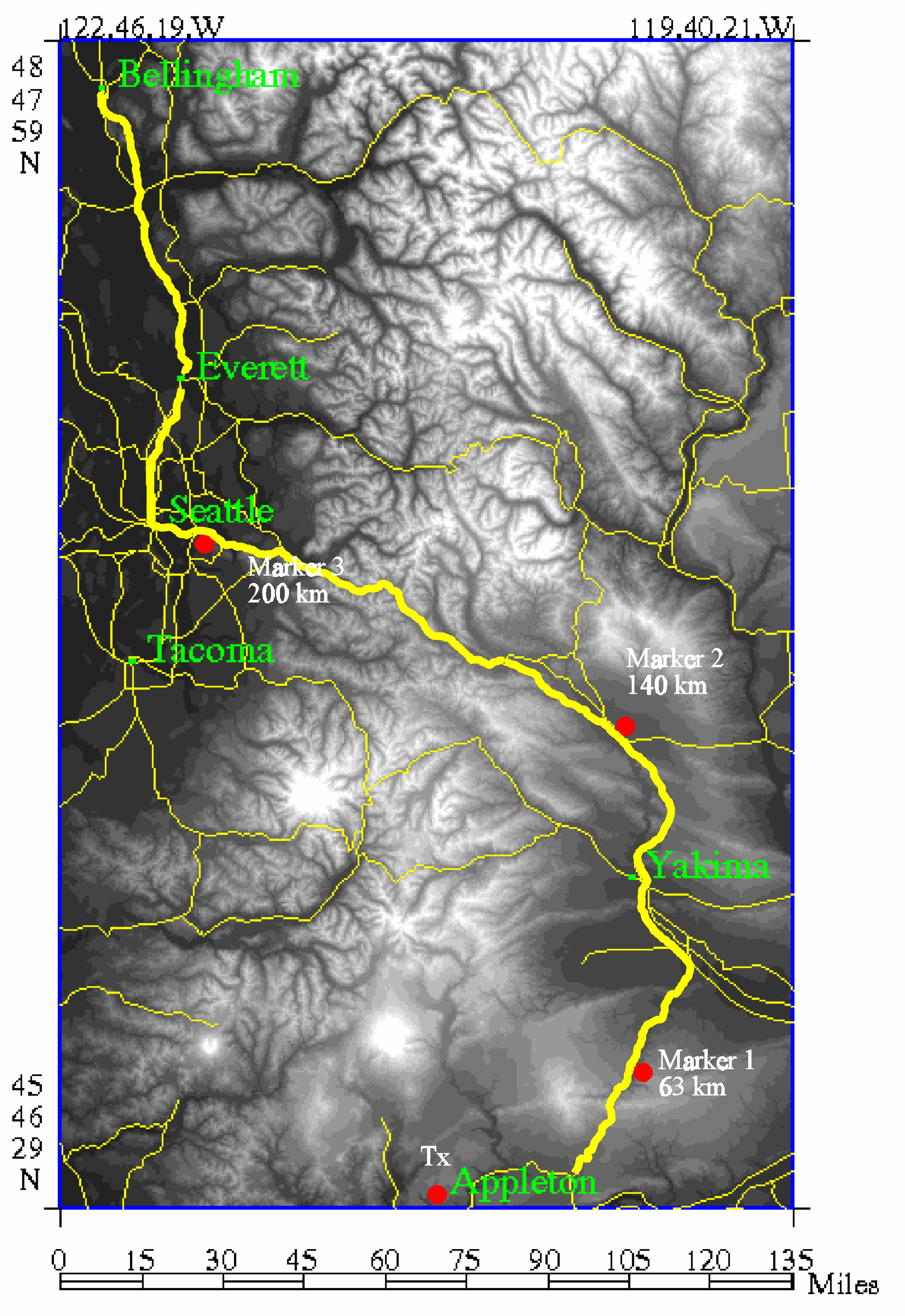

Figure 13. **Topography for the route (yellow line) between the Appleton GWEN site and Bellingham, Washington.**

