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Estimates of Maximum Electric Field Strengths in the Automobile Environment

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ESTIMATES OF MAXIMUM ELECTRIC FIELD STRENGTHS IN THE AUTOMOBILE ENVIRONMENT

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Strong electromagnetic (EM) energy sources up into the microwave range are examined and estimates are made of maximum EM field conditions to which automobiles could be exposed. The results are meant to alert automotive engineers to potentially hazardous EM radiation that might upset on-board electronic control devices.

1. INTRODUCTION

The electromagnetic (EM) radiation environment of modern vehicles has become of concern as the number and complexity of on-board electronic devices is growing (Jurgen, 1978). There has been a tremendous proliferation of EM emitters permeating the air space. While typical electric field strengths E rarely exceed levels of one volt per meter, there are "brute-force" situations where increases into the kilovolt per meter range might endanger electronic control devices (fuel injection, ignition, anti-skid brakes, etc.). For example, metal oxide semiconductor (MOS) high-density circuits used as processors in those functions are susceptible to disruptions in the logic when $E > 2$ V/m and can be destroyed by fields $E > 200$ V/m (Dicken, 1978). To enable engineering predictions of the ambient fields, we have surveyed strong sources of EM energy across the radio frequency portion of the spectrum (from dc up to 30 GHz) and estimated the order of magnitude for the maximum field strength levels to be expected, in particular when approaching at road level the radiation source as close as possible ($R > 3$ m).

Strong EM radio sources are legion and fall broadly into five categories:

1. Broadcast radiation (AM, FM, TV and Mobile).
2. Microwave satellite communication and energy beaming.
3. Microwave radar (pulsed fields).
4. High-Voltage overhead power transmission line.
5. Transients (radio flash) due to lightning and EMP from nuclear explosions.

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Each category has its own set of specific variables. However, the more intriguing question: "how does the ambient field couple into on-board devices?", is not addressed.

2. GENERAL CONSIDERATIONS

An electric field E is generated and moves outward from an emitter where charges are accelerated. The field diminishes inversely proportional to distance (1/R) outside the sphere of direct influence from the charges. The fields examined are assumed "free" meaning they are not modified by reflecting objects, nearby scatters, or the vehicle itself. Knowing the radiated power P (kW) emitted from a point source in a given direction yields at a distance R (m) that (note the mixed units, kW and m)

$$E = 173 \quad P/R \qquad (V/m). \qquad (1)$$

The radiated power P in (1) is equal to the transmitter power P_t if energy is radiated uniformly in all directions. An antenna always has directivity in its energy distribution. A power factor G is introduced to indicate the gain over the isotropic radiator. The effective isotropic radiated power (EIRP) in main beam direction is

$$P = G\, P_t \qquad (kW). \qquad (2)$$

Microwave transmitters with EIRP's as high as $3 \cdot 10^7$ kW are in operation (Hankin, 1974).

The electric field intensity $|E|^2$ can be converted into an equivalent plane wave power density $S(W/m^2)$ or electric field energy density $U(nJ/m^3)$ by

$$E^2 = 377\ S = 226\ U \qquad (V/m)^2 \quad . \qquad (3)$$

All three exposure units [$(V/m)^2$, (W/m^2)=0.1 (mW/cm^2), or (nJ/m^3)] are in use.

Routine environmental field monotoring at a point x, y, z in space is generally done with an isotropic probe yielding the RMS magnitude,

$$E^2 = E_x^2 + E_y^2 + E_z^2 \quad , \qquad (4)$$

which includes the contribution of all wave polarization components (Larsen and Shafer, 1977).

Motor vehicles are moving in and out of different EM environments. The problem in using the simple equation (1) lies in finding the maximum EIRP in the direction of a point located approximately 1.5 m above ground and approaching the origin of the radiation (e.g., antenna base) as close as $R \approx 3$ m. The EM field considerations fall broadly into two ranges, the far and the near field. Far-field conditions are relatively easy to analyze and measure; the field quantities E, S, U have the simple interrelationship (3). Experience is needed to recognize reflections from other objects including the ground that can add to or subtract from the primary signal.

The near field is most important in terms of "hazardous" consequences. It is characterized by interactions with the emitter and displays a complicated structure including reactive (stored) and real (radiated) energies, multipath reflections, irregular phase surfaces and unknown polarizations. The waves have not formed into a pattern making measurements exceedingly difficult. Far-field instruments do not achieve meaningful results. Hence, the measured electric field strength E is not a measure of the energy density (i.e., (3) is not valid). If far-field values of the EIRP are used at close range, the field strength of E is generally overestimated. In some cases (see later) approximations are available to assess the near-field strength E_0. Depending upon antenna dimensions in relationship to the wavelength, the near-field domain can range from less than one meter from the antenna (mobile radio) up to several thousand meters (satellite microwave earth terminal).

Several Federal agencies are currently involved in assessing and measuring the EM radiation environment (e.g., EPA, DoT, DoD, DoC-NBS, FCC). In particular, the U.S. Environmental Protection Agency is working to develop a data base on EM radiation exposure for the high density population centers (e.g., Tell and Janes, 1976; Tell, 1977; Tell et al., 1977); and the National Bureau of Standards has pioneered the development of EM measurement instrumentation, methodology, and refined measurements of EM radiation (e.g., Adams et al., 1977; Larson and Shafer, 1977). We have drawn heavily upon their results for the purpose of this overview. In the following, the conditions for high electric field strengths are examined more closely; additional variables are introduced that govern the EIRP in ground level direction; and the findings are, whenever available, backed up by verified or verifiable evidence.

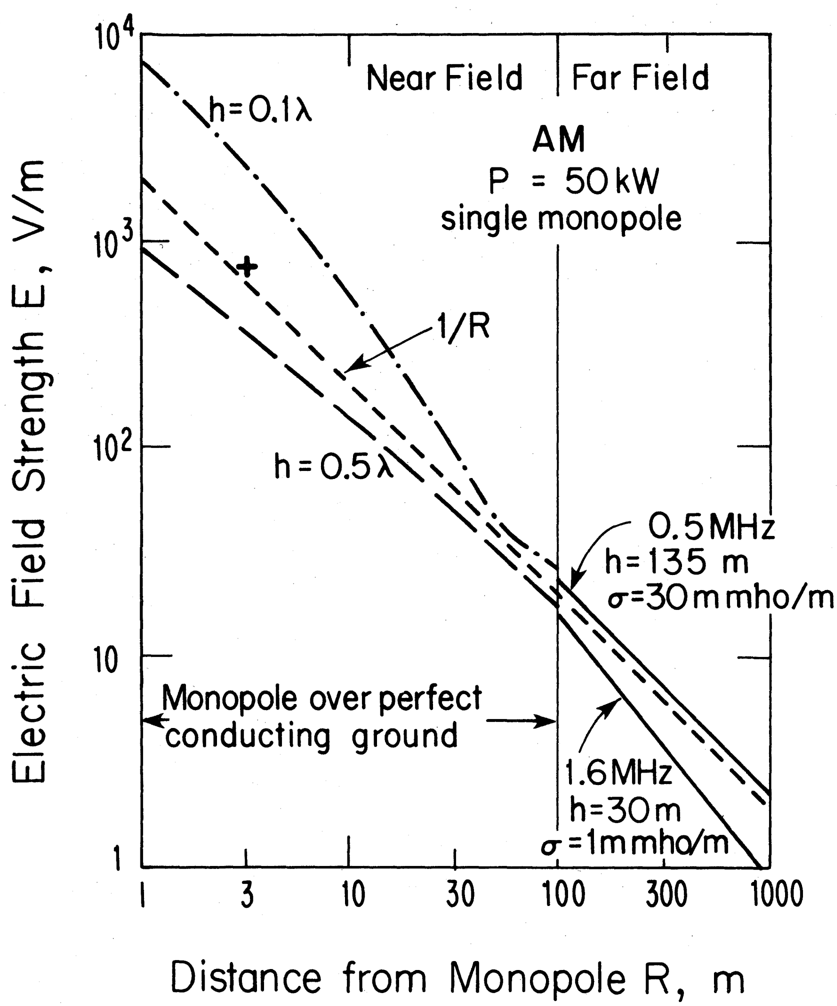


Figure 1. Ground-level electric field strength estimates for a 50 kW AM broadcast station employing a single monopole antenna. + Measured (Adams et al., 1977); near field calculations (Tell and Janes, 1976); far field (Berry, 1978).

