GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. ______

Project No. A-3089 DATE 10/20/81

Project Director: J. A. Woody School/Lab ECSL/ECD

Sponsor: The Aerospace Corporation

Type Agreement: Purchase Order No. W-0350 (under DOE Prime #DEAC08-80-CS-50101)

Award Period: From 10/9/81 To ~~10/8/82~~ ~~4/9/82~~ ~~2/9/83~~ 3/31/83 (Performance) 12/8/82 (Reports)

Sponsor Amount: $49,964 Contracted through:

Cost Sharing: N/A GTRI/GIT

Title: Investigation of Electric Vehicle EMI/EMC and its Control.

ADMINISTRATIVE DATA OCA Contact Faith G. Costello

1) Sponsor Technical Contact:

L. Kahal
Suite 4000
The Aerospace Corporation
955 L'Enfant Plaza, SW
Washington, DC 20024

2) Sponsor Admin/Contractual Matters:

G. A. Pierce, Buyer
Suite 4000
The Aerospace Corporation
955 L'Enfant Plaza SW
Washington, DC 20024

Defense Priority Rating: N/A

Security Classification: Unclassified*

RESTRICTIONS

See Attached (Gov't) Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval ~~where total will exceed greater of $500 or 125% of approved proposal budget category~~.

Equipment: Title vests with sponsor

COMMENTS:

*No public disclosure regarding the award of this contract or any phase of same may be made without the express written permission of the Sponsor.

OCT 1981 RECEIVED Research Reports Office

COPIES TO:

Administrative Coordinator
Research Property Management
Accounting
Procurement/EES Supply Services
Research Security Services
~~Reports Coordinator (OCA)~~
Legal Services (OCA)
Library
EES Public Relations (2)
Computer Input
Project File
Other ______

FORM OCA 4:781

GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 5/4/83

Project Title: Investigation of Electric Vehicle EMI/EMC and its Control

Project No: A-3089

Project Director: J. A. Woody

Sponsor: The Aerospace Corporation

Effective Termination Date: 3/31/83

Clearance of Accounting Charges: 3/31/83

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice and Closing Documents
- [ ] Final Fiscal Report
- [x] Final Report of Inventions
- [x] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Assigned to: ECSL/ECD (~~School~~/Laboratory)

COPIES TO:

Administrative Coordinator
Research Property Management
Accounting
Procurement/EES Supply Services
Research Security Services
Reports Coordinator (OCA)
Legal Services (OCA)
Library
EES Public Relations (2)
Computer Input
Project File
Other Woody

FORM OCA 10:781

A-3089

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

9 November 1981

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 1, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 9 to 31 October 1981

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles, to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
   1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities
   1B. Vehicle circuit studies
   1C. Selection of EMI evaluation methodology

II. EMI/EMC vehicle investigations

III. Documentation

During this initial reporting period, primary emphasis has been placed on formulating the basic plans for the overall program and initiating Task I. The results of the effort directed toward defining the overall program plan is the Program Schedule. This schedule is currently being finalized and will be submitted early next month.

Particular emphasis has been given this month to obtaining background information and literature on current electric vehicle technology, trends, and activities. Specifically, J. A. Woody attended the 1981 Electric Vehicle Symposium and Exposition which was held in Baltimore, MD on 21-23 October 1981. The purpose of this symposium was to present a broad perspective on the worldwide electric vehicle industry which is moving "from concept to consumer." The symposium consisted of a total of 13 technical sessions including a large number of papers on electric vehicle batteries, fleet use and demonstration analyses, market strategies, drive train testing, etc. Although attending these technical sessions was a very expedient method of

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

obtaining valuable background information on the current electric vehicle technology, it was noted that none of the technical papers were directly concerned with the electromagnetic aspects of electric vehicles. It appears that to date the primary emphasis has been on developing and/or improving the operational aspects of the electric vehicle. In relation to this contract, the fact that apparently very little, if any, research has been conducted on electromagnetic emissions and susceptibilities of electric vehicles is a significant conclusion.

In addition to the technical sessions, an exposition of electric vehicle hardware was held concurrently. A total of 44 exhibitors were listed in the program. The exposition provided an excellent opportunity to view various types of electric vehicle hardware and to obtain literature from a large number of manufacturers and distributors. This literature is currently being reviewed to identify potential sources to be contacted for more detailed information.

At the symposium/exposition, contacts were made with Mr. Ohba of Soleq Corporation of Chicago and Dr. Dieter Nowak of the University of Alabama in Huntsville concerning future visits to their facilities. These visits are for the purposes of further defining current technology in electric vehicles and of discussing their potential emission and susceptibility characteristics. In addition, trips are currently being planned to NBS and to the SAE EMR Subcommittee meeting to be held in Detroit in November.

During the next month, it is anticipated that some of the planned trips will be taken and that Subtask 1A will be initiated. The financial report for October is attached.

Respectfully submitted.

Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
9 to 31 October 1981

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures: Category	Person-hours
I	$1721	$1721	$23,087	Professional Engineers	33
				Clerical/ Technical Assistants	1
II	0	0	$16,542	Professional Engineers	0
				Clerical/ Technical Assistants	0
III	0	0	$ 8,616	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$1721	$1721	$48,245	Professional Engineers	33
				Clerical/ Technical Assistants	1

*Includes estimate for current month

A-3089

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

15 December 1981

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 2, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 30 November 1981

Reference: Georgia Tech Monthly Progress and Financial Report No. 2, dated 7 December 1981.

Gentlemen:

The Financial Report portion of the reference report was inadvertently omitted. Ten copies of the completed version are attached and should supercede the original submission.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

7 December 1981

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 2, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 30 November 1981

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles, to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
 1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (initiated)
 1B. Vehicle circuit studies (initiated)
 1C. Selection of EMI evaluation methodology

II. EMI/EMC vehicle investigations

III. Documentation

Project activities this month have been directed towards Subtasks 1A and 1B. In addition, a program planning and review meeting was held at Georgia Tech on 4 November 1981. Attending this meeting were Mr. Robert E. Barnstead, Mr. Larry A. Kahal, Mr. George A. Pierce, Mr. Rex Chian, and Mr. Richard T. Hall of the Aerospace Corporation and Mr. Jimmy A. Woody, Mr. Hugh W. Denny, Mr. William R. Free, and Mr. John K. Daher of Georgia Tech. The following activities were undertaken during this meeting:

- The Program Schedule was presented and reviewed
- The general approach to completing the initial subtasks was discussed
- The possibility of making measurements on three additional cars was also discussed (a formal proposal is currently being formulated)
- Various Georgia Tech test facilities were toured.

In addition, the total quantity of contract deliverables was reviewed. In an effort to minimize the number of the separate items of required documentation, it was decided that the Monthly Financial Report could be submitted as an attachment to the Monthly Progress Report.

Initial emphasis on Task 1A has been placed on identifying points of contact with various governmental and professional organizations involved in regulatory and standardization activities, as well as other organizations who may have concerns or interests in the EMC/EMI aspects of electric vehicles. Plans are currently being made to contact several different individuals in order to identify and assess current concerns and requirements. Potential points of contact include Mr. Art Wall of the Federal Communications Commission, Dr. Wu of the National Highway Traffic and Safety Administration, Mr. Joe Doster of the Federal Aviation Agency, and Mr. Paul Ruggera of the Bureau of Radiological Health. In addition, Mr. John K. Daher and Mr. Robert E. Barnstead attended an SAE Electromagnetic Radiation Subcommittee meeting on 20 November 1981 in Milford, Michigan. Mr. Daher and Mr. Barnstead were invited to discuss specific items concerning electric vehicles with particular reference to Appendix B of SAE J551. A summary of the events and discussions which occurred during this meeting have been documented and are included as Attachment I.

Initial efforts on Task 1B have primarily been directed toward obtaining and reviewing information on current electric vehicle technology. A large amount of literature has been acquired and is currently being reviewed in detail. In addition, Mr. Hugh W. Denny visited Mr. S. Ohba of Soleq Corporation in Chicago on 11 November 1981 for the purpose of obtaining detailed technical information on their transistorized solid state controller. The information obtained from Mr. Denny's discussions with Mr. Ohba have been documented and are included as Attachment II.

During the next month, it is anticipated that Subtasks 1A and 1B will be continued. The Estimated Monthly Expenditure Plan is currently being revised as requested in Aerospace's letter, dated 11 November 1981. The revised plan will be submitted early next month. The financial report for November is attached.

Respectfully submitted.

Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

Attachment I

Visit With: SAE EMR Subcommittee of the Electrical Equipment Committee

Address: General Motors Proving Ground, Milford, Michigan

Date: November 20, 1981

By: John K. Daher

Project: A-3089

The November SAE EMR Subcommittee meeting was held at the General Motors Proving Ground Facility on 20 November 1981 in Milford, Michigan. Mr. Robert E. Barnstead of the Aerospace Corporation and myself were invited as special guests to discuss some particular items related to Appendix B of SAE J551 which concerns electric vehicles. A primary objective of our attendance at the meeting was to exchange information related to potential emission and susceptibility measurement procedures/techniques as applied to electric vehicles. (It is noted that the SAE EMR Subcommittee developed the existing standard SAE J551 "Performance Levels and Methods of Measurement of Electromagnetic Radiation from Vehicles and Devices (20-1000 MHz)." This document predominantly addresses measurement procedures for internal combustion engines; the information on electric vehicles (Appendix B) has not been finalized since the test procedures have yet to be tested and are open to input.)

After some preliminaries were completed, the agenda switched to the topic of electric vehicles and to Appendix B of SAE J551 in particular. First, it was agreed upon by all in attendance that the performance levels or limits for electric vehicles should be identical to those for internal combustion engines. No further discussion was deemed necessary on this topic. During the discussions, I was asked to give a brief presentation describing our current program with Aerospace. This presentation included a discussion of those components of major concern in an EMC/EMI evaluation of electric vehicles and an overview of the primary tasks to be performed on the program.

Next, Mr. Barnstead presented some opinions related to Appendix B of SAE J551. He began by explaining that he views this appendix (as it presently stands) as simply a committment to include procedures on electric vehicles in the future. With this in mind, Mr. Barnstead expressed some concerns with regard to Appendix B. The first paragraph states that a determination be made of the vehicle speed and operating conditions which result in worst case radiation from the vehicle. Mr. Barnstead emphasized that electromagnetic emissions may vary with the loading on the propulsion system as well as its speed. One concern is that the standard would permit testing the vehicle with the wheels off the ground, i.e., under no-load conditions. Dr. W. Hsu of General Motors agreed and expressed his opinion that load is the most important parameter. Mr. Barnstead said that he had talked this over with Mr. Ed McBryan, who had suggested the possibility of weighting the wheels. Mr. Barnstead emphasized that, whatever technique is utilized, repeatability and standardization should be of primary concern. Dan McGrew of General Motors expressed his opinion that the power train should be exercised over the full range of loading expected to be encountered for various road conditions. He said that both torque/load and speed must be varied, which can only be done repeatedly using a dynamometer. It is Mr. Barnstead's contention that the dynamometer will perturb the fields and that the properties of the dynamometer must therefore be known and suppression provided. Dr. Hsu argued that it would be too time consuming to measure the vehicle under many different load conditions and, therefore, testing must be restricted to a limited number of load conditions.

Mr. Fred Bauer, who is chairman of the EMR Subcommittee, suggested that the pros and cons of testing with a dynamometer vs. inertial loading vs. wheels in the air be investigated further. It was suggested that Georgia Tech/Aerospace consider the inertial loading and the wheels in the air cases while Dan McGrew of General Motors considers the case of testing with a dynamometer. It was tentatively planned that the findings of these investigations be presented at the February SAE Subcommittee meeting.

One other major concern was that although the standard requires testing of on-board battery chargers, it does not specify any details for connecting the charger to the ac power grid. The power cable used for this purpose may itself radiate significant levels which depend on a number of variables that are not addressed in the standard (i.e., length, impedance, polarization, etc.). As a result, variations in test conditions could mean the difference between meeting or failing to meet the limits of the standard. This concern was apparently shared by the rest of those in attendance based on the fact that there were no disagreements voiced. Mr. Barnstead suggested that a power line filter (low pass) could possibly be used to standardize the length of the "antenna". Mr. Bauer believes that there is an existing standard (which addresses emissions from commercial items such as electric hairdryers) that specifies a network for interfacing with the ac line during tests. Mr. Bauer stated that he would attempt to obtain information on this matter.

Several significant conclusions may be drawn from this meeting. First, it is generally agreed upon that the loading on the propulsion system is an important parameter when testing the vehicles and, as such, must be included in any EMI/EMC test procedure. If a dynamometer is employed, its properties must be known and appropriate suppression used so as not to distort the test results. Also, the test conditions must be clearly specified and adequately standardized so that measurement results are repeatable.

Attachment II

Visit With: S. Ohba and Larry Hirschberger

Address: Soleq, Inc., Chicago, IL

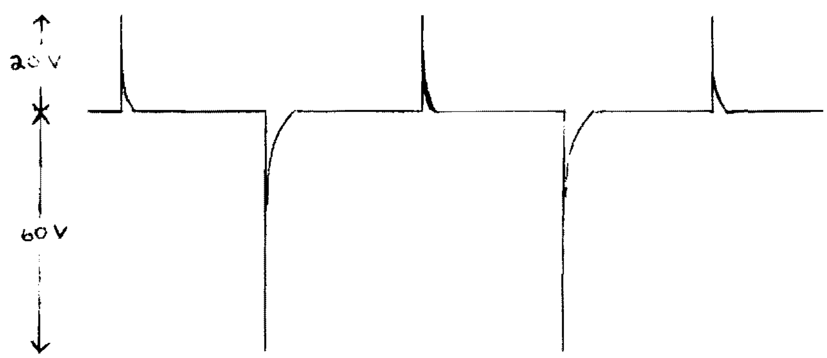
Date: November 11, 1981

By: H. W. Denny

Project: A-3089

Upon arriving at Soleq, Inc., Mr. Ohba and Mr. Hirschberger described Soleq's activities relative to solid state controllers for electric vehicle applications. A general tour of their design, production and test facilities was then taken. Subsequently, an existing vehicle (an older model made by Unique Mobility) was demonstrated. During the demonstration, oscilloscope displays of the motor drive and control current waveforms were examined.

Considerable time was spent discussing Soleq's transistorized controller. Their current controller is capable of providing up to 360 A or 400 A of drive current, depending upon the particular drive motor (and vehicle). Controller output is that of a pulse-width modulated waveform at frequencies ranging from approximately 400 Hz up to nominally 1200-1600 Hz (with 2000 Hz being reached under some possible conditions). For the particular Unique Mobility vehicle observed, for about 5 to 6 seconds following takeoff (during acceleration), the main chopper (armature current) reaches 400 A. Then upon reaching running speed, control reverts to motor field current which is typically 20 A. (These currents were quickly observed during the demonstration ride with an ac-coupled oscilloscope and the following type of waveform was observed:



No effort was made to measure accurately the pulse amplitudes nor their rise and fall times. (The oscilloscope bandwidth was only 15 MHz). Under idle conditions, these pulse trains were not visible.)

Limited tests have been run wherein land mobile receivers in the 150 and 800 MHz bands were operated in this vehicle, which has a fiber glass body. No interference was noted in these bands. AM radio interference was detected in this vehicle, however.

The controller which was described incorporates a large number (some 60 to 100) of silicon power transistors (equivalent No's: 2N6259/2N2773/2N3773). These transistors are supplied by Solitron and are rated at 2A (each) for 1 second with 100 V secondary breakdown characteristics. These transistors are single diffused types with f_T's less than 1 MHz. Mr. Ohba noted that a low f_T is very desirable from the standpoint of low harmonic production (i.e., minimization of EMI). This particular controller was designed for high reliability which explains the very high number of transistors. A less expensive controller could be manufactured with fewer transistors (at a sacrifice in reliability, however).

Mr. Ohba was asked as to sources of information on representative vehicles and controllers. He said that the DOE ESCORT made by EVA probably was the most current and representative vehicle presently available. He suggested that we obtain MERADCOM data, the functional block diagram, and available circuit diagrams from DOE/Aerospace.

Conclusions: Mr. Ohba and Mr. Hirschberger were very cordial and very helpful in sharing their opinions and observations on electric vehicle controller technology. They offered to assist in locating needed information.

From the conversations and the observations made, an improved assessment of controller parameters likely to impact the total vehicle EMI properties was obtained. For example, it can be projected that the initial acceleration phase is likely to be when the strongest emissions will occur. Detailed time waveform and frequency data will be needed to accurately quantify the specific properties of these emissions.

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 December 1981

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures Category	Person-hours
I	$2590	$8703	$16,105	Professional Engineers	74
				Clerical/ Technical Assistants	21
II	0	0	$16,542	Professional Engineers	0
				Clerical/ Technical Assistants	0
III	0	0	$ 8,616	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$2590	$8703	$41,263	Professional Engineers	74
				Clerical/ Technical Assistants	21

*Includes estimate for current month

/| 3089

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

11 January 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 3, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 31 December 1981

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles, to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

- I. Definition of EMC/EMI requirements for electric vehicles (underway)
  - 1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
  - 1B. Vehicle circuit studies (underway)
  - 1C. Selection of EMI evaluation methodology
- II. EMI/EMC vehicle investigations
- III. Documentation

Primary emphasis this month has been directed towards expanding the Estimated Monthly Expenditure Plan and efforts were continued on Subtasks 1A and 1B. The Estimated Monthly Expenditure Plan was originally submitted on 5 November 1981. This Plan was a straight-line estimate by month for each task, since a significant amount of time and labor is required for a detailed estimate including materials, travel, etc., by task for each month of the 14 months of the program. On 16 November 1981, a letter was received from Aerospace stating that the original Plan required amplification. Thus, a revised Plan, dated 8 December 1981, was prepared and subsequently submitted to Aerospace.

Continuing efforts on Subtask 1A have been placed on identifying points of contact with specific governmental and professional organizations involved in regulatory and standardization activities, as well as other organizations who have concerns or interests in the EMC/EMI aspects of electric vehicles. Mr. Joe Doster of the FAA (Frequency Management Division, Southern Regional Office) was contacted via telephone this past month. Mr. Doster indicated

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

that his office would be receptive to future discussions on the electromagnetic aspects of electric vehicles and their relationship to FAA operations and requirements. He also identified Mr. Ray Johnson and Mr. Jerry Markey as two potential contacts at their Washington, DC office.

On Subtask 1B, project activities directed toward reviewing the literature on current electric vehicle technology has continued. Primary emphasis is being placed on switching circuits and highly susceptible components. In addition, Mr. Don Kimball of the Electric Car Company of Atlanta was contacted and arrangements have been made to obtain a copy of their shop manual for subsequent review.

During the next month, it is anticipated that Subtasks 1A and 1B will be continued. A program review meeting is scheduled at Georgia Tech for 14 January 1982. The financial report for November is attached.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 December 1981

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures: Category	Person-hours
I	$2590	$8703	$16,105	Professional Engineers	74
				Clerical/ Technical Assistants	21
II	0	0	$16,542	Professional Engineers	0
				Clerical/ Technical Assistants	0
III	0	0	$ 8,616	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$2590	$8703	$41,263	Professional Engineers	74
				Clerical/ Technical Assistants	21

*Includes estimate for current month

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

8 February 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 4, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 31 January 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles, to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

- I. Definition of EMC/EMI requirements for electric vehicles (underway)
  - 1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
  - 1B. Vehicle circuit studies (underway)
  - 1C. Selection of EMI evaluation methodology (initiated)
- II. EMI/EMC vehicle investigations
- III. Documentation

Emphasis this month has been placed on continuing Task I. In addition, issues were addressed related to the Aerospace/Georgia Tech presentation for the upcoming SAE EMR Subcommittee meeting. This presentation will be concerned with the pros and cons of simulating electric vehicle (EV) load conditions by (a) inertial loading of the drive wheels and (b) acceleration of drive train system with the wheels elevated above the ground and no weights attached. In particular, the answers to two key questions are being addressed. The first question concerns the time required to perform a complete electromagnetic scan of the vehicle at a given operating point. The second question concerns the feasibility of scanning the entire frequency spectrum of interest while varying the load in order to determine worst-case operating points (where a full set of tests may subsequently be performed). Mr. Terry Ryback (GM/EMC Facility) was contacted via telephone and he provided useful information in this regard. A technical discussion of these topics will be submitted to Aerospace under separate cover in the near future.

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

During this reporting period, efforts on Subtask 1A were placed on contacting individuals within specific governmental organizations involved in regulatory and standardization activities and who might have concerns or interests in the EMC/EMI aspects of EV's. Mr. Paul Ruggera of the Bureau of Radiological Health (BRH) and Mr. David Segerson of the Bureau of Medical Devices (BMD) were contacted this month. Both of these individuals indicated that the EMI/EMC aspects of electric vehicles were of no conern at present to their respective organizations. The BRH is concerned with human health hazards. Mr. Ruggera indicated that although peak emission levels from electric vehicles may be significant, current limits are based on average levels (i.e. heating effects in tissues) and that the average levels expected from EV's are far below those of concern. Mr. Segerson indicated that the only type vehicle which might be of concern to the BMD is an emergency-type vehicle which is actually carrying an assortment of medical devices.

Initial efforts on Subtask 1C this month were directed toward evaluating potentially applicable measurement procedures. The specific documents being analysed are SAE J551 ("Performance Levels and Methods of Measurement of Electromagnetic Radiation from Vehicles and Devices (20-1000 MHz)"), SAE J1113 ("Electromagnetic Susceptibility Test Procedures for Vehicle Components (Except Aircraft)"), MIL-STD-462 ("Measurement of Electromagnetic Interference Characteristics"), and IEEE Std. 263 ("Standard for Measurement of Radio Noise Generated by Motor Vehicles and Affecting Mobile Communications Receivers in the Frequency Range 25 to 1000 Megacycles per Second"). From the vehicle circuit studies made to date, it is clear that the pulse characteristics associated with EV's are significantly different than those associated with internal combustion powered vehicles. Hence, a different scan rate will likely be required for EV's. Also, the test procedures must provide for measurements made below 20 MHz, since a significant amount of energy is expected below this frequency. The test procedures must also reflect the fact that the EMI characteristics of EV's will be a strong function of the loading on the motor. It has been suggested that the only way to accurately and repeatably apply different load conditions is with the use of a dynamometer. A mechanical (i.e. non-electrical) dynamometer is desirable to limit the ambient noise levels. A draft test procedure which incorporates these and other ideas is being prepared.

In response to conversations between Mr. Walt Dippold (DOE) and Mr. Hugh Denny (Georgia Tech) and between Mr. Larry Kahal (Aerospace) and Mr. Jimmy Woody (Georgia Tech), it was decided to place primary and immediate emphasis on Subtask 1C and Task II. In the coming weeks, a significant level of effort will be devoted to: (a) finalizing the test methodology and procedures and (b) solving the logistical problems associated with the measurement phase (i.e., procurement of dynamometer arrangements for transportation and storage of the test EV, etc.). These logistical problems must be resolved in order to eliminate any dead time between receipt of the EV and the start date of the measurements.

During the next month, it is anticipated that Tasks 1 and 2 will be continued and the draft test procedures will be finalized. Also, trips are being planned to the University of Alabama in Huntsville and to NBS in Boulder, Colorado for the purposes of discussing current EV technology and test methodologies. The financial report for January is attached.

Respectfully submitted

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 January 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures: Category	Person-hours
I	$2145	$10,848	$13,960	Professional Engineers	90
				Clerical/ Technical Assistants	23
II	0	0	$16,542	Professional Engineers	0
				Clerical/ Technical Assistants	0
III	0	0	$ 8,616	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$2145	$10,848	$39,118	Professional Engineers	90
				Clerical/ Technical Assistants	23

*Includes estimate for current month

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

1 March 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 5, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 28 February 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EVs), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
 1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
 1B. Vehicle circuit studies (underway)
 1C. Selection of EMI evaluation methodology (underway)

II. EMI/EMC vehicle investigations (initiated)

III. Documentation (initiated)

Emphasis this month was placed on continuing Task I and initiating Tasks II and III. In addition to these activities, a program planning and review meeting was held at Georgia Tech on 4 February 1982. Attending this meeting were Mr. Robert E. Barnstead of The Aerospace Corporation and Mr. Jimmy A. Woody, Mr. Hugh W. Denny, Mr. William R. Free, Mr. John K. Daher, and Mr. D. Jay Freedman of Georgia Tech. (Biosketches of Mr. Daher and Mr. Freedman accompany this report.) Several of the topics discussed and conclusions reached during this meeting were as follows:

- A reorganization of the program time schedule is necessary in order to accomodate testing of an electric vehicle during the month of April. This will require that the majority of current program funds be reapportioned to accomplishing the above objective. The program schedule should be revised to reflect this reorganization.

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

- Arrangements should be made to procure a dynamometer for testing in April, if possible. Also should consider other means of repeatably and reliably loading the vehicle.
- Development of a test methodology has become increasingly important.
- Emission measurements have higher priority than susceptibility measurements.
- It is desirable to obtain data below 20 MHz, but it is not desirable to push the state-of-the-art for automotive measurements.
- It is desirable to schedule a trip to National Bureau of Standards in Boulder as soon as possible.
- A proposed program schedule should be drafted to include measurements on three additional vehicles.
- Necessary steps should be taken immediately to resolve the logistical problems associated with the measurements phase of the current and proposed programs.

Several of these action items have already been undertaken. These and other program activities conducted this month are discussed below.

On 12 February 1982, Mr. Hugh Denny met with Mr. Robert Barnstead and Mr. Larry Kahal of The Aerospace Corporation and Mr. Walt Dippold of the Department of Energy in Washington, DC for the purposes of further defining the program objectives. The details of the discussions and conclusions of this meeting have been documented and are included as Attachment I. It was decided that initial emphasis should be placed on quantifying the relative magnitude of the EV EMI problem. Once the existence of problems, if any, are established, then efforts can be focused on the refinement of the test procedures.

During this reporting period, efforts on Subtask 1A were continued by contacting individuals within specific governmental organizations involved in regulatory and standardization activities and who might have concerns or interests in the EMC/EMI aspects of EV's. Mr. Art Wall (FCC-Radio Frequency Devices Branch) and Mr. Fred Bauer (Chairman of the SAE Electromagnetic Radiation Subcommittee) were contacted via telephone this past month. Mr. Wall indicated that FCC involvement will probably be minimal as long as adequate standards exist which are being followed by industry. Mr. Bauer maintained that SAE J551 should, at the very least, be a model for the standard pertaining to EV's. The information obtained from telephone conversations with these individuals has been documented and is included as Attachments II and III.

Efforts this reporting period on Subtask 1C were directed toward developing a test procedure for evaluating the EMI/EMC characteristics of an EV. The test procedure development is being guided by analyses of potentially applicable measurement procedures, such SAE J551, SAE J1113, MIL-STD-462, and IEEE Std. 263. The completed document will include procedures for near-field probing, radiated emission and susceptibility testing, and a limited amount of conducted emission and susceptibility measurements. Primary emphasis is being given to radiated emission measurements, which will likely include procedures for testing the vehicle with a dynamometer, with the drive wheels off the ground, and under a number of actual operating modes (i.e., accelerating, continuous drive by, and braking). In addition to this effort, Mr. Jimmy A. Woody and Mr. William R. Free of Georgia Tech and Mr. Robert E. Barnstead of The Aerospace Corporation visited Mr. Harold E. Taggert and Mr. John W. Adams of NBS and Mr. Joseph A. Hall, Dr. Arthur D. Spaulding, Mr. R. J. Matheson and Mr. Glenn D. Falcon of NTIA on 16 February 1982 at Boulder, CO. This visit included a demonstration of an NTIA developed distribution meter (called the DM-4), which measures the amplitude probability distribution (APD) and average crossing rate (ACR) of various waveforms, including noise-like and impulsive waveforms. The information obtained from these discussions has been documented and is included as Attachments IV and V.

Efforts this past month on Task II have been concentrated on identifying and resolving the logistics for electric vehicle measurements. These efforts included the following:

- Locating and securing a chassis dynamometer. Mr. Jimmy A. Woody visited Dr. Bernard J. Schroer, Mr. F. Peters, and Mr. Dwayne Freeman of the University of Alabama in Huntsville to examine their dynamometers and to discuss the possibility of leasing or borrowing one of them for use on the current program. The information obtained from this visit has been documented and is included as Attachment VI. It appears that an ARCO "Drive for Conservation" portable dynamometer (manufactured by Clayton Manufacturing Company) will be available for use during the month of April. In addition, 11 manufacturers of chassis dynamometers have been written in an effort to borrow or lease a suitable instrument. One local concern has agreed to lease a trailer-mounted chassis dynamometer, provided he is satisfied with our ability to secure his equipment against damage by weather and vandals. Finally, the Marietta-Cobb Co. Vocational and Technical Education School has agreed to make their dynamometer available for experiments at their facility, if needed.

- Considering various ways of sheltering the dynamometer. Various portable shelters have been considered for covering the dynamometer at the field site. These include metal buildings, wood precut buildings, and large tents. At this point, primary consideration is being given to high quality, waterproof tarps available locally.

- Considering the possibility of having to ship the electric vehicles either to and from their suppliers or to a remote testing location. TNT, Inc. specializes in this kind of transport, moving vehicles either point to point or door to door.

- Determining what applicable insurance policies exist with regard to our temporary possession of the EV. Georgia Tech carries driver's liability insurance which would cover any driving accidents in the electric vehicles. As Government Furnished Equipment, any damage which may occur to the vehicle itself is the responsibility of the sponsor.

- Locating a suitable vehicle trailer. The Georgia Tech Physical Plant Department owns an equipment trailer which may be suitable. As a backup to this source, however, commercial suppliers of vehicle trailers in the Atlanta metro area were identified. Three were found and rental fees were all about $35/day or $300/mo. One company, Buford Tool Rent or Sell, said they had a trailer which they would sell for $800. Because of the distance to Buford, and because of the likelihood of the Georgia Tech Physical Plant Department's cooperation, this trailer has not yet been examined. Also, it appears that the possibility of using the trailer associated with the ARCO portable dynamometer (see Attachment VI) looks promising.

- Securing use of the field site. The field site has been requested and reserved for the April tests.

- Considering equipment needs for testing purposes. Tentative equipment and instrumentation lists have been drawn up based on past experience and current expectations. These lists include some 28 items in the categories of electrical, electronic, mechanical, and instrumentation needs anticipated for these experiments. Efforts have already commenced to secure, reserve, buy and calibrate these items as needed.

Initial efforts on Task III this month were directed toward analyzing the scan rate limitations for electromagnetic emissions measurements on electric vehicles. In particular, the time required to determine worst-case operating points and the time required to completely scan a vehicle at a fixed operating point have been addressed. The results of these analyses have been documented and submitted to Aerospace in the form of a technical report. One conclusion of these analyses was that the limitations in scan rate are not expected to be as severe for EV's as for internal combustion engine vehicles.

During the next month, it is anticipated that Tasks I and II will be continued and the test procedure will be completed. The financial report for February is attached.

Respectfully submitted,

for J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 28 February 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures Category	Person-hours
I	$5636	$16,484	$ 8324	Professional Engineers	132
				Clerical/ Technical Assistants	21
II	$4087	$ 4087	$12,455	Professional Engineers	164
				Clerical/ Technical Assistants	0
III	$616	$ 616	$ 8,000	Professional Engineers	24
				Clerical/ Technical Assistants	4
Overall Summary	$10,339	$21,187	$28,779	Professional Engineers	320
				Clerical/ Technical Assistants	25

*Includes estimate for current month

Georgia Institute of Technology
Engineering Experiment Station

BIOGRAPHICAL SKETCH

DAHER, JOHN K.--Research Engineer I
Electronics and Computer Systems Laboratory

Education

B.E.E., University of Dayton	1979
B.A., Mathematics, Oberlin College	1977
Graduate courses in electrical engineering, Georgia Institute of Technology	1979-Present

Employment History

Georgia Institute of Technology Research Engineer I, EES	1979-Present
Monarch Marking Systems, Lab Technician	1977-1978
Cox Heart Institute, Researcher's Assistant	1977

Experience Summary: At Georgia Tech, currently involved with evaluation of verious radiated susceptibility and emissions test techniques. Also involved in the measurement and analytical modeling of intermodulation generation in passive components. Recently, was project director on a program to evaluate the shielding effectiveness of conductive plastics. Has also been active in the measurement and evaluation of various VHF/UHF antennas, preamplifiers, and transmission line components. Conducted research into the electromagnetic susceptibility of various solid-state devices and integrated circuits. With Monarch Marking Systems, was active in the testing and evaluation of novel materials (porous rubbers, inks, etc.). With the Cox Heart Institute, conducted a computer-aided statistical analysis of research data. Also designed various crossover networks for private designer and manufacturer of speaker systems.

Current Fields of Interest

Antenna design; shielding effectiveness of conductive plastics; electromagnetic effects; circuit design; electroacoustics; applied electromagnetic theory; passive filter design.

Major Reports and Publications

1. "Management and Design Guidance--Electromagnetic Radiation Hardness for Air Launched Ordnance Systems," Interim Military Handbook, Project A-2358, 20 August 1979, with others
2. "EMR Hardness Design Guidance--Task 2," Interim Technical Report, Project A-2358, April 1980, with others
3. "Program to Improve UHF Television Reception," Final Report, Project No. A-2475, September 1980, with others
4. "Management and Design Guidance--Electromagnetic Radiation Hardness for Air Launched Ordnance Systems," Military Handbook, 15 November 1980, with others
5. "EMR Hardness Design Guidance," Final Technical Report, Contract No. F30602-79-C-0132, November 1980, with others

6. "Integration of Electromagnetic Environmental Effects (E^3) Test and Evaluation," Final Technical Report, Project A-2641, November 1980, with others
7. "Identification of Aircraft Passive Nonlinear Interference," Test Plan I, IM Measurement Procedures, Project A-2845, April 1981, coauthor
8. "Evaluation of EMP Protection Measures for Defense Electronics Installations," Draft Final Report, Contract No. DNA 001-80-C-0292, 30 May 1981, with others
9. "Shielding Effectiveness Evaluations of Thermoformable Laminates," Final Report, Project No. A-2897, July 1981

Georgia Institute of Technology
Engineering Experiment Station

BIOGRAPHICAL SKETCH

FREEDMAN, D. JAY--Research Scientist I
Electronics and Computer Systems Laboratory

Education

M.S., Physics, University of Alabama in Birmingham	1979
B.A., Physics, Emory University	1974

Employment History

Georgia Institute of Technology Research Scientist I, EES	1979-Present
University of Alabama/Birmingham, Teaching Assistant	1977-1979
Emory University, Teaching Assistant	1975-1977

Experience Summary: Is involved in design of exposure facility to study effects of low-level EM fields on experimental animals. Also working on EM-produced hyperthermia. Both teaching assistantships involved instruction of introductory laboratory sections. At University of Alabama in Birmingham, physical science for non-science majors was also taught.

Current Fields of Interest

Medical applications of physics; temperature dosimetry; developing empirical methods for determining specific absorption rate; hyperthermia; patient management; environmental effects; research management.

Major Reports and Publications

1. "Phototype Circular Parallel Plate Facility for Chronically Exposing Large Rodent Populations to 420-450 MHz Radiofrequency Radiation," Final Report on Subcontract No. SCEE ARB/79-20, Project A-2392, January 1980, coauthor
2. "Construction of a 435 MHz Radiofrequency Radiation Facility for Long Term Bioeffects Studies Involving Large Rodent Populations," Final Report on Subcontractor NO.'s SCEEE ARB/80-34 and SCEEE ARB/81-34, Project 42650, July 1981, coauthor

Attachment I

Visit With: R. Barnstead, L. Kahal, and W. Dippold

Firm: The Aerospace Corp./Dept. of Energy

Date: February 12, 1982

Hour: 8:30 - 11:00 am

By: H. W. Denny

Project: A-3089

As a result of earlier telephone conversations with Mr. Dippold and Mr. Kahal, the previously submitted program schedule has been revised. The purpose of this meeting was to discuss the revised schedule, to examine in detail the planned activities, and to obtain agreement on priorities of activities.

A copy of the proposed revised schedule is attached. The revised schedule reflects the placement of emphasis on the measurement of an electric vehicle as soon as logistical arrangements could be completed. Via this revised schedule, Georgia Tech promised to apply full efforts toward accomplishing a first set of measurements on a vehicle during April 1982. All program activities were to be reoriented toward completing a set of test procedures and handling the logistical aspects (obtaining a dynamometer, transporting it to the test site, arranging for transportation and storage of the test vehicle, etc.) of the measurements. It was agreed that DOE/Aerospace would seek to have a vehicle available in April for testing. Georgia Tech is not responsible for transporting the test vehicle to and from Atlanta; however, we stand ready to assist in whatever manner necessary commensurate with available resources.

A generalized approach to the tests on the first vehicle was outlined. This approach consisted of a sequential series of tests as follows:

1. Vehicle only
2. Vehicle with loading of individual wheels
3. Vehicle loaded with a dynamometer
4. Dynamometer alone
5. Vehicle with dynamometer with screen

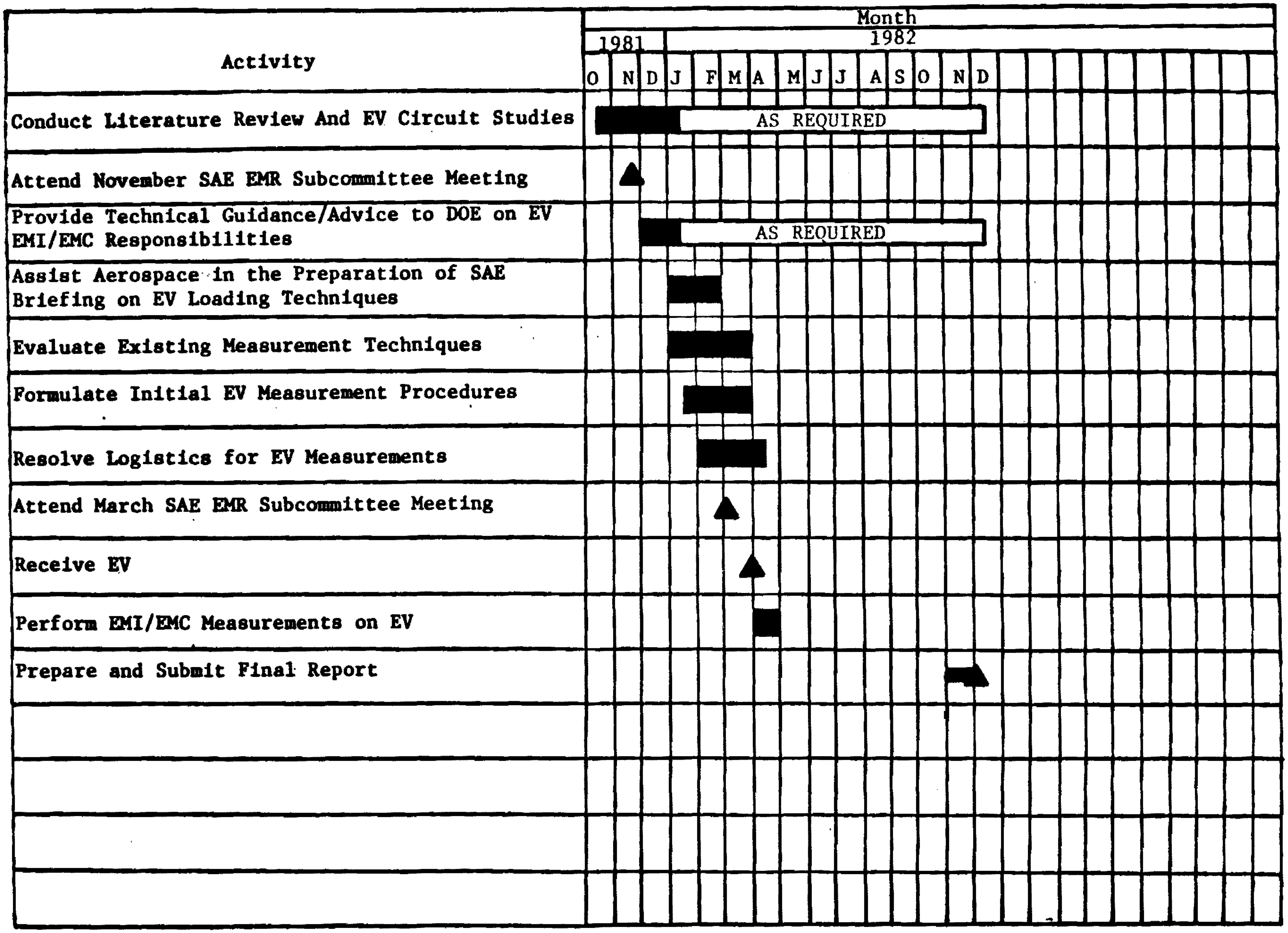
Mr. Dippold responded by saying that on the first vehicle he wants a quick, first look taken. He wants more emphasis placed on characterizing the general

EMI properties of the vehicle itself, rather than initially worrying about how to separate possible polluting effects of the dynamometer from combined vehicle-dynamometer tests. As part of this emphasis, he wants "drive by" vs. static tests conducted. Since the Georgia Tech field site will accommodate "drive-by" tests, it was agreed to conduct a limited series of dynamic tests to encompass acceleration, steady speed, and deceleration.

Mr. Barnstead asked about the relative emphasis to be placed on developing the "best" test procedure, i.e., one that reflects all the considerations that must ultimately be incorporated into a standard accepted by government and industry. Mr. Dippold indicated that initial emphasis is to be placed on quantifying the relative magnitude of the EV EMI problem. Once the existence of problems, if any, are established, then efforts can be focused on refinement of procedures in anticipation of eventual standardization. With this emphasis on obtaining definitive data on a representative vehicle as soon as possible, it was decided to deemphasize efforts to provide formal inputs to SAE Committee standards activities. It was emphasized that in order to satisfy the logistical requirements associated with measuring a vehicle in April, the amount of time available to formulate inputs to the SAE would have to be curtailed. This was agreed to by all present.

The need for frequent and comprehensive documentation of all activities, to include observations made and conclusions reached, was emphasized by Mr. Dippold. Mr. Denny agreed to encourage all program participants to expand their reporting efforts and to forward them in a timely manner.

REVISED PROGRAM SCHEDULE
FOR CURRENT EFFORT
Purchase Order W-0350



Attachment II

Telephone Conversation With: Art Wall

Firm: Federal Communications Commission (FCC)

Date: 22 February 1982

Hour: 0930

By: D. J. Freedman

Project: A-3089

In order to determine whether the FCC had any regulatory interests in electric vehicles, we contacted Art Wall of the Radio-Frequency Devices Branch in the FCC's Office of Science and Management. Declining to take an official stand without benefit of written questions, Mr. Wall was willing to give us some guidance, nonetheless.

Since to date there has been little, if any, indication of any need for regulation, the FCC is likely to remain in the background. This is especially true if the industry continues to regulate itself satisfactorily as it has done in the past.

As a guide for developing test procedures, Mr. Wall suggested we use SAE J551. Further, he indicated that only two parts of the FCC rules might apply: 15.25 and 15.7. Both rules say, for the most part, that the system should not interfere with telecommunications. With respect to frequency bands, Mr. Wall indicated that no particular band could be singled out as more important or susceptible, from a user point of view. "Everyone", he said, "is going to want their services protected."

Finally, as long as someone is writing adequate standards (such as SAE or ANSI) and as long as industry follows those standards, FCC interest in electric vehicles will remain minimal, at most. Consequently, Mr. Wall recommended we speak with Fred Bauer.

Attachment III

Telephone Conversation With: Fred Bauer

Firm: Federal Communications Commission (FCC)

Date: 22 February 1982

Hour: 0930

By: D. J. Freedman

Project: A-3089

Fred Bauer is chairman of the SAE Electromagnetic Radiation (EMR) Subcommittee of the Electrical Equipment Committee, Technical Advisor to the U.S. National Committee of the International Electrotechnical Commission (IEC) for the Affairs of the International Special Committee on Radio Interference (CISPR) and Chief U.S. Delegate to CISPR (Ignition Interference). He contends that the FCC really has no applicable regulations, but, in agreement with Mr. Wall, maintains that SAE J551 should, at the very least, be the model for rules pertaining to electric vehicles. Mr. Bauer cautions, though, that there is a high probability of the method of measurement slanting test results. In any event, the world is in agreement that all vehicles should look the same from the outside with respect to EMI/EMC irregardless of their power plants.

Mr. Bauer said he had two main concerns. First, the development of test procedures to measure electrical propulsion systems should also allow for the measurement of hybrid systems. Secondly, the measurement of any on-board charging equipment must be incorporated. There are problems with respect to connections to the utility mains. The development of a uniform matching network may help alleviate these problems, but the method of test may still sway the result. The United States is attempting to incorporate as many of the European standards as possible. Indeed, it is his intent to adopt the Common Market standards for transients from the charging units.

According to Mr. Bauer, the test conditions do not necessarily have to match road conditions in order to have a good test. The real desire is to develop tests which are independent of load and speed while at the same time keeping the manufacturer's test equipment and procedure costs to a minimum. Therefore, he suggests we keep in mind that small manufacturers of items such as golf carts are likely to fall under any standards which may be forthcoming, and we do not want to write a standard which will require an immediate exemption because of cost.

As far as test frequencies are concerned, Mr. Bauer believes that any safeguards taken for emissions from 20-1000 MHz will also take care of noise below 20 MHz. He stated, however, that NASA is of a different opinion and thinks there may be significant interference below 20 MHz. Unfortunately, there is a practical problem which arises at lower frequencies. The antenna test height prescribed by SAE J551 is such that the lowest frequency dipole antenna clears the ground for vertical polarization measurements by a minimal distance.

In closing, Mr. Bauer said that, "SAE J551 has been totally vindicated in twenty five years of usage in the U.S., Canada, the Common Market, and Japan." He believes that the signal limits imposed therein are proper. He also recommended that we examine CISPR Publication #12 to acquaint ourselves with the European standards.

Attachment IV

Visit With: Bud Taggart & John Adams (NBS), Joe Hull & Don Spalding (NTIA)
Firm: NBS and NTIA
Date: February 16, 1982
Hour: 2:00 - 5:00 pm
By: W. R. Free
Project: A-3089

J. A. Woody and W. R. Free (Ga. Tech EES) and Bob Barnstead (Aerospace-Sponsor of A-3089) visited the NBS/NTIA facility at Boulder, CO on 2/16/82. The visit was made at the direction of the sponsor with the stated purpose of discussing possible measurement techniques and procedures for performing EMI/EMC measurements of electric vehicles. A joint meeting with the NBS and NTIA personnel was held in Joe Hull's office (Associate Director of ITS/NTIA). The personnel from both organizations have performed EMI/EMC measurements on internal combustion engine vehicles and had a good appreciation of the problems associated with measuring EM noise emissions from vehicles, although they had not measured electric vehicles per se. The Georgia Tech personnel indicated that the current plan is to perform the measurements on the electric vehicle as near as possible in accordance with the measurement procedures described in SAE J551 for internal combustion engine vehicles unless better approaches are found. Don Spalding indicated that he felt it was necessary to measure more detailed statistical data to adequately describe the EM noise emissions from vehicles. However, in ensuing discussions, several problems associated with this approach were identified: (1) adequate instrumentation to perform these types of measurements is not currently commercially available, (2) the statistical data could not be correlated with existing data measured in accordance with J551, and (3) there are no standardized procedures for utilizing the statistical data in EMC analyses.

The need to make the measurements with the electric vehicle in various modes of operation (acceleration, constant speed, inclines, braking) was discussed in some detail. It was agreed that it would probably be necessary to use some type of dynamometer, but there were no conclusions as to what type of dynamometer (passive or active) should be used, how to best apply the dynamometer, or the effects of the dynamometer on the measured data. Both the NBS and the NTIA personnel indicated an interest in obtaining the results from the measurements.

At the conclusion of the meeting, R. J. Matheson and G. D. Falcon demonstrated an NTIA developed distribution meter, called the DM-4. This instrument measures amplitude probability distributions (APD) and average crossing rates (ACR) of waveforms, including noise-like and impulsive waveforms. The APD describes the percentage of time a waveform exceeds specified levels and the ACR describes the average rate the waveform crosses specified levels. The DM-4 provides the capability to establish 31 reference levels at 3-dB increments.

Attachment V

Visit With: See Below

Firm: National Bureau of Standards (NBS) and National Telecommunications and Information Administration (NTIA)

Date: February 16, 1982

By: J. A. Woody

Project: A-3089

On 16 February 1982, W. R. Free and myself, along with R. E. (Bob) Barnstead of Aerospace Corp., visited the following people at NBS/NTIA:

Mr. Harold E. (Bud) Taggart	NBS 303-497-3462
Mr. John W. Adams	NBS
Mr. Joseph A. Hull	NTIA 303-497-5136
Dr. Arthur D. Spaulding	NTIA 303-497-5201
Mr. R. J. Matheson	NTIA
Mr. Glenn D. Falcon	NTIA 303-497-5361

The purpose of this trip was to solicit information/suggestions/recommendations from NBS/NTIS related to the measurements of the EMI/EMC characteristics of EVs based on their experiences (and opinions) concerning the measurements of impulsive noise, in general, and the measurements of internal combustion (IC) automobiles, specifically.

First, we gave them a brief description of the current program indicating that it was a small effort aimed at obtaining EMI/EMC data on a single EV. We told them that we are currently formulating the measurement technique and that we planned on using SAE J551 as the basis for the resulting technique. We requested any suggestions or related information that they could supply.

Mr. Hull indicated that IRAC (Intergovernmental Radio Advisory Committee of WRAC (World Radio Administrative Conference)) was interested in the EMI/EMC characteristics (and their measurement) for EVs because of the potential for impacts on telecommunication, especially land-based mobile (LBM) communications services. (I think that Mr. Hull is chairman of a Standards Working Group (SWG) of a Technical Subcommittee (TSC) of IRAC.) He pointed out that the Radio Noise Working Party of IRAC is chaired by

Dr. Spaulding and that both John Adams and Bud Taggert are members of the SAE EMR Subcommittee (developer of SAE J551). He also indicated that IRAC had some questions concerning the measurement methods employed (and maybe some of the results) of measurements performed on an EV by NASA Lewis. Apparently, the measurements were performed on a modified car (I do not know how it was modified); the car was not a new technology vehicle; and dynamic operation was achieved by repeatedly driving the car past the antenna.

Bob Barnstead described the difficulties in measuring a state-of-the-art EV in such a rapidly emerging and changing technology area. For example, the controller is changing from an SCR-type (100's of Hz) to bipolar transistor-type (1000's of Hz) and is expected to change soon to FET-type (10's of 1000's of Hz). He noted that the upper frequency limit for each type is set by the switching loss (time) in changing from full-off to full-on; it is normally required to be less than 5%. John (I think) stated that the problem with SAE J551 is that they use CW measurement techniques to measure impulsive noise. It was stated that the resulting data is not sufficient and/or is not of the correct type to analyze the potential for interference to other systems, especially LBM communication systems. John indicated that he thinks that the problems associated with emission/susceptibility measurements are generic. He has been involved with these types of measurements for NTS (on electric rail system), NHTSA, and SERI (solar-to-dc-to-ac conversion, specifically the dc-to-ac inverters). He said that he was aware of the problem, that he had thought about it, and that he hasn't put the parts of the "jig saw puzzle" together yet. He thinks that it may be possible to use a digital spectrum analyzer with its peak hold feature; however, in general, he does not like to use spectrum analyzers for impulsive measurements.

Matheson and Spaulding have developed an Amplitude Probability Distribution (APD) analyzer which is used to measure the appropriate descriptors of random impulsive noise to permit the analysis of interference potential. It was noted, however, that such a device is not presently commercially available. The closest commercially available instrument is an HP Vibration Analyzer.

Spaulding stated that MVMA has performed tests to make sure that if IC autos meet the limits for the peak tests in SAE J551 then the APD of their emissions would probably not be severe enough to affect LBM communications. He indicated that similar tests should be performed to determine if this relation is true for EVs. He thinks that eventually more definitive descriptions of emissions from EVs will be needed than simply peak envelop (i.e., SAE J551).

The requirements for varying load conditions on the EV-under-test and for the test site were discussed. A potential technique for measuring an EV under various load conditions would be to use a near-field probe with on-board instrumentation while the EV is being driven. The near-field data would then be extrapolated to far-field data. (This technique would require extensive development and validation; however, it may be appropriate for consideration in the future to eliminate a dynamometer.) It was noted that the use of a metal ground plane when performing emission tests on IC autos drastically affects the results. This effect exists because a significant portion of the emissions is from the bottom of the auto and is reflected off the ground plane to the antenna.

Test instrumentation was again discussed. It was pointed out that one problem with "pulling instruments off the shelf" is that the user must make sure that the "peak" switch position on the receiver yields true peak readings instead of the peak of the logarithm (i.e., the receiver must have a linear IF instead of a logarithmic IF). For example, the ETV-1 tests used a receiver with a logarithmic IF which measures the peaks of CW signals but which does not take into account the compression that occurs with impulsive signals.

At the end of the technical discussions, Bob Barnstead described in detail the apparent future trends in EV technology:

- ac motors are highly likely,
- JEVA (Japanese EV Association) will have EVs on market by 1990; these EVs will use ac motors with inverters,
- GM, GE, Eaton, Gould, etc. are working hard in US, and
- Future controllers will probably be frequency variable.

Conclusions:

- NTIA/NBS are aware of the potential problems associated with EMI/EMC measurements on automobiles; they have measured IC autos but not EVs.
- NTIA/NBS strongly advocates APD-type measurements to obtain appropriate data even though APD instrumentation is not

commercially available and even though APD data on EVs can not be directly compared with existing SAE J551 data on IC autos.

- o It was recommended that, as a minimum, tests should be performed to determine the applicability of SAE J551 test results to evaluating interference to LBM communications.

- o Care must be exercised in the selection and use of the receiver employed in EV emission measurements (linear vs. log IF, scan times, bandwidth, etc.).

- o In the future, the applicability of NF-field measurements with on-board instrumentation while the auto is being driven should be evaluated. If this technique could be adequately developed, it may be possible to eliminate the requirement for a dynamometer.

- o NBS/NTIA is very much interested in what is being done and would like to be kept informed.

Attachment VI

Visit With: Bernard J. Schroer, Joseph F. Peters, and Dwayne Freeman (?)

Firm: University of Alabama in Huntsville (UAH)

Date: 22 February 1982

By: J. A. Woody

Project: A-3089

I visited UAH to examine their dynamometers and to discuss the possibility of leasing/borrowing one of them. H. W. Denny (GIT), Bob Barnstead (Aerospace), and Walt Dippold (DOE) had previously discussed such possibilities with Dieter Nowak of UAH and H. W. Denny had also telephoned B. J. Schroer.

UAH has an ARCO Drive for Conservation portable dynamometer which was manufactured by Clayton Manufacturing Company. It appears that this dynamometer would be available for our use during the month of April. The observations and the comments concerning this portable dynamometer are as follows:

- The dynamometer and its trailer weigh approximately 6000 lbs; therefore, a heavy truck will be required to pull the dynamometer/trailer.

- The dynamometer is approximately 2-feet high, 3-feet wide, and 6 to 8-feet long; the trailer is approximately 2-feet wider and longer.

- At the test site, the trailer is tilted and a winch is used to roll the dynamometer off the trailer. The vehicle is then placed on the trailer and the trailer is aligned with the dynamometer. The dynamometer and the trailer are the same height such that the drive wheels of the vehicle can be rolled onto the dynamometer.

- The UAH personnel saw no reason why the trailer can not be used to transport the test vehicle.

- The dynamometer needs to be covered with a tarp when not in use and in bad weather.

- We need to devise a method to chain down the vehicle during testing and transporting.

- The dynamometer has either an electric motor or an electrically-driven air compressor to lift the drive wheels out from between the rollers; however, there is no requirement to run this electric part of the dynamometer during the test.

- The dynamometer and the trailer must be perfectly level; therefore, they must be located on a level surface.

- The estimated time to align and fasten together the trailer and dynamometer each day is approximately 2 hrs; this time may be reduced to 30 minutes after it has been performed many times.

- The cooling capacity and the water requirements need to be determined by calling Clayton.

- The ARCO portable dynamometer is designed to simulate an actual level road driving condition and, hence, the load against the drive wheels is not adjustable.

- It has a flywheel for inertia simulation and a hydrokinetic power absorbtion unit (PAU) to simulate the effects of wind resistance (power increases as the cube of the increase in speed).

- The flywheel mass was specially designed to simulate the inertial conditions experienced by a 1979 Chevrolet Malibu at a vehicle weight of 3,200 lbs. The drive wheel weight probably should be less than 1600 lbs.

- The PAU is a special variation of Clayton's single-curve dynamometer PAUs, which essentially provides a power vs. speed curve from 0 through 10 HP at 50 MPH on a cubic curve basis.

- This dynamometer can be used to permit acceleration of the vehicle from any speed up to 55-60 MPH as if it were on level terrain.

- UAH personnel recommended that we contact Clayton (Mr. Jim Bergen, Service Branch Manager, Atlanta, 404-875-0631) and determine if this dynamometer could be modified (in a reversible manner) to permit verying the load applied to the test vehicle (e.g. by changing the flywheel).

- When ARCO donated this dynamometer to UAH, ARCO personnel gave UAH a thorough debriefing on its use. For this reason, UAH personnel recommended that, if we do use this dynamometer, they should deliver it to Georgia Tech, instruct us on its setup and use, and then pick it up at the completion of the test.

- UAH personnel prefer that we formally handle the arrangements through a small Service Contract. They have prepared such a document and submitted it to Georgia Tech; it is currently being reviewed.

- If it is decided that the ARCO portable dynamometer is not appropriate (i.e., can not be used), then UAH also has a C-700 Series (Model C-720) Chassis Dynamometer manufactured by Clayton which probably can be obtained. It is a variable load dynamometer which can be used to simulate practically any grade.

- This variable load dynamometer is mounted in a concrete pit which is approximately 2-feet deep, 3-feet wide, and 6 to 8-feet long. A comparable arrangement, or some type of ramp, would have to be fabricated at the Georgia Tech field site if this dynamometer is required.

- It was indicated that a considerable amount of effort (approximately 1 week of continuous work) would be required in removing the variable load dynamometer from its present installation, transporting it to Georgia Tech, and installing it at Georgia Tech (even if the Georgia Tech site is already prepared).

- Any information required on the variable load dynamometer can be obtained from the Atlanta Service Branch of Clayton.

Conclusions: The UAH personnel were very courteous and helpful. They have a portable ARCO (Clayton) fixed-load dynamometer and a Clayton variable-load dynamometer. They were receptive to working out the arrangements for using one of these dynamometers at Georgia Tech in April. It would be preferable to use the ARCO portable dynamometer if it is determined to be appropriate technically because of the ease with which it can be transported. Its major disadvantage is that it only simulates one load condition (i.e., a level road) for a 1979 Malibu. Conversely, the other dynamometer is adjustable to simulate any load condition; however, it will be very difficult and time consuming to dismantle, transport, and set up.

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

1 April 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 6, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 30 April 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
  1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
  1B. Vehicle circuit studies (underway)
  1C. Selection of EMI evaluation methodology (underway)

II. EMI/EMC vehicle investigations (underway)

III. Documentation (underway)

Efforts this month were continued on Tasks I and II. In addition, a formal proposal was submitted to The Aerospace Corporation for evaluation. The proposal was written in response to a letter from Aerospace dated 11 March 1982 which indicated a potential change in the current contract to include measurements on three additional vehicles as well as additional travel requirements. A revised program schedule and detailed costing information were included in the proposal.

Efforts this reporting period on Subtask 1C were directed toward completion of the test procedure. The purpose of the test procedure is to provide guidance in obtaining data and information from which a characterization of the EMI/EMC features of an EV can be made. The test procedure covers the measurement of radiated emissions from an EV over the frequency range of 14 kHz to 1000 MHz. Radiated emissions will be measured under varying load conditions and engine speeds. Procedures are given for determining worst-case load conditions. Also included is a procedure for measuring representative electromagnetic emission levels while the vehicle is

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

actually being driven at a constant speed, during acceleration, and during deceleration. Copies of the test procedure have been submitted to Mr. Larry Kahal of The Aerospace Corporation and to Mr. Walt Dippold of the Department of Energy. Another copy of the procedure is attached to this report.

Efforts this past month on Task II have been placed on resolving logistical problems in order to prepare for vehicle testing on 1 April 1982. The major items which have been resolved are as follows:

- Locating and securing a chassis dynamometer. Eleven different sources of a dynamometer were identified and contacted, including the University of Alabama in Huntsville, Clayton Manufacturing Company, and the Marietta-Cobb County (Ga) Area Vocational and Technical School. The decision has been made to lease a reconditioned Clayton Model CT 150 dynamometer from Tri State Sales in Smyrna, Georgia. Tri State will deliver, install, test, and remove the dynamometer as part of the lease. Water is required to operate the dynamometer. Since testing will be performed at a location approximately 600 feet from the nearest spigot, plastic pipe has been installed to supply this requirement.

- Considering various ways of sheltering the vehicle. A temporary garage has been constructed at the testing site. The garage was built in order to avoid the problems associated with transporting the vehicle to and from an overnight storage location. The use of the garage should result in longer daily testing periods, since this will avoid the wasted time and potential discharging of the batteries associated with transporting the vehicle over a significant distance.

- Considering equipment needs for testing purposes. All necessary equipment and miscellaneous accessories have been identified and located. The instrumentation has been calibrated and/or repaired as needed.

During the reporting period, it is anticipated that Task II will be continued. The financial report for March is attached.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 30 March 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures: Category	Person-hours
I	$3823	$20,307	$ 4501	Professional Engineers	123
				Clerical/ Technical Assistants	26
II	$4749	$ 8836	$ 7706	Professional Engineers	151
				Clerical/ Technical Assistants	83
III	0	$ 616	$ 8,000	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$8572	$29,759	$20,207	Professional Engineers	274
				Clerical/ Technical Assistants	109

*Includes estimate for current month

RADIATED EMISSION TEST PROCEDURES FOR ELECTRIC VEHICLES

1. Purpose

1.1 The purpose of these test procedures is to provide guidance in obtaining baseline information and data from which a characterization of the EMI/EMC features of an electric vehicle can be made.

2. Scope

2.1 The test procedures cover the measurement of radiated emissions from an electric vehicle over the frequency range of 14 kHz to 1000 MHz. Radiated emissions will be measured under varying load conditions and engine speeds. Procedures are given for determining worst-case load conditions. Also included is a procedure for measuring representative electromagnetic emission levels while the vehicle is actually being driven at a constant speed, during acceleration, and during deceleration (braking).

3. Equipment

3.1 Receivers - The receiver's impulse bandwidth must be measured and should not exceed 10% of the frequency at which measurements are being made.

3.1.1 Spectrum Analyzer: HP-141T Display Section, 8554L RF Section, 8552B IF Section.

3.1.2 NFIM: EMC-25 Interference Analyzer.

3.2 Scanning Plotters - The sine wave response at 0.5 in. peak-to-peak shall not be down by more than 3 dB at 10 Hz from the 1 Hz response.

3.2.1 X-Y Plotter: Houston 2000 X-Y Recorder

3.3 Calibrated Signal Source, Precision Attenuator, & Power Meter - Used for signal substitution method.

3.3.1 Signal Source: HP-8640B

3.3.2 Attenuator: Weinschel 905

3.3.3 Power Meter: HP-435A

3.4 Frequency Counter: HP-5245L

3.5 Antennas - Use the following antennas:

Frequency Range	Type	Manufacturer/Model #
14 kHz - 20 MHz	Rod	Fairchild RVR-25
	Loop	Fairchild ALR-25
20 MHz - 200 MHz	Biconical	Fairchild BIA-25
200 MHz - 1000 MHz	Log Conical	Fairchild LCA-25

3.6 Transmission Line - Use double shielded coaxial cable between receive antenna and receiver.

3.6.1 RG-55/U (50 ft.)

4. Equipment Calibration

4.1 Receiver calibration

4.1.1 Amplitude Calibration - The receiver shall be calibrated at the center frequency of the band being measured by using the standard signal substitution method. Note: 0 dBm (50 Ω) = + 107 dB μV (50 Ω)

4.1.2 Bandwidth Calibration - The impulse bandwidth (BW_i) of the receiver shall be measured if unknown (at each bandwidth setting used during measurements).

4.1.2.1 Spectrum Analyzer Impulse Bandwidth Measurement:

(a) Connect 30 MHz calibrator signal to input terminal.
(b) Select linear display mode
(c) Set linear sensitivity to 1 mV/div.
(d) Tune to 30 MHz and set bandwidth to desired position.
(e) Narrow the scan width until displayed signal nearly fills the CRT.
(f) Peak the display to the top graticule line with the reference vernier.
(g) Read the frequency difference between the half-voltage (-6 dB) points.
(h) BW_i = 6 dB bandwidth.

4.1.2.2 Use existing data for EMC-25 impulse bandwidth.

Note: $R(dB\mu V/kHz) = V(dB\,\mu V) - B$
$= P(dBm) + 107 - B$

where: R = impulse noise intensity in dB above 1 μV/kHz
V = voltage measured in dB above 1 μV
P = power measured in dB above 1 mW
$B = 20 \log (BW_i/1\ kHz)$

4.2 X-Y Plotter Calibration

4.2.1 Calibrate Y-axis by comparison with the spectrum analyzer display and adjusting log reference level in conjunction with the recorder's vertical controls to obtain linearity (at the center frequency only).

4.2.2 Calibrate X-axis with the use of a frequency counter. Use manual scan mode to set start and stop frequencies.

4.3 Antenna Calibration.

4.3.1 Antenna Factor - Use measured data on all four antennas.

4.3.1.1 Verify at center frequency by making a gain measurement and then use the following equation (for a 50 ohm system):

$$\text{Antenna Factor} = \frac{E}{V} = \sqrt{\frac{4\pi(377)}{50\,G\lambda^2}}\quad m^{-1}$$

where

E = electric field strength in μV/m,
V = voltage in μV,
G = gain of antenna, and
λ = wavelength in meters.

4.4 Transmission Line Calibration.

4.4.1 Insertion Loss - The insertion loss of the RG-55/U cable used to connect the receive antenna to the receiver shall be calculated or measured as a function of frequency over the frequency range of interest.

5. Setup

5.1 Vehicle and Antenna Positions (See Figure 1)

5.1.1 Vehicle Position - Orient the vehicle on test pad as shown in Figure 1.

5.1.2 Antenna Position - Set the receive antenna as shown in Figure 1 at a height of 3 m. above ground level (or above the bottom of vehicle tires if ground is not level).

5.2 Test Site and Test Conditions.

5.2.1 Use pad near gate entrance.

5.2.2 Put equipment on wooden bench in region shown in Figure 1.

5.3 Polarization: Below 200 MHz, both vertical and horizontal components of impulse electric field strength shall be measured at each vehicle position. (Below 20 MHz, this includes vertical and horizontal components of both electric and magnetic fields.) Above 200 MHz, only measure circular polarization with the log conical antenna.

6. Measurements

6.1 Ambient Measurement - Evaluate the effect of ambient noise, RF carriers, etc.

6.1.1 Measurements will be made over the applicable frequency range immediately before the vehicle measurements. Procedure will be the same as below except that vehicle will be inoperative.

6.2 Far-field Radiated Emission Measurements (20 - 1000 MHz)

6.2.1 Frequency Range - The frequency range of 20 - 1000 MHz will be divided into eight frequency bands.

6.2.2 Scan Rate - The frequency scan shall be at a rate which will insure that peak levels have been detected.

6.2.2.1 Procedure - Reduce scan rate until levels do not increase significantly (1 dB increase or greater) over previous results.

6.2.3 Antenna and Vehicle Orientation - Make complete set of measurements with antenna at position 1 and next at position 2 (see Figure 1). Then turn the EV around 180 degrees and repeat measurements at both antenna positions. (Note: Can do this assuming the dynamometer can be driven in reverse. If not, then must station the antenna on all four sides of vehicle or rotate the dynamometer itself 180 degrees.)

6.2.4 Define frequency bands as follows:

Band 1:	20 - 60 MHz	Band 5:	200 - 400 MHz
Band 2:	60 - 110 MHz	Band 6:	400 - 600 MHz
Band 3:	110 - 160 MHz	Band 7:	600 - 800 MHz
Band 4:	160 - 200 MHz	Band 8:	800 - 1000 MHz

6.2.5 Wheels-in-the-Air Measurements (Note: These tests will only be conducted if it has been verified that no damage will result to the EV as a result of no-load operation. If it is determined that damage would result, inertial loading may be used or one may proceed directly to the dynamometer loading tests.)

6.2.5.1 Operating Conditions - Electric vehicle will be operated in first gear at a constant speed of 1500 rpm with the drive wheels suspended in the air during these tests. (Note that the gear to be used will depend on the vehicle being tested and the transmission type that it uses. The Electrica has manual transmission and first gear has been selected as being appropriate for testing of this vehicle at 1500 rpm.)

6.2.5.2 Spectrum Analyzer Settings - Set center frequency to center frequency of each band. Use the following control settings:

	Bands 1-4	Bands 5-8
Scan Width:	5 MHz/div	20 MHz/div
IF Bandwidth:	1 kHz	1 kHz
Video Filtering:	none	none
RF Attenuation:	0 dB	0 dB
Scan Time:	See 6.2.2	

Increase RF attenuation to 10 dB. If levels drop by 10 dB, then set RF attenuation to 0 dB. However, if levels drop by less than 10 dB, then increase attenuation to 20 dB. If levels now drop by 10 dB, then set RF attenuation to 10 dB. If levels instead drop by less than 10 dB, add external attenuation as required.