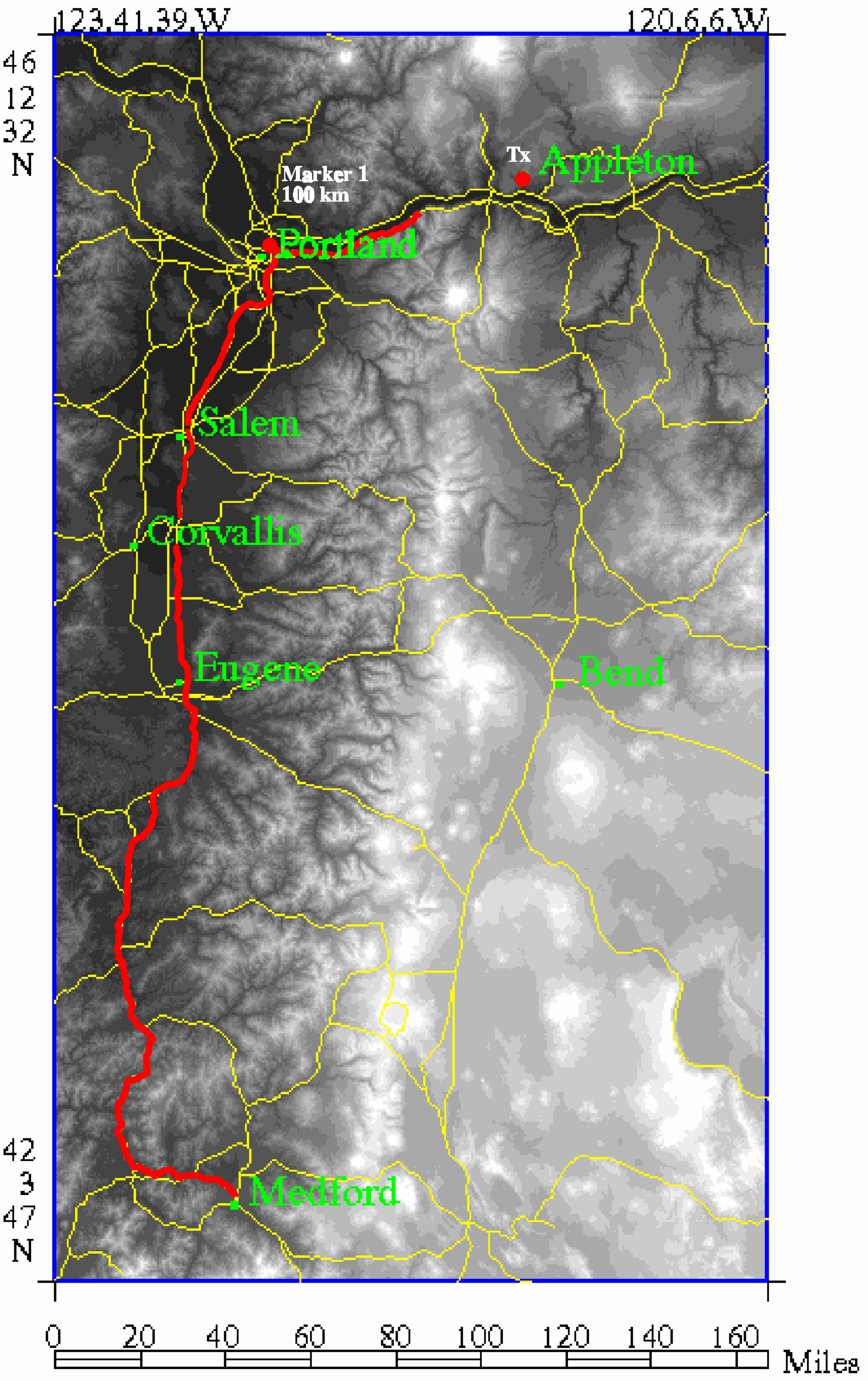

Figure 14. Topography for the route (red line) between the Appleton GWEN site and Medford, Oregon.

9. COMPARISON OF MEASUREMENTS WITH MODELS

Predictions of signal strength for the Appleton GWEN site were generated using the Institute for Telecommunication Sciences medium frequency propagation models. These models are described by DeMinco [2] and by Haakinson, Rothschild, & Bedford. [3]. Model inputs include transmitter location, frequency, field strength at a reference distance, time of day, and ground conductivity.