3. BROADCAST RADIATION

On a per area average, most of the EM radiation results from broadcasting. There are roughly 10^4 commercial stations in the U.S. plus an additional $2 \cdot 10^7$ licensed mobile (CB) transmitters. Maximum broadcast power is regulated in terms of either the transmitter power P_t (AM, Mobile) or the EIRP (P_o) (FM, TV).

3.1. AM Standard Radio

In the U.S., the following specifications apply: Frequency, f = 0.5 to 1.6 MHz, wavelength, λ = 600 to 188 m; maximum permissible transmitter power, P_t = 50 kW - amplitude modulated; number of stations is 4500 of which 135 use 50 kW (Tell and Janes, 1976).

The antenna is a vertical monopole but sometimes a phased-array of several towers is employed to reduce far-range coverage in a particular direction (Barlett, 1977). A vertically polarized ground-wave signal is propagated in an initially omni-directional pattern. The earth acts as ground plane for the antenna. Factors, besides the transmitter power P_t, that influence the emitted field strength are the monopole height h (up to $5\lambda/8$) and the soil conductivity $\sigma(\lambda)$ (10^{-3} to 0.03 mho/m). A program that uses these three variables to compute the ground-level field strength E for ranges R > 1 km is described by Berry (1978). A field strength estimate in the near field (R < 0.1 km) is obtained from the solution for the hypothetical case of a monopole over perfectly conducting ground.

Figure 1 combines far- and near-field results for a 50 kW station. The two far-field curves represent the limits for variations of $\sigma(f)$ and $h(\lambda)$ typical for AM radio broadcast conditions. A value, E = 23 V/m, is predicted at ground level for the distance, R = 100 m, from the antenna base decreasing with the inverse of the distance. The near-field "half" of Figure 1 represents electric field strengths for two antenna heights. Equations for field calculations at the surface of the monopole are given by Jordan (1950). The electric field strength at the antenna base can reach very high values (2 kV/m for $P_t \approx 1$ kW).

Based on measurements carried out when $R \geq 1$ km, the following gain factors are typical (Sams, 1977),

$$G = 1.7 \quad \text{when } h = (0.15 \text{ to } 0.25)\lambda ,$$
$$G = 1.9 \quad \text{when } h = (0.25 \text{ to } 0.40)\lambda , \qquad (5)$$
$$G = 2.3 \text{ (max)} \quad \text{when } h = (0.40 \text{ to } 0.65)\lambda ,$$

to be inserted in (2) to calculate field strengths using (1). A station with an optimum antenna height ($h = 5\lambda/8$) and an excellent ground system might slightly exceed the limits shown in Figure 1. A measurement close to a 50 kW AM antenna ($h = 5\lambda/8$) yielded at ground level E = 800 V/m when R = 3 m (Adams et al., 1977). Measurements around 8 and 12 MHz avionic communication transmitters with 15 kW power showed field hot spots, E = 830 V/m, close (≈ 0.5 m) to the feeder point of a rhombic antenna system about 2 m above ground (Larsen and Shafer, 1977).

3.2. VLF-LF Transmission

Transmissions in the 10 to 300 kHz range are used for special long-range ground-wave communication and long-range navigation (e.g., pulsed fields of LORAN C at 100 kHz). The influence of soil conductivity on propagation is pronounced. The EM wave penetration into the ground varies between 3 and 150 meters (at 10 kHz). When the transmitter power P_t is available, field strength estimates may be obtained as discussed under 3.1. and 5.

3.3. FM and TV Stations

Broadcast FM and TV stations operate in the VHF and UHF portions of the spectrum. They usually employ antennas which radiate in a uniform azimuthal pattern and concentrate the power into a vertical plane beam. A small degree of tilt might be used to optimize the coverage. One tower sometimes supports antenna systems for several TV and/or FM transmitters. The following table summarizes pertinent station data:

	VHF-TV	FM-Radio	VHF-TV	UHF-TV
Frequency Range f, MHz	54 - 88	88 - 108	174 - 216	470 - 890
Wavelength λ, m	5.5 - 3.4	3.4 - 2.7	1.7 - 1.4	0.63 - 0.34
Max. Permissible Radiated Power P_o, kW	100	100 vertic. +100 horiz.	316	5000
Common Polarization	horiz.	circular	horiz.	horiz.
No. of Stations in U.S.	610	3400		350

Propagation at VHF and UHF is along a line-of-sight path. Antenna systems are mounted typically between 50 and 350 m high. Soil conductivity plays little part (except for possible reflections) in determining the field strength at a ground location. A relative field factor $F_A \leq 1$ is introduced to account for angle deviations from the horizontal main beam axis due to the directional pattern of the antenna. A plot of F_A is shown in Figure 2 for a typical UHF dipole array. The effective radiated power to be inserted in (1) becomes

$$P = F_A^2 \; P_o \; = \; F_A^2 \; G \; P_t \quad (\mathrm{kW}) \; . \qquad (6)$$

The influence of the field factor is elucidated in Figure 3. Variations of field strength with distance are depicted for an UHF transmitter assuming several vertical levels below the beam center. In this case, main beam exposure at close range ($R < 1$ km) is only possible on upper levels of tall, nearby buildings. FM stations using dual polarization have the largest field strengths in the vertical plane (up to +5 dB relative to horizontal) (Tell, 1974).

Worst case field strengths in the main beam of FM and TV broadcasting stations operating with maximum authorized effective radiated power P_o are calculated with (1) (see Fig. 4). An even more conservative way of estimating the maximum field strength is to include in (6) a factor two to account for reflections of the incident wave which lead to a standing wave field.

