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Communications Range Predictions for Mobile Radio Systems

NIJ Report 201-88

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Technology Assessment Program

Communications Range Predictions for Mobile Radio Systems

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National Institute of Justice

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FOREWORD

The Law Enforcement Standards Laboratory (LESL) of the National Bureau of Standards (NBS) furnishes technical support to the National Institute of Justice (NIJ) program to strengthen law enforcement and criminal justice in the United States. LESL's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

LESL is: 1) Subjecting existing equipment to laboratory testing and evaluation and 2) conducting research leading to the development of several series of documents, including national voluntary equipment standards, user guides, and technical reports.

This document covers research on law enforcement equipment conducted by LESL under the sponsorship of NIJ. Additional reports as well as other documents are being issued under the LESL program in the areas of protective equipment, communications equipment, security systems, weapons, emergency equipment, investigative aids, vehicles, and clothing.

Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Law Enforcement Standards Laboratory, National Bureau of Standards, Gaithersburg, MD 20899.

Lester D. Shubin
Program Manager for Standards
National Institute of Justice

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COMMONLY USED SYMBOLS AND ABBREVIATIONS

A	ampere
ac	alternating current
AM	amplitude modulation
cd	candela
cm	centimeter
CP	chemically pure
c/s	cycle per second
d	day
dB	decibel
dc	direct current
°C	degree Celsius
°F	degree Fahrenheit
diam	diameter
emf	electromotive force
eq	equation
F	farad
fc	footcandle
fig.	figure
FM	frequency modulation
ft	foot
ft/s	foot per second
g	acceleration
g	gram
gr	grain
H	henry
h	hour
hf	high frequency
Hz	hertz (c/s)
i.d.	inside diameter
in	inch
ir	infrared
J	joule
L	lambert
L	liter
lb	pound
lbf	pound-force
lbf·in	pound-force inch
lm	lumen
ln	logarithm (natural)
log	logarithm (common)
M	molar
m	meter
min	minute
mm	millimeter
mph	mile per hour
m/s	meter per second
N	newton
N·m	newton meter
nm	nanometer
No.	number
o.d.	outside diameter
Ω	ohm
p.	page
Pa	pascal
pe	probable error
pp.	pages
ppm	part per million
qt	quart
rad	radian
rf	radio frequency
rh	relative humidity
s	second
SD	standard deviation
sec.	section
SWR	standing wave radio
uhf	ultrahigh frequency
uv	ultraviolet
V	volt
vhf	very high frequency
W	watt
λ	wavelength
wt	weight

area = unit^2 (e.g., ft^2, in^2, etc.); volume = unit^3 (e.g., ft^3, m^3, etc.)

PREFIXES

d	deci (10^{-1})
c	centi (10^{-2})
m	milli (10^{-3})
μ	micro (10^{-6})
n	nano (10^{-9})
p	pico (10^{-12})
da	deka (10)
h	hecto (10^2)
k	kilo (10^3)
M	mega (10^6)
G	giga (10^9)
T	tera (10^{12})

COMMON CONVERSIONS
(See ASTM E380)

ft/s × 0.3048000 = m/s
ft × 0.3048 = m
ft·lbf × 1.355818 = J
gr × 0.06479891 = g
in × 2.54 = cm
kWh × 3 600 000 = J
lb × 0.4535924 = kg
lbf × 4.448222 = N
lbf/ft × 14.59390 = N/m
lbf·in × 0.1129848 = N·m
lbf/in^2 × 6894.757 = Pa
mph × 1.609344 = km/h
qt × 0.9463529 = L

Temperature: $(T_{°F} - 32) \times 5/9 = T_{°C}$

Temperature: $(T_{°C} \times 9/5) + 32 = T_{°F}$

COMMUNICATIONS RANGE PREDICTIONS FOR MOBILE RADIO SYSTEMS

W. A. Kissick and J. M. Harman*

National Telecommunications and Information Administration, Boulder, CO 80303

In earlier work, azimuthal power gain radiation patterns of mobile antennas mounted in six different locations on a test vehicle were measured with and without typical lights and siren mounted on the roof. The patterns were measured in each of four public safety frequency bands and, in addition, the patterns of several covert antennas and a slot antenna were measured. This report extends that work by computing the cumulative distribution of power gain for each of the measured radiation patterns. The usefulness of this information is further extended by computing estimates of propagation range for each case—based on nominal assumptions of certain system and environmental parameters. These new results also provide a realistic way of comparing antenna performance, since the orientation of the vehicle and the direction to a base station are unknown.

Key words: antenna measurements; antenna patterns; cumulative distributions; mobile antennas; power gain; radiation patterns.

1. INTRODUCTION

Of the equipment used by law enforcement and other public safety personnel, mobile radio systems are a necessity. There is usually one, and often more than one, transceiver mounted in each patrol car or emergency vehicle. Adequate mobile radio performance is a requirement, and important features of that performance are coverage and range. The focus of the work presented in this report is the mobile antenna, its location on a patrol car and how the radio frequency and antenna location affect azimuthal coverage and nominal range.

The power gain radiation patterns for vertical (whip) antennas mounted in six different locations on a vehicle were measured at four discrete frequencies [1][1]. In addition, the patterns of three disguised antennas operating at three discrete frequencies mounted in one location and the pattern of a covert (slot) antenna were also measured. In all cases, the measurements were made with and without the lights and siren mounted on the roof of the test vehicle. Figures 1 and 2, from [1], show the antenna locations and the dimensions of the test vehicle.

In order to assess or rank the performance of the various antenna locations, with and without the lights and siren and at the various radio frequencies, a way of presenting and comparing the azimuthal antenna patterns is needed. It is very difficult to compare the radiation patterns directly because an important feature is the number and depth of nulls in the pattern. Any direct comparison of the radiation patterns either must be subjective or computationally intensive. However, the cumulative distributions of the patterns can be compared objectively. One can easily determine the percentage of the full azimuth for which the antenna gain remains above a specific level—an aggregate measure of the number and depth of the nulls. This approach is well-suited to the situation where both the orientation of the vehicle and the direction to the distant terminal are unknown.

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* Institute for Telecommunication Sciences.

[1] Numbers in brackets refer to references in section 5.

