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Authors
Harms, M.G.
Leung, L.P.
Verderber, R.R.

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M.G. Harms, L.P. Leung, and R.R. Verderber

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M. G. Harms, L. P. Leung, and R. R. Verderber

Lighting Systems Research
Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720

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ELECTROMAGNETIC INTERFERENCE FROM FLUORESCENT LIGHTING OPERATED WITH SOLID-STATE BALLASTS IN VARIOUS SITES

Michael G.A. Harms, Leon P. Leung, and Rudolph R. Verderber

Lighting Systems Research
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Abstract: Solid-state ballasts with 20-30 kHz fundamental frequencies were used to operate fluorescent lamps in office, screen room, and open-field sites. The test equipment and layout are described and the radiated and conducted electromagnetic interference (EMI) data are given for six commercially available ballasts from different manufacturers. EMI data from each location are presented that indicate the suitability of using an office site for future EMI measurements. Broadband EMI data are compared with data from a spectrum analyzer, which justifies the use of an RMS voltmeter in these measurements. A reduction in radiated EMI of 36 dB is achieved by replacing a strip fixture with an EMI-hardened fixture that has a wire grid embedded in its lens. Results of increasing lamp/antenna distance are given; we verify that, for distances greater than 1 meter, the radiated EMI amplitude drops off as a function of $1/d^3$.

Introduction

Solid-state ballasts for operating fluorescent lamps have been developed during the past seven years to improve the overall performance of lighting systems. These ballasts have improved system efficacies by 20 to 25% [1]. The ballasts operate lamps at 20 to 30 kHz, which results in the emission of radiated electromagnetic interference (EMI) from the lamp, and conducted EMI from the semiconductor switching devices that are part of the switching power supply circuit. The power of a single two-lamp ballast is less than 100 watts, but since many ballasts are used in a small area, the lighting community has been concerned that these systems, as well as other high-frequency light sources and control systems, could interfere with other equipment and communication systems. Several early measurements of the radiated and conducted EMI from these high-frequency systems showed levels higher than the acceptable levels generated by the standard 60-Hz fluorescent lamp systems [2]. Two large-scale on-site demonstrations monitored EMI levels from solid-state systems and reported no adverse interference [2] [3]. This provided some evidence that these systems could be employed in locations where existing 60-Hz fluorescent lamps were used. However, further documentation was needed from other sites to provide the credibility needed to satisfy endorsers of this product.

A two-day seminar in 1982 discussed various aspects of the general EMI problem in lighting and identified several areas to be addressed [4]. Subsequent work [5] has shown that as an increasing number of high-frequency fluorescent systems are used, the conducted EMI asymptotically approaches a maximum level, and the radiated EMI presents a minimal interference potential.

This study compares EMI measurements for high-frequency fluorescent lamp systems in three environments: an office site, under controlled laboratory conditions, and in an open field. Laboratory-type EMI measuring instruments and some simple broadband instruments were used. In addition, measurements were made of the high-frequency lamp/ballast system in a fixture designed to attenuate EMI radiation, to study levels that could be achieved if these lighting systems were employed in areas having EMI-sensitive equipment.

Experimental

Lamp/Ballast Fixture

Two standard F40, T-12, rapid-start fluorescent lamps were operated by a two-lamp solid-state ballast. Data were obtained from commercially available solid-state ballasts produced by six different manufacturers. Since the white noise emanating from the electrodes may vary from lamp to lamp [7], the same lamps were tested with all the ballasts. The test lamps were new and were seasoned for 100 hours prior to the measurements. The EMI from a standard core-coil ballast was used to obtain a reference level. The two lamp/ballast systems are measured in a standard, open-air, strip-type fixture.

The strip fixture was used for all measurements except when the commercial EMI-hardened fixture was used. This EMI-hardened fixture is completely metal except for its diffusing lens. A 1-square-cm wire grid is molded into the lens and makes electrical contact with the grounded metal frame. The fixture is an effective EMI shield for frequencies below a few megahertz.

Radiated and Conducted Test Circuit

Figure 1 shows a schematic representation of the test circuit for measuring the radiated and conducted EMI. For lighting equipment in most spaces (office or industrial areas), one is concerned with interference within 20 feet of the EMI source (light fixture). At this distance the measurements made of the high-frequency ballasts (20 to 30 kHz) are in the extreme near field. The fields are characterized by the wavelength (λ) of the radiation, where Lλ/6 is defined as the near field, >λ is defined as the far field, and the intermediate distance is defined as the middle field. For 20 to 30 kHz, the wavelength is 10^4 meters and the near field less than 1.7×10^3 meters. Even for measurements in the megahertz region, the near field is less than 17 meters. Since most EMI test procedures provide information for measurements in the far field, above 300 mHz, where the far field is one meter, a 2-foot source-to-antenna distance was arbitrarily selected. This distance is the same as being considered for measuring EMI from computing systems and games. Most procedures position the rod antenna in a plane normal to direction of the field from the EMI source. These measurements were made with the rod antenna directed at the ballast/lamp system under test, since this produced the highest readings. The antenna-to-source distance was maintained at 2 meters, measured from the center of the rod antenna, since this produced a satisfactory signal-to-noise ratio.