Broadcast antennas for FM and VHF-TV have wide beamwidth in the vertical plane when compared to UHF and in some instances less well controlled

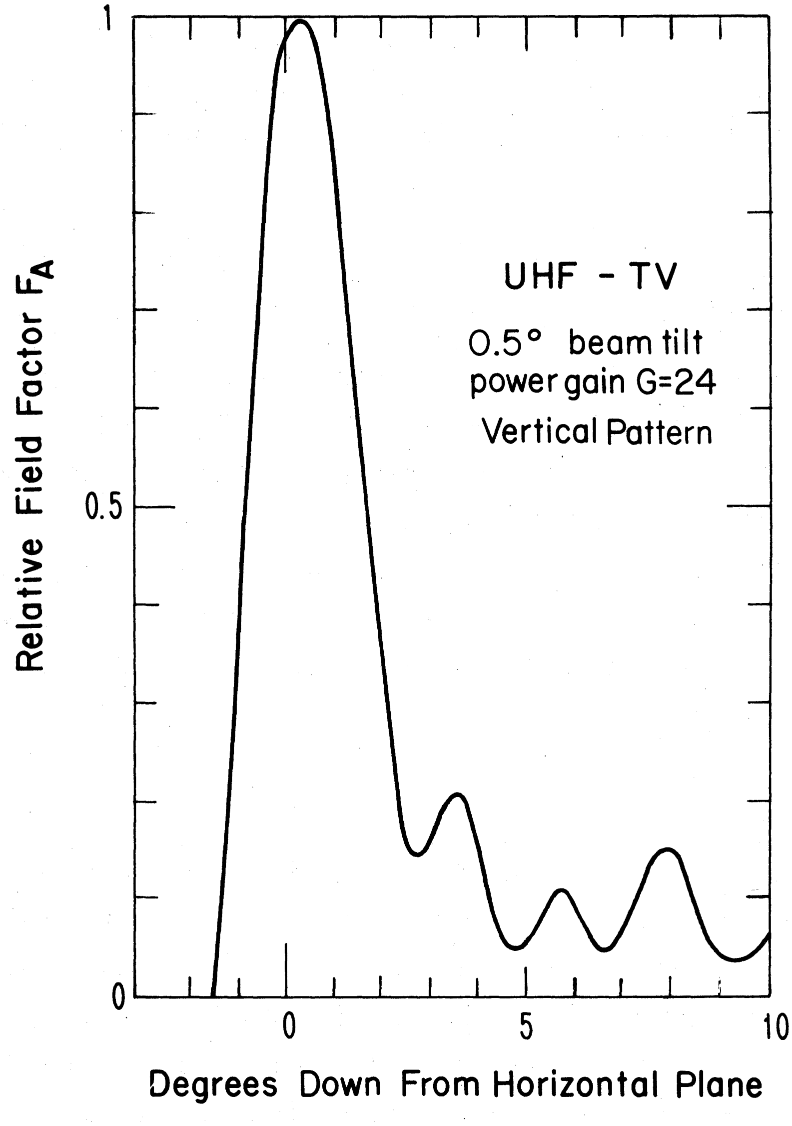


Figure 2. Vertical radiation pattern of typical UHF TV antenna (Tell and Janes, 1976).

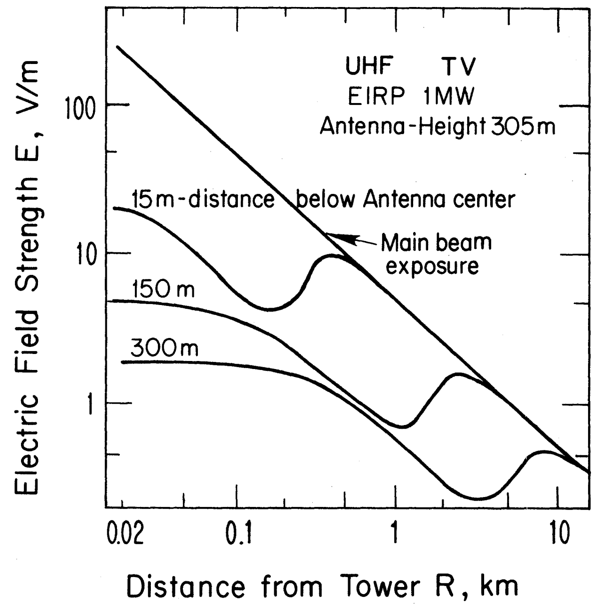


Figure 3. Electric field strength of UHF TV station (Tell and Janes, 1976).

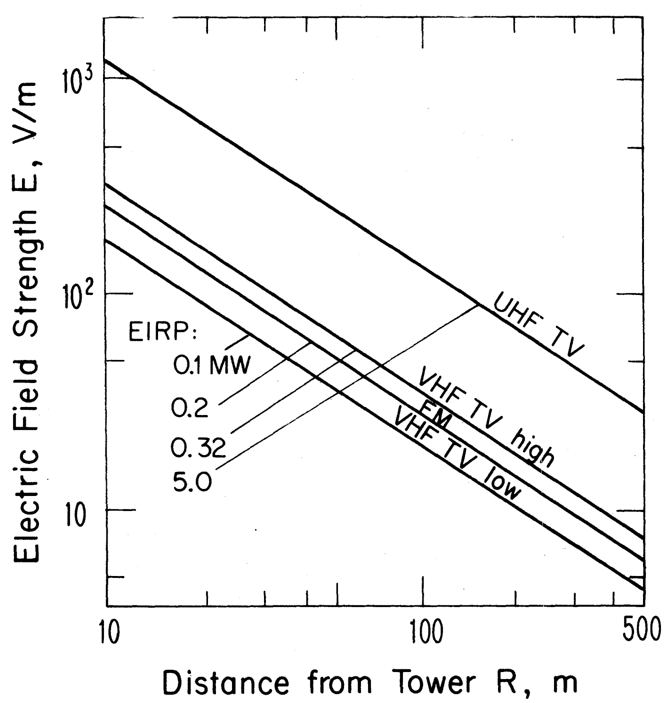


Figure 4. Maximum free-space electric field strength from FM and TV broadcasting (equations 1, 6) for main beam exposure.

Table 1. Measured Electric Near Field Strength at VHF and UHF

Electr. Field Str. E	Distance to Tower Base R	Effective Power P_o	Transm. Power P_t	Frequency f	Antenna Height	Service	Reference
V/m	m	kW	W	MHz	m		
823	0 (at dipole)	--	25	123	--	FM	a
184	0 (at dipole)	--	5	278	--	TV	a
124	0	100	--	90.7	28	FM	b
80	160	5000	--	600	--	TV	b
38	0	100	--	103	96	FM	b
25	1	--	150	110	--	FM	a
10	160	100	--	--	--	FM	b
8	200	105	--	104	36	FM	b
6	200	2300	--	735	54	TV	b
4	200	186	--	199	72	TV	b
1	6600	4000	--	UHF	247	TV	c

a) Larsen and Shafer, 1977
b) Tell and Janes, 1976
c) Tell, 1974

illumination of the array. The result is that power is lost in grating lobes directing radiation straight up and down the vertical antenna plane. In extreme cases, the electric field strength at the base of such antenna tower can therefore be as intense as in the main lobe at a distance equal to the tower height (Tell and Janes, 1976). Examples of field strength levels in the immediate vicinity of transmitting antennas are in Table 1.

3.4. Mobile Radio (HF, VHF, UHF)

The following frequency bands are reserved for mobile radio communication: 25-50 MHz, 150-175 MHz, and 406-512 MHz. All three are used with vertically polarized radiation and relatively low transmitter power ($P_t \leq 110$ W). As a short-range emitter, a mobile radio can generate potentially hazardous fields. There have been reported incidences where the fuel injection of a passer-by car was blocked or, even more serious, where blasting caps for dynamite were triggered at highway construction sites or munition was detonated accidentally by stray EM radiation. Since the antenna is located on the vehicle the concept of a "free" EM field is useless; the interaction with the car's body determines the EM radiation environment. Such a complicated near-field structure calls for measurements.