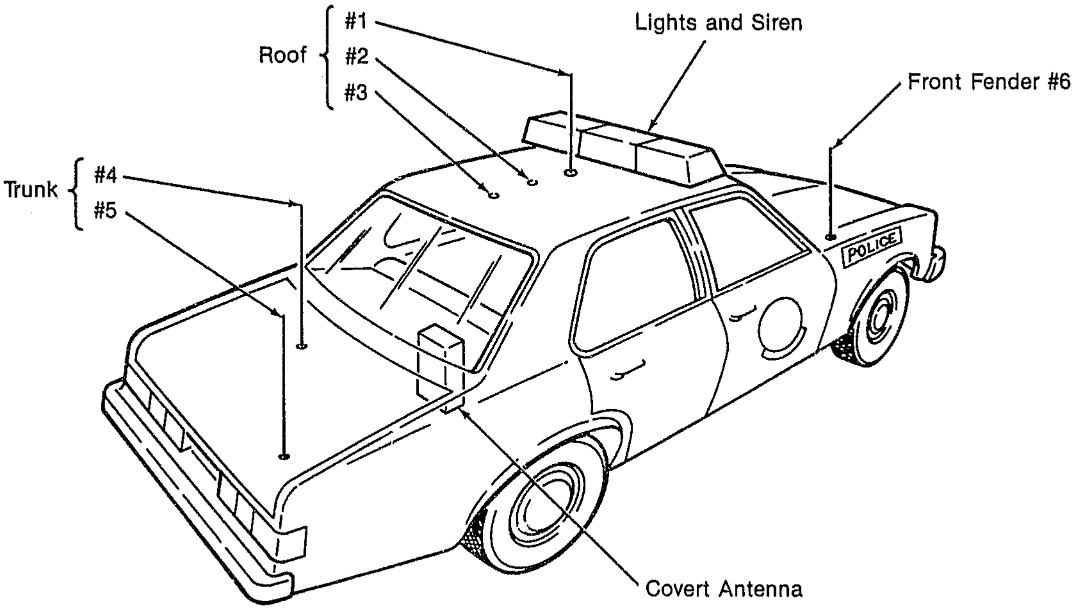


Figure 1. *Vehicle antenna locations [1].*

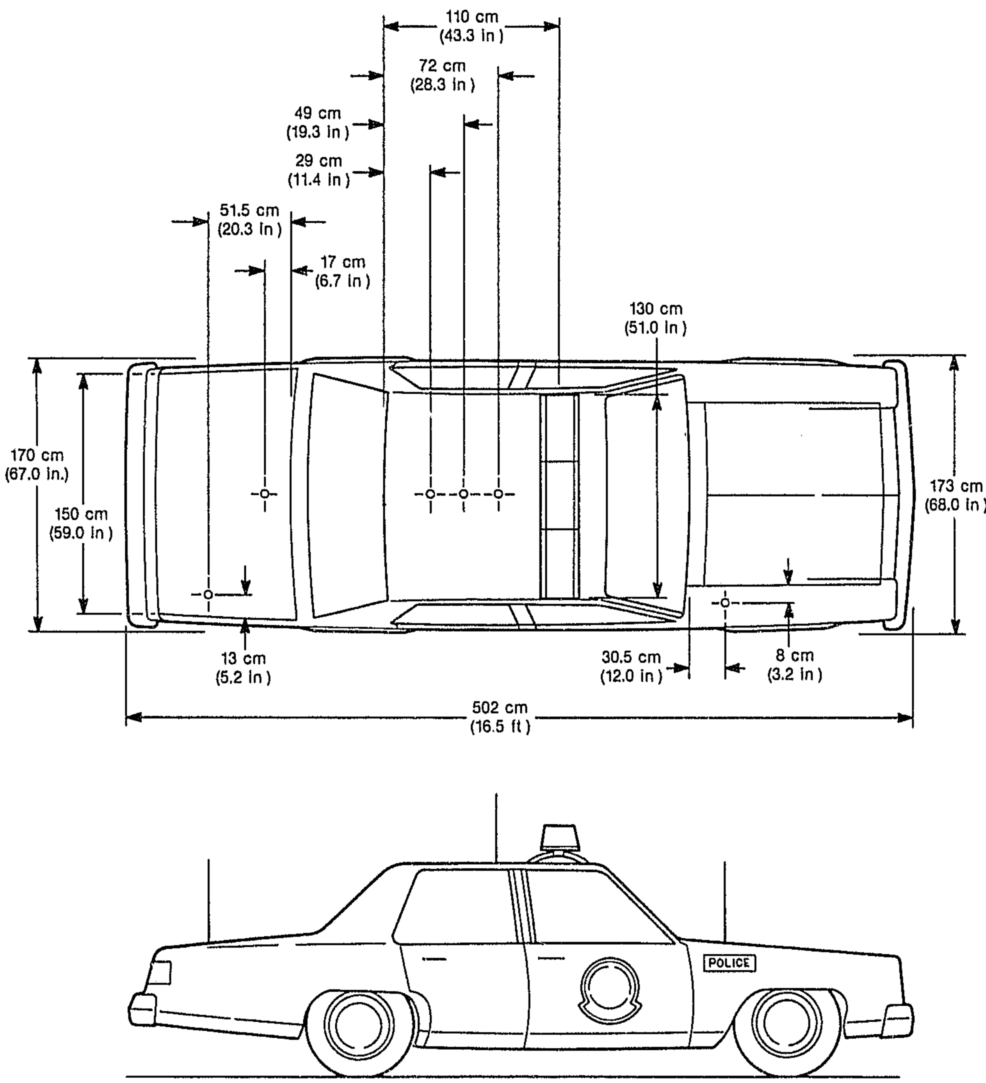


Figure 2. *Vehicle dimensions and mounting locations [1].*

2. CUMULATIVE GAIN DISTRIBUTIONS

Using the data measured by Jesch [1], this report presents cumulative distributions for each of 56 antenna configurations. Measurements were originally made at each of six antenna locations on the vehicle at frequencies of 840, 460, 150, and 40 MHz, both with and without the lights and siren in place. In addition, measurements were made using disguised or covert antennas at 416, 413, 162, and 40 MHz, also with and without the lights and siren in place.

Figures 3 and 4 show the original power gain radiation patterns in the upper portion and cumulative distributions for the same data in the lower portion. Figure 3 depicts the measurements at 840 MHz with the antenna mounted in position 1, both with and without the lights and siren in place. Figure 4 depicts measurements with an 840 MHz antenna in positions 1, 2, and 3 with the lights and siren mounted.

The left ordinate scale of the cumulative distribution shows the absolute gain in decibels (dB) from the original measurements. The abscissa scale is in percent of azimuth directions as the vehicle is rotated through 360 °. As the orientation of the vehicle is changed, the signal available to and from the antenna increases and decreases due to the amount of interference created by the antenna's immediate surroundings. Using the power gain pattern, the reader can determine an orientation of the vehicle to achieve maximum signal. However, by using the cumulative distribution, one can see instantly to what extent the radio frequency signal is degraded by the antenna's location on the vehicle and/or by the lights and siren. For example, in figure 3 the coverage is almost uniform in all directions without the lights and siren bar, but is very dependent on the azimuth involved with the bar installed. In addition, one can see from the distribution that, with the lights and siren bar in place during a full rotation of the vehicle, the signal may be degraded more than 10 dB. As the antenna position and frequency are changed, the signal may be degraded more than 20 dB.

The cumulative distribution simply shows graphically the percentage of vehicle orientations for which the antenna gain is above or below a certain level. As an example, assume the horizontal line across the data in figure 5 represents a minimally acceptable transmitted signal. By drawing a vertical line from the point where the horizontal line intersects antenna positions 5 and 6, we see that communication is probable with the vehicle orientated in less than 50 percent of its possible directions. If the capability of the equipment is such that communication from a specific location is marginal and the desired direction is known, the operator may achieve an improved signal by using the power gain radiation pattern to orient the vehicle in the most advantageous direction, as was previously shown in figure 3.

Use of the power gain pattern alone, however, will not give the operator a maximum or minimum distance over which the equipment being used should be able to communicate. For this determination, the cumulative distribution becomes a valuable tool. If the capabilities of the equipment and the terrain over which communication must take place are known, a range of distances may be assigned to the distribution allowing the operator to see within what area communications are probable.

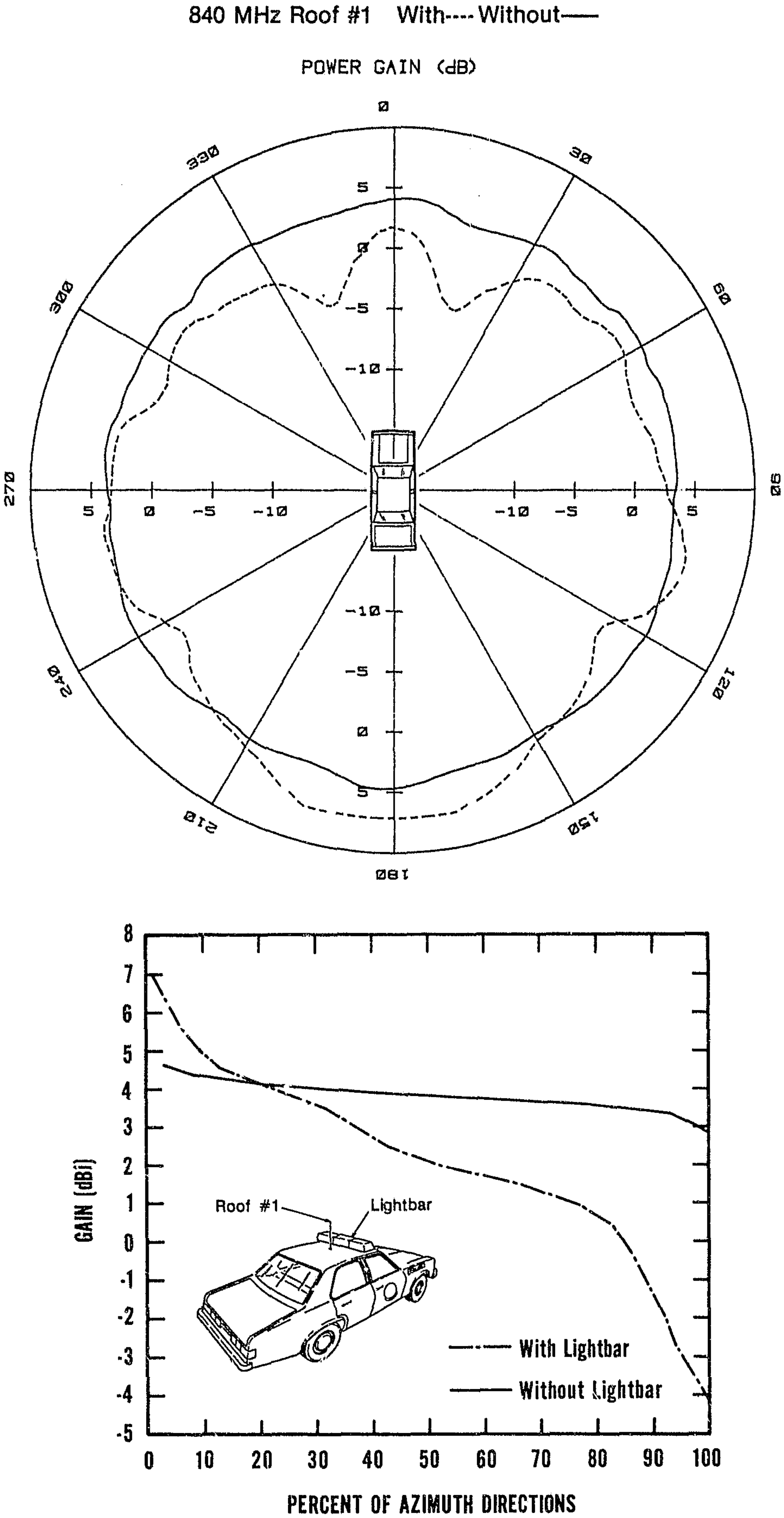
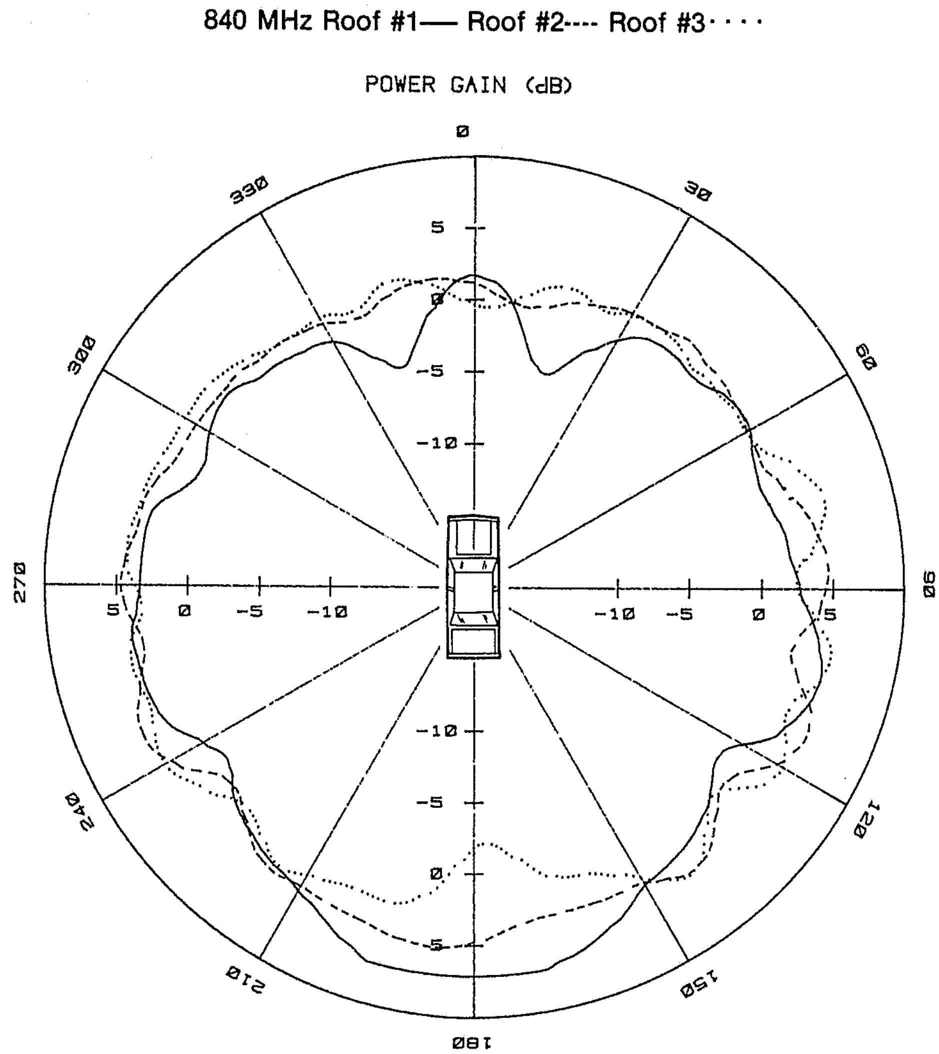