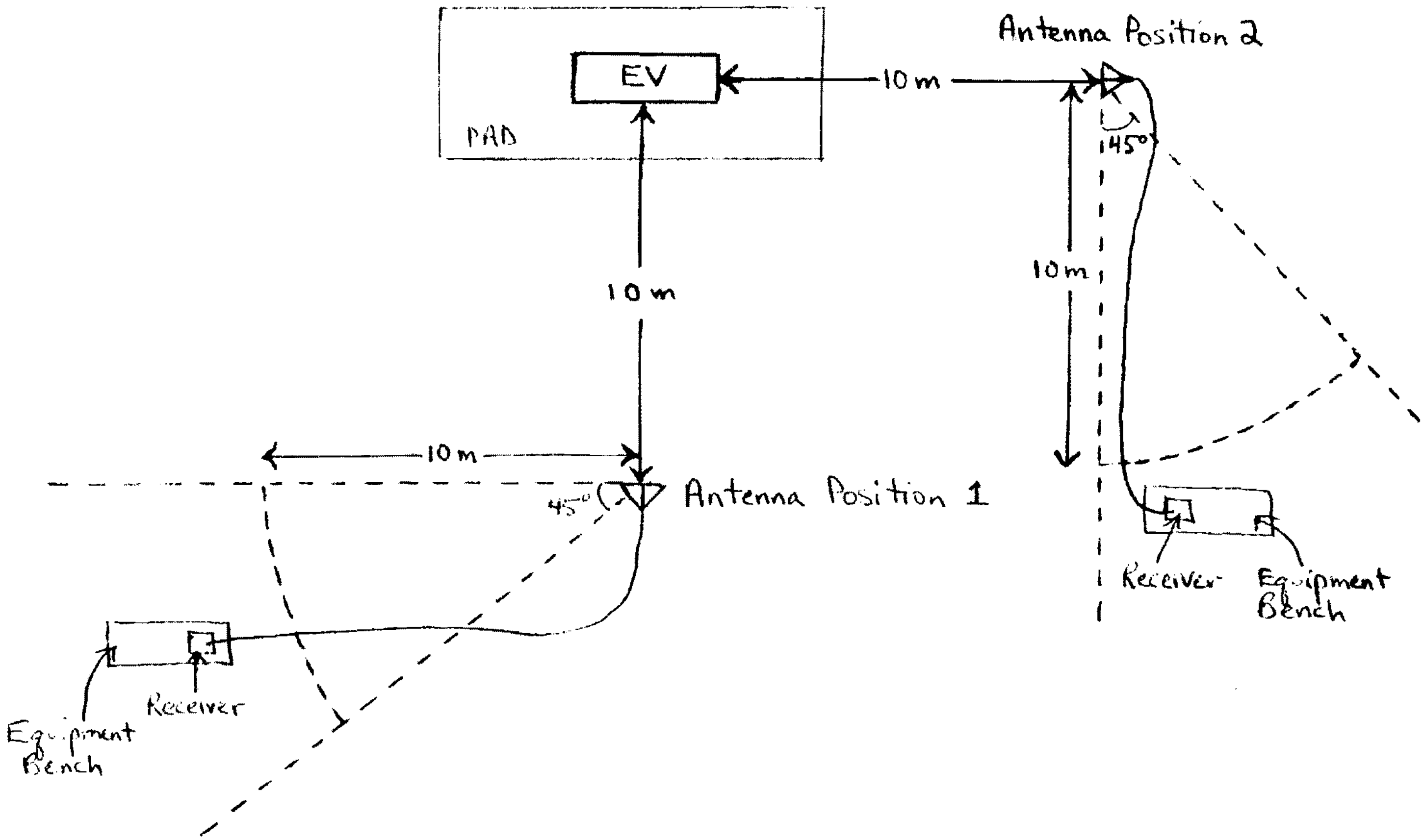


Figure 1. Top View of Test Setup.

6.2.5.3 Make an X-Y plot using the spectrum analyzer in conjunction with the X-Y recorder for each of the eight frequency bands with the antenna in position 1 (measure horizontal polarization only for bands 1-4). This requires a total of 8 plots. The vehicle should be operating at 1500 rpm and with the drive wheels suspended in the air for each test.

6.2.5.4 Verify the above results by using the EMC-25 in the internal sweep mode with remote connections to the X-Y recorder. Use peak detector and operate in narrow band (NB) mode. Sweep bands 11 through 15 of EMC-25 for antenna position 1. Compare results with those obtained above. (Note: If results are within expected measurement error of spectrum analyzer results, use spectrum analyzer as the receiver for the remaining tests. If significant differences are noted, use the EMC-25 for the remaining tests.)

6.2.5.5 Scan bands 1-4 with the antenna oriented for vertical polarization in position 1. Then scan each of the eight bands for the other three antenna/vehicle orientations and for each polarization. This will require, including the 8 plots obtained in 6.2.5.3, a total of 48 plots (two polarizations at four positions for bands 1-4 plus one polarization at four positions for bands 5-8).

6.2.6 Determination of Worst-Case Load Condition (Note: If dynamometer not available for use, proceed to 6.4.)

6.2.6.1 Operating Conditions - Electric vehicle will be operated in first gear at 1500 rpm with a variable load induced by the dynamometer.

6.2.6.2 Use spectrum analyzer (HP-8554L RF Section) with the following settings:

Center Frequency: 100 MHz	RF Attn: 20 dB
Scan Width: 20 MHz/div	Video Filtering: none
Scan Time: 1 ms/div	IF Bandwidth: 300 kHz

Use biconical antenna with horizontal polarization as receive antenna.

6.2.6.3 Beginning at minimum loading, increment the accelerator pedal position (physically or electronically) while varying torque with the dynamometer control unit in order to hold the rpm level as constant as possible (at approximately 1500 rpm). Record the load condition (i.e., torque) which results in worst-case emission levels.

6.2.6.4 Repeat above measurement for vertical polarization.

6.2.6.5 Use spectrum analyzer with the following settings:

Center Freq: 600 MHz	RF Attn: 20 dB
Scan Width: 100 MHz/div	Video Filtering: none
Scan Time: 5 ms/div	IF Bandwidth: 300 kHz

Use log conical as receive antenna. Again repeat measurement of 6.2.6.3.

6.2.6.6 Decide what the worst-case load condition is at 1500 rpm based on results of 6.2.6.3 through 6.2.6.5.

6.2.7 Worst-Case Load Condition Measurements.

6.2.7.1 Operating Conditions - Electric Vehicle will be operated in first gear at the worst-case load condition as determined in 6.2.6.

6.2.7.2 Spectrum Analyzer Settings - Same as in 6.2.5.2.

6.2.7.3 EMC-25 Settings - Same as in 6.2.5.4.

6.2.7.4 Make an X-Y plot using either the spectrum analyzer or EMC-25 in conjunction with the X-Y recorder for each of the eight frequency bands, for each antenna/vehicle orientation, and for each polarization. This requires a total of 48 plots.

6.2.8 Compare the results from 6.2.7 with those obtained from 6.2.5.

6.3 Low Frequency (Near-Field) Measurements (14 kHz to 20 MHz).

6.3.1 Frequency Range - The frequency range of 14 kHz - 20 MHz will be divided into ten frequency bands. These bands will be bands 1-10 of the EMC-25.

6.3.2 Scan Rate - The frequency scan rate will be approximately one minute per band, if the EMC-25 is used. If the spectrum analyzer is used, the rate will be such as to insure that peak levels have been detected.

6.3.2.1 Procedure (for spectrum analyzer only) - Reduce scan rate until levels do not increase significantly (1 dB or greater) over previous results.

6.3.3 Antenna and Vehicle Orientation - Use the antenna/vehicle orientation which resulted in the worst-case emission levels based on results of 6.2.

6.3.4 Operating Conditions - Electric vehicle will be operated at a constant speed of 1500 rpm under the worst-case load condition while in first gear (see note in 6.2.5.1).

6.3.5 Define frequency bands as follows:

Band 1: 14 - 30 kHz	Band 6: 0.48 - 1.10 MHz
Band 2: 28.5 - 61 kHz	Band 7: 1.05 - 2.4 MHz
Band 3: 59 - 128 kHz	Band 8: 2.3 - 5.3 MHz
Band 4: 120 - 260 kHz	Band 9: 5.0 - 11.4 MHz
Band 5: 240 - 520 kHz	Band 10: 11 - 25 MHz.

6.3.6 Spectrum Analyzer Settings - Set center frequency to center frequency of each band. Use the following control settings:

Control Setting	Band									
	1	2	3	4	5	6	7	8	9	10
Scan Width (kHz/div):	2	5	10	20	50	100	200	500	1000	2000
IF Bandwidth (kHz):	1	1	1	1	1	1	1	1	1	1
Video Filtering:	← none →									
RF Attenuation (dB):	← 0 →									
Scan Time:	← See 6.2.2 →									

Increase RF attenuation to 10 dB. If levels drop by 10 dB, then set RF attenuation to 0 dB. However, if levels drop by less than 10 dB, then increase attenuation to 20 dB. If levels now drop by 10 dB, then set RF attenuation to 10 dB. If levels instead drop by less than 10 dB, add external attenuation as required.

6.3.7 EMC-25 Settings: Use internal sweep mode with remote connections to X-Y recorder. Use peak detector and use wide band (WB) mode for bands 1-7 and narrow band mode for bands 8-10.

6.3.8 Make an X-Y plot for all 10 bands using both loop and rod antennas for both vertical and horizontal polarizations. This will require a total of 40 plots.

6.4 Drive-by Measurements.

6.4.1 Frequency Range - The frequency range will be determined from the results of measurements made in 6.2 and 6.3.

6.4.2 Scan Rate - The scan rate(s) will be the same as that used for tests conducted in 6.2 and 6.3.

6.4.3 Scan width (Frequency Bands) - Frequency band selection will be based on the results of 6.2 and 6.3.

6.4.4 Operating Conditions - The vehicle will be driven in three different operating modes for these measurements. The first operating mode will be at a constant speed of 1500 rpm in first gear. The second will be an acceleration run from a standing start in which the accelerator pedal is depressed to the floorboard beginning in the position indicated in Figure 2. The third operating mode will be a deceleration run from 20 mph in first gear to a stopping position as indicated in Figure 2. Braking will be as consistent and even as possible in order to provide relatively constant and repeatable deceleration.

6.4.5 Scan Zone - The scan zone shall not exceed the 5 meter distance (28 degree arc) shown in Figure 2. The lower frequency of the band being scanned should be initiated (either manually or via a trip switch) with the front of the vehicle at the beginning of the scan zone. The upper frequency of each band being scanned shall occur when the front of the vehicle is within the scan zone.

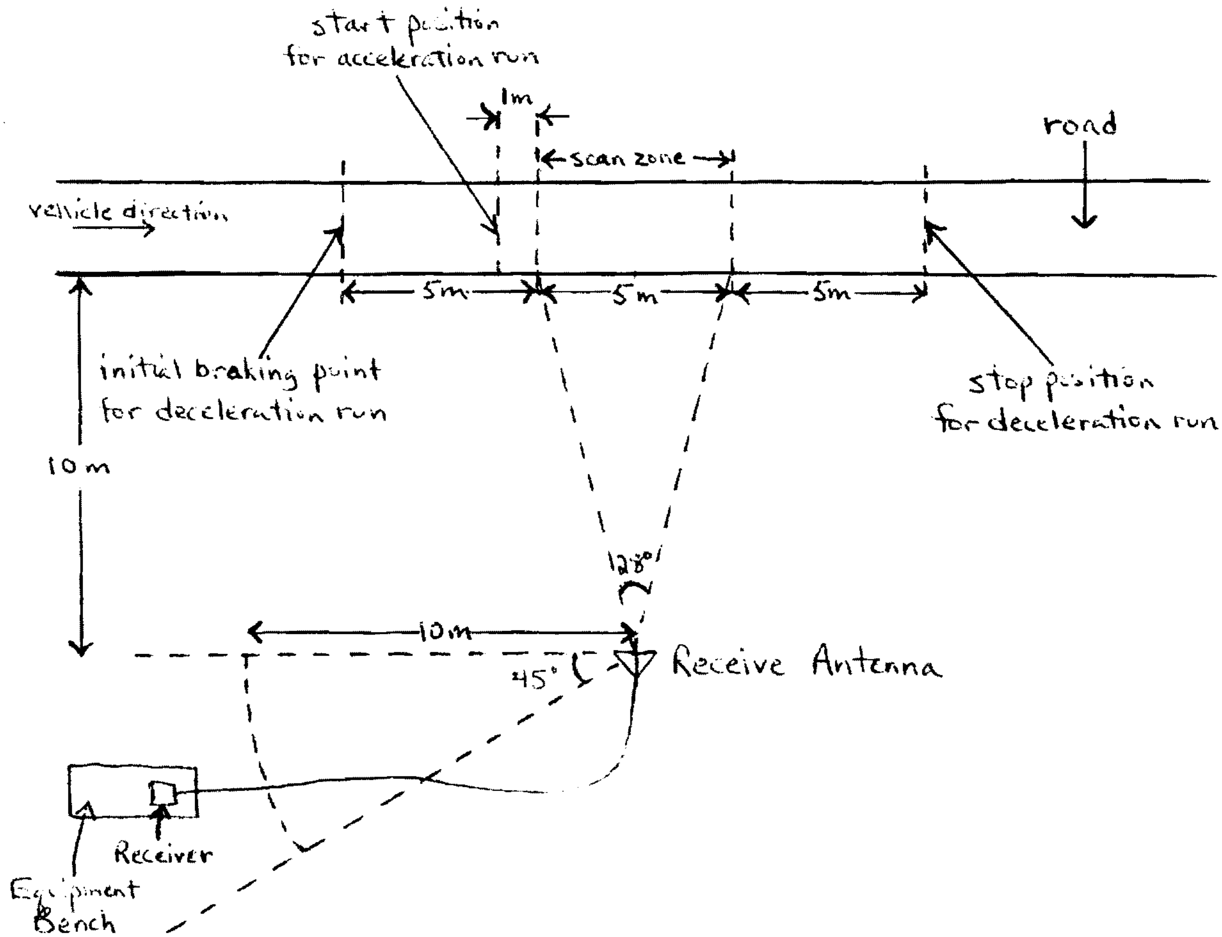


Figure 2. Test Setup for Drive-By Measurements.

6.4.6 Procedure - Scan the first band with a spectrum analyzer and appropriate antenna. Scan succeeding bands such that the start frequency of the band is equal to the stop frequency of the preceding band.

6.5 Engine Speed Variation on Radiated Emissions.

6.5.1 Repeat procedures of 6.2 and/or 6.3 (depending on relative emission levels above and below 20 MHz) for engine speeds of 2500 rpm and 3500 rpm.

A-3089

ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

7 May 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 7, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 30 April 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
   1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
   1B. Vehicle circuit studies (underway)
   1C. Selection of EMI evaluation methodology (underway)

II. EMI/EMC vehicle investigations (underway)

III. Documentation (underway)

Efforts this month were continued on Tasks I and II. Emphasis on Subtask 1C was placed on revising and improving the Test Procedure. For simplicity, a speed of 25 mph in fourth gear was selected in lieu of 1500 rpm as the constant motor speed to be used during the measurements. Also, a direct comparison was made of vehicle emission levels recorded with two different spectrum analyzers and an EMI receiver. This investigation indicated that the spectrum analyzers were inadequate for the purposes of accurately measuring impulsive noise. Consequently, all measurements were made using an Electro-Metrics Corporation Model EMC-25 Interference Analyzer.

Efforts this past reporting period on Task II were placed on testing the first electric vehicle (Electrica). The majority of the measurements outlined in the Test Procedure have been performed; however, a few of the measurements have not been completed due to inclement weather and equipment

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

malfunctions. A total of 189 plots of both electric and magnetic field emissions were made during the course of the month. Measurements were made on both the front and the driver's side of the EV with the antenna placed 3 meters high and 10 meters distant from the closest part of the vehicle. The interior of the vehicle was also sampled by placing a loop antenna on the passenger seat with the loop parallel to the seat back.

The data was obtained in single octave bands over the frequency range of 14 kHz to 1000 MHz. Four different load conditions were tested: (1) no load (drive wheels suspended in the air), (2) 150 amps, (3) 225 amps, and (4) 300 amps of motor drive current. The last three load conditions were established using a Clayton chassis dynamometer to load the vehicle. (This dynamometer is of the absorption variety and therefore contributes no electromagnetic noise of its own.) The vast majority of the energy radiated from the EV was below 20 MHz, as expected. In the interest of collecting the maximum amount of data for the limited time the vehicle was in our possession, the determination of several calibration factors was postponed. For this reason, it is not yet possible to present the data in completed form. Efforts are currently underway to include the necessary calibration factors and to reduce the data.

During the next reporting period, it is anticipated that Tasks II and III will be continued. The financial report for April is attached.

Respectfully submitted,

J. A. Woody
Project Director

JAW:gh

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 30 April 1982

atement of rk Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures Category	Person-hours
I	$3631	$23,938	$ 870	Professional Engineers	254
				Clerical/ Technical Assistants	0
II	$7042	$18,578**	$ 664	Professional Engineers	43
				Clerical/ Technical Assistants	185
III	0	$ 616	$ 8,000	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$10,673	$43,132**	$ 9,534	Professional Engineers	297
				Clerical/ Technical Assistants	185

*Includes estimate for current month
**Includes $2700 for dynamometer lease

A-3089

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

31 May 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 8, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 31 May 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
   1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
   1B. Vehicle circuit studies (underway)
   1C. Selection of EMI evaluation methodology (underway)

II. EMI/EMC vehicle investigations (underway)

III. Documentation (underway)

Efforts this month were continued on Tasks I, II and III. The status of these tasks is as follows:

Task I: Major emphasis this month was placed on reviewing and evaluating potentially applicable measurement procedures. The specific documents analyzed were Sections 2, 3, and 4 of C.I.S.P.R. Publication 16 ("C.I.S.P.R. Specification for Radio Interference Measuring Apparatus and Measurement Methods") and the tentative revision to SAE J551, Appendix B written by Mr. Fred Bauer, Chairman of the SAE EMR Subcommittee. The CISPR document defines an "artificial mains network" which is intended to provide a well-defined impedance across the terminals of the device under test at the test frequency and also isolate the device from undesired RF signals originating from the (AC) mains supply. This network or some other suitable network (e.g. a line impedance stabilization network (LISN)) is certainly required in the measurement procedure for testing EMI conducted emissions from on-board battery chargers. The "artificial mains network" would probably be adequate up to approximately 30 MHz. Above 30 MHz, radiated interference typically begins to dominate over conducted interference. The absorbing clamp described in the C.I.S.P.R. document might be useful for battery-charger interference measurements in the VHF frequency range (30-300 MHz).

The test procedure outlined in the tentative revision to Appendix B of J551 is considered to be a valid one. It is very similar to the Georgia Tech Test Procedure, the motivation being to test ala J551 under worst-case operating conditions. However, the instructions in Step 1 ("Determine speed of maximum radiation between 15-30 mph using absorption dynamometer and steady-state conditions.") is much too vague. There are a multitude of different operating and test conditions encompassed by this statement when one considers differing speeds from 15-30 mph, various dynamometer load conditions, various frequencies (say from 14 kHz to 20 MHz), two different polarizations for both electric and magnetic fields, and four sides of the vehicle. Some of these conditions will necessarily have to be specified. Also, no mention is ever made of magnetic fields, which may be a larger problem at low frequencies than electric fields.

Task II: Emphasis this reporting period was given to completing the measurements on the EV and processing the data. Drive-by tests were conducted at ten different frequencies. Measurements were made with the vehicle accelerating, braking, coasting, and at constant speed. All data obtained to date will be digitized and the data will then be replotted with calibration factors appropriately added. The necessary software has been written to digitize the data and to include bandwidth factors, antenna factors, transmission line losses, and receiver correction factors.

Task III: Efforts are currently underway to document the results of the EMI/EMC vehicle investigations. This document will include a description of the measurements performed and the test procedures. It will also include a summary of the significant findings with conclusions and recommendations.

During the next reporting period, it is anticipated that Tasks I, II, and III will be continued. The financial report for May is attached.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 May 1982

tatement of 'ork Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures Category	Person-hours
I	$1022	$24,960	$ 650	Professional Engineers	41
				Clerical/ Technical Assistants	0
II	$7580	$23,458**	$ 0	Professional Engineers	41
				Clerical/ Technical Assistants	141
III	$4151	$ 4767	$ 7871	Professional Engineers	149
				Clerical/ Technical Assistants	3
Overall Summary	$12,753	$53,185**	$ 8521	Professional Engineers	231
				Clerical/ Technical Assistants	143

*Includes estimate for current month

**Includes $4185 for lease of a chassis dynamometer. This dynamometer was required to support measurements on the test vehicle. It will be available (at no further costs) to support additional tests, if necessary.

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

1 July 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 9, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 30 June 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
   1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
   1B. Vehicle circuit studies (underway)
   1C. Selection of EMI evaluation methodology (underway)

II. EMI/EMC vehicle investigations (underway)

III. Documentation (underway)

Efforts this month were continued on Tasks I and III. The status of these tasks is as follows:

Task I: Major emphasis this reporting period was placed on vehicle circuit studies in connection with a susceptibility investigation on the Jet Industries Electrica. This initial investigation involved the interference scenario judged to be of major concern. A very dangerous condition could exist if sufficient RF energy were coupled onto the cable connected between the speed control potentiometer wiper contact and the speed control input to the PMC controller of the Electrica. The RF signal could then undergo rectification at the emitter base junction of the first transistor in the input to the controller. If the rectified signal applied a sufficient bias to the transistor, loss of speed control could occur. This cable was modeled as a 3 meter long conductor (the approximate distance from the speed control unit located in the DCS box to the controller). A worst-case analysis was then performed to determine the amount of RF energy which might be coupled from a

CB transmitting antenna to the cable of interest. Finally, the potentially degrading effects on the PMC controller was examined. The details of the susceptibility investigation are being documented in an Interim Technical Report which will be submitted to Aerospace under separate cover.

Task III: The majority of this month's efforts were placed on documenting the results of the EMI/EMC investigations on the first vehicle in the above-mentioned Interim Technical Report. This document includes a radiated emission test procedure and a description of all measurements performed to date. It also includes a summary of the significant findings with conclusions and recommendations.

During the next reporting period, it is anticipated that Tasks I, II, and III will be continued. The financial report for June is attached.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 30 June 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures: Category	Person-hours
I	$1542	$26,502	$ 0	Professional Engineers	57
				Clerical/ Technical Assistants	0
II	$ 0	$23,458**	$ 0	Professional Engineers	0
				Clerical/ Technical Assistants	0
III	$7312	$12,079	$ 559	Professional Engineers	219
				Clerical/ Technical Assistants	144
Overall Summary	$8854	$62,039**	$ 559	Professional Engineers	276
				Clerical/ Technical Assistants	144

*Includes estimate for current month

**Includes $4185 for lease of a chassis dynamometer. This dynamometer was required to support measurements on the test vehicle. It will be available (at no further costs) to support additional tests, if necessary.

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

1 August 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 10, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 31 July 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

- I. Definition of EMC/EMI requirements for electric vehicles (underway)
  - 1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
  - 1B. Vehicle circuit studies (underway)
  - 1C. Selection of EMI evaluation methodology (underway)
- II. EMI/EMC vehicle investigations (underway)
- III. Documentation (underway)

Efforts this month were continued on Tasks I, II, and III. The status of these tasks is as follows:

Task I: Major emphasis this month was placed on the development of measurement methodologies concerned with susceptibility of the EV and with conducted emissions from on-board battery chargers. Susceptibility levels will be determined by coupling a given current/voltage onto signal or power leads of interest. A current probe will be used to monitor the RF current levels injected. The primary signal lead of interest is the speed control input to the controller. Any rotation of the drive wheels with the controller energized will be considered a susceptible condition. The EV will be placed on jack stands in order to minimize the loading on the motor and to eliminate potential safety hazards.

The technique to be used for conducted emission measurements of on-board battery chargers will involve the use of line impedance stabilization networks (LISN's). This technique has been selected in favor of several other available techniques (including the absorbing clamp, directional current probe, maximum available power (MAP), and feedthrough capacitor techniques). This technique was selected based upon criterion such as performance, cost and complexity. The test configuration will include a LISN in each power line. An EMI receiver will be used as the detection device.

Task II: Measurement efforts have been initiated this month on EV No. 2. This EV is manufactured by Electric Vehicle Associates (EVA) and it uses a Soleq controller. The controller has a chopper frequency of 400 hertz with pulsewidth control of the specially wound shunt DC motor. Susceptibility measurements are currently underway with conducted emissions testing of the on-board battery charger to follow.

Task III: Documentation of the results of EMI/EMC investigations on EV No. 1 were completed this month. The Interim Technical Report has been submitted to Aerospace under separate cover.

During the next reporting period, it is anticipated that Tasks I and II will be continued. The financial report for July is attached.

Respectfully submitted,

G. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 July 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures: Category	Person-hours
I	$3352	$30,647	$ 7165	Professional Engineers	78
				Clerical/ Technical Assistants	115
II	$3351	$27,602**	$ 30,500	Professional Engineers	77
				Clerical/ Technical Assistants	116
III	$3607	$14,100	$ $9,950	Professional Engineers	98
				Clerical/ Technical Assistants	16
Overall Summary	$10,310	$72,349**	$ 47,615	Professional Engineers	253
				Clerical/ Technical Assistants	247

*Includes estimate for current month

**Includes $4185 for lease of a chassis dynamometer. This dynamometer was required to support measurements on the test vehicle. It will be available (at no further costs) to support additional tests, if necessary.

A-3089

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

1 September 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 11, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 31 August 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
 1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
 1B. Vehicle circuit studies (underway)
 1C. Selection of EMI evaluation methodology (underway)

II. EMI/EMC vehicle investigations (underway)

III. Documentation (underway)

Major efforts this month were placed on Task II. In addition to these activities, a program planning and review meeting was held at Georgia Tech on 24 August 1982. Attending this meeting were Mr. Walter J. Dippold of the Department of Energy (DOE), Mr. Robert E. Barnstead of The Aerospace Corporation, Mr. Noel B. Sargent of NASA LeRC, and Mr. Jimmy A. Woody, Mr. John K. Daher, and Mr. William R. Free of Georgia Tech. Some of the topics discussed and conclusions reached during this meeting were as follows:

o The Interim Technical Report entitled "EMC/EMI Investigations on Jet Industries' Electrica" was reviewed and some recommended revisions were discussed. Mr. Dippold recommended that selected sentences on pages 2, 5, and 7 be deleted and/or reworded. These changes were subsequently made and copies of the revised report have been sent to Mr. Larry A. Kahal of Aerospace and Mr. Dippold of DOE.

- o Mr. Woody and Mr. Daher briefed Mr. Sargent on the objectives and activities to date on the current program. Mr. Sargent subsequently made a presentation on a proposed effort to be performed by NASA LeRC to characterize the EMI/EMC aspects of advanced components for electric vehicles.
- o Various Georgia Tech test facilities were toured.

Efforts on Task II were directed towards measurement of the Electric Vehicle Associates (EVA) Electric Escort. Susceptibility measurements were made by coupling a known RF current level to signal input leads of the controller. Four separate leads were tested. A current probe was used to monitor the current levels injected. Any rotation of the drive wheels was to be considered a susceptible condition. The EV was placed on jack stands in order to minimize the loading on the motor and also to eliminate potential safety hazards. Frequencies within some eleven commonly used frequency bands (citizens band, amateur radio band, etc.) ranging from 3.8 to 83.25 MHz were tested. These bands were selected as the ones most likely to exhibit large field intensities within the environment of the EV. No susceptible conditions were found to exist for currents up to approximately 11 milliamps continuous. However, a momentory current level of approximately 36 milliamps at 52.5 MHz caused the drive wheels to turn several times. It was also determined that the EV was rendered inoperable due to a blown 400 amp fuse and some damaged components within the controller. (Arrangements were subsequently made for Soleq Corporation to repair the vehicle. Mr. Dennis Frye of Soleq arrived on 18 August 1982 and finished the repair on 19 August 1982.)

Conducted emission testing was also performed on the on-board battery charger of the EV. The measurement technique involved "breaking" the power line in between the ac mains and the power cord which connects to the EV. Line impedance stabilization networks (LISN's) were then inserted in both the black (phase) and white (neutral) wires. A current probe was placed around each wire between the LISN and the battery charger power cord with the probe output connected to an EMI receiver. Current levels were measured from 14 kHz to 50 MHz. The data is currently being reduced and the final results plotted.

During the next reporting period, it is anticipated that Tasks I and II will be continued. The financial report for August is attached.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 August 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures Category	Person-hours
I	$ 0	$ 30,647	$ 7165	Professional Engineers	0
				Clerical/ Technical Assistants	0
II	$9536	$ 37,138	$ 20,964	Professional Engineers	246
				Clerical/ Technical Assistants	184
III	$ 0	$ 14,100	$ 9,950	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$9536	$ 81,885	$ 38,079	Professional Engineers	246
				Clerical/ Technical Assistants	184

*Includes estimate for current month

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

1 October 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 12, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 30 September 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
   1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
   1B. Vehicle circuit studies (underway)
   1C. Selection of EMI evaluation methodology (underway)

II. Vehicle EMI/EMC investigations (underway)

III. Documentation (underway)

Efforts this month were continued on Task II. Emphasis was placed on the measurement of radiated emission levels from the EVA Electric Escort. A total of 101 plots of both electric and magnetic field emissions were made over the course of the month. Measurements were made on the front side of the EV (since the front side was determined to be the direction of maximum radiation during preliminary near-field probing experiments). Data was collected in octave bands over the frequency range of 14 kHz to 1000 MHz. Four different test conditions were established by operating the vehicle under minimum and maximum load conditions at two different road speeds (5 mph and 25 mph). The EVA car's radiated emission levels were significantly lower than those of the Jet Industries car for the majority of the bands measured. However, whereas very little radiated energy was detected above 20 MHz for the Jet Industries car, larger levels were measured in this frequency range for the EVA car. The data is currently being digitized and replotted with calibration factors appropriately added.

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

During the next reporting period, it is anticipated that Tasks I and II will be continued. The financial report for September is attached.

Respectfully submitted.

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 August 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures Category	Person-hours
I	$ 0	$ 30,647	$ 7165	Professional Engineers	0
				Clerical/ Technical Assistants	0
II	$9338	$ 46,476	$ 11,626	Professional Engineers	241
				Clerical/ Technical Assistants	122
III	$ 0	$ 14,100	$ 9,950	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$9338	$ 91,223	$ 28,741	Professional Engineers	241
				Clerical/ Technical Assistants	122

*Includes estimate for current month

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

1 November 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 13, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 31 October 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
  1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
  1B. Vehicle circuit studies (underway)
  1C. Selection of EMI evaluation methodology (underway)

II. Vehicle EMI/EMC investigations (underway)

III. Documentation (underway)

Efforts this month were continued on Tasks I and II. In addition to these activities, Georgia Tech personnel made presentations to both the SAE EMR Subcommittee and the IRAC Standards Subcommittee. The presentations summarized the accomplishments to date on the current programs and both were well received. A number of additional tasks were suggested during the meetings which represent logical extensions to the present scope of the current program. Potential tasks include:

(1) Measure radiated emissions from standard internal combustion engine vehicles;

(2) Prepare technical paper on a recommended test procedure for submission to CISPR;

(3) Prepare material for a future IRAC meeting and for a future SAE EMR Subcommittee meeting;

(4) Attend IRAC and SAE EMR Subcommittee meetings and make presentations;

(5) Evaluate proposed worldwide test conditions distributed at October SAE meeting;

(6) Make comparative measurements on the same vehicle equipped first with an unmodified controller and next with a controller modified to suppress emissions;

(7) Examine the emission and susceptibility properties of electronic modules used on EV's;

(8) Prepare a handbook of EMI suppression measures for use by EV manufacturers; and

(9) Identify and formulate an appropriate measurement/control standard for EV EMI performance.

A formal proposal addressing the first four tasks above has been prepared and submitted to Aerospace under separate cover. A proposal concerning the other tasks identified above will be prepared and submitted next month. The status of Tasks I and II is as follows:

Task I: Major emphasis this month was placed on determining the approximate levels coupled into the speed control input of the Soleq controller used in the EVA Escort. The circuit was modelled as a two-conductor transmission line terminated at both ends. The conductor spacing was approximated to be 1 cm and the length to be 1 m. A model developed by Clayton R. Paul of the University of Kentucky was implemented on an HP-1000 computer*. The program plots the power coupled into the 47 k Ω input impedance of the controller as a function of propagation direction and polarization angle. Figure 1 illustrates the levels obtained for a normalized field intensity of 1.0 volt/meter and a frequency of 100 MHz (FM). Levels based on maximum expected field intensities from various transmitters will be calculated subsequently. These levels will then be injected into the input of the Soleq controller used in the Unique Mobility Electrek and responses noted.

Task II: Emphasis this reporting period was given to completing the measurements on the EVA Escort and beginning the measurements on the Electrek. The susceptibility measurements were completed on the EVA Escort and the modified controller was not susceptible to 11.4 mA at any of the RF test frequencies. Radiated emission measurements have been made on the Electrek under three different load conditions and on the two sides of the vehicle determined (during preliminary scans) to be the directions of maximum radiation. Also, conducted emission tests have been performed on the battery charger. The data on the Electrek is being digitized and replotted with calibration factors appropriately added.

*Clayton R. Paul, "Applications of Multiconductor Transmission Line Theory to the Prediction of Cable Coupling," RADC-TR-76-101, Volume VI, Phase Report, February 1978.

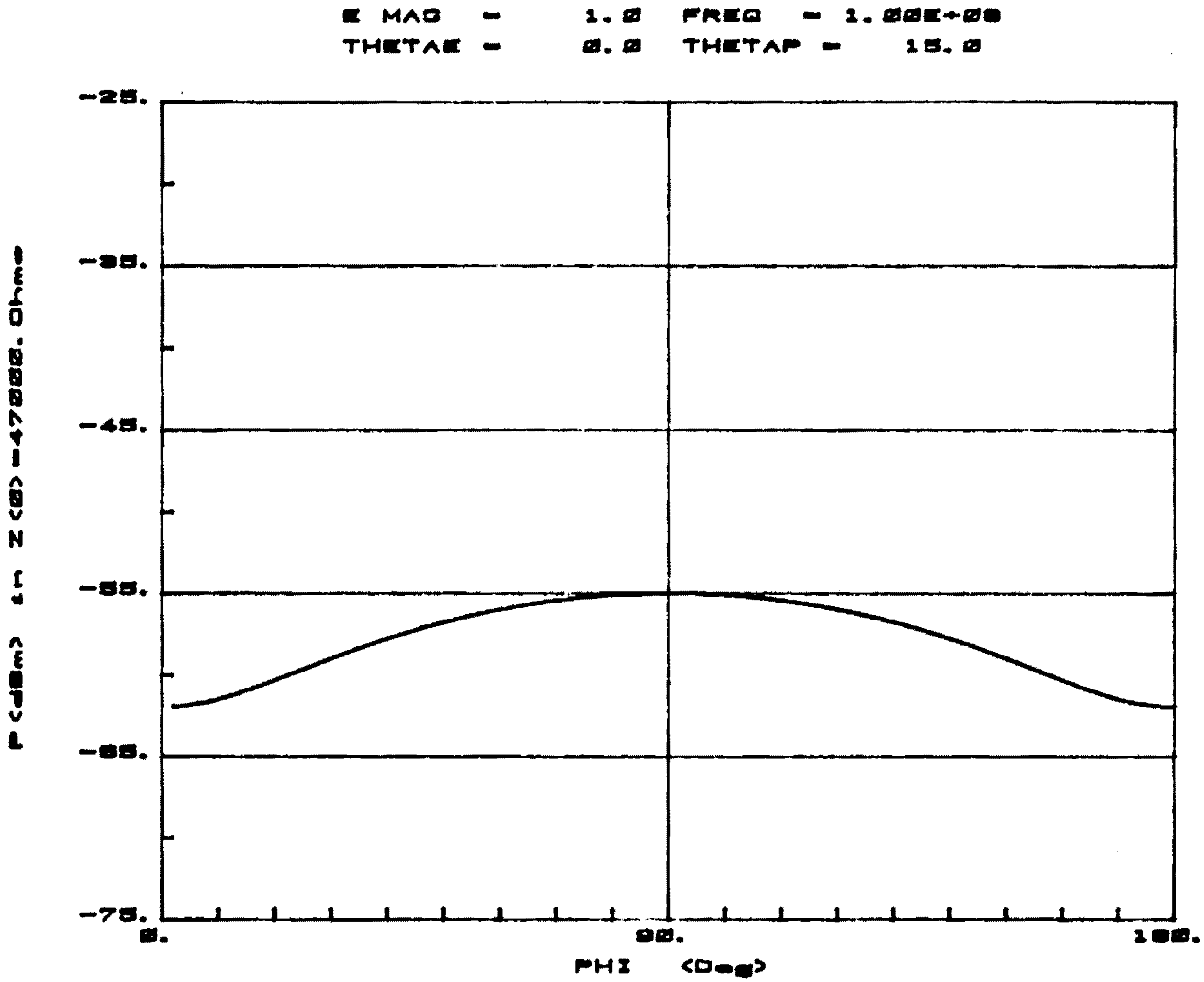


Figure 1. Calculated Power Levels Coupled Into EV Controller From 100 MHz FM Transmitter.

During the next reporting period, it is anticipated that Tasks I and II will be continued. The financial report for October is attached.

Respectfully submitted,

J. A Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 October 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures: Category	Person-hours
I	$ 3408	$ 34,055	$ 3757	Professional Engineers	66
				Clerical/ Technical Assistants	0
II	$7048	$ 53,524	$ 9,546	Professional Engineers	185
				Clerical/ Technical Assistants	116
III	$ 0	$ 14,100	$ 9,950	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overall Summary	$10,456	$101,679	$ 23,253	Professional Engineers	251
				Clerical/ Technical Assistants	116

*Includes estimate for current month

A-3089

ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

2 December 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G.A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 14, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 30 November 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
  1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities (underway)
  1B. Vehicle circuit studies (underway)
  1C. Selection of EMI evaluation methodology (underway)

II. Vehicle EMI/EMC investigations (underway)

III. Documentation (underway)

Efforts this month were continued on Tasks I and II. The status of these tasks is as follows:

<u>Task I</u>: Emphasis this month was continued on the susceptibility investigation. The transmission line coupling model was used to

calculate the approximate levels coupled into the speed control/regenerative braking input of the Soleq controller used in both the EVA Escort and the Unique Mobility Electrek. The analysis included all possible propagation directions and polarizations. The maximum coupled power was calculated based on the maximum expected field intensities from various transmitters operating between 1 MHz and 1 GHz. These levels were subsequently injected into the input of the Soleq controller used in the Electrek. The results of this investigation indicate that the Soleq controller configurations used in the Electrek and the Escort are not susceptible to radiated fields from transmitters operating in the frequency range between 1 MHz and 1 GHz.

Task II: Emphasis this reporting period was given to completing the measurements on the Unique Mobility Electrek. Radiated emission measurements were made which included three different load conditions, two sides of the vehicle, and both electric and magnetic field intensities. All of the data on the Electrek has been digitized and replotted with calibration factors appropriately added. A preliminary analysis of the data indicates that the radiated emission levels for the Electrek are higher, in general, than the corresponding levels for the Escort. This result was anticipated since the Escort should benefit from the electromagnetic shielding properties of its metal body whereas the Electrek has a fiberglass body, which would be expected to provide much less shielding effectiveness. The radiated levels for the Electrek still appear to be below the SAE J551 limit, however.

Recent telephone conversations between personnel from The Aerospace Corporation and Georgia Tech have indicated that Aerospace considers it desirable to prepare a technical document for submission to CISPR in preference to measurement of a fourth EV. The objective of the document is to recommend practical and valid test procedures for measuring the EMC/EMI characteristics of EV's. A revised proposal which reflects these modifications has, therefore, been prepared and submitted to Aerospace under separate cover.

During the next report period, it is anticipated that Tasks I and III will be continued. The financial report for November is attached.

Respectfully submitted,

J.A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

JAW:ae

FINANICAL REPORT

Purchase Order No. W-0350
1 to 30 November 1982

Statement of Work Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures: Category	Person-hours
I	$ 3,054	$ 37,109	$ 703	Professional Engineers	100
				Clerical/ Technical Assistants	0
II	$ 6,436	$ 59,960	$ 3,110	Professional Engineers	151
				Clerical/ Technical Assistants	122
III	$ 0	$ 14,100	$ 9,950	Professional Engineers	0
				Clerical/ Technical Assistants	0
Overal Summary	$ 9,490	$111,169	$13,763	Professional Engineers	251
				Clerical/ Technical Assistants	122

*Includes estimate for current month.

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

3 January 1983

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 15, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 31 December 1982

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (completed)
   1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities
   1B. Vehicle circuit studies
   1C. Selection of EMI evaluation methodology

II. Vehicle EMI/EMC investigations (completed)

III. Documentation (underway)

Efforts this month were continued on Tasks I, II, and III. The status of these tasks is as follows:

Task I: Emphasis this month was placed on finalization of the EMI test procedures. Two test procedures have been formulated which describe methods of measurement of both radiated and conducted emissions from electric vehicles. These procedures have been tested and verified during the vehicle EMI investigations phase of the program. The significant findings of the testing phase of the program were used to eliminate unnecessary measurements and to specify the proper equipment, configurations, and measurement parameters (e.g., frequency, speed, load, state of charge, etc.). For example, it was determined that testing time (and consequently testing costs) could be greatly reduced by eliminating radiated measurements above 20 MHz. This was justifiable in that the impulse electric field intensities were

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

always well below the CISPR Publication 12 limit (which extends from 40 MHz to 250 MHz) and were also, in general, well below the SAE J551 limit (which covers the 20 MHz to 1000 MHz frequency range). It was also determined that considerable expense could be saved by relaxing the requirement for a dynamometer to load down the propulsion system. This was justified by the fact that even though load variations had a minor influence on the "shape" of the frequency spectrum, no significant and consistent differences in the overall radiated emission levels were observed.

Performance levels were also selected for both radiated and conducted emission measurements. The radiated electric field intensity limit (14 kHz - 20 MHz) coincides with the J551 limit at 20 MHz but increases at 20 decibels per decade as frequency decreases below 20 MHz. The increasing limit with decreasing frequency corresponds to the expected decrease in coupling of the radiated energy to receptors as frequency decreases. The radiated magnetic field intensity limit (14 kHz - 20 MHz) also reflects this expected decrease in coupling and represents the equivalent far-field magnetic field intensity corresponding to the electric field limit described above (i.e., magnetic field equals electric field divided by 377 ohms). The conducted emission limit was based on the MIL-STD-461B broadband emission limit for ac power leads. The limit was modified for load currents greater than 1 ampere in accordance with this standard by assuming that a typical on-board battery charger draws approximately 20 amperes of load current and relaxing the 14 kHz limit by 20 log[load current] or 26 dB.

Task II: Major emphasis this month was placed on analysis of the measurement results on the three EV's tested. During this analysis, it was discovered that the antenna factors used for the Fairchild Model ALR-25 loop antenna were misinterpreted to be those which convert from terminal voltage to magnetic field intensity. In actuality, the published data for this antenna converts from terminal voltage to the far-field equivalent of the corresponding electric field intensity. The result of the misinterpretation is that the previously calculated values of the magnetic field intensities are greater than the actual values by 51.5 dB. These corrections have been made and the results will be replotted. The corrected pages of the Interim Technical Report "EMC/EMI Investigations on Jet Industries' Electrica" will be submitted to Aerospace under separate cover in the near future.

Task III: Emphasis this reporting period was given to preparation of the technical document for submission to CISPR. The objective of the document is to recommend practical and valid test procedures and performance levels for electric vehicles. Recommended performance levels and methods of measurement for both radiated and conducted emissions have been documented. Susceptibility test procedures and performance levels will require significant investigations in addition to those undertaken on the current program and will, therefore, not be included in the recommendations to CISPR.

Preparation of the final technical report was also initiated this past month. During the next reporting period, it is anticipated that Task III will be continued. The financial report for December is attached.

Respectfully submitted

for J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 December 1982

:tatement of 'ork Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures Category	Person-hours
I	$ 2,901	$ 40,010	$ 0	Professional Engineers	82
				Clerical/ Technical Assistants	0
II	$ 3,110	$ 63,070	$ 0	Professional Engineers	67
				Clerical/ Technical Assistants	111
III	$ 2,728	$ 16,828	$ 5,024	Professional Engineers	97
				Clerical/ Technical Assistants	0
Overall Summary	$ 8,739	$119,908	$ 5,024	Professional Engineers	246
				Clerical/ Technical Assistants	111

*Includes estimate for current month.

A-3089

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

3 February 1983

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Monthly Progress and Financial Report No. 16, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 1 to 31 January 1983

Gentlemen:

The objective of this program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. The specific tasks to be performed are:

I. Definition of EMC/EMI requirements for electric vehicles (underway)
  1A. Technical guidance to DOE in the determination of vehicle EMI/EMC responsibilities
  1B. Vehicle circuit studies
  1C. Selection of EMI evaluation methodology

II. Vehicle EMI/EMC investigations (completed)

III. Documentation (underway)

Efforts this month were continued on Task III. In addition, modifications to the current contract were made this past month to include additional funding and a time extension for presentations to the SAE EMR Subcommittee in Detroit, Michigan and the IRAC Standards Subcommittee in Washington, DC. The presentations will summarize the accomplishments and significant conclusions obtained on the present program. Task I will, therefore, be continued to include these presentations. The status of Task III is as follows:

Task III: Emphasis this reporting period was given to preparation of the technical document for submission to CISPR and preparation of the final report. The objective of the CISPR document is to recommend practical and valid test procedures and performance levels for electric vehicles.

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

Recommended performance levels and methods of measurement for both radiated and conducted emissions have been documented. These recommendations will be submitted to Aerospace for approval in the near future. Also, preparation of the final technical report was continued this past month and is expected to be completed by the end of February.

During the next reporting period, it is anticipated that Tasks I and III will be continued. The financial report for January is attached.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

Hugh W. Denny, Chief
Electromagnetic Compatibility Division

FINANCIAL REPORT

Purchase Order No. W-0350
1 to 31 January 1983

tatement of ork Task	Estimated Current Month Expenditures	Contract-to-Date Expenditures*	Projected Cost to Complete	Current Month Estimated Person-hours Expenditures Category	Person-hours
I	$ 0	$ 40,010	$4,141	Professional Engineers	0
				Clerical/ Technical Assistants	0
II	$ 0	$ 63,070	$ 0	Professional Engineers	0
				Clerical/ Technical Assistants	0
III	$ 4,707	$ 21,535	$ 5,405	Professional Engineers	180
				Clerical/ Technical Assistants	8
Overall Summary	$ 4,707	$124,615	$ 9,546	Professional Engineers	180
				Clerical/ Technical Assistants	8

*Includes estimate for current month.

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

27 October 1981

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Estimated Monthly Expenditures Plan, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 9 October 1981 to 8 December 1982

Gentlemen:

The Estimated Monthly Expenditures Plan as required by Article IX, "Financial Reporting Requirements," of the subject purchase order is attached. This plan sets forth, by Statement of Work task, the estimated dollar and person-hour expenditures per month for the period of contract performance. It also presents a summary of the estimated monthly dollar and person-hour expenditures for the overall program.

Respectfully submitted,

G. A. Woody
Project Director

Approved:

H. W. Denny, Chief
Electromagnetic Compatibility Division

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

Attachment

Estimated Monthly Expenditures Plan

Statement of Work Task	Planned Monthly Dollar Expenditure	Planned Monthly Person-hour Expenditures: Category	Planned Monthly Person-hour Expenditures: Person-hours
I	3101	Professional Engineers	82
		Clerical/Technical Assistants	10
II	2757	Professional Engineers	70
		Clerical/Technical Assistants	33
III	2872	Professional Engineers	78
		Clerical/Technical Assistants	25
Overall Summary	3569	Professional Engineers	94
		Clerical/Technical Assistants	25

A-3089

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

10 August 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Revised Estimated Monthly Expenditures Plan, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 9 October 1981 to 8 December 1982

Gentlemen:

A revised Estimated Monthly Expenditures Plan as requested in our telephone conversation on 9 August 1982 is attached. This plan represents our best estimate at this time; deviations may be required depending on the specific tasks being performed during any given month.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

H. W. Denny, Chief
Electromagnetic Compatibility Division

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

	August 82			September 82				October 82				Nov. 82	Dec. 82
	Task 1	Task 2	Total	Task 1	Task 2	Task 3	Total	Task 1	Task 2	Task 3	Total	Task 3	Task 3
Professional Engineers Person-hours	82	164	246	60	164	22	246	80	118	51	249	271	107
Clerical/ Technical Assistants Person-hours	0	164	164	0	164	0	164	0	80	5	85	35	15
Direct Salaries and Wages ($)	1419	3821	5240	1038	3821	381	5240	1384	2522	912	4818	4898	1941
Fringe Benefits ($)	298	802	1100	218	802	80	1100	291	530	191	1012	1029	408
Materials and Supplies ($)	0	1050	1050	0	500	50	550	0	500	100	600	200	200
Travel ($)	0	200	200	0	200	0	200	1400	200	0	1600	900	0
Total Direct Cost ($)	1717	5873	7590	1256	5323	511	7090	3075	3752	1203	8030	7027	2549
Overhead ($)	816	2789	3605	597	2528	243	3368	1461	1782	571	3814	3338	1211
Total Cost ($)	2532	8663	11,195	1853	7851	754	10,458	4536	5534	1774	11,844	10,365	3760

A-3089

Georgia Institute of Technology

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

9 November 1981

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Program Schedule, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 9 October 1981 to 8 December 1982

Gentlemen:

The Program Schedule as required by Paragraph 5.0 of the Statement-of-Work for the subject purchase order is attached. This schedule represents our current concepts for performing the activities on this program; however, it may be modified as the program progresses if the changes are mutually agreeable.

Respectfully submitted,

J. A. Woody
Project Director

Approved:

H. W. Denny, Chief
Electromagnetic Compatibility Division

PROGRAM SCHEDULE

Purchase Order W-0350

Task No.	Activity	Month 1981 O	N	D	1982 J	F	M	A	M	J	J	A	S	O	N	D				
I	Attend 81 EV Symposium/Expo	▲																		
	Prepare Program Plan	■																		
	Visit Soleq		▲																	
	Attend SAE EMR Subcommittee Meeting		▲																	
	Visit NBS			▲																
1A	Catalog Relative Requirements and Limits Imposed by Various Agencies	■	■	■	■															
	Assess Impacts these Requirements/ Controls Imply for EVs			■	■															
	Formulate Advice/Recommendations on Voids and Courses of Action					■														
1B	Review Literature on EV Devices, Circuits, and Systems		■	■	■	■														
	Contact Manufacturers/Developers				■	■	■													
	Examine Representative EVs and Their Technical/Shop Manuals				■	■	■													
	Identify and Characterize from EMI Viewpoint EV Devices, Circuits, Systems					■	■	■												
1C	Review Applicable Measurement Procedures						■	■	■											
	Select EMI Evaluation Methodology							■	■	■										

PROGRAM SCHEDULE (Continued)

Purchase Order W-0350

Task No.	Activity	Month																		
		1981			1982															
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D				
II	Receive EV							▲												
	Probe Near-Field Emissions							■	■											
	Measure Far-Field Radiated Emissions and Susceptibility								■	■	■	■								
	Perform Conducted Tests										■	■	■	■						
III	Monthly Progress Reports		▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲						
	Final Report															▲				

Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

4 August 1982

The Aerospace Corporation
Suite 4000
955 L'Enfant Plaza, S.W.
Washington, DC 20024

Attention: Mr. G. A. Pierce
Subcontracts Administration

Subject: Program Schedule, Project A-3089, Purchase Order No. W-0350 (Prime Contract DE-AC08-80-CS 50101), "Investigation of Electric Vehicle EMI/EMC and Its Control" covering the period from 9 October 1981 to 8 December 1982

Gentlemen:

The Program Schedule as required by Contract Change Notice No. 2 for the subject purchase order is attached. This schedule represents our current concept for performing the activities on this program; however, it may be modified as the program progresses if the changes are mutually agreeable.

Respectfully submitted,

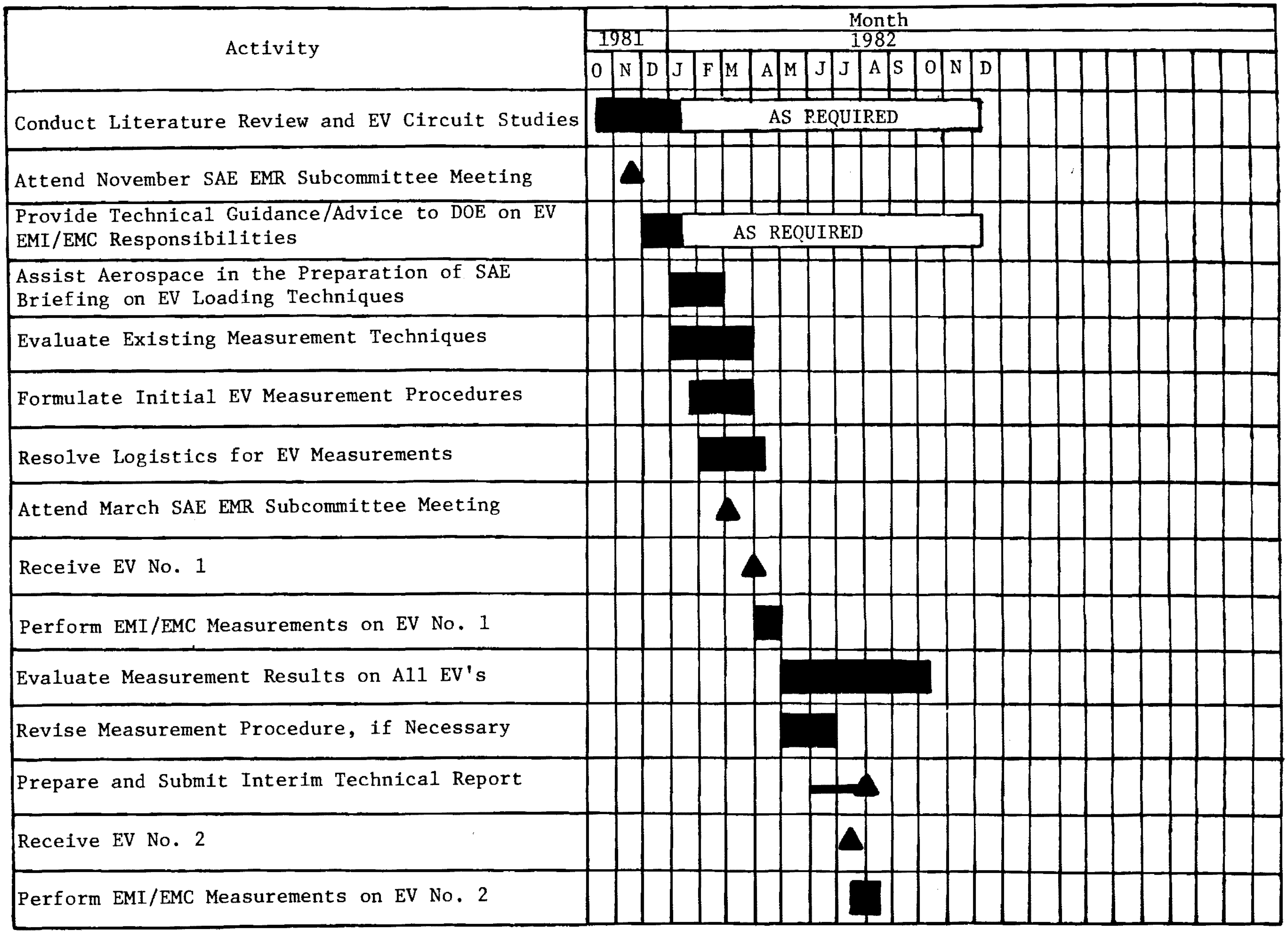
J. A. Woody
Project Director

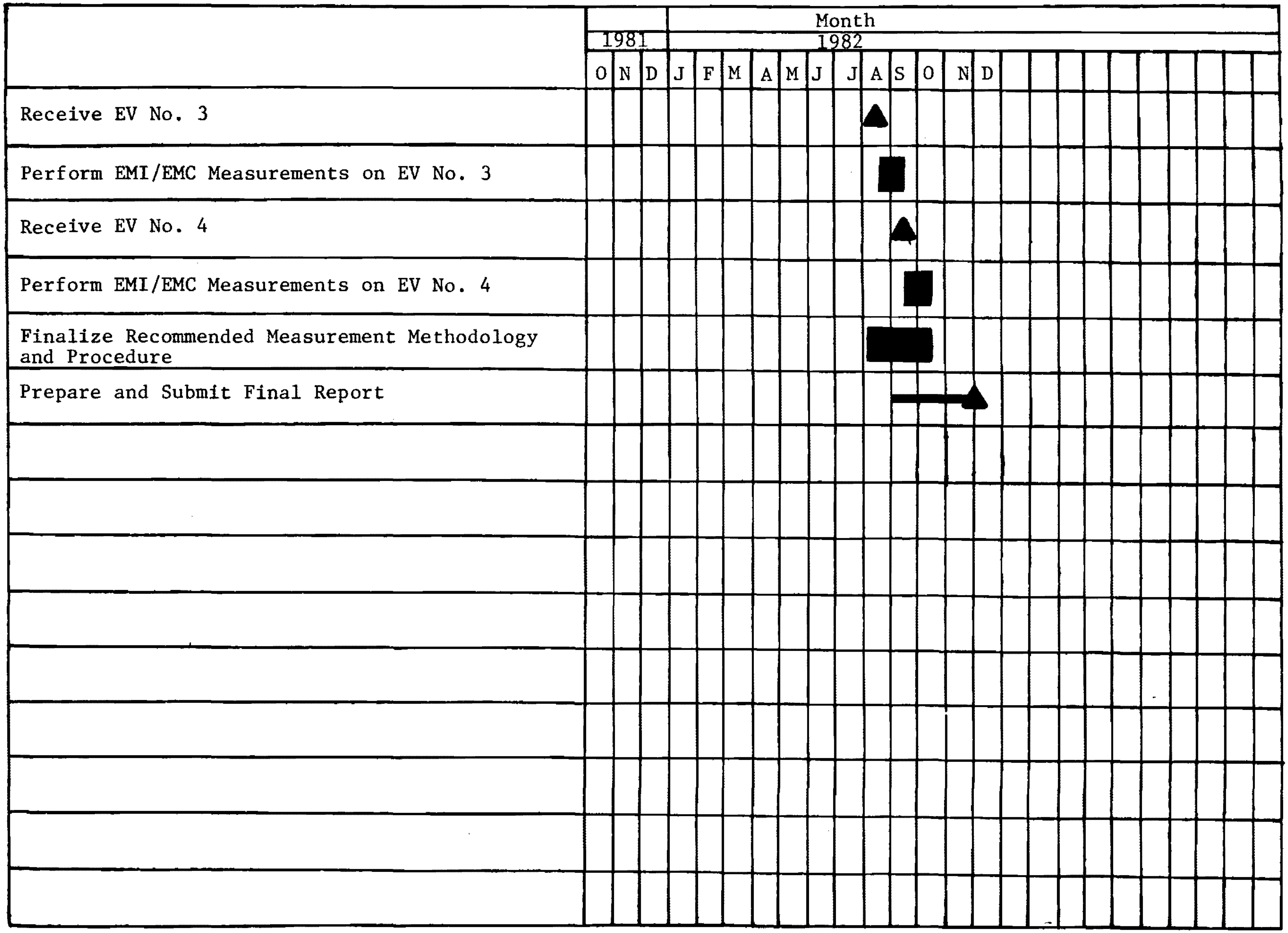
Approved:

H. W. Denny, Chief
Electromagnetic Compatibility Division

AN EQUAL EMPLOYMENT/EDUCATION OPPORTUNITY INSTITUTION

REVISED PROGRAM SCHEDULE
FOR CURRENT EFFORT
Purchase Order W-0350




Month
1981
1982
O N D J F M A M J J A S O N D
Receive EV No. 3
Perform EMI/EMC Measurements on EV No. 3
Receive EV No. 4
Perform EMI/EMC Measurements on EV No. 4
Finalize Recommended Measurement Methodology and Procedure
Prepare and Submit Final Report

A-3089

TECHNICAL REPORT

Project A-3089

LIMITATION IN SWEPT RECEIVER SCAN RATES FOR IMPULSIVE NOISE MEASUREMENTS

By

John K. Daher

February 1982

Submitted to

THE AEROSPACE CORPORATION
SUITE 4000
995 L'ENFANT PLAZA, S.W.
WASHINGTON, DC 20024

Prepared by

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

The purpose of this technical report is to discuss how the time required to make a complete frequency scan of an electric vehicle (EV) is related to the signal parameters of the radiated electromagnetic emissions as well as the characteristics of the receiver used to measure the emission levels. A spectrum analyzer is the preferred receiving instrument due to the ease and flexibility in varying IF bandwidths, frequency range, frequency scan rates, etc. Therefore, the present discussion will be made with regard to spectrum analyzers, but applies to swept receivers in general. Also, this discussion hinges on the validity of a major assumption made about the nature of the radiated emissions. The assumption made here is that the most significant levels of radiation are pulsed at a rate determined by the EV controller. The validity of this assumption can only be verified by actual measurements on the EV, which will be made during the testing phase of the current program. However, an assumption of some sort is necessary for maximum scan rates to be predicted.

The response characteristics of the spectrum analyzer to periodically pulsed signals can be one of two kinds. One response is termed the line spectrum and the other a pulse spectrum. The line spectrum (Fourier series response) occurs when the 3-dB IF bandwidth (B) is small compared to the pulse repetition frequency (PRF) of the input signal. Each component on the spectrum analyzer display then behaves like a CW signal. As in the case of CW signals, the maximum scan rate (SR) in Hz per second is determined by the IF bandwidth:

$$SR < B^2. \qquad (1)$$

Scan rates which do not satisfy Equation (1) will yield incorrect values under any measurement conditions.

The pulse spectrum (Fourier transform response), on the other hand, occurs when the 3-dB IF bandwidth is large compared to the PRF. Spectral lines can no longer be resolved and the displayed "lines" are generated in the time domain by the individual pulses. The envelope of the frequency spectrum is displayed in the frequency domain and the level of this envelope increases with increasing bandwidth. The pulse spectrum is a measure of the power per unit bandwidth at a particular frequency, which can be related back to the impulse field strength by applying the appropriate bandwidth, antenna, and transmission line factors. Since the spectrum analyzer gives a time domain display of the pulse lines, there exists one limitation in the rate of scan which is a function only of the PRF of the applied signal. That is, the scan time (ST) in seconds should be long enough to allow a sufficient number of pulses to occur in order to be able to resolve the spectrum envelope on the display. For at least 100 lines to appear, we must have

$$ST \geq \frac{100}{PRF}. \tag{2}$$

For example, a PRF of 100 Hz requires the scan time to be greater than one second. (Note that this time requirement is independent of the frequency range covered during the scan.) Another limitation exists on the scan rate for pulse spectrum analyses which is almost always more severe than the scan time requirement. In order to allow at least one pulse (and preferably several) to be captured by the "window" as it scans across the spectrum of interest, the scan rate must be less than the product of the IF bandwidth and the PRF. Allowing for an average of ten pulses to ensure true peak levels, one has

$$SR < \frac{(PRF)(B)}{10}. \tag{3}$$

In determining the operating point(s) at which more extensive testing should be performed, it is only necessary to observe relative differences in the measured levels. Sufficient time should be alotted for a complete frequency scan to be made before the operating point is varied. Obviously, the faster the scan rate, the quicker the desired operating point(s) may be determined. The fastest scan rates may be achieved with the widest IF bandwidths. Therefore, it would be advantageous to set a spectrum analyzer (or swept receiver) for maximum IF bandwidth, set the center frequency and scan width for coverage of the frequency range of interest (likely to be limited by the receiving antenna), and scan at the highest possible rate. Since only relative levels are of concern (not absolute peak levels nor specific frequencies within a frequency band), one should be able to relax the restriction in Equation (3) and only be concerned with Equation (1). If an IF bandwidth of 100 kHz is selected, for example, the maximum scan rate would be approximately 10 GHz per second. Since the frequency range of interest will likely be significantly less than 10 GHz, it should be possible to continuously adjust the operating point without delay. Consequently, variations in the relative levels may be observed in order to determine the operating point(s) where more thorough testing may subsequently be performed.

Determination of the time required to make a complete frequency scan of the vehicle at a fixed operating point should insure that the absolute levels, not just the relative levels, are measured. Therefore, it is noted that Equation (3) must be satisfied for valid test results. Consequently, the maximum scan rate will depend on the PRF and the IF bandwidth. The PRF's used in current technology electric vehicle controllers are on the order of 1 kHz and are likely to be significantly higher than this in the not too distant future. For standard internal combustion engine vehicles idling at 1500 rpm (as per SAE J551), the PRF's range from 50 Hz (4 cylinders) to 100 Hz (8 cylinders). Clearly, one should be able to scan EV's at a much faster rate than standard vehicles.

Selecting the maximum available IF bandwidth will result in the maximum allowable scan rate. As an example, assume that an IF bandwidth of 100 kHz is selected to measure an EV with a controller PRF of 4 kHz. The maximum scan rate may then be calculated from Equation (3) to be 40 MHz persecond. An SAE J551 type measurement from 20 MHz to 1000 MHz would, therefore, require approximately 25 seconds. Increasing the bandwidth to 300 kHz would reduce the scan time to under 10 seconds. An increase in bandwidth also results in an increase in the sensitivity (a peculiar characteristic of pulse spectrum measurements) since the pulsed spectrum levels increase linearly with bandwidth, while the receiver noise floor increases as the square root of the bandwidth. However, increasing the bandwidth also decreases the resolution of the spectrum envelope.

Thus, limitations in scan rate are not expected to be as severe for electric vehicles as for internal combustion engine vehicles. It should be a relatively quick and simple procedure to determine worst-case operating points by scanning very rapidly over the frequency range of interest and noting the relative differences in emission levels as the operating point is continuously varied. Absolute level readings will require a decrease in scan rate in order to ensure true peak level indications on the meter or video display of the receiver. The amount of spectrum envelope resolution desired will likely dictate the limiting IF bandwidth, which in turn will limit the rate at which one may scan the vehicle.

[redacted]

INTERIM TECHNICAL REPORT

Project A-3089

EMC/EMI INVESTIGATIONS ON JET INDUSTRIES' ELECTRICA

By

John K. Daher

Jimmy A. Woody

July 1982

Submitted to

THE AEROSPACE CORPORATION
Suite 4000
955 L'Enfant Plaza
Washington, DC 20024

Prepared By

Electronics and Computer Systems Laboratory
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

A Unit of the University System of Georgia

FOREWORD

This report was prepared by the Electronics and Computer Systems Laboratory of the Engineering Experiment Station at the Georgia Institute of Technology under Purchase Order No. W-0350, Georgia Tech Project A-3089. The work described in this report was directed by Mr. J. A. Woody, Project Director, and Mr. J. K. Daher, Assistant Project Director, under the general supervision of Mr. H. W. Denny, Chief of the Electromagnetic Compatibility Division.

ABSTRACT

This report summarizes the technical efforts and conclusions to date resulting from an investigation of the effects of EMI and EMC on and by electric vehicles. An EMI/EMC evaluation methodology for electric vehicles is presented along with the results of measurements made on the Jet Industries' Electrica. Radiated emission levels were measured from 14 kHz to 1000 MHz.

The radiated emission spectrum of the Electrica reveals that the majority of the electromagnetic energy produced by the vehicle lies below 20 MHz. Based upon the results of these measurements, it is concluded that this particular EV is not likely to create an interference problem with communications services operating above 20 MHz. No conclusive remarks can be made at the present time about the possibility of detrimental effects to electronic systems operating below 20 MHz, though relatively high field intensities were measured in this frequency range.

TABLE OF CONTENTS

1. Introduction

1.1 Background

Electrically powered vehicles (EV's) are currently receiving considerable attention as an alternative to gasoline powered vehicles. The various propulsion and control systems on the electric vehicle inherently produce electromagnetic signals at frequencies in addition to those associated with normal operation. For example, brushes, sliprings, and commutators on motors exhibit sparking and produce surges in power leads. SCR or transistor controllers, diode rectifiers, switches, and relays typically have large electrical transients associated with their operations. These sudden and large changes in the electric power system cause spurious electromagnetic signals to be generated. Through propagation along the wiring harnesses, such signals can radiate into the environment and thus pose a potential threat of interference to other electric vehicles, land mobile communication systems, air traffic controllers, or other electrical/electronic systems.

In addition to contributing to the electromagnetic environment, electric vehicles (and any others containing electronic systems) are potentially susceptible to the varied EM fields to which they will be exposed. These fields result from electric power transmission lines, commercial radio and television broadcast stations, land mobile radio services (to include citizens band), military installations, and natural sources such as lightning. The fields can exhibit intensities of up to hundreds of volts per meter. Such intense fields may penetrate the body of the vehicle* and induce voltages and currents on cables and in devices at sufficient levels to cause damage or momentary upset in critical vehicle components. Of particular concern are susceptible components which might jeopardize the safety of passengers or other individuals in the vicinity of the vehicle.

So long as only a limited number of EV's are in use, associated EMI effects are not expected to be one of the major problems with the nation's transportation system. In the event, however, that there should some day be millions of such vehicles on the road, the total impact of vehicular

---

*The degree of coupling of external EM fields to internal circuits can be expected to increase as the use of non-metallic bodies for vehicles becomes more prevalent.

emanations could be large. (Gasoline engine exhaust emissions are a good case in point.) Therefore, a definition of the nature of potential EMI/EMC problems that may be associated with electrically propelled vehicles during the early stages of their development is appropriate. In this way, the problems can be assessed and corrective actions defined at minimum costs to the motoring public. (It has been historically experienced by the defense and communications communities that EMI suppression and correction can be applied with less costs during design phases than they can as post-design retrofits.)

1.2 Program Scope and Objective

The scope of the program is an investigation of electric vehicle EMI and EMC.

The objective of the program is to investigate the effects of EMI and EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. Specific tasks include: (1) a study to define the EMI-related requirements for EV's; (2) performance of a representative set of emission and susceptibility measurements on selected current production EV's; and (3) documentation of the results.

1.3 Report Summary and Organization

This interim report describes the significant findings to date on the current program. In particular, the results of measurements performed on the first test vehicle (Jet Industries' Electrica) are documented.

The material which follows in this report is divided into four major sections. The EMI/EMC evaluation methodology for EV's is presented in Section 2. The measurements performed and a summary of the findings are given in Section 3. Section 4 presents conclusions drawn from the measurement results and provides recommendations for future investigation.

Two appendices are included in the report. Appendix I is the radiated emissions test procedure. Appendix II presents the radiated emissions data collected on EV No. 1.

2. Selection of EMI/EMC Evaluation Methodology

2.1 Method of Approach

The approach utilized in the selection of an EMI/EMC evaluation methodology began with an anlysis of several applicable measurement procedures. The procedures of major emphasis included SAE J551c ("Performance Levels and Methods of Measurements of Electromagnetic Radiation from Vehicles and Devices (20-1000 MHz)"), SAE J1113 ("Electromagnetic Susceptibility Test Procedures for Vehicle Components (Except Aircraft)"), MIL-STD-462 ("Measurement of Electromagnetic Interference Characteristics") and IEEE Std. 263 ("Standard for Measurement of Radio Noise Generated by Motor Vehicles and Affecting Mobile Communications Receivers in the Frequency Range 25 to 1000 Megacycles per Second"). These documents were analyzed in depth to assess their applicability to the fulfillment of regulatory and technical requirements of EV's.