Results for the electric field distribution around cars are reported by Adams et al. (1977). The measurements were made with all common combinations of mobile transmitters and antennas. The maximum legal transmitter power (110 W) was used at the test frequencies 40, 162, 416 MHz; and at the citizen band frequency of 27 MHz, the power was boosted to 100 W with a special authorization. Electric field strengths at about 0.3 m distance from vehicles with on-board transmitters ranged mostly between 10 and 300 V/m with an occasional hot spot reaching 500 V/m. The field strengths around cars parked adjacent to a mobile transmitter were, as expected, somewhat lower in the 1 to 100 V/m range. In about 2 m distance from a free-standing car, the values had dropped to roughly one tenth of the 0.3 m value. The field strengths were measured on concrete or asphalt roads and some values doubled over metal surfaces due to reflections (e.g., on bridges).

4. MICROWAVE SATELLITE COMMUNICATION AND ENERGY BEAMING

Under this heading fall the high gain ($G > 10^4$) antennas which, in combination with kilowatt transmitter powers P_t, are the strongest EM continuous wave (CW) field sources. In 1976, there were about 250 stations on record in the U.S. emitting in main beam direction EIRP's of larger than one megawatt and operating in several frequency bands between 0.2 and > 30 GHz as satellite communication earth terminals. High ground-level field strengths become a possibility when low elevation angles are used in tracking satellites. Although, international regulations limit the minimum elevation angle to 3 degrees and the maximum EIRP in the direction of the horizon to 2.5 mW/Hz bandwidth, only to be exceeded in special cases (e.g., deep space research) by no more than a factor of 30 (ITU Radio Regulations 470). The bandwidth for maximum power distribution is limited to 4 kHz for frequencies 1 to 15 GHz and to a 1 MHz band above 15 GHz.

Specifications for three typical earth terminals operating in the 7.9 to 8.4 GHz band and employing circular parabolic reflector antennas are as follows (Hankin, 1974):

Transm. Power P_t (kW)	Main Dish Diameter D (m)	Gain G	Beam Width (degree)	Aperture Efficiency η (%)
2.5	4.5	$6.3 \cdot 10^4$	0.6	50
4	5.5	$1.6 \cdot 10^5$	0.5	75
4	18	$1.3 \cdot 10^6$	0.1	50

The near field range,

$$R \leq R_o \approx 0.2D^2/\lambda \qquad \text{(m)}, \qquad (7)$$

is considerably spread out for large-aperture antennas. The maximum on-axis electric field strength is approximately given by

$$E_o \approx 1.4 \cdot 10^3 \sqrt{\eta P_t(\text{kW})}/D(\text{m}) \qquad \text{(V/m)}, \qquad (8)$$

a constant across the diameter D and over the range R_o. This assumes (i) that the near-field power flux density in front of a highly directional antenna is obtained by dividing the available power at the feed point by one-fourth of the cross-sectional area of the circular antenna (Hankin, 1974) and (ii) that (3) holds. Various illumination problems force a reduction of the

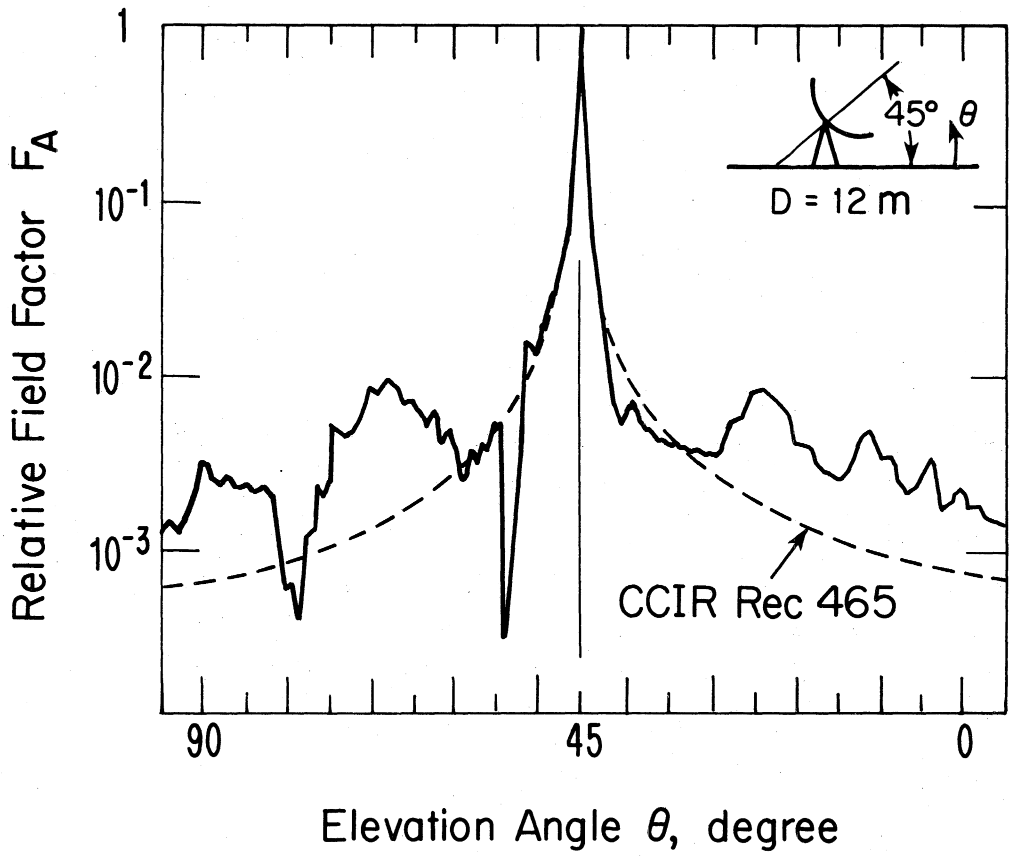


Figure 5. Measured sidelobe structure of a D = 12 m reflector antenna operating around 4 GHz.

theoretical optimum described by the aperture efficiency η (typically between 0.5 and 0.9). Between the near-field limit R_o and the far-field limit,

$$R \geq R_1 \approx 0.35D^2/\lambda \qquad (m), \tag{9}$$

one assumes an intermediate range with a linear drop of the power density with distance yielding

$$E_i \approx E_o\sqrt{R_o/R} \quad . \tag{10}$$

In the far field, the wave form is well defined (plane wave behavior perpendicular to direction of propagation) and the normal 1/R -dependence holds expressed as

$$E \approx 2E_o\ (R_o/R) \quad . \tag{11}$$

Predictions for the near field based upon (7) and (8) have been confirmed by measurements in the vicinity of the three satellite earth terminals given as examples above. For the D = 18 m system, the calculated on-axis field strength is E_o = 110 V/m and the near-field range extends up to $R_o \leq$ 1600 m. The measured values at R = 18 and 100 m were E = 91 and 106 V/m, respectively. The relative field factor F_A for a D = 12 m reflector antenna is depicted in Figure 5. The sidelobes are well above CCIR recommended levels causing higher field strengths in the horizontal plane even at more common elevation angles ($\theta > 10°$).

Solar power satellites (SPS) are emerging as a seriously considered source for "clean" energy. There may be many (> 100) in orbit within the next thirty years. It is proposed to capture in geostationary orbit electrical energy from the sun and, after conversion, to beam it at 2.5 GHz to a dipole array (D ≈ 3 km) located in an area of exclusion. The array is projected to be capable of extracting as much as five gigawatts of power from an on-axis power flux, S = 230 W/m^2 (Nalos, 1978). At the perimeter, the power density would fall-off to "safe" levels ($\leq$ 2 W/m^2). The maximum power density is about twice the "safe" U.S. biological limit for microwave exposure (100 W/m^2). One might consider driving service cars for short time periods under full exposure within the antenna field.