FIGURE 3. *Power gain radiation pattterns (upper figure, [1]) and cumulative distributions (lower figure) for antenna location 1 at 840 MHz with and without light and siren bar.*



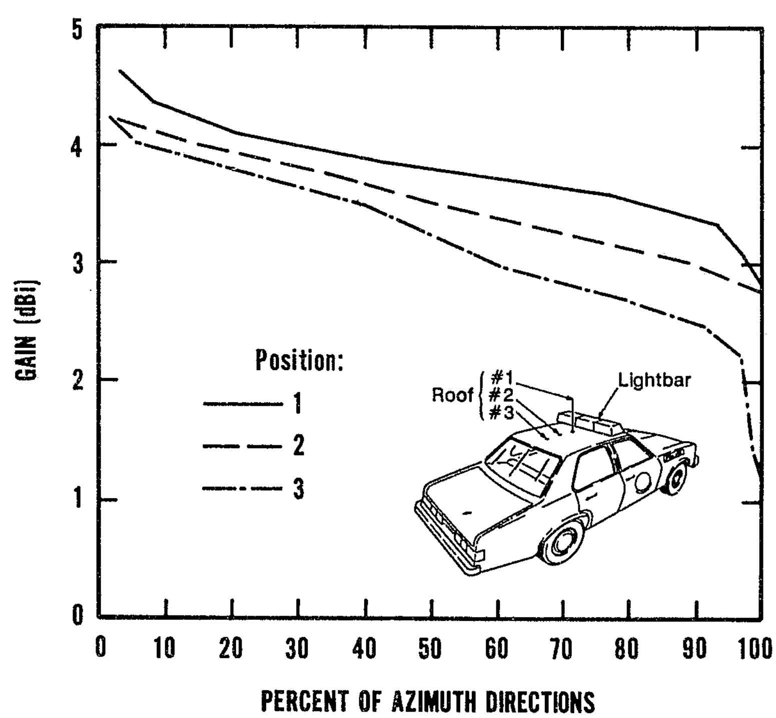


FIGURE 4. *Power gain radiation patttems (upper figure, [1]) and cumulative distributions (lower figure) for antenna locations 1, 2, and 3 at 840 MHz with the light and siren bar.*

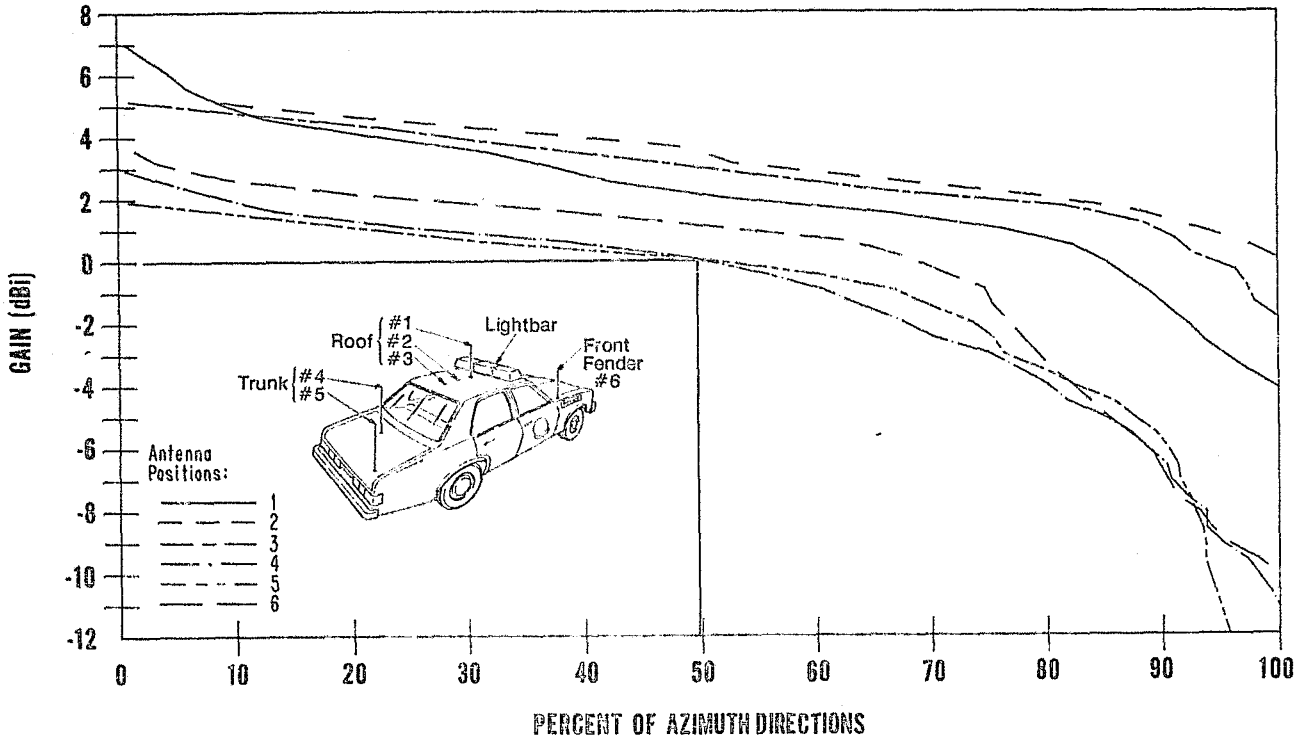


FIGURE 5. *Example of how to use a cumulative distribution.*

3. COMMUNICATION RANGE PREDICTIONS

The range of a radio signal transmitted from an antenna mounted on a vehicle to a distant base station depends not only on the gain of that antenna but also on the transmitter power, the receive antenna gain, the receiver sensitivity, and the transmission loss. The transmission loss, in turn, depends on several other variables, such as the intervening terrain profile, the antenna heights, and the radio frequency.

There are a number of VHF/UHF propagation models that can be used to make communications range predictions. More correctly, the propagation model is used to make the transmission loss prediction, and that prediction, together with a power budget for the radio link, allows one to make the communication range prediction. For the case at hand—land mobile radio in the situation where the actual terrain profile is unknown—a propagation model that includes the effects of irregular terrain in a statistical fashion is needed. This need is filled by an "area" type propagation model. The other type of propagation model, called a "point-to-point" model, uses the detailed knowledge of the terrain profile between transmitter and receiver to make a transmission loss prediction. A point-to-point model can produce a more precise prediction, but that prediction is only good for a fixed radio link operating over the specified path. An area model produces a prediction that is useful over all terrain profiles that have the same "roughness" or "irregularity."

As mentioned above, the point-to-point model is not appropriate here, but is described to provide the reader with some background. The terrain features typically needed by a point-to-point model are shown in figure 6. These include the terrain elevation (ELV) at each end of the path, the antenna heights (HT), the distance to each horizon (HZ D), the horizon elevations (HZ ELV), and the path distance (DIST). In the point-to-point model, all of these parameters are determined from the actual terrain profile and used in the model to make a transmission loss prediction.

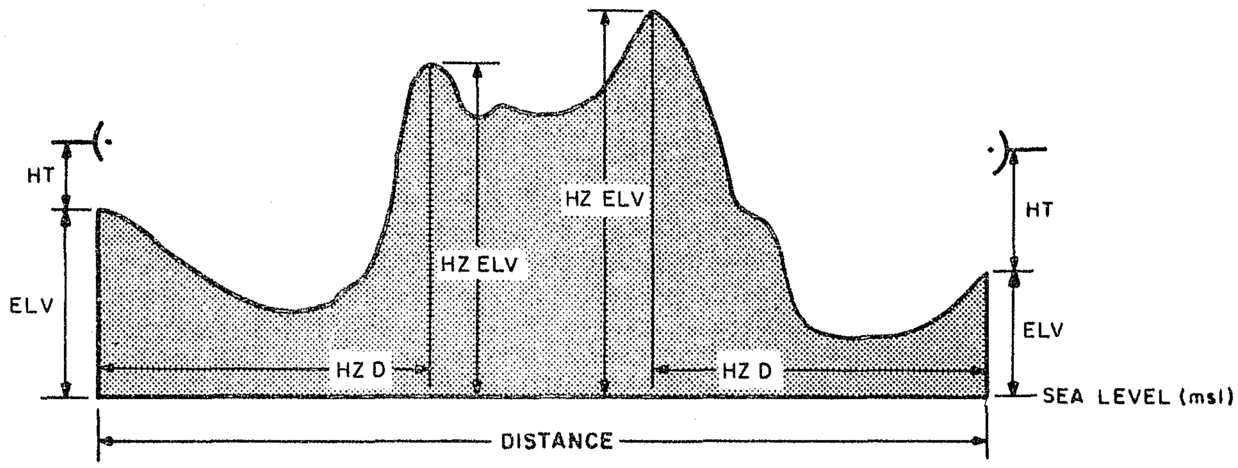


FIGURE 6. *Terrain features used for point-to-point propagation (communication range) predictions.*

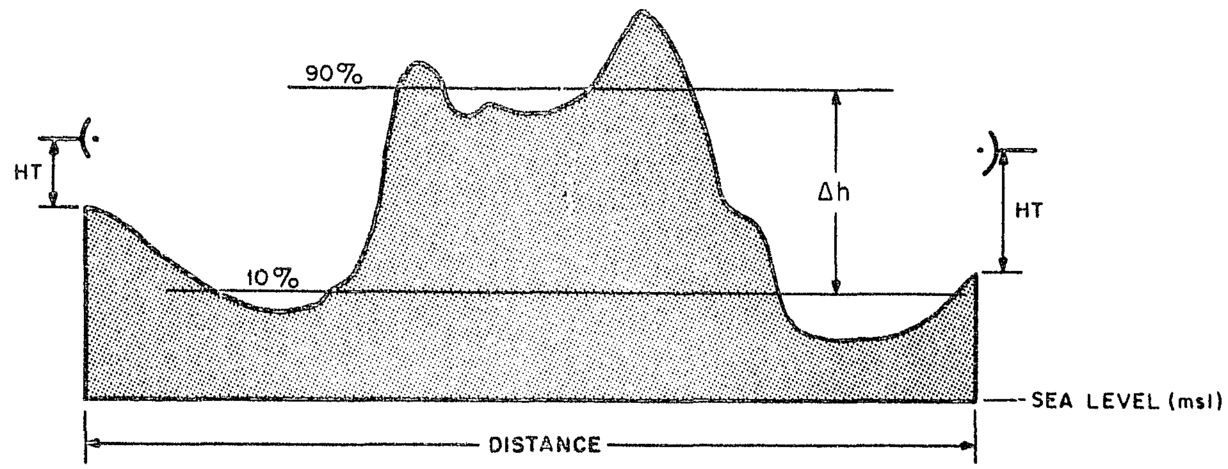


FIGURE 7. *Terrain features used for area propagation (communication range) predictions.*

Another parameter which can be extracted from a terrain profile is the terrain irregularity, h. It is the difference between the 10-percentile and the 90-percentile of all the elevations of the terrain between the end points as shown in figure 7. With an area model, all that is needed from the terrain profile to make a transmission loss prediction is the path distance, the terrain irregularity, and the antenna heights. This method of making transmission loss predictions is best suited for those cases where the actual terrain profile is not known, e.g. for broadcast and mobile applications.