Conducted EMI measurements were made using a 50-ohm/50 μH line impedence stabilization network (LISN). Both the hot and neutral ac leads from the ballast were connected to the LISN with a 1-meter power cord. This short cord exhibits lower line losses than would occur in the wiring of an office building due to the inductive nature of the power lines, thus these measurements represent a worst-case situation.

The amplitude of the LISN output at 60 Hz was larger than the spectrum analyzer input would allow. Since its input operates "wide open," a large-amplitude signal, even though it is not in the displayed scan range, will saturate the spectrum analyzer, causing gain compression and incorrect readings. Therefore, a 30-dB attenuator was inserted in the LISN output and 30 dB were added to the values displayed on the spectrum analyzer.

Both the lamp/ballast systems under test and the LISN were located above a 1.8-by-3.7-meter hardware cloth ground plane, which was electrically connected to the light fixture, the LISN, and the spectrum analyzer.

The test procedure did not conform to any specific EMI standards because none have been established for lighting system products. The layout generally followed that specified in the Federal Communications Commission (FCC) Measurement Procedure MP-4 [6], which limits conducted EMI above 450 kHz and radiated EMI above 30 MHz. At the frequency at which these ballasts operate, the amount of EMI they radiate is less than specified in FCC MP-4 (which applies to electronic devices that generate and use RF energy for timing and control purposes).

Test Sites

Office - The office measurements were made in an unoccupied building on the Lawrence Berkeley Laboratory grounds. The space measured 10 meters by 4.5 meters in a framed building constructed with steel girders. The overhead fluorescent fixtures were turned off during the tests.

Shielded Room - The shielded room measured 4.5 by 3.5 meters and was fully enclosed and double-insulated. All input ac power to the shielded space was filtered.

Open Field - The open-field measurements were made in a large pasture, surrounded by mountains, on a ranch in Napa County, California. The lighting system under test and the measuring equipment were placed on a 6-by-9-meter ground plane of hardware cloth grounded with a 1-meter steel rod. There was no artificial lighting at this site and the power to operate the equipment came from a portable gasoline generator. The use of an open-field site allows the measurement of EMI without reflections from walls.

Results

Office Site

Radiated EMI: Figure 2 shows the background level and the spectrum analyzer noise floor (a), the radiated EMI from a standard core-core ballast (b), and two different solid-state ballasts (c and d), for frequencies from 0 to 200 kHz. The spectrum analyzer vertical scale is displayed in dBV, but can be converted to dBμV/m by the relation:

$$dB\mu V/m = dBV + 120 + \text{antenna factor}.$$

The 120 converts from volts to microvolts; the antenna factor for the rod antenna over the frequency range from 10 kHz to 40 MHz is 5 dB.

The EMI signature of the background and the magnetic ballast is broadband, measured with a 300-Hz bandwidth. The frequency distribution of the solid-state ballast system is narrowband, standard practices were used to measure the narrowband signals. Note that a 1-kHz bandwidth was used to measure the EMI from the solid-state ballast, B. This increases the background broadband noise by a factor of 3.3. The background, Fig. 2a, identifies a source of noise in the space that becomes evident below 40 kHz and is about 70 dBμV/m at 0 Hz. The EMI from the magnetic system is about 20 dBμV/m above this background at low frequencies (below 40 kHz) and gradually decreases to 0 dBμV/m above the noise floor by 180 kHz.

Figure 2 c and d shows two types of EMI signatures generally observed in solid-state fluorescent ballast systems. Ballast A clearly identifies the fundamental frequency at which the lamp is driven, and its harmonics. This particular ballast design exhibits two drive frequencies, 20 and 25 kHz; most others show a single fundamental. The harmonics reflect the non-sinusoidal wave shape of the voltage across the lamps.

An EMI signature having wider fundamental frequency peaks (up to 10 kHz wide) is presented by ballast B. A view of the signal with an oscilloscope indicates that the fundamental drive frequency is being swept between 23 and 33 kHz at a 120-Hz rate. This frequency modulation increases the EMI level between the two frequency limits.

Figure 3 a and b displays the radiated EMI from solid-state ballasts A and B, respectively, from 0 to 3 MHz. Note that the intensity was measured with a 3-kHz bandwidth. The peak intensity of the broader band measurements at the lower frequency is virtually equal to the peak intensity of the narrowband measurements: compare Fig. 3 a and b with Fig. 2 c and d. The maximum intensities are 122 dBμV/m. At frequencies above 300 kHz, the EMI levels from ballast A are 10 dBμV/m above the levels from ballast B.

The ranges of EMI radiated levels up to 3 MHz for all the solid-state ballasts tested are plotted in Fig. 4 on semi-log scale. The EMI from all but one of the solid-state ballasts tends to fall in a small range of levels for each frequency; e.g., at 40 kHz the EMI levels ranged from 97 to 113 dBμV/m. Below 200 kHz, one particular solid-state ballast (designated C) produced EMI levels considerably below the other ballasts.