5. MICROWAVE RADARS

In the vicinity of airports and military installations, high-power ($P_t > 5$ kW) radars are a major source of EM radiation. The radar field is pulsed, concentrated by a high-gain ($G = 10^2 - 10^4$) antenna into a narrow beam, and on the average reduced by the antenna rotation. In field strength calculation two cases need to be distinguished, (i) the peak value E_{pk} present for the duration τ of the radar pulse and (ii) the average value E_{av} being the time-averaged mean over pulse duty cycle and antenna rotation. The relationship between average and peak power density is defined by a duty factor

$$d = S_{av}/S_{pk} = E_{av}^2/E_{pk}^2 = P_{av}/P_{pk} = f_p\tau \quad , \qquad (12)$$

where f_p is the pulse repetition rate and τ the pulse width. A rotational reduction factor ρ relates the point average to on-axis power density; e.g.,

$$\rho = (3 \text{ dB horizontal beam width})/360° \qquad (13)$$

for a fully rotating antenna. Hence, the radiated power to be inserted in (1) is given by

$$P_{pk} = F_A^2\, G\, P_t/d \quad \text{or} \quad P_{av} = F_A^2\, \rho G\, P_t \quad . \qquad (14\ a,b)$$

Experimental high field strength data measured in the vicinity of eight radars (technical specifications, see Table 2) are enumerated in Table 3. The values are selected from a larger body of data obtained from surveys at radar sites (Tell and Nelson, 1974; Larsen and Shafer, 1977). The on-axis ($F_A = 1$) radiated peak pulse power can reach levels as high as $P_{pk} \approx 7$ GW (radar #1 in Table 2) causing at the far-field limit $R_1 = 230$ meters a field strength of $E \approx 2$ kV/m. The example shown in Figure 6 is for a radar with a relatively small aperture (D = 0.5 m — slot array) and the 1/R-dependence of E (Eqs. 1 and 14a) holds to close range (R > 7m). Under normal conditions the measured off-axis behavior is of concern. The significant ($\geq$ -10 dB) spectral field components of a radar pulse train are spread typically over a $\pm$ 10 to $\pm$ 30 MHz interval around the center frequency (Tell and Nelson, 1974).

As pointed out in the previous section, the calculation of field strengths in the near-zone range (7) is complicated especially for the case of large-aperture antennas. A more rigorous approach to the near-field problem has

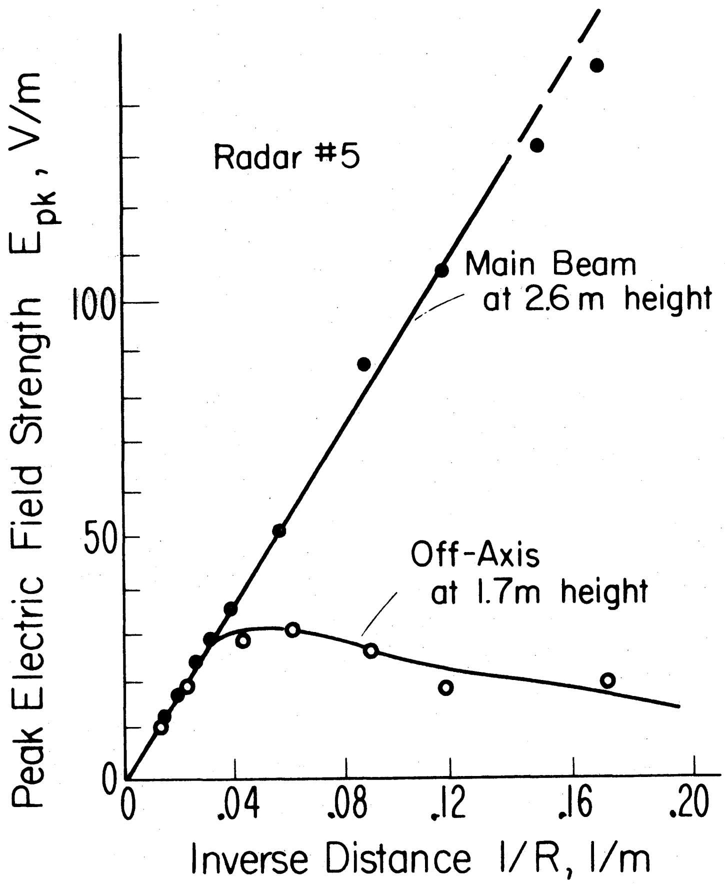


Figure 6. Measured on-axis and off-axis electric field strength from 100 to 5 m approaching radar #5 (Table 2) (Larsen and Shafer, 1977).

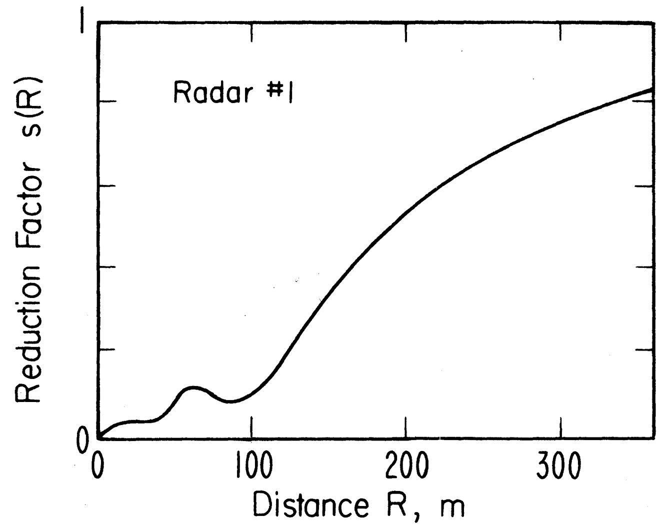


Figure 7. Computer near-field gain reduction factor for uniform aperture illumination from 300 to 1 m approaching radar #1 (Table 2) (Larsen and Shafer, 1977)

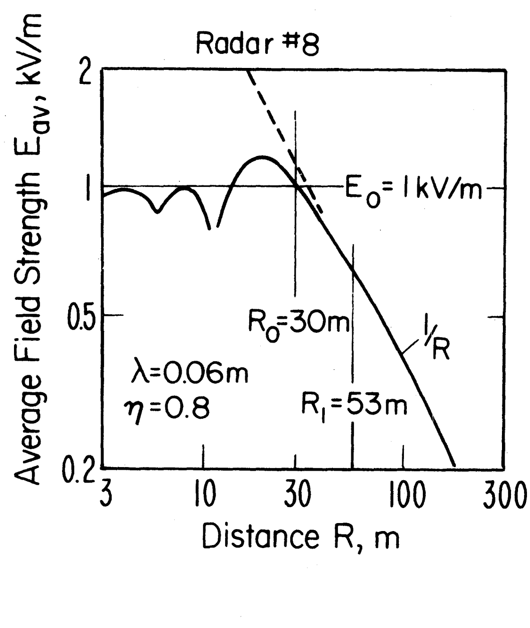


Figure 8. Measured on-axis electric near field strength from 300 to 3 m approaching radar #8 (Table 2) (Glaser and Heimer, 1971).