Next, a brief review and analysis of current EV technology was undertaken in order to determine potential measurement requirements which might be unique to electric vehicles. A review of current controller technology indicated that the pulse characteristics associated with EV's are significantly different than those associated with internal combustion powered vehicles (ICV's). An analysis of the impact of these characteristics on the maximum scan rate was made and documented in a technical report [1]. The analysis and review also indicated that the test procedures should provide for measurements below 20 MHz, since a significant amount of energy is expected below this frequency. In addition, the test procedures should reflect the fact that the EMI characteristics of EV's will be a function of the loading on the motor. A dynamometer may be used accurately and repeatably to apply different load conditions. An absorption (i.e., non-electrical) dynamometer is desirable to limit the ambient noise levels and to avoid having to distinguish the electromagnetic emissions of the vehicle from that of the dynamometer.

2.2 Radiated Emission Test Procedure

A radiated emission test procedure was prepared using the method of approach outlined above. (The Radiated Emission Test Procedures for Electric Vehicles is included in Appendix I.) The purpose of this test procedure was to provide guidance in obtaining information and data from which a characterization of the EMI features of an EV can be made. The test procedure covers the measurement of radiated emissions from an EV over the frequency range of 14 kHz to 1000 MHz. Procedures are given for determining worst-case load conditions and for measuring radiated emissions under varying load conditions and motor speeds. Also included is a procedure for measuring representative electromagnetic emission levels while the vehicle is driven past the receiver at a constant speed, during acceleration, and during deceleration (braking).

2.3 Test Procedure for On-Board Battery Chargers

The test procedure for on-board battery chargers has not been finalized at this time. However, several documents have been reviewed and assessed for their applicability to battery charger measurements. In addition to conducted emission procedures outlined in MIL-STD-462, C.I.S.P.R. Publication 16 ("C.I.S.P.R. Specification for Radio Interference Measuring Apparatus and Measurement Methods") was analyzed. The CISPR document defines an "artificial mains network" which is intended to provide a well-defined impedance across the terminals of the device under test at the test frequency and also isolate the device from undesired RF signals originating from the (ac) mains supply. This network or some other suitable network (e.g., a line impedance stabilization network (LISN)) is certainly required in the measurement procedure for testing EMI conducted emission from on-board battery chargers. The "artificial mains network" would probably be adequate up to approximately 30 MHz. Above 30 MHz, radiated interference typically begins to dominate over conducted interference. The absorbing clamp described in the CISPR document might be useful for battery-charger interference measurements in the VHF frequency range (30-300 MHz).

The results of these analyses will be utilized in the development of a test procedure for on-board battery chargers. This procedure will be employed on at least one of the next three EV's in order to characterize the conducted emissions from on-board battery charger.

2.4 Susceptibility Investigation

The susceptibility investigation for electric vehicles has not been completed at this time. The objective is to determine if potential problem areas exist in which electromagnetic energy from external sources causes degradation in the normal operation of the EV. The scope of the investigation will be limited to those vehicle malfunctions which might jeopardize the safety of passengers or other individuals in the vicinity of the vehicle.

Susceptibility investigations may be conducted analytically, experimentally, or a combination of the two. Comprehensive radiated susceptibility measurements would require (to be meaningful) exposing the EV to a realistic electromagnetic environment and determining if interference results in the normal operation of the vehicle. Establishing the proper field distribution of sufficient level over a test object the size of an EV proves to be extremely difficult. A purely experimental approach to EV susceptibility investigations, therefore, has not been selected. An anlytical approach, on the other hand, requires a number of simplifying assumptions to be made concerning the degree of coupling from the exterior electromagnetic environment to a conductor inside the EV. These assumptions ultimately limit the accuracy of the results. Therefore, assumptions will be made in such a way that the predicted levels will be near the upper limit of what might realistically be encountered in actual operation. A potential interference condition may then be examined by actually injecting the predicted levels on signal or power leads of interest. In this way, one may (1) evaluate the implication of field distribution and intensities unachievable with conventional instrumentation and (2) better characterize the interference levels of potentially susceptible circuits and devices. This is the approach that has been selected for the susceptibility investigation of EV's.

The interference scenario of major concern is the possibility of RF energy being coupled to the cable connected between the speed control potentiometer wiper contact and the speed control input to the PMC controller of the Electrica. The RF signal could then undergo rectification at the emitter-base junction of the first transistor in the input to the controller. If the rectified signal applies a sufficient bias to the transistor, loss of speed control could occur. This cable will be modeled as a 3 meter long conductor (the approximate distance from the speed control unit located in the DCS (Disconnect, Contactor, Speed control) box to the controller).

The initial analysis will involve a citizen band (CB) radio transmitter as the potential interfering source. The power coupled between two antennas of known effective apertures may be calculated from the well known Friis transmission formula

$$P_r = P_t \frac{A_{er} A_{et}}{\lambda^2 r^2} \tag{1}$$

where

P_r = power received by receiving antenna,

P_t = power transmitted by transmitting antenna,

A_{er} = effective aperture of the receiving antenna,

A_{et} = effective aperture of the transmitting antenna,

λ = wavelength, and

r = separation distance between the antennas.

This formula is accurate provided that the following far-field condition holds:

$$r \geq \frac{2d^2}{\lambda} \tag{2}$$

where d is the maximum dimension of either the transmitting or receiving "antenna". (Note that we are considering the speed control cable in the EV as a receiving antenna.) Assuming a frequency of 27 MHz, the free space wavelength turns out to be 11.11 meters. Using a value of 3 meters for d (i.e., the length of the cable), the far-field distance boundary is approximately 1.6 meters. The distance (r) assumed for this analysis will be 2 meters, which therefore satisfies the far-field condition.

Both of the effective apertures could be assumed to be equal to the maximum effective aperture of a tuned dipole ($0.13\lambda^2$) in order to determine the maximum amount of interference power that might be coupled to the EV cable. However, the effective apertures are actually much smaller due to the fact that the transmitting antenna is vertically polarized whereas the receiving antenna is horizontally polarized. This may be accounted for by letting

$$A_{er} = A_{et} = 0.1 \times 0.13\lambda^2 \tag{3}$$

in Equation (1). Assuming a transmitted power of 5 watts (the maximum legally allowable input power to the final stage of a CB transmitter), the power received is approximately 26 milliwatts.

The susceptibility of transistors is often measured in terms of the rectification factor [2], [3]. The rectification factor of a transistor is an experimentally determined parameter and is a function of gain-bandwidth product, frequency, bias level, and RF input power. Assume that the rectification factor for the transistor of interest is 0.006 amps/watt (a typical rectification factor for bipolar junction transistors) [4]. If 26 milliwatts of input power were incident on the base of the transistor, an equivalent dc base bias current of 156 microamps (0.006 amps/watt x 26 milliwatts) will be induced due to square-law rectification at the emitter base junction. An input impedance of 2000 ohms would therefore result in a bias voltage of greater than 300 mV. This would almost certainly cause an interference condition in the case of a germanium transistor, but would not for a silicon transistor.

Confidence in the validity of the above analysis can be gained by empirically determining the response of the EV to a 27 MHz signal injected into the controller speed control input. The power level required to cause speed control malfunction may then be determined. If no response from the EV is obtained for injected power levels up to 26 milliwatts, it can be concluded that a susceptibility problem for this situation does not likely exist. Radiated measurements may also be undertaken to further substantiate the analytical results.

3. EMI/EMC Vehicle Investigations

3.1 Preliminary Investigations

A number of preliminary investigations were required before the test procedure and instrumentation could be finalized for the radiated emissions measurements. The initial measurement activities were focused on a comparison of Noise Field Intensity Meters (NFIM's) and spectrum analyzers for use as the EMI receiver. The NFIM used in this comparison was an Electro-Metrics EMC-25 Interference Analyzer. The spectrum analyzers utilized were an HP-8554L and a Tektronics 492-P. Several X-Y plots were recorded for selected bands in the 14 kHz to 1000 MHz frequency range. Measurements were made with each receiver using a number of different bandwidths, RF attenuation settings, and sweep rates. The objective of these measurements was to determine the validity of results obtained with each receiver and to determine optimal instrumentation settings (see Reference 1). The spectrum analyzers proved to be inferior to the NFIM for two major reasons. First, the vertical output of the spectrum analyzers tended to respond to the time-averaged broadband noise levels whereas the NFIM responded to peak levels. Second, neither spectrum analyzer is equipped with an RF preselector (unlike the NFIM) and therefore they suffer problems with intermodulation interference generation and limited dynamic range. It was therefore determined to use the EMC-25 for the remainder of the measurements. Operation of this receiver in the wide-band mode enables the widest dynamic range to be achieved. The EMC-25 has a field sweep rate of 60 seconds per octave band which was slow enough to reliably detect peak levels for all bands tested.

3.2 Radiated Emissions Measurements

The test procedure given in Appendix I was revised to maximize the efficiency with which meaningful data could be collected. The original test procedure called for making the measurements at a constant EV motor speed of 1500 rpm, which is identical to that specified in SAE J551. However, since no real correlation from an EMI point of view exists between electric motor speed and internal combustion engine speed and since rpm measurements for an EV would require instrumentation not commonly available, the vehicle speed (in mph) was selected as the control variable. The arbitrarily selected speed of 25 mph in fourth gear was chosen as the constant vehicle speed to be used during the measurements. Measurements were made on both the front and driver's side of the EV with the antenna placed 3 meters high and 10 meters distant from the closest part of the vehicle. Measurements of the magnetic field inside the vehicle were made by placing a loop antenna on the passenger seat with the loop parallel to the seat back. Four different load conditions were tested: (1) no load (drive wheels suspended in the air), (2) 150 amps, (3) 225 amps, and (4) 300 amps of motor drive current. (The last three load conditions were established using a Clayton chassis dynamometer to load the vehicle. This dynamometer is of the abosprtion variety and therefore contributes no electromagnetic noise of its own.) Drive-by measurements were also made at ten different frequencies. The measurements were made with the vehicle accelerating, braking, coasting, and at constant speed. The results of the drive-by measurements have not been analyzed at this time, but will be included in the final report.

3.3 Data Reduction

The radiated emissions data was recorded in the form of X-Y plots of received voltage versus frequency. This raw data had to be digitized and subsequently replotted with calibration factors appropriately added. Software was written to digitize the data; to include bandwidth factors, antenna factors, transmission line losses, and receiver correction factors; and to finally replot the data in semilogarithmic format. The finished data plots in the form of field intensity versus frequency are documented in Appendix II.

3.4 Summary of Findings

A number of observations can be made based upon a preliminary analysis of the test results obtained to date on this program. However, definitive conclusions must be tempered by the acknowledgement of two major unknowns. First, even though the absolute radiated emission levels are known, the radiated emission levels for other potential interfering sources (such as internal-combustion-powered vehicles (ICV's)) should be known in order to compare the relative severity of the EV as a potential interference source. This is particularly true at frequencies below 20 MHz (the lower frequency limit of SAE J551), where definitive data on ICV's is scarce. The second unknown concerns the fact that data has been obtained on but one vehicle and generalizations to the entire class of EV's must, therefore, be avoided. The observations which are made here, therefore, apply only to the Jet Industries Electrica (and possibly to the PMC controller which is utilized in this vehicle).

The measurement results on the first EV do, however, allow a number of observations and conclusions to be made concerning the overall levels outside and inside the vehicle as a function of frequency; and the effects of load and polarization on the overall levels radiated from the vehicle. Analysis of the measurement data resulted in the following observations:

(a) Radiated Levels as a Function of Frequency. The exact electric field intensity at a given frequency depends upon factors such as load condition, polarization, and side of vehicle. However, the vast majority of the data fell between 0 to +40 dBμV/m/kHz for frequencies below 10 MHz and tended to decrease at approximately 40 dB per decade above this frequency. In general, the radiated emission levels were below the limits given in SAE J551. The only apparent exceptions appear to be for the case of the vertical electric field at approximately 21 MHz for 150 amps of armature current and the horizontal electric field between 20 and 22.5 MHz for no loading on the motor. However, both measured values were less than 1 dB above the SAE limit and are within the measurement accuracy achievable. The majority of the magnetic field intensity data ranged from -60 to -30 dBμA/m/kHz below 2 MHz and tended to decrease at approximately 20 dB per decade above this frequency.

(b) Emission Levels Within the Vehicle. The magnetic field intensity inside the vehicle was significantly greater than the magnetic field intensity outside the vehicle, as expected. The levels ranged from +6 to +27 dBμA/m/kHz for frequencies below 200 kHz, decreased at approximately 20 dB per decade for frequencies up to 2 MHz, and decreased at approximately 40 dB per decade above 2 MHz.

(c) Effects of Load. The load conditions on the Electrica did not appear to significantly affect the overall radiated emission levels. However, the position (frequency) at which relative peaks and valleys occurred in the frequency spectrum were shifted for different load conditions. This shifting of the spectrum is probably due to the varying pulse width of the armature voltage waveform as determined by the PMC controller. The radiated emission levels were expected to increase (especially at lower frequencies) as the load increased due to the increase in the pulse width of the controller output as well as the increase in armature current. This phenomenon was not observed for the Electrica, however. It is noted, however, that the ambient noise levels were exceptionally large at the lower frequency bands (probably due in many instances to background lightning radiation) and this may have masked the radiation level differences at the lower frequencies.

(d) Polarization of Radiated Fields. The magnetic field was highly polarized whereas the electric field was not. For the magnetic field, the vertical polarization was dominant when measuring the left side of the vehicle. The radial component was the next largest component and the horizontal component was the smallest. For the front side of the vehicle, the horizontal component of magnetic field was significantly greater than the radial component. The vertical component was not measured. No consistent relationship was found between polarizations for the electric field.

4. Conclusions and Recommendations

Measurements have been completed on the first (Jet Industries' Electrica) of four electric vehicles to be tested during the current program. Efforts thus far have been focused on developing test procedures for and performance of radiated emission measurements on an electric vehicle. Measurements were made on both the front and driver's side of the EV with the antenna placed 3 meters high and 10 meters distant from the closest part of the vehicle. Measurements of the magnetic field inside the vehicle were made by placing a loop antenna on the passenger seat with the loop parallel to the seat back. Four different load conditions were tested ranging from no load (drive wheels suspended in the air) to 300 amps of motor drive current. Drive-by measurements were also made with the vehicle accelerating, braking, coasting, and at constant speed.

The radiated emission spectrum of the Electrica reveals that the majority of the electromagnetic energy produced by the vehicle lies below 20 MHz. The majority of the emissions data above 20 MHz were well below the SAE J551 limit when measured over four different load conditions ranging from minimum to maximum motor loading. Motor vehicles conforming to the SAE limit, in turn, have been shown by experience to be compatible with the various communications services and equipment operating in the frequency range of 20 to 1000 MHz. It is concluded that, based on the results of these measurements, this particular EV is not likely to create an interference problem with communications services operating above 20 MHz.

Conclusive remarks cannot be made at this point about the possibility of detrimental effects to electronic systems due to radiation below 20 MHz. It is clear from the data obtained thus far that the radiated levels tend to significantly increase as frequency decreases. Based upon these results, it can be said that there exists a potential radiated interference problem at frequencies below 20 MHz. However, as was previously mentioned, the radiated emission levels for other potential interfering sources should be known in order to compare the relative severity of the EV radiated emissions with other interfering sources. Radiated emissions data below 20 MHz on ICV's are very scarce. Therefore, if sufficient data to characterize these vehicles in this frequency range cannot be found, it would be desirable to measure an ICV at selected frequency bands in order to allow comparisons to be made.

Another major concern is the electromagnetic effects of EV emissions on biomedical devices. A number of investigations have been undertaken on the susceptibility of cardiac pacemakers to electromagnetic radiation [5]-[8]. The only existing standard for pacemakers is the AAMI (The Association for the Advancement of Medical Instrumentation) Pacemaker Standard ("Labeling Requirements, Performance Requirements, and Terminology for Implantable Artificial Cardiac Pacemakers") which requires pacemakers to operate satisfactorily under a 200 V/m pulsed field at 450 MHz. Using the specified pulse width of 1 millisecond and a commonly employed pulse repetition frequency of 1.5 pulses per second, the amplitude of the frequency spectrum for the pulsed field at 450 MHz can be calculated to be 0.3 V/m (200 V/m x 1 ms x 1.5 pps) or 109.5 dB μV/m. Since this narrowband susceptibility level is more than 100 dB above the broadband levels radiated by the Electrica, it is concluded that it is highly unlikely that EV's similar in design to the Electrica would interfere with cardiac pacemakers.

Preliminary analyses of the data on one vehicle indicate that there is no significant and consistent variation in radiated emission level with load conditions. If this result holds true for the next three vehicles (and different controller schemes) it could probably be concluded that the tests can be performed simply with the drive wheels elevated (i.e., a dynamometer would not be required).

The remaining efforts on the current program will be focused on the measurement of three additional vehicles. Two of the vehicles will be used primarily for radiated and conducted emissions testing. The radiated emissions results will be used to expand the current data base to include other types of motor controllers. The objective of the conducted emissions measurements will be to characterize the EMI aspects of on-board battery chargers. One of the next three vehicles will be used primarily for the susceptibility investigation. The susceptibility investigation will include radiated and, to a limited extent, direct injection testing in conjunction with an analysis of potentially susceptible components and circuits.

In addition to the tasks on the current program, future investigations in this area would be highly desirable and should include: (1) measurement of the complete radiated emissions spectrum of an ICV from 14 kHz to 1000 MHz for comparison with that of EV's and (2) an in-depth investigation to evaluate the susceptibility of a representative electric vehicle and the development of meaningful test procedures for EV susceptibility evaluations.

REFERENCES

(1) J. K. Daher, "Limitation in Swept Receiver Scan Rates for Impulsive Noise Measurements," Technical Report, Project A-3089, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, GA, February 1982.

(2) R. E. Richardson, V. G. Puglielli, and R. A. Amadori, "Microwave Interference Effects in Bipolar Transistors," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-17, No. 4, p. 216, November 1975.

(3) Naval Surface Weapons Center, "Solid State Component RF Susceptibility Program," Progress Report FY-73.

(4) R. A. Amadori, V. G. Puglielli, and R. E. Richardson, "Prediction Methods for the Susceptibility of Solid-State Devices to Interference and Degradation of Microwave Energy," Proceedings of the International Electromagnetic Compatibility Symposium, 1973, pp. 184-200.

(5) B. M. Jenkins and J. A. Woody, "Cardiac Pacemaker Responses to Power Frequency Signals," IEEE 1978 International Symposium on Electromagnetic Compatibility, June 20-22, 1978, pp. 273-277, Atlanta, GA.

(6) H. W. Denny, B. M. Jenkins, and J. C. Toler, "Behavior of Cardiac Pacemakers in Pulsed EM Fields," IEEE 1977 International Symposium on Electromagnetic Compatibility, August 2-4, 1977, pp. 272-277, Seattle, Washington.

(7) J. C. Toler and F. R. Williamson, "Electromagnetic Characteristics of Cardiac Pacemakers," Georgia Tech Final Technical Report on Standard Industrial Agreement dated April 17, 1972, with CORDIS CORPORATION, February 1973.

(8) J. C. Toler and F. R. Williamson, "Effect of Electromagnetic Fields at 450 MHz on Pacemakers," Georgia Tech Final Technical Report on Project A-1481 for MEDTRONIC, INC., January 1973.

APPENDICES

APPENDIX I

RADIATED EMISSION

TEST PROCEDURES

FOR

ELECTRIC VEHICLES

1. Purpose

1.1 The purpose of these test procedures is to provide guidance in obtaining baseline information and data from which a characterization of the EMI/EMC features of an electric vehicle can be made.

2. Scope

2.1 The test procedures cover the measurement of radiated emissions from an electric vehicle over the frequency range of 14 kHz to 1000 MHz. Radiated emissions will be measured under varying load conditions and engine speeds. Procedures are given for determining worst-case load conditions. Also included is a procedure for measuring representative electromagnetic emission levels while the vehicle is actually being driven at a constant speed, during acceleration, and during deceleration (braking).

3. Equipment

3.1 Receivers - The receiver's impulse bandwidth must be measured and should not exceed 10% of the frequency at which measurements are being made.

3.1.1 Spectrum Analyzer: HP-141T Display Section, 8554L RF Section, 8552B IF Section.

3.1.2 NFIM: EMC-25 Interference Analyzer.

3.2 Scanning Plotters - The sine wave response at 0.5 in. peak-to-peak shall not be down by more than 3 dB at 10 Hz from the 1 Hz response.

3.2.1 X-Y Plotter: Houston 2000 X-Y Recorder

3.3 Calibrated Signal Source, Precision Attenuator, & Power Meter - Used for signal substitution method.

3.3.1 Signal Source: HP-8640B

3.3.2 Attenuator: Weinschel 905

3.3.3 Power Meter: HP-435A

3.4 Frequency Counter: HP-5245L

3.5 Antennas - Use the following antennas:

Frequency Range	Type	Manufacturer/Model #
14 kHz - 20 MHz	Rod Loop	Fairchild RVR-25 Fairchild ALR-25
20 MHz - 200 MHz	Biconical	Fairchild BIA-25
200 MHz - 1000 MHz	Log Conical	Fairchild LCA-25

3.6 Transmission Line - Use double shielded coaxial cable between receive antenna and receiver.

3.6.1 RG-55/U (50 ft.)

4. Equipment Calibration

4.1 Receiver calibration

4.1.1 Amplitude Calibration - The receiver shall be calibrated at the center frequency of the band being measured by using the standard signal substitution method. Note: 0 dBm (50 Ω) = + 107 dB μV (50 Ω)

4.1.2 Bandwidth Calibration - The impulse bandwidth (BW_i) of the receiver shall be measured if unknown (at each bandwidth setting used during measurements).

4.1.2.1 Spectrum Analyzer Impulse Bandwidth Measurement:

- (a) Connect 30 MHz calibrator signal to input terminal.
- (b) Select linear display mode
- (c) Set linear sensitivity to 1 mV/div.
- (d) Tune to 30 MHz and set bandwidth to desired position.
- (e) Narrow the scan width until displayed signal nearly fills the CRT.
- (f) Peak the display to the top graticule line with the reference vernier.
- (g) Read the frequency difference between the half-voltage (-6 dB) points.
- (h) BW_i = 6 dB bandwidth.

4.1.2.2 Use existing data for EMC-25 impulse bandwidth.

Note: R(dBμV/kHz) = V(dB μV) - B
= P(dBm) + 107 - B

where: R = impulse noise intensity in dB above 1 μV/kHz
V = voltage measured in dB above 1 μV
P = power measured in dB above 1 mW
B = 20 log (BW_i/1 kHz)

4.2 X-Y Plotter Calibration

4.2.1 Calibrate Y-axis by comparison with the spectrum analyzer display and adjusting log reference level in conjunction with the recorder's vertical controls to obtain linearity (at the center frequency only).

4.2.2 Calibrate X-axis with the use of a frequency counter. Use manual scan mode to set start and stop frequencies.

4.3 Antenna Calibration.

4.3.1 Antenna Factor - Use measured data on all four antennas.

4.3.1.1 Verify at center frequency by making a gain measurement and then use the following equation (for a 50 ohm system):

$$\text{Antenna Factor} = \frac{E}{V} = \sqrt{\frac{4\pi(377)}{50\,G\lambda^2}}\ \ m^{-1}$$

where

E = electric field strength in μV/m,
V = voltage in μV,
G = gain of antenna, and
λ = wavelength in meters.

4.4 Transmission Line Calibration.

4.4.1 Insertion Loss - The insertion loss of the RG-55/U cable used to connect the receive antenna to the receiver shall be calculated or measured as a function of frequency over the frequency range of interest.

5. Setup

5.1 Vehicle and Antenna Positions (See Figure 1)

5.1.1 Vehicle Position - Orient the vehicle on test pad as shown in Figure 1.

5.1.2 Antenna Position - Set the receive antenna as shown in Figure 1 at a height of 3 m. above ground level (or above the bottom of vehicle tires if ground is not level).

5.2 Test Site and Test Conditions.

5.2.1 Use pad near gate entrance.

5.2.2 Put equipment on wooden bench in region shown in Figure 1.

5.3 Polarization: Below 200 MHz, both vertical and horizontal components of impulse electric field strength shall be measured at each vehicle position. (Below 20 MHz, this includes vertical and horizontal components of both electric and magnetic fields.) Above 200 MHz, only measure circular polarization with the log conical antenna.

6. Measurements

6.1 Ambient Measurement - Evaluate the effect of ambient noise, RF carriers, etc.

6.1.1 Measurements will be made over the applicable frequency range immediately before the vehicle measurements. Procedure will be the same as below except that vehicle will be inoperative.

6.2 Far-field Radiated Emission Measurements (20 - 1000 MHz)

6.2.1 Frequency Range - The frequency range of 20 - 1000 MHz will be divided into eight frequency bands.

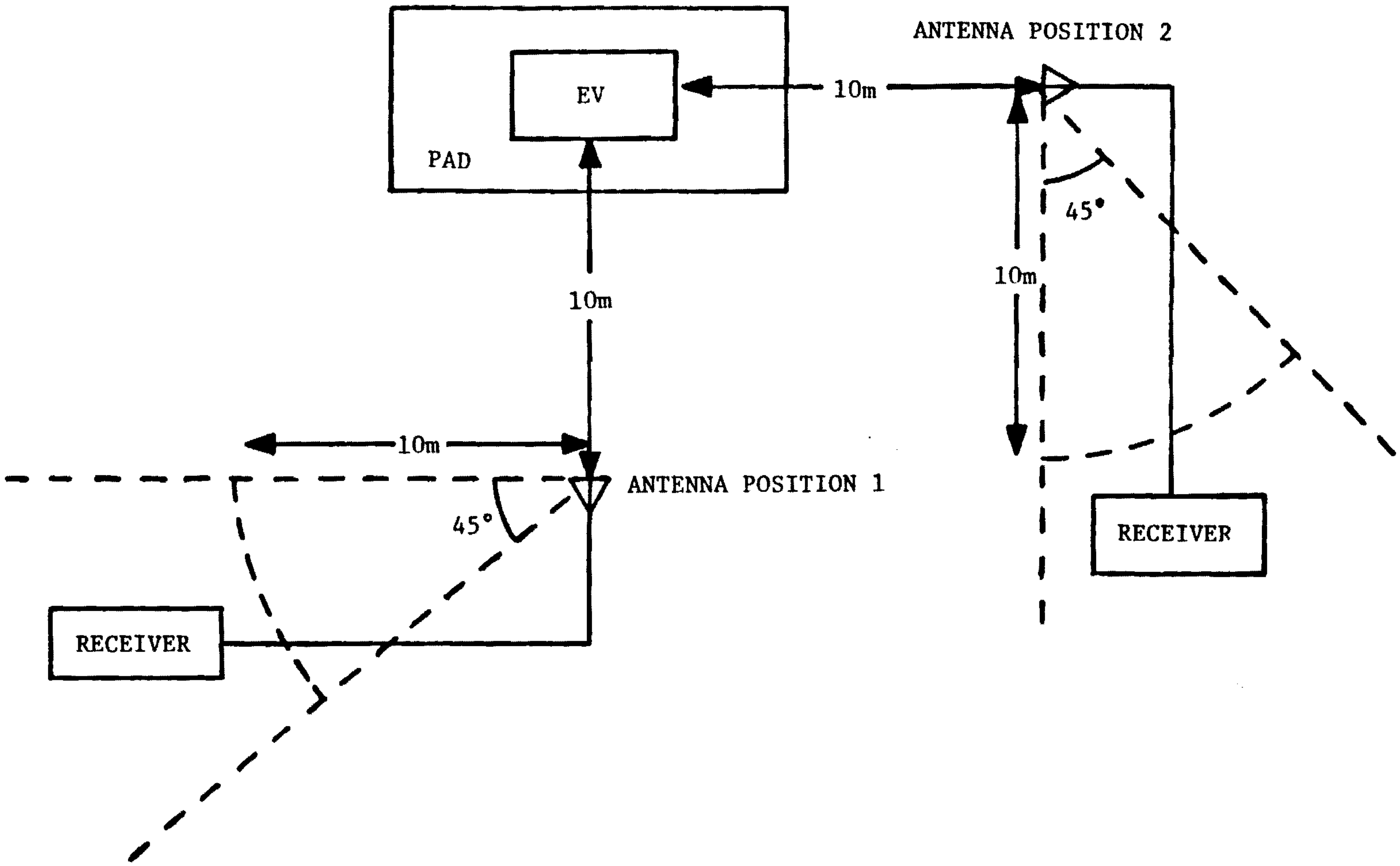


FIGURE 1. TOP VIEW OF TEST SETUP.

6.2.2 Scan Rate - The frequency scan shall be at a rate which will insure that peak levels have been detected.

6.2.2.1 Procedure - Reduce scan rate until levels do not increase significantly (1 dB increase or greater) over previous results.

6.2.3 Antenna and Vehicle Orientation - Make complete set of measurements with antenna at position 1 and next at position 2 (see Figure 1). Then turn the EV around 180 degrees and repeat measurements at both antenna positions. (Note: Can do this assuming the dynamometer can be driven in reverse. If not, then must station the antenna on all four sides of vehicle or rotate the dynamometer itself 180 degrees.)

6.2.4 Define frequency bands as follows:

Band 1:	20 - 60 MHz	Band 5:	200 - 400 MHz
Band 2:	60 - 110 MHz	Band 6:	400 - 600 MHz
Band 3:	110 - 160 MHz	Band 7:	600 - 800 MHz
Band 4:	160 - 200 MHz	Band 8:	800 - 1000 MHz

6.2.5 Wheels-in-the-Air Measurements (Note: These tests will only be conducted if it has been verified that no damage will result to the EV as a result of no-load operation. If it is determined that damage would result, inertial loading may be used or one may proceed directly to the dynamometer loading tests.)

6.2.5.1 Operating Conditions - Electric vehicle will be operated in first gear at a constant speed of 1500 rpm with the drive wheels suspended in the air during these tests. (Note that the gear to be used will depend on the vehicle being tested and the transmission type that it uses. The Electrica has manual transmission and first gear has been selected as being appropriate for testing of this vehicle at 1500 rpm.)

6.2.5.2 Spectrum Analyzer Settings - Set center frequency to center frequency of each band. Use the following control settings:

	Bands 1-4	Bands 5-8
Scan Width:	5 MHz/div	20 MHz/div
IF Bandwidth:	1 kHz	1 kHz
Video Filtering:	none	none
RF Attenuation:	0 dB	0 dB
Scan Time:	See 6.2.2	

Increase RF attenuation to 10 dB. If levels drop by 10 dB, then set RF attenuation to 0 dB. However, if levels drop by less than 10 dB, then increase attenuation to 20 dB. If levels now drop by 10 dB, then set RF attenuation to 10 dB. If levels instead drop by less than 10 dB, add external attenuation as required.

6.2.5.3 Make an X-Y plot using the spectrum analyzer in conjunction with the X-Y recorder for each of the eight frequency bands with the antenna in position 1 (measure horizontal polarization only for bands 1-4). This requires a total of 8 plots. The vehicle should be operating at 1500 rpm and with the drive wheels suspended in the air for each test.

6.2.5.4 Verify the above results by using the EMC-25 in the internal sweep mode with remote connections to the X-Y recorder. Use peak detector and operate in narrow band (NB) mode. Sweep bands 11 through 15 of EMC-25 for antenna position 1. Compare results with those obtained above. (Note: If results are within expected measurement error of spectrum analyzer results, use spectrum analyzer as the receiver for the remaining tests. If significant differences are noted, use the EMC-25 for the remaining tests.)

6.2.5.5 Scan bands 1-4 with the antenna oriented for vertical polarization in position 1. Then scan each of the eight bands for the other three antenna/vehicle orientations and for each polarization. This will require, including the 8 plots obtained in 6.2.5.3, a total of 48 plots (two polarizations at four positions for bands 1-4 plus one polarization at four positions for bands 5-8).

6.2.6 Determination of Worst-Case Load Condition (Note: If dynamometer not available for use, proceed to 6.4.)

6.2.6.1 Operating Conditions - Electric vehicle will be operated in first gear at 1500 rpm with a variable load induced by the dynamometer.

6.2.6.2 Use spectrum analyzer (HP-8554L RF Section) with the following settings:

Center Frequency: 100 MHz	RF Attn: 20 dB
Scan Width: 20 MHz/div	Video Filtering: none
Scan Time: 1 ms/div	IF Bandwidth: 300 kHz

Use biconical antenna with horizontal polarization as receive antenna.

6.2.6.3 Beginning at minimum loading, increment the accelerator pedal position (physically or electronically) while varying torque with the dynamometer control unit in order to hold the rpm level as constant as possible (at approximately 1500 rpm). Record the load condition (i.e., torque) which results in worst-case emission levels.

6.2.6.4 Repeat above measurement for vertical polarization.

6.2.6.5 Use spectrum analyzer with the following settings:

Center Freq: 600 MHz	RF Attn: 20 dB
Scan Width: 100 MHz/div	Video Filtering: none
Scan Time: 5 ms/div	IF Bandwidth: 300 kHz

Use log conical as receive antenna. Again repeat measurement of 6.2.6.3.

6.2.6.6 Decide what the worst-case load condition is at 1500 rpm based on results of 6.2.6.3 through 6.2.6.5.

6.2.7 Worst-Case Load Condition Measurements.

6.2.7.1 Operating Conditions - Electric Vehicle will be operated in first gear at the worst-case load condition as determined in 6.2.6.

6.2.7.2 Spectrum Analyzer Settings - Same as in 6.2.5.2.

6.2.7.3 EMC-25 Settings - Same as in 6.2.5.4.

6.2.7.4 Make an X-Y plot using either the spectrum analyzer or EMC-25 in conjunction with the X-Y recorder for each of the eight frequency bands, for each antenna/vehicle orientation, and for each polarization. This requires a total of 48 plots.

6.2.8 Compare the results from 6.2.7 with those obtained from 6.2.5.

6.3 Low Frequency (Near-Field) Measurements (14 kHz to 20 MHz).

6.3.1 Frequency Range - The frequency range of 14 kHz - 20 MHz will be divided into ten frequency bands. These bands will be bands 1-10 of the EMC-25.

6.3.2 Scan Rate - The frequency scan rate will be approximately one minute per band, if the EMC-25 is used. If the spectrum analyzer is used, the rate will be such as to insure that peak levels have been detected.

6.3.2.1 Procedure (for spectrum analyzer only) - Reduce scan rate until levels do not increase significantly (1 dB or greater) over previous results.

6.3.3 Antenna and Vehicle Orientation - Use the antenna/vehicle orientation which resulted in the worst-case emission levels based on results of 6.2.

6.3.4 Operating Conditions - Electric vehicle will be operated at a constant speed of 1500 rpm under the worst-case load condition while in first gear (see note in 6.2.5.1).

6.3.5 Define frequency bands as follows:

Band 1: 14 - 30 kHz	Band 6: 0.48 - 1.10 MHz
Band 2: 28.5 - 61 kHz	Band 7: 1.05 - 2.4 MHz
Band 3: 59 - 128 kHz	Band 8: 2.3 - 5.3 MHz
Band 4: 120 - 260 kHz	Band 9: 5.0 - 11.4 MHz
Band 5: 240 - 520 kHz	Band 10: 11 - 25 MHz.

6.3.6 Spectrum Analyzer Settings - Set center frequency to center frequency of each band. Use the following control settings:

Control Setting	Band									
	1	2	3	4	5	6	7	8	9	10
Scan Width (kHz/div):	2	5	10	20	50	100	200	500	1000	2000
IF Bandwidth (kHz):	1	1	1	1	1	1	1	1	1	1
Video Filtering:	← none →									
RF Attenuation (dB):	← 0 →									
Scan Time:	← See 6.2.2 →									

Increase RF attenuation to 10 dB. If levels drop by 10 dB, then set RF attenuation to 0 dB. However, if levels drop by less than 10 dB, then increase attenuation to 20 dB. If levels now drop by 10 dB, then set RF attenuation to 10 dB. If levels instead drop by less than 10 dB, add external attenuation as required.

6.3.7 EMC-25 Settings: Use internal sweep mode with remote connections to X-Y recorder. Use peak detector and use wide band (WB) mode for bands 1-7 and narrow band mode for bands 8-10.

6.3.8 Make an X-Y plot for all 10 bands using both loop and rod antennas for both vertical and horizontal polarizations. This will require a total of 40 plots.

6.4 Drive-by Measurements.

6.4.1 Frequency Range - The frequency range will be determined from the results of measurements made in 6.2 and 6.3.

6.4.2 Scan Rate - The scan rate(s) will be the same as that used for tests conducted in 6.2 and 6.3.

6.4.3 Scan width (Frequency Bands) - Frequency band selection will be based on the results of 6.2 and 6.3.

6.4.4 Operating Conditions - The vehicle will be driven in three different operating modes for these measurements. The first operating mode will be at a constant speed of 1500 rpm in first gear. The second will be an acceleration run from a standing start in which the accelerator pedal is depressed to the floorboard beginning in the position indicated in Figure 2. The third operating mode will be a deceleration run from 20 mph in first gear to a stopping position as indicated in Figure 2. Braking will be as consistent and even as possible in order to provide relatively constant and repeatable deceleration.

6.4.5 Scan Zone - The scan zone shall not exceed the 5 meter distance (28 degree arc) shown in Figure 2. The lower frequency of the band being scanned should be initiated (either manually or via a trip switch) with the front of the vehicle at the beginning of the scan zone. The upper frequency of each band being scanned shall occur when the front of the vehicle is within the scan zone.

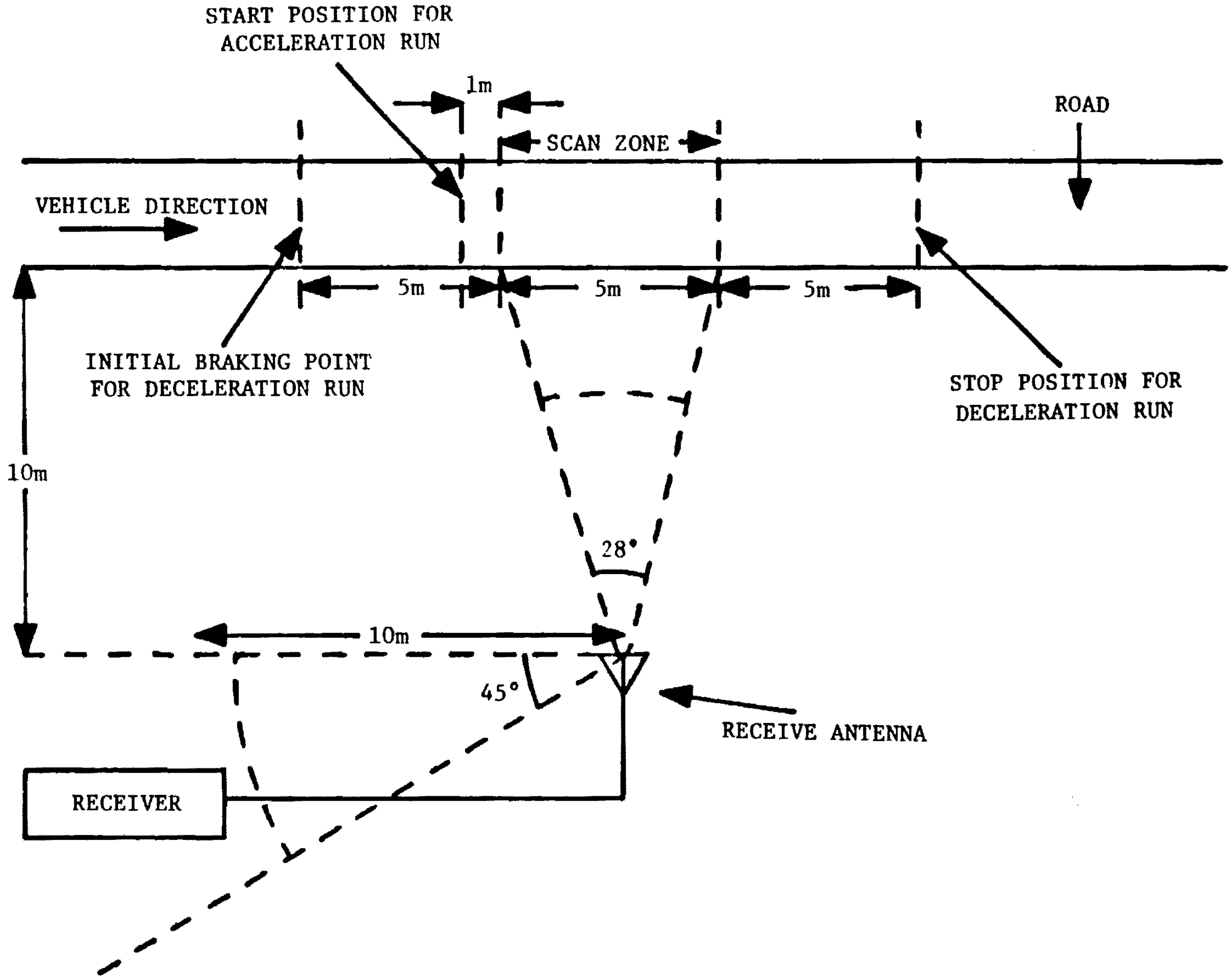


FIGURE 2. TEST SETUP FOR DRIVE-BY MEASUREMENTS.

6.4.6 Procedure - Scan the first band with a spectrum analyzer and appropriate antenna. Scan succeeding bands such that the start frequency of the band is equal to the stop frequency of the preceding band.

6.5 Engine Speed Variation on Radiated Emissions.

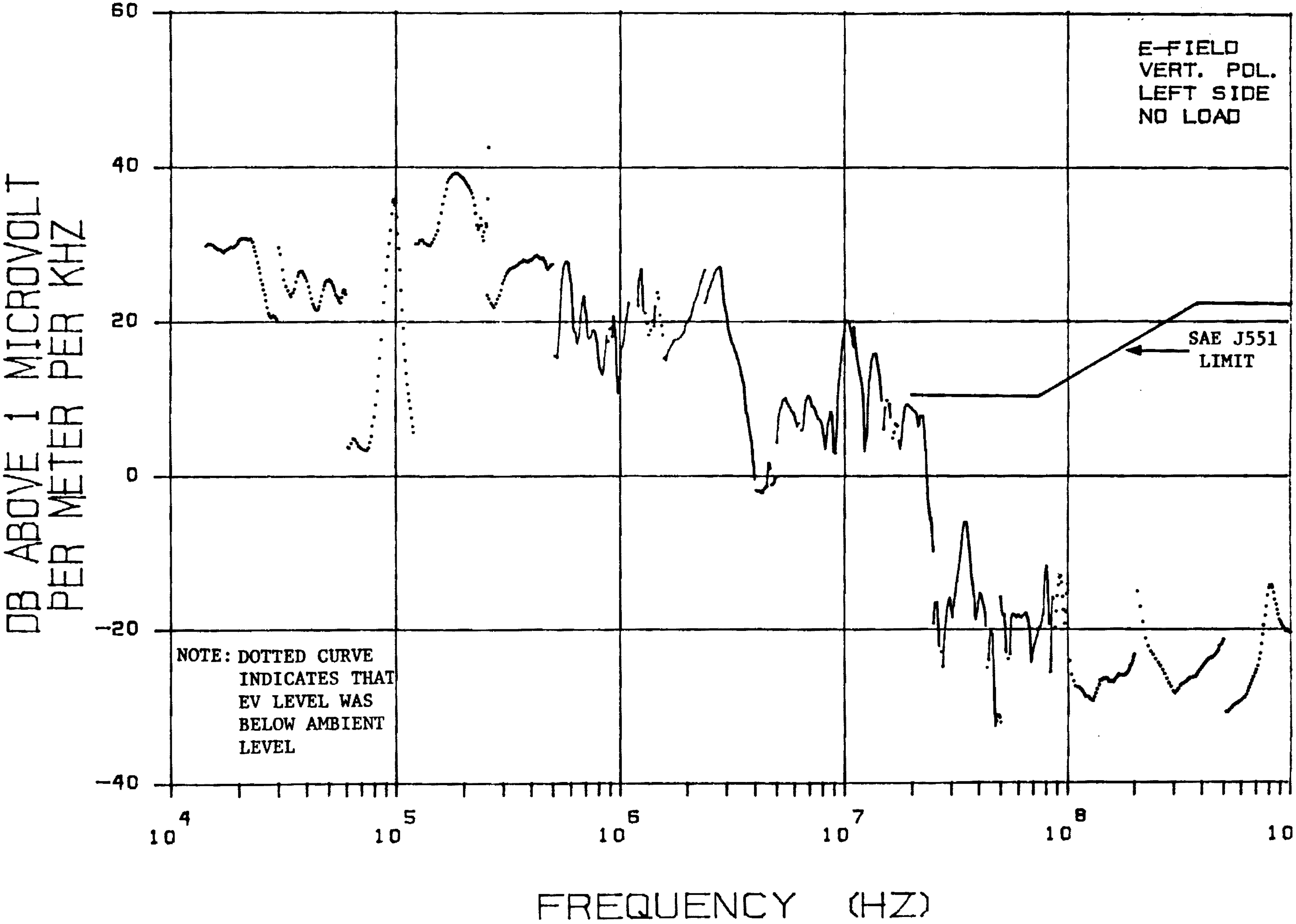
6.5.1 Repeat procedures of 6.2 and/or 6.3 (depending on relative emission levels above and below 20 MHz) for engine speeds of 2500 rpm and 3500 rpm.

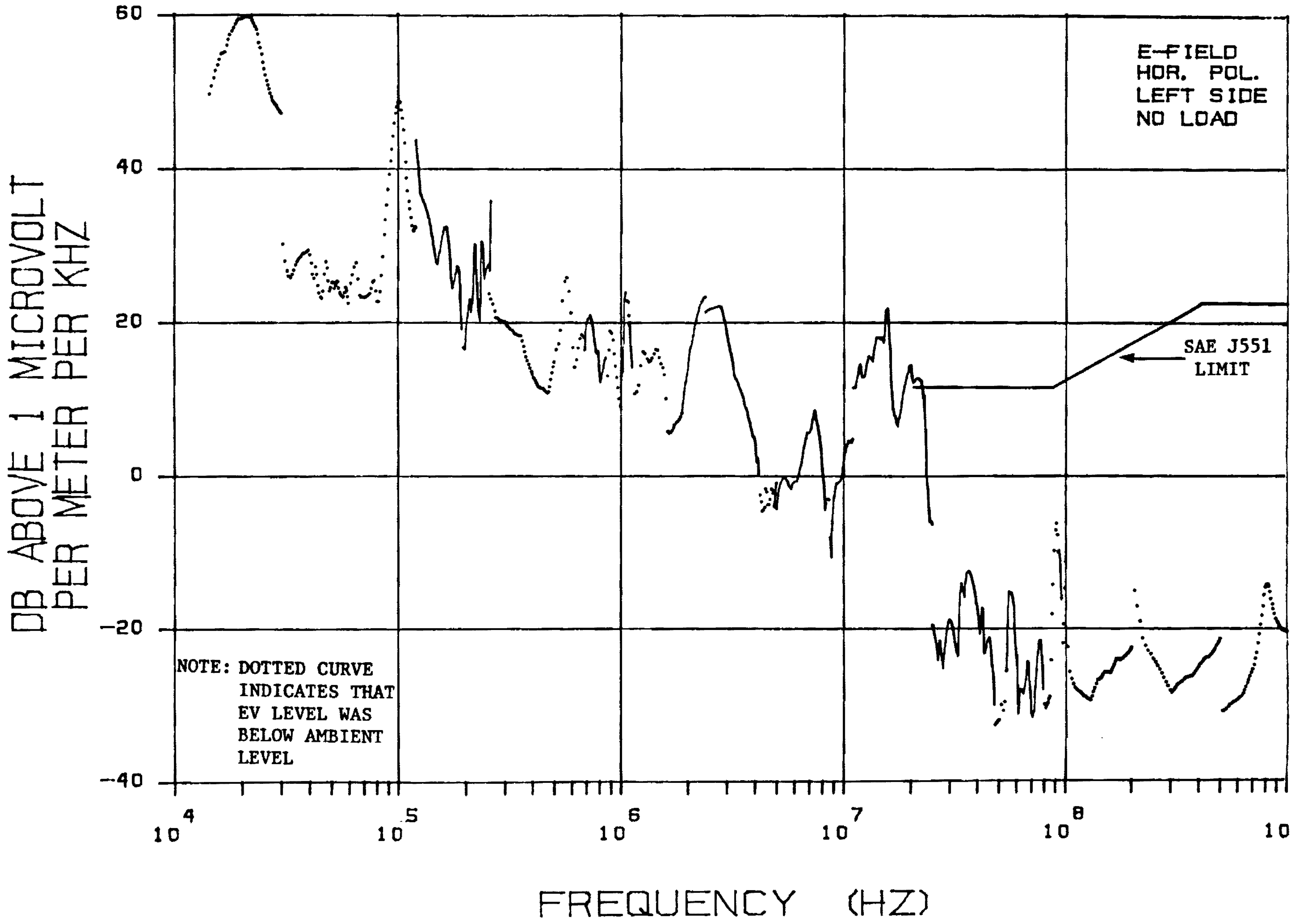
APPENDIX II

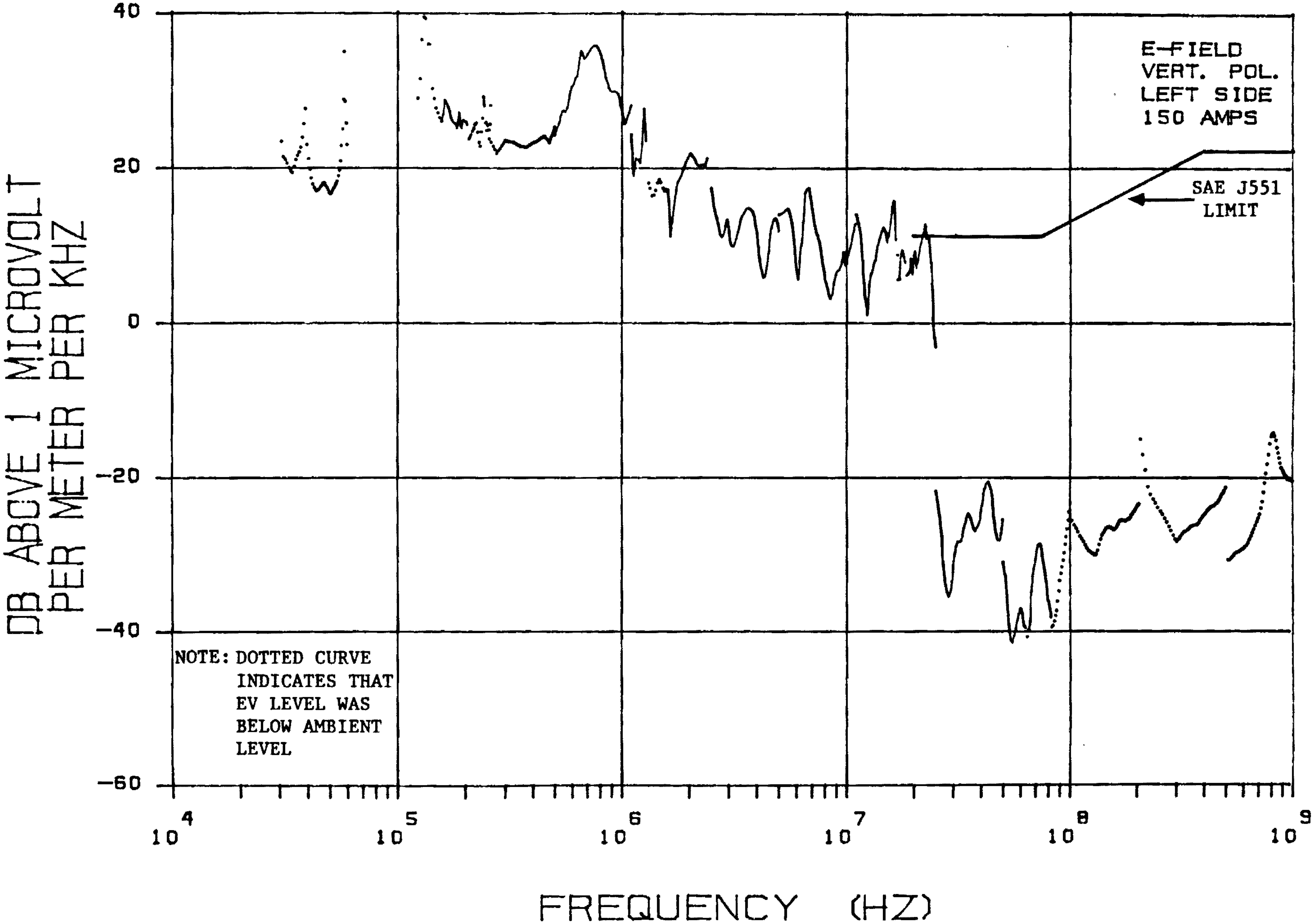
RADIATED EMISSIONS DATA

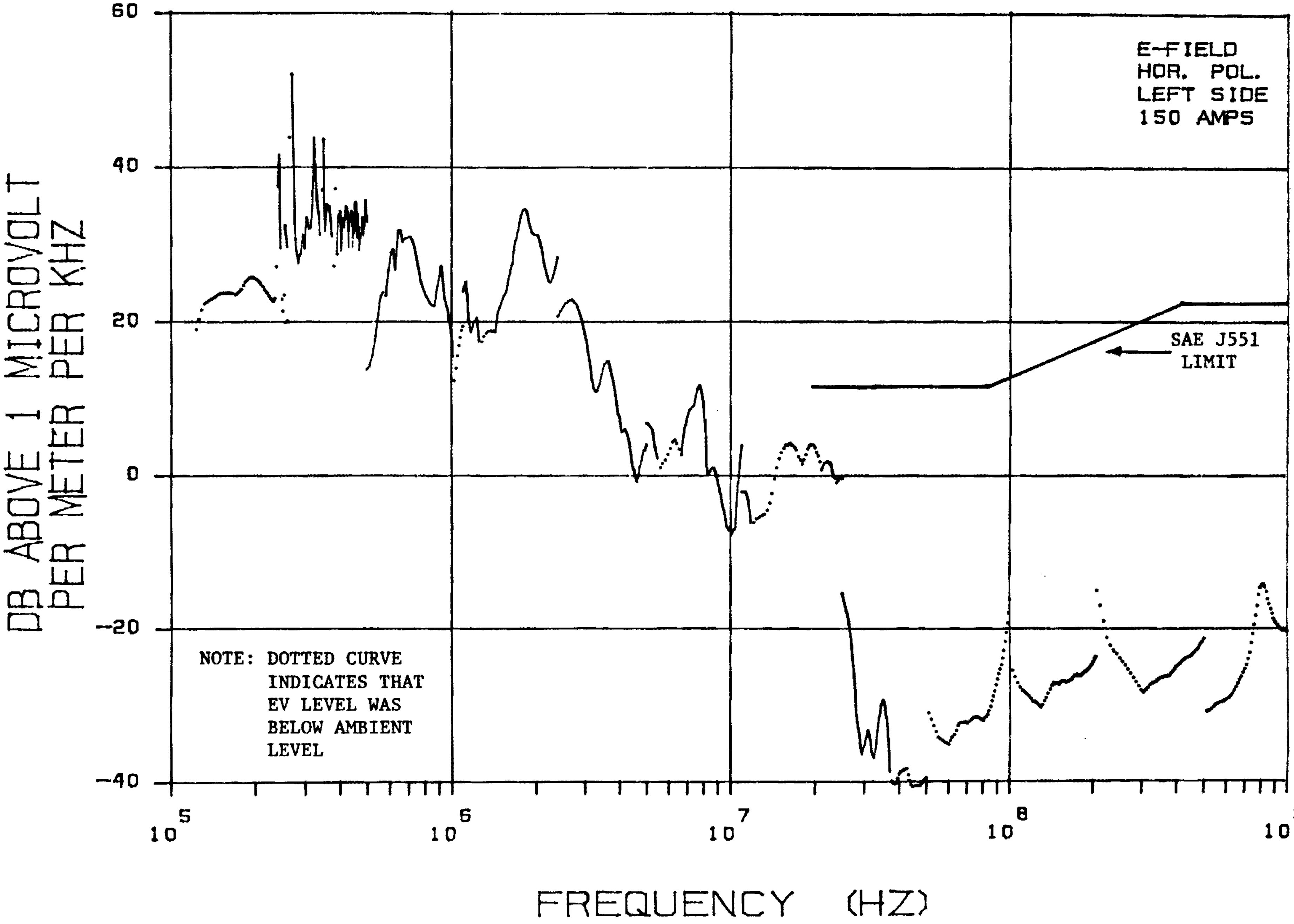
FOR

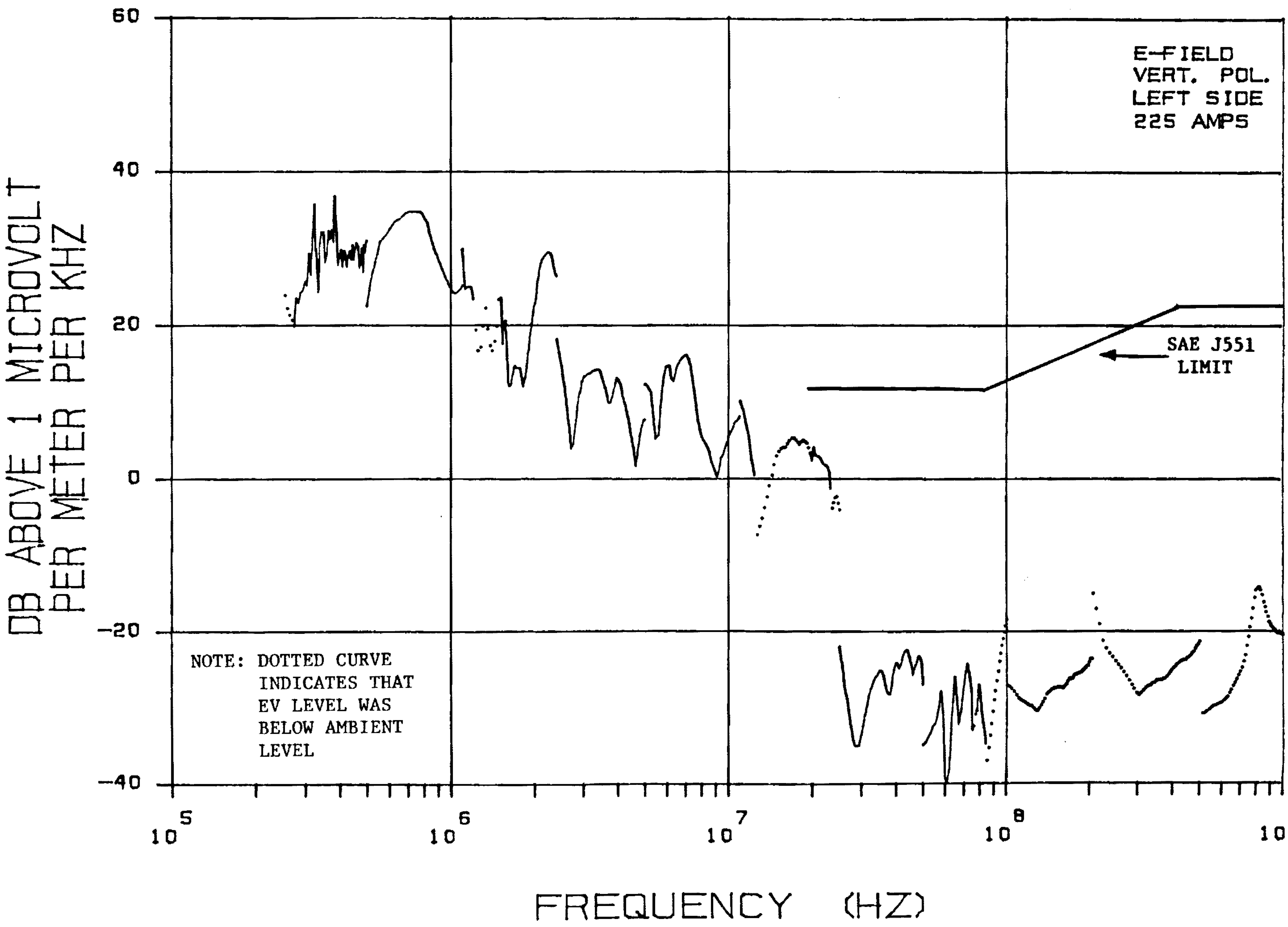
JET INDUSTRIES' ELECTRICA

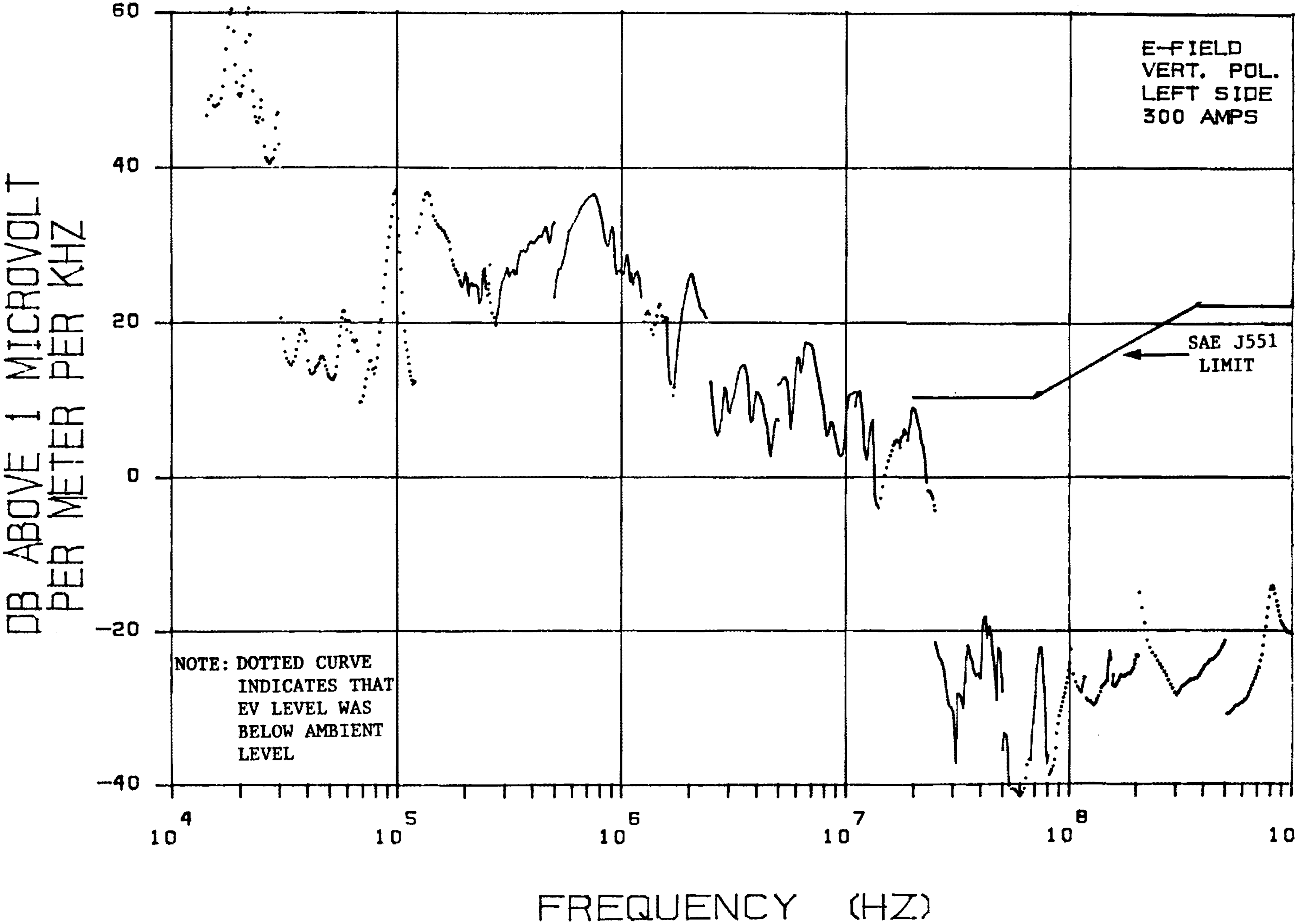

E-FIELD
VERT. POL.
LEFT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
DB ABOVE 1 MICROVOLT PER METER PER KHZ
60
40
20
0
-20
-40
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)


E-FIELD
HOR. POL.
LEFT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
DB ABOVE 1 MICROVOLT PER METER PER KHZ
60
40
20
0
-20
-40
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

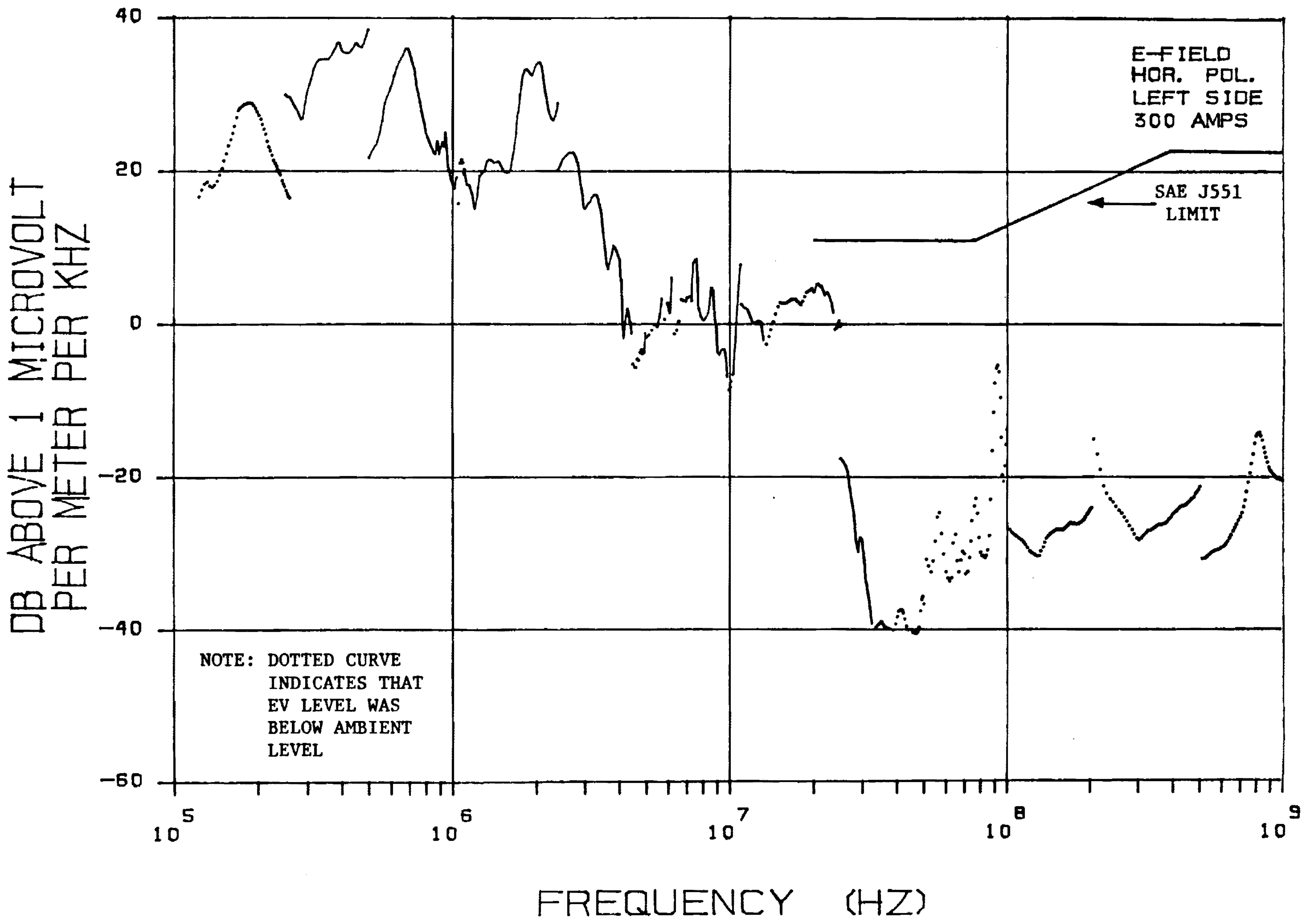

E-FIELD
VERT. POL.
LEFT SIDE
150 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
DB ABOVE 1 MICROVOLT PER METER PER KHZ
40
20
0
-20
-40
-60
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

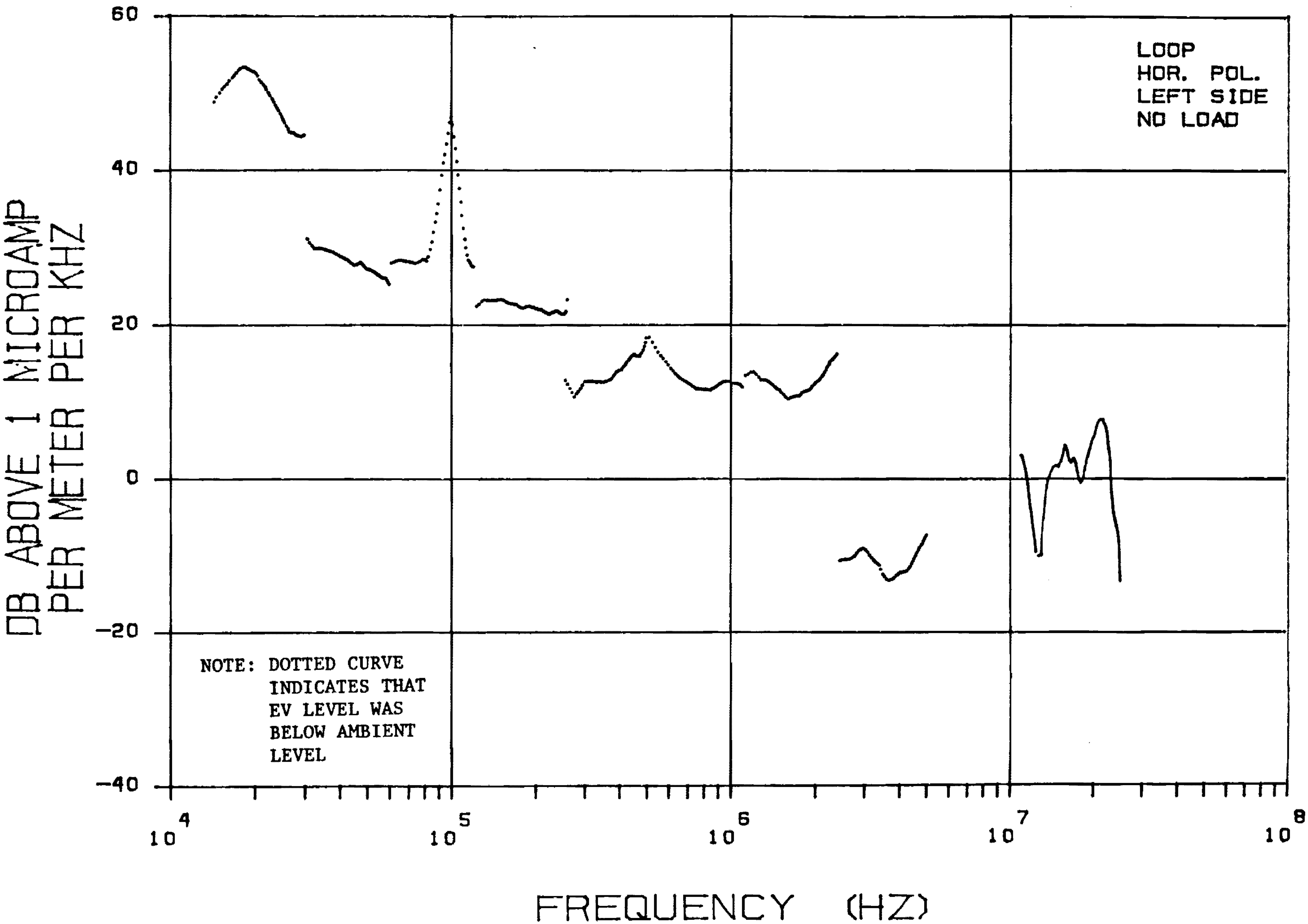

E-FIELD
HOR. POL.
LEFT SIDE
150 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
DB ABOVE 1 MICROVOLT PER METER PER KHZ
60
40
20
0
-20
-40
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