This work is in agreement with previous measurements that show that the radiated EMI levels from solid-state ballast/lamp systems are greater than from 60-Hz magnetic ballast/lamp systems.

Table 1 lists the EMI levels from the various ballast/lamp systems, measured with two different broadband instruments.

Conducted EMI: The range of narrowband conducted EMI levels over a frequency span of 20 kHz to 3 MHz measured for the six solid-state ballast/lamp systems is plotted in Fig. 5. The conducted EMI from the 60-Hz

Table 1. Broadband Radiated EMI--Office Site (dBμV/m)

Ballast	RMS Voltmeter and Rod Antenna (10-MHz Bandwidth)	E-Field Sensor (200-MHz Bandwidth)
Lamps Off	75	-
Core-Coil	91	-
A	121	122
B	122	124
C	93	-
D	123	125
E	108	-
F	98	-

core-core ballast is virtually at the noise level. The range of values exceeds 45 dBμV at some frequencies, indicating the effectiveness of different methods of filtering the EMI generated in the circuit.

Table 2 lists the broadband measurements of the conducted EMI made with the LISN and the RMS voltmeter. The voltage readings were converted to dBμV using the relationship:

$$dB\mu V = 20 \log V + 120 \quad .$$

The noise floor of this instrument obscures the measurements for ballasts D and F. Also included in Table 2 are the narrowband measurements of the voltage at the fundamental drive frequency for each solid-state ballast system.

Table 2. Conducted EMI--Office Site (dBμV)

Ballast	Broadband LISN and RMS Voltmeter (10-MHz bandwidth)	Narrowband LISN and Spectrum Analyzer (1-kHZ bandwidth)
Lamps Off	115	58
Core-Coil	115	58
A	130	120
B	139	139
C	119	116
D	115	92
E	129	121
F	115	98

Shielded Room

The same set of measurements was made of the ballast/lamp system in the EMI-shielded room described previously. The range of EMI levels measured for all the ballasts is plotted in Fig. 6. The range of values from 20 kHz to 3 mHz is similar to the measurements for these systems in the office space.

The ballast/lamp systems were also measured with the broadband EMI field instruments. Table 3 lists the data.

Table 3. Broadband Radiated EMI--Shielded Room (dBμV/m)

Ballast	RMS Voltmeter and Rod Antenna (10-MHz Bandwidth)	E-Field Sensor (200-MHz Bandwidth)
Lamps Off	74	-
Core-Coil	91	-
A	119	122
B	117	123
C	89	-
D	120	124
E	107	-
F	98	-

Open Field

Figure 7 is a plot of the measured radiated EMI for the ballast/lamp system in an open field. Table 4 lists radiated EMI measurements taken with the broadband field instruments.

Table 4. Broadband Radiated EMI--Open Field (dBμV/m)

Ballast	RMS Voltmeter and Rod Antenna (10-MHz Bandwidth)	E-Field Sensor (200-MHz Bandwidth)
Lamps Off	80	-
Core-Coil	95	-
A	122	124
B	124	128
C	97	-
D	124	127
E	110	-
F	101	-

EMI-Hardened Fixture

The attenuation of the radiated EMI in an EMI-hardened fixture is illustrated in the photographs in Fig. 8 a and b. The EMI level at the fundamental frequency for a solid-state ballast/lamp in a strip fixture at a 1-meter source/antenna distance was 136 dBμV/m. This is greater than in the previous measurements, which used a source/antenna distance of 2 meters. Figure 8 a shows the intensity of the radiated EMI measured with the same ballast/lamp system in the EMI-hardened fixture, without the special lens in place. Figure 8 b shows the intensity with the lens. Results show that an enclosed metal fixture without the special lens can provide some attenuation of the radiated EMI; in our measurement, the attenuation was 8 dB. With the special lens in place, radiated EMI can be reduced 36 dB compared to the strip fixture. This is an EMI reduction of 63 times, with a reduction in illumination of about 10%. Notice that in Fig. 8 a and b all the peaks below 72 dBμV/m, as measured without the special lens, are attenuated below the noise floor when the complete EMI-hardened fixture is used.

Figure 8 c shows the radiated EMI with the fixture wrapped in copper window screen. The EMI has been reduced to the noise floor of the instrumentation at the expense of a 90% reduction in light level.

These experiments show that radiated EMI can be attenuated to virtually the level of ambient noise. It should be possible to coat the lens with a transparent conducting film to obtain this attenuation when required.

Discussion

Near Field

To verify that the near-field amplitude versus distance relationships are valid even for these extreme near-field distances, measurements of the fundamental and third harmonic were made at various source/antenna distances from 1 to 26 meters. In the near field, the electric field should decrease as a function of the reciprocal of the distance cubed. These measurements were made in the open field site. The results are plotted in Fig. 9. The slope of these curves between 2 and 26 meters varies as the reciprocal of the distance cubed. At measurements less than 2 meters there is a slight deviation from this dependence, suggesting that the size of the rod antenna affects the radiated field.