Table 2. Microwave Radar Specification

ID# (See Table 3)	Type		Freq. f_p	Power P_{pk}	Power P_t	Pulse Width τ	Rep. Rate f_τ	Duty Factor d	Rotation Rate	Gain G	Diameter D	Beam Width 3dB horizontal	Center Height h
			Transmitter						Antenna				
			GHz	kW	W	μs	Hz	$x10^{-4}$	rpm	dB	m	degrees	m
1	Air Route Surveil-lance	ARSR-1D	1.34	4000	2880	2	360	7.2	6	34	12	1.4	24
2	Air Port Surveil-lance	ARS-4B	2.72	425	403	0.83	1140	9.5	15	34	5.5	1.4	22.5
3	Air Port Surveil-lance	ASR-7	2.82	425	336	0.83	950	7.9	13	34	5.5	1.4	8
4	Air Port Surveil-lance	ASR-8	2.7	1160	725	1.4				34	5.5	1.4	15
5(Fig.6)	Aircraft Nose-Cone	AVQ-10	5.4	75	60	2	400	8	Fixed		0.5		2.6
6	Aircraft Nose-Cone	RDR-1B	9.35	40	24	1.5	400	6	Fixed		0.5		3.9
7	Airport	ASDE-2	23.9	49	14	0.02	14000	2.9	60	45	1	0.25	30
8(Fig.8)	Military	AN-SPG-99	4-6 (C-band)	-	6000	-	-	-	-	-	3	-	10

Table 3. Selected maximum electric field strength data measured in the vicinity of ground-based radars (ID # see Table 2).

Elect. Field Strength E_{pk}	E_{av}	Distance to center R	Test point location above ground	Antenna Rotating	Radar ID #	See Figure	Reference
V/m	V/m	m					
-	1200	20	on-axis	stopped	8	8	a
9700	238	2.3	"	-	6		b
2740	67	9.1	1.8 m, off-axis	-	6		b
1700	52	84	on-axis	yes	2		b
1060		1	"	yes	2,3,4		b
549		0.05	"	stopped	7		b
412		4	"	yes	2		b
250	7.8	260	1.7 m, on road	stopped	3		c
194		4.6	1.7 m	-	5	6	b
194		3	1.7 m	-	6		b
173		0.5	on-axis	stopped	7		b
83	2.1	260	1.7 m, on road	yes	2		c
12	0.6	260	" , "	yes	1		c

a) Glaser and Heimer, 1971
b) Larsen and Shafer, 1977
c) Tell and Nelson, 1974

been taken by postulating that the full gain G is only realized in the far field (9). A theoretical reduction factor s(R) for (14) is formulated based upon the "known" aperture illumination. The derivation involves inserting the illumination distribution into the power-density field equation and solving for the on-axis field intensity (Larsen and Shafer, 1977). Figure 7 gives an example for s(R); however, the difficulty, besides considerable mathematical effort, lies in the uncertain knowledge of the illumination function. The measured electric field strength close to a powerful radar (see Figure 8) provides some quantitative data for on-axis - versus - distance response. The near-field calculation using (7) to (11) seems to provide reasonable estimates.

6. OVERHEAD POWER TRANSMISSION LINE

Extreme high-voltage (EHV) power lines above 300 kV are a source of high field strength when approaching their right-of-way zone. The principal EM environmental effects are (i) the electric field intensity near the ground causing induced voltages on objects positioned underneath the conductors, and (ii) high conductor surface fields producing weather-dependent corona phenomena such as radio noise. Some specifications for three-phase high voltage transmission lines in the U.S. are (Tell et al., 1977):

Transmission Voltage	V(kV)	765	500
Frequency	f(Hz)	60	60
Min. Conductor Height Above Ground	h_o(m)	21-12	18-10 .

When the complete electrical and geometric characteristics of a line are provided, the ground-level electric field can be calculated with the fundamental field equation,

$$E = 1.80 \cdot 10^7 \; CV/r \qquad (V/m) \; , \qquad (15)$$

where C is the capacitance per unit length to ground in farads per meter, V is the voltage impressed on conductor in kilovolts, and r is the distance from the charge CV in meters. An example of computed ground-level field strength is plotted in Figure 9 versus the distance R from the center of the transmission tower. The peak values of E for the 765 kV case vary from 12 to 5 kV/m underneath the outer conductor depending on the clearance height h_o.

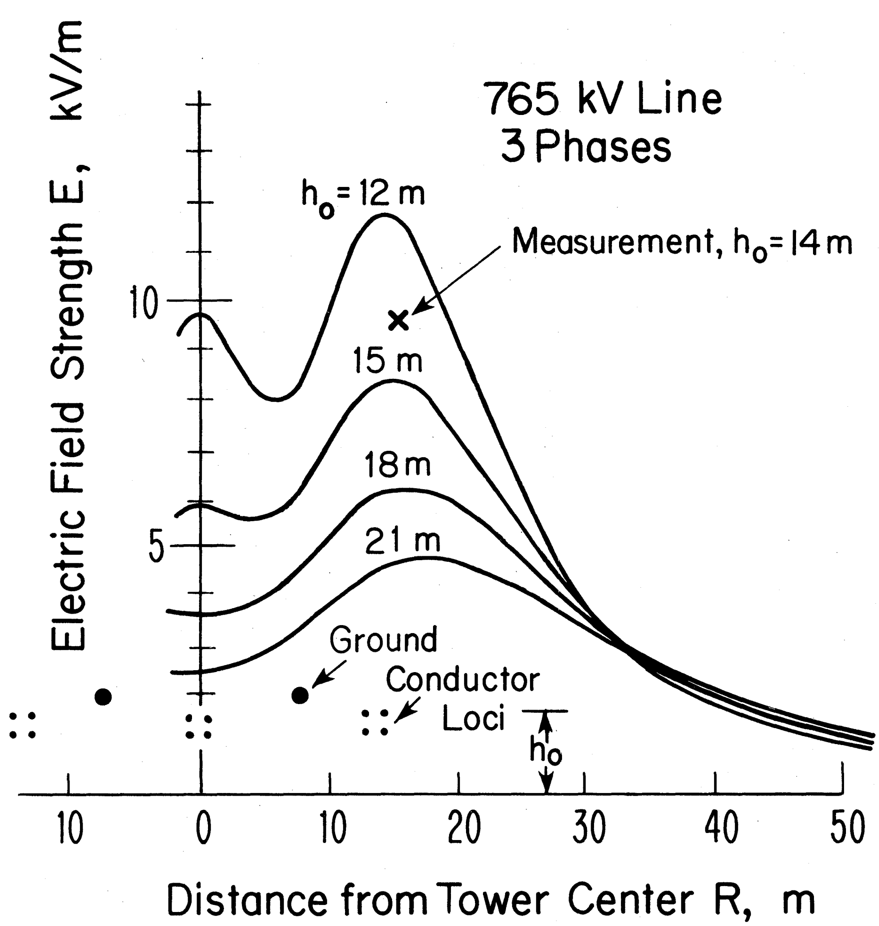


Figure 9. Calculated electric field strength profile at ground level (1 m) for 765 kV line (Tell et al., 1977).

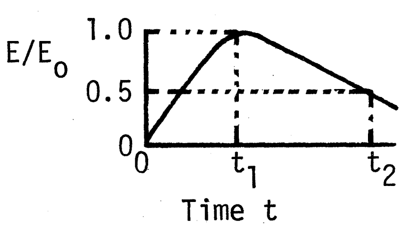
The field strength has dropped to about 1 kV/m when R = 50 m and falls off from this point as 1/R reaching 0.1 kV/m at R ≈ 100 m. More details and further calculations for other line types are found in two publications (Tell et al., 1977; Stewart and Wilson, 1977).