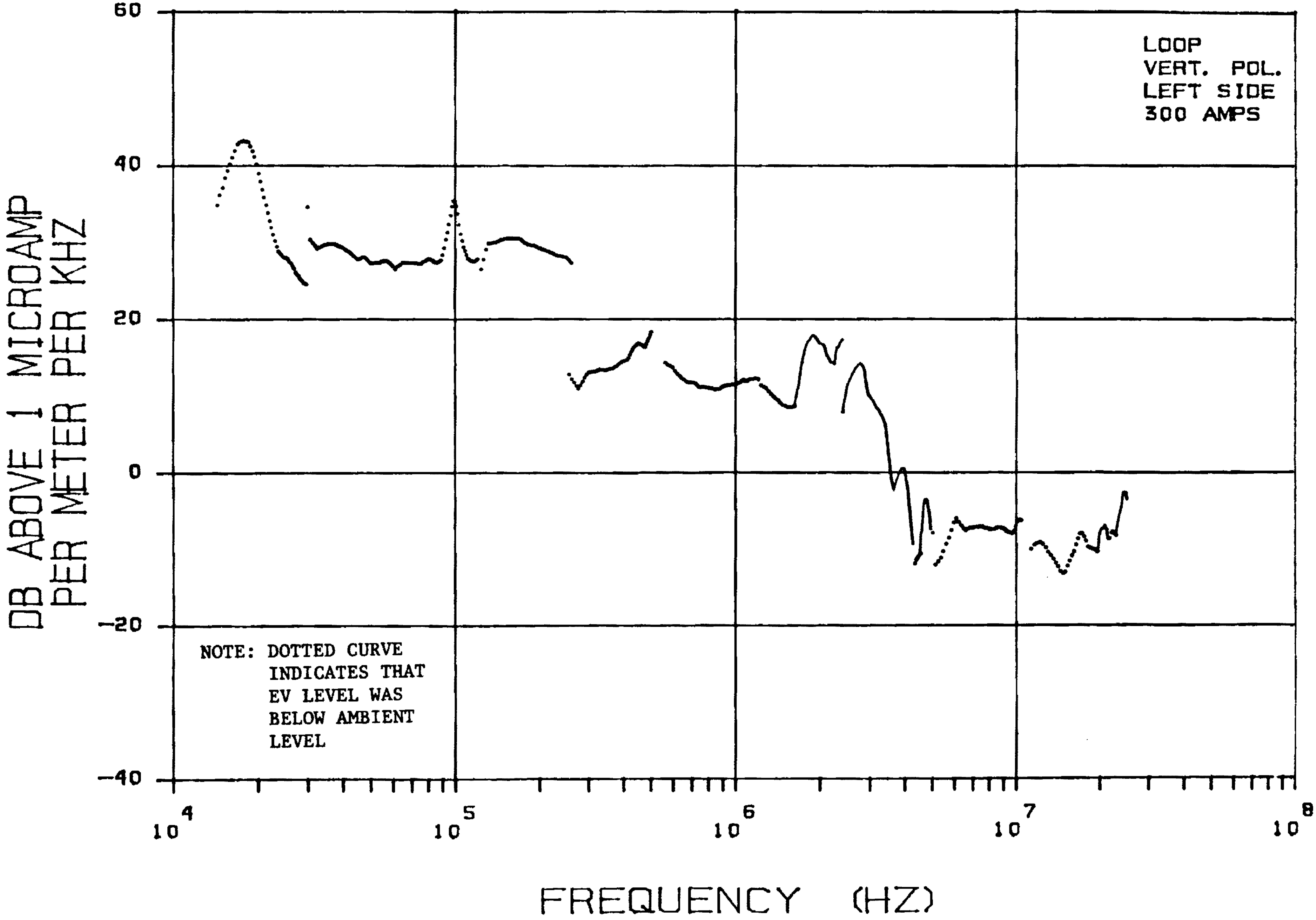

60
40
20
0
-20
-40
DB ABOVE 1 MICROVOLT PER METER PER KHZ
E-FIELD
VERT. POL.
LEFT SIDE
225 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)



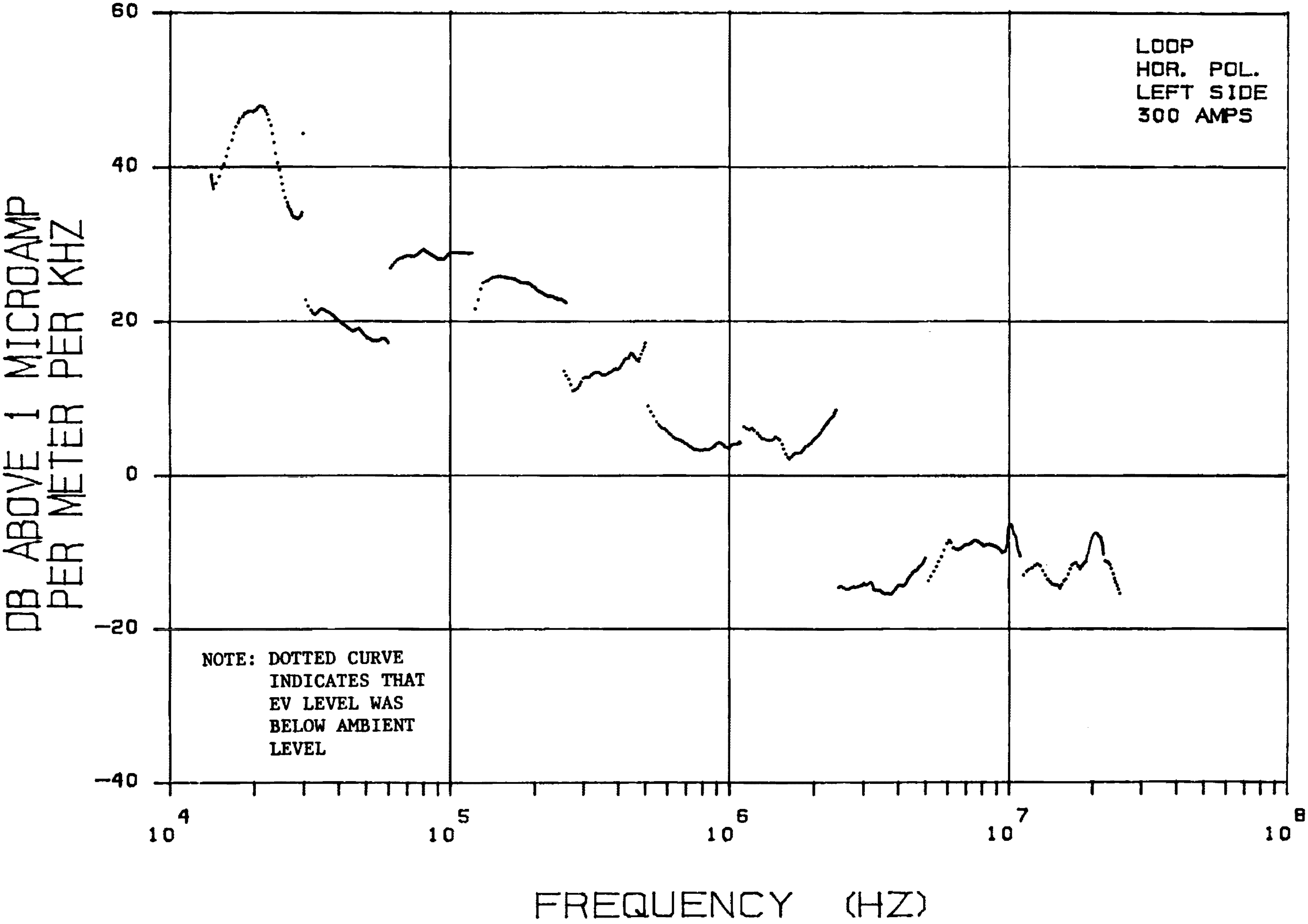
E-FIELD
VERT. POL.
LEFT SIDE
300 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
DB ABOVE 1 MICROVOLT PER METER PER KHZ
FREQUENCY (HZ)
60
40
20
0
-20
-40
10^4
10^5
10^6
10^7
10^8
10^9


40
20
0
-20
-40
-60
DB ABOVE 1 MICROVOLT PER METER PER KHZ
E-FIELD
HOR. POL.
LEFT SIDE
300 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

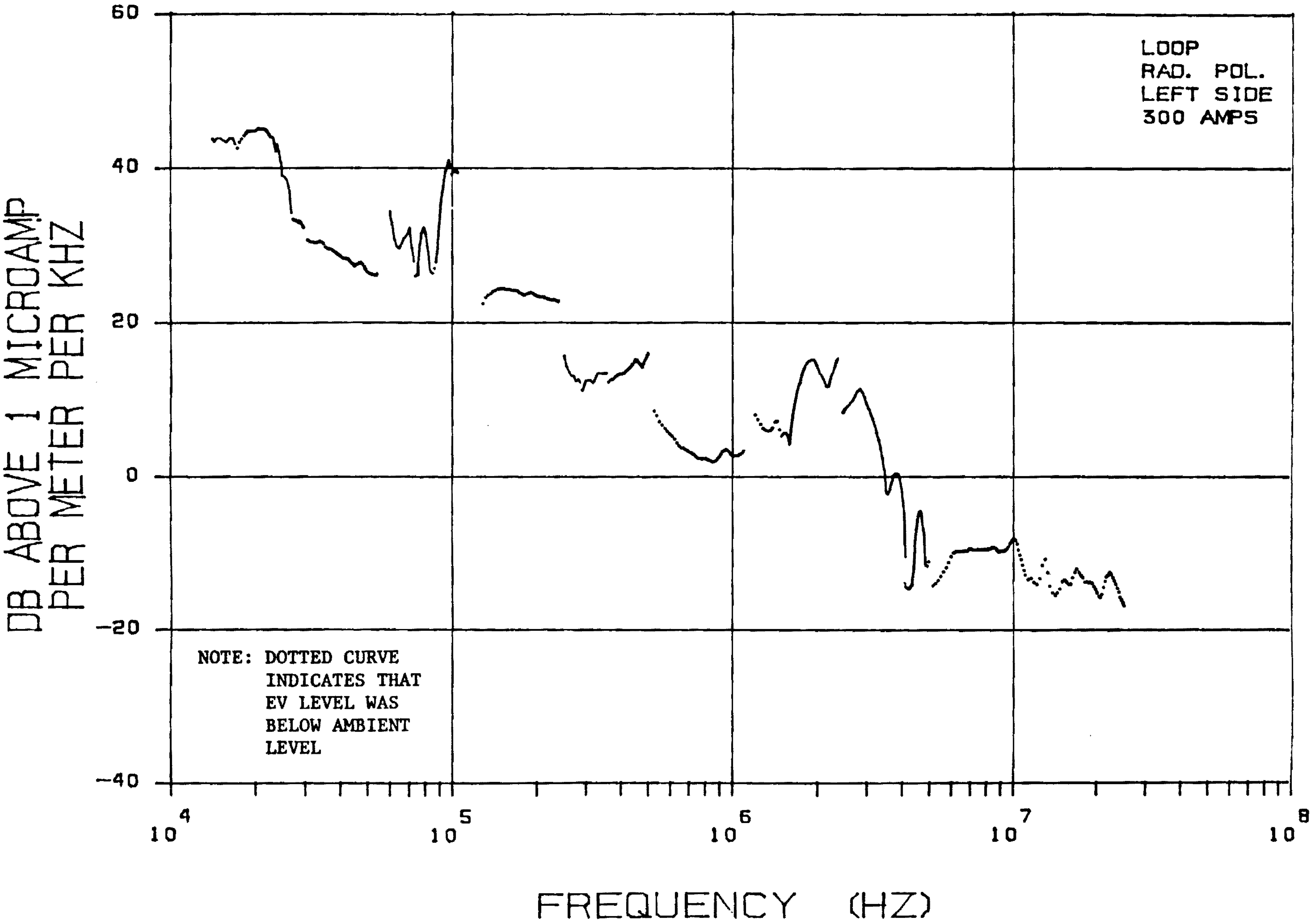

LOOP
HOR. POL.
LEFT SIDE
NO LOAD
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
DB ABOVE 1 MICROAMP PER METER PER KHZ
FREQUENCY (HZ)
60
40
20
0
-20
-40
10^4
10^5
10^6
10^7
10^8



LOOP
VERT. POL.
LEFT SIDE
300 AMPS
60
40
20
0
-20
-40
DB ABOVE 1 MICROAMP PER METER PER KHZ
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL

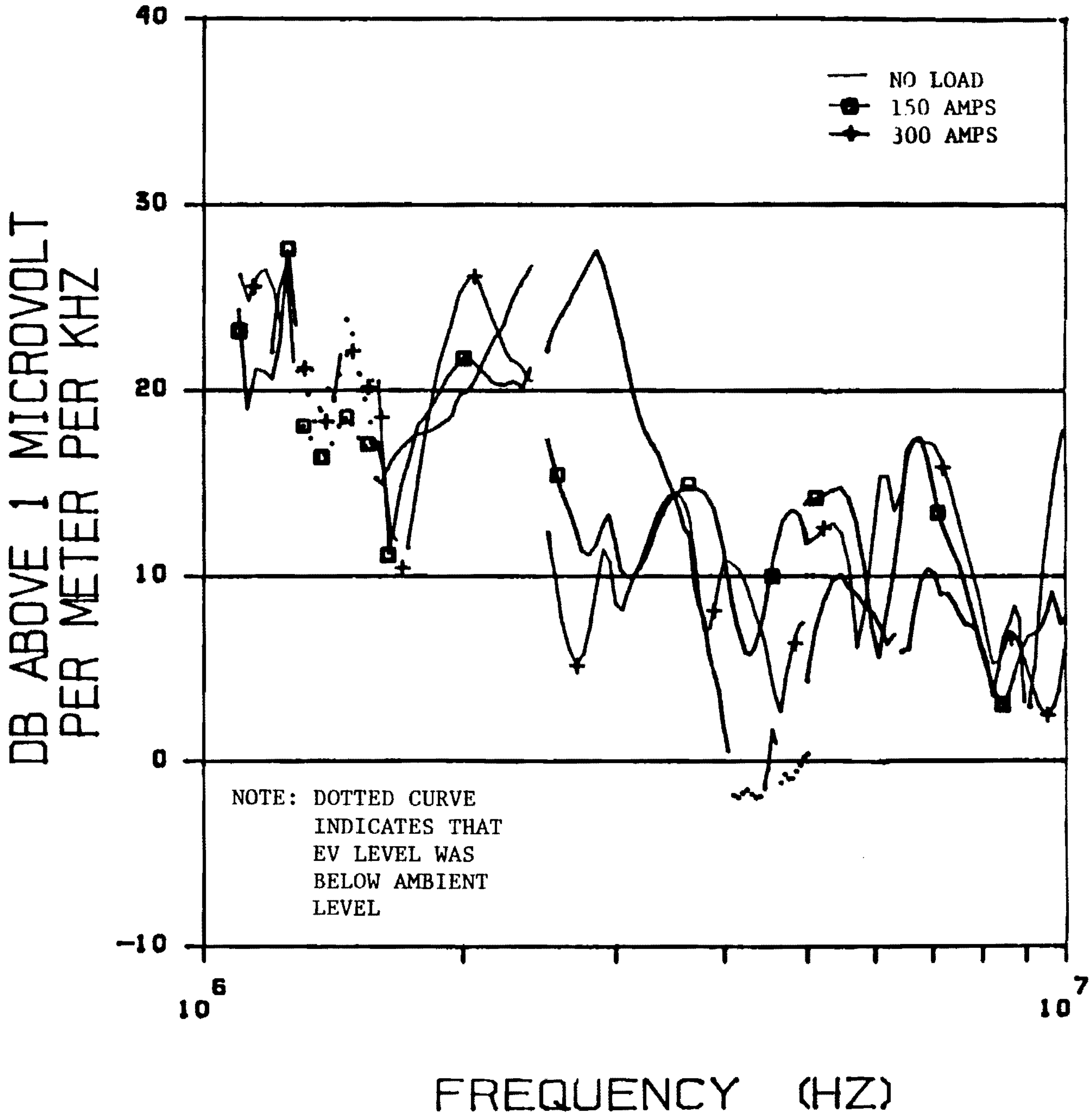


60
40
20
0
-20
-40
DB ABOVE 1 MICROAMP PER METER PER KHZ
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)
LOOP
HOR. POL.
LEFT SIDE
300 AMPS
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL

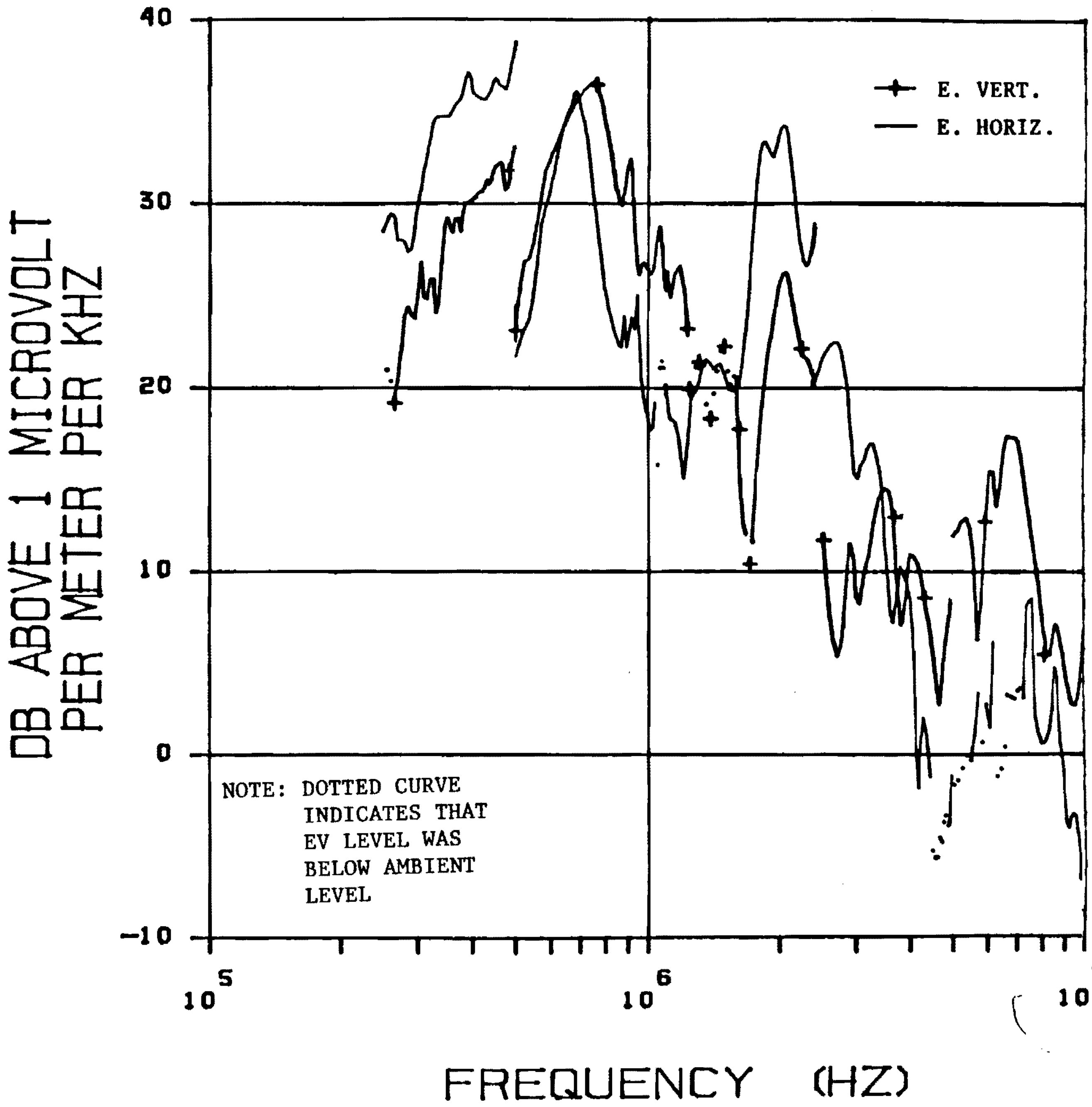


60
40
20
0
-20
-40
DB ABOVE 1 MICROAMP PER METER PER KHZ
LOOP
RAD. POL.
LEFT SIDE
300 AMPS
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT LEVEL
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

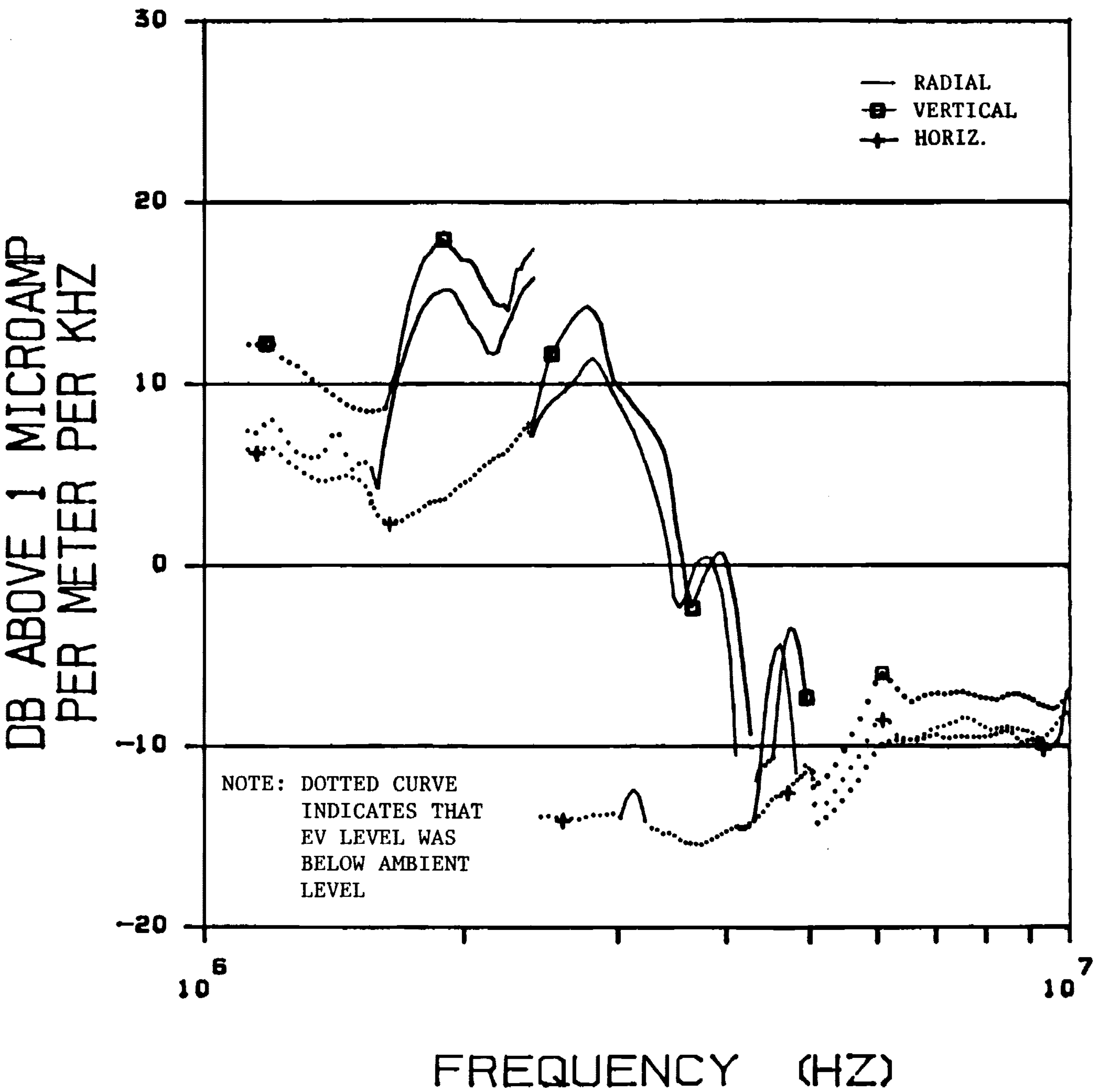
ROD
VERT. POL.
LEFT SIDE



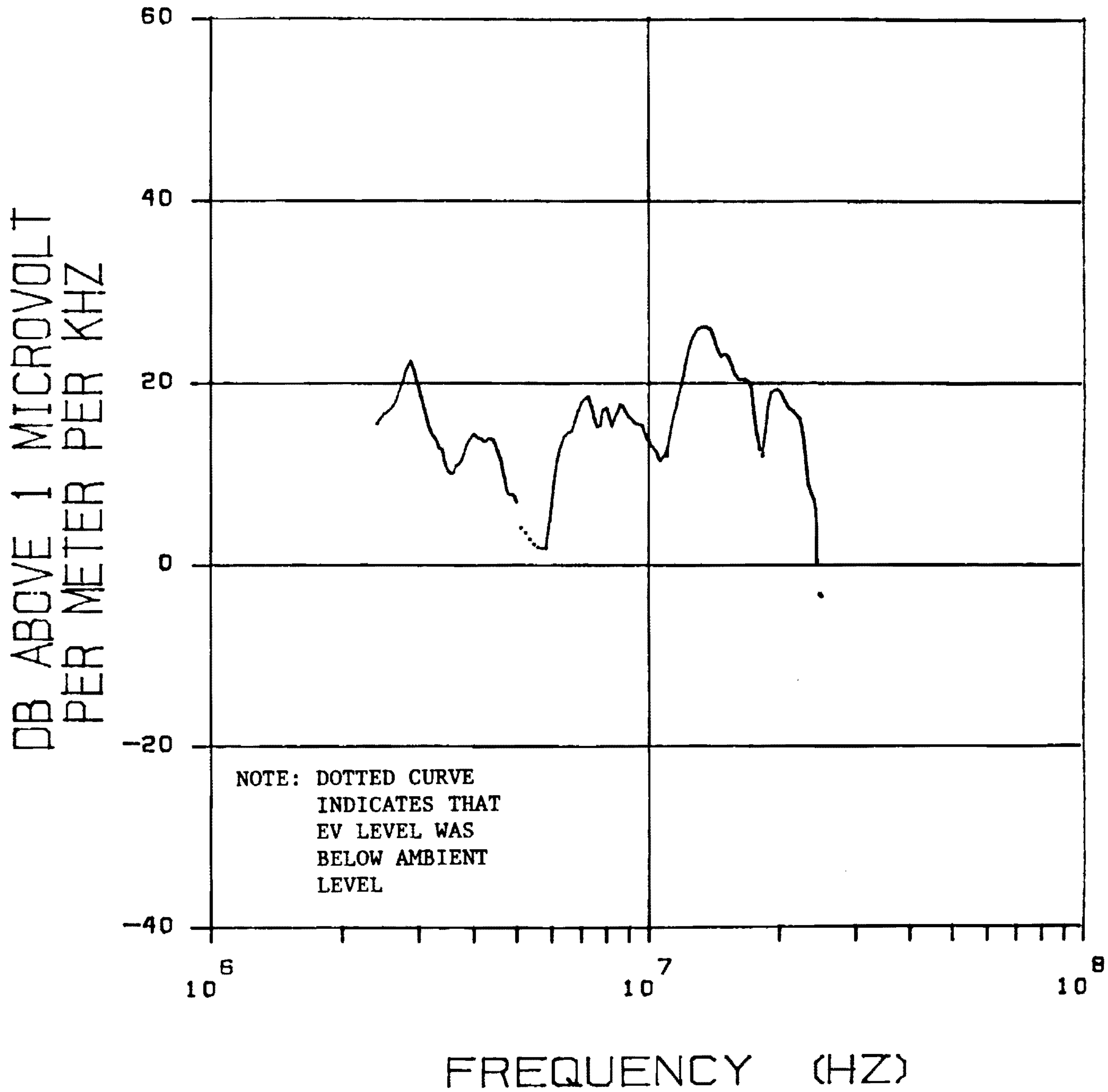
ROD
LEFT SIDE
300 AMPS

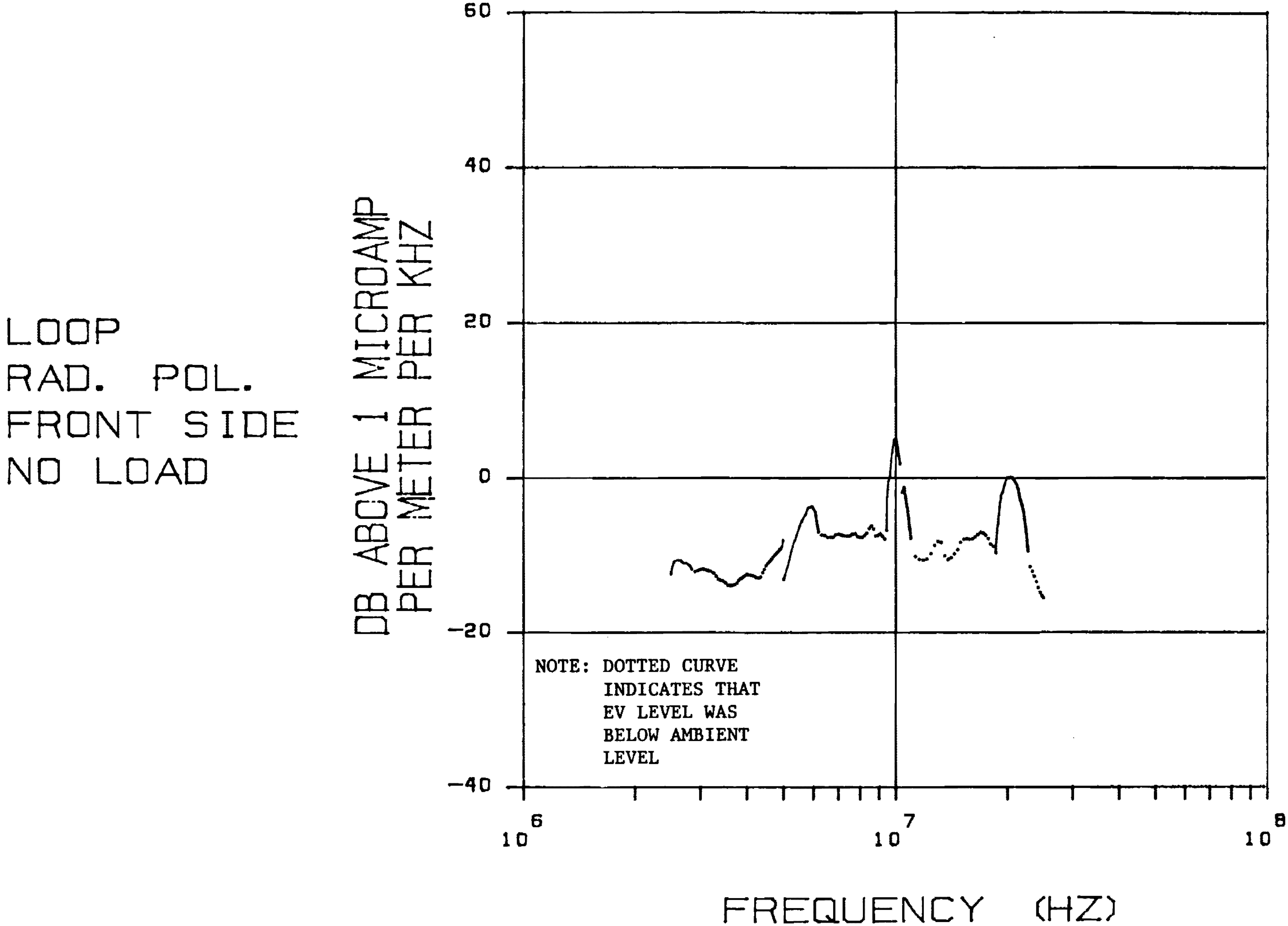


LOOP
LEFT SIDE
300 AMPS

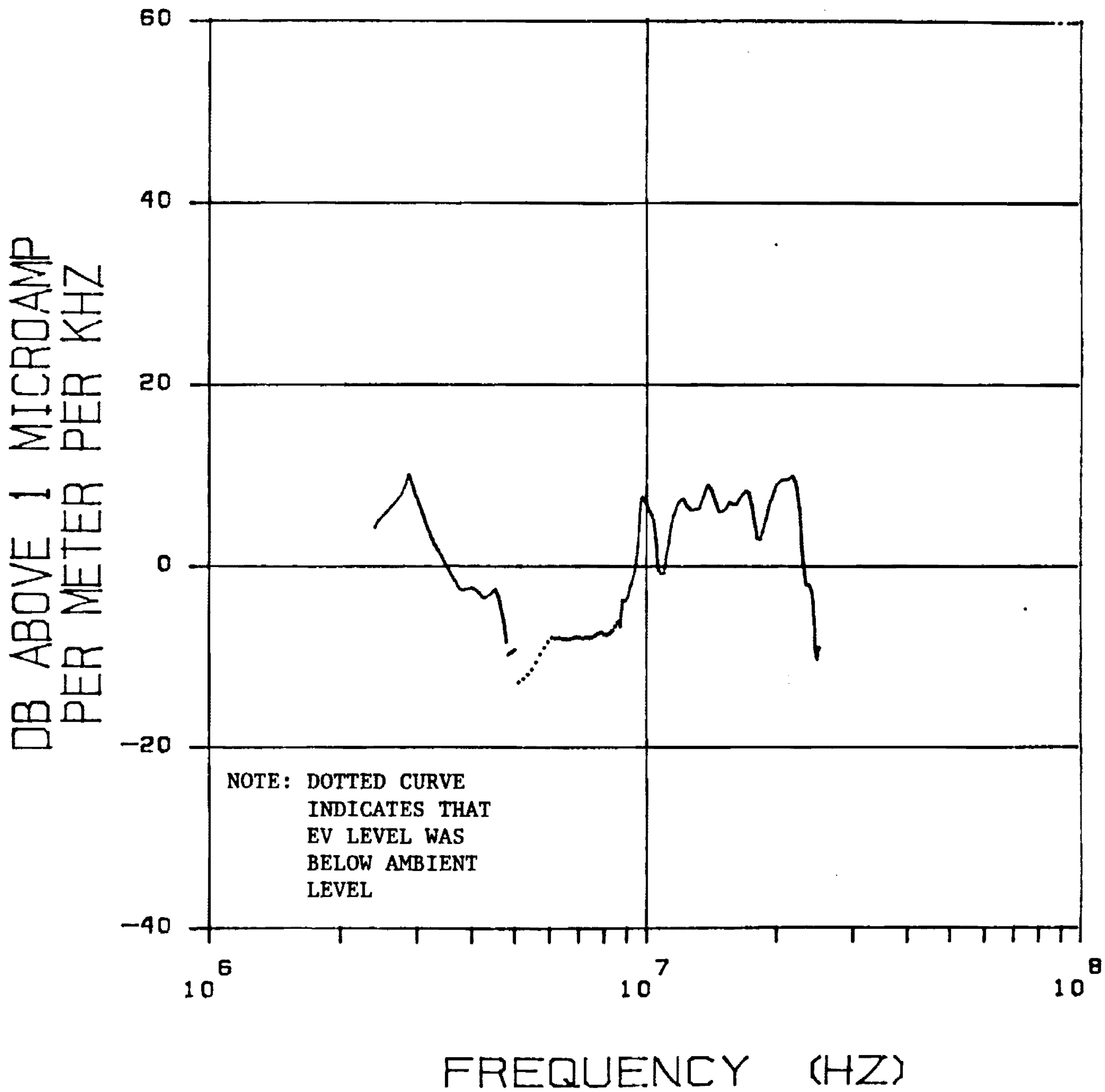


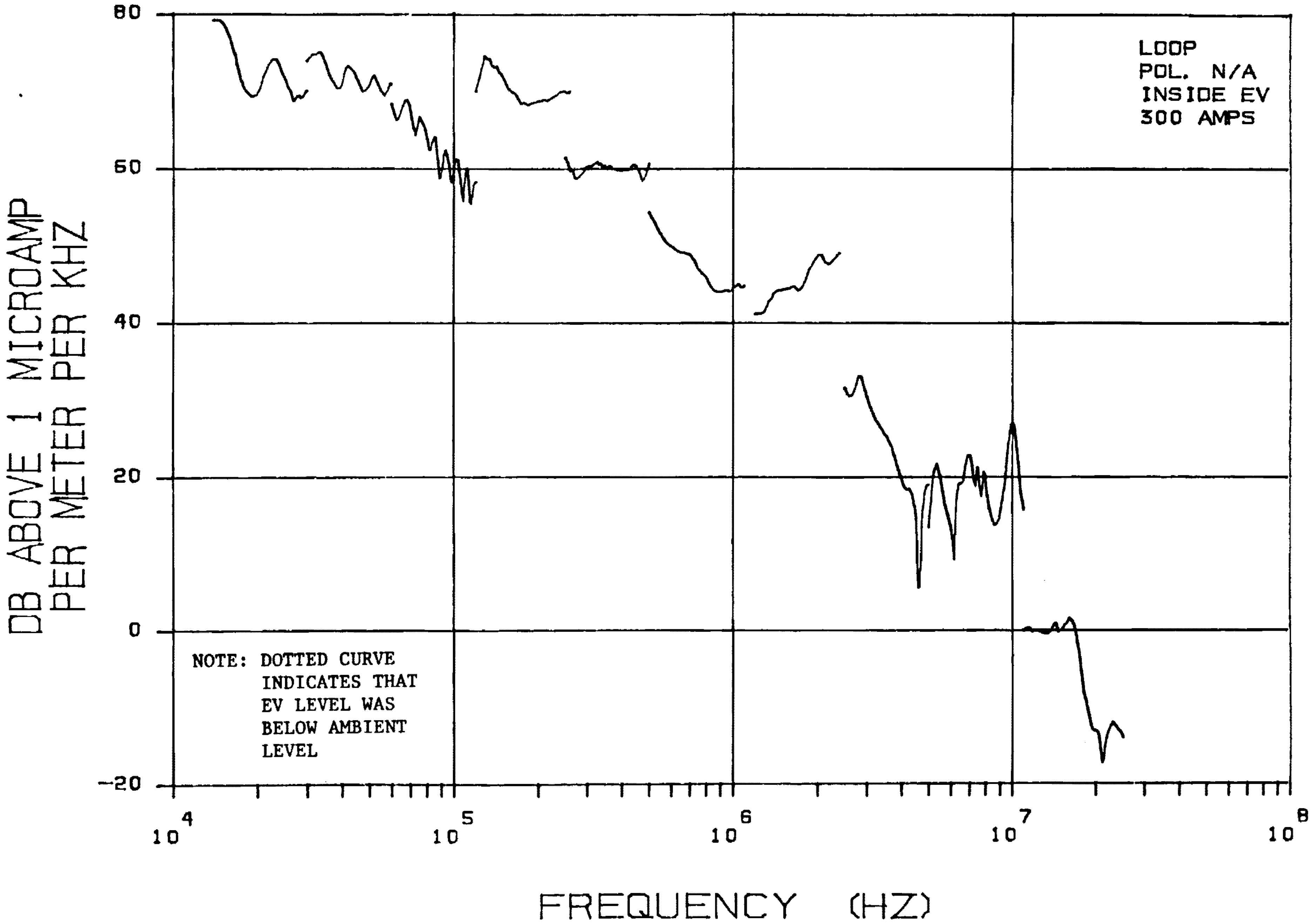
ROD
VERT. POL.
FRONT SIDE
NO LOAD

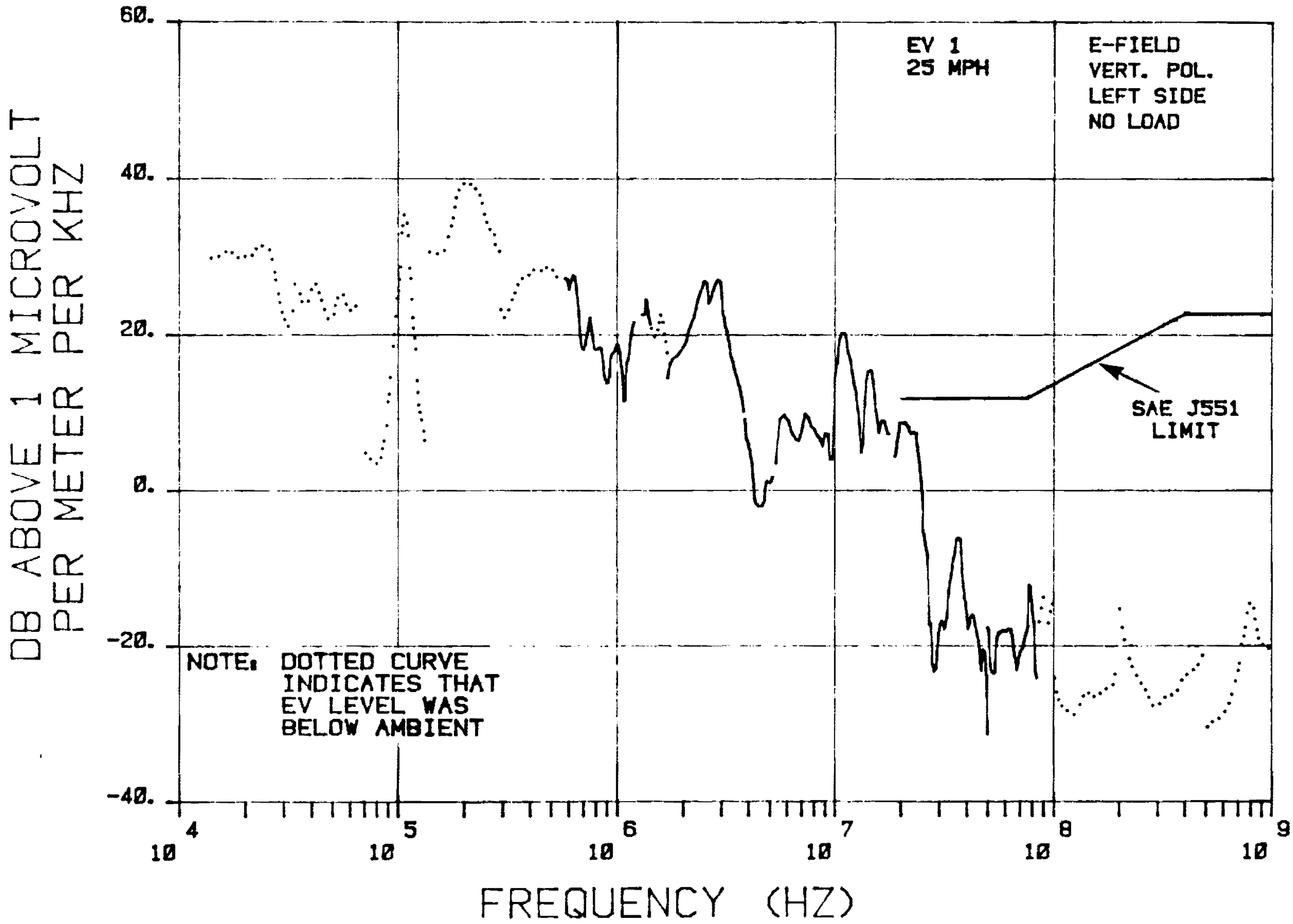


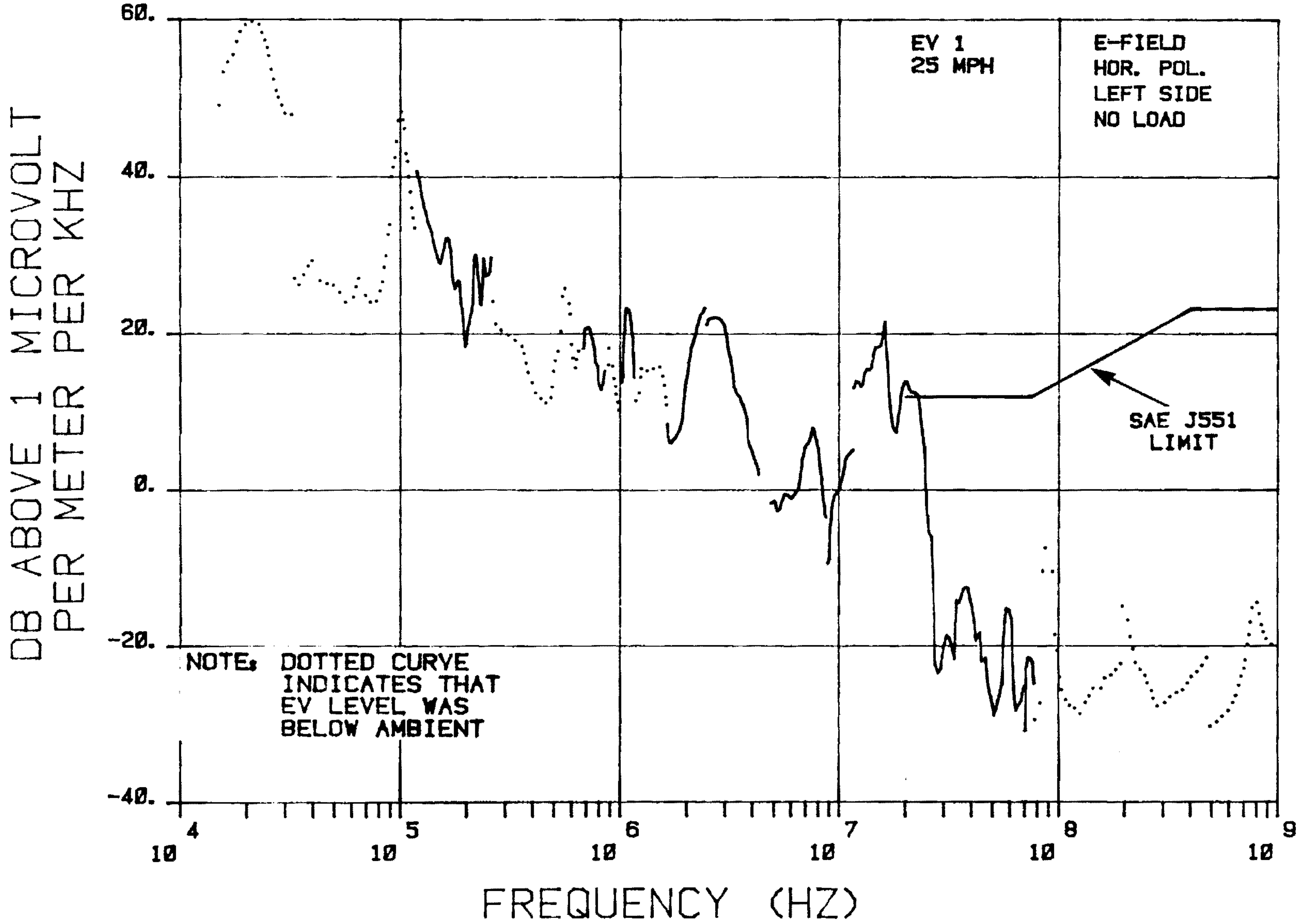

LOOP
RAD. POL.
FRONT SIDE
NO LOAD
DB ABOVE 1 MICROAMP
PER METER PER KHZ
60
40
20
0
-20
-40
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
LEVEL
10^6
10^7
10^8
FREQUENCY (HZ)

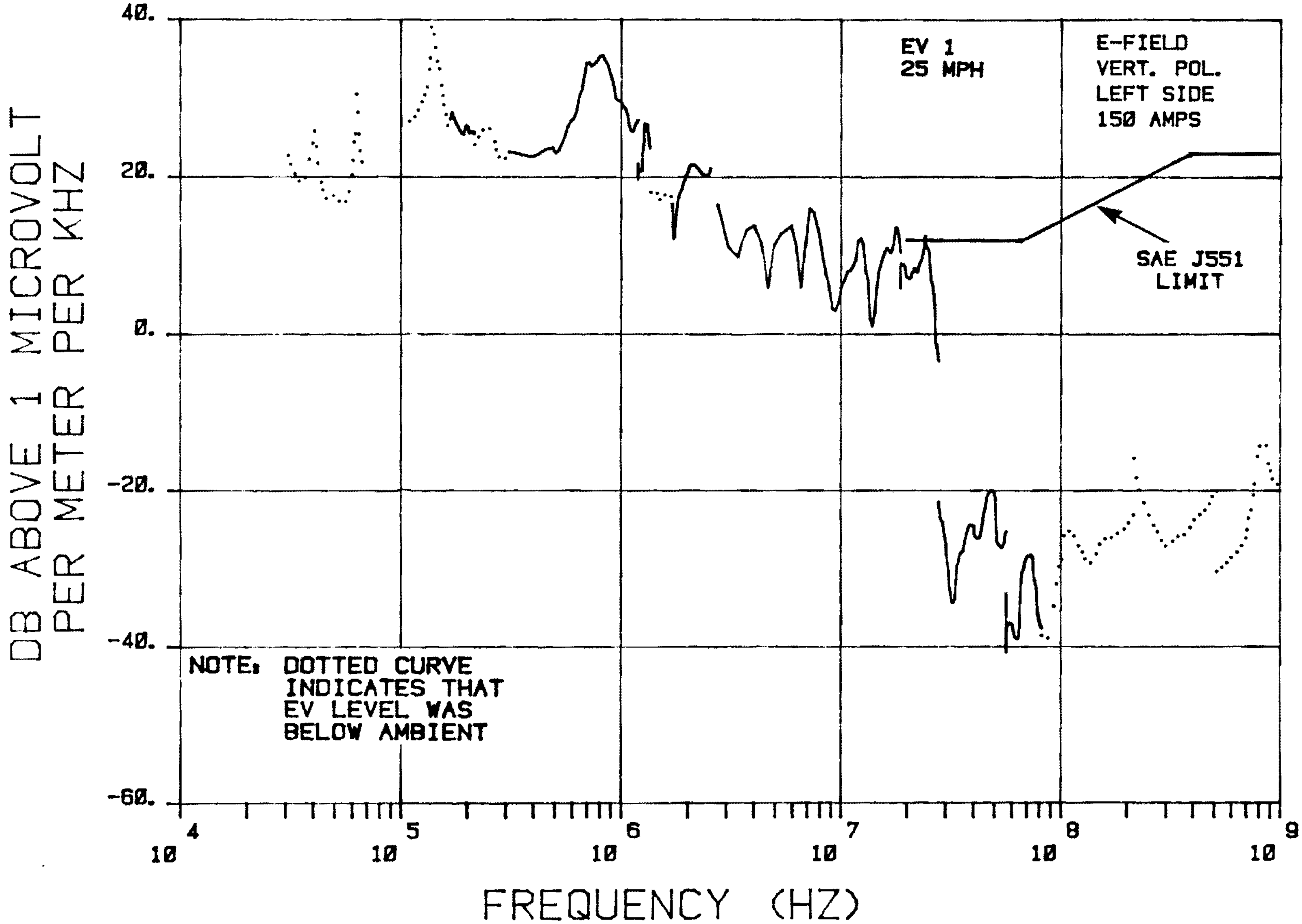
LOOP
HOR. POL.
FRONT SIDE
NO LOAD

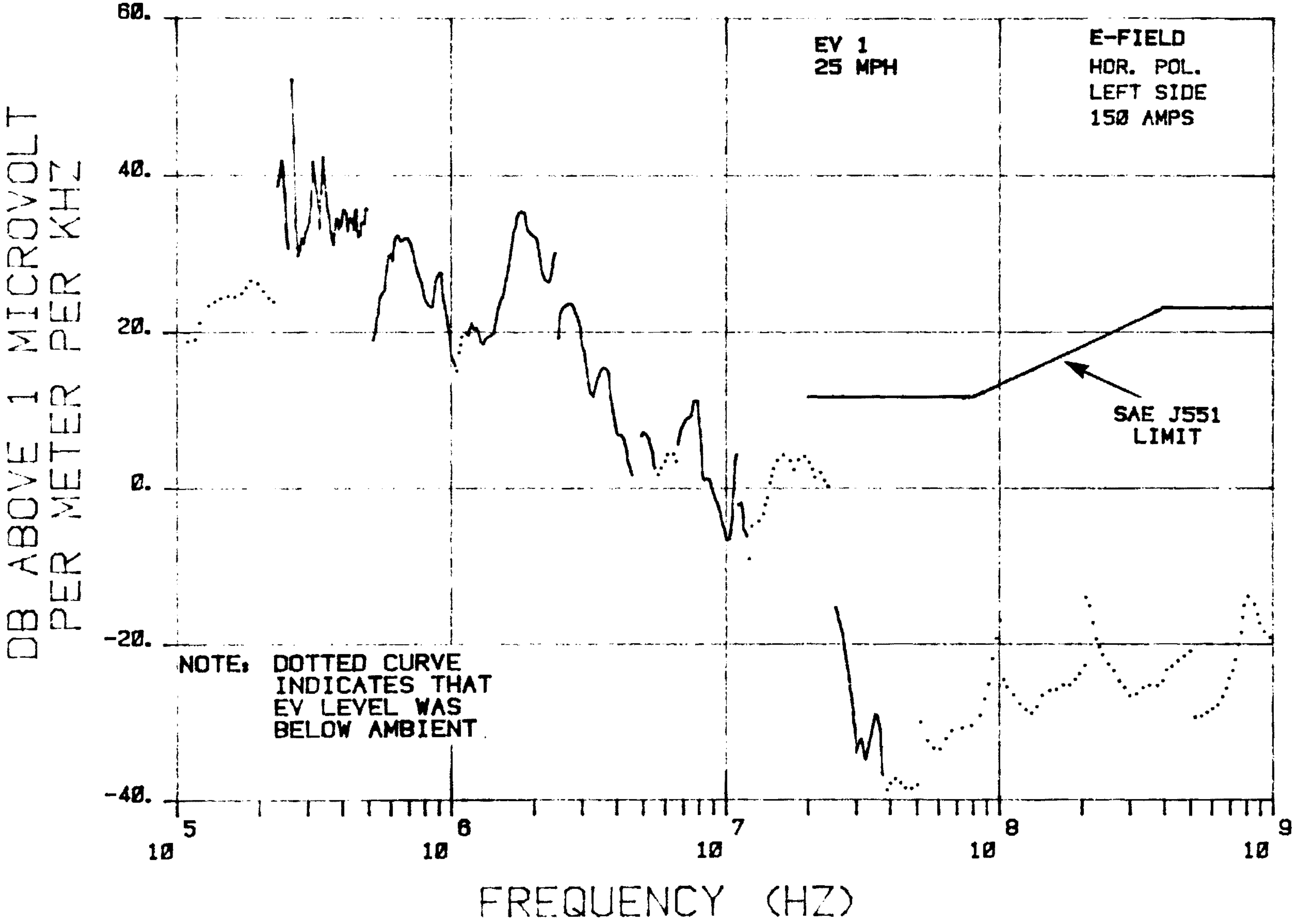


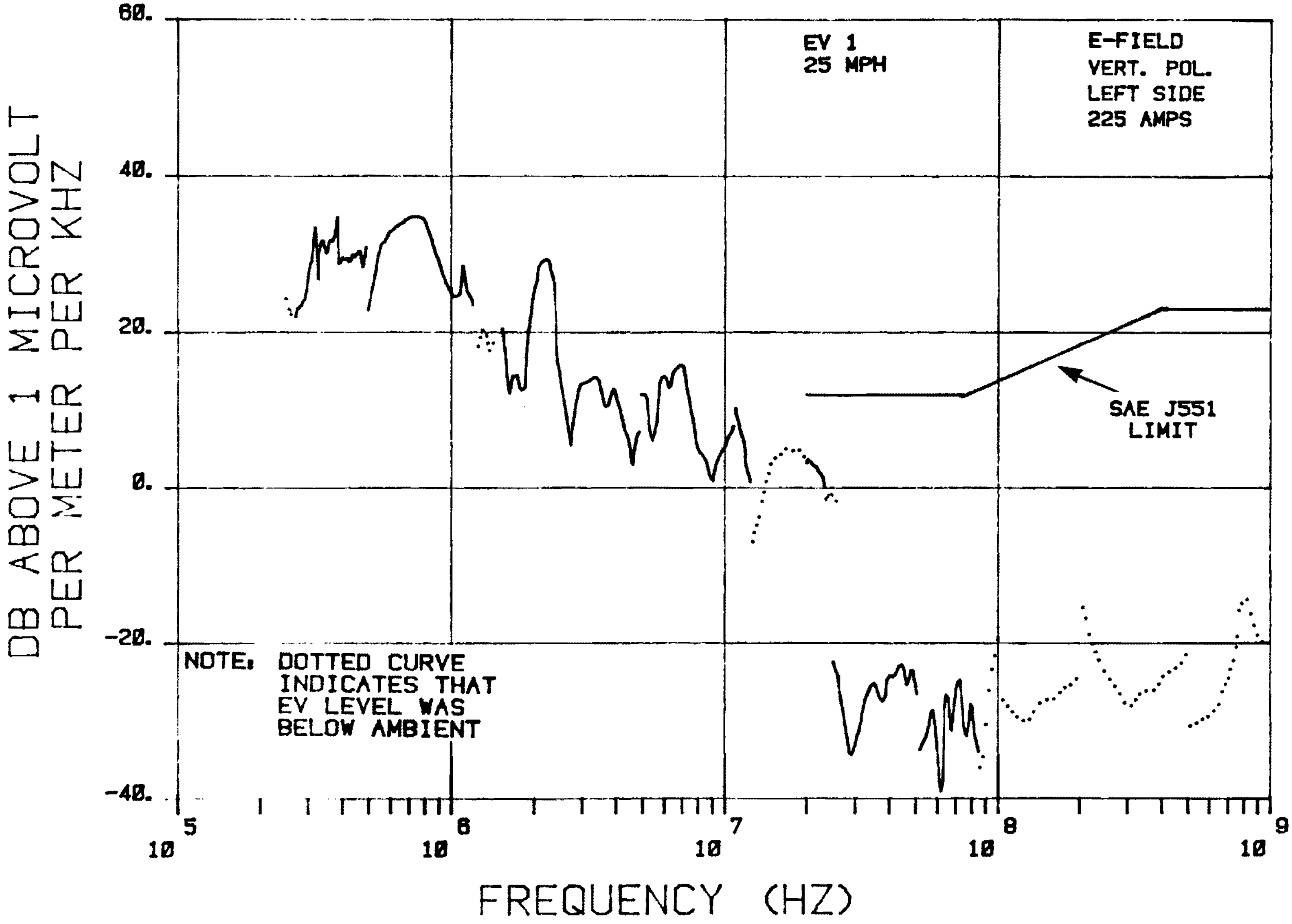

80
60
40
20
0
-20
DB ABOVE 1 MICROAMP
PER METER PER KHZ
LOOP
POL. N/A
INSIDE EV
300 AMPS
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
LEVEL
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

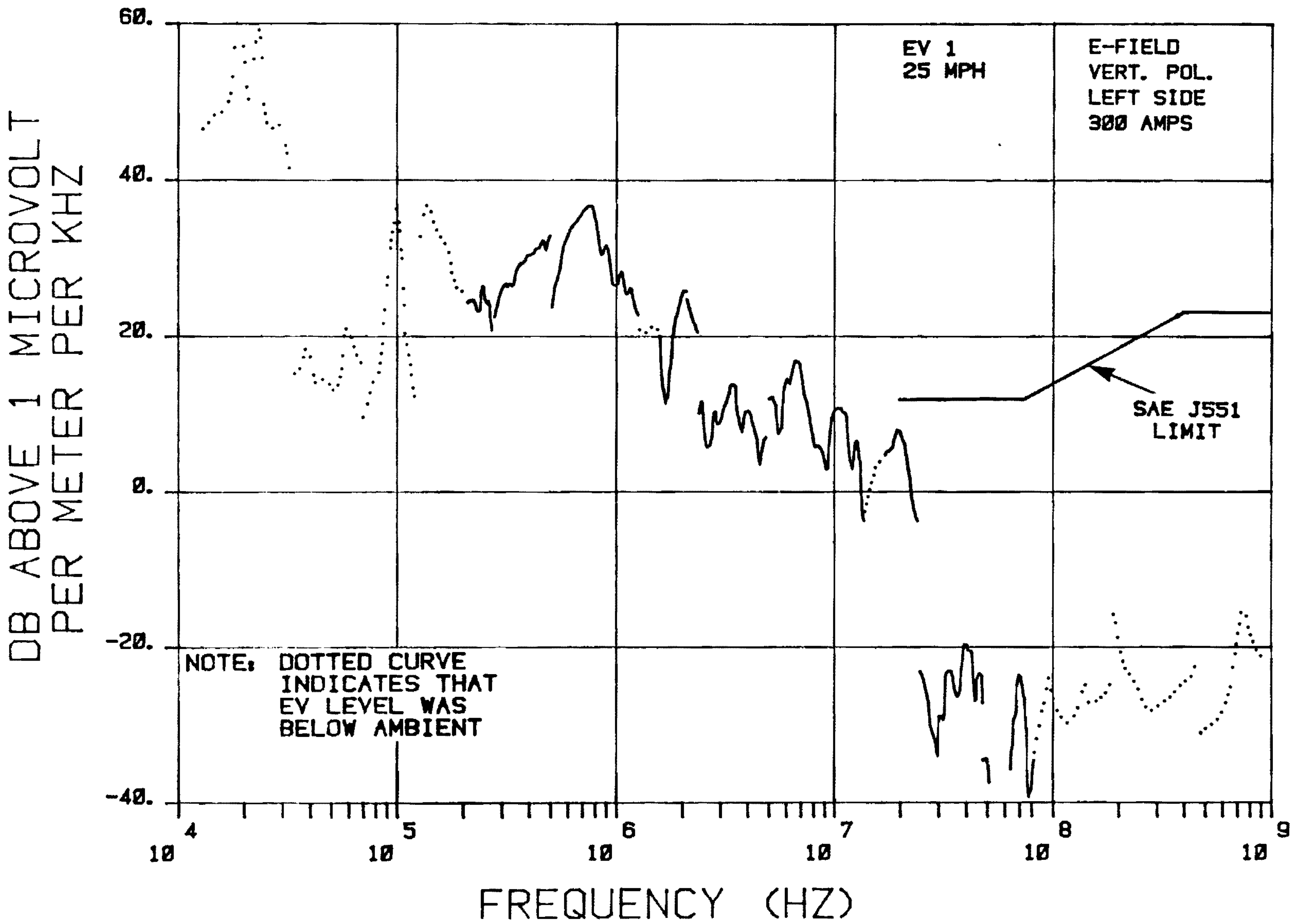

EV 1
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROVOLT PER METER PER KHZ
60.
40.
20.
0.
-20.
-40.
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

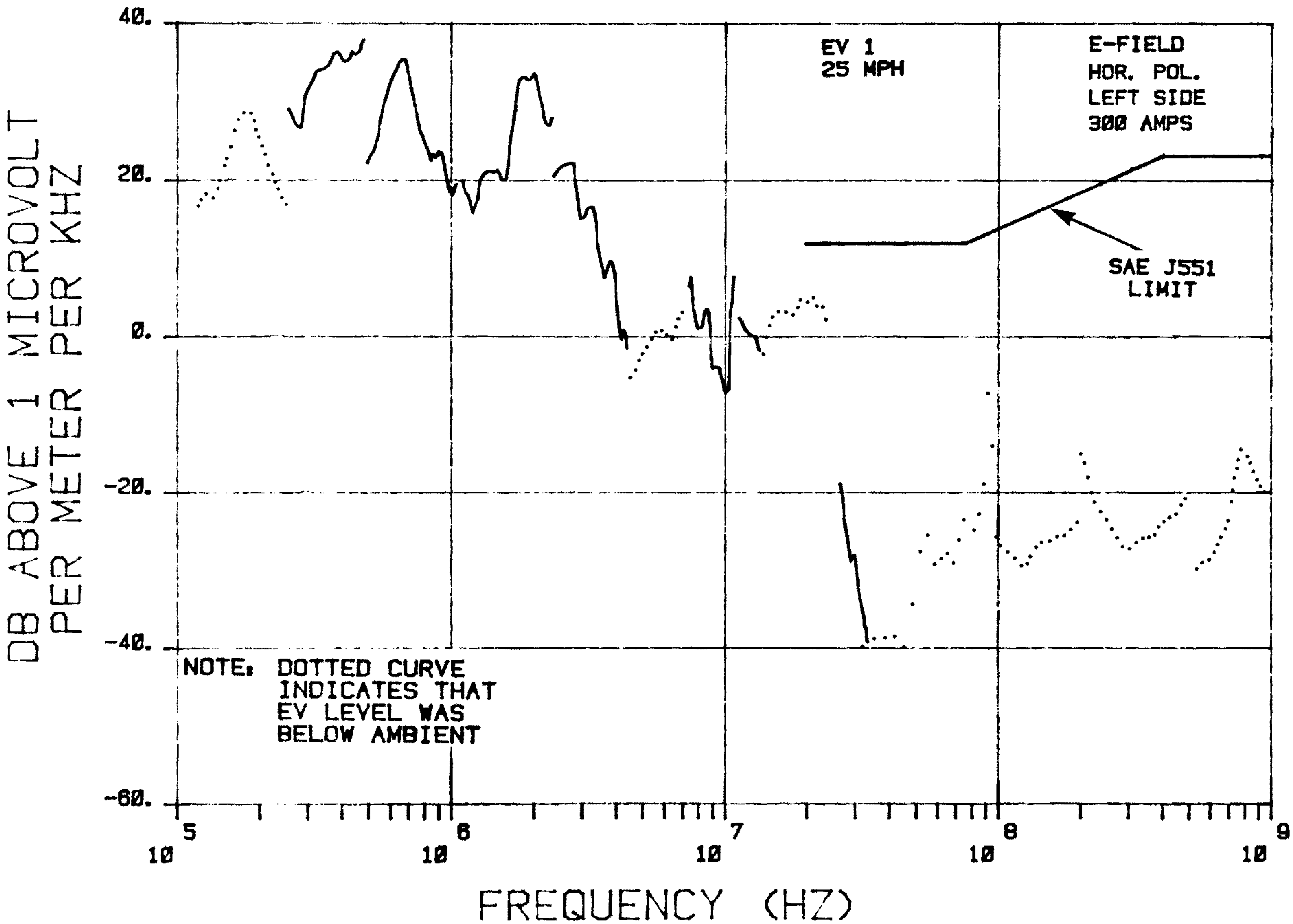

60.
40.
20.
0.
-20.
-40.
DB ABOVE 1 MICROVOLT PER METER PER KHZ
EV 1
25 MPH
E-FIELD
HOR. POL.
LEFT SIDE
NO LOAD
SAE J551 LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4 10^5 10^6 10^7 10^8 10^9
FREQUENCY (HZ)

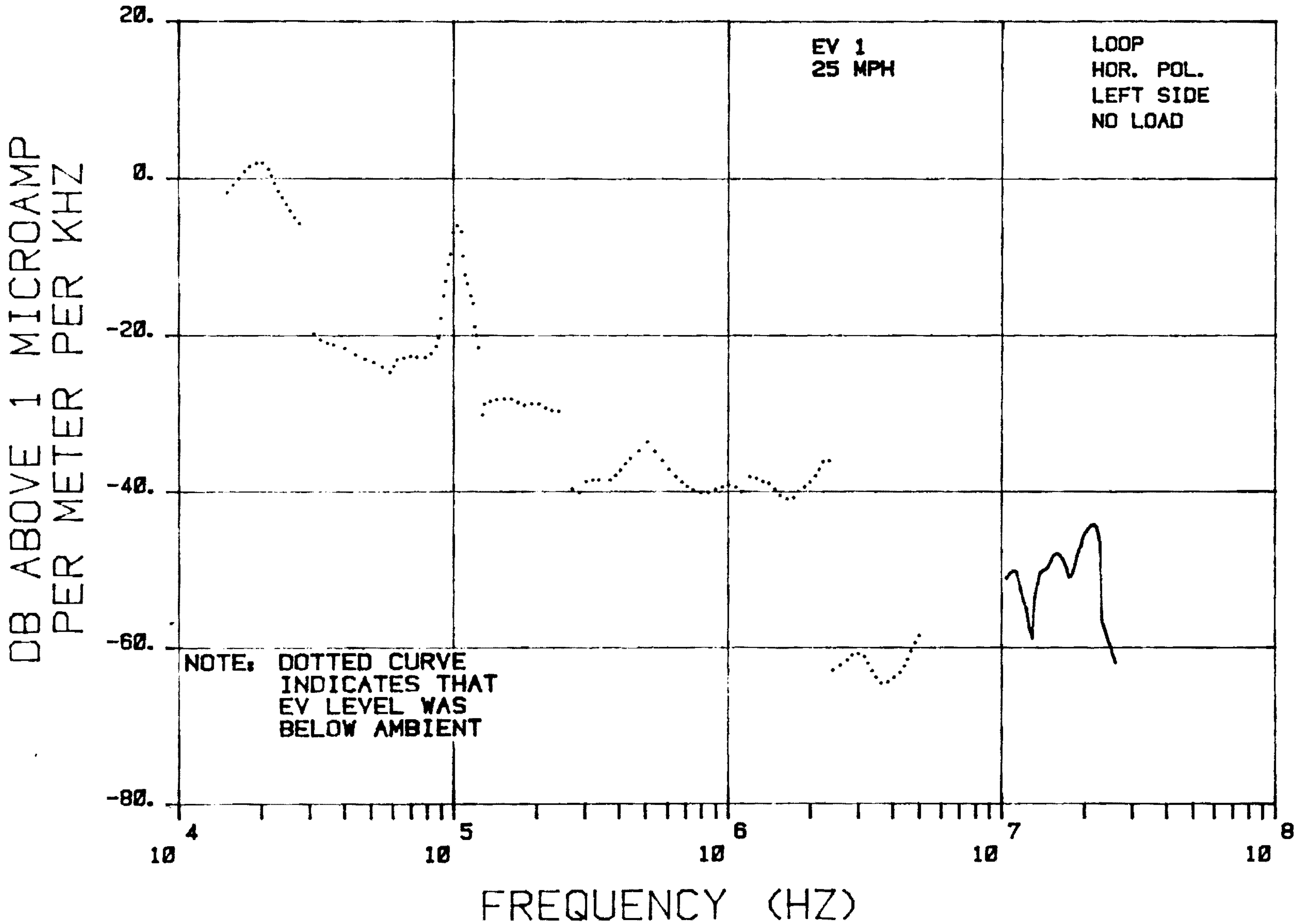

EV 1
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
150 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
40.
20.
0.
-20.
-40.
-60.
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