Comparison of Results from Different Sites

The radiated EMI data for solid-state ballasts A and B measured in the office site and the shielded room are compared in Fig. 10 a and b. At higher EMI levels, below 100 kHz, the results of the same system at different sites are within 2 dB of each other. At lower EMI levels (above 100 kHz), the screen room measurements are generally lower than the measurements made at the office site.

Table 5 compares the peak of the narrowband measurements of the fundamental drive frequency for all the solid-state ballast systems measured at the three sites. The fundamental frequency of each ballast appears in parentheses. Results show that the relative performances of different solid-state ballasts are preserved. However, some care must be exercised in comparing measurements at different sites. On the average, the office and open-field measurements are 2.4 and 5 dBμV/m above the screen room measurements, respectively.

Within the above limits, measurements from different sites and from laboratory and field conditions can be compared.

Table 5. Comparison of Narrowband Peak Fundamental Amplitudes (dBμV/m)

Ballast (fundamental frequency)	Shielded Room	Office Site	Open Field
Noise Floor (200 kHz)	38	38	38
A (24.2 kHz)	118.9	120.7	121.9
B (28.4 kHz)	118.0	122.6	124.8
C (14.3 kHz)	85.8	89.1	96.3
D (22.8 kHz)	120.7	123.8	124.4
E (34.1 kHz)	109.4	110.3	111.4
F (34.4 kHz)	97.2	98.4	100.4

Comparison of Instruments

Table 6 lists the radiated EMI measurements made at the three sites; broadband with the RMS voltmeter and narrowband with the spectrum analyzer. The agreement of the measurements from both instruments is good. The averages for the broadband and narrowband measurements in the shielded room, office, and open-field sites are 108 and 108.3, 111 and 110.8, and 113 and 113.2 dBμV/m, respectively. They all agree within 1%.

Table 6. Summary of Radiated EMI (dBμV/m)

	Shielded Room		Office Site		Open Field	
Ballast	Broadband	Narrowband	Broadband	Narrowband	Broadband	Narrowband
Noise Floor	74		75		80	
A	119	118.9	121	120.7	122	121.9
B	117	118.0	122	122.6	124	124.8
C	89	85.8	93	89.1	97	96.3
D	120	120.7	123	123.8	124	124.4
E	107	109.4	108	110.3	110	111.4
F	98	97.2	98	98.4	101	100.4

The good agreement between the narrow- and broadband radiated measurements suggests that the EMI at the fundamental frequency is the dominant contributor to the radiated EMI level. Hence, any method used to compare the radiated EMI from a solid-state ballast system must use a bandwidth that includes the fundamental drive frequency of the lamp.

Table 2 compares the conducted broad- and narrowband measurements. In general, the broadband measurements are greater than the narrowband measurements. This is due to the LISN characteristic output impedance, which at the ballast fundamental frequency produces an impedance mismatch with the measuring instrument, thereby reducing the overall contribution from the fundamental and enhancing the contribution from the harmonics. Thus it is impossible to compare broadband and narrowband conducted EMI measurements made with the LISN.

Summary

Measurements of the radiated EMI levels from various solid-state fluorescent ballast/lamp systems in the laboratory and on installation sites can be compared. Suitable approximations of EMI levels can be obtained with simple broadband E-Field instruments.

The EMI radiated from these ballast/lamp systems can be significantly attenuated using commercially available EMI-hardened fixtures.

Acknowledgment

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References

[1] R.R. Verderber, "Electronic Ballast Improves Efficiency," Electrical Consultant (Nov.-Dec. 1980), pp. 22-26.

[2] A.A. Arthur, R.R. Verderber, F.M. Rubinstein, and O.C. Morse, "Electromagnetic Interference Measurements of Fluorescent Lamps Operated with Solid-State Ballasts," IEEE Trans. Ind. Appl., Vol. IA-18 (Nov.-Dec. 1982) pp. 647-652.

[3] J.E. Jewell, S. Selkowitz, and R.R. Verderber, "Energy Efficiency and Performance of Solid-State Ballasts," Lawrence Berkeley Laboratory Report, LBL-9960, Berkeley, CA (1979).

[4] R.R. Verderber and S.M. Berman, eds., Proceedings of the Lighting-Electromagnetic Compatibility Conference, Lawrence Berkeley Laboratory Report, LBL-15199, Berkeley, CA (1982).

[5] S. Javidi, "Multiple Source Conducted and Radiated EMI from Electronic Fluorescent Lighting Systems," in Conference Record, 1984 IEEE National Symposium on Electromagnetic Compatibility, pp. 287-292.

[6] Office of Science and Technology, "FCC Methods of Measurement of Radio Noise Emissions from Computing Devices," FCC/OST MP-4 (1983), Federal Communications Commission, Washington, D.C.

[7] J.W. Culp, "Noise in Gaseous Discharge Lamps," Illuminating Engineering, Vol. 67 (1952), p. 35.