Measurements agreed well with calculations based upon (15) (Tell at al., 1977). The maximum field strength for a 765 kV line was measured to be 9.5 kV/m at one meter above ground occurring just outside the outer conductor at R = 16 meters (h_o = 14 m). That field strength induced short-circuit currents of 0.5 to 2 mA from limousine-type cars to ground. The vehicle's presence increased the field strength at 0.3 m above the car's roof from 10 to 16 kV/m.

Secondary variables influencing E are conductor motion due to wind, high load surges (> 5 GW), and shedding of ice (Stewart and Wilson, 1977). The radio noise due to conductor corona effects is broadband (≈ 30 Hz to 50 MHz) at much lower field strengths (< 0.1 V/m) and is a complex function of conductor size, conductor bundling, surface conditions, insulator aging, and meteorological parameters.

7. LIGHTNING AND NUCLEAR EM RADIATION (EMP)

Lightning discharges and nuclear explosions emit strong transitory fields over a broad frequency band although little energy is contained in them compared to CW or pulsed fields. Transients are best described by Joule energy content since average power flow has no meaning for a single pulse. The electric field can be calculated if the temporal and spatial distributions of the charges (i.e., currents) at the source are known. A lightning flash involves a multiplicity of sparks; a nuclear electromagnetic pulse (EMP) is one single event producing all EM field emissions almost simultaneously. The time history typical to both transients is roughly described by the following pulse:



	Lightning	EMP	
t_1 (μs)	0.1	0.01 - 0.02	
t_2 (μs)	200-1000	0.05 - 0.5	(16)
E_o (kV/m)	17 a)	20 - 80 b)	

a) Measured maximum field strength E_0 at the center of a return stroke from a cloud-to-ground lightning flash (Cianos and Pierce, 1972).

b) Estimated maximum electric field strength in the source region of a near-surface burst (60-80 kV/m), as well as maximum horizontal component of a high altitude EMP (20-50 kV/m) at ground level (Longmire, 1978).

The different time scales for lightning and EMP place the peaks of the occurring broadband emission spectra around 5 kHz (Cianos and Pierce, 1972) and 10 MHz (Ricketts, 1976), respectively. The EMP spectrum occupies AM radio to UHF TV frequency bands (see Figure 12).

<u>The EM fields due to lightning</u> are a common threat to vehicular electronics. There are about 10^5 lightning flashes per day in the U.S. A typical event consists of a fast upward-going leader and several powerful return strokes (peak current 50 - 200 kA). The total charge exchange is on the order of 20 to 50 coulombs. Lightning is initiated when the fair weather electrostatic field of about 100 V/m is raised by charged clouds to the breakdown point of air, which is given approximately by (Sams, 1977)

$$E_\infty \approx 3 \cdot 10^6 (p/1010)(298/T) \quad (V/m) , \qquad (17)$$

where p is the pressure in millibars and T the temperature in degrees Kelvin.

The fields generated by lightning are different for each of the various stages in a flash and very complex in many respects (Levine and Meneghini, 1978; Cianos and Pierce, 1972). In general, near- and far-field components have to be separated. Far fields are radiated from the conducting channel between a cloud and ground (average length is 5 km), and their spectral distribution was measured as shown in Figure 10. Scaling of the envelope inversely with distance R from the center is appropriate when $R \geq 10$ km.

The static and inductive fields at close distance to a flash in general are very large when compared with the radiated component. These fields are a function of the interplay between the charge drawn from the cloud, the charge deposited along the channel (on the order of 1 C/km), and the redistribution of charge during various current stages in the flash. Electrostatic fields of 200 kV/m have been observed close ($R < 100$ m) to flashes to occur transiently just before the leader makes contact with the ground. The steady field between ground and cloud is limited by screening space charges due to

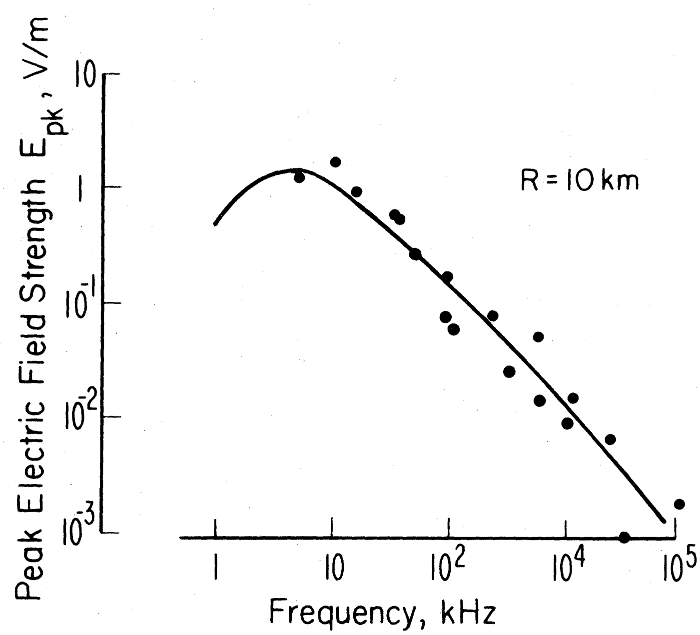


Figure 10. Peak field strength for radiated lightning emission received with 1 kHz bandwidth (Cianos and Pierce, 1972).

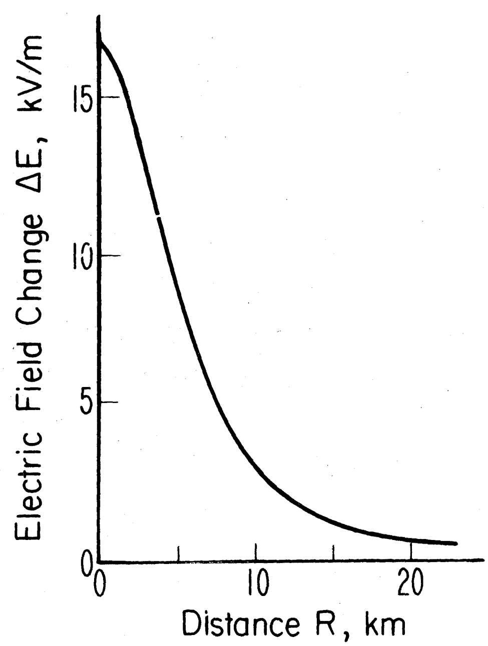


Figure 11. Change in static field strength versus distance for a lightning flash (charge exchange 39C) to ground (cloud height 6.4 km) (Cianos and Pierce, 1972).