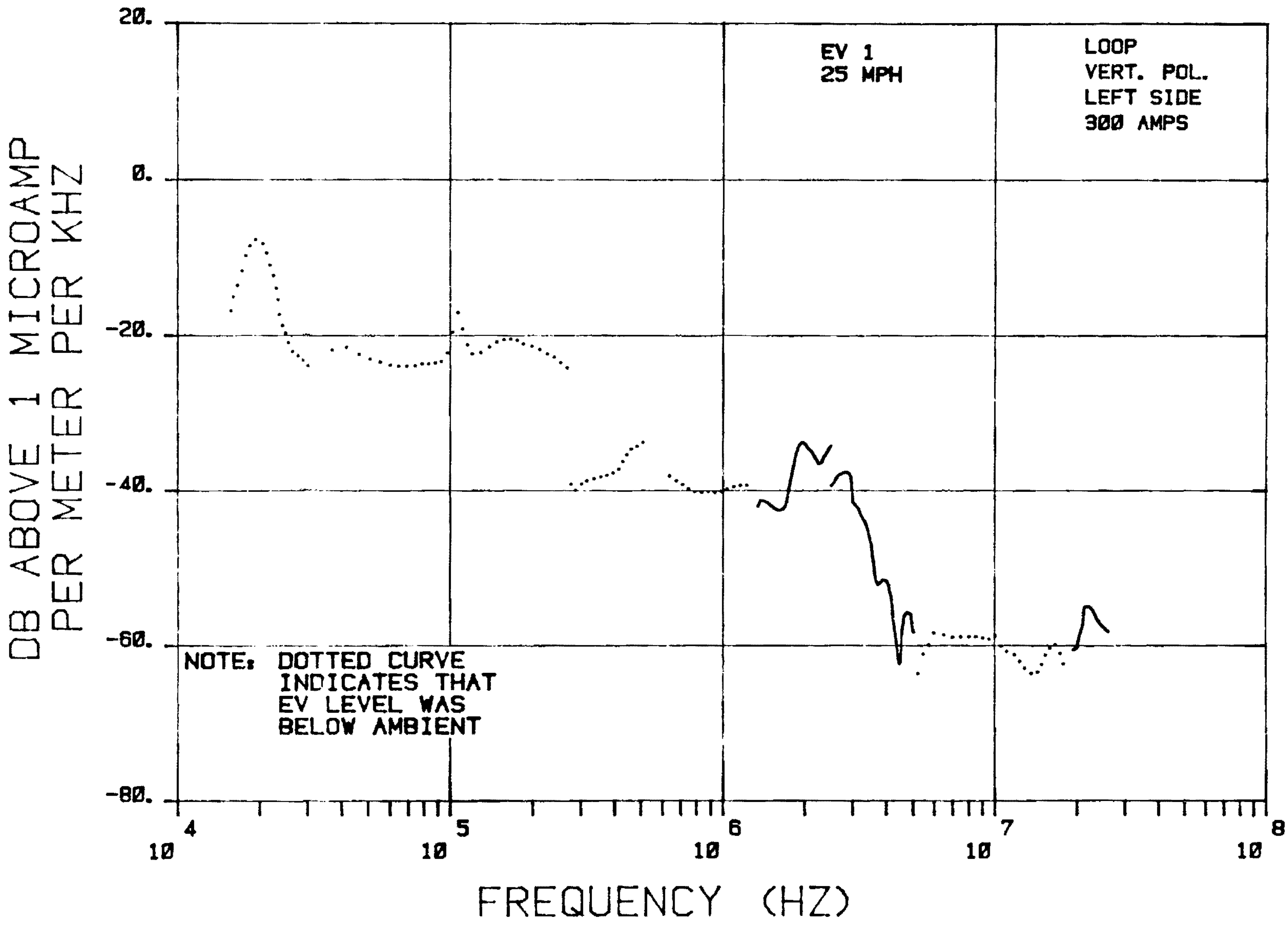

EV 1
25 MPH
E-FIELD
HOR. POL.
LEFT SIDE
150 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
60.
40.
20.
0.
-20.
-40.
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

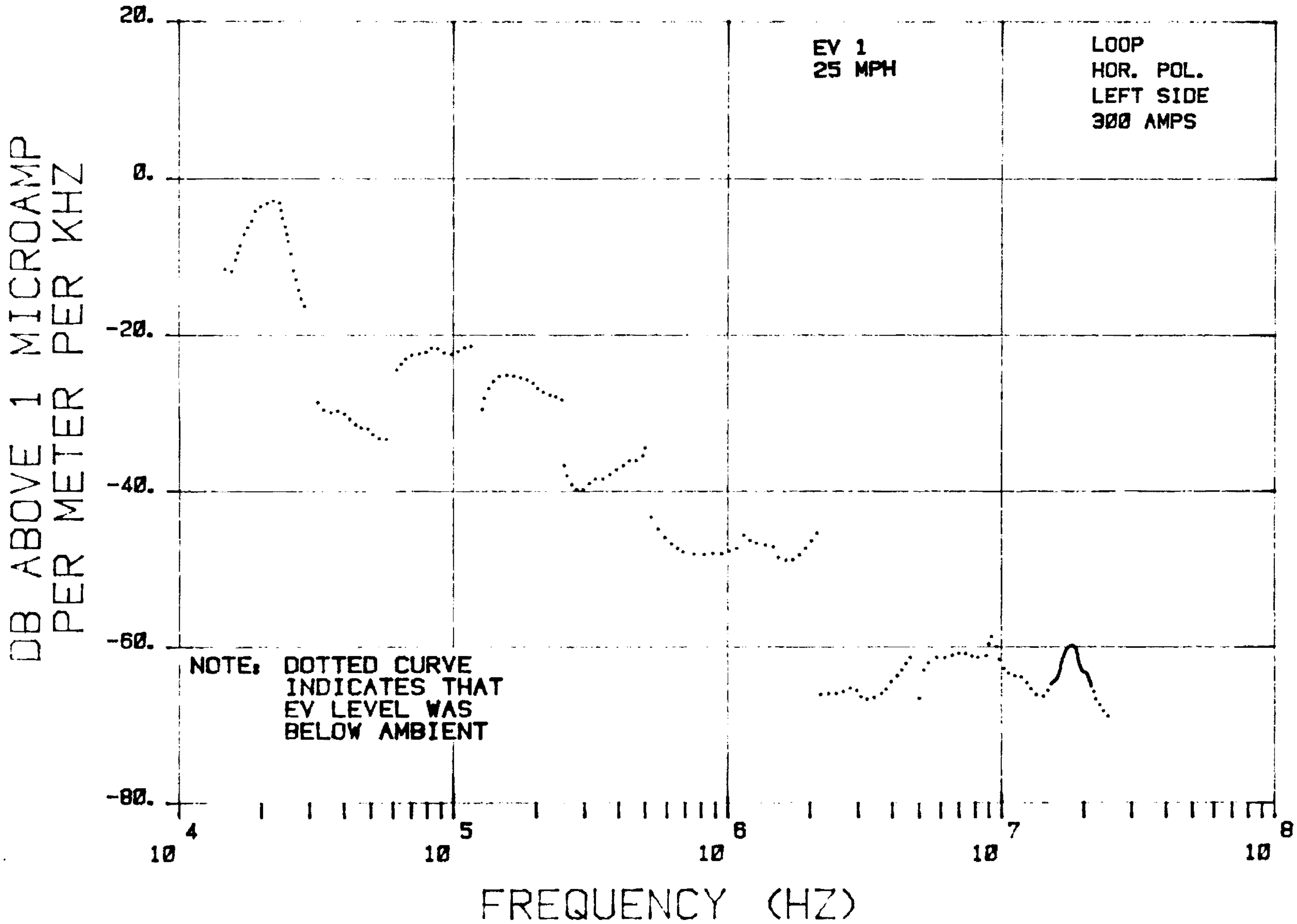

60.
40.
20.
0.
-20.
-40.
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
EV 1
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
225 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
10 5
10 6
10 7
10 8
10 9
FREQUENCY (HZ)

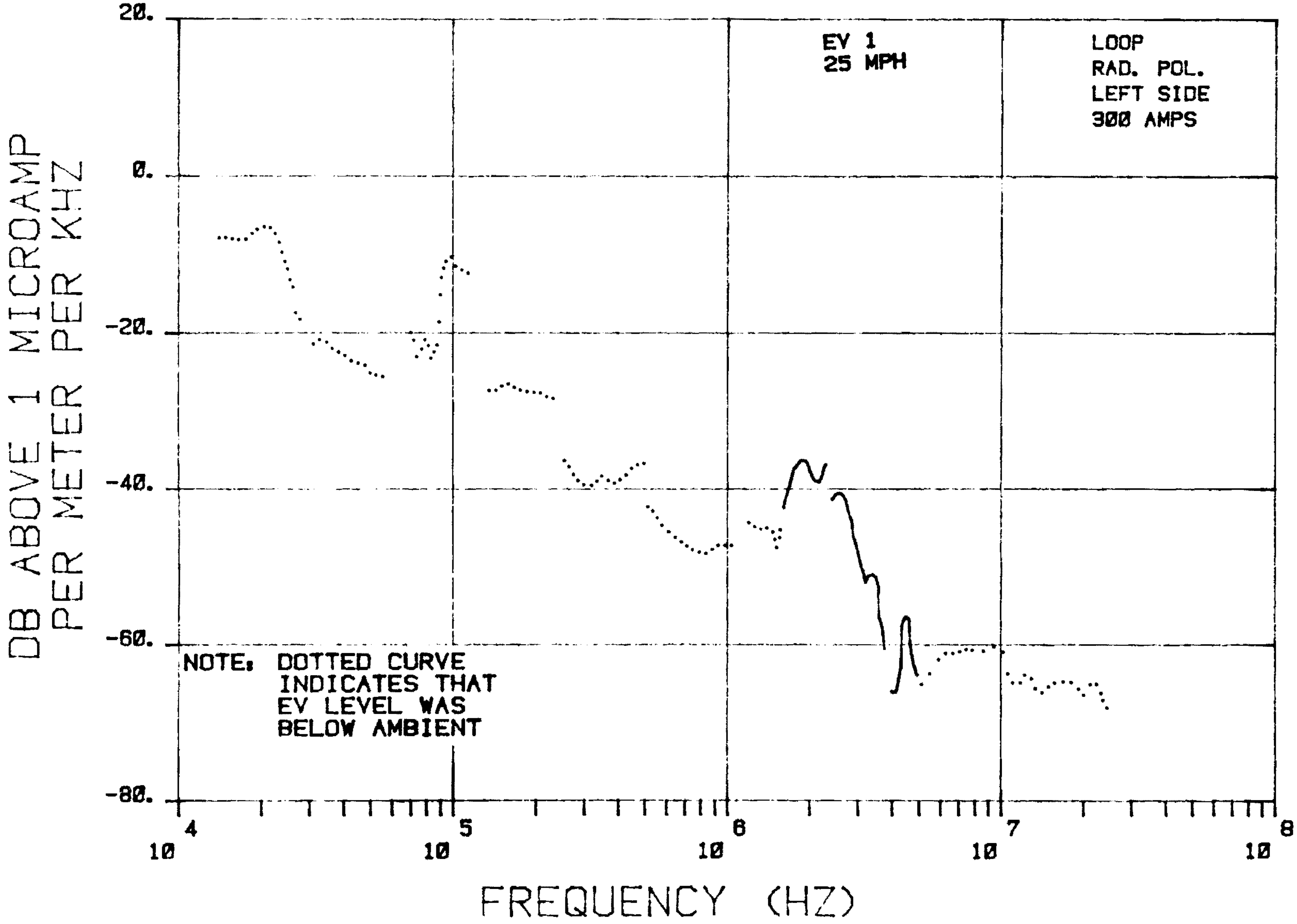

60.
40.
20.
0.
-20.
-40.
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
EV 1
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
300 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)


DB ABOVE 1 MICROVOLT PER METER PER KHZ
40.
20.
0.
-20.
-40.
-60.
EV 1
25 MPH
E-FIELD
HOR. POL.
LEFT SIDE
300 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)


EV 1
25 MPH
LOOP
HOR. POL.
LEFT SIDE
NO LOAD
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

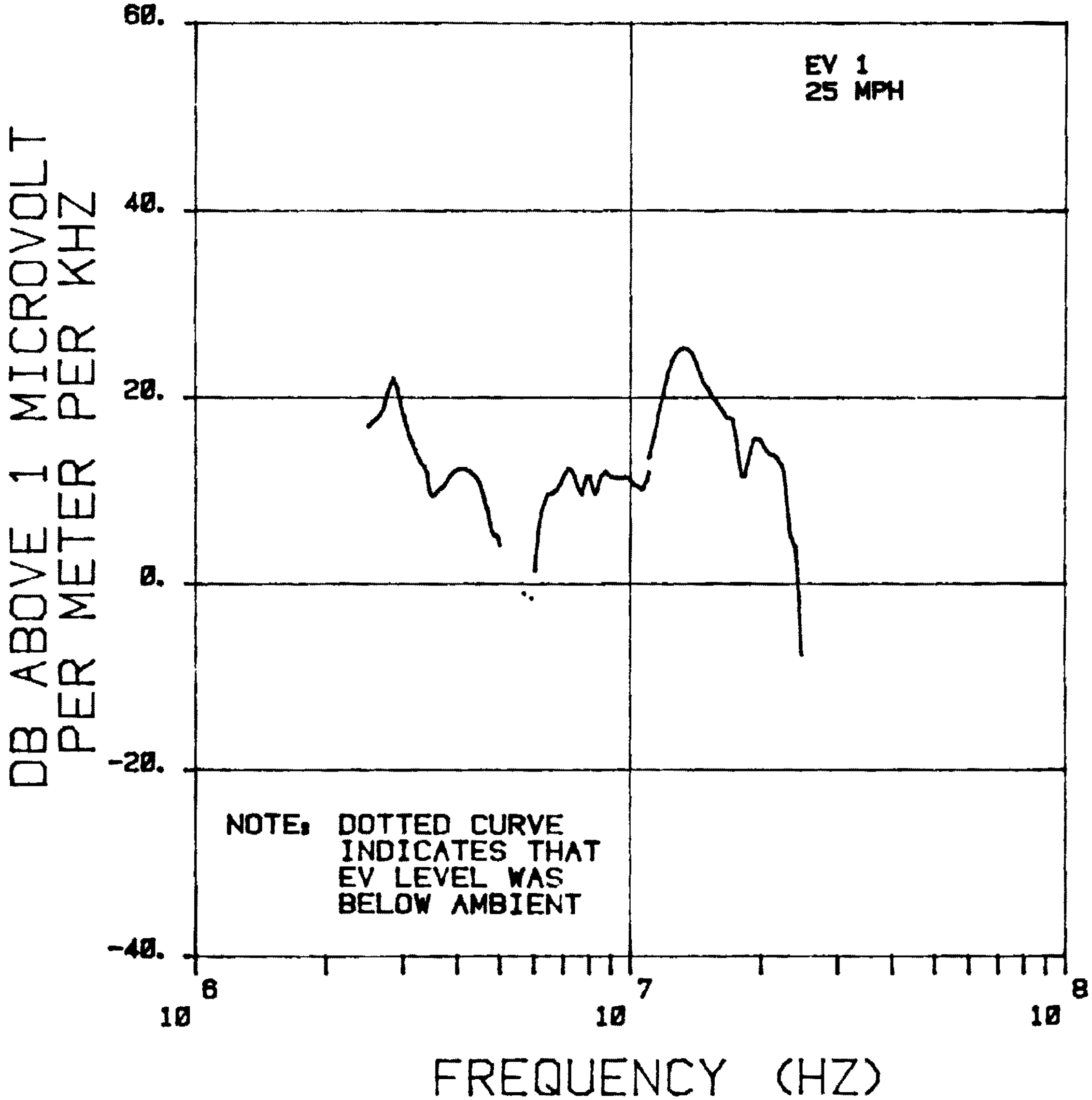

EV 1
25 MPH
LOOP
VERT. POL.
LEFT SIDE
300 AMPS
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER METER PER KHZ
FREQUENCY (HZ)
20.
0.
-20.
-40.
-60.
-80.
10^4
10^5
10^6
10^7
10^8


EV 1
25 MPH
LOOP
HOR. POL.
LEFT SIDE
300 AMPS
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

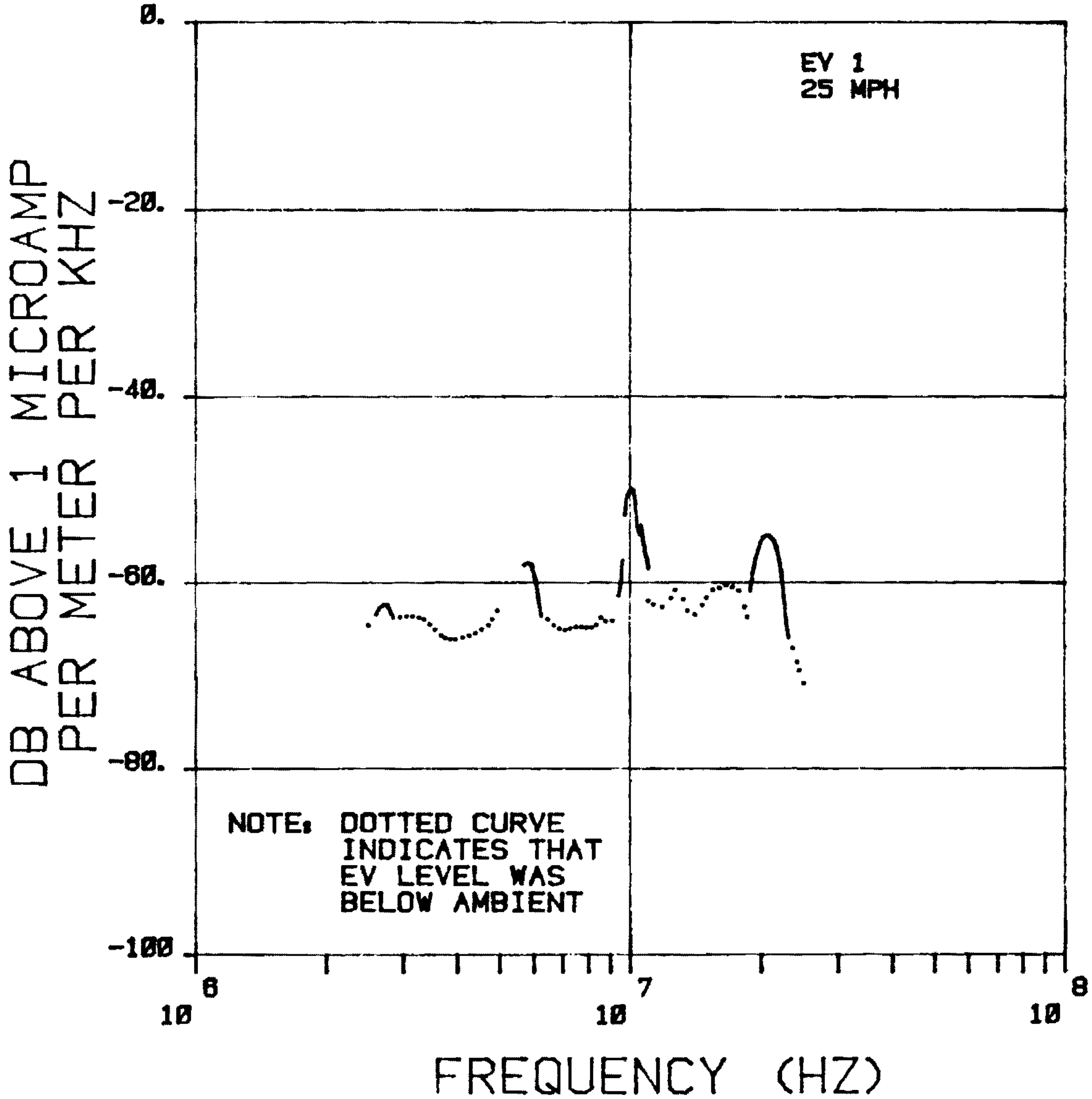


EV 1
25 MPH
LOOP
RAD. POL.
LEFT SIDE
300 AMPS
DB ABOVE 1 MICROAMP PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

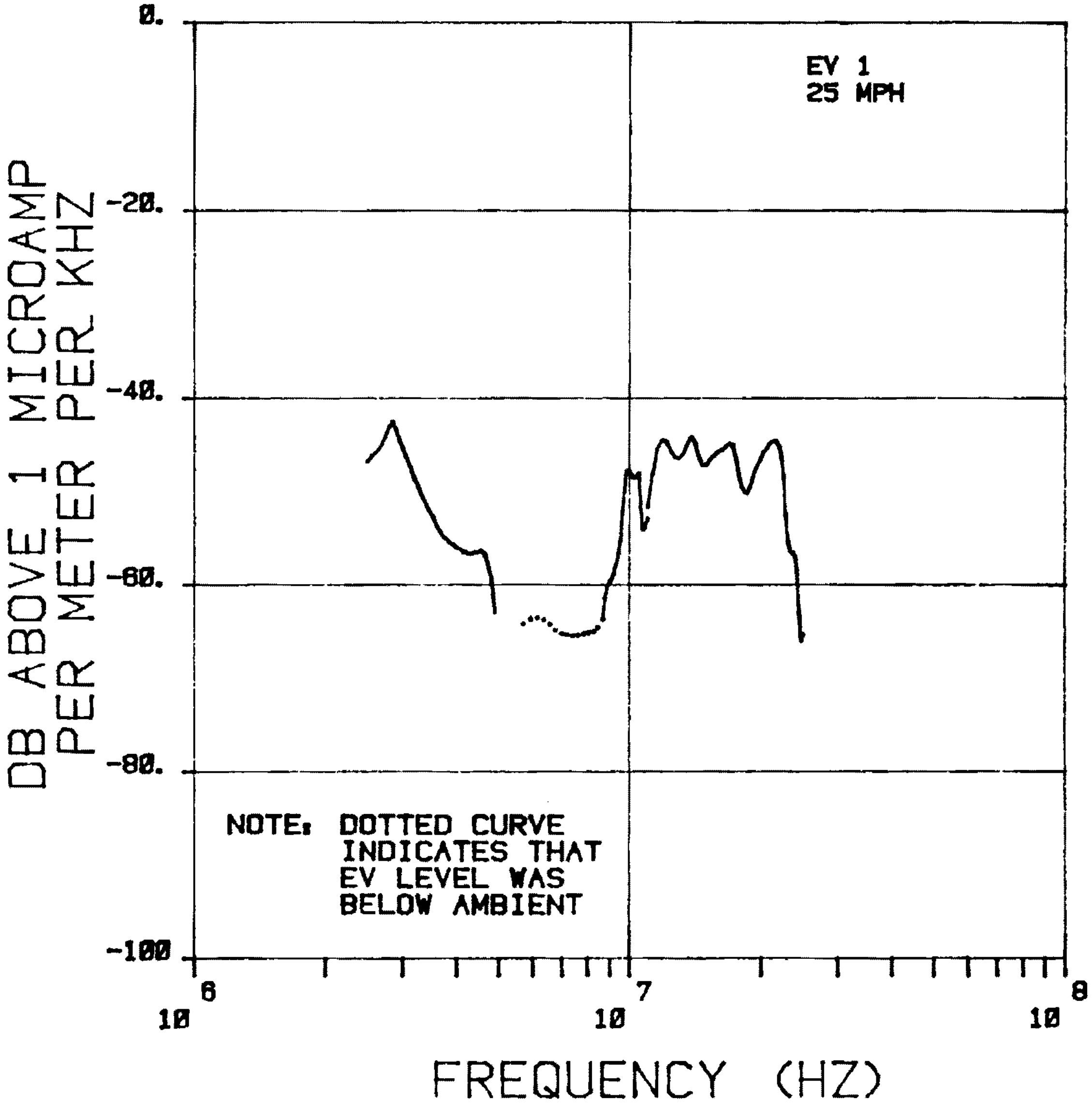
ROD
VERT. POL.
FRONT SIDE
NO LOAD

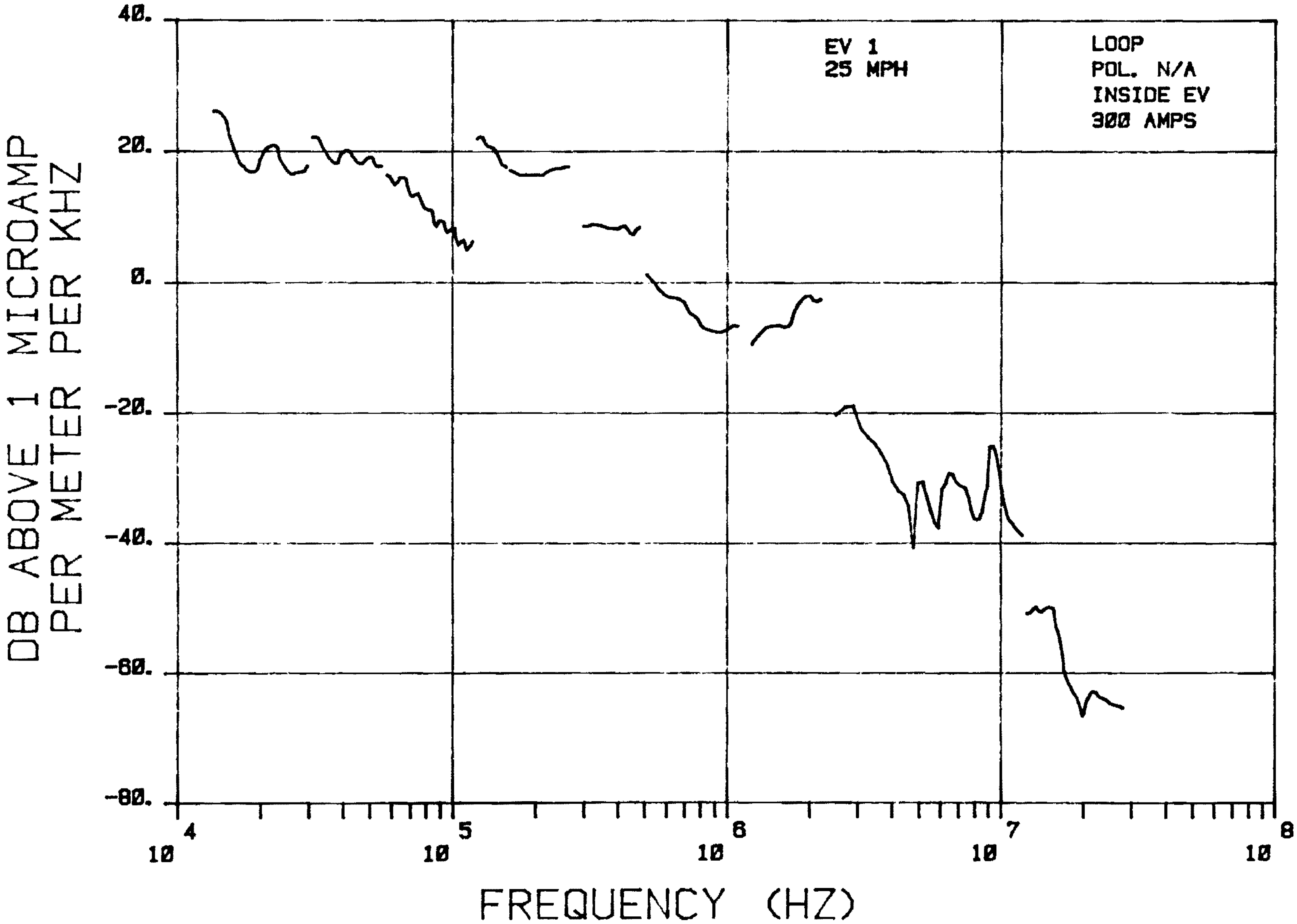


LOOP
RAD. POL.
FRONT SIDE
NO LOAD



LOOP
HOR. POL.
FRONT SIDE
NO LOAD




EV 1
25 MPH
LOOP
POL. N/A
INSIDE EV
300 AMPS
DB ABOVE 1 MICROAMP PER METER PER KHZ
40.
20.
0.
-20.
-40.
-60.
-80.
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

RECOMMENDED TEST PROCEDURES
FOR ELECTRIC VEHICLES

Project A-3089

By

John K. Daher

February 1983

Submitted to

THE AEROSPACE CORPORATION
Suite 4000
955 L'Enfant Plaza
Washington, DC 20024

Prepared By

Electronics and Computer Systems Laboratory
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

A Unit of the University System of Georgia

Original: English

CISPR/D/WG1 (Daher/Woody -USA)
January 1983

INTERNATIONAL ELECTROTECHNICAL COMMISSION

INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE (CISPR)

SUB-COMMITTEE D: INTERFERENCE RELATING TO MOTOR VEHICLES AND INTERNAL COMBUSTION ENGINES

WORKING GROUP 1

Subject: Recommended Electric Vehicle Test Procedures

During the past fifteen months, a program has been undertaken to characterize the electromagnetic interference (EMI) aspects of electric vehicles (EV's) and to develop appropriate test procedures which account for the unique characteristics of these vehicles. In order to accomplish the program objectives, three different EV's were selected and tested. A brief description of these vehicles is given in Table 1. These vehicles were selected as being representative of the current state-of-the-art in EV technology and as having characteristics similar to what might be expected of EV's over the next several years.

TABLE 1. Electrical Characteristics of EV's Tested

	EV No. 1	EV No. 2	EV No. 3
Motor	Series DC, 400A	Shunt DC, 400A	Shunt DC, 300A
Controller	Transistorized 4 kHz PRF Pulse Width Modulation	Transistorized 400 Hz PRF Pulse Width Modulation	Transistorized 400 Hz PRF Pulse Width Modulation
Battery Voltage	96V	108V	96V
Battery Charger	220 VAC Input 96/12 VDC Output 30 A Max. Current	120 VAC Input 108/12 VDC Output 16 A Max. Current	120 VAC Input 96/12 VDC Output 16 A Max. Current
Body Type	Metal Body	Metal Body	Fiberglass Body

Development of the test procedures proceeded in three stages: (1) an evaluation methodology was developed to serve as a guideline for performing measurements to be used in defining the radiated and conducted emission characteristics of EV's; (2) the evaluation methodology was used to collect a significant amount of data on EV's; and (3) the results were used to refine the evaluation methodology into practical and time/cost-efficient test procedures. The recommended test procedures for radiated and conducted emissions are presented in Attachments I and II, respectively.

Development of an EMI evaluation methodology began with a review of several applicable measurement procedures. Included in the analysis were CISPR Publication 12, Society of Automotive Engineers (SAE) J551 (JUN 81), and the United States Department of Defense's MIL-STD-462. Next, an analysis of current EV technology was undertaken in order to determine potential measurement requirements which might be unique to electric vehicles. The analysis and review indicated that the test methodology should provide for measurements below 20 MHz, since a significant amount of energy was expected below this frequency. In addition, the evaluation methodology was structured to reflect that the EMI characteristics of EV's were expected to be a function of the loading on the motor. Considering these and other similar factors, radiated and conducted emission evaluation methodologies were prepared.

Using these evaluation methodologies, radiated emission tests were performed on the three EV's over the frequency range from 14 kHz to 1000 MHz and conducted emission measurements were made on the on-board battery chargers of the last two vehicles tested. A number of measurement parameters were varied during the testing (e.g., frequency, speed, load, direction, state of battery charge, etc.). An absorption dynamometer was used to accurately and repeatably apply different load conditions without raising the ambient noise levels. Each vehicle was also tested under no load conditions (i.e., with the drive wheels elevated on jack stands). The measurement results allowed for a number of observations to be made concerning the overall levels outside and inside the vehicle as a function of frequency; the effects of load, speed, and polarization; the relative levels of the electric and magnetic field radiated from the vehicle; and the conducted RF levels on the ac power line from battery chargers as a function of frequency.

The final stage of the test procedure development consisted of refining the evaluation methodology to retain only those measurements which are essential for a comprehensive EMI assessment of EV's. Originally, the evaluation methodology was broadly based so that the influence of many of the potential contributors to the EMI characteristics of EV's could be examined. Subsequent usage of the methodology revealed areas where refinements could be made to eliminate unnecessary tests and, thus, reduce testing time and costs. The refined methodology was formulated into comprehensive test procedures which define the proper equipment, test configurations, and measurement parameters.

The results of the measurements effort were used to characterize the EMI aspects of electric vehicles. Specifically, the radiated emission data indicate that: (1) the impulse electric field intensity levels are relatively large (in some cases in excess of +60 dBμV/m/kHz (peak) with a 10 meter antenna-to-vehicle separation distance) at frequencies below approximately 20 MHz, (2) the impulse electric field intensities are far below both the CISPR limit (which extends from 40 MHz to 250 MHz) and the SAE limit (which covers the 20 MHz to 1000 MHz frequency range) for frequencies greater than 100 MHz, and (3) the electric field intensity levels decrease significantly at higher frequencies. It is recommended, therefore, that the lower frequency limit for EV testing be extended down to 14 kHz to account for the relatively large radiated field intensities at the lower frequencies. Despite the relatively low field intensity levels measured at higher frequencies, it is considered preliminary at the present time to exclude measurements in this frequency range, primarily because only a limited number of vehicles have been tested. The measurement procedures specified in SAE J551 are recommended for use over the 20 to 1000 MHz frequency range using the test conditions specified in Part 2 of Attachment I. However, if further investigations on a number of other present and future technology EV's confirm that radiated emission levels continue to be localized in the lower frequency range, it is recommended that the 1000 MHz upper test frequency for measuring radiated emissions be lowered.

The data also reveals that varying the load condition from no load (drive wheels elevated) to full load (maximum rated armature current) has a minor influence on the "shape" of the frequency spectrum, but has no significant and consistent effect on the overall radiated emission levels. Consequently, it is recommended that the requirement of a dynamometer to load down the propulsion system be relaxed (which should result in a considerable reduction in testing costs). Magnetic field testing was determined to be necessary due to the large pulsed current levels associated with normal operation of the vehicle and the fact that magnetic fields are a primary source of interference at relatively low frequencies.

Recommended performance levels for both radiated and conducted emission measurements are contained in Attachments I and II, respectively. The radiated impulse electric field intensity limit (14 kHz to 20 MHz) coincides with the SAE J551 limit at 20 MHz (which is equivalent to the CISPR limit at 40 MHz) but increases at 20 decibels per decade as frequency decreases below 20 MHz. The increasing limit with decreasing frequency corresponds to the expected decrease in coupling of the radiated energy to potentially susceptible receptors as frequency decreases. The recommended limit for electric fields in the 20 MHz to 1000 MHz frequency range is identical to that given in SAE J551. The radiated impulse magnetic field intensity limit (14 kHz to 20 MHz) also reflects the expected decrease in coupling and represents the equivalent far-field magnetic field intensity corresponding to the electric field limit described above (i.e., magnetic field equals electric field divided by 377 ohms). The conducted emission limit was based on the United States Department of Defense's MIL-STD-461B broadband emission limit for ac power leads. The limit is modified for load currents greater than 1 ampere by assuming that a typical on-board battery charger draws approximately 20 amperes of load current and relaxing the 14 kHz limit by 20 $\log_{10}$ [load current] or 26 decibels.

The recommended test procedures and performance levels presented here are considered to be preliminary. The test procedures for EV's are considerably more extensive and time consuming than those for internal combustion engine vehicles (as specified by CISPR Publication 12 or SAE J551). Therefore, it is recommended that more investigation be undertaken to further refine the test procedures with the goal of eliminating unnecessary measurements and to establish limits which correspond to acceptable levels with regard to interference with communications services and equipments over the applicable frequency range. However, the attached test procedures and performance levels are recommended for use in the interim period pending further investigation.

It is recommended that the control of potential interference from electric vehicles be exercised at an early stage in their development and on an international basis. The recommended test procedures and performance limits which follow were developed with the objective of achieving these goals.

ATTACHMENT I

RECOMMENDED PERFORMANCE LEVELS AND METHODS OF MEASUREMENT OF RADIATED EMISSIONS FROM ELECTRIC VEHICLES (14 kHz - 1000 MHz)

Attachment I is composed of two parts. Part 1 includes the recommended performance levels and methods of measurement of radiated emissions over the 14 kHz to 20 MHz frequency range. Part 2 presents the recommended performance levels and methods of measurement of radiated emissions over the 20 MHz to 1000 MHz frequency range.

Part 1: Recommended Performance Levels and Methods of Measurement of Radiated Emissions (14 kHz - 20 MHz).

1. Purpose - The purpose of these test procedures is to provide guidance in the measurement of electromagnetic radiation from an electric vehicle (EV). Recommended performance levels are given in order to establish uniform requirements and to minimize the likelihood of large populations of electric vehicles interfering with equipment or communication services.

2. Scope - The test procedures and limits cover the measurement of radiated emission levels from EV's over the frequency range of 14 kHz to 20 MHz.

3. Equipment[1]

3.1 Accuracy - The measurement instrumentation shall be capable of measuring impulse electric and magnetic field intensity over the frequency range of 14 kHz to 20 MHz with an amplitude error of no greater than ± 5 dB and a frequency error of no greater than ± 3 percent.

3.2 Receivers

3.2.1 Spectrum Analyzer - Used for preliminary scanning purposes only.

3.2.2 Electromagnetic Interference (EMI) Receiver - Used for measuring absolute field intensity levels. The EMI receiver shall have peak or quasi-peak detection capabilities over the frequency range of 14 kHz to 20 MHz. The nominal input impedance shall be 50 ohms with a voltage standing wave ratio (VSWR) of less than 2.0:1 over the applicable frequency range. The impulse bandwidth must be known and shall not exceed 10% of the frequency at which measurements are being made.

3.3 Scanning Plotter - The sine wave response at 1.25 cm (0.5 in) peak-to-peak shall not be down by more than 3 dB at 10 Hz from the 1 Hz response.

---

[1] If measurements are made outdoors, the test equipment should be protected from direct sunlight and/or extreme temperatures. Environments which are significantly different from normal indoor lab environments may degrade equipment performance and cause erroneous results.

3.4 Calibrated Signal Source, Impulse Generator, Precision Attenuator, and Frequency Counter - Used for calibration purposes.

3.5 Antennas - The receive antennas to be used are the loop (electrostatically shielded) and the rod above a ground plane, each equipped with switchable impedance matching networks.

3.6 Transmission Line - It is recommended that double shielded coaxial cable be used between receive antenna and receiver. The characteristic impedance of the transmission line shall be 50 ohms (nominal).

4. Equipment Calibration

4.1 Receiver Calibration

4.1.1 Frequency Calibration - Frequency calibration shall be accomplished with a signal source and a frequency counter using standard techniques.

4.1.2 Amplitude Calibration - Amplitude calibration shall be made in one of two ways. The first method involves calibration of the receiver at the arithmetic center frequency of the band being measured by using the standard signal substitution method. If this method of calibration is used, a bandwidth calibration factor (BF), determined in Paragraph 4.1.4, must subsequently be applied. The second method involves the use of a calibrated impulse generator. An impulse signal of known level is injected into the receiver input, so that the receiver can be calibrated (via a look-up table or other suitable method) in terms of dBμV/kHz. Use of the latter method precludes the need for a separate bandwidth calibration.

4.1.3 Bandwidth Calibration - The impulse bandwidth of the receiver must be known for each frequency band. Published data should be used if available. If unavailable, receiver impulse bandwidth shall be measured using standard techniques.

4.1.4 Bandwidth Calibration Factor - The bandwidth calibration factor, BF, shall be calculated for each frequency band according to the relationship:

$$BF = 20 \log_{10} [BW_i] \text{ dB}$$

where: BW_i = Impulse bandwidth in kHz.

4.2 Scanning Plotter Calibration - Calibrate the scanning plotter with a signal source, precision attenuator, and frequency counter using standard techniques.

4.3 Antenna Calibration

4.3.1 Antenna Factor - The antenna factor for a rod antenna (in m^{-1}) is defined to be the ratio of the incident electric field intensity (in μV/m) to the voltage delivered to a 50 ohm load (in μV). The antenna factor for a loop antenna (in mhos/m) is defined to be the ratio of the incident magnetic field intensity (in μA/m) to the voltage delivered to a 50 ohm load (in μV). The antenna factor shall include the effects of baluns, impedance matching networks, and mismatch losses. Antenna factors are normally supplied by the manufacturer of EMC antennas. If unknown, determine using standard techniques (e.g., SAE ARP 958).

4.4 Transmission Line Calibration

4.4.1 Insertion Loss - The insertion loss of the transmission line used to connect the receive antenna to the receiver shall be measured as a function of frequency over the frequency range of interest using standard techniques.

5. Test Site Conditions

5.1 Field Site - An outdoor field site may be used for vehicle testing provided that it is free from metallic surfaces within a circle of 30 m radius (minimum) measured from a point midway between the EV and antenna. The ground surfaces shall be natural to the vehicle (e.g., asphalt or concrete). All surfaces shall be dry during testing.

5.2 Indoor Test Site - A shielded enclosure or an anechoic chamber may also be used for vehicle testing provided that the vehicle-to-antenna spacing and the antenna height is preserved. In addition, the antenna-to-wall and the EV-to-wall separation distances shall be at least one meter. The chamber or enclosure floor shall have electrical constants (dielectric constant, conductivity, etc.) approximating the average surface of an outdoor site.

6. Preliminary Scan Procedure

6.1 Elevate the drive wheels using jack stands as supports.[2]

6.2 Use a rod antenna mounted above a ground plane and tuned to approximately 500 kHz.

6.3 Establish steady-state condition of 25 mph (40 kph) in high gear.

6.4 Beginning with the base of the rod antenna one meter above the ground and one meter away from the nearest part of the front end of the vehicle, scan the radiated emission levels from 0-20 MHz. Use a spectrum analyzer as the receiver with the following settings:

Center Freq.: 10 MHz	RF Attn: 0 dB
Scan Width: 2 MHz/div.	Video Filtering: none
Scan Time: 500 ms/div.	IF Bandwidth: 100 kHz

6.5 Take photographs of the display (or tabulate the data in sufficient detail) in order to characterize the received power levels over the 0-20 MHz frequency range for both vertical and horizontal antenna polarizations.

6.6 Repeat Paragraphs 6.3-6.5 for the other three sides of the vehicle.

[2] If operation of the vehicle in the unloaded state would cause damage to the propulsion system, an absorption-type (i.e., non-electrical) dynamometer should be used.

6.7 Determine the direction of maximum radiation based upon the results of Paragraphs 6.1 - 6.6. This determination should be based on the larger of the two levels obtained for vertical and horizontal polarizations. If the levels are approximately equal for two different sides of the vehicle, either of these sides may be selected as the direction of maximum radiation.

6.8 With the antenna positioned and oriented for maximum received signal (i.e., the side and polarization determined in Paragraphs 6.1-6.7), repeat Paragraphs 6.4-6.5 for steady-state conditions of 10 mph (16 kph) and 40 mph (64 kph) in order to determine the speed of maximum radiation.

7. Measurements

7.1 Frequency Range - Measurements shall be performed over the frequency range of 14 kHz to 20 MHz. This range shall be divided into a minimum of 10 bands with approximately one band per frequency octave. Each band shall be scanned either manually or automatically to determine the radiated field strength as a function of frequency. As an example, one possible band selection would be:

Band 1:	14 kHz - 30 kHz	Band 6:	500 kHz - 1.1 MHz
Band 2:	30 kHz - 60 kHz	Band 7:	1.1 MHz - 2.4 MHz
Band 3:	60 kHz - 120 kHz	Band 8:	2.4 MHz - 5.0 MHz
Band 4:	120 kHz - 250 kHz	Band 9:	5.0 MHz - 10.0 MHz
Band 5:	250 kHz - 500 kHz	Band 10:	10.0 MHz - 20.0 MHz

Spot frequency measurements, although not recommended, shall be considered sufficient provided that a minimum of two frequencies are measured per octave and the ratio of successive frequencies does not exceed 1.6.

7.2 Sweep Rate - Either manual or automatic frequency scanning may be used, provided the scanning is sufficiently slow to ensure that the peak field intensities have been measured. As a check, fix tune the receiver to a frequency in the band in question and observe the measured level. Then reduce the scan rate for that band until the detected level approximates (within 1 dB) the fix-tuned level at that particular frequency.

7.3 Operating Conditions - All of the following radiated emission measurements should be made with the EV's drive wheels elevated and supported by jack stands[3]. The EV shall be operated at the speed of maximum radiation (determined in Paragraph 6.8) during all of the testing.

7.4 Vehicle and Antenna Positions (See Figure 1) - Locate the vehicle and the antenna such that all test site conditions are satisfied as stated in Section 5.

7.4.1 Antenna Position - Position the receive antenna: (1) on the side of the EV found to emit maximum radiation (as determined in Paragraph 6.7) and (2) with the electrical center of the antenna (considered to be the base of the rod or the center of the loop) 10 m from the closest part of the vehicle at a height of 3 m above ground level (or above the bottom of the tires if ground is unlevel).

7.4.2. Antenna Polarization - Both vertical and horizontal components of impulse electric and magnetic field strengths shall be measured. The polarization for a magnetic loop antenna is referenced to an imaginary axis perpendicular to the plane of the loop. In the case of horizontal polarization, for example, the imaginary axis would be horizontally oriented in the plane transverse to the direction of propagation.

7.5 Measurement Instrumentation - The measurement instrumentation must be located within the permitted regions shown in Figure 1.

7.6 Measurement Procedure

7.6.1 Ambient Measurements - The purpose of these measurements is to determine the levels of ambient noise and RF carriers. The measurements shall be

[3]If Note 2 applies or if desired, measurements may be made using an absorption dynamometer to load the EV at the zero-grade road load for the particular speed determined in Paragraph 6.8 to yield maximum radiation levels.

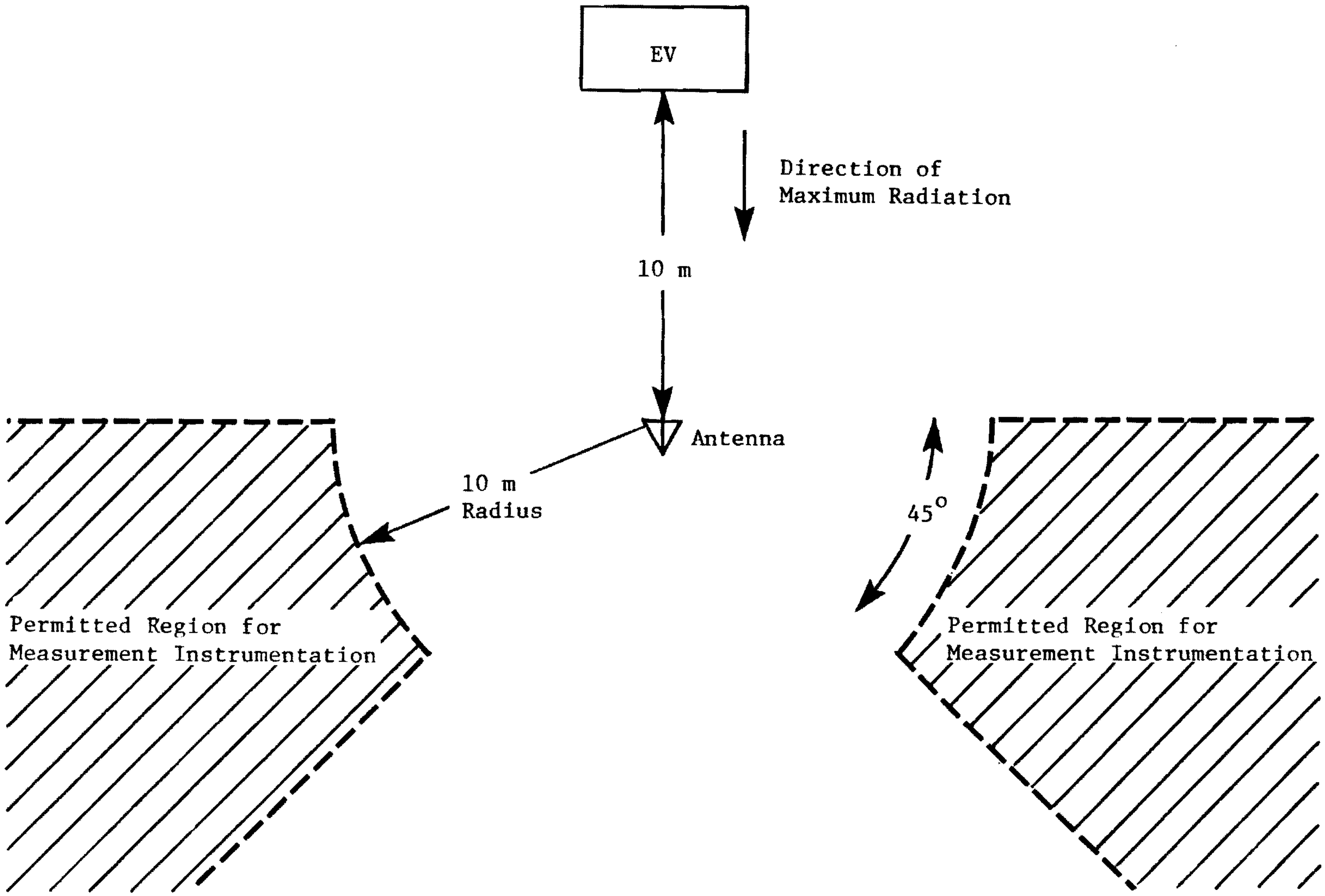


Figure 1. Vehicle and Antenna Positions for Radiated Emission Measurements

made over the applicable frequency range for both the electric and magnetic field tests. Ambient measurements shall be made for each band with the vehicle completely inoperative and shall be made immediately before the vehicle measurements. Data shall be recorded in terms of received voltage (in either dBμV or dBμV/kHz) versus frequency.

7.6.2 Vehicle Measurements - The EV shall be measured for each band as stated in the previous paragraph except that the vehicle will be operative as specified in Paragraph 7.3. Data shall be recorded in terms of received voltage (in either dBμV or dBμV/kHz) versus frequency.

8. Data Reduction - The impulse electric field intensity and the impulse magnetic field intensity shall be calculated from the received voltage levels as measured in Paragraph 7.6.2.

8.1 Impulse Electric Field Intensity - Impulse electric field intensity shall be expressed in units of decibels above one microvolt per meter per kilohertz bandwidth (dBμV/m/kHz). If the receiver has not been calibrated with an impulse generator, the equation relating impulse magnetic field intensity to the received voltage level is:

$$E_i = V_r + AF_r + TL - BF$$

where: E_i = Impulse electric field intensity in dBμV/m/kHz,
V_r = Received voltage level in dBμV,
AF_r = Antenna factor for rod antenna in dB (see Paragraph 4.3.1),
TL = Transmission line insertion loss in dB (see Paragraph 4.4.1), and
BF = Bandwidth calibration factor in dB (see Paragraph 4.1.4).

If the receiver has been calibrated with an impulse generator, the equation which should be used is:

$$E_i = V' + AF_r + TL$$

where V' is the receiver reading in dBμV/kHz.

8.2 Impulse Magnetic Field Intensity - Impulse magnetic field intensity shall be expressed in decibels above one microampere per meter per kilohertz bandwidth (dBμA/m/kHz). If the receiver has not been calibrated with an impulse generator, the equation relating impulse magnetic field intensity to the received voltage level is:

$$H_i = V_r + AF + TL - BF$$

where: H_i = Impulse magnetic field intensity in dBμA/m/kHz and
AF = Antenna factor for loop antenna in dB (see Paragraph 4.3.1).

If the receiver has been calibrated with an impulse generator, the equation which should be used is:

$$H_i = V' + AF + TL.$$

9. Assessment of Results

9.1 Characteristic Level - The characteristic level for each band (used for the purpose of comparison with the recommended level) is defined to be the maximum measured value obtained for that band for both polarizations. The characteristic level shall be compared to the recommended performance level at the arithmetic center frequency of the band. Known ambient carriers and broadband noise shall be ignored in determining characteristic levels.

9.2 Recommended Performance Levels - The recommended performance levels, based on peak measurements, are given in Appendix I. The corresponding quasi-peak levels are 20 dB lower than the peak levels.

9.3 Method of Checking for Compliance with Recommended Limits - Results from a single vehicle may be used to determine compliance provided that the vehicle tested is representative of production-line vehicles. Measurements may also be made on a sample of six or more vehicles and statistical analysis applied to the characteristic levels in order to determine compliance. In this case, the characteristic levels shall be evaluated as given in Appendix II.

Part 2: Recommended Performance Levels and Methods of Measurement of Radiated Emissions (20 MHz - 1000 MHz).

The recommended performance levels for electric vehicles over the 20 MHz to 1000 MHz frequency range are identical to that given in SAE J551 (JUN 81). The following test conditions are recommended:

(1) The EV shall be operated with the drive wheels elevated (unloaded) unless such operation is likely to cause damage to the vehicle. If operation in the unloaded state would cause damage, the vehicle should be operated on an absorption-type dynamometer at a load corresponding to the zero-grade load at a given speed.

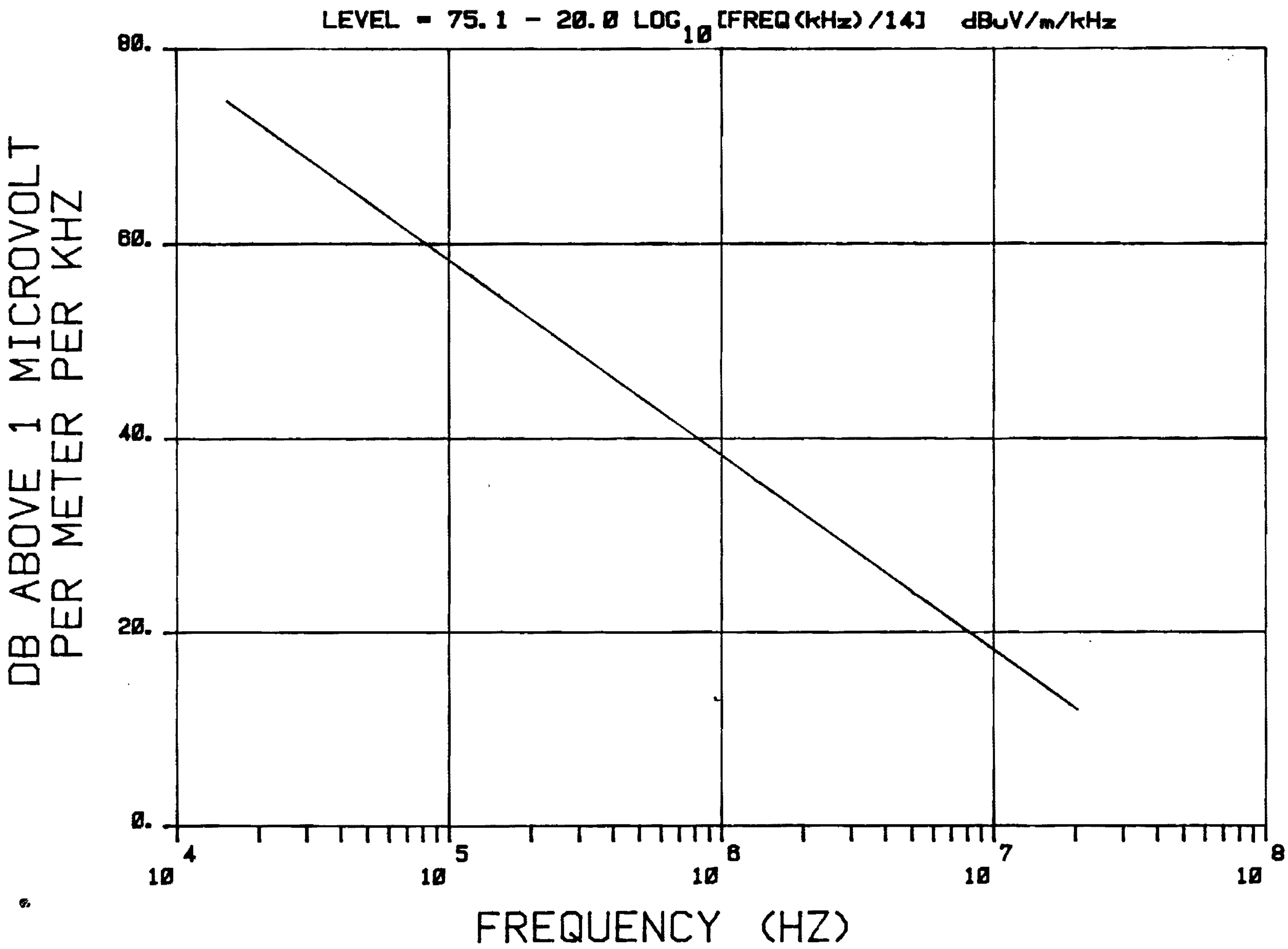
(2) A preliminary test shall be made to determine the vehicle speed which produces maximum radiation levels.

(3) Final testing shall be conducted on all four sides of the vehicle at the speed which produces worst-case load conditions.

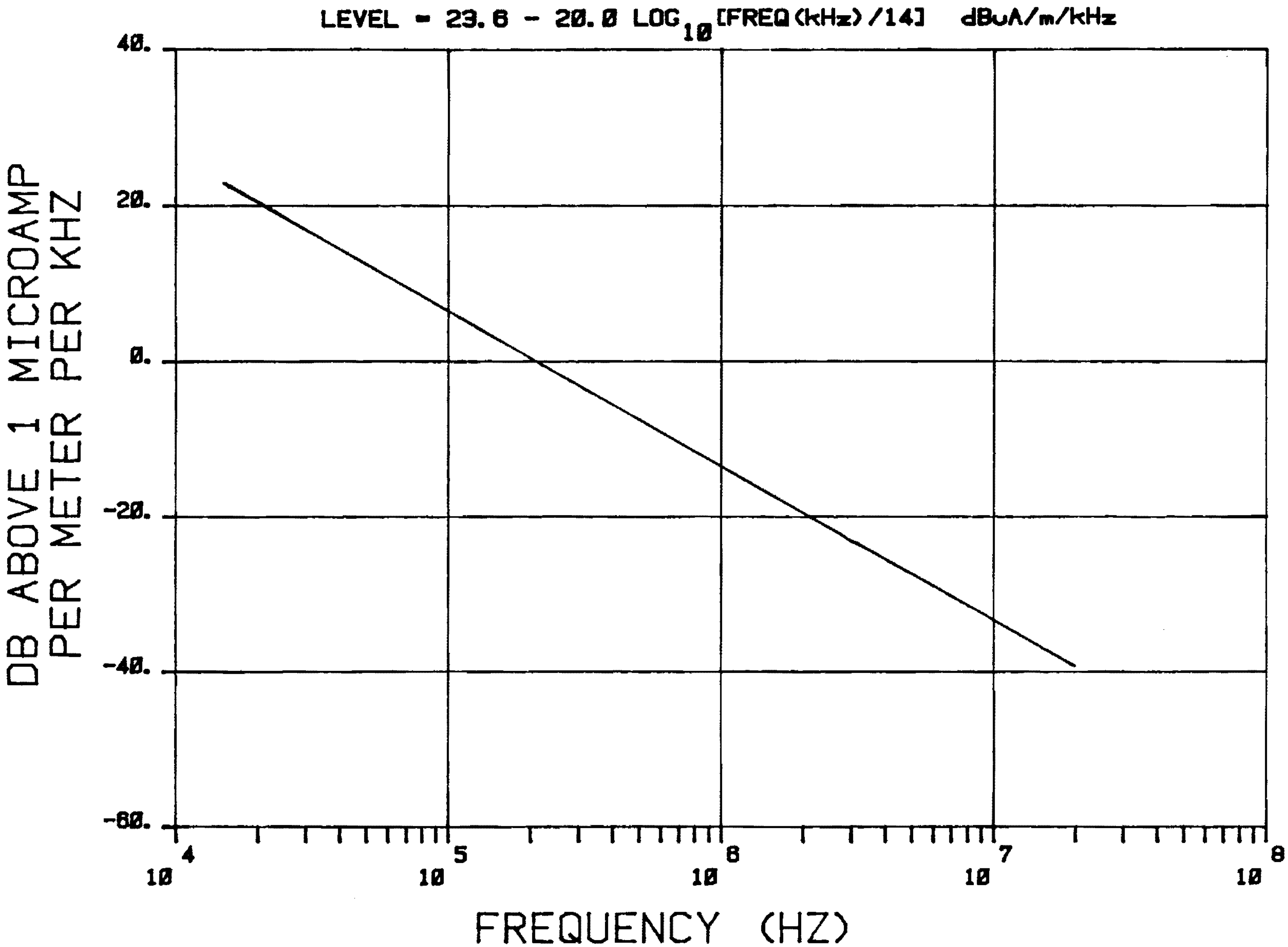
Radiated testing of on-board battery chargers is not required. All other requirements of the SAE standard shall apply.

APPENDIX I

RECOMMENDED PERFORMANCE LEVELS FOR RADIATED PEAK AND MAGNETIC FIELD INTENSITY



Recommended Performance Levels For Peak Impulse Electric Field Intensity.



Recommended Performance Levels For Peak Impulse Magnetic Field Intensity.

APPENDIX II

STATISTICAL ANALYSIS OF MEASUREMENT RESULTS ON SIX OR MORE VEHICLES

The criteria to be used is 80% conformance with 80% confidence. The following condition must therefore be satisfied:

$$\bar{x} + kS_n \leq L$$

where: $\bar{x}$ = Arithmetic mean of the results on n vehicles,

k = Statistical parameter dependent on n,

S_n = Standard deviation of results on n vehicles,

L = Recommended performance level, and

$\bar{x}$, S_n, and L are all expressed in the units used for the recommended performance levels.

The statistical parameter k is determined using the following table:

n =	6	7	8	9	10	11	12
k =	1.42	1.35	1.30	1.27	1.24	1.21	1.20

The standard deviation, S_n, is determined by the following equation:

$$S_n = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}$$

where x_i is the individual result for the i^{th} vehicle tested.

ATTACHMENT II

RECOMMENDED PERFORMANCE LEVELS AND METHODS OF MEASUREMENT OF CONDUCTED EMISSIONS FROM ELECTRIC VEHICLE ON-BOARD BATTERY CHARGERS (14 kHz - 20 MHz)

1. Purpose - The purpose of these test procedures is to provide guidance in the measurement of conducted emission levels from electric vehicle (EV) on-board battery chargers. Recommended performance levels are given in order to establish uniform requirements and to minimize the likelihood that conducted levels on ac power leads (from on-board battery chargers) will interfere with potentially susceptible equipments which are connected to the same mains supply.

2. Scope - The test procedures and performance levels cover the measurement of conducted emission levels from on-board battery chargers on ac power leads over the frequency range of 14 kHz to 20 MHz.

3. Equipment[1]

3.1 Accuracy - The measurement instrumentation shall be capable of measuring impulse current levels over the frequency range of 14 kHz to 20 MHz with an amplitude error of no greater than ±3 dB and a frequency error of no greater than ±3 percent.

3.2 Electromagnetic Interference (EMI) Receiver - The EMI receiver shall have peak or quasi-peak detection capabilities over the frequency range of 14 kHz to 20 MHz. The nominal input impedance shall be 50 ohms with a voltage standing wave ratio (VSWR) of less than 2.0:1 over the applicable frequency range. The impulse bandwidth must be known and shall not exceed 10% of the frequency at which measurements are being made.

3.3 Scanning Plotters - The sine wave response at 1.25 cm (0.5 in) peak-to-peak shall not be down by more than 3 dB at 10 Hz from the 1 Hz response.

3.4 Calibrated Signal Source, Impulse Generator, Precision Attenuator, and Frequency Counter - Used for calibration purposes.

3.5 EMI Current Probe - The current probe shall be free of resonances at frequencies below 20 MHz and the saturation current rating for the probe

[1] If measurements are made outdoors, the test equipment should be protected from direct sunlight and/or extreme temperatures. Environments which are significantly different from normal indoor lab environments may degrade equipment performance and cause erroneous results.

at the power-mains frequency shall exceed the maximum rated charger supply current by at least 10 amperes. The transfer impedance must be known from 14 kHz to 20 MHz.

3.6 Line Impedance Stabilization Networks (LISN's) - A 50 μH/50 ohm LISN (free of resonances at frequencies below 20 MHz) is required for each current carrying conductor of the ac power line.

3.7 50 Ohm Resistive Terminations - A termination shall be used on the receiver output port of each LISN. Each termination shall have a voltage standing wave ratio (VSWR) of less than 1.3:1 over the applicable frequency range.

3.8 Transmission Line - It is recommended that double shielded coaxial cable be used between the current probe and the receiver. The characteristic impedance of the transmission line shall be 50 ohms (nominal).

3.9 Audio Isolation Transformer - Used for preventing radio frequency (RF) ground currents from flowing in the EMI receiver chassis ground.

3.10 Power Cables (2) - Two short sections (1 m or less) of power cable shall be made up with a connector on one end of each cable. One connector shall be a male plug and the other shall be a female receptacle. The outer sheath shall be removed from a short section (30 cm or less) of each cable at the end opposite from the connector in order to allow the conductors to be separated at this end. The power cable with the male connector will subsequently be identified as PCM and the power cable with the female connector will be identified as PCF.

4. Equipment Calibration

4.1 Receiver Calibration

4.1.1 Frequency Calibration - Frequency calibration shall be accomplished with a signal source and a frequency counter using standard techniques.

4.1.2 Amplitude Calibration - Amplitude calibration shall be made in one of two ways. The first method involves calibration of the receiver at the arithmetic center frequency of the band being measured by using the standard signal substitution method. If this method of calibration is used, a bandwidth calibration factor (BF), determined in Paragraph 4.1.4, must subsequently be applied. The second method involves the use of a calibrated impulse generator. An impulse signal of known level is injected into the receiver input, so that the receiver can be calibrated (via a look-up table or other suitable method) in terms of dBμV/kHz. Use of the latter method precludes the need for a separate bandwidth calibration.

4.1.3 Bandwidth Calibration - The impulse bandwidth of the receiver must be known for each frequency band. Published data should be used, if available. If unavailable, receiver impulse bandwidth shall be measured using standard techniques.

4.1.4 Bandwidth Calibration Factor - The bandwidth calibration factor, BF, shall be calculated for each frequency band according to the relationship:

$$BF = 20\ \log[BW_i]\ \text{dB}$$

where: BW_i = Impulse bandwidth in kHz.

4.2 Scanning Plotter Calibration - Calibrate the scanning plotter with a signal source, precision attenuator, and frequency counter using standard techniques.

4.3 Current Probe Calibration

4.3.1 Transfer Impedance - The transfer impedance, Z_t, for a current probe (in ohms) is defined to be the ratio of the voltage delivered to a 50 ohm load (in μV) to the current passing through the probe (in μA). Transfer impedance is a function of frequency and, therefore, must be known over the entire frequency range of interest. The transfer impedance shall include the effects of impedance mismatch. Transfer impedances are normally supplied by the manufacturer. If unknown, determine by measuring the probe output voltage with a 50 ohm receiver for a known injected current level and then calculating the transfer impedance according to the relationship:

$$Z_t(f) = 20 \log \left[\frac{V(f)}{I(f)}\right]$$

where: $Z_t(f)$ = Transfer impedance (in dB) at frequency f,
$V(f)$ = Probe output voltage amplitude (in μV) at frequency f, and
$I(f)$ = Injected current amplitude (in μA) at frequency f.

4.4 Transmission Line Calibration

4.4.1 Insertion Loss - The insertion loss of the transmission line used to connect the current probe to the receiver shall be measured as a function of frequency over the frequency range of interest using standard techniques.

5. Test Site Conditions - Any test site may be used provided that sufficient space is available to extend the ac power cord (provided with the battery charger) such that the cord is uncoiled and does not lie within 10 cm of any metallic surface. All surfaces shall be dry during testing.

6. Measurements

6.1 Frequency Range - Measurements shall be performed over the frequency range of 14 kHz - 20 MHz. This range shall be divided into a minimum of 10 bands with approximately one band per frequency octave. Each band shall be scanned either manually or automatically to determine the conducted current level as a function of frequency. As an example, one possible band selection would be:

Band 1:	14 kHz - 30 kHz	Band 6:	500 kHz - 1.1 MHz
Band 2:	30 kHz - 60 kHz	Band 7:	1.1 MHz - 2.4 MHz
Band 3:	60 kHz - 120 kHz	Band 8:	2.4 MHz - 5.0 MHz
Band 4:	120 kHz - 250 kHz	Band 9:	5.0 MHz - 10.0 MHz
Band 5:	250 kHz - 500 kHz	Band 10:	10.0 MHz - 20.0 MHz

Spot frequency measurements, although not recommended, shall be considered sufficient provided that a minimum of two frequencies are measured per octave and the ratio of successive frequencies does not exceed 1.6.

6.2 Sweep Rate - Either manual or automatic frequency scanning may be used, provided the scanning is sufficiently slow to ensure that the peak current levels have been measured. As a check, fix tune the receiver to a frequency in the band in question and observe the measured level. Then reduce the scan rate for that band until the detected level approximates (within 1 dB) the fix-tuned level at that particular frequency.

6.3 Operating Conditions - All of the following conducted emission measurements shall be made while the batteries are at less than 80% energy capacity and with the battery charger operating in the charge mode.

6.4 Measurement Setup - Position the EV and associated measurement equipment such that the test site conditions given in Section 5 are satisfied. Hook up the equipment as shown in Figure 1. Connect the ground leads of PCF and PCM to the "ground" connector (or its equivalent) of one LISN. Keeping the leads as short as possible, connect the "ground" connector(s) of the other LISN(s) together (see Figure 1). Connect each current carrying conductor of PCF to the "test sample" connector (or its equivalent) of an LISN. Next, connect each current carrying conductor of PCM to the corresponding "power source" connector (or its equivalent) of an LISN. Connect the ac power cord (provided with the battery charger) to the PCF such that both cords are uncoiled and do not lie within 10 cm of any metallic surface. Measurements shall be made on each current carrying conductor of PCF by clamping the current probe around the appropriate conductor.