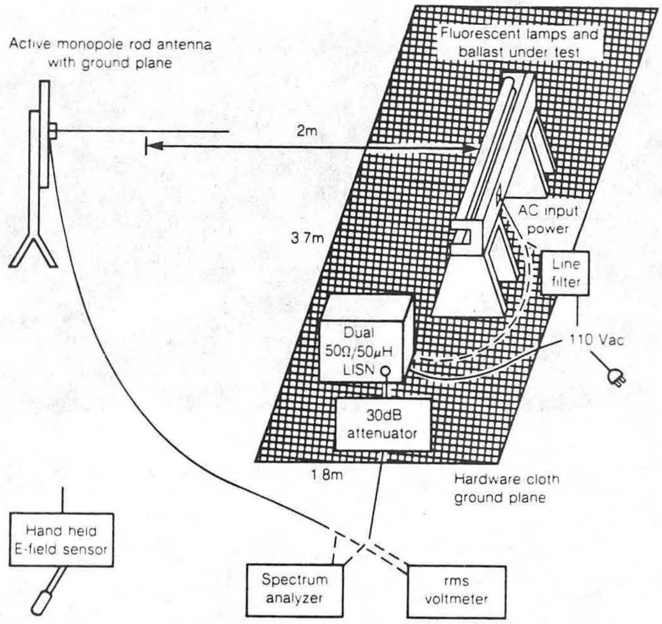
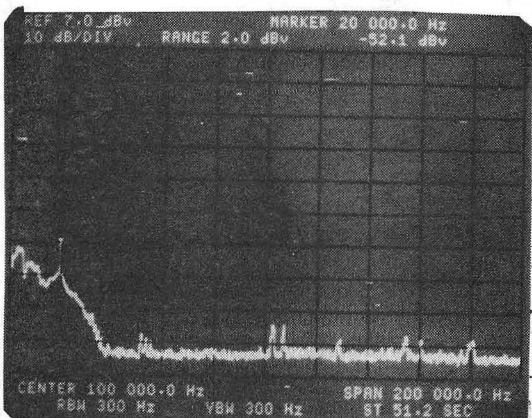


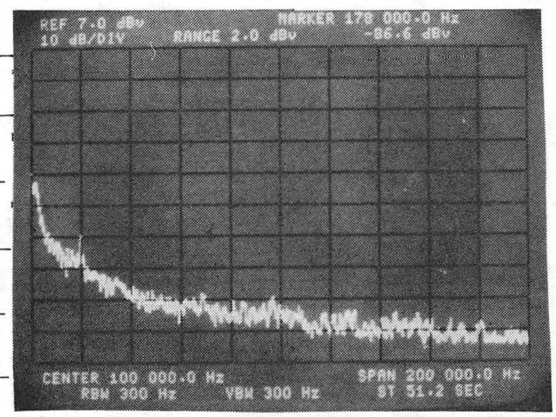
Figure 1. Test equipment set-up.

dBμV/m

132
112
92
72
52
32



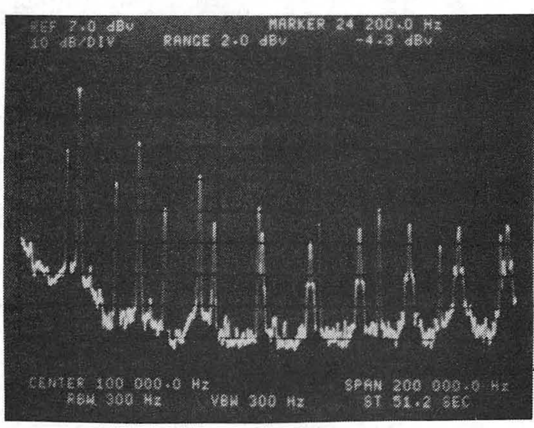
(a) Lamps off.



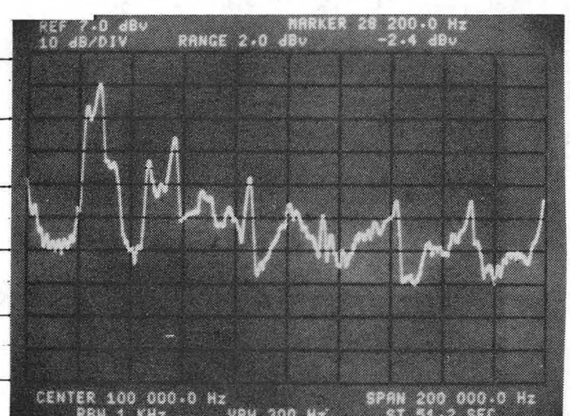
(b) Core-coil ballast.