Predictions of field strength versus distance were not developed along each of the routes. This is because the complicated routes and irregularities in terrain and ground conductivity would make a comparison between predicted and measured field strengths quite tedious, although in principle such a comparison could be made by making propagation predictions at numerous points along each route. Instead, measured results were compared against the signal strength contours of a coverage plot.

Figure 16 is a signal coverage plot for the Appleton GWEN site during daytime hours, when there is no significant skywave propagation. The boundaries between the five concentric regions in the plot are contours of groundwave field strength corresponding to 37.5, 50.0, 60.0, and 70.0 dBµV/m. The U.S. Coast Guard specifies a minimum field strength of 37.5 dBµV/m for DGPS signal coverage.

The plot was generated using a smooth earth propagation model, which neglects irregular terrain effects but takes into account varying ground conductivity using a conductivity database. The irregular terrain model was not used to generate this plot because terrain effects are generally not expected to be significant at this frequency (300 kHz) and because the irregular terrain model is not numerically stable beyond approximately 250 km, whereas the signal coverage and measured data extend to considerably greater distances. However, a signal coverage plot to distances of 250 km from the transmitter was generated using the irregular terrain model, and is not significantly different from that using the smooth earth model.

Comparisons of the signal coverage plot to the measured data indicate that for the route between Appleton and Spokane, the model and measurements are in close agreement. However, for the other routes, which were driven in hilly or mountainous terrain, the measured field strengths are generally less than those predicted by the model. For example, at Bellingham the difference between the measured and predicted field strengths is greater than 10 dB.

The fact that the irregular terrain and smooth earth models make similar predictions suggests that the larger discrepancies between the model and measurements are not due to irregular terrain effects, but are presumably due to inadequacies in the conductivity database, which is quite sparse at some geographic locations. In mountainous terrain, the ground conductivities are typically poor, and this may not be fully represented in the database.
To further investigate this possibility, the propagation model was used in a mode that does not access the conductivity database, but in which the ground conductivity is entered manually. For example, the values of ground conductivity in the database at the geographic locations corresponding to Spokane and Bellingham are both 0.004 S/m, which is a typical value of conductivity for average ground. Using this value of conductivity, the propagation model predicts that the field strength at Spokane (350 km from Appleton) is 43 dBµV/m, in good agreement with the measured data.