6.5 Measurement Procedure

6.5.1 Ambient Measurements - The purpose of these measurements is to determine the levels of ambient noise and RF carriers. Measurements shall be made over the applicable frequency range for each ac current carrying conductor. Measurements shall be made for each band with the charger

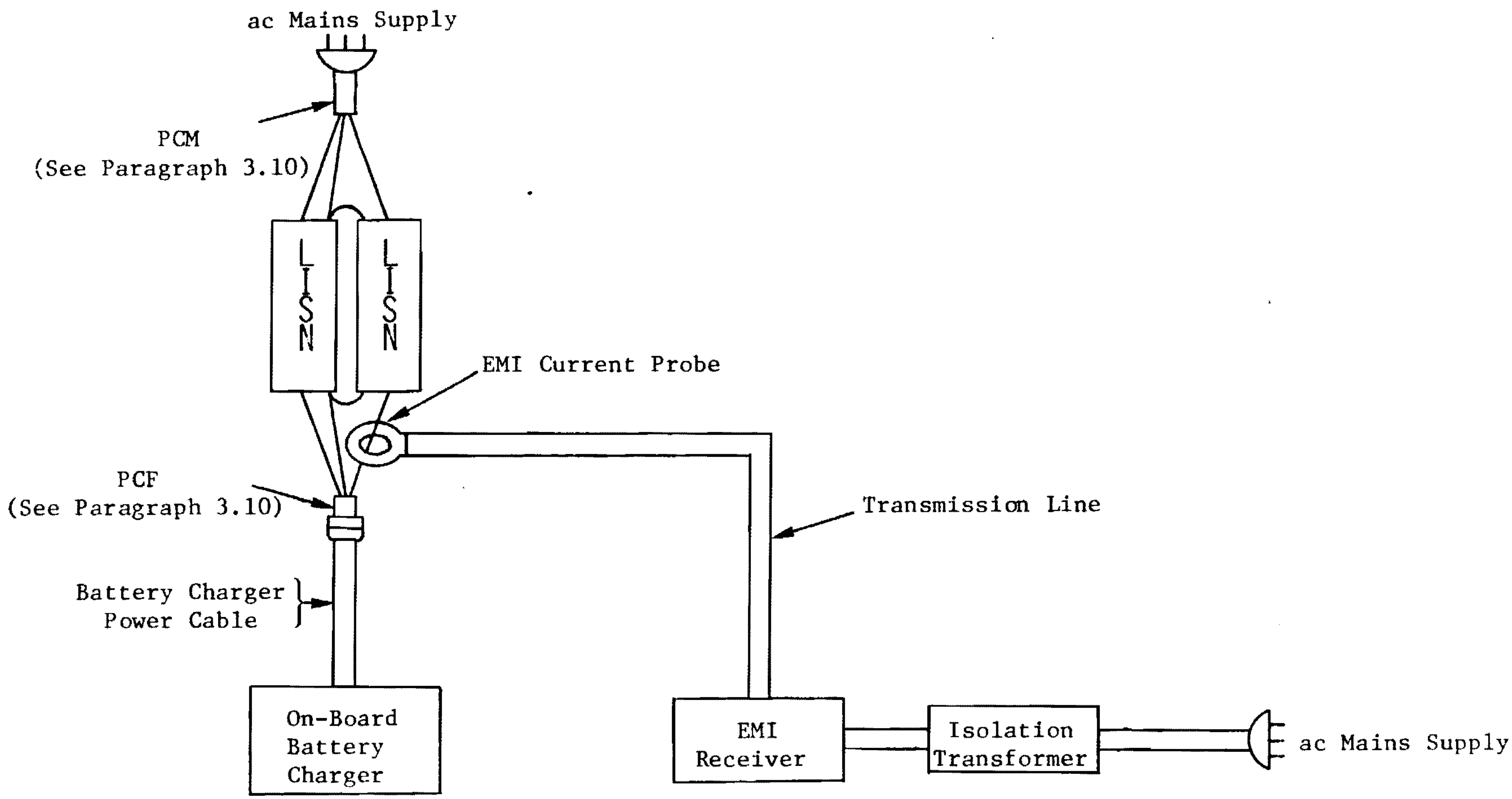


Figure 1. Block Diagram of Conducted Emission Measurement Setup

power cable disconnected at the input to the battery charger and immediately before the charger measurements. Data shall be recorded in terms of received voltage (in dBμV or dBμV/kHz) versus frequency.

6.5.2 Battery Charger Measurements - The battery charger shall be measured for each band as stated in the previous paragraph except that the charger power cable will be connected and the charger will be operative as specified in Paragraph 6.3. Data shall be recorded in terms of received voltage (in dBμV or dBμV/kHz) versus frequency.

7. Data Reduction - The impulse current level shall be calculated from the received voltage levels as measured in Paragraph 6.5.2.

7.1 Impulse Current Level - Impulse current level shall be expressed in units of decibels above one microampere per kilohertz bandwidth (dBμA/kHz). If the receiver has not been calibrated with an impulse generator, the equation relating impulse current level to the received voltage level is:

$$I_i = V_r + TL - BF - Z_t$$

where:
- I_i = Impulse current level in dBμA/kHz,
- V_r = Received voltage level in dBμV,
- TL = Transmission line insertion loss in dB (see Paragraph 4.4.1),
- BF = Bandwidth calibration factor in dB (see Paragraph 4.1.4), and
- Z_t = Transfer impedance of current probe in dB (see Paragraph 4.3.1).

If the receiver has been calibrated with an impulse generator, the equation which should be used is:

$$I_i = V' + TL - Z_t$$

where V' is the receiver reading in dBμV/kHz.

8. Assessment of Results

8.1 Characteristic Level - The characteristic level for each band (used for the purpose of comparison with the recommended level) is defined to be the maximum measured value obtained for that band for all leads tested. The characteristic level shall be compared to the recommended performance level at the arithmetic center frequency of the band. Known ambient carriers and broadband noise shall be ignored in determining characteristic levels.

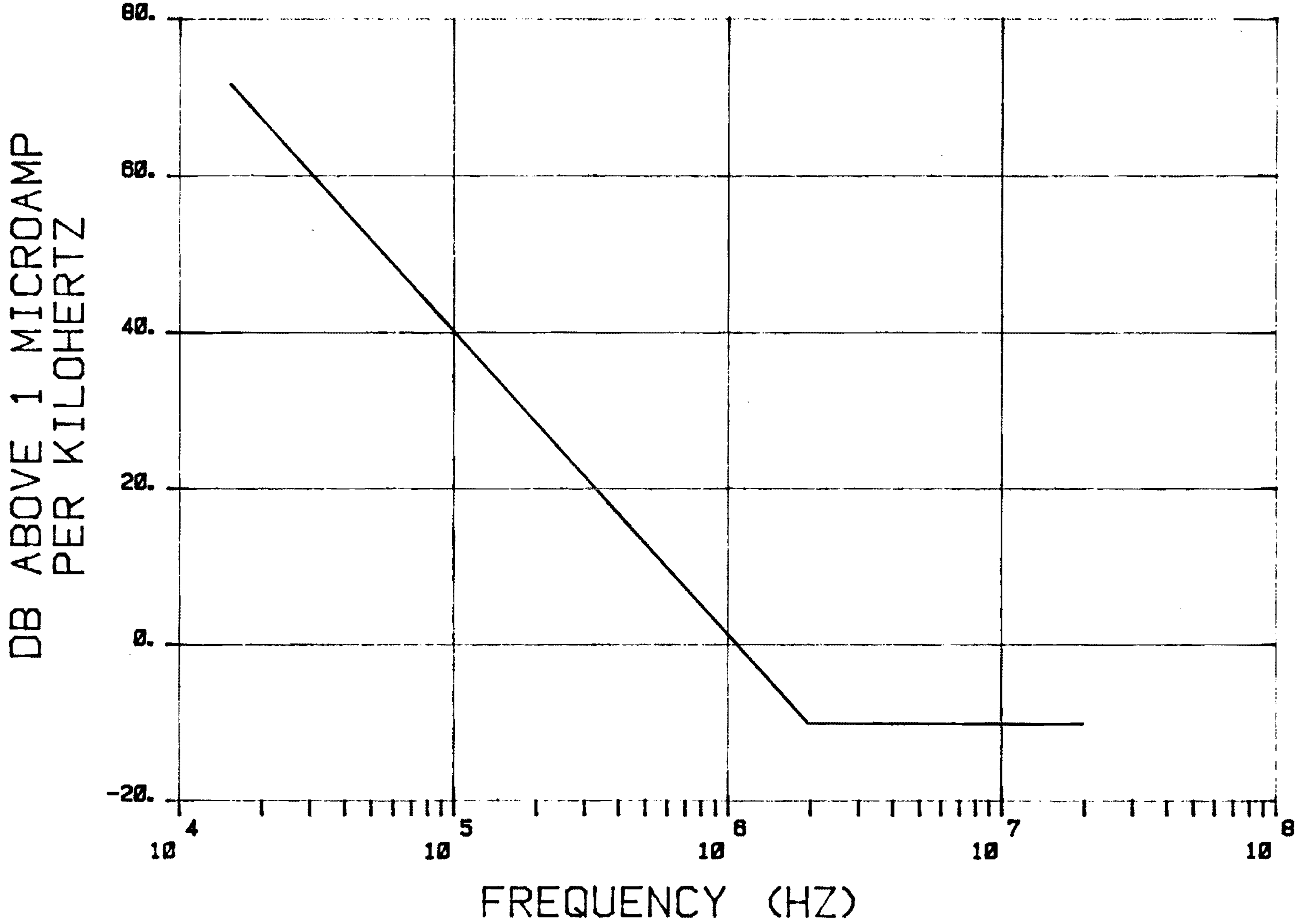
8.2 Recommended Performance Levels - The recommended performance levels, based on peak measurements, are given in Appendix I. The corresponding quasi-peak levels are 20 dB lower than the peak levels.

8.3 Method of Checking for Compliance with Recommended Limits - Results from a single battery charger may be used to determine compliance provided that the battery charger tested is representative of production-line battery chargers. Measurement may also be made on a sample of six or more chargers and statistical analysis applied to the characteristic levels in order to determine compliance. In this case, the characteristic levels shall be evaluated as given in Appendix II.

APPENDIX I

RECOMMENDED PERFORMANCE LEVELS FOR CONDUCTED PEAK IMPULSE CURRENT AMPLITUDE

$$\text{LEVEL} = \begin{cases} 71.0 - 38.12 \log_{10}[\text{FREQ(kHz)}/15] \ \text{dBuA/kHz} & (14 \text{ kHz} \leq \text{FREQ} < 2 \text{ MHz}) \\ -10.0 \ \text{dBuA/kHz} & (2 \text{ MHz} \leq \text{FREQ} \leq 20 \text{ MHz}) \end{cases}$$



Recommended Performance Levels For Conducted Peak Impulse Current Amplitude.

APPENDIX II

STATISTICAL ANALYSIS OF MEASUREMENT RESULTS ON SIX OR MORE BATTERY CHARGERS

The criteria to be used is 80% conformance with 80% confidence. The following condition must therefore be satisfied:

$$\bar{x} + kS_n \leq L$$

where: $\bar{x}$ = Arithmetic mean of the results on n battery chargers,

k = Statistical parameter dependent on n,

S_n = Standard deviation of results on n battery chargers,

L = Recommended performance level, and

$\bar{x}$, S_n, and L are all expressed in the units used for the recommended performance levels.

The statistical parameter k is determined using the following table:

n =	6	7	8	9	10	11	12
k =	1.42	1.35	1.30	1.27	1.24	1.21	1.20

The standard deviation, S_n, is determined by the following equation:

$$S_n = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}$$

where x_i is the individual result for the i^{th} battery charger tested.

INVESTIGATION OF ELECTRIC VEHICLE EMI/EMC AND ITS CONTROL

By

John K. Daher
Jimmy A. Woody

Submitted to

THE AEROSPACE CORPORATION

FINAL TECHNICAL REPORT

Project A-3089

INVESTIGATION OF ELECTRIC VEHICLE EMI/EMC AND ITS CONTROL

By

John K. Daher

Jimmy A. Woody

March 1983

Submitted to

THE AEROSPACE CORPORATION
Suite 4000
955 L'Enfant Plaza
Washington, D.C. 20024

Prepared by

ELECTROMAGNETIC COMPATIBILITY DIVISION
Electronics and Computer System Laboratory
Georgia Institute of Technology
Atlanta, Georgia 30332

A Unit of the University System of Georgia

ABSTRACT

The overall objective of this program was to characterize the electromagnetic interference (EMI) and electromagnetic compatibility (EMC) of electric vehicles (EV's). In order to accomplish this objective, various radiated and conducted measurements were performed on three different EV's. Radiated emission test procedures were developed which are consistent with current practices of the Society of Automotive Engineers (SAE) and the International Special Committee on Radio Interference (CISPR). Conducted emission test procedures, patterned after the United States Department of Defense's MIL-STD-462, were also developed for on-board battery chargers. Radiated susceptibility of EV's was investigated by injecting signals into potentially susceptible ports, the levels of which were calculated from a coupling model using the maximum expected field level from various radio transmitters as input.

The radiated emission measurement results indicate that the majority of the electromagnetic energy was concentrated below 100 MHz and it was concluded that EV's similar in design to those tested are not likely to create an interference problem with communication services operating above 100 MHz. The radiated levels at lower frequencies were often quite large, however, and it appears that EMI suppression may be required on some EV's in order to avoid interference to users in the medium and high frequency bands. Conducted emission levels from on-board battery chargers were also quite large and EMI suppression is probably needed in this area as well. EV susceptibility to the electromagnetic environment is not considered to be a problem area.

FOREWORD

This report was prepared by the Electronics and Computer Systems Laboratory of the Engineering Experiment Station at the Georgia Institute of Technology under Purchase Order No. W-0350, Georgia Tech Project A-3089. The work described in this report was directed by Mr. J. A. Woody, Project Director, and Mr. J. K. Daher, Assistant Project Director, under the general supervision of Mr. H. W. Denny, Chief of the Electromagnetic Compatibility Division.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

APPENDICES **PAGE**

LIST OF FIGURES AND TABLES

FIGURES **PAGE**

TABLES

1. Introduction

1.1 Background

Electrically powered vehicles (EV's) are currently receiving considerable attention as an alternative to gasoline powered vehicles. The various propulsion and control systems on the electric vehicle inherently produce electromagnetic (EM) signals at frequencies in addition to those associated with normal operation. For example, brushes, sliprings, and commutators on motors exhibit sparking and produce surges in power leads. Silicon controlled rectifier (SCR) or transistor controllers, diode rectifiers, switches, and relays typically have large electrical transients associated with their operations. These sudden and large changes in the electric power system cause spurious electromagnetic signals to be generated. Through propagation along the wiring harnesses, such signals can radiate into the environment and thus pose a potential threat of electromagnetic interference (EMI) to other electric vehicles, land mobile communication systems, air traffic controllers, or other electrical/electronic systems.

In addition to contributing to the electromagnetic environment, electric vehicles (and any others containing electronic systems) are potentially susceptible, i.e., may experience electromagnetic compatibility (EMC) problems, to exposure to various EM fields. These fields result from electric power transmission lines, commercial radio and television broadcast stations, land mobile radio services (including citizens band radio), military installations, and natural sources such as lightning. These fields can exhibit intensities of up to hundreds of volts per meter. Such intense fields may penetrate the body of the vehicle* and induce voltages and currents on cables and in devices at sufficient levels to cause damage or momentary upset in critical vehicle components. Of particular concern are susceptible components which might jeopardize the safety of passengers or other individuals in the vicinity of the vehicle.

So long as only a limited number of EV's are in use, associated EMI effects are not expected to be one of the major problems with the nation's transportation system. In the event, however, that there should some day be millions of such vehicles on the road, the total impact of vehicular

---

*The degree of coupling of external EM fields to internal circuits can be expected to increase as the use of non-metallic bodies for vehicles becomes more prevalent.

emanations could be large. (Gasoline engine exhaust emissions are a good case in point.) Therefore, a definition of the nature of potential EMI/EMC problems that may be associated with electrically propelled vehicles during the early stages of their development is appropriate. In this way, potential problems can be assessed and corrective actions defined at minimum costs to the motoring public. (It has been historically experienced by the defense and communications communities that EMI suppression and correction can be applied with lower costs during design phases than they can as post-design retrofits.)

1.2 Program Scope and Objective

The scope of the program was an investigation of electric vehicle EMI and EMC.

The objective of the program was to investigate the effects of EMI/EMC on and by electric vehicles (EV's), to determine problem areas, and to identify potential corrective measures. Specific tasks included: (1) a study to define the EMI-related requirements for EV's; (2) development of appropriate test procedures; (3) performance of a representative set of emission and susceptibility measurements on selected current production EV's; and (4) documentation of program activities and results.

1.3 Report Summary and Organization

This technical report describes the significant findings obtained during the program. In particular, the results of measurements performed on three different test vehicles are documented.

The material which follows in this report is divided into five major sections. The EMI/EMC evaluation methodology for EV's is presented in Section 2. The measurements performed and a summary of the findings are given in Section 3. The EMI test procedures are presented in Section 4. Section 5 presents the conclusions, and Section 6 provides recommendations for future investigations.

Five appendices are included in the report. Appendices I and II contain the radiated and conducted emission data, respectively. Appendix III presents an analysis of the potential impact of EV emissions on standard AM broadcast reception. Appendix IV is the radiated emission test procedure, and Appendix V is the conducted emission test procedure.

2. EMI/EMC Evaluation Methodologies

2.1 Radiated Emissions From Electric Vehicles

The approach utilized in the selection of a radiated emission evaluation methodology began with an analysis of several applicable measurement procedures. The procedures of major emphasis included the Society of Automotive Engineers (SAE) J551 JUN81 ("Performance Levels and Methods of Measurements of Electromagnetic Radiation from Vehicles and Devices (20-1000 MHz)"), the International Special Committee on Radio Interference (CISPR) Publication 12 ("Limits and Methods of Measurement of Radio Characteristics of Vehicles, Motor Boats, and Spark-Ignited Engine-Driven Devices"), the United States Department of Defense's MIL-STD-462 ("Measurement of Electromagnetic Interference Characteristics"), and the Institute of Electrical and Electronics Engineers (IEEE) Std. 263 ("Standard for Measurement of Radio Noise Generated by Motor Vehicles and Affecting Mobile Communications Receivers in the Frequency Range 25 to 1000 Megacycles per Second"). These documents were analyzed in depth to assess their applicability to the fulfillment of regulatory and technical requirements of EV's.

Next, a brief review and analysis of current EV technology was undertaken in order to determine potential measurement requirements which might be unique to electric vehicles. A review of current controller technology indicated that the pulse characteristics associated with EV's are significantly different than those associated with internal combustion powered vehicles (ICV's). An analysis of the impact of these characteristics on the maximum receiver scan rate required for peak pulse measurements was made and documented in a technical report [1]. The analysis and review also indicated that the evaluation procedures should provide for measurements below 20 MHz since a significant amount of energy was expected below this frequency. In addition, the EMI characteristics of EV's were expected to be a function of the loading on the motor and, therefore, the evaluation methodology was structured to allow examination of loading effects.

Finally, a radiated emission evaluation methodology was prepared using the method of approach outlined above. The radiated emission methodology was documented in Appendix I of the Interim Technical Report entitled "EMC/EMI Investigations on Jet Industries Electrica" and will not be repeated here. The purpose of the evaluation methodology was to provide guidance in obtaining information and data from which a characterization of the EMI features of an EV can be made. Detailed guidelines were outlined for measuring the radiated emission characteristics of an EV over the frequency range of 14 kHz to 1000 MHz. Procedures were also given for determining worst-case load conditions and for measuring radiated emissions under varying load conditions and motor speeds. Also included were guidelines for measuring representative electromagnetic emission levels while the vehicle is driven past a receiving antenna at a constant speed, during acceleration, and during deceleration (braking). The radiated emission evaluation methodology was utilized in obtaining baseline data on the emission characteristics of the three test vehicles.

Measurement of radiated emissions from on-board battery chargers was considered to be inappropriate for the following reasons. First, radiated measurements on battery chargers were concluded to be impractical due to a lack of repeatability, primarily associated with the random positioning of the charger power cord which can act as a radiating element for the RF emissions from the battery charger. Second, the radiated levels are expected to be a function of the characteristics of the ac power mains (i.e., impedance, load, geometry, etc.), which are difficult to control. Finally, it is believed that conducted emission testing (which would be required with or without radiated testing) gives a good indication of the relative potential for excessive radiated emissions. That is, large conducted levels typically imply large radiated levels and vice versa. For these reasons, radiated testing of battery chargers was considered to be inappropriate and conducted testing was considered to be the preferred approach.

2.2 Conducted Emissions From On-Board Battery Chargers

A conducted emission evaluation methodology was also prepared using a method of approach similar to that given above. Several documents covering various conducted emission measurement techniques, apparatus, and requirements were assessed for their applicability to battery charger measurements [2]-[8]. The conducted emission measurement techniques which were considered for the present application can be categorized as being either stabilizing or non-stabilizing. Stabilizing techniques attempt to fix the ac power line impedance at some arbitrary but known value whereas non-stabilizing techniques measure emission characteristics while creating a minimum amount of disturbance to the power line circuit (i.e., no networks or devices are inserted in series or parallel with the power line). The non-stabilizing techniques which received consideration include the absorbing clamp [5], the directional current probe [6], and the maximum available power techniques [7]. These techniques suffer from the problem of an unknown and variable power line impedance which may significantly influence the accuracy and repeatability of the measurement results. Since the absorbing clamp technique is specified for use in some European EMC standards [8], [9], it was initially considered as a potential technique. This technique was later discarded as being too costly to justify its usefulness over a single decade in frequency range (30-300 MHz).

In addition to the three non-stabilizing techniques mentioned above, two stabilizing techniques were considered: namely, the line impedance stabilization network (LISN) and the feedthrough capacitor techniques. In concept, both techniques attempt to provide a well-defined impedance across the terminals of the device under test at the test frequency while simultaneously isolating the undesired RF signals existing on the power line from the emission currents. The feedthrough capacitor technique is required by Test Methods CE01 and CE03 of MIL-STD-462 and the test configuration is shown schematically in Figure 1. The capacitor is intended to offer a low shunt impedance to both the emission source and the undesired RF power line signals while passing the power line 60 Hz signal to the device-under-test. In practice, the capacitor impedance at frequencies below about 10 kHz is comparable to or greater than that of power line. At higher frequencies, the nonzero capacitor impedance still allows the power line impedance to influence the measurement results. Measurement error with this technique has been shown to be large in some instances and, in fact, to exceed that resulting from the LISN technique [10].

The LISN technique was, therefore, selected in favor of the feedthrough capacitor technique due to improved measurement accuracy over a broad frequency range. The particular LISN technique utilized is a slight modification to that of Test Methods CE02 and CE04 of MIL-STD-462 Notice 3. The test setup may be represented schematically as shown in Figure 2. The "P" subscripts refer to the ac power line quantities and the "E" subscripts refer to the battery charger emission quantities. The battery charger and the ac power source are each represented by their Thevenin equivalent voltages, V_E and V_P, and their equivalent impedances, Z_E and Z_P, respectively. The shunt

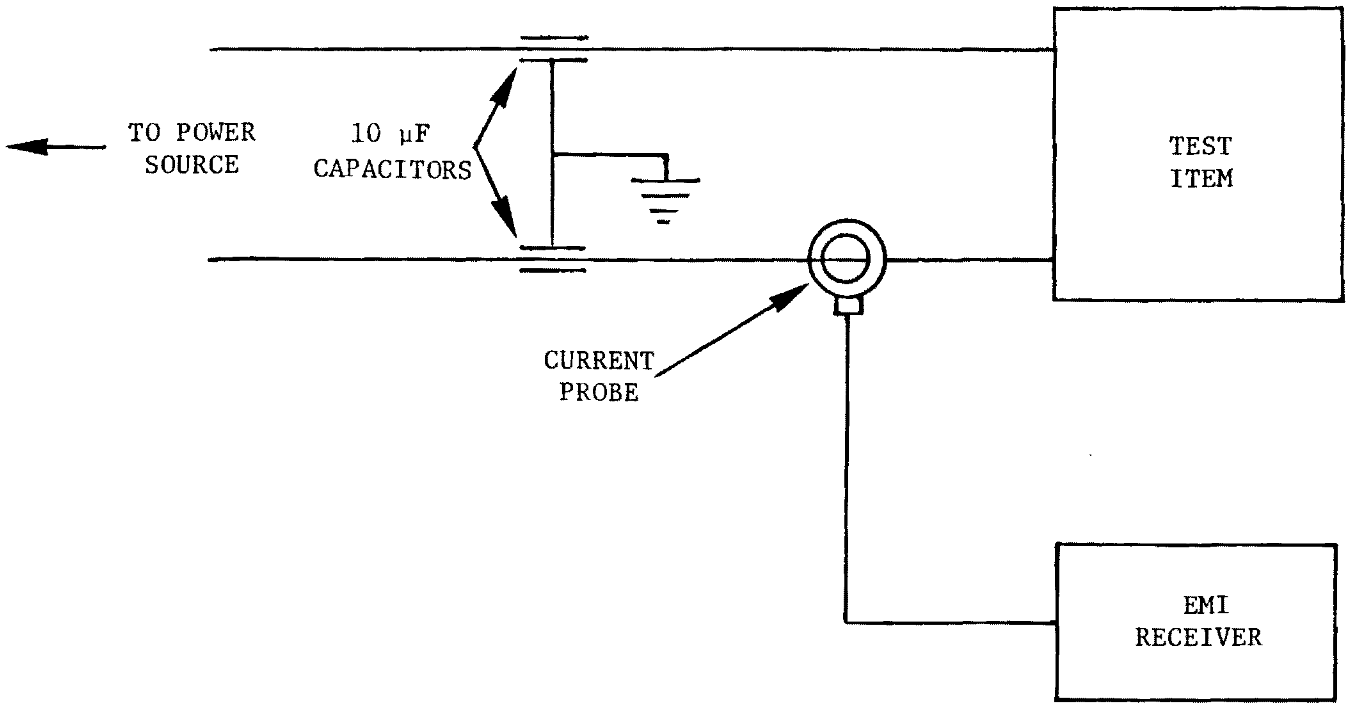


Figure 1. Basic Test Method CE01 and CE03 Test Configuration.

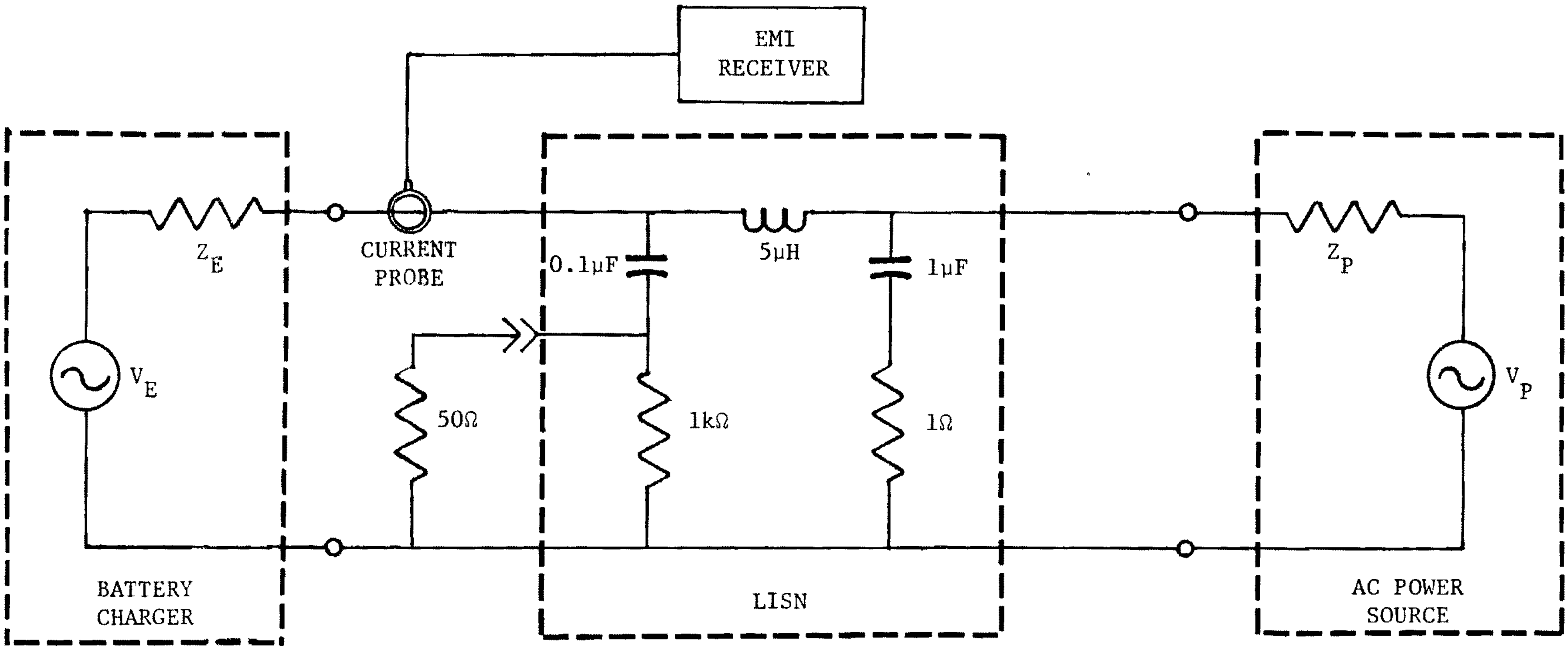


Figure 2. Schematic Representation of Conducted Emission Test Setup.

capacitors and series inductor are designed to pass the 60 Hz power current while isolating the undesired RF signals on the ac power line from the emission currents. The conducted emission current levels are monitored with an EMI current probe whose output is connected to a receiver. The output port of the LISN is terminated with a 50 ohm load so that the battery charger "sees" a nominal 50 ohm impedance over an appreciable frequency range, which allows for improved repeatability in the measurement results.

The test setup used for measuring conducted emissions from on-board battery chargers is diagrammed in Figure 3. The measured quantity is the impulse (broadband) current amplitude which emanates from the battery charger. A short piece of power cord (less than 30 cm) is plugged into the end of the battery charger power cable which is provided by the EV manufacturer. The three wires (black, white, and green) of the short cord are then separated and the black and white wires fed into the test sample input of each of two LISN's. The green wire is electrically connected to the metal case of both LISN's. A current probe is then successively clamped around both black and white wires to measure the broadband emission current levels. An audio isolation transformer is used to prevent RF ground currents from flowing in the EMI receiver chassis ground. A lower frequency limit of 14 kHz was selected for these measurements because of the difficulties associated with isolating the relatively high RF and 60 Hz harmonic levels on ac power lines from the test sample EMI currents at lower frequencies. The upper frequency limit was selected to be 50 MHz since: (1) distributed and parasitic effects in the LISN circuitry and power line cabling reduce the accuracy of the test setup at higher frequencies and (2) radiation interference tends to dominate over conducted interference at VHF frequencies and above. The conducted emission test setup was used to evaluate the EMI characteristics of the battery charger located on board each of the last two vehicles tested.

2.3 Electromagnetic Susceptibility of Electric Vehicles

The objective of the susceptibility investigation was to determine if potential problem areas exist in which electromagnetic energy from external sources could cause degradation to the normal operation of the EV. The scope of the investigation was limited to those vehicle malfunctions which potentially jeopardize the safety of passengers or other individuals in the vicinity of the vehicle. Radiated, rather than conducted, susceptibility

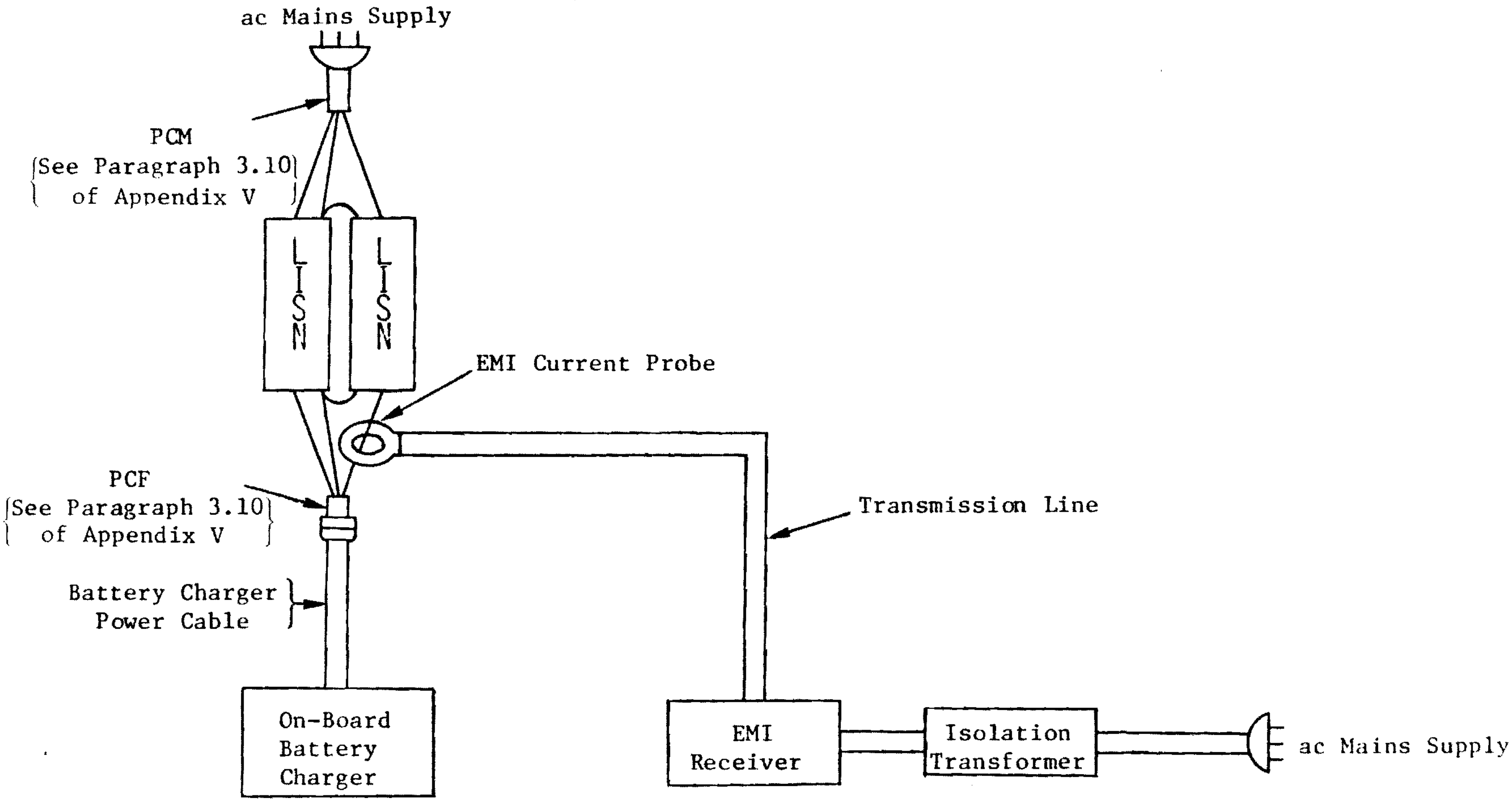


Figure 3. Block Diagram of Conducted Emission Measurement Setup.

was, therefore, of primary concern since no conduction paths should exist when the vehicle is in operation.

Susceptibility may be evaluated via measurements, analysis, or a combination of the two. Susceptibility measurements may either be performed at the component level or the vehicle may be tested as an entire unit. SAE J1113a ("Electromagnetic Susceptibility Procedures for Vehicle Components (Except Aircraft)") provides test procedures applicable to EV's at the component level. However, experience has shown that meaningful radiated susceptibility measurements require the entire system (vehicle) to be exposed to its intended RF environment since individual components, which may not be susceptible when tested individually, may indeed be susceptible when tested together as a whole. SAE J1338 JUN81 ("Open Field Whole-Vehicle Radiated Susceptibility, 10 kHz - 18 GHz, Electrical Field") covers system susceptibility measurements and is entirely applicable to EV's provided that means are available to vary the operating conditions (load, speed, etc.) during the testing. This procedure has some technical drawbacks, however, because of the severe requirements created from the recommended 200 volts per meter field intensity which is to be generated over a wide frequency range. These requirements necessitate the use of a large number of transmitting antennas and high power signal sources, as well as extremely close spacing (1 meter) between the transmitting antenna and the vehicle-under-test. The large number of transmitting antennas and high power sources add significantly to the costs of performing the susceptibility tests. The short separation distance of 1 meter leads to a number of measurement uncertainties and inaccuracies (particularly at low frequencies) which are characteristic of almost all radiated tests which are performed in the extreme near-field. This procedure is nevertheless recommended over other currently existing measurement procedures. SAE J1338 was not used on this program, however, primarily because of scheduling conflicts due to an estimated three to four month time requirement for obtaining an FCC experimental license (which must be obtained before these open field radiated susceptibility tests can be initiated). For the technical and scheduling reasons given above, a purely experimental approach was not utilized on this program.

An analytical approach to EV susceptibility evaluation involves the use of coupling analyses to predict the signal levels induced on the leads of potentially susceptible components by electromagnetic fields incident on the vehicle. The approach taken on this program utilized both measurement and analysis in evaluating susceptibility. First, the coupling from known RF transmitters to conductors within the EV was predicted, expedited by a number of simplifying assumptions. Since these assumptions ultimately limit the accuracy of the results*, they were made in such a way that the predicted levels would be near the upper limit of what might realistically be encountered in actual operation. A potential interference condition was then examined by actually injecting the predicted levels on the signal leads of interest. In this way, (1) the potential effects of field distributions and intensities which are difficult or impossible to achieve with conventional instrumentation was evaluated and (2) the interference levels of potentially susceptible circuits and devices were directly characterized.

---

*A precise analytical evaluation of EV susceptibility would require the entire vehicle (including structural geometries and internal wiring configurations) to be accurately modeled and a numerical solution of Maxwell's equations to be found for the particular transmitter, vehicle, and orientation being analyzed. This approach was clearly beyond the scope of the program, particularly since the analysis must be repeated for each permutation of vehicle, transmitter, and orientation to be considered.

3. EMI/EMC Vehicle Investigations

3.1 Vehicle Descriptions

Three different electric vehicles were tested with the objective of defining their electromagnetic emission and susceptibility characteristics. A brief description of these vehicles is given in Table 1. These vehicles were selected as being representative of the current state-of-the-art in EV technology and as having characteristics similar to what might be expected of EV's over the next several years.

TABLE 1. Electrical Characteristics of EV's Tested

Characteristic	Jet Industries/ Electrica	Electric Vehicle Associates/ Evcort	Unique Mobility/ Electrek
Motor	Series DC, 400A	Shunt DC, 400A	Shunt DC, 300A
Controller	Transistorized 4 kHz PRF Pulse Width Modulation	Transistorized 400 Hz PRF Pulse Width Modulation	Transistorized 400 Hz PRF Pulse Width Modulation
Battery Voltage	96V	108V	96V
Battery Charger	220 VAC Input 96/12 VDC Output 30 A Max. Current	120 VAC Input 108/12 VDC Output 16 A Max. Current	120 VAC Input 96/12 VDC Output 16 A Max. Current
Body Type	Metal Body	Metal Body	Fiberglas Body

3.2 Preliminary Investigations

A number of preliminary investigations were required before the test procedure and instrumentation could be finalized for the radiated and conducted emission measurements. The initial measurement activities were focused on a comparison of noise field intensity meters (NFIM's) and spectrum analyzers for use as the EMI receiver. The NFIM used in this comparison was an Electro-Metrics EMC-25 Interference Analyzer. The spectrum analyzers utilized were an HP-8554L and a Tektronics 492-P. Several X-Y plots of EV radiated emission levels were recorded for selected bands in the 14 kHz to 1000 MHz frequency range. Measurements were made with each receiver using a number of different bandwidths, RF attenuation settings, and sweep rates. The objective of these measurements was to determine the validity of results obtained with each receiver and to determine optimal instrumentation settings. The spectrum analyzers proved to be inferior to the NFIM for two major reasons. First, the vertical output of the spectrum analyzers tended to respond to the time-averaged broadband noise levels rather than peak levels. (The envelope detectors utilized in these instruments are apparently too slow to capture the peak amplitude of the impulsive signals being measured.) However, the charge time of the EMC-25's peak detector is much less than the reciprocal of all IF bandwidth settings, which allowed true peak levels to be detected. Second, neither spectrum analyzer is equipped with an RF preselector (unlike the NFIM) and therefore they suffer problems with intermodulation interference generation and limited dynamic range. It was therefore determined that the EMC-25 was required to measure absolute emission levels and would be used for this purpose for the remainder of the vehicle investigations. The receiver was operated in the wide-band mode which enabled maximum sensitivity to be achieved. A sweep rate of approximately 60 seconds per octave band was utilized in order to reliably detect peak levels for all bands tested.

3.3 Radiated Emission Measurements

The radiated emission measurements began with near field probing at a one meter antenna-to-vehicle separation distance in order to determine the direction of maximum radiation. A spectrum analyzer was used during the probing to permit a visual display of the relative received signal levels over a wide bandwidth. The EV was then tested using an NFIM as the receiver with the receiving antenna placed 3 meters high and 10 meters distant from the side of the vehicle found to emit maximum radiation. Both vertical and horizontal polarizations of the electric and magnetic field intensities were measured from 14 kHz to 20 MHz using tunable rod and loop antennas. A biconical antenna was used to measure both vertical and horizontal components of the electric field intensity from 20 MHz to 200 MHz. A log conical spiral antenna was employed over the 200 MHz to 1000 MHz frequency range. The log conical spiral antenna is circularly polarized and therefore responds to both vertically and horizontally polarized fields. Measurements were also made of the magnetic field intensity inside the vehicle by placing a loop antenna on the passenger seat with the loop parallel to the seat back. Each vehicle was tested under three or four different load conditions ranging from no load (drive wheels suspended in the air) to maximum load (maximum recommended armature current draw or maximum obtainable current, whichever is less). An absorption (i.e., non-electrical) dynamometer was used to accurately and repeatably apply different load conditions without contributing additional electromagnetic energy of its own. The majority of the data was obtained while the vehicle was operated in high gear at 25 mph. However, tests were conducted on the EVA Evcort at 5 mph in first gear in addition to the 25 mph tests.

Drive-by measurements were also made on the Electrica at ten different frequencies. These measurements were made with the vehicle accelerating (in both forward and reverse gears), braking, coasting, and at constant speed. The radiated emission levels were recorded as the vehicle was driven by a receive antenna located 10 meters away from, and directed broadside to, the road. A vehicle speed of 15 mph in first gear was used for the constant speed tests. During the braking tests, the vehicle was driven at an initial speed of 15 mph in first gear and the brakes were subsequently applied in order to bring the vehicle to an even stop beginning 10 meters before and ending 10 meters past the antenna. The coasting tests were conducted in the same way as the braking tests except that neither the accelerator nor the brake pedal was depressed over the 20 meter distance. The acceleration tests were run with the vehicle in first (or reverse) gear beginning in each of three stationary positions: with the vehicle's leading (or trailing) edge 10 meters before, even with, and 10 meters past the receive antenna. Beginning at a standstill, the accelerator pedal was fully depressed until the vehicle was some 25 meters past the antenna.

The maximum impulse electric field intensity for each of the drive-by test conditions is shown in Table 2. The levels measured during vehicle acceleration exceeded those for constant speed, braking, and coasting at all test frequencies except 870 kHz and 22 MHz, at which the levels for the acceleration modes were significantly less than the levels for the other three modes of operation. Unlike the "static" dynamometer tests, these tests could not be performed while the receiver was scanning in frequency since the vehicle position relative to the antenna was changing with time. The drive-by tests were therefore more time consuming and also lacked repeatability due to the additional "operator" variables which were difficult to control precisely. The drive-by tests were subsequently discarded in favor of the tests run on the dynamometer.

TABLE 2. Jet Industries Electrica Radiated Emission Data From Drive-By Measurements

	Maximum Impulse Electric Field Intensity (dBμV/m/kHz)				
FREQ. (MHz)	CONST. SPEED	BRAKING	COASTING	FWD. ACC.	REV. ACC.
0.45	23.9	14.9	15.4	24.9	24.9
0.87	40.9	38.9	38.9	21.7	21.7
1.0	<7.2	<7.2	<7.2	16.9	16.1
2.0	24.1	10.1	12.1	25.6	26.6
2.2	18.1	9.6	10.6	21.5	21.2
2.5	11.2	5.7	5.7	13.7	13.5
3.5	11.1	1.6	3.6	13.0	13.4
4.8	8.4	-0.6	-0.1	9.4	9.4
7.0	1.5	-2.5	-1.0	1.5	2.0
22.0	39.1	36.1	35.6	7.1	9.1

3.4 Conducted Emission Measurements

The conducted emissions from on-board battery chargers were measured for two different EV's. Conducted interference currents from both the black (phase) and white (neutral) conductors were measured in octave bands over the frequency range of 14 kHz to 50 MHz using the test configuration shown in Figure 3. Measurements on the Evcort were made with the batteries at near full charge capacity. Consequently, the battery charger toggled back and forth during the measurements between the full charge and the trickle charge modes of operation. As can be seen in Figure 4, the resultant conducted emission levels also switched back and forth, from a relatively large level for high charging rates to a relatively low level during trickle charge operation. (The same frequency band was often repeated so that these large variations could be recorded.) Measurements on the Electrek were made with the batteries sufficiently discharged to insure that the battery charger was in the full-charge mode so that worst-case emission levels could be measured.

3.5 Electromagnetic Susceptibility Investigations

The interference scenario of major concern was the possibility of RF energy being coupled to the cables connected between the speed control potentiometer wiper contact and the speed control input to the controller. An RF signal coupled onto the control cable could then undergo audio rectification at the emitter-base junction of the first transistor in the input to the controller. If the rectified signal should supply sufficient bias to the transistor, loss of speed control could occur.

The initial analysis involved a citizen band (CB) radio transmitter as the potential interfering source. The power coupled between two antennas of known effective apertures was calculated from the well known Friis transmission formula,

$$P_r = P_t \frac{A_{er} A_{et}}{\lambda^2 r^2} , \qquad (1)$$

where:

P_r = power received by receiving antenna,

P_t = power transmitted by transmitting antenna,

A_{er} = effective aperture of the receiving antenna,

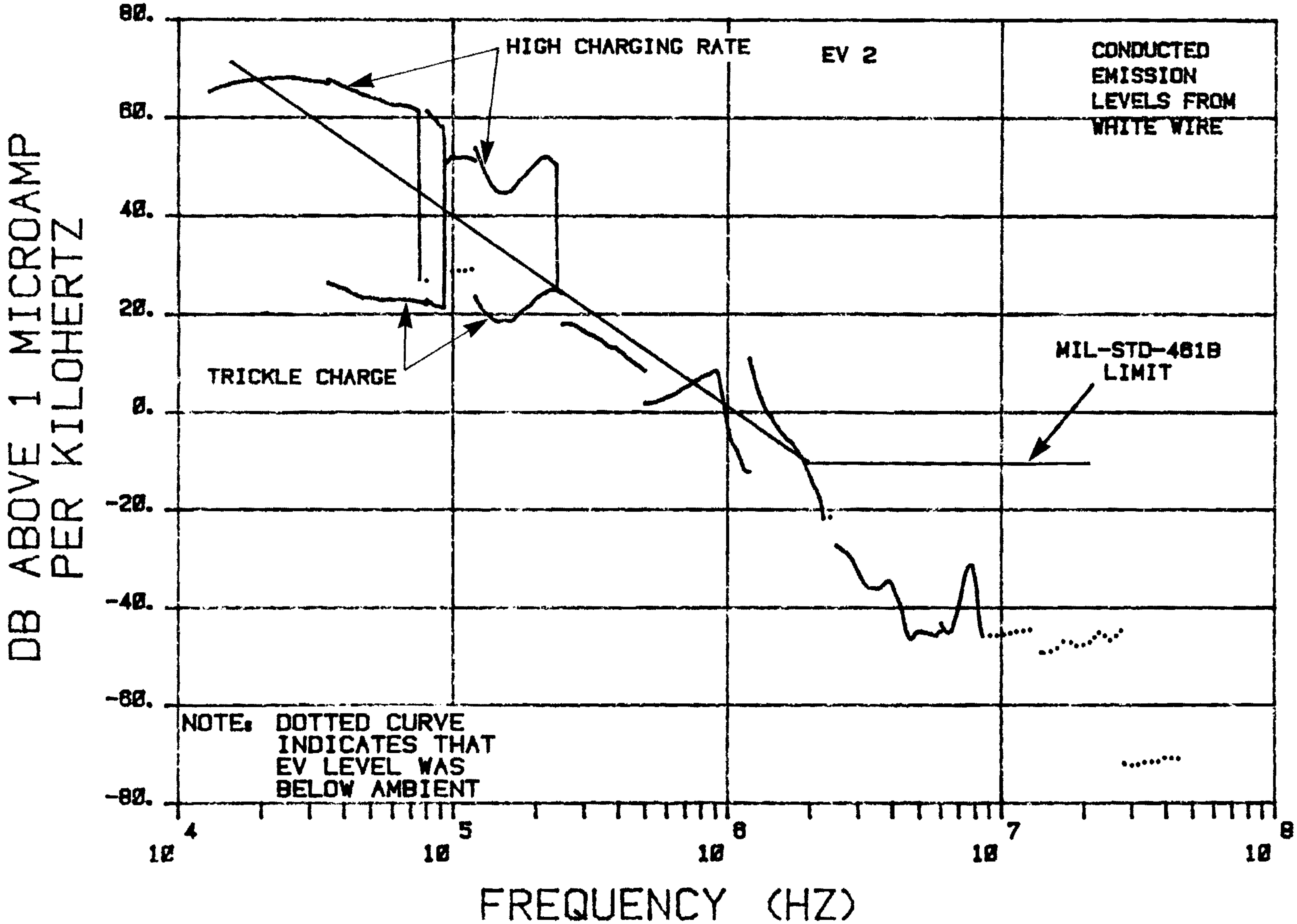


Figure 4. Conducted Emission Levels From Battery Charger of the Evcort.

A_{et} = effective aperture of the transmitting antenna,

λ = wavelength, and

r = separation distance between the antennas.

This formula is accurate provided that the following far-field condition holds:

$$r \geq \frac{2d^2}{\lambda} , \tag{2}$$

where d is the maximum dimension of either the transmitting or receiving "antenna". (Note that we are considering the speed control cable in the EV as a receiving antenna.) Assuming a frequency of 27 MHz, the free space wavelength turns out to be 11.11 meters. Using a value of 3 meters for d, the far-field distance boundary is approximately 1.6 meters. The distance (r) assumed for this analysis was 2 meters, which therefore satisfies the far-field condition.

Both of the effective apertures could be assumed to be equal to the maximum effective aperture of a tuned dipole ($0.13\lambda^2$) in order to determine the maximum amount of interference power that might be coupled to the EV cable. However, the effective apertures are actually much smaller due to the fact that the transmitting antenna is vertically polarized whereas the receiving antenna is horizontally polarized. This may be accounted for by assuming a 20 dB cross-coupling loss or, equivalently, by letting

$$A_{er} = A_{et} = 0.1 \times 0.13\lambda^2 \tag{3}$$

in Equation (1). Assuming a transmitted power of 5 watts (the maximum legally allowable input power to the final stage of a CB transmitter), the power received would be approximately 26 milliwatts or approximately 3.6 milliamps into a 2000 ohm input impedance. Transmitted power levels of 50 watts and 500 watts (not uncommon in the amateur radio bands) would result in RF current levels of approximately 11.4 milliamps and 36.1 milliamps, respectively.

Susceptibility measurements were made on the last two EV's tested by transformer coupling a known RF current level onto signal input leads of the controller. The four leads associated with vehicle speed control/regenerative braking were tested on both vehicles. A current probe was used to monitor the current levels injected. Any rotation of the drive wheels was to be considered a susceptible condition. The EV was placed on jack stands in order to minimize the loading on the motor and also to eliminate potential safety hazards. The initial test frequencies were selected within eleven commonly used frequency bands (citizens band, amateur radio band, etc.) ranging from 3.8 to 83.25 MHz. These bands are ones in which EV's are likely to be exposed to large field intensities. The first EV to undergo susceptibility testing was the Evcort. No susceptible conditions were found to exist for currents up to 11.4 milliamps continuous. However, a momentary current level of approximately 36 milliamps at 52.5 MHz caused the drive wheels to turn several times. The EV was also rendered inoperable due to a blown 400 amp fuse and some damaged components within the controller.

The damaged controller was subsequently replaced with a controller which had been modified to include bypass capacitors on all input ports in order to improve its susceptibility characteristics. The same four input leads were tested again at the eleven test frequencies. No susceptible conditions were found to occur with the modified controller for continuous input current levels of up to 11.4 milliamperes.

The model used in the initial coupling prediction was later refined to be more realistic and also to include several additional test frequencies lying within the AM/FM broadcast, VHF/UHF TV, and Public Service bands. Each input lead in conjunction with its (common) return lead was modeled as a two-conductor transmission line terminated at both ends. The model neglects the effects of other wires which were in close proximity to those of interest. With no depression of the accelerator pedal (which was the case during testing), one end of the transmission line is terminated in a short circuit. The other end of the transmission line is terminated with the controller input impedance. The conductor spacing was approximated to be 1 cm and the length to be 1 m. A model developed by Clayton R. Paul of the University of Kentucky [11] was implemented on an HP-1000 computer. The program plots the power coupled into the input of the controller as a function of propagation direction and polarization. For a fixed elevation angle of propagation and a fixed polarization, the coupled power into the controller was plotted as the azimuthal angle of propagation was continuously varied over a 180 degree range. By holding the polarization fixed while incrementing (in small angular steps) the elevation angle and vice versa, a series of plots was generated from which the maximum expected power (or current) level was determined for each of the various transmitter frequencies. Figure 5 illustrates the levels obtained for a normalized field intensity of 1.0 volt/meter and a frequency of 500 MHz (UHF TV). Levels based on maximum expected field intensities from various transmitters were subsequently calculated. (For example, the maximum coupled power level at 500 MHz was calculated to be -32.1 dBm.) These levels were then injected into the input of the controller used in the Unique Mobility Electrek and the responses were noted. No susceptible conditions were found. It should be noted that the Electrek's controller had also been equipped with bypass capacitors as had the modified controller used in the Evcort.

3.6 Data Reduction

The radiated and conducted emission data were recorded in the form of X-Y plots of received voltage level versus frequency. An example of a typical X-Y plot of the radiated emission levels is shown in Figure 6. Software was written to enable the raw data to be digitized and subsequently replotted in semilogarithmic format with calibration factors appropriately added. The calibration factors included: receiver bandwidth and gain correction factors, antenna and current probe calibration factors, and transmission line insertion loss. The calibrated results from the radiated and conducted emission measurements are contained in Appendices I and II, respectively.

3.7 Summary of Findings

A number of observations can be made based upon an analysis of the test results obtained during the program. However, definitive conclusions must be tempered by the acknowledgement of two major unknowns. First, even though the absolute radiated emission levels of three EV's are known, radiated emission data for internal-combustion-powered vehicles (ICV's) at frequencies below 20 MHz (the lower frequency limit of SAE J551) are scarce. Therefore, the severity of EV's as potential interference sources relative to ICV's is unknown. The second unknown concerns the fact that data has been obtained on only three EV's and generalizations to the entire class of current technology EV's must, therefore, be approached with caution. Also, new technologies appear to be on the horizon (e.g., ac propulsion systems) and

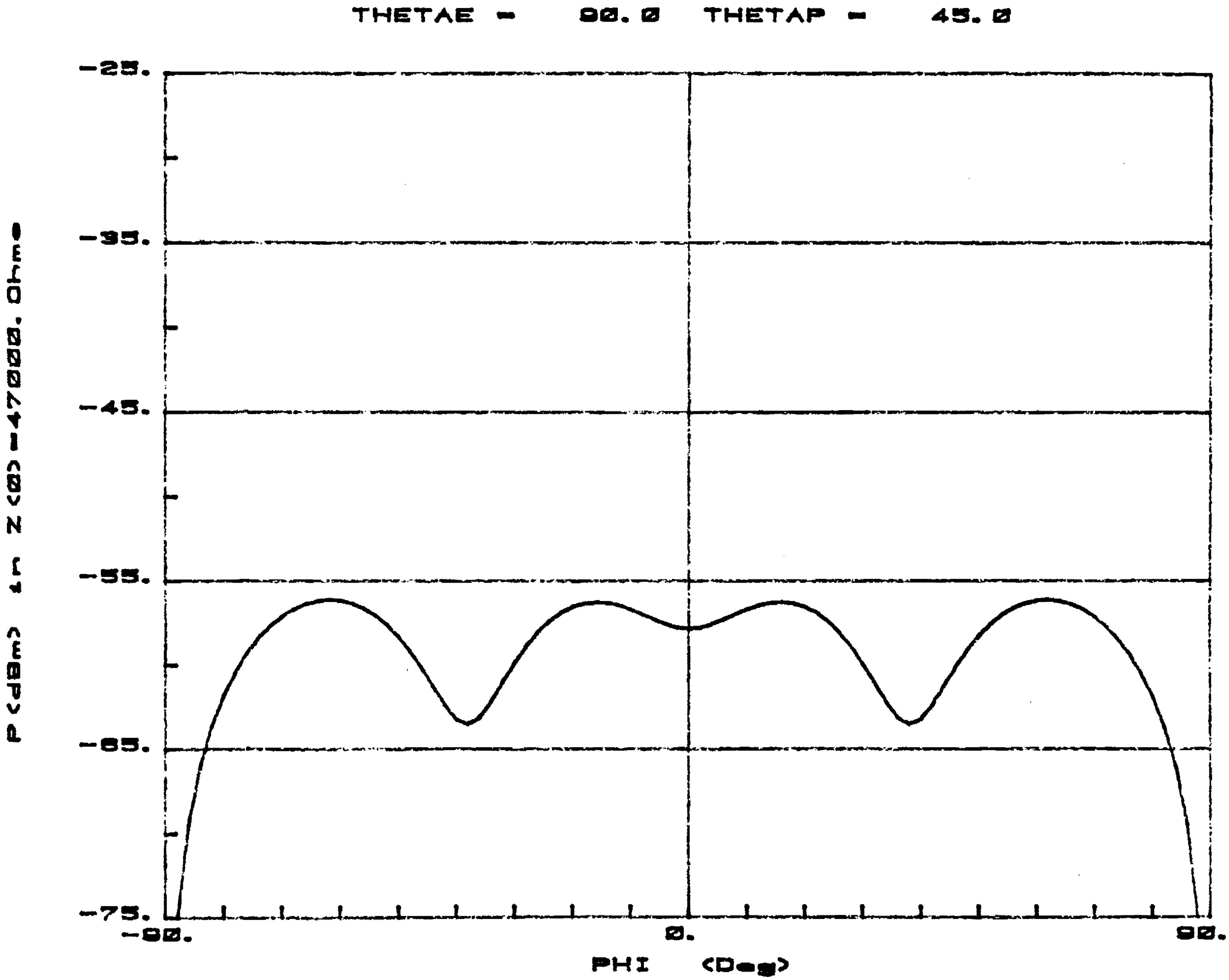


Figure 5. Calculated Power Levels Coupled Into EV Controller From 500 MHz UHF TV Transmitter.

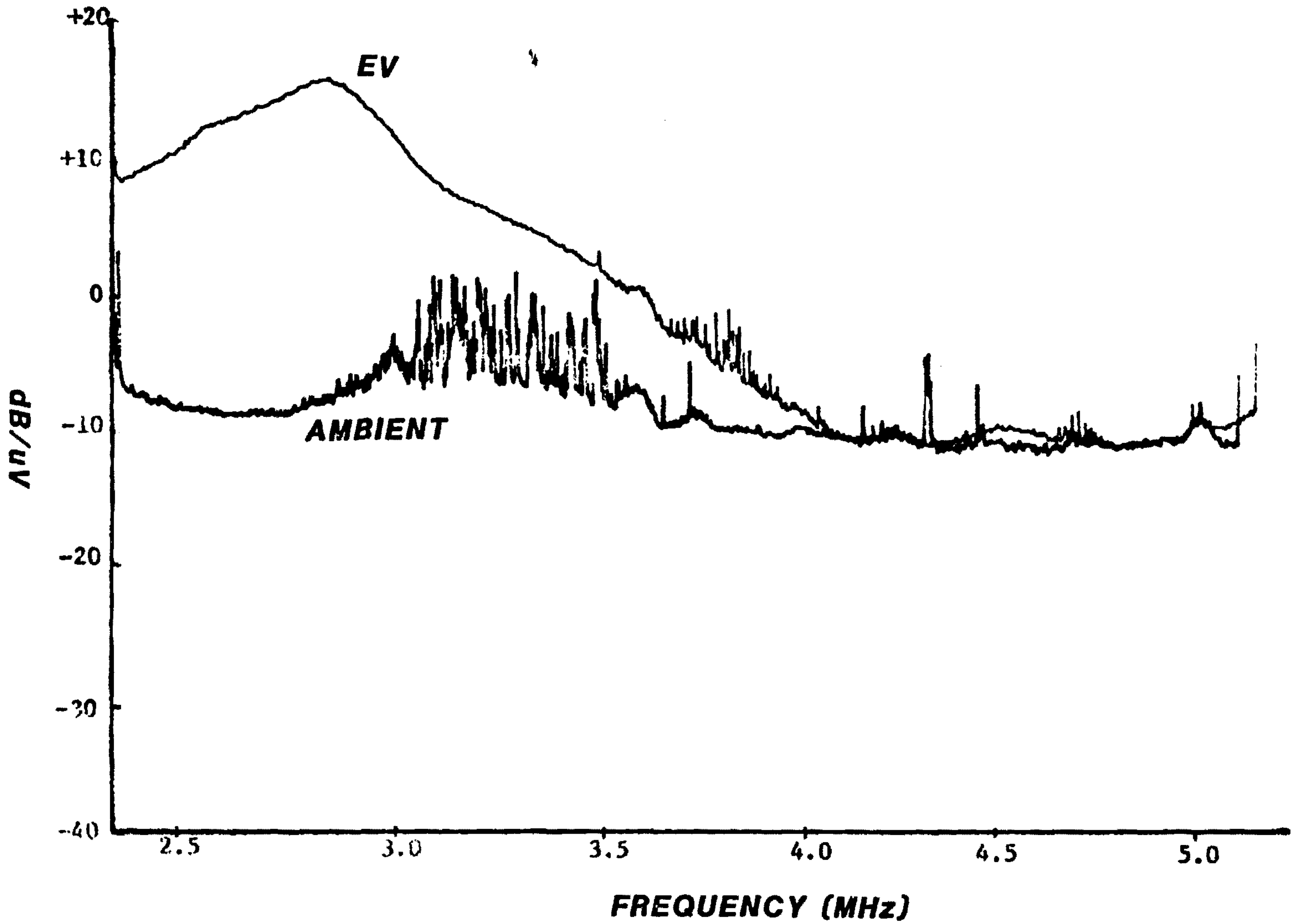


Figure 6. A Typical X-Y Plot of the Voltage Received Versus Frequency (Recorded During Radiated Emission Testing of the Electrica).

future vehicles that employ these new technologies may be expected to exhibit different EMI characteristics than those exhibited by current technology EV's.

Keeping the above precautions in mind, it is nevertheless possible to make a number of observations which apply not only to the EV's tested on the current program, but to a wide class of EV's employing similar technologies as well. Several trends surfaced in the measurement results which enables a number of conclusions to be drawn concerning the overall field intensity levels as a function of frequency both outside and inside the vehicle; the effects of EV load and speed on the overall radiated levels; the potential impact of EV's on standard AM broadcast reception; the potential of EV interference to cardiac pacemakers; the potential of EV interference to equipment and appliances connected to the ac power grid; and the potential susceptibility of the EV to transmitters operating in the 1 MHz to 1000 MHz frequency range. Analysis of the measurement data resulted in the following significant findings:

(a) Radiated Levels as a Function of Frequency. The exact electric or magnetic field intensity at a given frequency depends upon factors such as load condition, speed, polarization, and side of vehicle. In general, the radiated levels were relatively large for the Electrek and the Electrica (particularly below 20 MHz) and were relatively low for the Evcort. The vast majority of the electric field data for both the Electrek and the Electrica fell between 0 and +40 dBμV/m/kHz for frequencies below 10 MHz and tended to decrease at approximately 20 dB per decade (for the Electrek) or 40 dB per decade (for the Electrica) above 10 MHz. The impulse electric field intensities for these two vehicles exceeded the SAE J551 limits when tested under certain specific operating conditions. The Electrica exceeded the SAE limit at approximately 21 MHz for the case of the vertical electric field at 25 mph with 150 amps of armature current and for the horizontal electric field at 25 mph with no loading on the motor. However, both measured values were less than 2 dB above the SAE limit and are within measurement accuracy. The Electrek, which was the only vehicle of the three with a fiberglas body, had the highest overall radiation levels and exceeded the limit by 2 dB near 20 MHz when operated at 25 mph under maximum load (240 amps), and by as much as 6 dB at selected frequencies between 20 MHz and 75 MHz when operated at 25 mph under no load conditions. Above 80 MHz, the impulse electric field levels were below the SAE limit for all three vehicles and under all test conditions.

The overall radiated emission levels for the Evcort were much lower than those for the other two vehicles tested. However, the impulse electric field intensity did exceed the SAE limit by 2 dB at 22 MHz and levels as high as +38 dBμV/m/kHz were measured at frequencies near 500 kHz.

The impulse magnetic field intensity levels for the Electrek were the highest overall with the majority of the data falling between -60 and +5 dBμA/m/kHz in the 14 kHz to 20 MHz frequency range. The majority of the magnetic field data for the Electrica ranged from -60 to -30 dBμA/m/kHz at frequencies below 2 MHz and tended to decrease at approximately 20 dB per decade above this frequency. The Evcort emitted the lowest magnetic field levels, all of which fell below ambient levels.

(b) Emission Levels Within the Vehicle. The magnetic field intensity inside the vehicle was significantly greater than the magnetic field intensity outside the vehicle, as expected. The levels inside the Electrica ranged from +6 to +27 dBμA/m/kHz between 14 kHz and 200 kHz, decreased at approximately 20 dB per decade for frequencies up to 2 MHz, and decreased at approximately 40 dB per decade above 2 MHz. The magnetic field intensity inside the Electrek was significantly higher: +81 dBμA/m/kHz at 14 kHz, decreasing at approximately 20 dB per decade for the first decade above 14 kHz, and finally decreasing at approximately 40 dB per decade over the next two decades.

(c) Effects of Load. The load conditions did not have a signficant effect on the overall radiated emission levels for the three EV's tested. However, the position (frequency) at which relative peaks and valleys occurred in the frequency spectrum were shifted for different load conditions. The shifting of the spectrum could be caused by variations in the armature voltage pulse width, which is adjusted by the controller in response to different load conditions. The radiated emission levels were expected to increase (especially at lower frequencies) as the load increased due to the increase in the pulse width of the controller output as well as the increase in armature current. This phenomenon was not observed, though ambient noise levels were large at the lower frequency bands which, in some instances, could have masked the radiation level differences at the lower frequencies.

(d) Effects of Speed. Changing the speed of the Evcort from 25 mph to 5 mph had an insignificant effect on the overall radiated emission levels. In addition to these data, measurements were also made with a spectrum analyzer to determine if more drastic speed variations would cause significant differences in radiated levels. The magnetic field was monitored for the Evcort at a 1 meter antenna-to-vehicle spacing for speeds of 15, 30, 45 and 60 mph. Since the maximum received levels varied only 3 dB over the 15 to 60 mph range, vehicle speed was concluded to have an insignificant effect on the overall radiated levels of the Evcort. More data is needed on the effects of varying speed before this conclusion may be expanded to EV's in general.

(e) Potential Impact on Standard AM Broadcast Reception. The potential impact of EV radiated emission levels on the reception of standard AM broadcasts (535 kHz - 1.605 MHz) has been studied. The details of the analysis are presented in Appendix III. The study demonstrates that a large population of EV's (with similar characteristics to the Electrek and Electrica) could reduce the interference-free range of a 50 kW AM broadcast station by a factor as high as 2 to 1. Also, many other communication services operating below 20 MHz could be affected by radiated emissions from a large number of EV's. Therefore, it is concluded that EMI suppression will probably be required in many instances to avoid interference to these services (particularly in the MF and HF bands). However, it should also be noted that the Evcort radiated significantly less than either the Electrek or the Electrica and a large population of these or similarly designed vehicles would probably have a negligible effect on AM broadcast reception.

(f) Potential Impact on Cardiac Pacemakers. Another major concern is the electromagnetic effects of EV emissions on biomedical devices. A number of investigations have been undertaken on the susceptibility of cardiac pacemakers to electromagnetic radiation [12]-[14]. The only existing standard for pacemakers is the AAMI (The Association for the Advancement of Medical Instrumentation) Pacemaker Standard ("Labeling Requirements, Performance Requirements, and Terminology for Implantable Artificial Cardiac Pacemakers") which requires pacemakers to operate satisfactorily under a 200 V/m pulsed field at 450 MHz. Using the specified pulse width of 1 millisecond and a commonly employed pulse repetition frequency of 1.5 pulses per second, the amplitude of the frequency spectrum for the pulsed field at 450 MHz can be calculated to be 0.3 V/m (200 V/m x 1 ms x 1.5 pps) or 109.5 dBμV/m. Though pacemaker susceptibility data is scarce at lower frequencies, discussions with J. C. Toler, Chief of the Biomedical Research Division at the Georgia

Tech Engineering Experiment Station, have indicated that the susceptibility levels of typical pacemakers tend to increase at approximately 20 dB per decade as the frequency of the radiated field is decreased below 450 MHz. Since the resulting narrowband susceptibility levels are more than 100 dB above the broadband levels measured for the three vehicles tested, it is highly unlikely that EV's of similar design to those tested would interfere with cardiac pacemakers.