dBμV/m

132
112
92
72
52
32

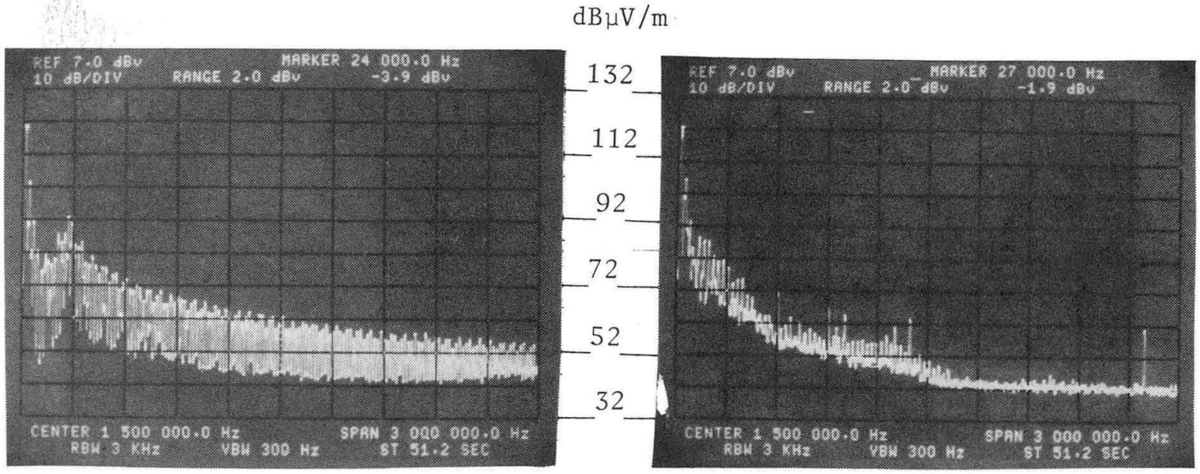


(c) Solid-state ballast A.



(d) Solid-state ballast B.

Figure 2. Radiated EMI for office site, 0 to 200 kHz.



(a) Solid-state ballast A.

(b) Solid-state ballast B.

Figure 3. Radiated EMI for office site, 0 to 3 MHz.

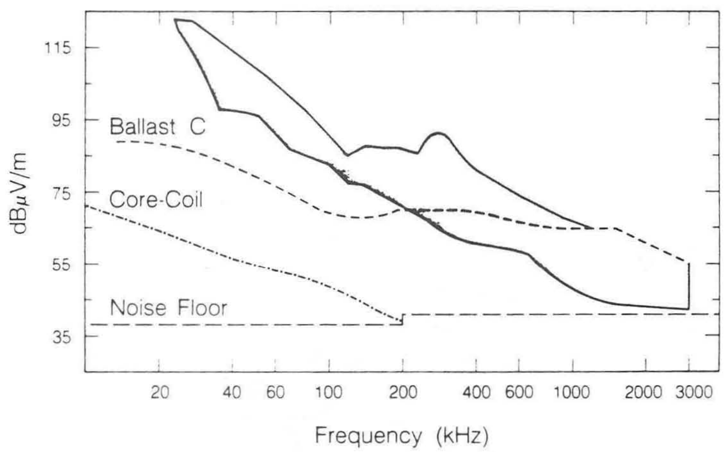


Figure 4. Graph of radiated EMI for office site, 0 to 3 MHZ.

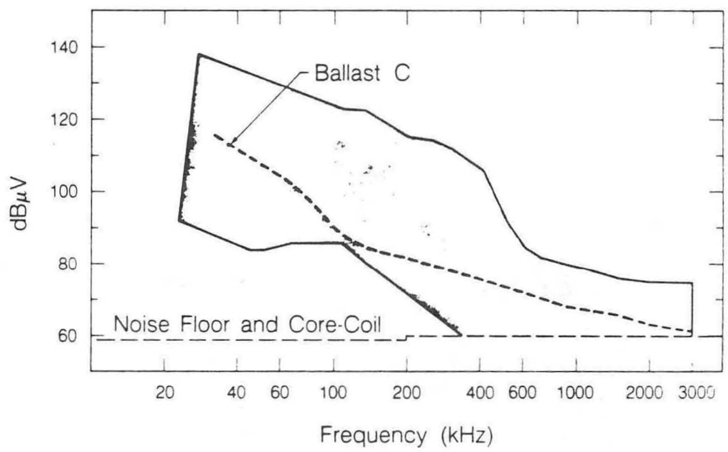


Figure 5. Graph of conducted EMI, 0 to 3 MHz.

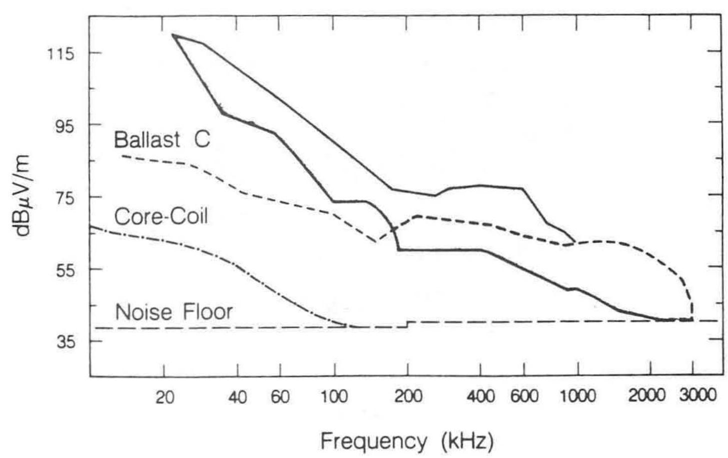


Figure 6. Graph of radiated EMI for shielded room, 0 to 3 MHz.