3.1 Propagation Model and Assumptions

The propagation model used to make the transmission loss predictions is based on the ITS ITM (Institute for Telecommunication Sciences Irregular Terrain Model) [2], called RAPIT (Radio Propagation over Irregular Terrain). The RAPIT model is available as a dial-up, time-share service offered by ITS in Boulder, Colorado.[2] The interested reader is referred to Hufford et al. [2] for a detailed discussion of the ITM and area type VHF/UHF propagation models for irregular terrain.

[2] Interested parties should contact Mr. J. E. Adams at 303-497-5301 or at NTIA/ITS.S4, U.S. Department of Commerce, 325 Broadway, Boulder, CO 80303.

In order to make transmission loss predictions for this work, values for a number of variables (inputs) must be assumed. The most important assumptions are as follows. Wave polarization was considered to be vertical. The ground constants used in the model to compute the effects of ground reflections were assigned average values of 0.005 mho/m for conductivity and 15.0 for relative permittivity. The climate region was assumed to be "continental temperate." The surface atmospheric refractivity was assigned the value associated with sea level conditions. The antenna heights were given values of 1.5 m (4.9 ft) for the mobile transmitter and 30.0 m (98.4 ft) for the base station receiver. The assumed mobile transmitter power was 100 watts, and the receive antenna was given a value of 0 dBi gain for a receiver sensitivity of 0.4 μV into a typical 50 Ω resistance.

In addition to the above assumptions, three values of Δh (see fig. 7) were used: 25 m (82 ft) to represent smooth terrain, 100 m (328 ft) to represent average terrain, and 600 m (1968 ft) to represent rough terrain. And finally, two values of reliability were assumed: 50% to represent marginal conditions and 90% to represent good conditions. Reliability, as it is used here, can be interpreted to mean "first try success probability." In other words, for each short message transmitted, this is the probability that it is received on the first transmission. Most VHF/UHF propagation models use several characteristics to quality the transmission loss prediction. The ITM uses three characteristics: time, location, and confidence. If one sets the confidence to 90% and combines the time and location parameters, the result is the reliability as defined above. The interested reader is again referred to Hufford et al. [2] for a thorough treatment of these propagation characteristics.

3.2 Range Computation

The maximum range of a radio link (transmitter to receiver) is the distance at which the received signal is at the minimum required to achieve adequate performance. For this work, an assumed nominal receiver sensitivity defines the minimum received signal level. It is assumed that the mobile unit is the transmitter and that it transmits to a distant base station receiver.

The relationship between transmitter and receiver power for the radio link can be expressed as

$$P_r(d) = P_t - L_t + G_t - L_b(d) + G_r - L_r \text{ dBW} \quad (1)$$

where

$P_r(d)$ = *minimum* received power at the receiver terminals at distance d, in dBW,
P_t = transmitter output power, in dBW,
L_t = transmission line and other losses between the transmitter output and the antenna, in dB,
L_t = transmission line and other losses between the transmitter output and the antenna, in dB,
G_t = transmit antenna gain, in dBi,
$L_b(d)$ = *maximum* basic transmission loss between the lossless, isotropic transmit antenna and the lossless, isotropic receive antenna, in dB,
G_r = receive antenna gain, in dBi, and
L_r = transmission line and other losses between the receive antenna and the receiver input terminals, in dB.

The distance d is the value sought. The propagation model will provide the basic transmission loss as a function of d, Lb(d). The distance d is actually the (maximum) distance at which the maximum basic transmission loss is attained. Rearranging eq (1) one obtains

$$L_b(d) = G_t - Pr(d) + P_t - L_t + G_r - L_r. \quad (2)$$

The values for transmitter power, receive antenna gain, and the two transmission line losses are assumed as follows:

P_t = 20 dBW (100 W)
G_r = 0 dB
$L_t = L_r$ = 1 dB.

The value for the minimum received power, $P_r(d)$, is computed from the assumed receiver sensitivity of 0.4 μV into 50 Ω,

$$P_r(d) = V^2/4R = -151 \text{ dBW}. \quad (3)$$

Equation 2 can now be written to include the assumed values. The transmit antenna gain is the value given on the left ordinate of the cumulative gain plots and it will remain a variable in the equation. In addition, several other parameters that are inputs to the propagation model will be included as variables of L_b. Equation 2 becomes

$$L_b(d, Rel, \Delta h, f) = G_t + 169 \text{ dB} \qquad (4)$$

where

Rel = communication reliability, percent,
Δh = terrain roughness, m,
f = radio frequency, MHz.

This equation is used to compute values for the range scales appended to the right side of the cumulative gain (G_t) plots. For each radio frequency, this is accomplished as follows:

1. Choose a value of G_t (on the left ordinate scale) and compute L_{bt}, the total transmission loss.
2. Run the propagation model using the assumptions on antenna heights and the values of Δh and reliability to obtain a prediction of L_{bt} versus distance d.
3. Identify the distance d at which the L_{bt} computed in step 1 is reached.
4. The distance value determined in step 3 is plotted on the right ordinate scale at the same level as the G_t value chosen in step 1.

4. RESULTS AND INTERPRETATIONS

A cumulative distribution of the gain values for each power gain antenna pattern has been developed. The full set of distributions is presented in Appendix A to this report. The cumulative distribution of an antenna pattern is a practical, objective way of comparing the performance of different antenna configurations. Using the number of assumptions and the propagation model discussed earlier, the nominal communication range as a function of the antenna gain shown on the left-hand ordinate scale has been computed and is given on the right-hand ordinate scales. The range scales give an estimate of the communication range for the gain represented on the left-hand ordinate and for the assumptions about other system or environment parameters. There are six range scales based on two parameters—terrain roughness and communication reliability. Recall that reliability is defined as the probability that a short message will be successfully received on the first attempt. Figure 8 is an example of how to use the cumulative gain curves and the communication range scales.

Referring to figure 8, antenna position 1 will provide the highest gain, about 7 dBi. Although the 7 dBi gain is possible for only about 1% of the azimuth, one might ask what the maximum possible range would be. To answer the question, one could draw the lines labeled "limit A." The vertical line indicates (on the abscissa) the % of azimuth for which the indicated gain is equalled or exceeded. The horizontal line is used to read the range scales. Over smooth terrain with a reliability of 50%, the range estimate is about 57 km and over rough terrain with a 90% reliability the range estimate is about 1.3 km. If one wanted to know what the maximum possible range would be for the same antenna position but for the situation where the vehicle was oriented in the least advantageous way, one would use the lines labeled "limit C." The indicated gain is about −4 dBi and the range over smooth terrain with a reliability of 50% is about 40 km. Conversely, if one required a range of 30 km and a reliability of 90% over smooth terrain, the horizontal line can be drawn as in "limit B." One can then conclude that communication would be possible for about 74% of the vehicle orientations.

Use of the cumulative gain curves to compare the performance of different antenna positions is straightforward. If a required minimum gain value is known and a cumulative gain curve meets or exceeds that value for at least 85% of azimuth, the antenna position represented by that curve will probably provide sufficient performance. In general, the "flatter" the curve and the higher the curve, the better the antenna performance.

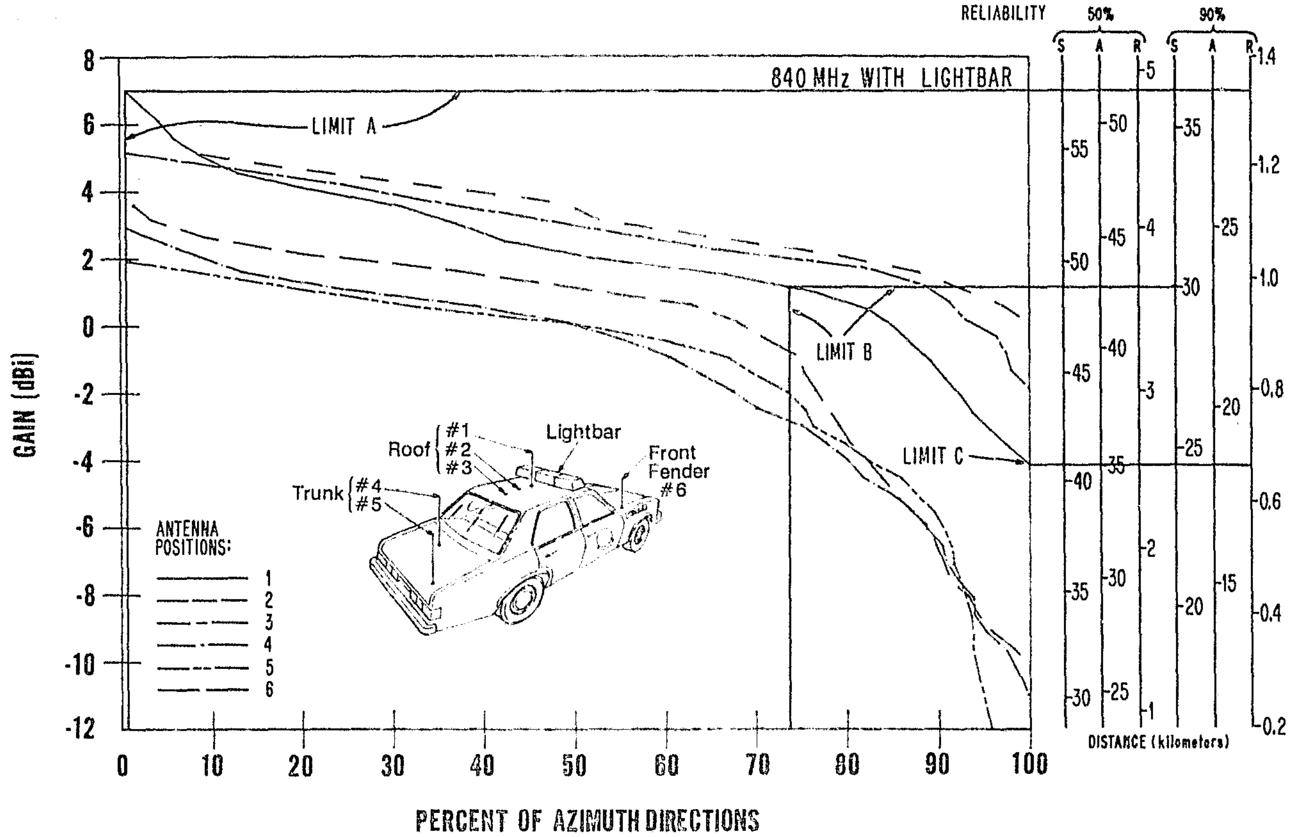


FIGURE 8. *Example of how to use the range scales to determine nominal communication distances.*