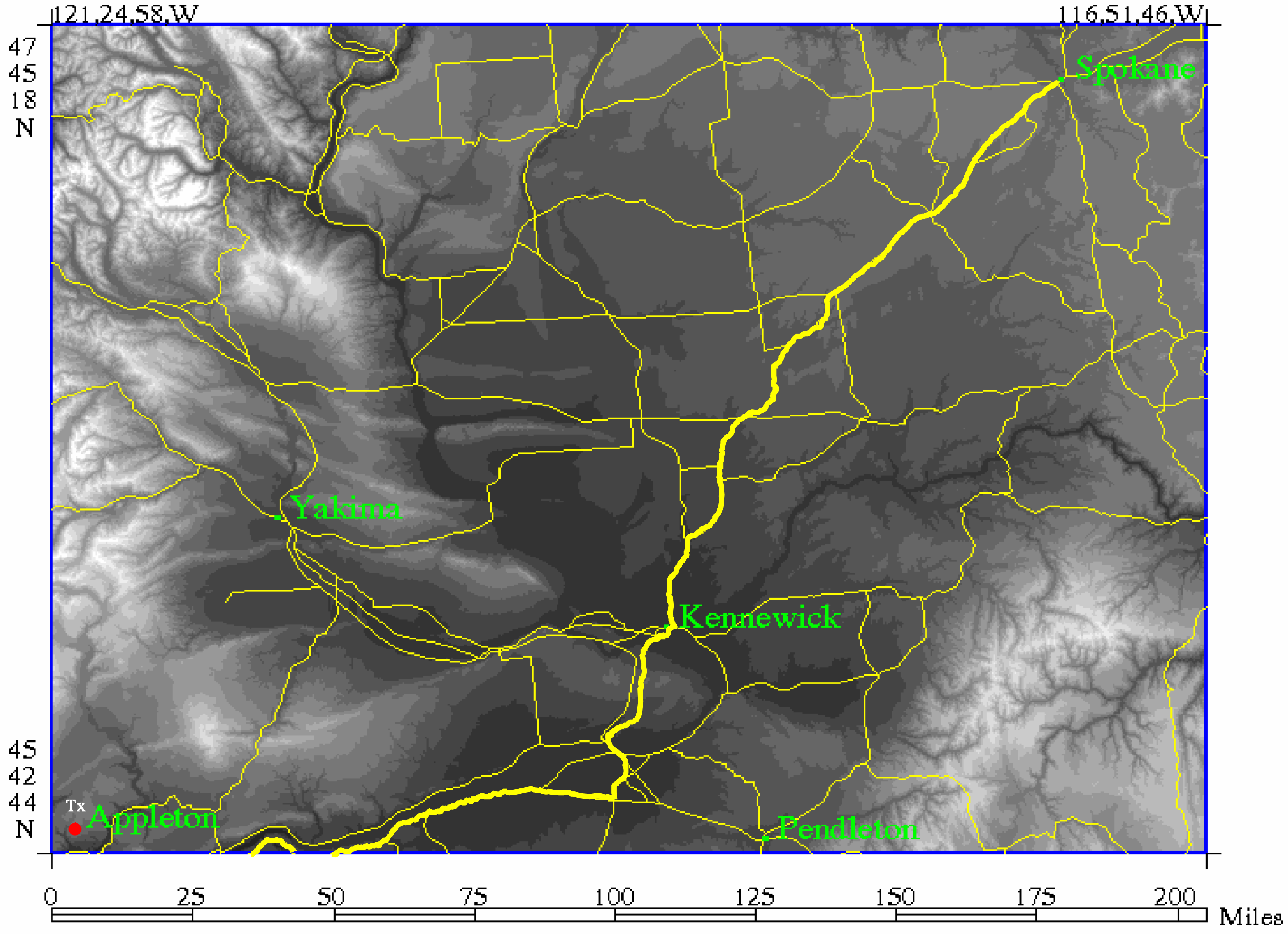

Figure 15. Topography for the route (thick yellow line) between the Appleton GWEN site and Spokane, Washington.