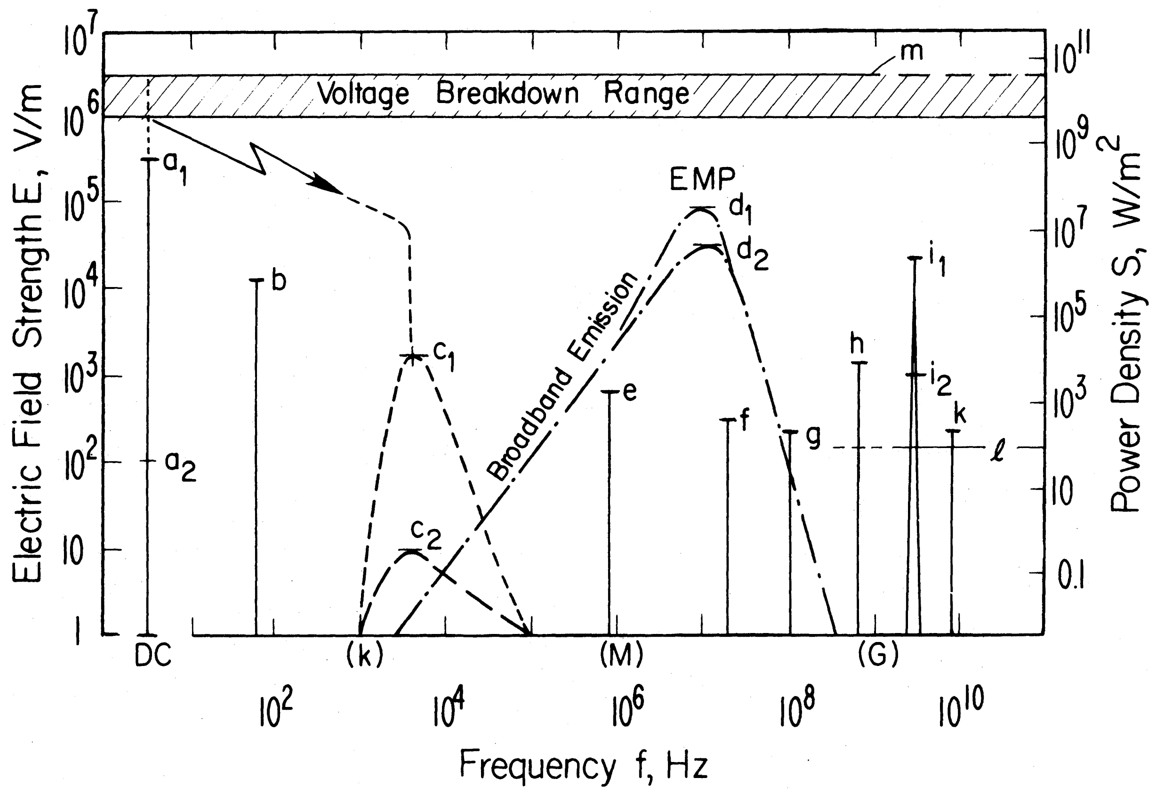
corona to 10 to 20 kV/m (Cianos and Pierce, 1972). The measured electrostatic field change for a typical flash is depicted as a function of distance in Figure 11.

The nuclear pulse (EMP) fields within a surface burst of a nuclear explosion are probably not of great interest because of other strong destructive forces. The source region is hemispherically-shaped several kilometers in diameter. Beyond this burst center potentially degrading EMP fields are radiated several tens of kilometers decreasing as 1/R.

A high-altitude burst presents a different picture with the resulting EMP the only prompt effect on the ground covering a large area. When the height of the burst is taken as 300 km, the distance to the horizon is 2000 km and the large-amplitude fields cover geographical regions of that tangential radius. The source region for the EMP lies in the altitude range 20 to 40 km where the gamma rays emitted from the burst begin to interact with the atmosphere thus generating the EMP. Representative pulse shapes similar to the one given in (16) are given by Ricketts (1976) with peak amplitudes ranging between 20 and 50 kV/m.

7. CONCLUSIONS

Auto makers are fearful that future investment in electronic control systems could be compromised by ambient EM fields. In the preceeding sections, order of magnitude estimates of maximum electric field strengths have been made that might be expected from d.c. up to the microwave range in the motor vehicle environment. Various expressions relating field strength to distance from the source, transmitter power, antenna characteristics, etc. are given; more elaborate modelling in general is available (see references); and a few supporting measurements have been reported. Extremes, important with respect to assessing possible electronic component degradations, are summarized in Figure 12. For all common failure modes (e.g., thermal overload, burn out, dielectric breakdown, malfunction, bit error and dropout, etc.), the strength E should be a realistic indicator of direct and indirect degradation energies. However, the conversion of the ambient E field into meaningful currents and voltages at the on-board electronics level has been a major difficulty and more research is needed to assure safe operation and, at the same time, avoid costly overdesign.



a) Static Electric Field
   1. Thunder cloud-to-ground, Fig. 11
   2. Fair weather

b) EHV Power Line
   Fig. 9, R = 16 m

c) Radiated Lightning Spectrum
   1. R → 0, center
   2. R = 1 km, Fig. 10

d) EMP Spectrum
   1. Surface
   2. High altitude

e) AM Radio
   Fig. 1, R = 3 m

f) Mobile

g) FM Radio
   Fig. 3, Table 1

h) TV
   Fig. 4, Table 1

i) Radar
   1. Table 3
   2. Fig. 8

k) Satellite Earth Station

l) Safe U.S. Biological Exposure Level for Microwaves

m) Dustfree Dry Air Breakdown Voltage at Sea Level ($3 \cdot 10^6$ V/m)

Figure 12. Schematic overview of possible maximum electric field strengths E (power density S) from 0 to 100 GHz in the automobile environment.

The highest field strengths (see Figure 12) are produced by transients due to the EMP from nuclear explosions or from a very close lightning stroke. In both cases, the peak values come near the breakdown field strength (17) of the surrounding air. Semiconductor devices (diodes, IC's) especially are targets for disruptions since they display a relative "softness" to transients. Matters will get worse if, as planned, further miniaturization reduces the activation current for a flip-flop from 10^{-12} to 10^{-16}A. Magnetic field components at low frequencies ($\approx$10 Hz) are impossible to shield, and they induce currents of that order in even the smallest wire loop. These fields probably set a natural limit to what degree miniturization can be pushed. The present degradation energy falls in the 1 to 10 microjoule per microsecond range. Most other electronic components can tolerate transient fields far above their rated maximum allowable CW level, a fact to be considered in cost-effective EM ruggedization measures. The next worst condition is under an EHV power transmission line. The quasi-static 60 Hz electric field is effectively shielded by the vehicle's body from penetrating the inside, but the strong magnetic field under full load of the line can induce internal currents. The maximum electric field strengths produced by AM, FM, TV transmitters, high-power radars and satellite earth terminals are, at the most, on the order of kilovolts per meter near the ground. These fields are essentially continuous. Should they degrade the performance of the electronics without destroying it, it would mean that the vehicle malfunctions until removed from the field.

Instances in which vehicles will be exposed to the highest field strengths will be extremely rare. Nevertheless, if modern automobiles with elaborate electronic controls are to be as reliable as their non-electronic predecessors they should be designed to operate under the field conditions displayed in Figure 12. Less conservative design, which might cause a vehicle to become inoperative from EMP and near lightning strokes, requires hardening (i.e., shielding) measures to withstand ambient fields on the order of 10 kV/m at 60 Hz and about 5 kV/m at frequencies above 0.5 MHz. It is worth conjecturing that if public policy dictates that vehicles should be able to withstand the fields from a high-altitude nuclear explosion (on the order of 20 kV/m), they will probably be able to tolerate any man-made EM field that is likely to occur between dc and microwave frequencies.

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Strong electromagnetic (EM) energy sources up into the microwave range are examined and estimates are made of maximum EM field conditions to which automobiles could be exposed. The results are meant to alert automotive engineers to potentially hazardous EM radiation that might upset on-board electronic control devices.

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