The communication range scales must be used with some caution. These values represent estimates and are best used in a relative fashion, for example, to compare the increase or decrease in range as a function of antenna gain. As discussed in section 3.1, a number of other system parameters were assumed to arrive at the values on the scales. The assumed mobile transmit power was 100 W which is greater than some police agencies use. To use a different value, for example 50 W, which is a 3 dB reduction from the assumed value, the transmit antenna gain must be reduced by 3 dB before the range scale is read. The assumed receive antenna gain of 0 dBi is conservative. If your base station antenna has a gain greater than 0 dBi, as most do, that value may simply be added to the transmit antenna gain before entering the tables. The transmit antenna height was assumed to be 1.5 m (4.9 ft). This is a nominal value and the results may be considered valid for transmit antenna heights of 1 to 3 m (3.28 to 9.84 ft). The base station receive antenna height was assumed to be 30 m (98.4 ft). The range estimates will not be valid for antenna heights that differ more than 5 or 10 m (16.4 to 32.8 ft) from this value. The assumed receiver sensitivity of 0.4 μV into 50 Ω is probably typical for most equipment. If one wants to use a different value, the difference between it and the assumed value in decibels can be added or subtracted from the transmit antenna gain value. The chosen or assumed values for climate zone, atmospheric surface refractivity, and the ground conductivity and relative dielectric constant are applicable to most conditions in the United States.

5. REFERENCES

[1] Jesch, R. L., Measured vehicular antenna performance, NIJ Report 201-85, National Institute of Justice, U.S. Department of Justice, Washington, DC 20531, 1983.

[2] Hufford, G. A., Longley, A. G., and Kissick, W. A., A guide to the use of the ITS Irregular Terrain Model in the area prediction mode, NTIA Report 82-100, 1982. Available from NTIS, Access. Order No. PB82-217977.

APPENDIX A—CUMULATIVE DISTRIBUTION RESULTS

This appendix contains a full set of cumulative gain distributions based on power gain measurements previously reported on. The left ordinate scale gives the gain of the mobile antenna and the right ordinate scales give the expected communication ranges. The utility of the cumulative distribution is that the performance of different antenna configurations can be objectively compared. A reasonable design criteria would be to ensure that the minimum gain needed is achieved for at least 80 to 85% of the azimuth directions.

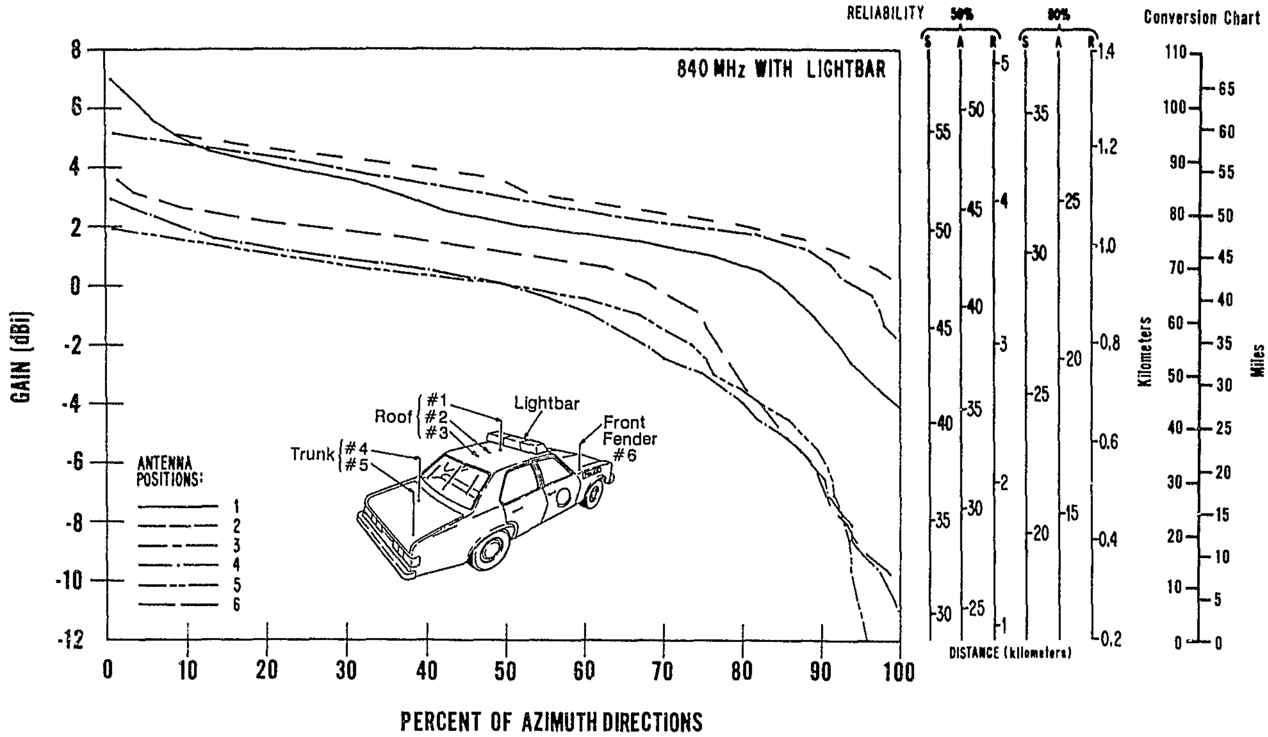


FIGURE A-1. *Cumulative distributions of the 840-MHz mobile antenna mounted in positions 1, 2, 3, 4, 5, and 6 with the light and siren bar in place.*

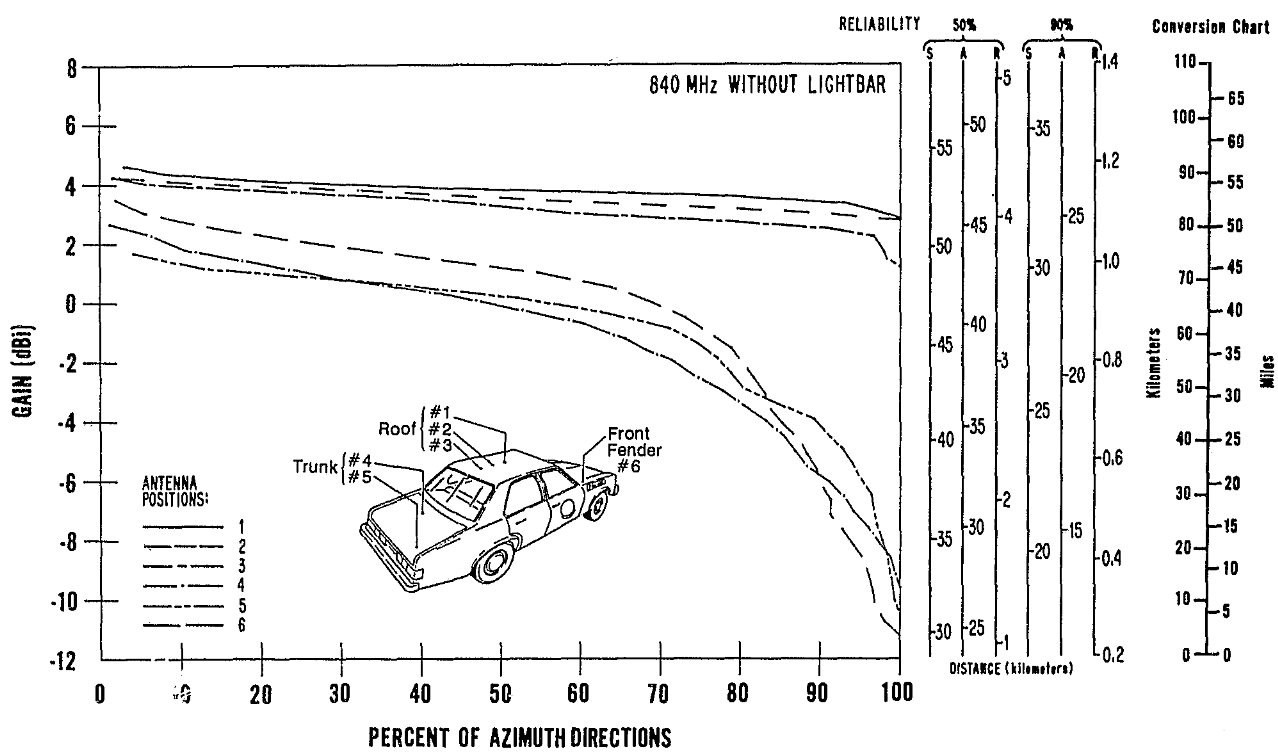


FIGURE A-2. *Cumulative distributions of the 840-MHz mobile antenna mounted in positions 1, 2, 3, 4, 5, and 6 without the light and siren bar in place.*