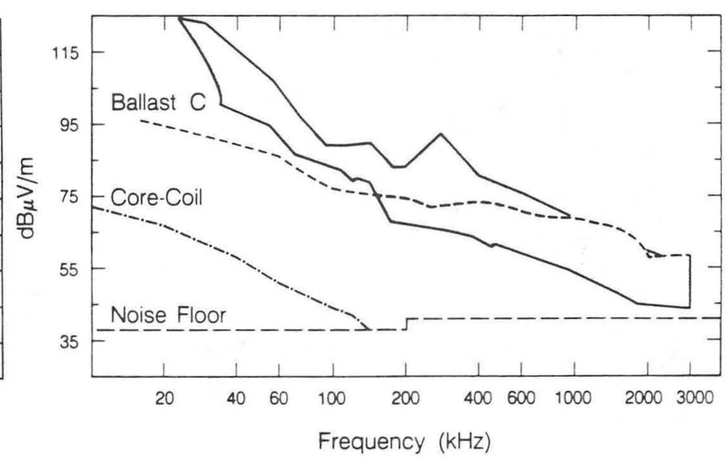
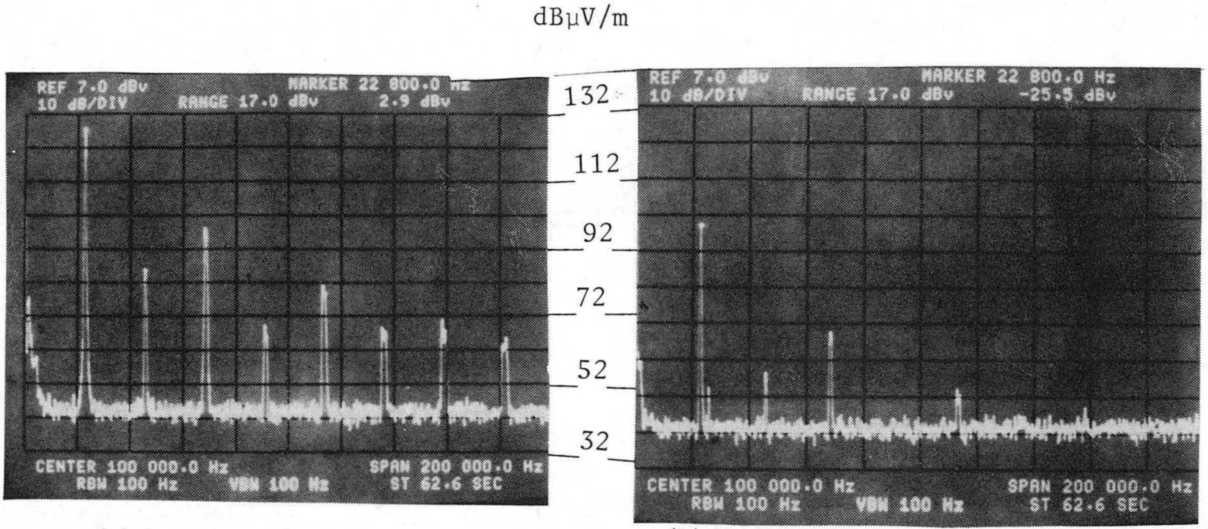
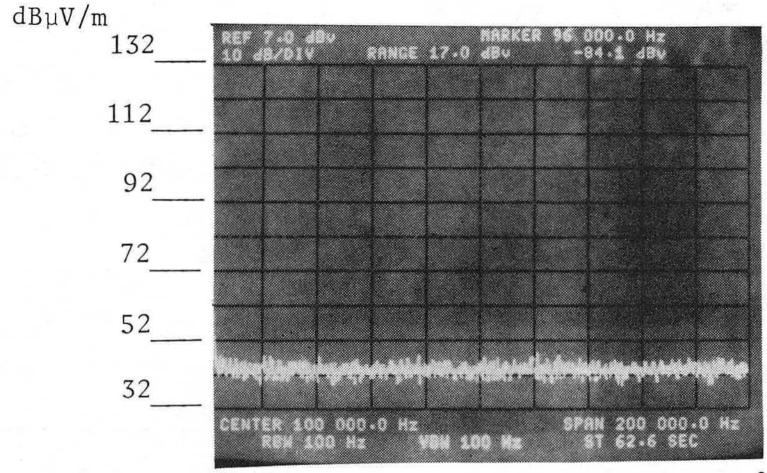


Figure 7. Graph of radiated EMI for open field, 0 to 3 MHz.



(a) Lens removed.

(b) Lens in place.



(c) Copper screen covering fixture, 0 to 200 kHz.

Figure 8. Radiated EMI for an enclosed fixture, 0 to 200 kHz.