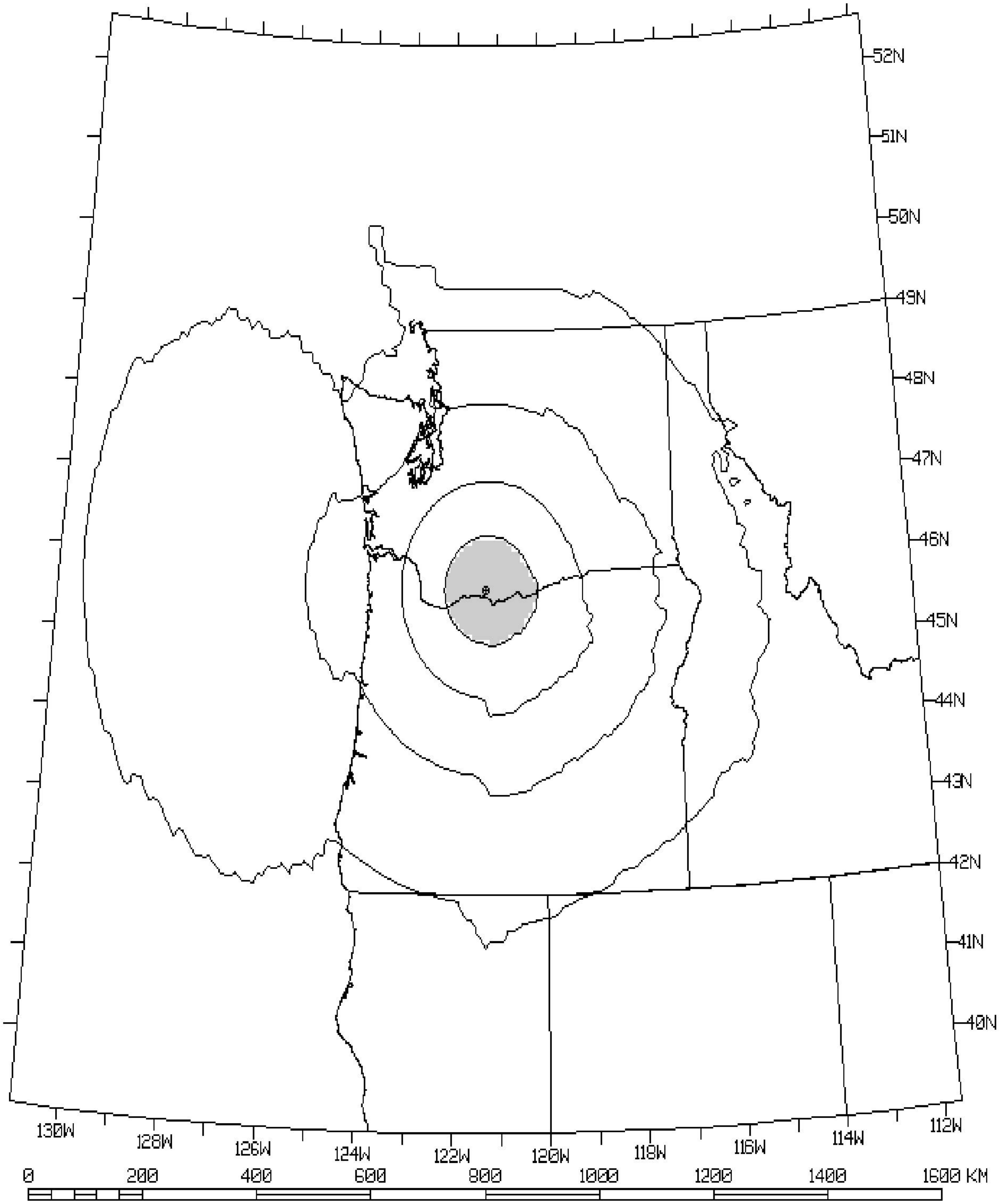

Figure 16. Signal coverage prediction plot for the Appleton GWEN site showing contours for field strengths of 37.5, 50.0, 60.0, and 70.0 dBμV/m.

However, to obtain the measured field strength of approximately 28 dBµV/m at Bellingham (330 km from Appleton), a conductivity of 0.0008 S/m had to be used in the model. This value of conductivity is typical of poor ground, which is often found in mountainous regions. Thus, realistic variations in ground conductivity that are not represented in the database could easily account for the discrepancies between the model and the measurements.

10. SUMMARY

Field strength measurements were conducted to determine the signal coverage generated by a GWEN antenna and a DGPS transmitter used by the U.S. Coast Guard. The measured field strengths at 10 km correspond closely to theoretical expectations based on detailed modeling of the GWEN antenna using an antenna efficiency of approximately 50%, producing a radiated power of 500 W for an input power of 1 kW.

The dependence of field strength with distance from the transmitter is in good agreement with the predictions of propagation models in the absence of irregular terrain. However, in hilly and mountainous terrain, the model tends to predict field strengths that are greater than those that were measured. Some of the smaller discrepancies (on the order of a few dB or less) appear to be due to irregular terrain effects, for example, decreases in field strength when the receiver is in the shadow of a large terrain feature. However, larger discrepancies (as large as 10 dB or more), are presumably due to an incomplete database of ground conductivities in irregular terrain. When using model predictions to plan a nationwide DGPS service, it should be realized that small gaps in coverage that are not predicted by the model may occur, and will have to be dealt with on a case-by-case basis.

11. REFERENCES

[1] "U.S. Air Force Ground Wave Emergency Network final operational capability: final environmental impact statement," Department of Air Force Report, Vol 1, Sep. 1987.

[2] N. DeMinco, "Ground-wave analysis model for MF broadcast systems," NTIA Report 86-203, Sep. 1986.