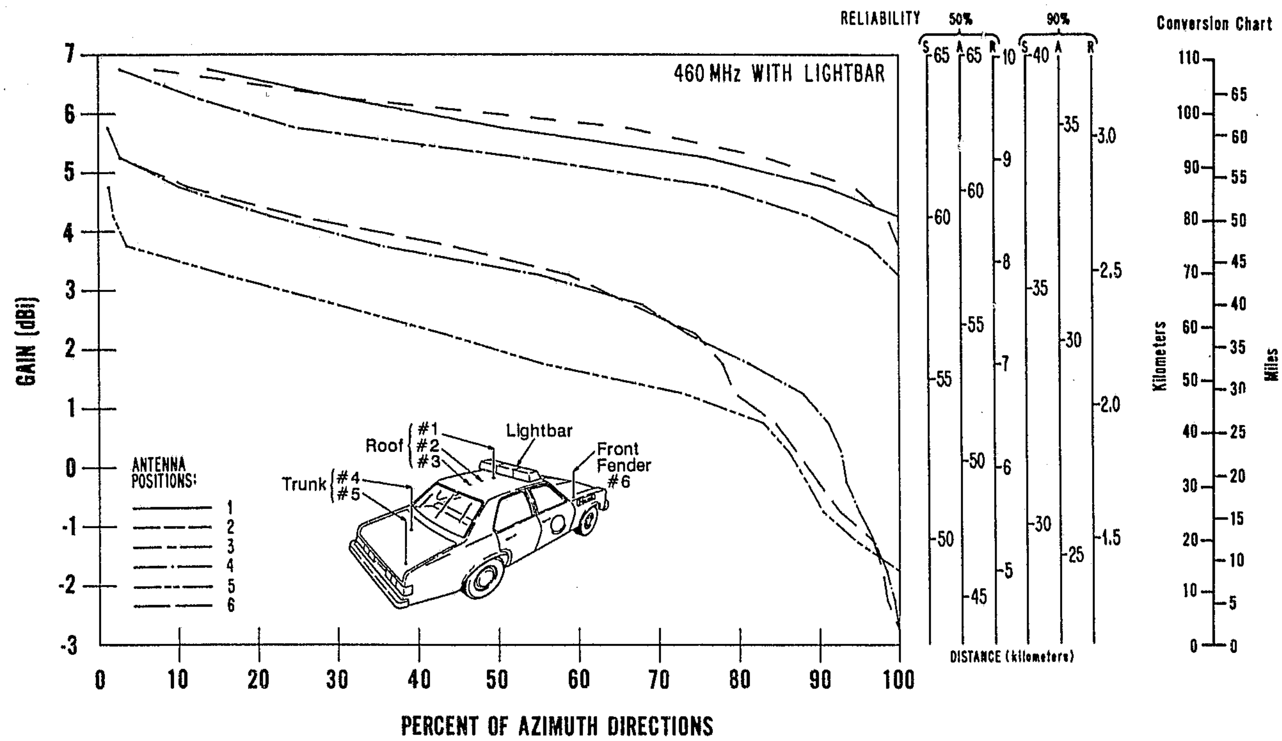


FIGURE A-3. *Cumulative distributions of the 460-MHz mobile antenna mounted in positions 1, 2, 3, 4, 5, and 6 with the light and siren bar in place.*

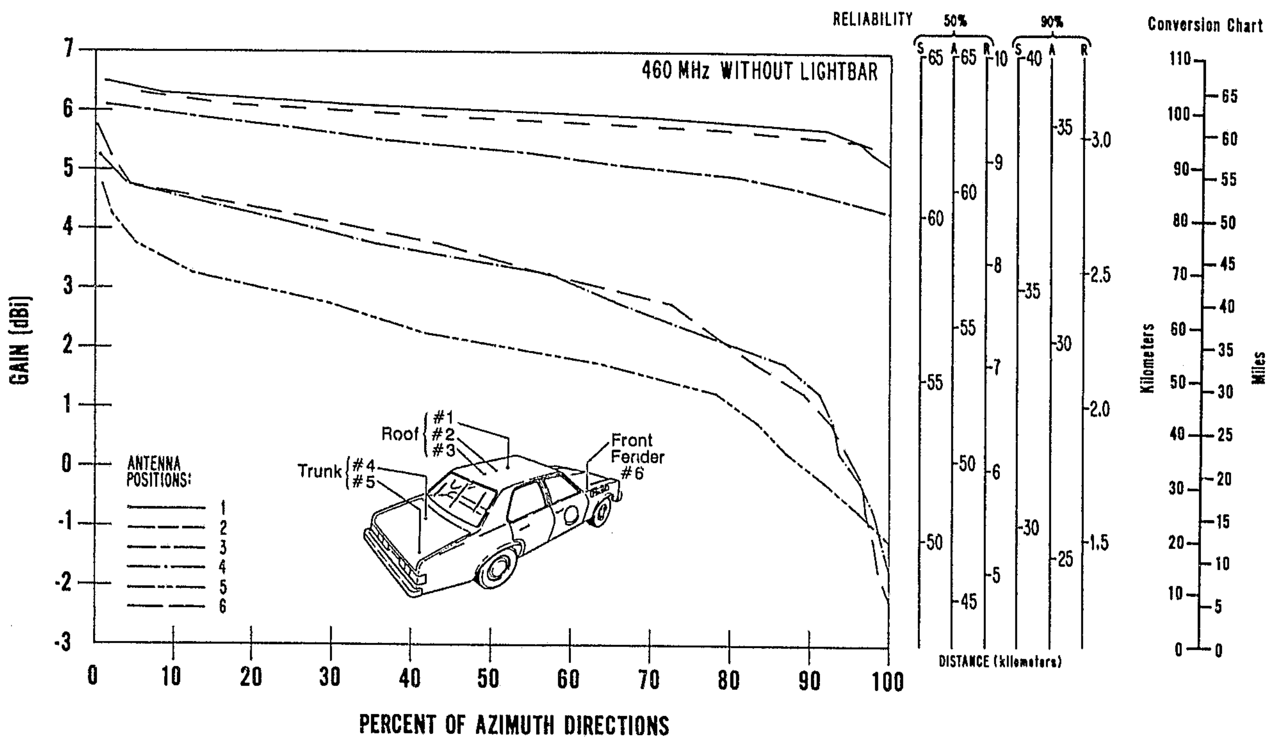


FIGURE A-4. *Cumulative distributions of the 460-MHz mobile antenna mounted in positions 1, 2, 3, 4, 5, and 6 without the light and siren bar in place.*

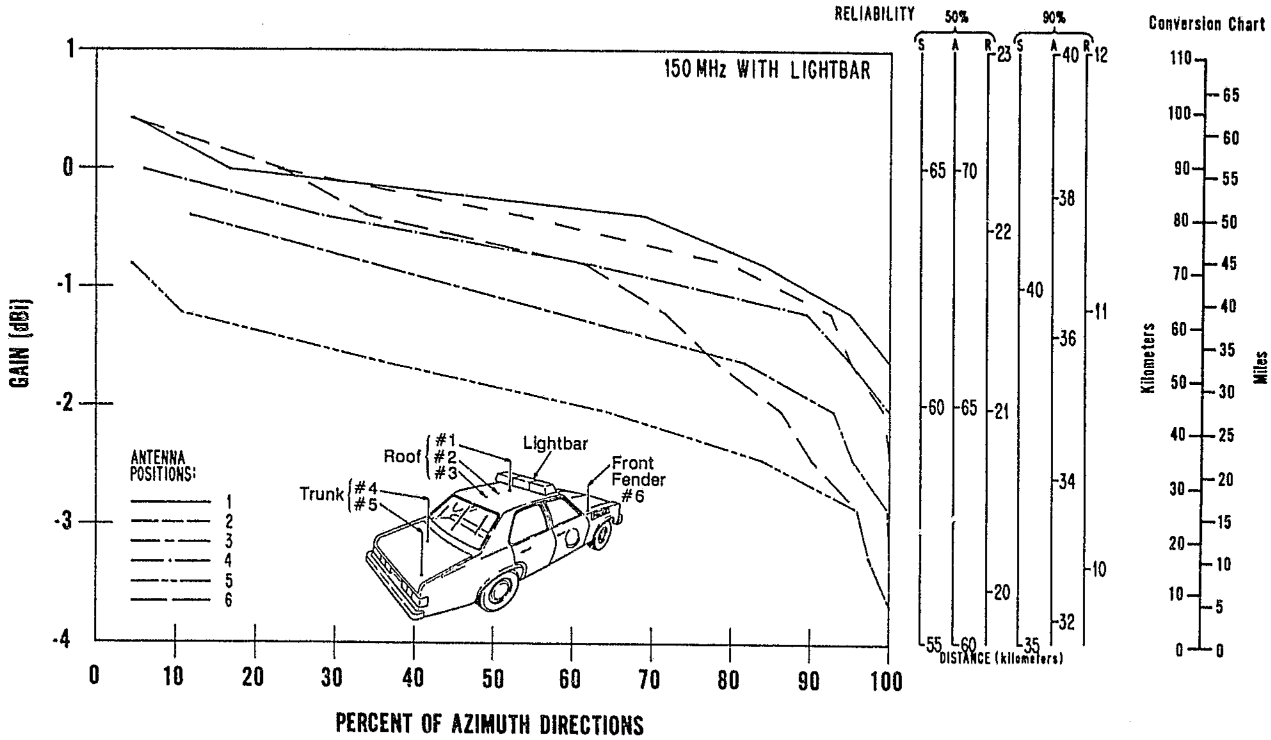


FIGURE A-5. *Cumulative distributions of the 150-MHz mobile antenna mounted in positions 1, 2, 3, 4, 5, and 6 with the light and siren bar in place.*