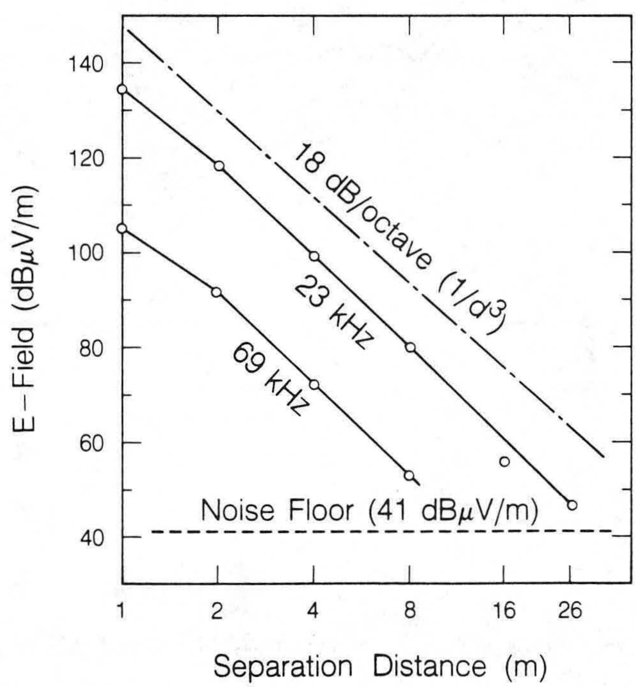


Figure 9. Graph of radiated EMI amplitude versus distance.

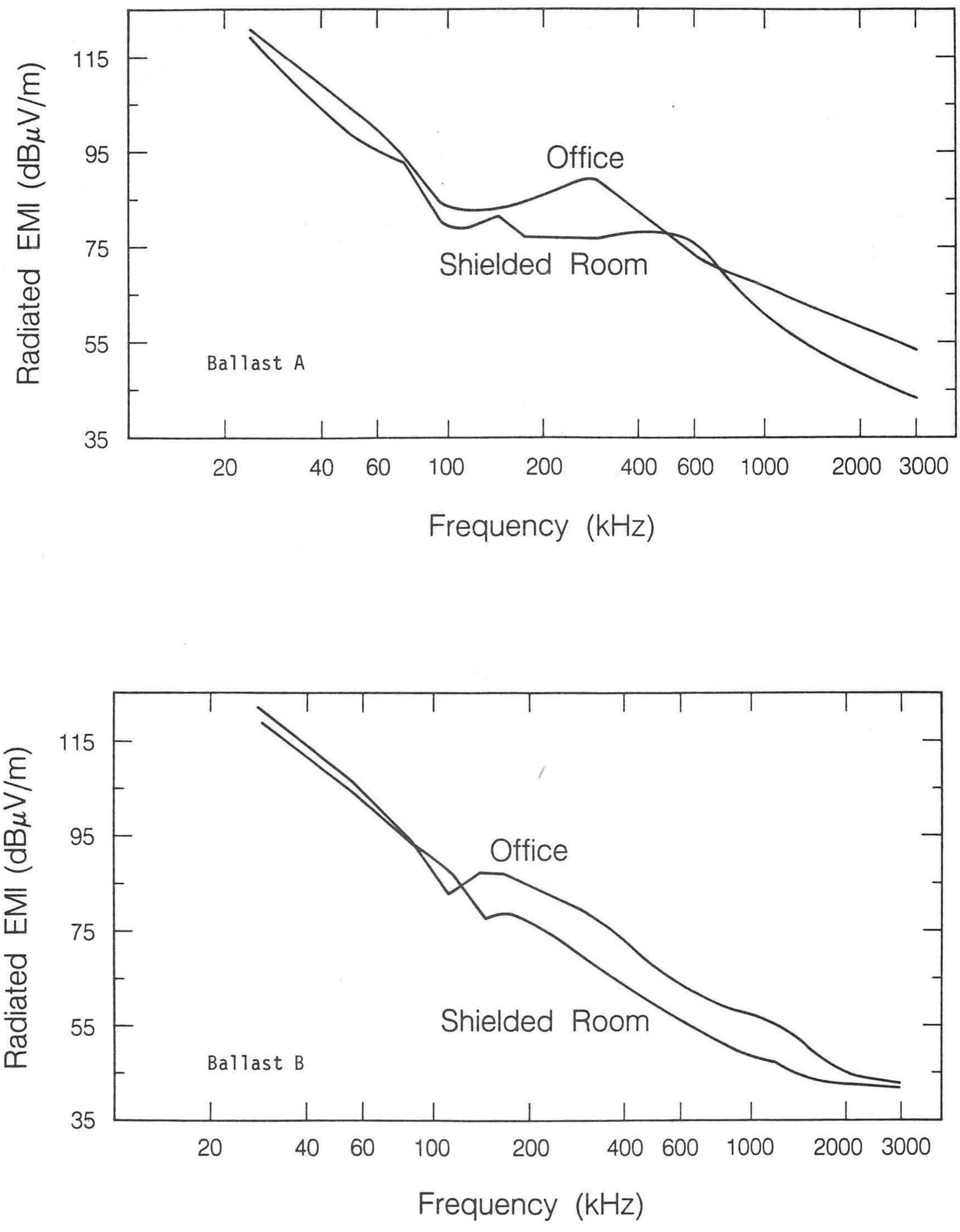


Figure 10. Comparison of EMI for office versus shielded room, ballasts A and B.

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UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720