(g) Potential Impact on Equipment/Appliances Connected to AC Power Grid. The effects of conducted emissions from the EV battery charger on equipment connected to the same ac power grid would be difficult to predict. However, the performance levels given in various standards may be used to assess the liklihood that interference conditions may arise. The MIL-STD-461B broadband conducted emission limit is based upon a measurement procedure entirely similar to the one which was used to test on-board battery chargers and was therefore used to assess their EMI performance. The limits provided in FCC Docket 20780 (which modifies Parts 2 and 15 of the FCC rules) and in the VDE (German) and CISPR standards are not given in traditional broadband units (i.e., amplitude per unit bandwidth) and a measurement parameter different from the one measured on this program is specified (i.e., noise voltage rather than noise current). Consequently, these limits were not used in the EMI assessment of EV battery chargers.

The conducted emission measurement results obtained for the Evcort and the Electrek, are contained in Appendix II. It is immediately obvious from these results that the conducted current levels far exceed the MIL-STD-461B limits over a large portion of the measured frequency range. It is therefore concluded that conducted interference problems could exist unless some EMI suppression is provided.

(h) EV Susceptibility. Radiation from various radio transmitters could potentially interfere with the normal operation of EV's. The unfiltered version of the Evcort was susceptible to 36 mA at 52.5 MHz (the maximum expected level coupled from a 500 watt amateur radio transmitter). However, no other susceptible conditions were found to exist for either the Evcort with the modified (filtered) controller or for the Electrek (which utilized a filtered controller). Since the vehicles were tested to the maximum expected incident field levels for transmitters operating between 1 MHz and 1 GHz, it is concluded that no susceptibility problems are expected for EV's, provided that appropriate filtering is applied to the controller input ports.

4. EMI Test Procedures

A technical document was prepared for submission to CISPR which recommends practical EMI test procedures/performance levels for EV's. Recommended performance levels and methods of measurement for both radiated and conducted emissions were documented. Susceptibility test procedures and performance levels will require significant investigations in addition to those undertaken on this program and were, therefore, not included in the recommendations to CISPR.

The results from the measurement phase of the program were used to refine the evaluation methodology (discussed in Section 2) into practical and time/cost-efficient test procedures. Originally, the evaluation methodology was broadly based so that the influence of many of the potential contributors to the EMI characteristics of EV's could be examined. Subsequent usage revealed areas where refinements could be made to eliminate unnecessary tests and thus reduce testing time and costs. The measurements which are essential for a comprehensive EMI assessment of EV's were retained. The refined methodology was formulated into comprehensive test procedures which define the proper equipment, test configurations, and measurement parameters.

The recommended test procedures for radiated and conducted emissions are presented in Appendices IV and V, respectively. Since load variations from no load (drive wheels elevated) to full load (maximum rated armature current) had no significant and consistent effect on the overall radiated emission levels, it was recommended that the requirement of a dynamometer to load down the propulsion system be relaxed (which should result in a considerable reduction in testing costs). It was recommended that the lower frequency limit for radiated testing be extended down to 14 kHz to account for the relatively large field intensities at the lower frequencies. Magnetic field testing was determined to be necessary at low frequencies (14 kHz - 20 MHz) due to the large pulsed current levels associated with normal operation of the vehicle and the fact that magnetic fields are a primary source of interference at relatively low frequencies. Despite the relatively low electric field intensity levels measured at higher frequencies, it was considered preliminary at the present time to exclude measurements in this frequency range, primarily because only a limited number of vehicles have been tested. The measurement procedures specified in SAE J551 were recommended for use over the 20 to 1000 MHz frequency range using the test conditions specified in

Part 2 of Appendix IV. However, it was recommended that the 1000 MHz upper test frequency for measuring radiated emissions be lowered if further investigations on a number of other present and future technology EV's confirm that radiated emission levels are localized in the lower frequency range.

Recommended performance levels for both radiated and conducted emission measurements are also contained in Appendices IV and V, respectively. The radiated impulse electric field intensity limit (14 kHz to 20 MHz) coincides with the SAE J551 limit at 20 MHz (which is equivalent to the CISPR limit at 40 MHz) but increases at 20 decibels per decade as frequency decreases below 20 MHz. The increasing limit with decreasing frequency corresponds to the expected decrease in coupling of the radiated energy to potentially susceptible receptors as frequency decreases. The recommended limit for electric fields in the 20 MHz to 1000 MHz frequency range was identical to that given in SAE J551. The radiated impulse magnetic field intensity limit (14 kHz to 20 MHz) also reflects the expected decrease in coupling and represents the equivalent far-field magnetic field intensity corresponding to the electric field limit described above (i.e., magnetic field equals electric field divided by 377 ohms). The conducted emission limit was based on the United States Department of Defense's MIL-STD-461B broadband emission limit for ac power leads. The limit was modified for load currents greater than one ampere by assuming that a typical on-board battery charger draws approximately twenty amperes of load current and relaxing the 14 kHz limit by 20 $\log_{10}$ (load current) or 26 decibels.

The performance levels and test procedures recommended to CISPR are considered to be preliminary. The recommended performance levels below 20 MHz are somewhat lenient and, in the AM broadcast band, are greater than 25 dBμV/m/kHz (a level which could result in significant interference to AM broadcast receivers, as was demonstrated in the analyses given in Appendix III). These analyses required several assumptions to be made, however, which should be verified through empirical investigations. In addition, definitive data on ICV's below 20 MHz are needed in order to make relative comparisons between EV's and ICV's. If ICV levels are equal to or greater than EV levels, there would be no reason to make the limits more severe since a large population of EV's would not have a signficant impact on the radiated levels from the entire class of automobiles. On the other hand, if ICV levels are significantly less than EV levels and if empirical investigations indicate that EV levels do indeed interfere with equipment and/or communications (e.g., AM radio receivers) operating below 20 MHz, then the performance levels should be made more stringent as necessary. Also, the test procedures for EV's are considerably more extensive and time consuming than those for internal combustion engine vehicles (as specified by CISPR Publication 12 or SAE J551). Therefore, it is recommended that additional investigations be undertaken to further refine the test procedures with the goal of eliminating unnecessary measurements. However, the test procedures and performance levels documented in this report are recommended for use in the interim period pending further investigation.

5. Summary and Conclusions

Radiated emission test procedures have been recommended for EV's which are consistent with current SAE and CISPR practices. Conducted emission test procedures for on-board battery chargers (patterned after MIL-STD-462 procedures) have also been recommended. Radiated susceptibility was investigated by injecting signals into potentially susceptible ports, the levels of which were calculated from a coupling prediction model using maximum expected field levels from various radio transmitters as input.

The radiated emission data indicate that the majority of the electromagnetic energy is concentrated below 100 MHz. The impulse electric field intensities were well below the SAE J551 limit (which extends from 20 MHz to 1000 MHz) for frequencies greater than 100 MHz. Motor vehicles conforming to the SAE limit, in turn, have been shown by experience to be compatible with the various communications services and equipment operating in the frequency range of 20 to 1000 MHz. It is concluded, therefore, that EV's similar in design to those tested are not likely to create an interference problem with communications services operating above 100 MHz.

The radiated levels in the 20 to 100 MHz range were also below the SAE limit under most test conditions. The only significant exception was for the Electrek, which radiated the highest overall levels of the three vehicles tested. Since the Electrek and the Evcort are nearly identical electrically, the major contributing factor to the relatively large differences in radiation levels for these vehicles (on the order of 30 dB) appears to be the difference in shielding effectiveness afforded by the different body type. The fiberglas body of the Electrek provides less electromagnetic shielding than the metal body of the Evcort. It is concluded that non-metallic bodied vehicles are more likely to experience EMI/EMC problems than their metal-bodied counterparts due to poorer electromagnetic isolation between the internal electrical components of the vehicle and the exterior environment. It is also suspected, based upon the relatively large radiated emission levels of the Electrica in comparison to that of the Evcort,* that more EMI problems will occur as higher pulse repetition rates are utilized in new technology vehicles. This will require further study, however, as these vehicles become available.

---

*It may be noted from Table 1 that the Electrica has a 4 kHz controller whereas the Evcort utilizes a 400 Hz controller.

The radiated electric field levels in the 14 kHz to 20 MHz range are in several instances much greater than the SAE 20 MHz limit. It has been demonstrated using reasonable assumptions and approximations that the useful range of standard AM broadcast transmitters could, in fact, be significantly reduced by the existence of a large population of unmodified EV's. Many other communication services operating below 20 MHz could also be affected by radiated emissions from a large number of EV's. As was mentioned before, however, ICV radiated emission data below 20 MHz are very scarce and direct comparisons cannot be made at present. Nevertheless, it does appear likely that EMI suppression will be required on some (though not all) EV's in order to avoid interference to users in the medium and high frequency bands.

Conducted emissions from on-board battery chargers could potentially degrade the performance of equipment and/or appliances (e.g., AM/FM/TV receivers, home audio systems, electronic calculators, household appliances, etc.) which are connected to the same ac power grid. The interference path could be either by conduction along the power conductor or via radiation from the power grid. Since the conducted emission levels measured were relatively large, it is concluded that EMI suppression is needed in this area as well. Low-pass filtering at the power input terminals of the battery charger would be an appropriate corrective measure.

Susceptibility of EV's to radiated signals is not considered to be a problem area. Because of the potential safety risks involved with sudden loss of vehicle control, however, it is recommended that the controller be well shielded with low-pass filtering applied to all input ports.

6. Recommendations for Future Research

Several additional investigations into EV EMI/EMC would be highly desirable in addition to those undertaken on this program. Recommended areas for future research include: (1) selection, design, construction, and testing of EMI reduction techniques for EV's, (2) an in-depth investigation to evaluate the susceptibility of a representative EV and the development of meaningful test procedures for EV susceptibility evaluations, (3) measurement of the complete radiated emissions spectrum from 14 kHz to 1000 MHz of ICV's (preferably ones employing microprocessors and/or capacitive discharge units) and additional EV's for comparative studies, and (4) empirical investigations concerning the impact of EV emissions on specific users in the lower frequency bands (e.g., AM radio, HF, and MF bands).

7. References

(1) J. K. Daher, "Limitation in Swept Receiver Scan Rates for Impulsive Noise Measurements," Technical Report, Project A-3089, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, GA, February 1982.

(2) MIL-STD-462, "Electromagnetic Interference Characteristics, Measurement of," Military Standard, Notice 3, 9 February 1971.

(3) CISPR Publication 14, "Limits and Methods of Measurement of Radio Interference Characteristics of Household Electrical Appliances, Portable Tools and Similar Electrical Apparatus," 1975.

(4) CISPR Publication 16, "C.I.S.P.R. Specification for Radio Interference Measuring Apparatus and Measurement Methods," International Electrotechnical Commission, International Special Committee on Radio Interference, 1977.

(5) "Absorbing Clamp MDS-20 for Interference Measurements in the VHF Range," News from Rohde and Schwartz, No. 46, p. 20.

(6) J. Willman and G. Van Steenberg, "Directional Current Probe Technique for Conducted EMI Measurements," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-11, No. 2, May 1969, p. 96.

(7) J. Mills, "Study to Establish Electromagnetic Interference Specification Limit," Final Report No. TR7-2873-9005, Contract No. NAS8-20142, Genisco Technology Corporation, 30 June 1966.

(8) CISPR Publication 2, "Specification for CISPR Radio Interference Measuring Apparatus for the Frequency Range 25 to 300 MHz," Paragraph 4.1.3, 1975.

(9) Verband Deutscher Elektrotechniker (VDE) Specification 0788, Part 2.

(10) J. A. Malack and J. R. Nicholson, "Effects of Measurement Devices on Conducted Interference Levels," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-15, No. 2, May 1973, pp. 61-65.

(11) Clayton R. Paul, "Applications of Multiconductor Transmission Line Theory to the Prediction of Cable Coupling," RADC-TR-76-101, Vol. VI, Phase Report, February 1978.

(12) B. M. Jenkins and J. A. Woody, "Cardiac Pacemaker Responses to Power Frequency Signals," IEEE 1978 International Symposium on Electromagnetic Compatibility, June 20-22, 1978, pp. 273-277, Atlanta, GA.

(13) H. W. Denny, B. M. Jenkins, and J. C. Toler, "Behavior of Cardiac Pacemakers in Pulsed EM Fields," IEEE 1977 International Symposium on Electromagnetic Compatibility, August 2-4, 1977, pp. 272-277, Seattle, Washington.

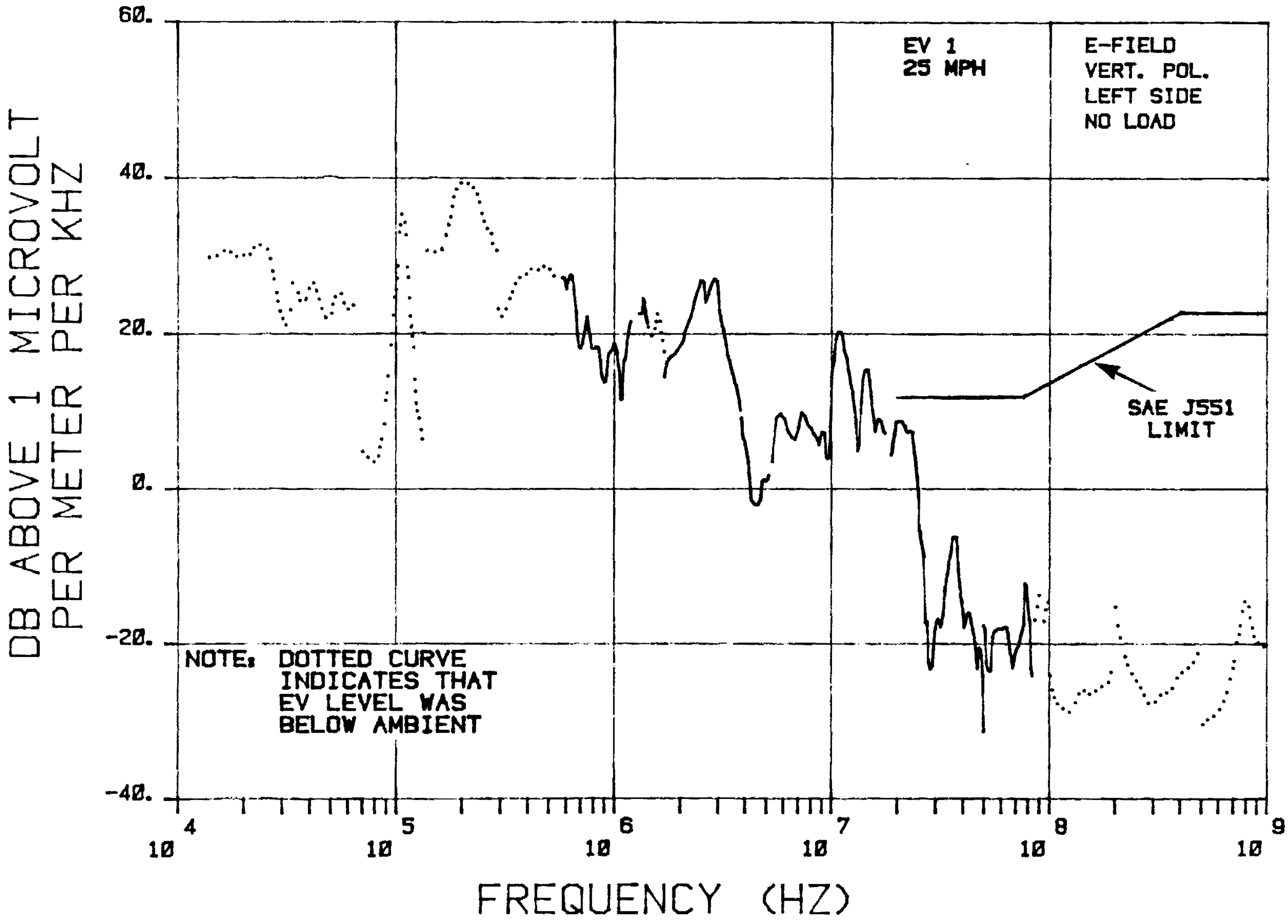
(14) B. M. Jenkins and H. W. Denny, "Cardiac Pacemaker Susceptibility Summary," Technical Report No. 3, Project A-1665, Contract DASG60-75-C-0010, November 1976.

(15) H. P. Westman (editor), Reference Data for Radio Engineers, Fourth Edition, International Telephone and Telegraph Corporation, New York, 1957.

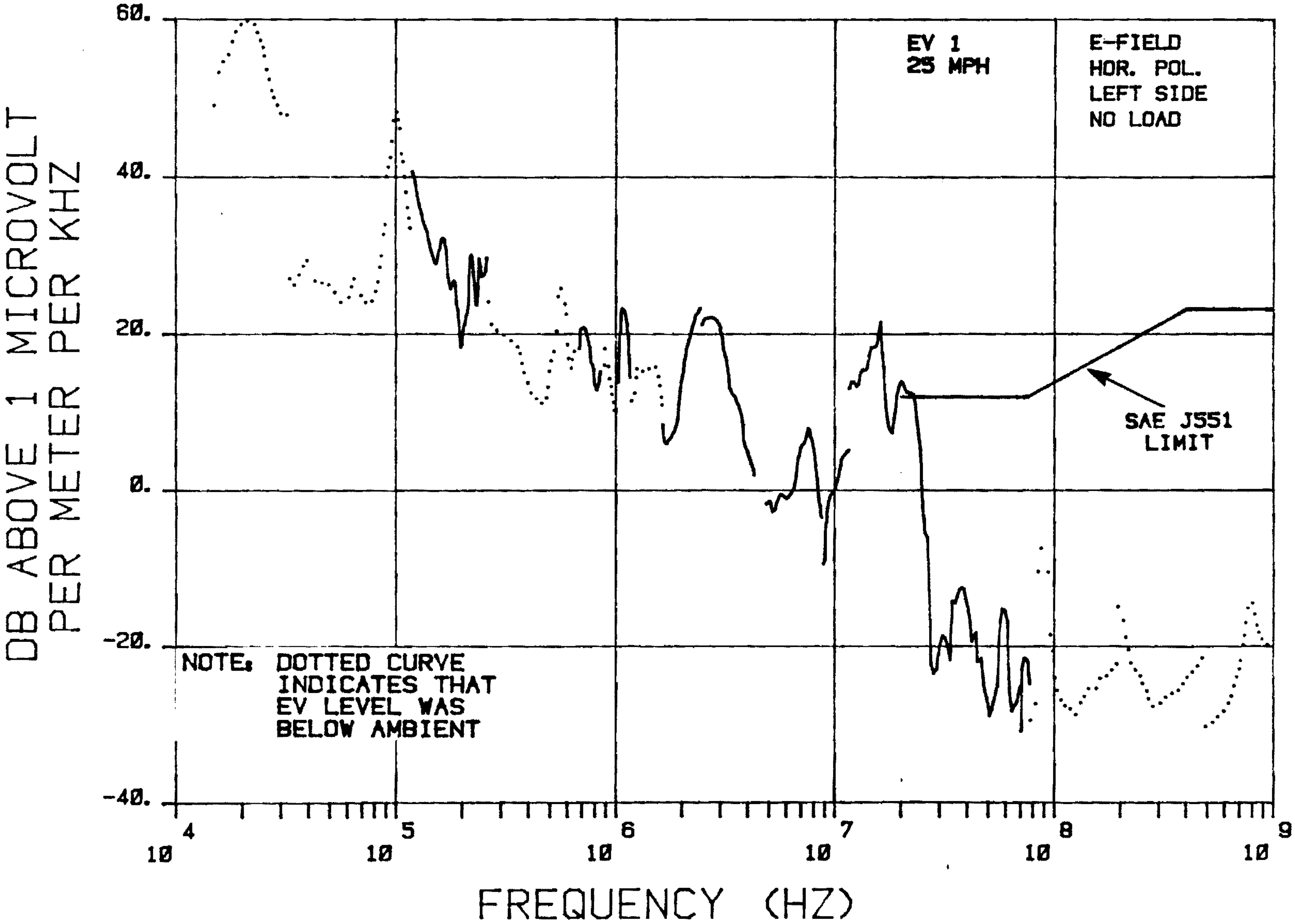
APPENDIX I

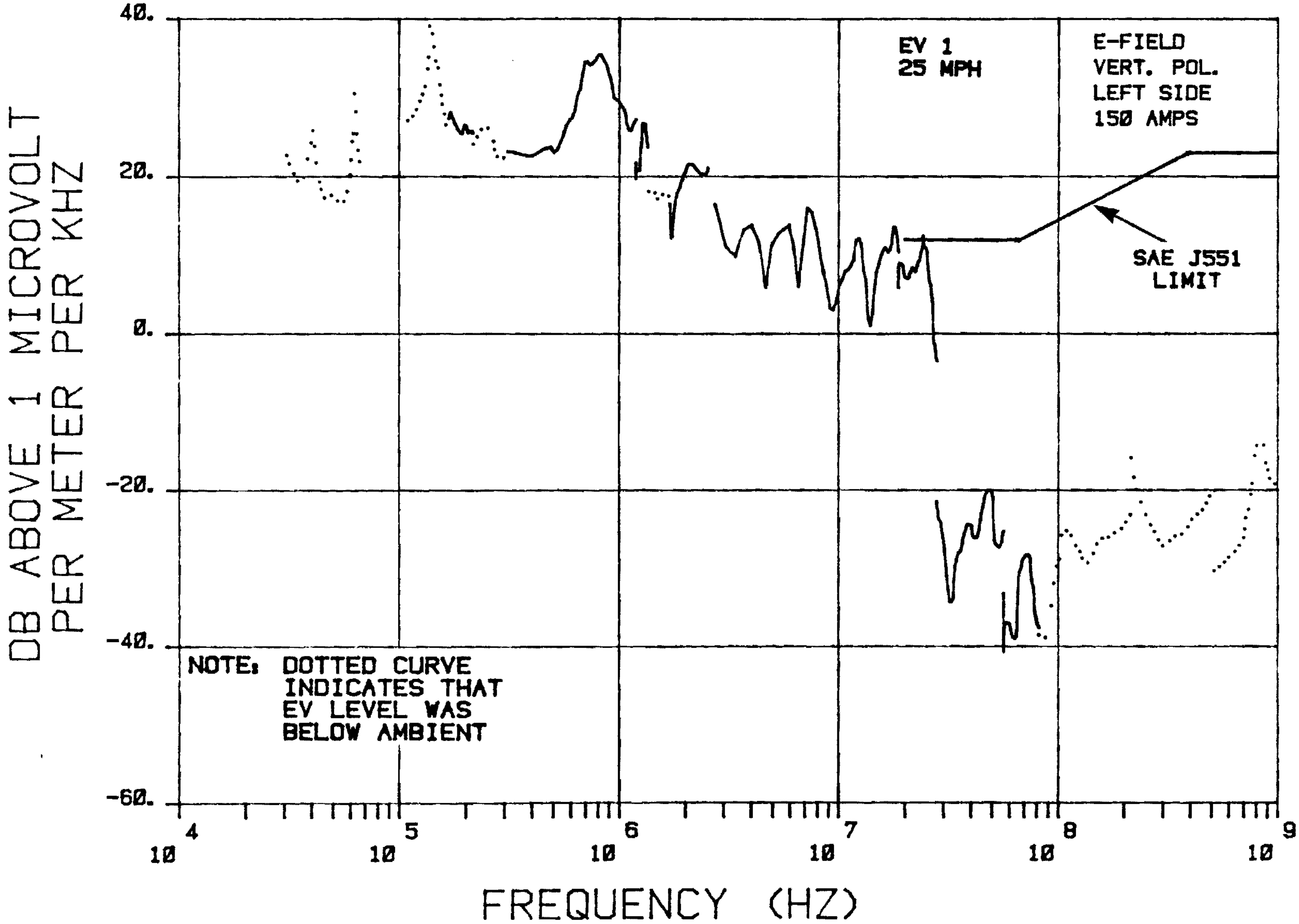
RADIATED EMISSION DATA FOR ELECTRIC VEHICLES

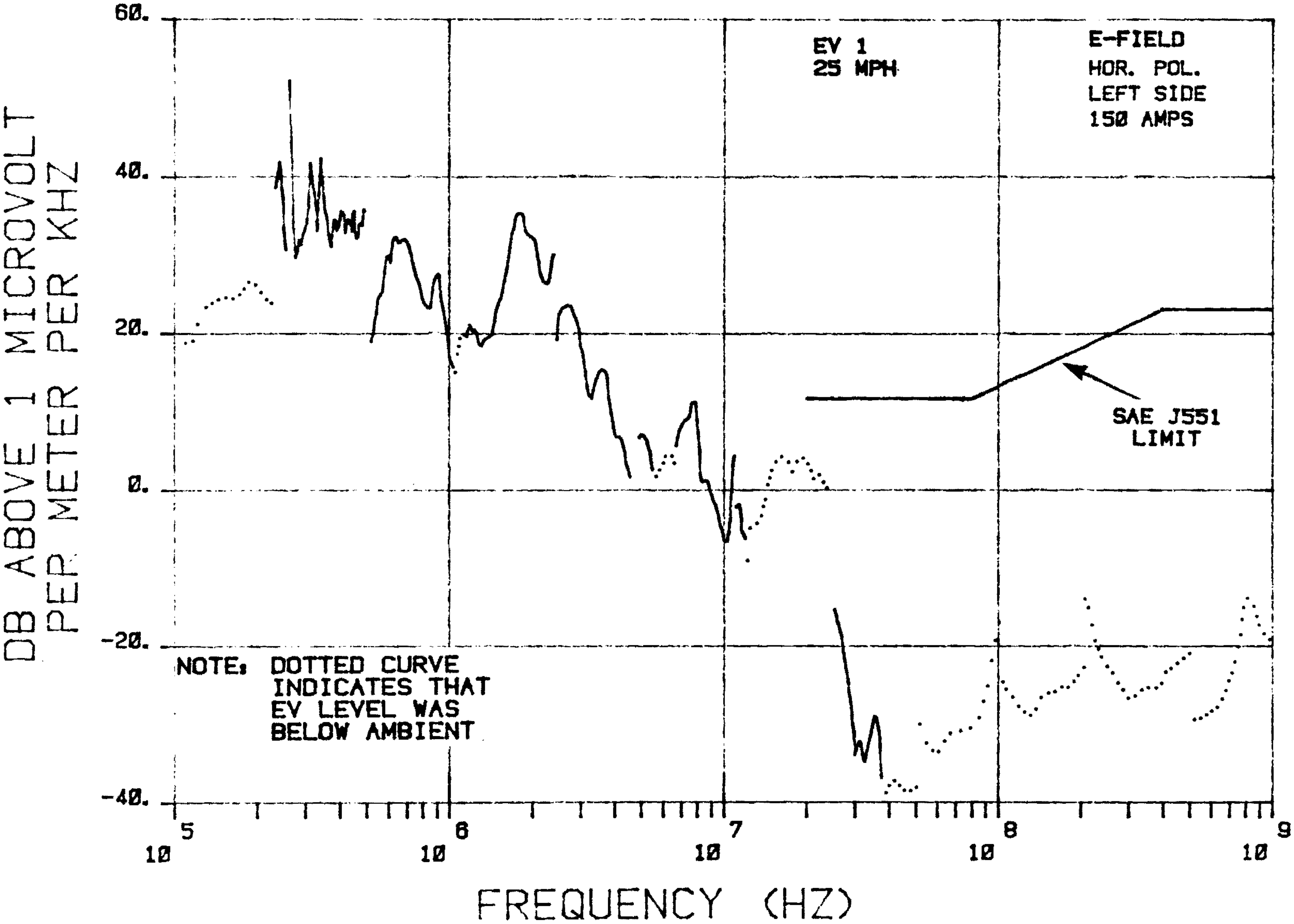
This appendix includes both the electric and magnetic field data for the three EV's tested. The EV's were coded on the data plots according to the order in which they were measured. That is, EV1 is the Jet Industries Electrica, EV2 is the EVA Evcort, and EV3 is the Unique Mobility Electrek.



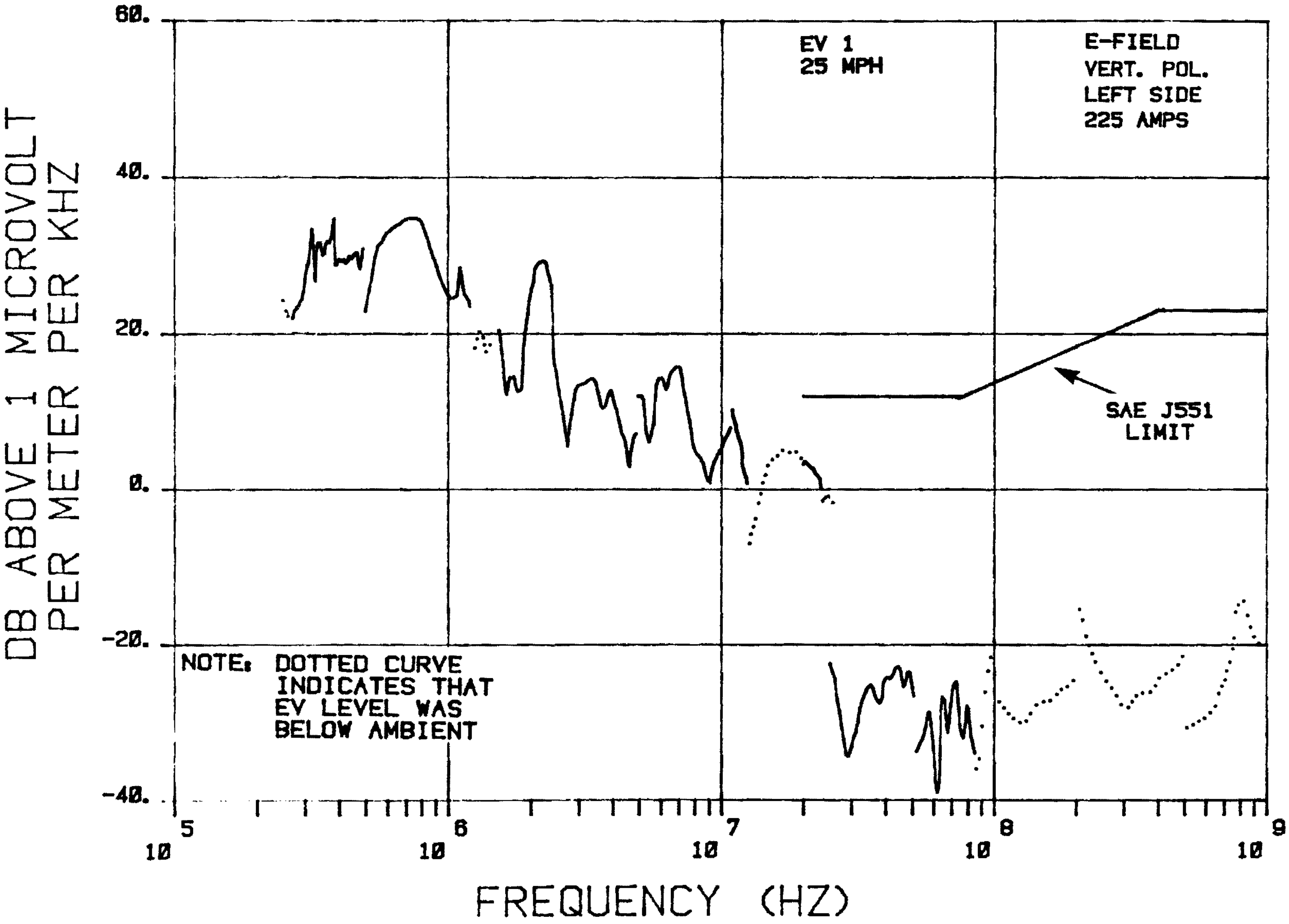
60.
40.
20.
0.
-20.
-40.
DB ABOVE 1 MICROVOLT PER METER PER KHZ
EV 1
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4 10^5 10^6 10^7 10^8 10^9
FREQUENCY (HZ)

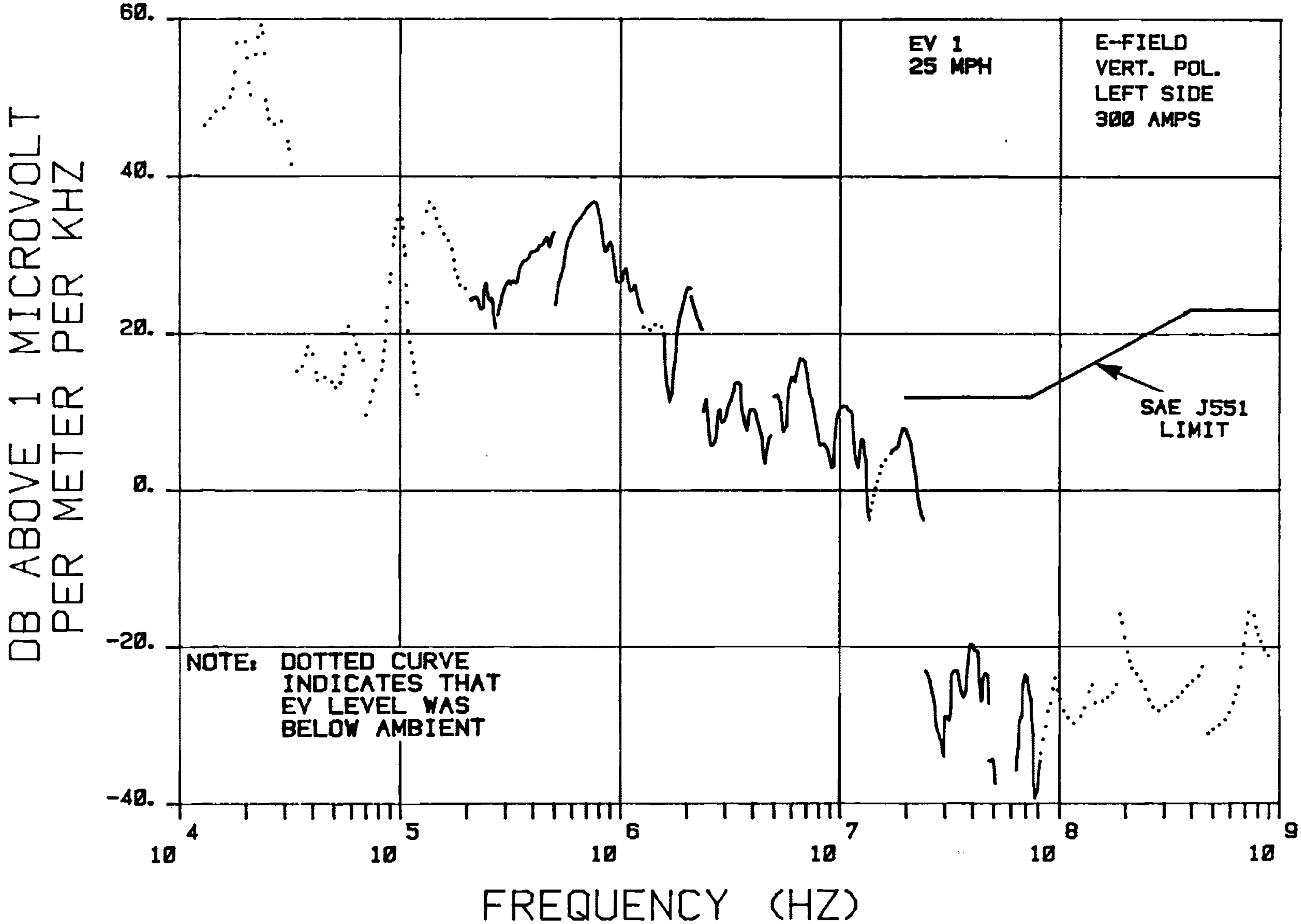

EV 1
25 MPH
E-FIELD
HOR. POL.
LEFT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
60.
40.
20.
0.
-20.
-40.
DB ABOVE 1 MICROVOLT PER METER PER KHZ
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)


40.
20.
0.
-20.
-40.
-60.
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
EV 1
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
150 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

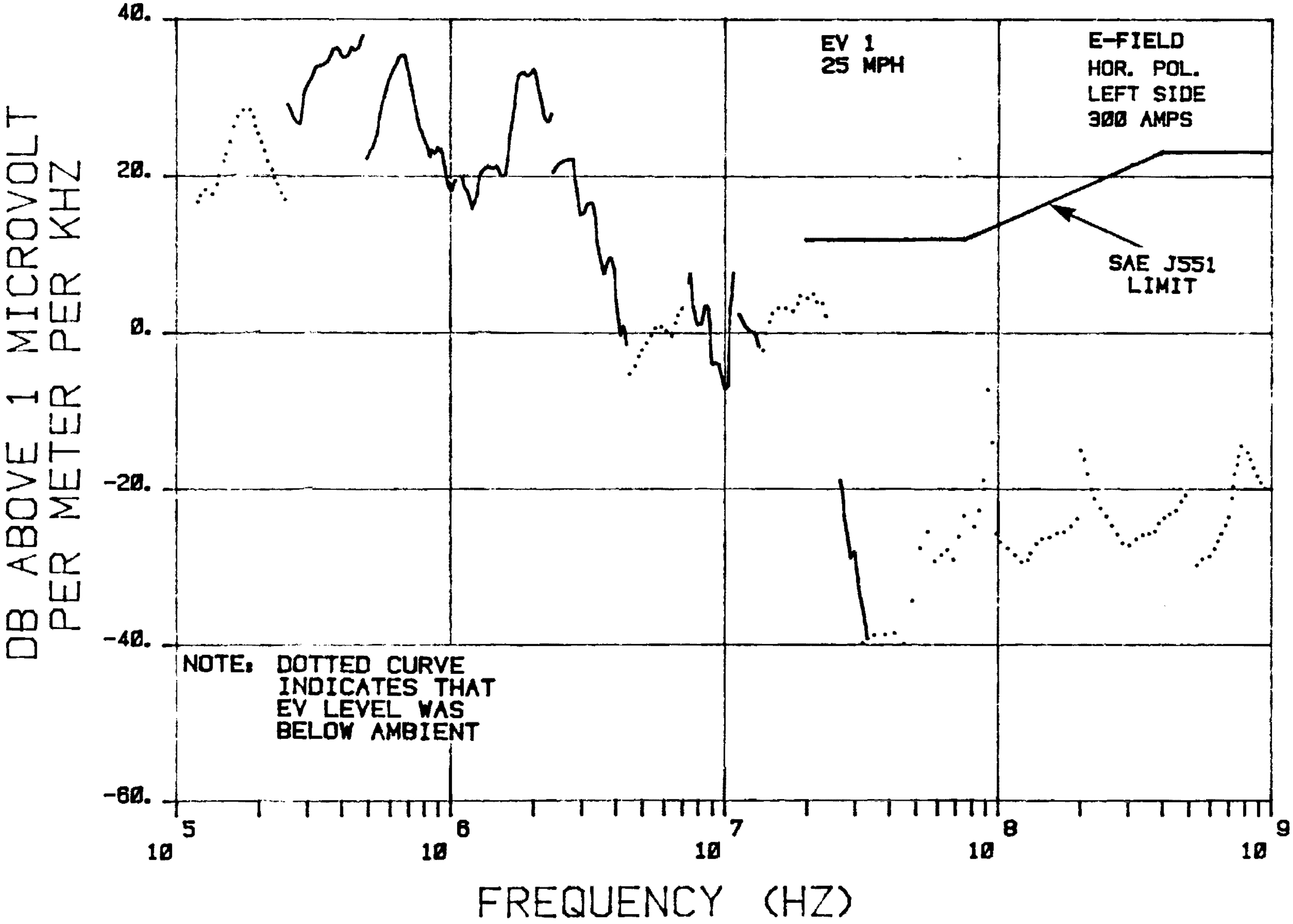


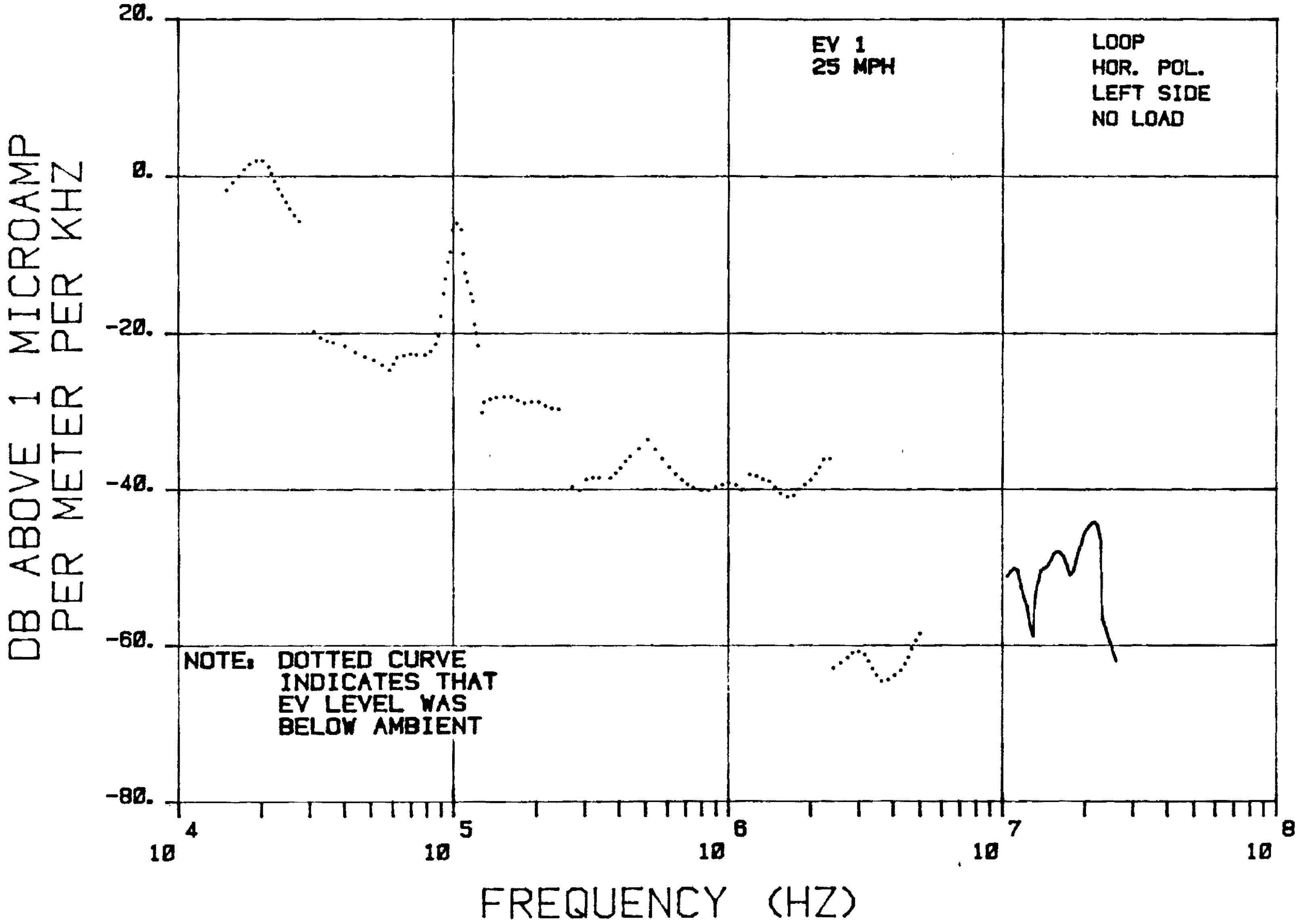
60.
40.
20.
0.
-20.
-40.
DB ABOVE 1 MICROVOLT PER METER PER KHZ
EV 1
25 MPH
E-FIELD
HOR. POL.
LEFT SIDE
150 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)


DB ABOVE 1 MICROVOLT
PER METER PER KHZ
60.
40.
20.
0.
-20.
-40.
EV 1
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
225 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

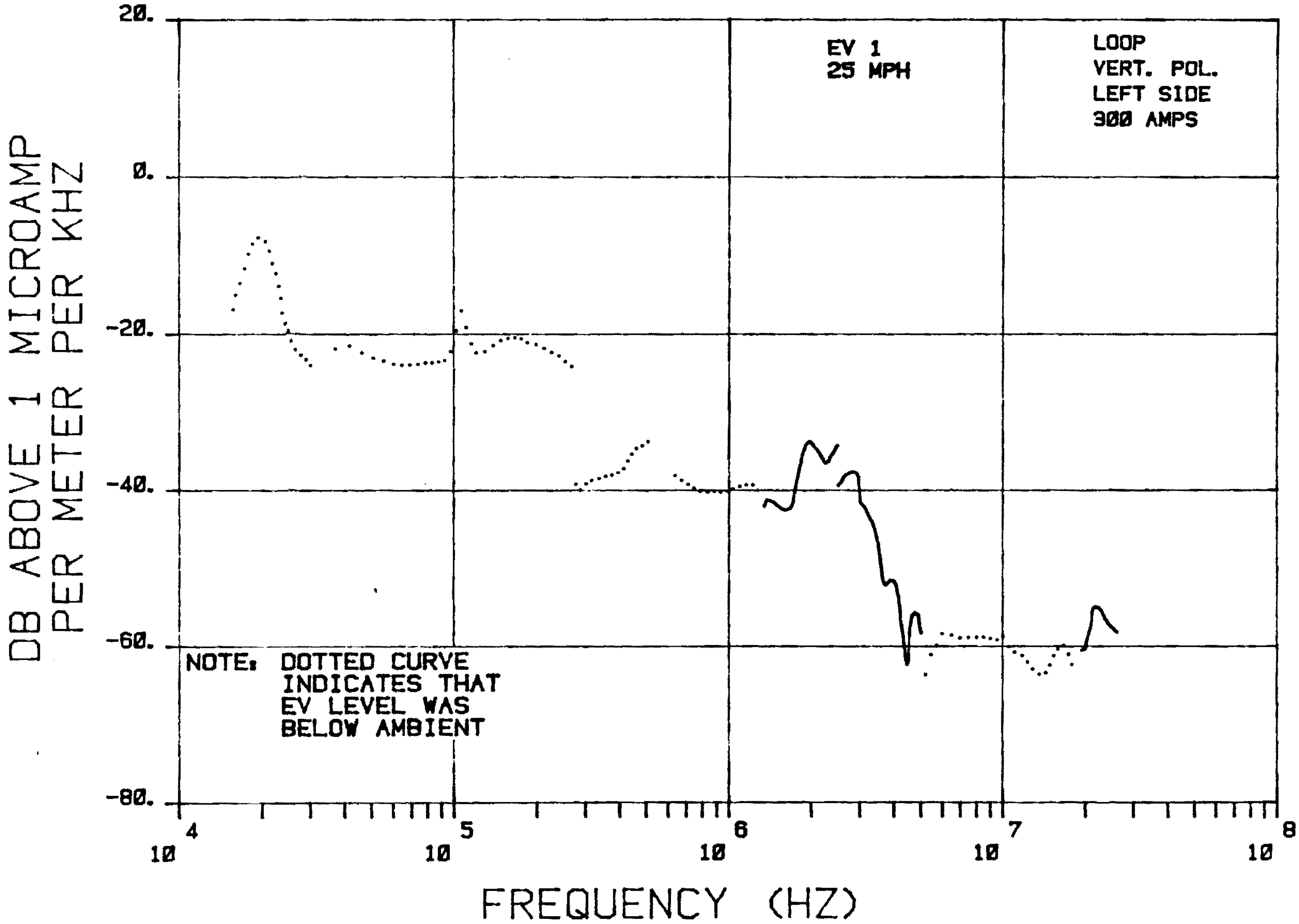


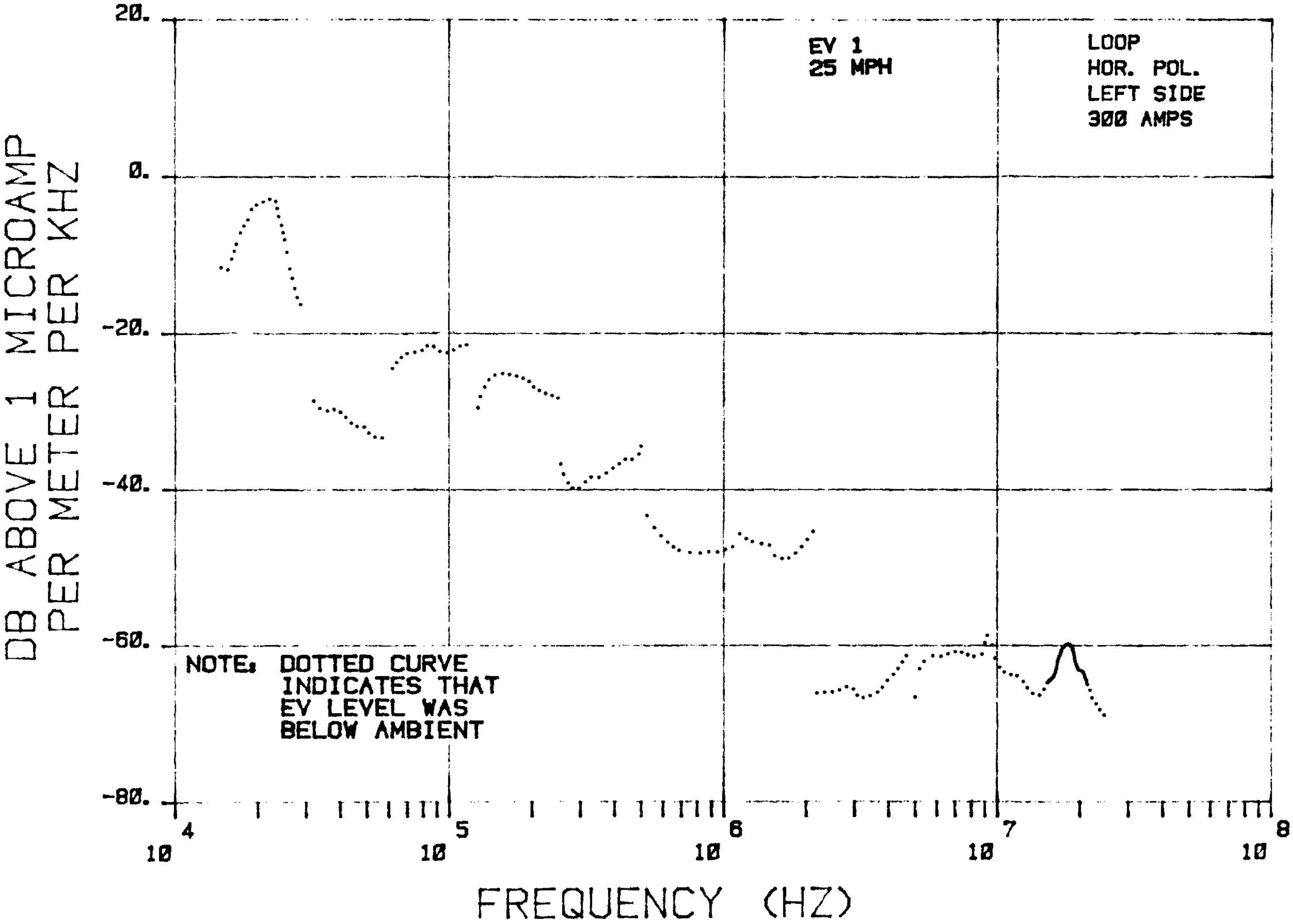
60.
40.
20.
0.
-20.
-40.
DB ABOVE 1 MICROVOLT PER METER PER KHZ
EV 1
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
300 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

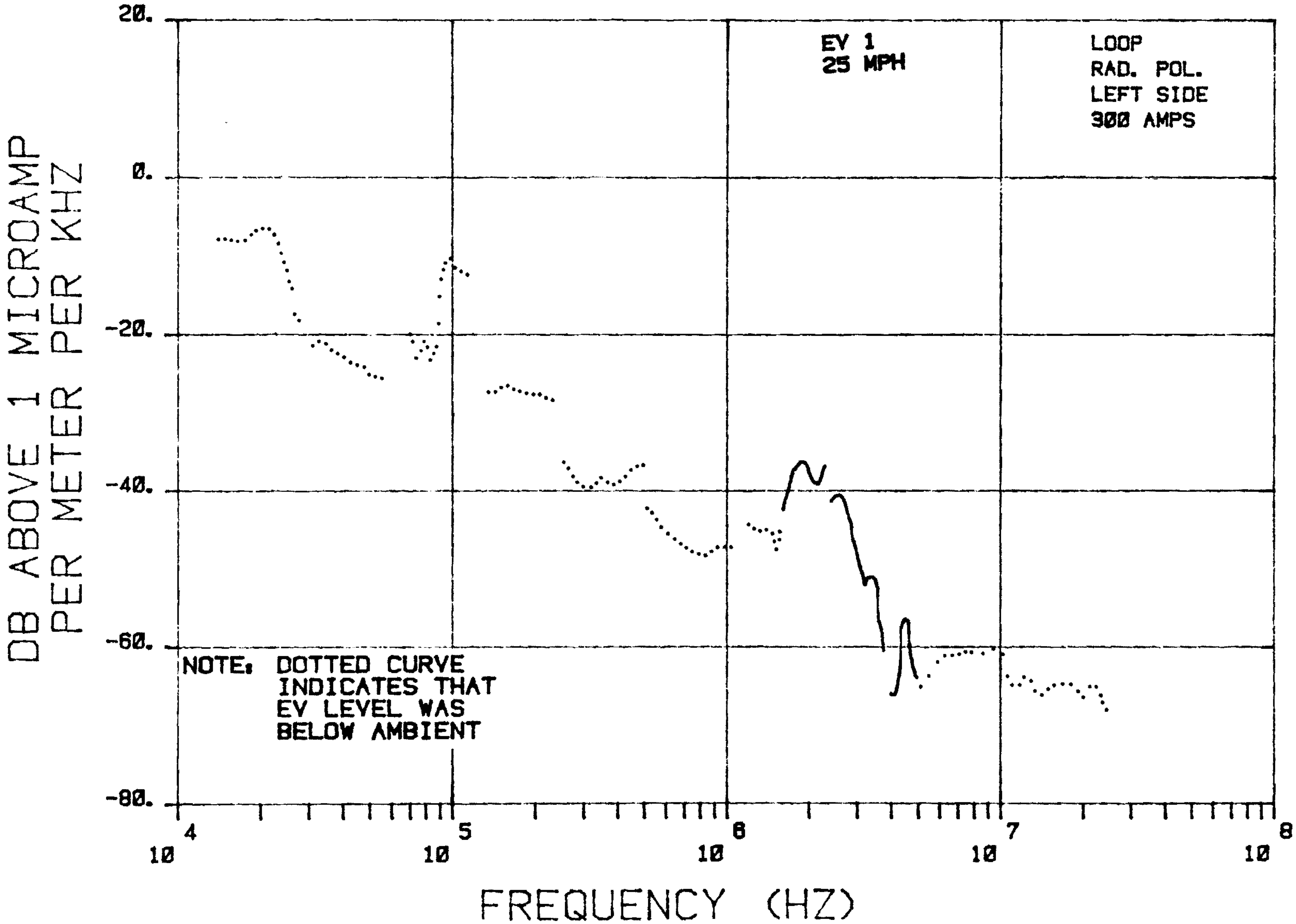

EV 1
25 MPH
E-FIELD
HOR. POL.
LEFT SIDE
300 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROVOLT PER METER PER KHZ
40.
20.
0.
-20.
-40.
-60.
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

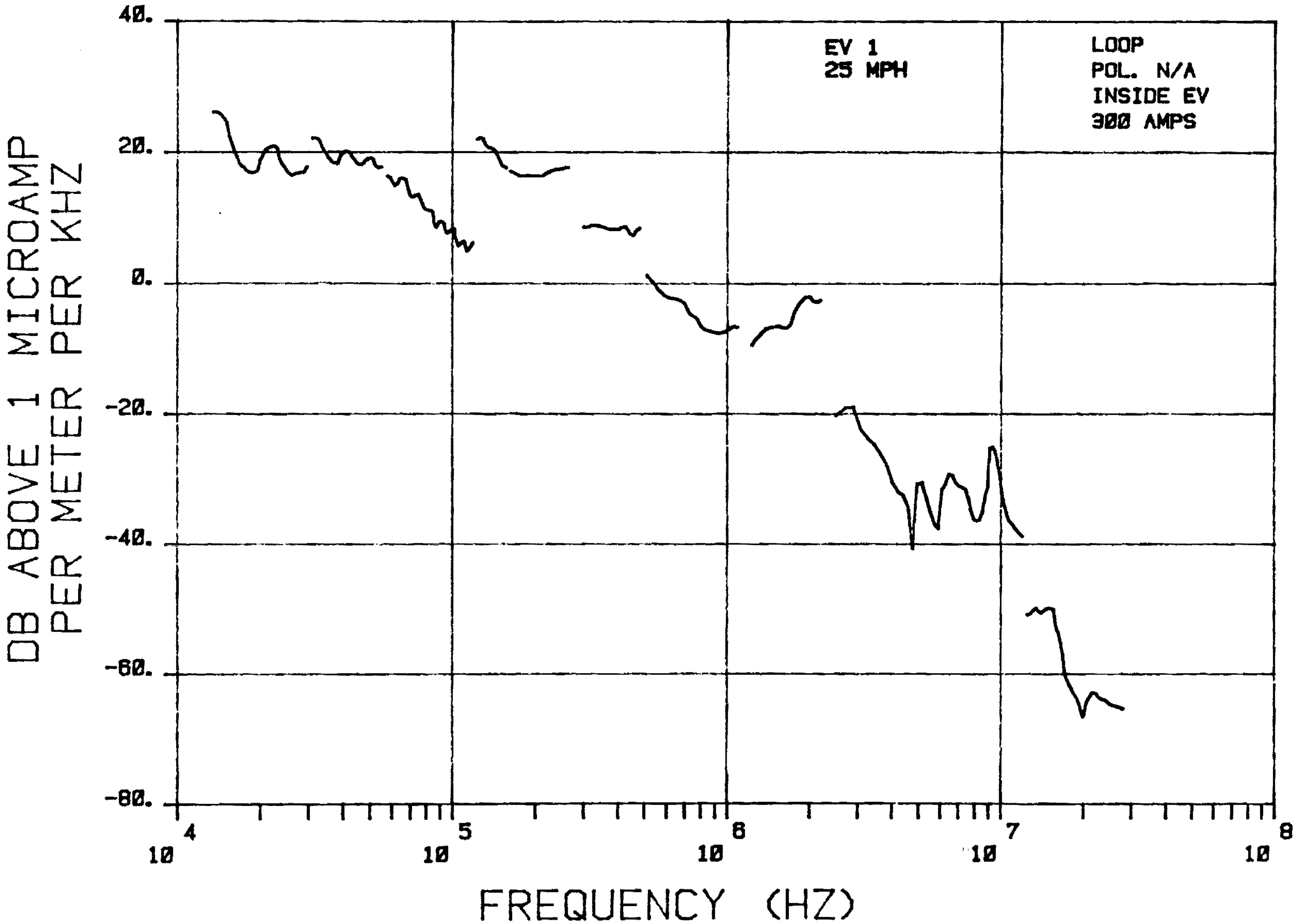


EV 1
25 MPH
LOOP
HOR. POL.
LEFT SIDE
NO LOAD
20.
0.
-20.
-40.
-60.
-80.
DB ABOVE 1 MICROAMP PER METER PER KHZ
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10 4
10 5
10 6
10 7
10 8
FREQUENCY (HZ)

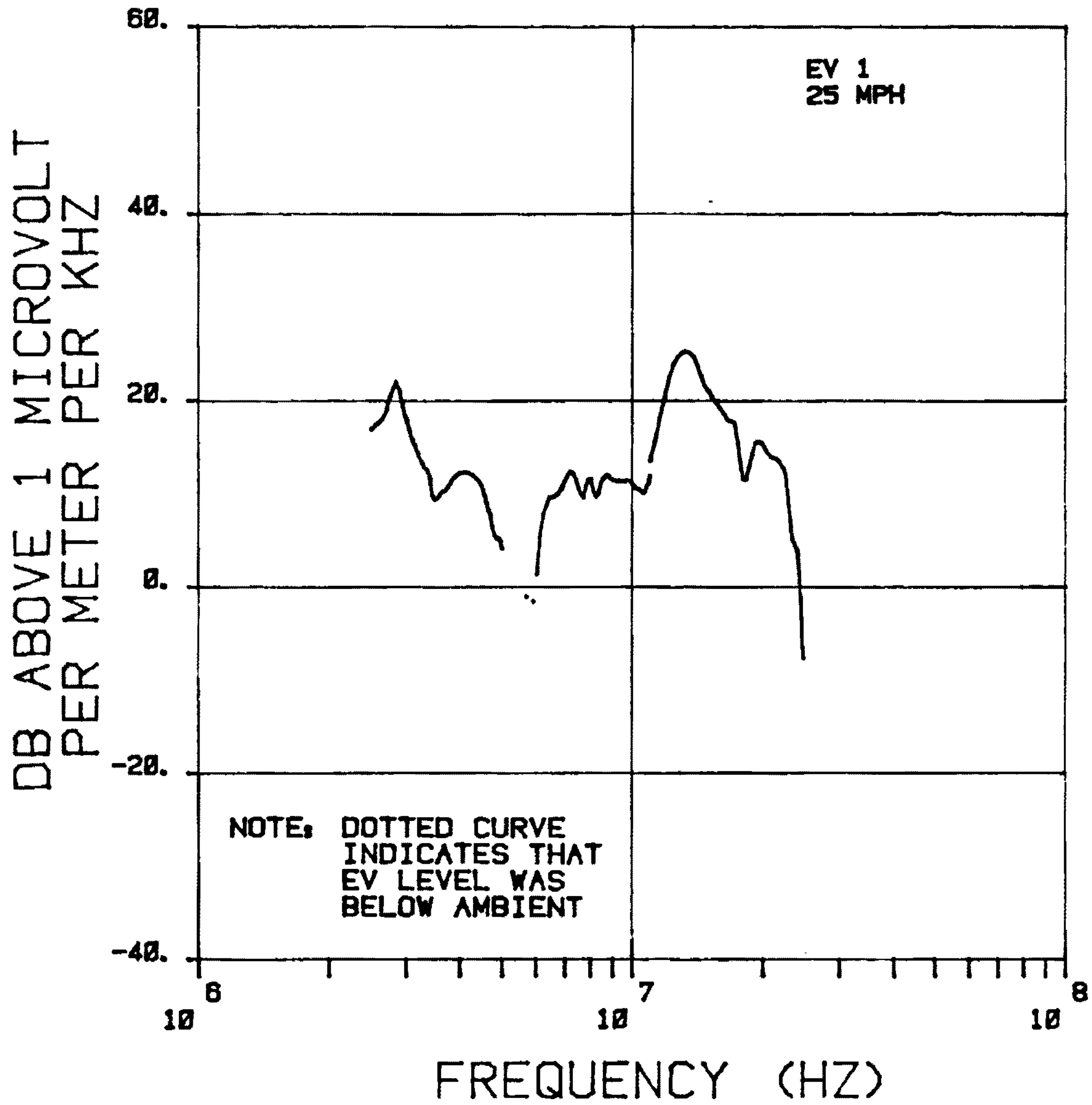

EV 1
25 MPH
LOOP
VERT. POL.
LEFT SIDE
300 AMPS
DB ABOVE 1 MICROAMP PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)


EV 1
25 MPH
LOOP
HOR. POL.
LEFT SIDE
300 AMPS
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
DB ABOVE 1 MICROAMP
PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

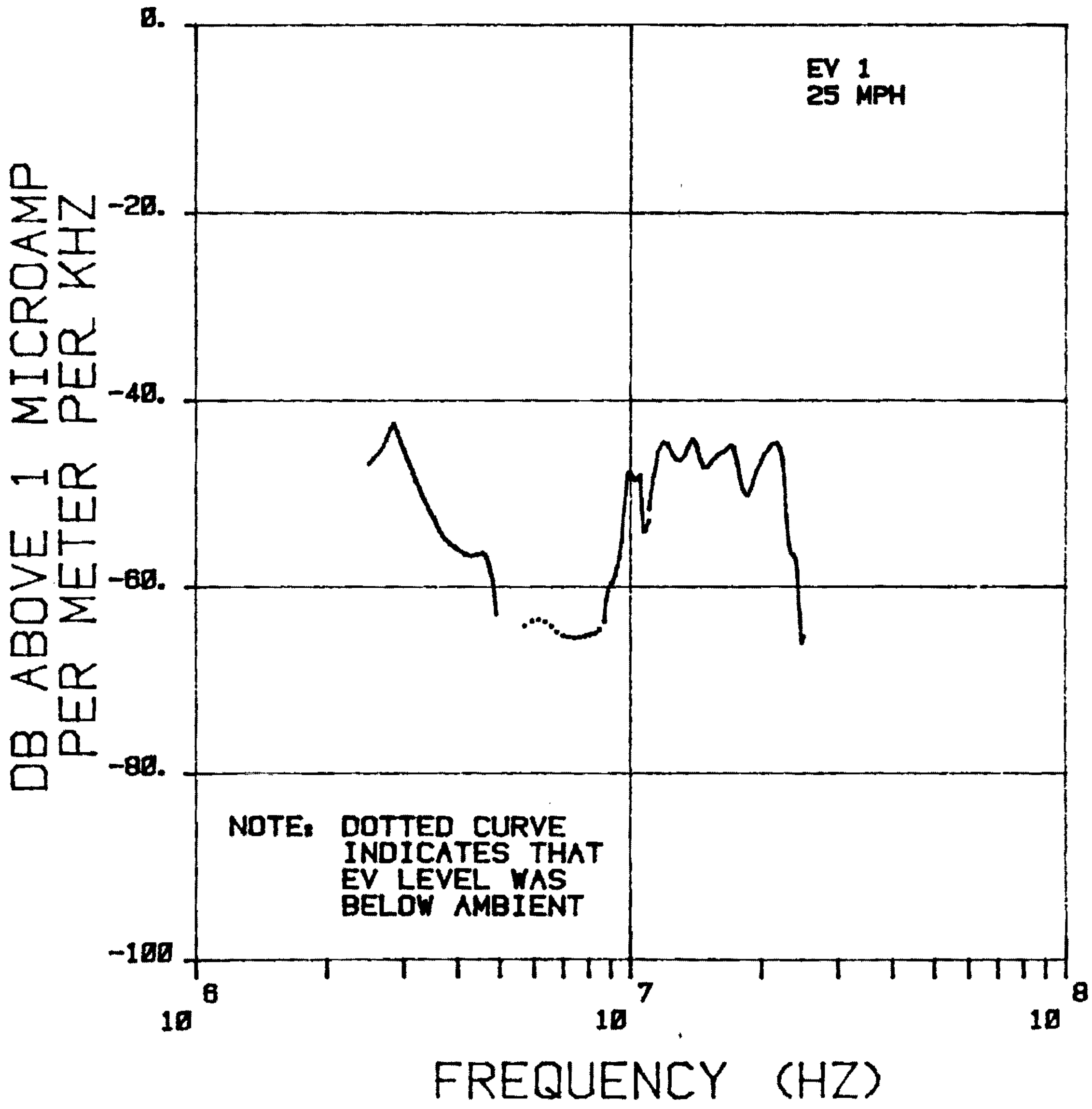

EV 1
25 MPH
LOOP
RAD. POL.
LEFT SIDE
300 AMPS
20.
0.
-20.
-40.
-60.
-80.
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER METER PER KHZ
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)


EV 1
25 MPH
LOOP
POL. N/A
INSIDE EV
300 AMPS
DB ABOVE 1 MICROAMP PER METER PER KHZ
40.
20.
0.
-20.
-40.
-60.
-80.
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