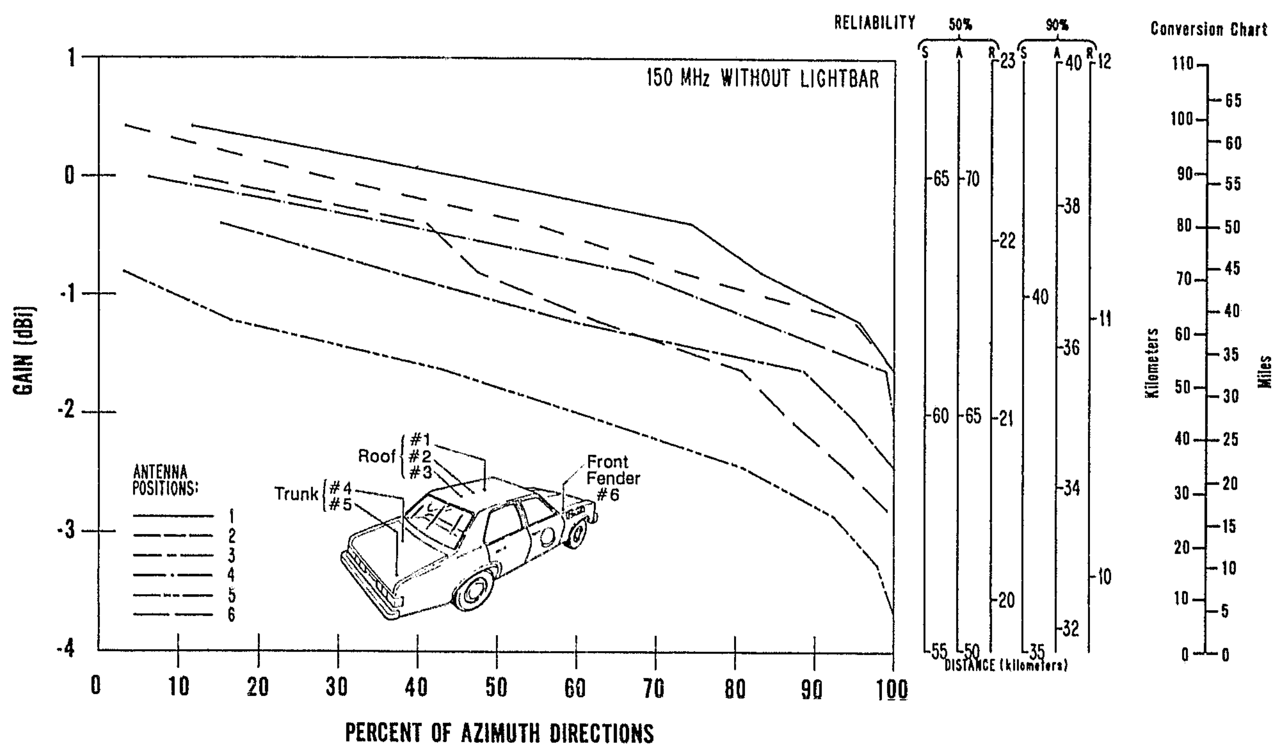


FIGURE A-6. *Cumulative distributions of the 150-MHz mobile antenna mounted in positions 1, 2, 3, 4, 5, and 6 without the light and siren bar in place.*

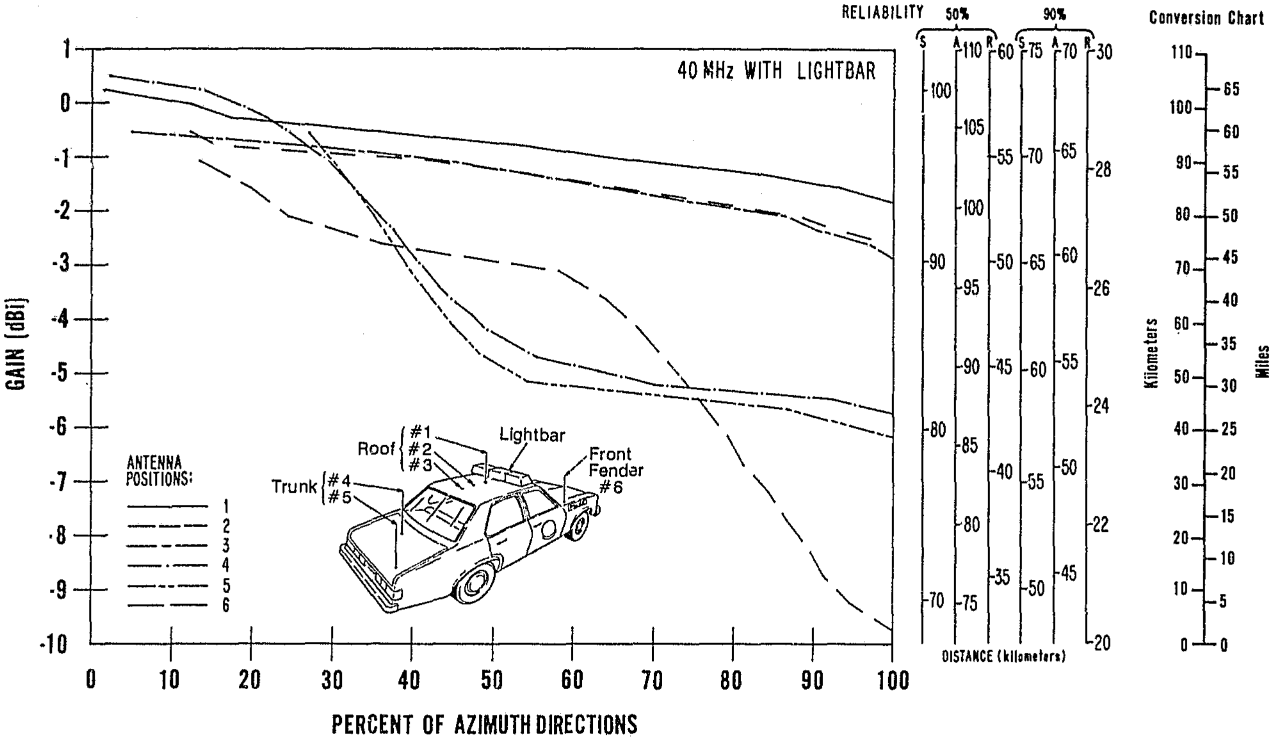


FIGURE A-7. *Cumulative distributions of the 40-MHz mobile antenna mounted in positions 1, 2, 3, 4, 5, and 6 with the light and siren bar in place.*

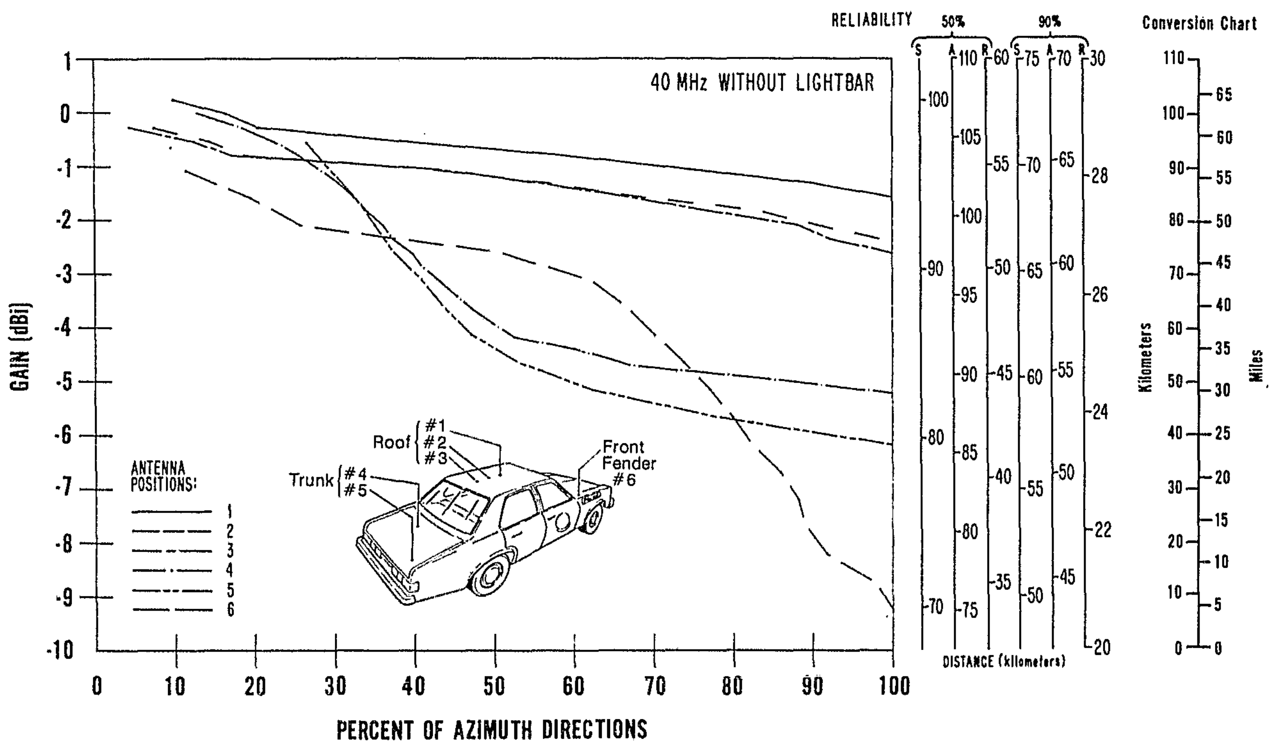


FIGURE A-8. *Cumulative distributions of the 40-MHz mobile antenna mounted in positions 1, 2, 3, 4, 5, and 6 without the light and siren bar in place.*

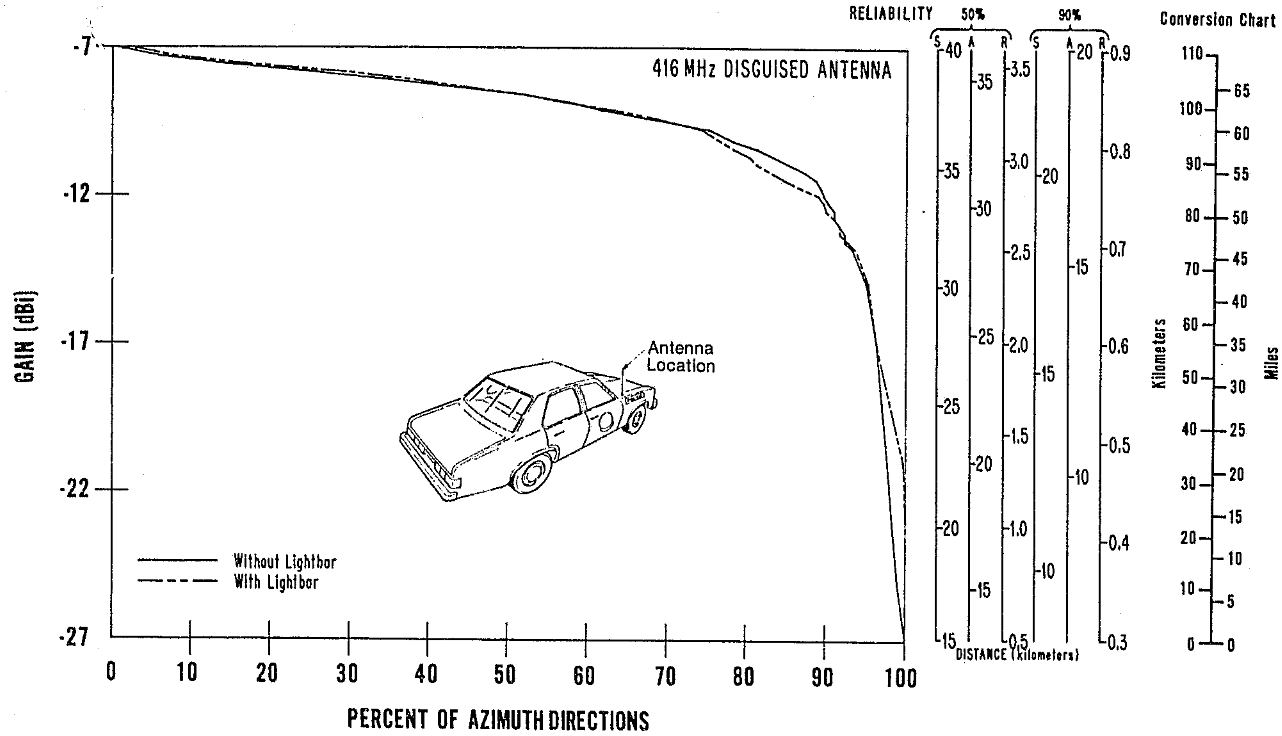


Figure A-9. *Cumulative distributions of the 416-MHz disguised antenna with and without the light and siren bar in place.*