[3] E. Haakinson, S. Rothschild, and B. Bedford, "MF broadcasting system performance model," NTIA Report 88-237, Aug. 1988.

APPENDIX A: COMPUTATION OF EXPECTED ELECTRIC FIELD STRENGTH

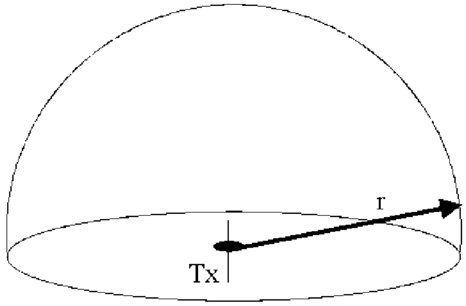

Figure A-1. Signal radiating isotropically into a hemisphere.

For a known power into a transmitting antenna and a given antenna efficiency, the expected signal strength in dBμV/m can be determined at a specified distance from the transmitter. Assuming the signal is radiating isotropically into a hemisphere (see Figure A-1), the power is evenly distributed over a surface equal to $2\pi r^2$ (where r is the distance from the transmitter in meters). The power density at the receiver expressed in watts/m^2 can be determined by

$$P_d = \frac{P_t \, e}{2 \pi r^2} \,, \tag{A1}$$

where e is the efficiency of the transmitting antenna, and P_t is the input power in watts.

The electric field E in dBμV/m is determined by

$$E = 20 \log_{10}(1e6 \sqrt{P_d \, 377}) \,, \tag{A2}$$

where 377 is the impedance of free space measured in ohms.

The efficiency and gain of the GWEN antenna at Appleton were determined by using the ITS antenna model, which is described by DeMinco [1] and references contained therein. The model is based on a set of algorithms that take into account the antenna tower, the radial ground plane, and the top loading of the antenna. The model predicts an antenna efficiency of approximately 50% and a directive gain for the ground wave (in the horizontal direction) of approximately 6 dB.

As an example, if the GWEN antenna were radiating isotropically with an efficiency e of 50% and signal power P_t into the antenna of 1000 W, the expected power density P_d at 10 km would be 7.96e-7 watts/m^2 (Equation A1). The expected electric field strength E at the same distance would be approximately 85 dBμV/m (Equation A2).

If the transmitting antenna is not radiating isotropically (as is usually the case), there is an additional gain that must be taken into consideration. For the example above, given a directive gain of 6 dB for the ground wave, the expected electric field strength *E* at 10 km is approximately 91 dBμV/m.

REFERENCE

[1] N. DeMinco, "Ground-wave analysis model for MF broadcast systems," NTIA Report 86-203, Sep. 1986.

APPENDIX B: SIGNAL FIELD STRENGTH COMPUTATIONS

Field strength is measured in dBµV/m as seen by the receiving antenna. This is calculated from the peak-power value and the antenna-correction factor using the following equations:

$$G_{dB_i} = -29.79 + 20\log_{10}(f_{MHz}) - ACF, \tag{B1}$$

where G_{dB_i} is the gain of the antenna in dBi, f_{mHz} is the frequency in MHz, and ACF is the antenna correction factor in dB;

$$A = \frac{\lambda^2 * 10^{\frac{G_{dB_i}}{10}}}{4\pi}, \tag{B2}$$

where A is the aperture of the antenna in units of m^2 and λ is the wavelength of the carrier frequency in meters;

$$\lambda = \frac{c}{f_{Hz}}, \tag{B3}$$

where c is the speed of light in m/s (3e8 m/s), and f_{Hz} is the carrier frequency in Hz;

$$P_d = \frac{P_{m(watts)}}{A}, \tag{B4}$$

where P_d is the power density in watts/m^2, and $P_{m(watts)}$ is the power in watts measured at the output of the antenna; and

$$E_{dB\left(\frac{\mu v}{m}\right)} = 20 * \log_{10}\left(1e6 * \sqrt{P_d * 377}\right), \tag{B5}$$

where $E_{dB\left(\frac{\mu v}{m}\right)}$ is the E field in dBµV/m measured at the antenna, and 377 is the impedance of free space measured in ohms.