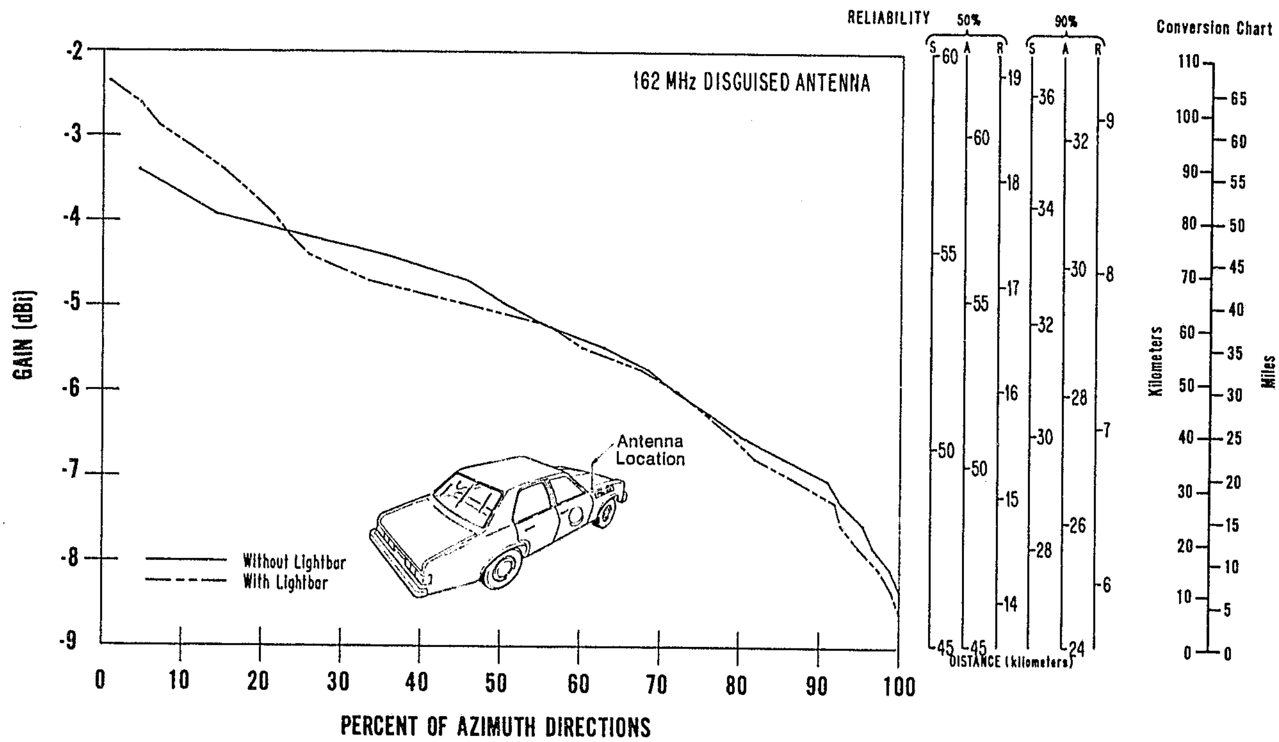


Figure A-10. *Cumulative distributions of the 162 disguised antenna with and without the light and siren bar in place.*

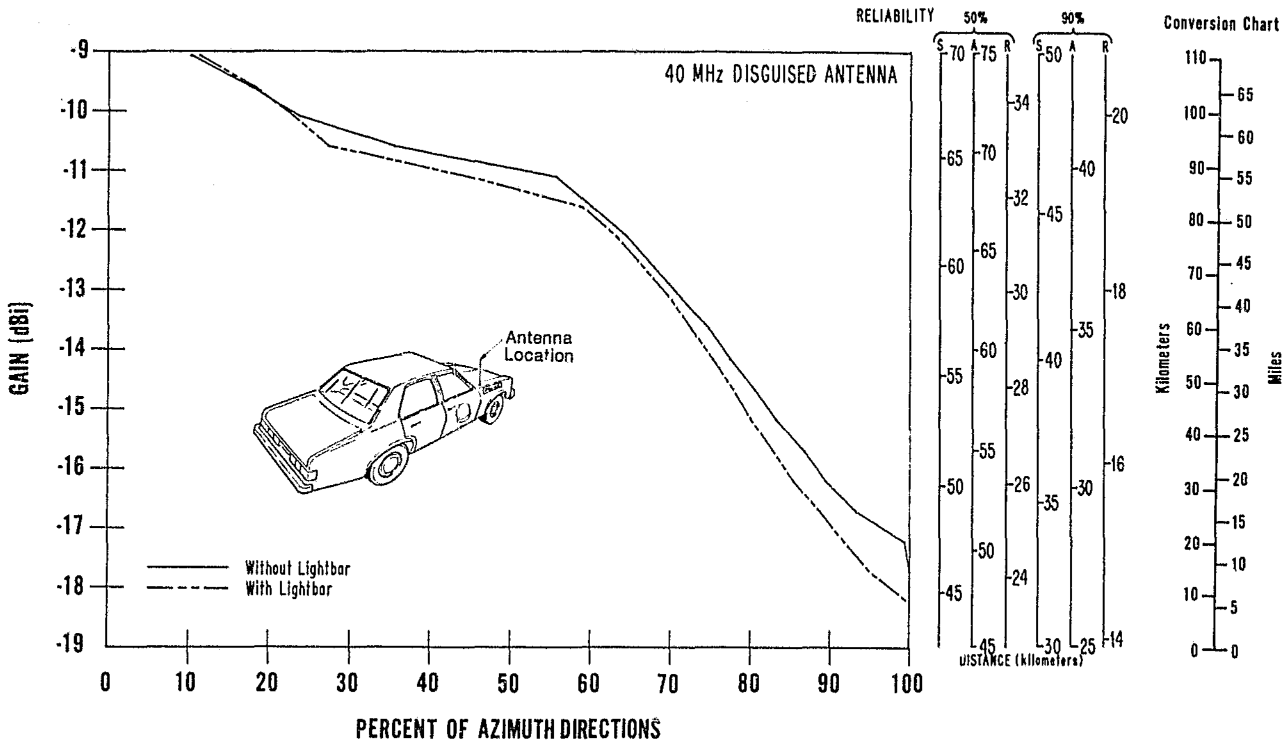


FIGURE A-11. *Cumulative distributions of the 40-MHz disguised antenna with and without the light and siren bar in place.*

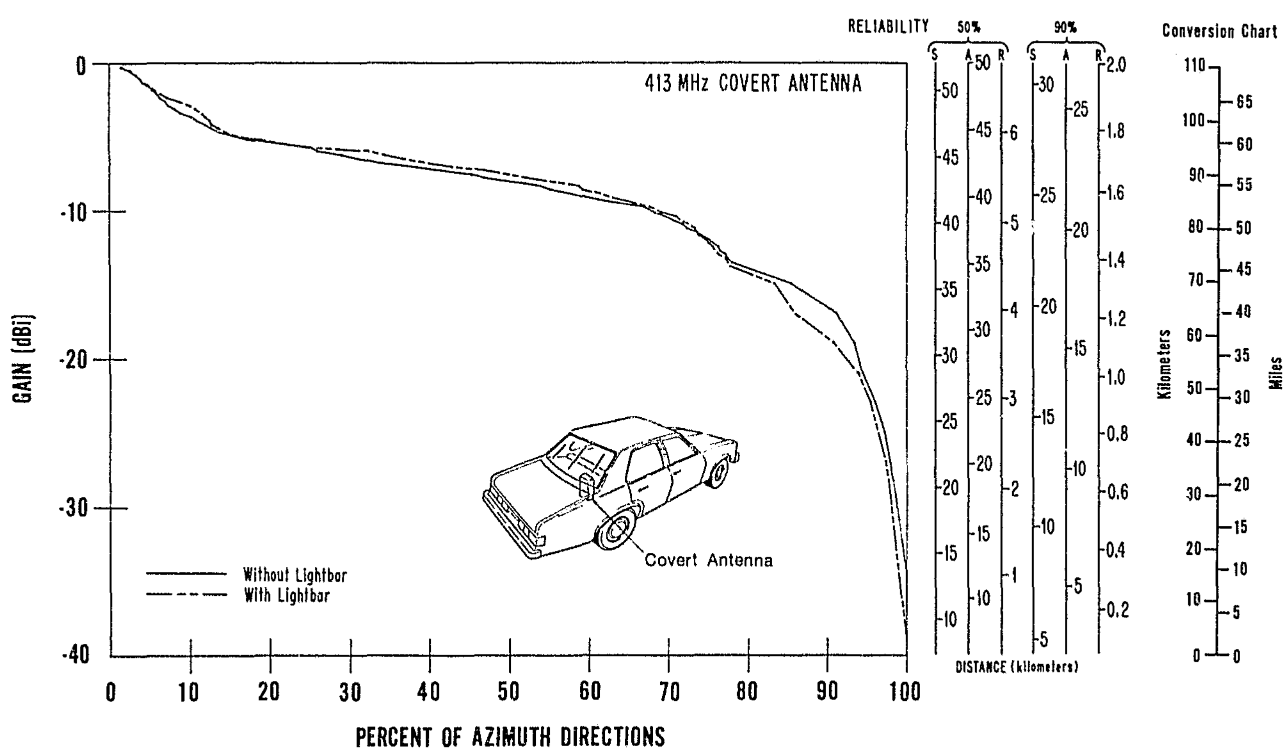


FIGURE A-12. *Cumulative distributions of the 413-MHz covert antenna with and without the light and siren bar in place.*

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