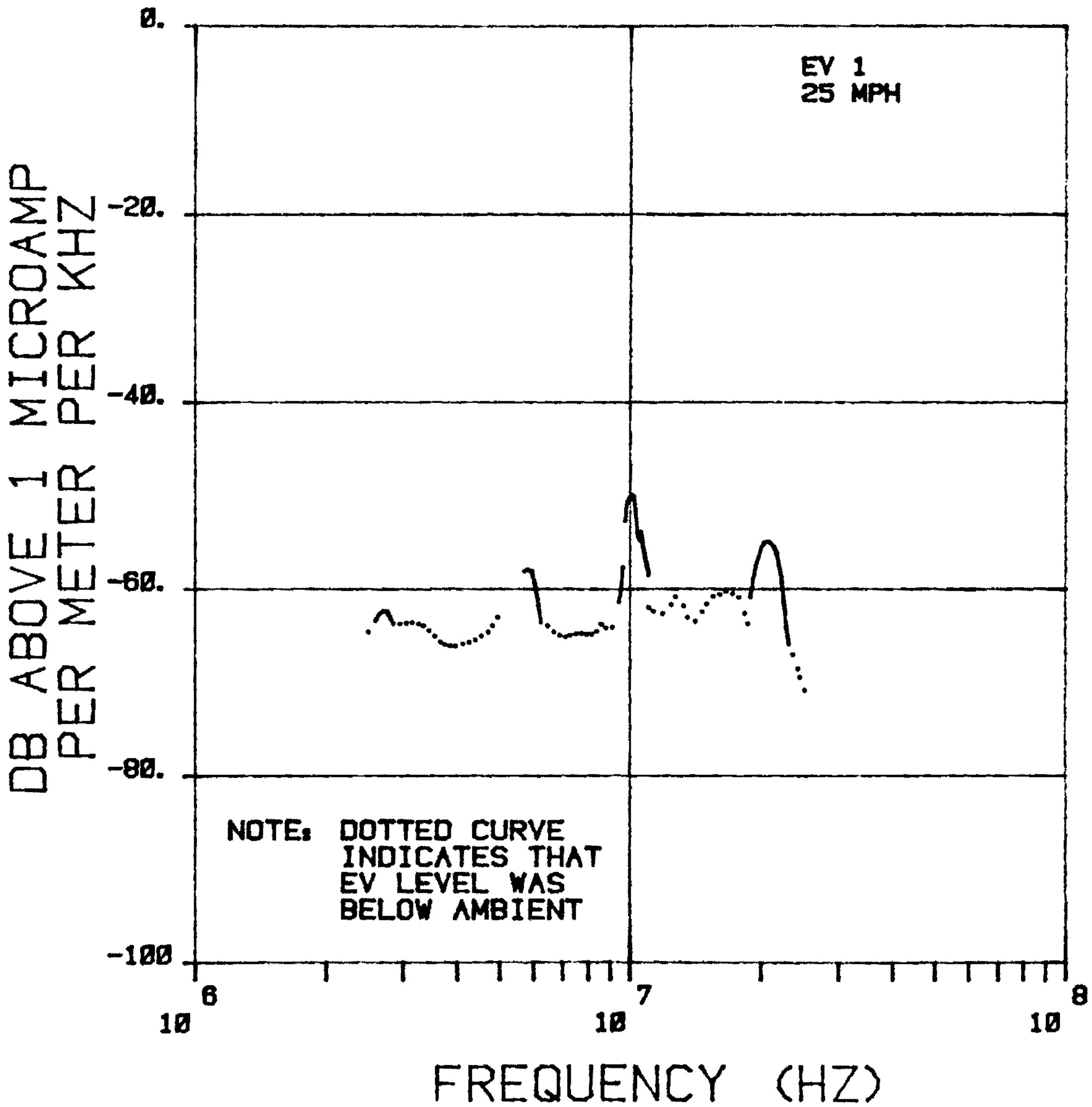
ROD
VERT. POL.
FRONT SIDE
NO LOAD

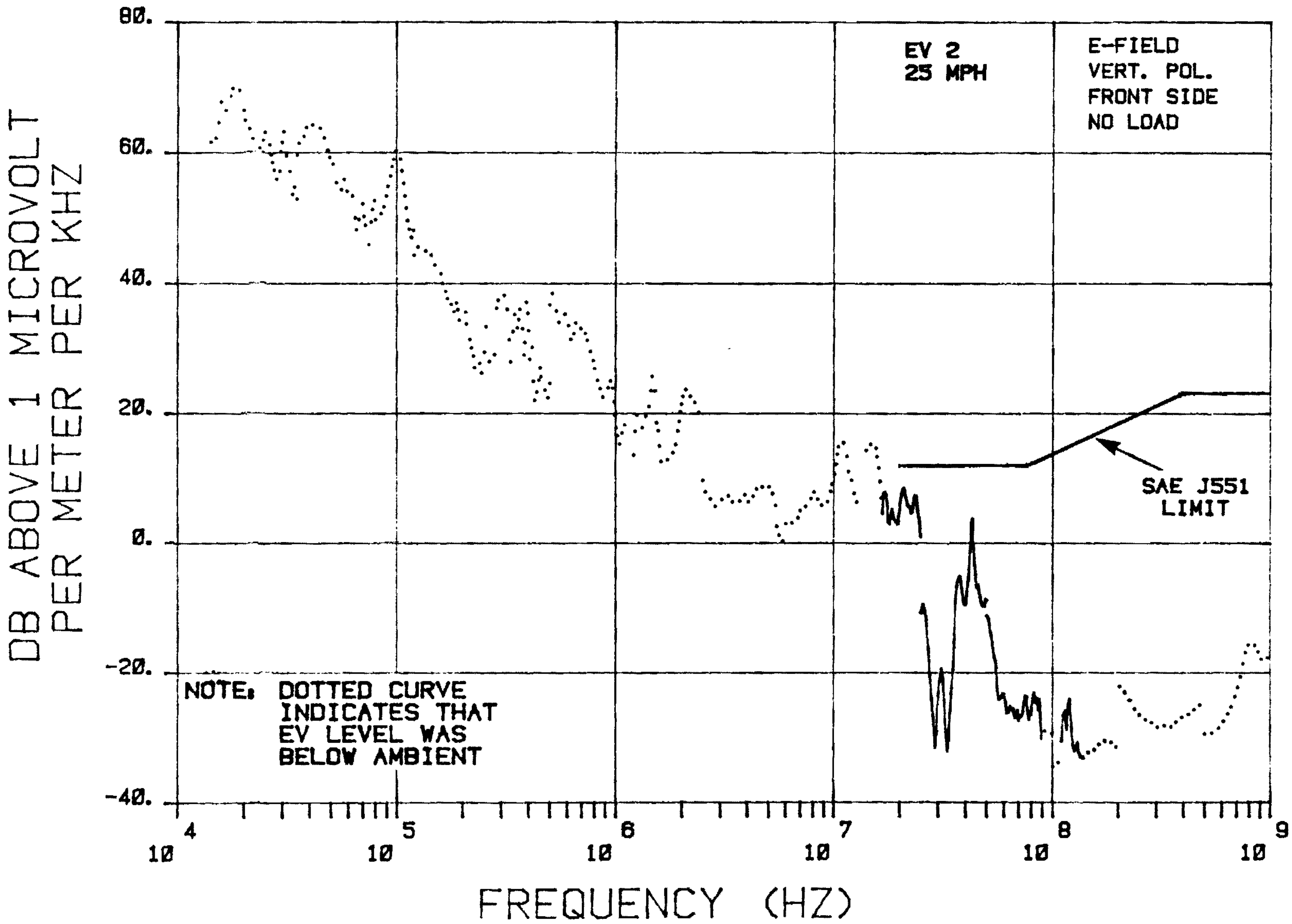


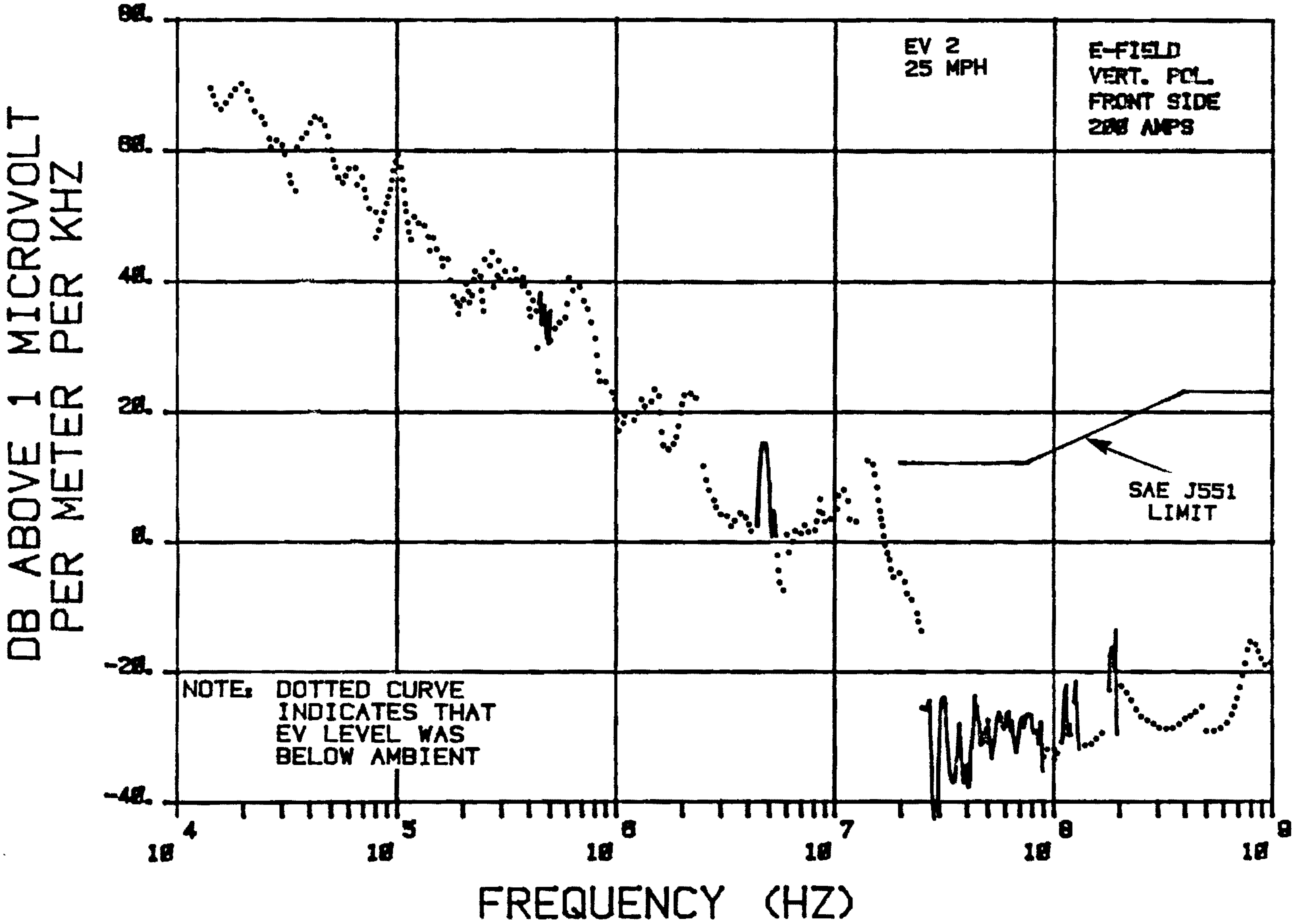
LOOP
HOR. POL.
FRONT SIDE
NO LOAD



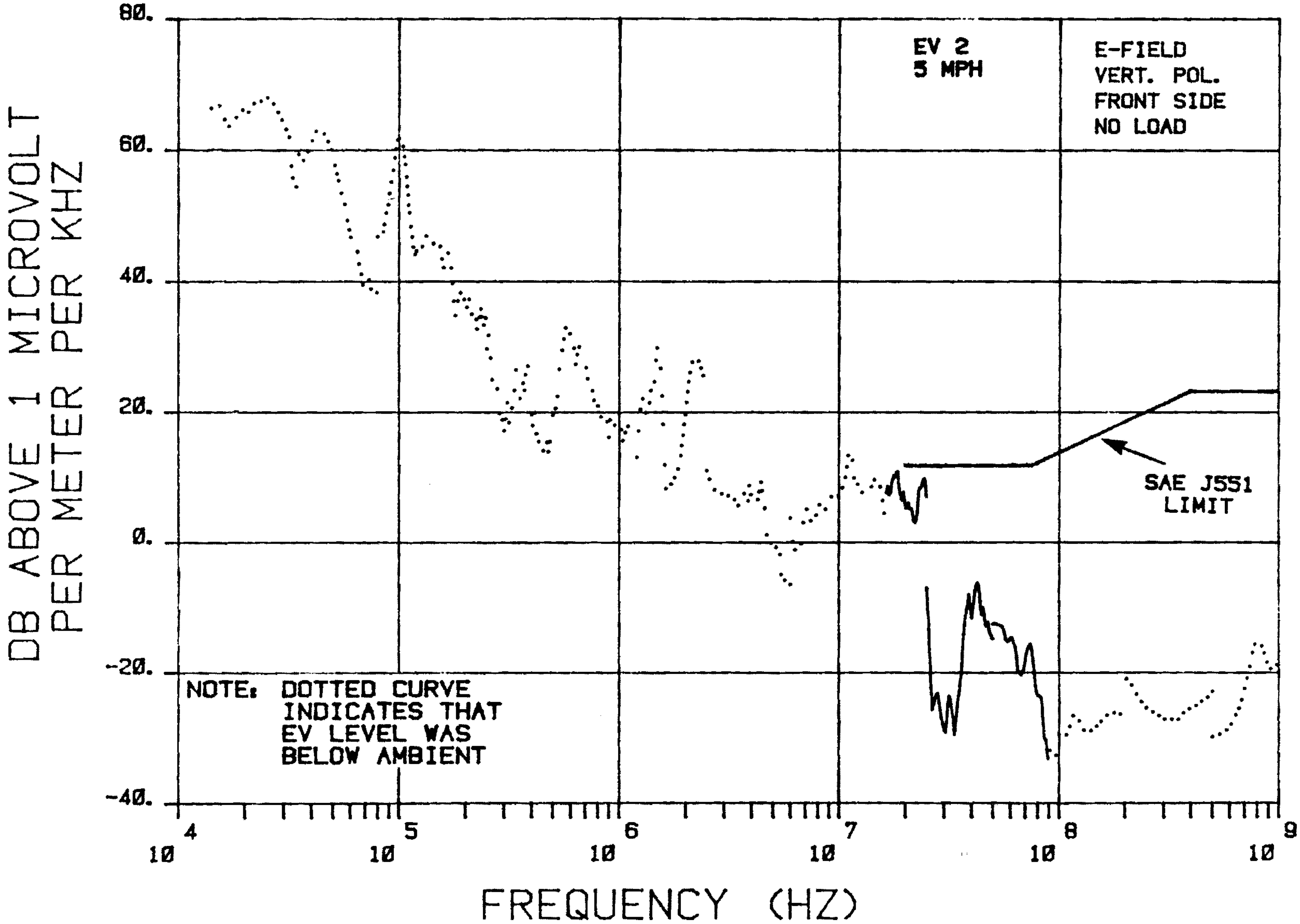
LOOP
RAD. POL.
FRONT SIDE
NO LOAD

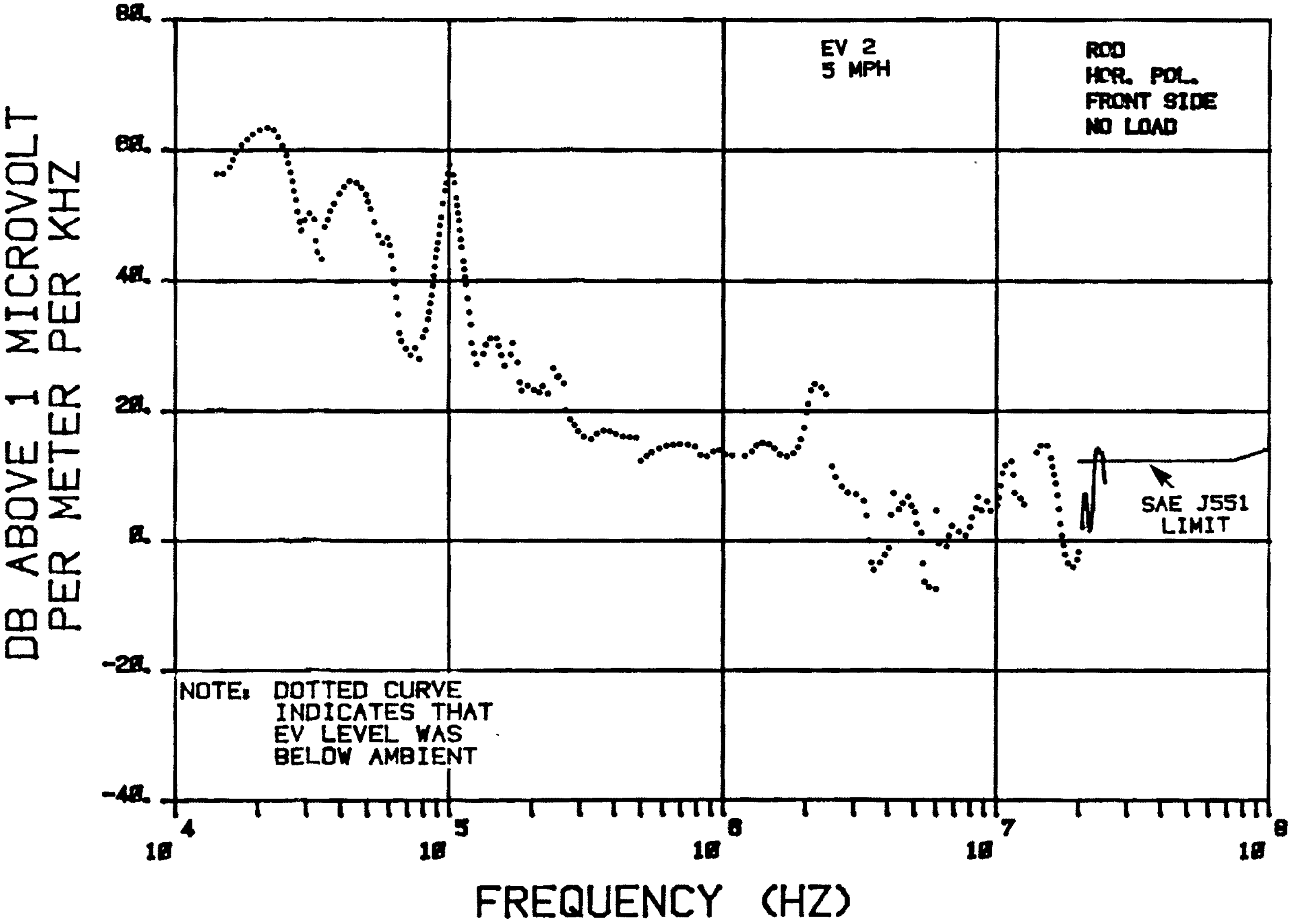


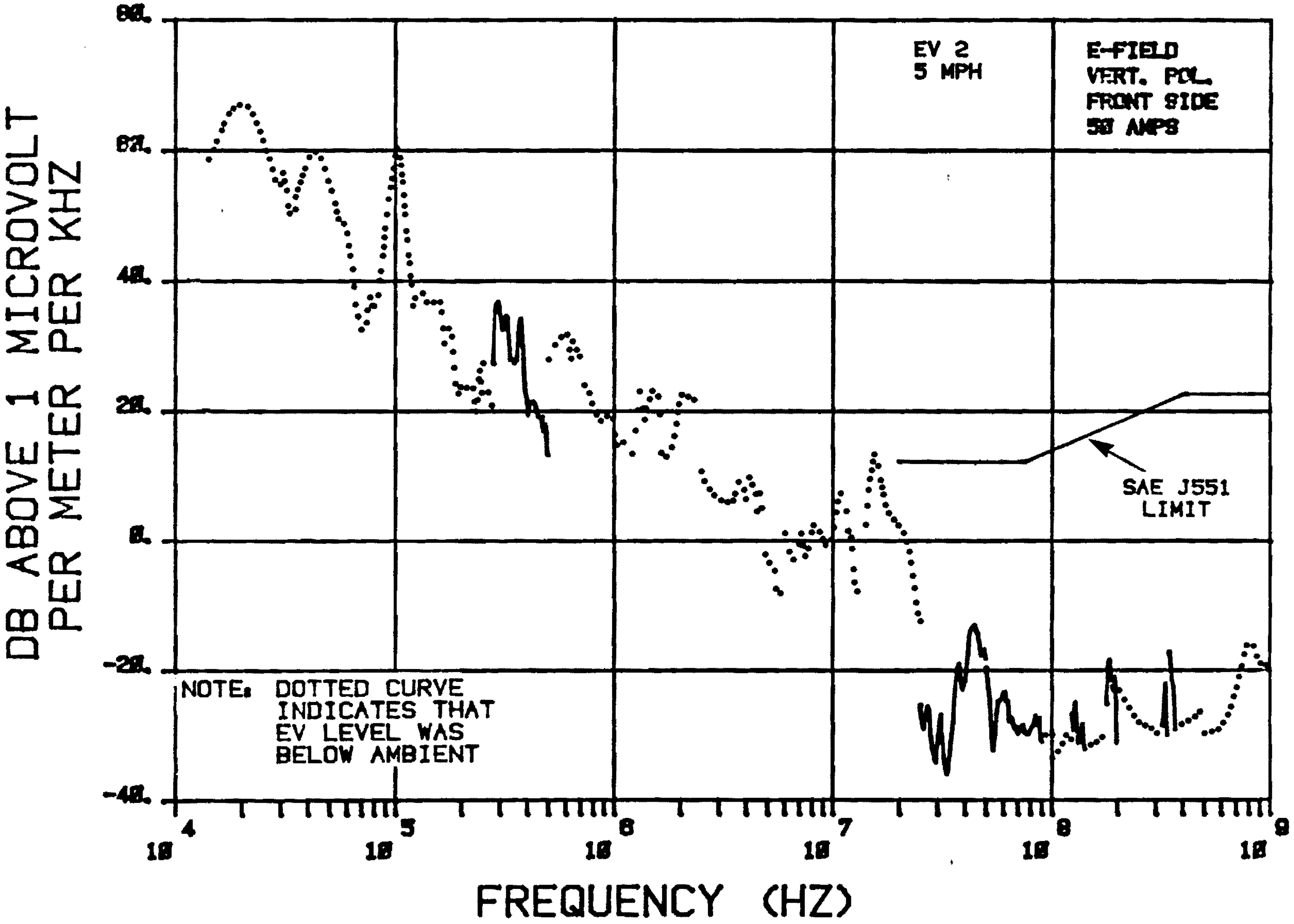

EV 2
25 MPH
E-FIELD
VERT. POL.
FRONT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
FREQUENCY (HZ)
80.
60.
40.
20.
0.
-20.
-40.
10^4
10^5
10^6
10^7
10^8
10^9



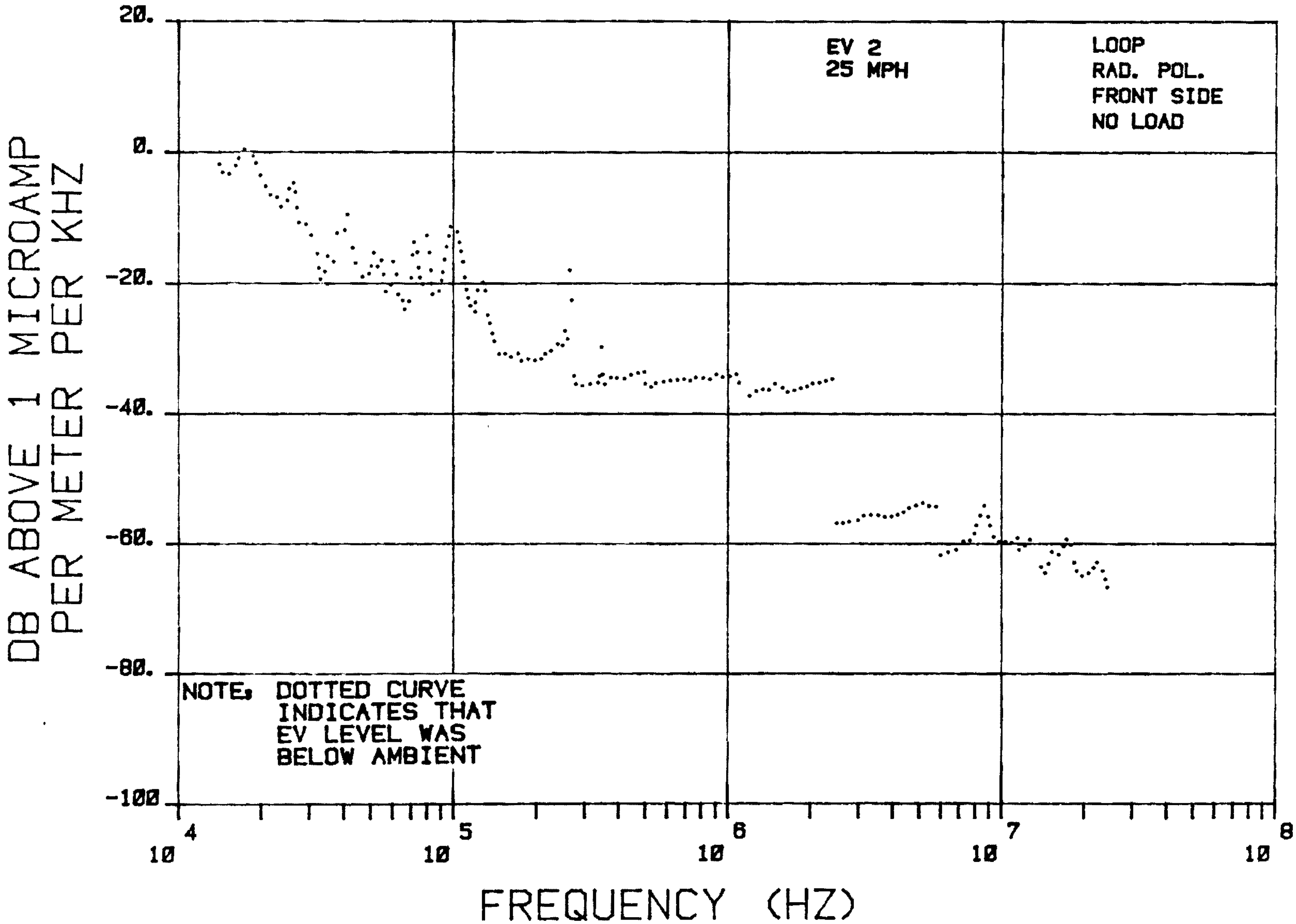
80.
60.
40.
20.
0.
-20.
-40.
DB ABOVE 1 MICROVOLT PER METER PER KHZ
EV 2
25 MPH
E-FIELD
VERT. POL.
FRONT SIDE
200 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)


DB ABOVE 1 MICROVOLT PER METER PER KHZ
80.
60.
40.
20.
0.
-20.
-40.
EV 2
5 MPH
E-FIELD
VERT. POL.
FRONT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

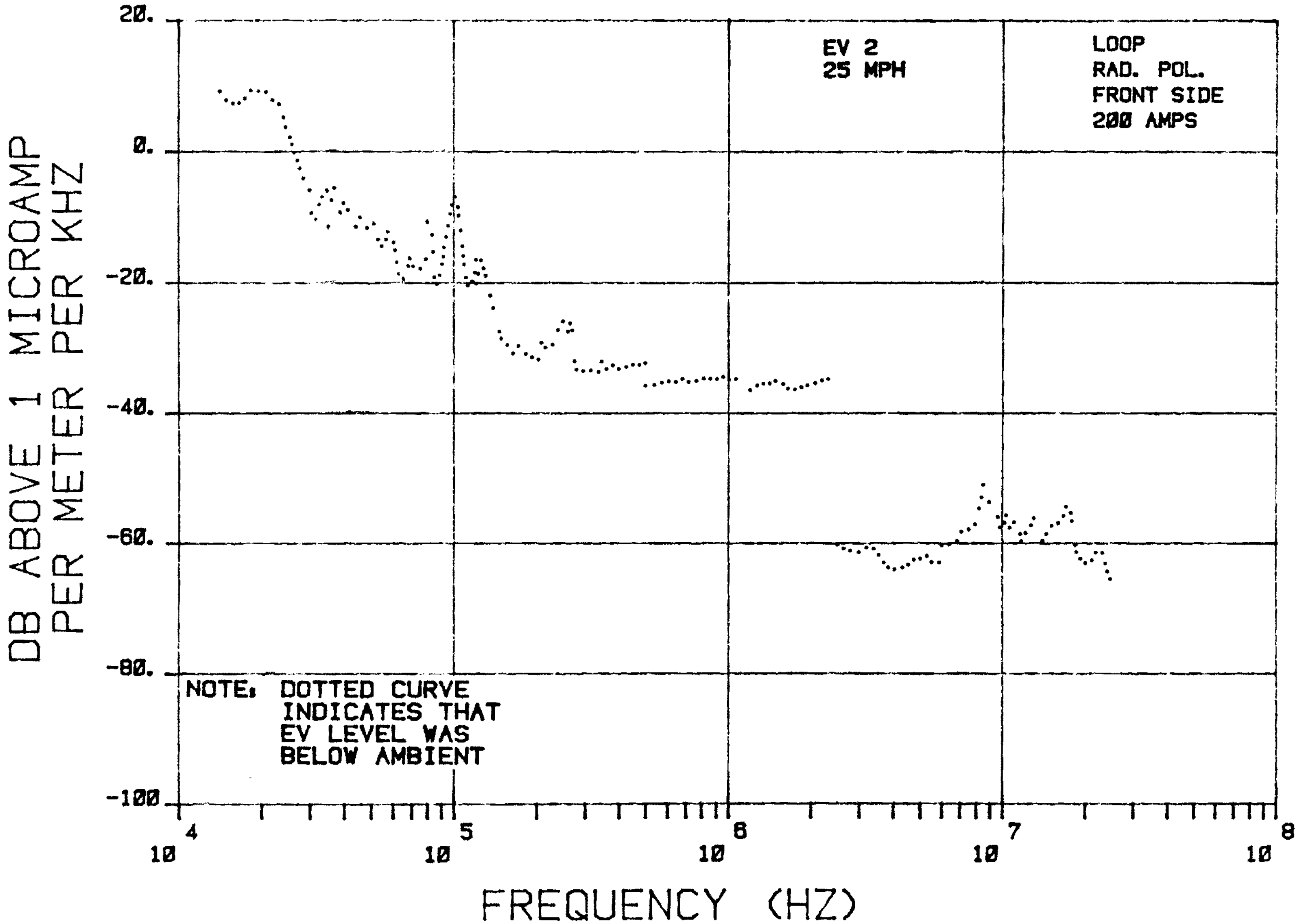

EV 2
5 MPH
ROD
HOR. POL.
FRONT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
80.
60.
40.
20.
0.
-20.
-40.
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)



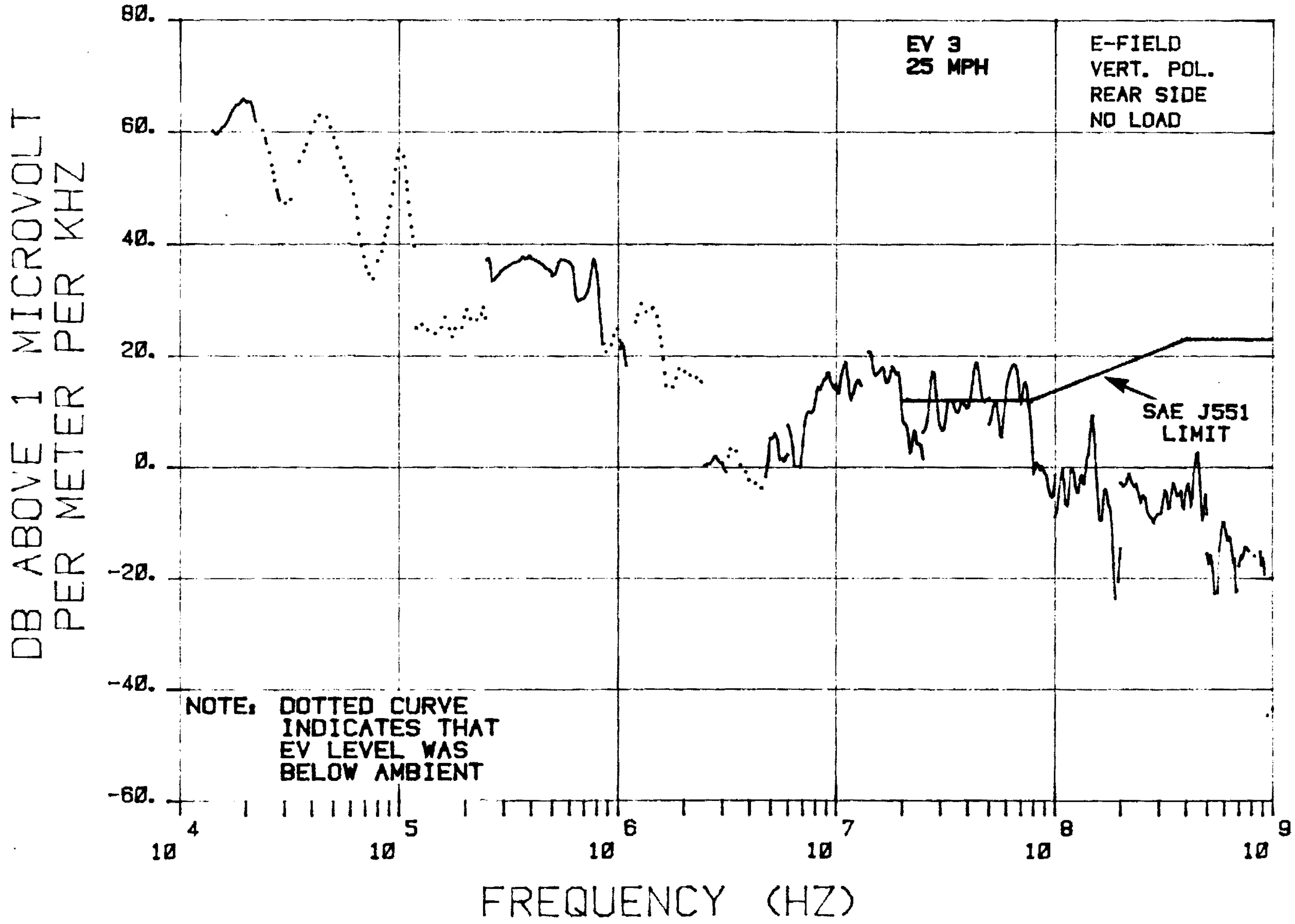
EV 2
5 MPH
E-FIELD
VERT. POL.
FRONT SIDE
50 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROVOLT PER METER PER KHZ
FREQUENCY (HZ)
80.
60.
40.
20.
0.
-20.
-40.
10^4
10^5
10^6
10^7
10^8
10^9

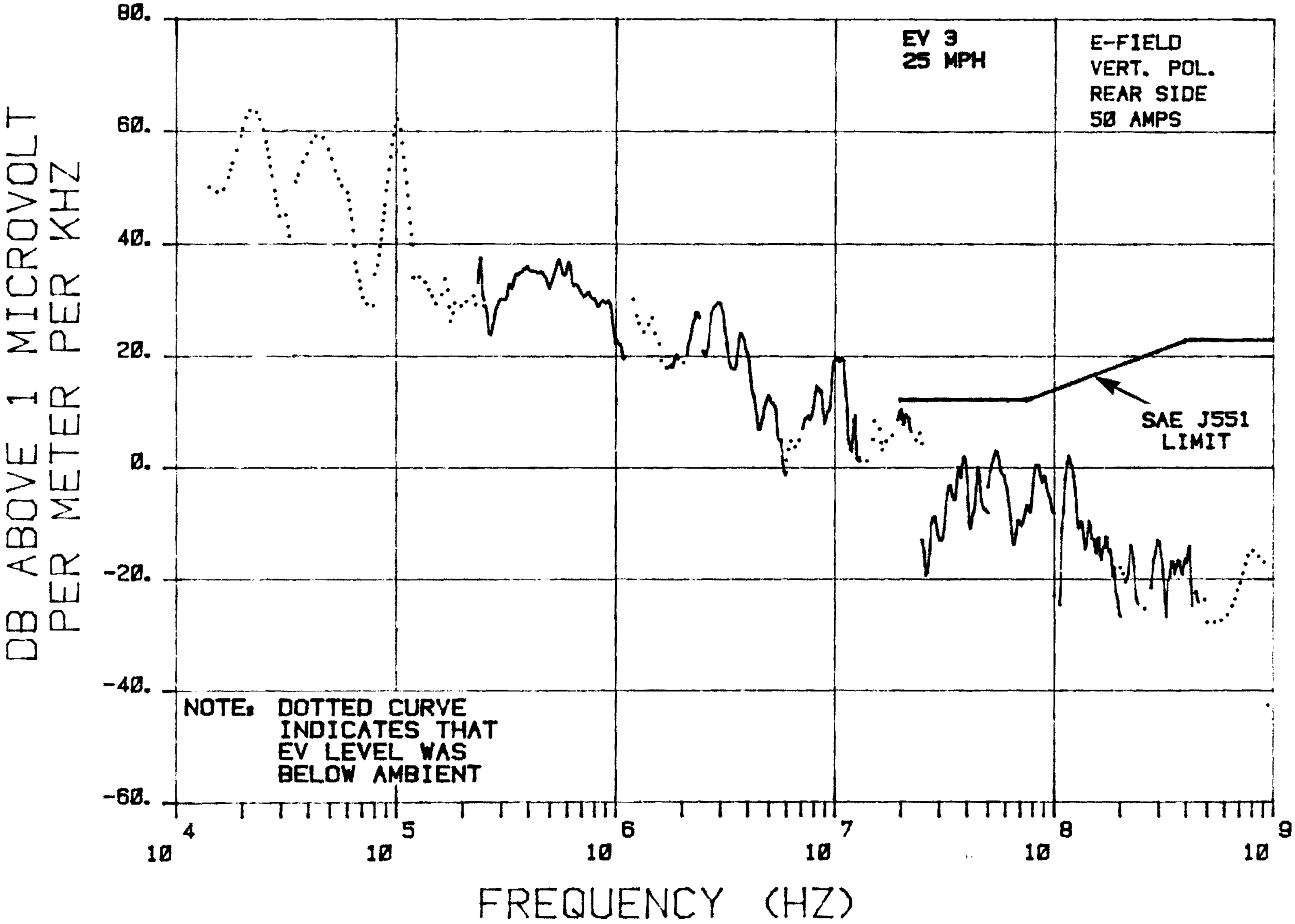


EV 2
25 MPH
LOOP
RAD. POL.
FRONT SIDE
NO LOAD
20.
0.
-20.
-40.
-60.
-80.
-100
DB ABOVE 1 MICROAMP PER METER PER KHZ
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

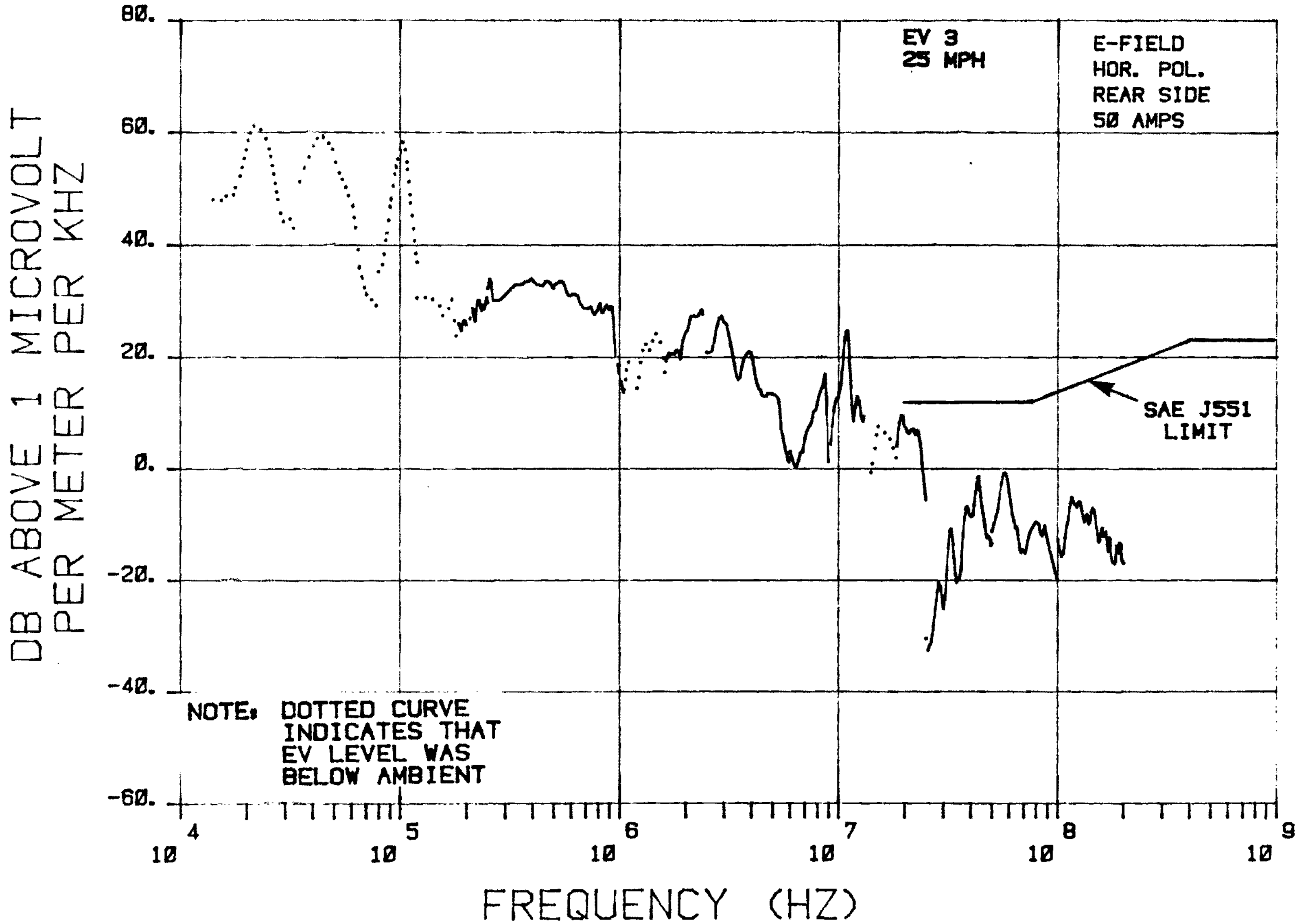


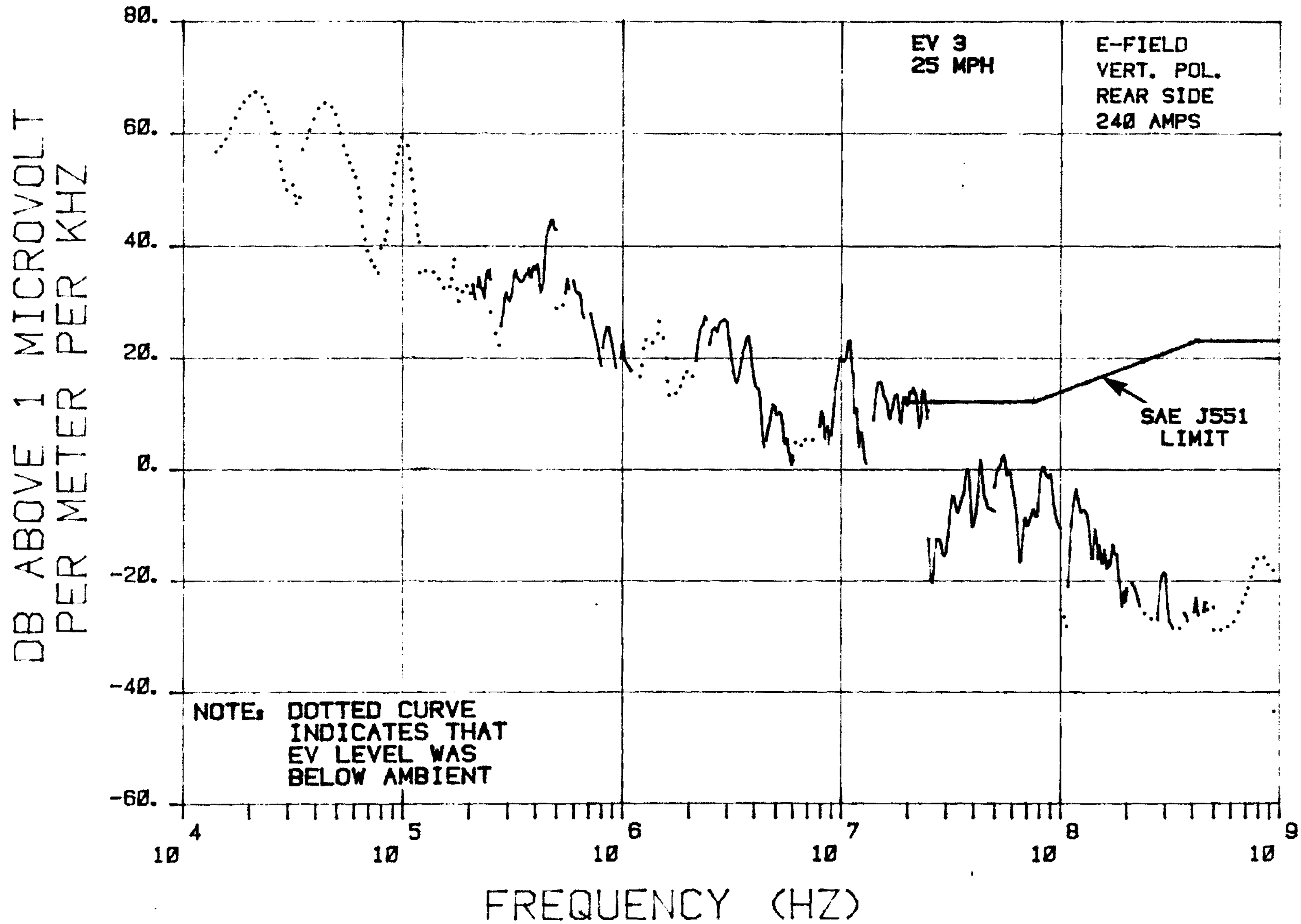
EV 2
25 MPH
LOOP
RAD. POL.
FRONT SIDE
200 AMPS
DB ABOVE 1 MICROAMP PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
-100
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

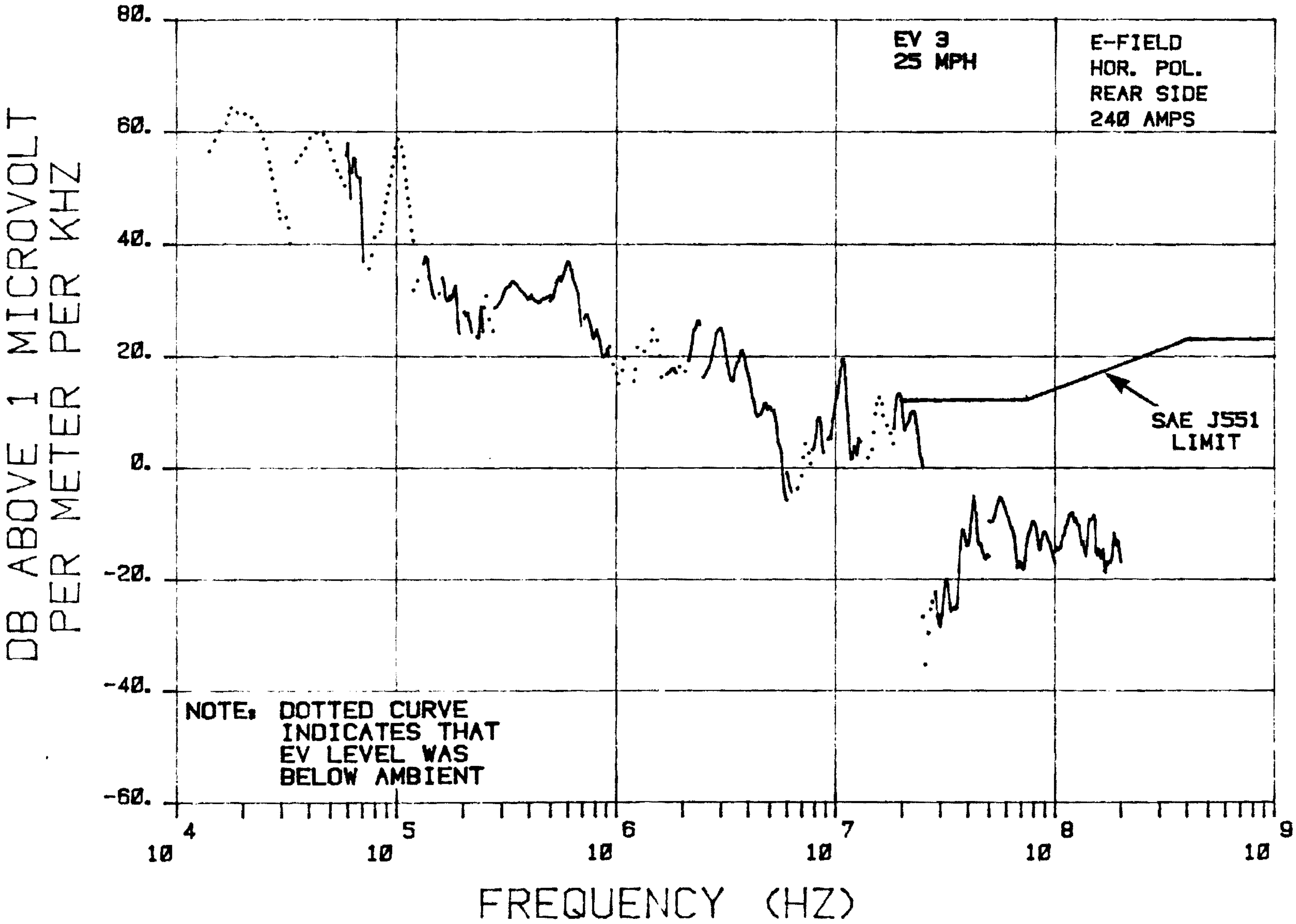

EV 3
25 MPH
E-FIELD
VERT. POL.
REAR SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROVOLT PER METER PER KHZ
80.
60.
40.
20.
0.
-20.
-40.
-60.
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

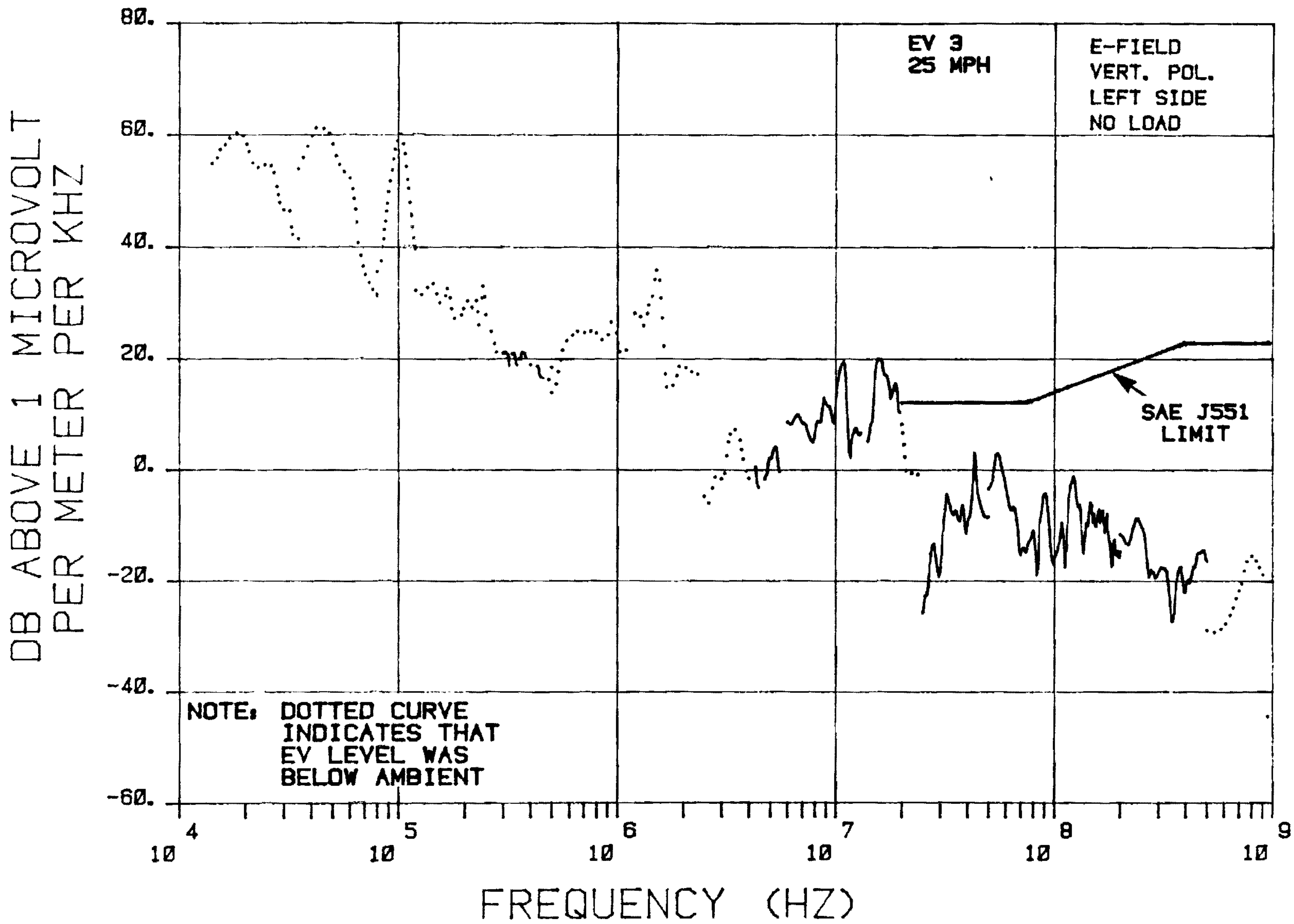


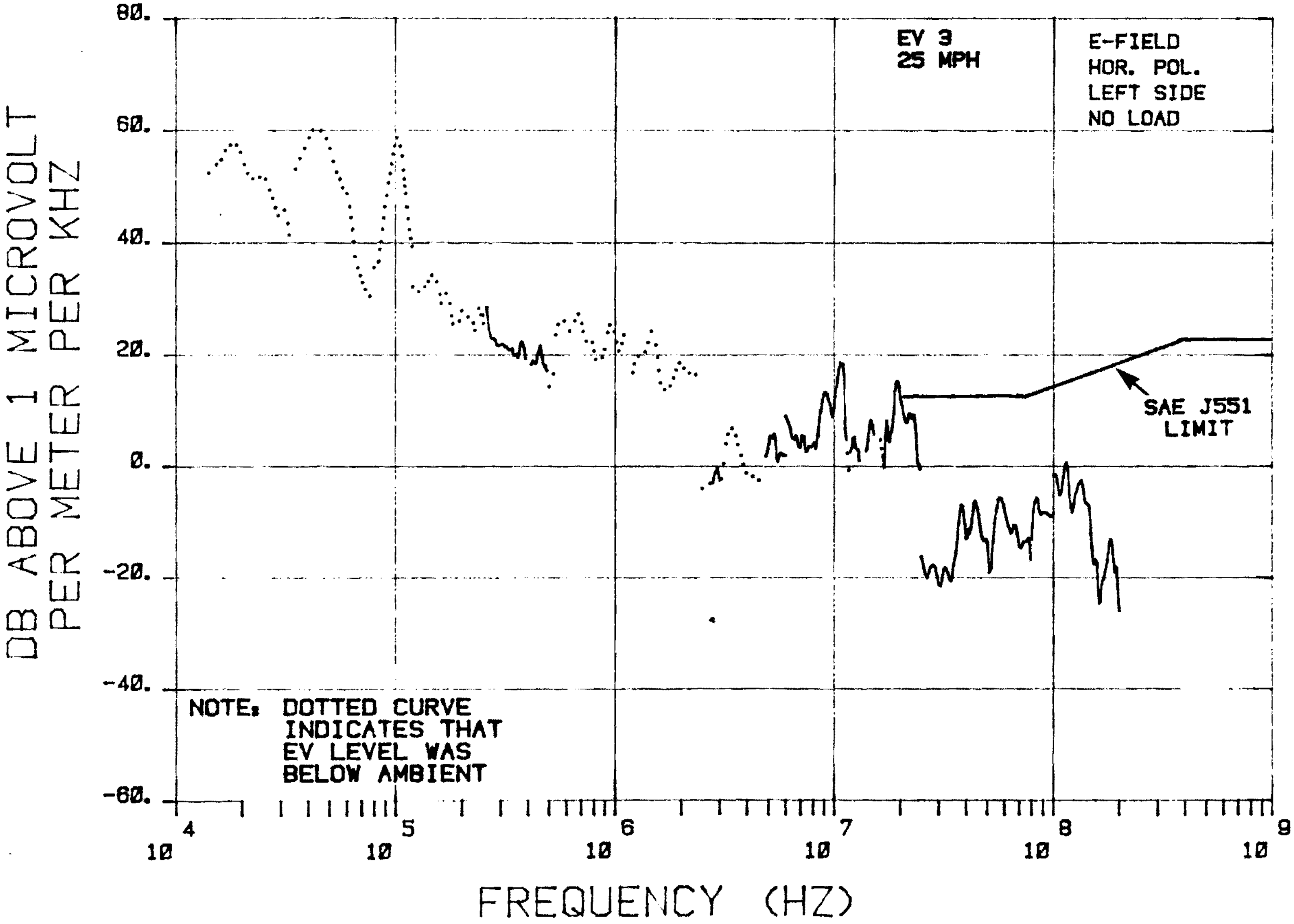
DB ABOVE 1 MICROVOLT PER METER PER KHZ
80.
60.
40.
20.
0.
-20.
-40.
-60.
EV 3
25 MPH
E-FIELD
VERT. POL.
REAR SIDE
50 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

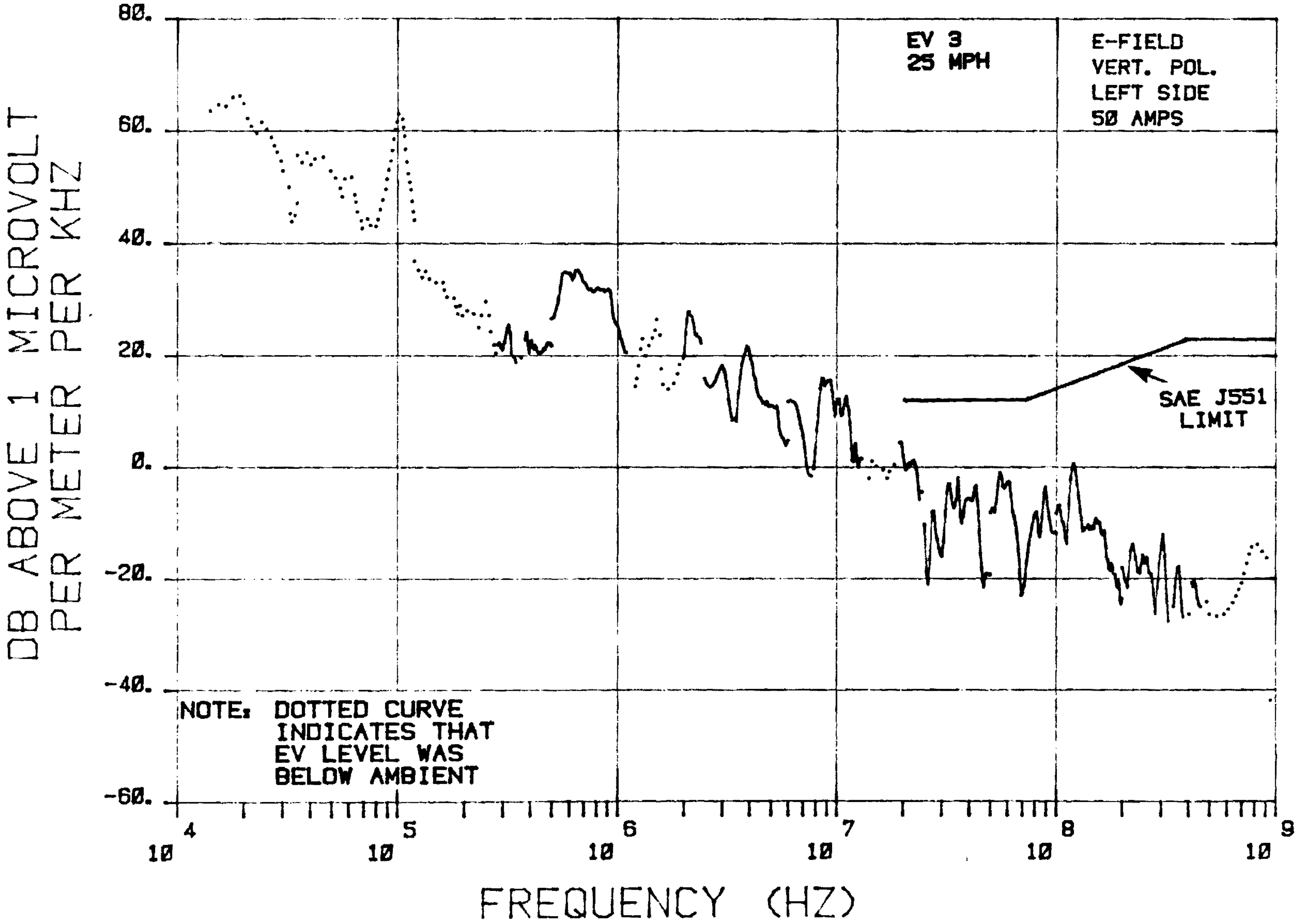

EV 3
25 MPH
E-FIELD
HOR. POL.
REAR SIDE
50 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROVOLT PER METER PER KHZ
80.
60.
40.
20.
0.
-20.
-40.
-60.
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)


EV 3
25 MPH
E-FIELD
VERT. POL.
REAR SIDE
240 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
80.
60.
40.
20.
0.
-20.
-40.
-60.
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

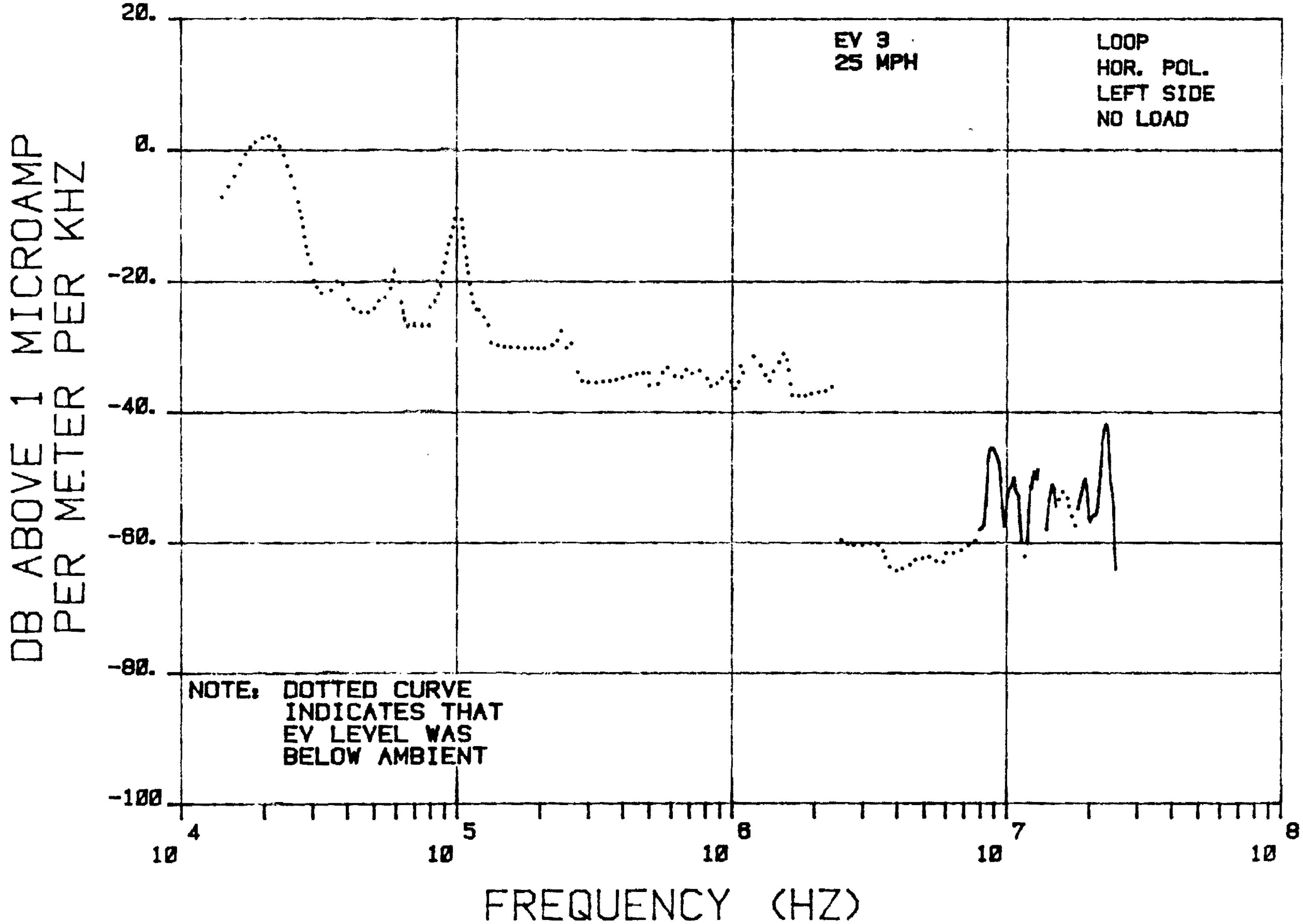

EV 3
25 MPH
E-FIELD
HOR. POL.
REAR SIDE
240 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
80.
60.
40.
20.
0.
-20.
-40.
-60.
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

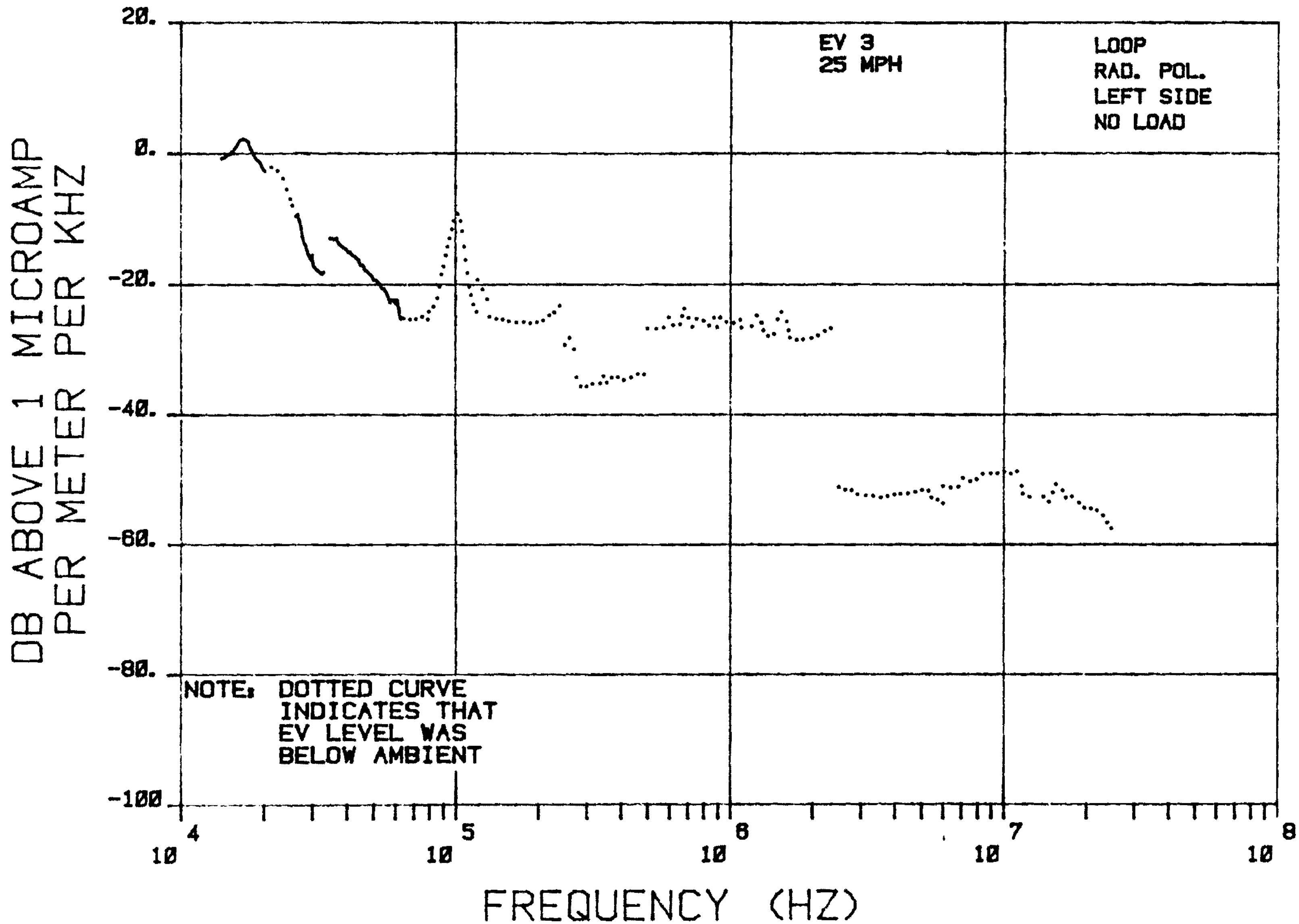

80.
60.
40.
20.
0.
-20.
-40.
-60.
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
EV 3
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

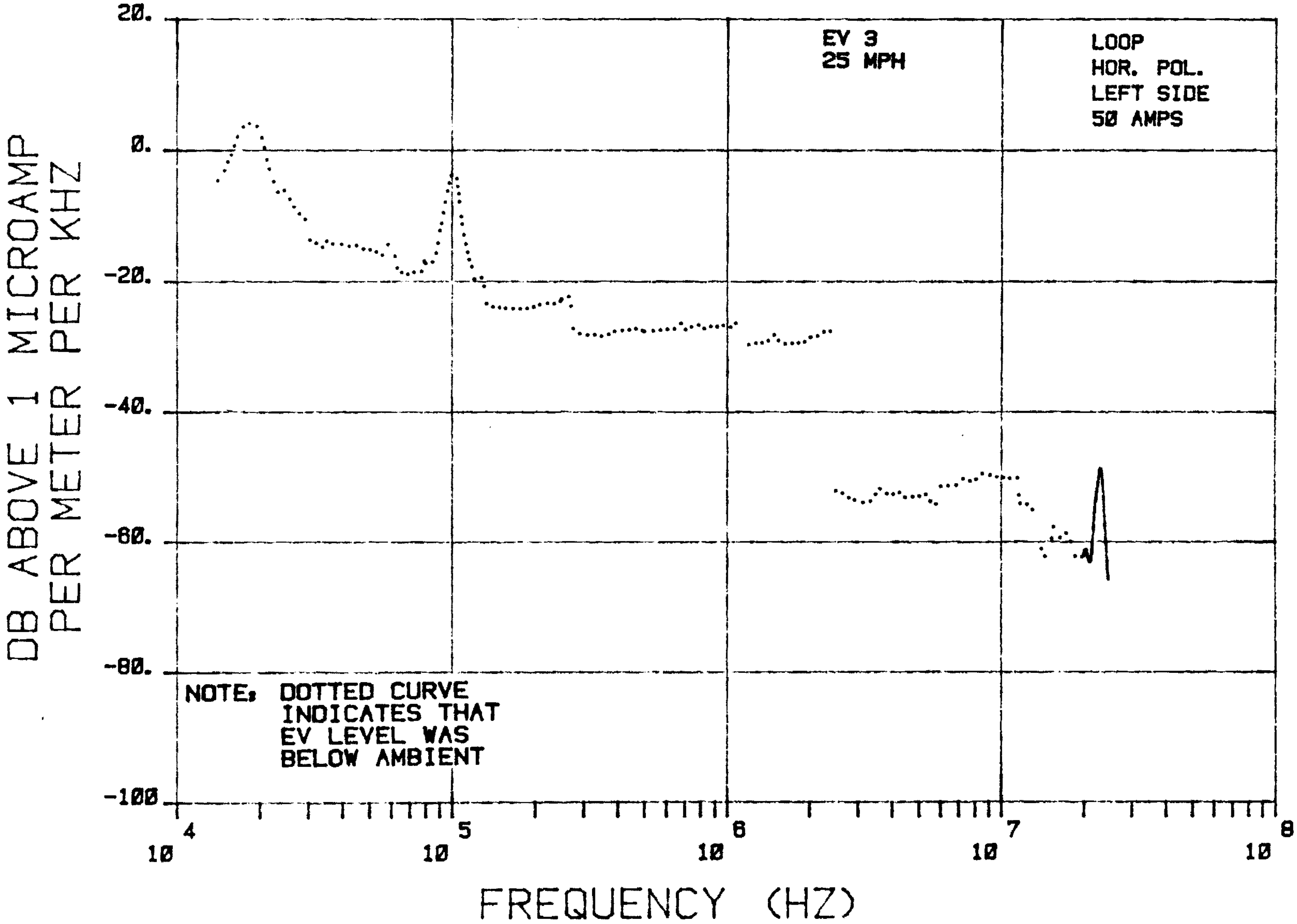

EV 3
25 MPH
E-FIELD
HOR. POL.
LEFT SIDE
NO LOAD
SAE J551
LIMIT
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
DB ABOVE 1 MICROVOLT
PER METER PER KHZ
80.
60.
40.
20.
0.
-20.
-40.
-60.
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)

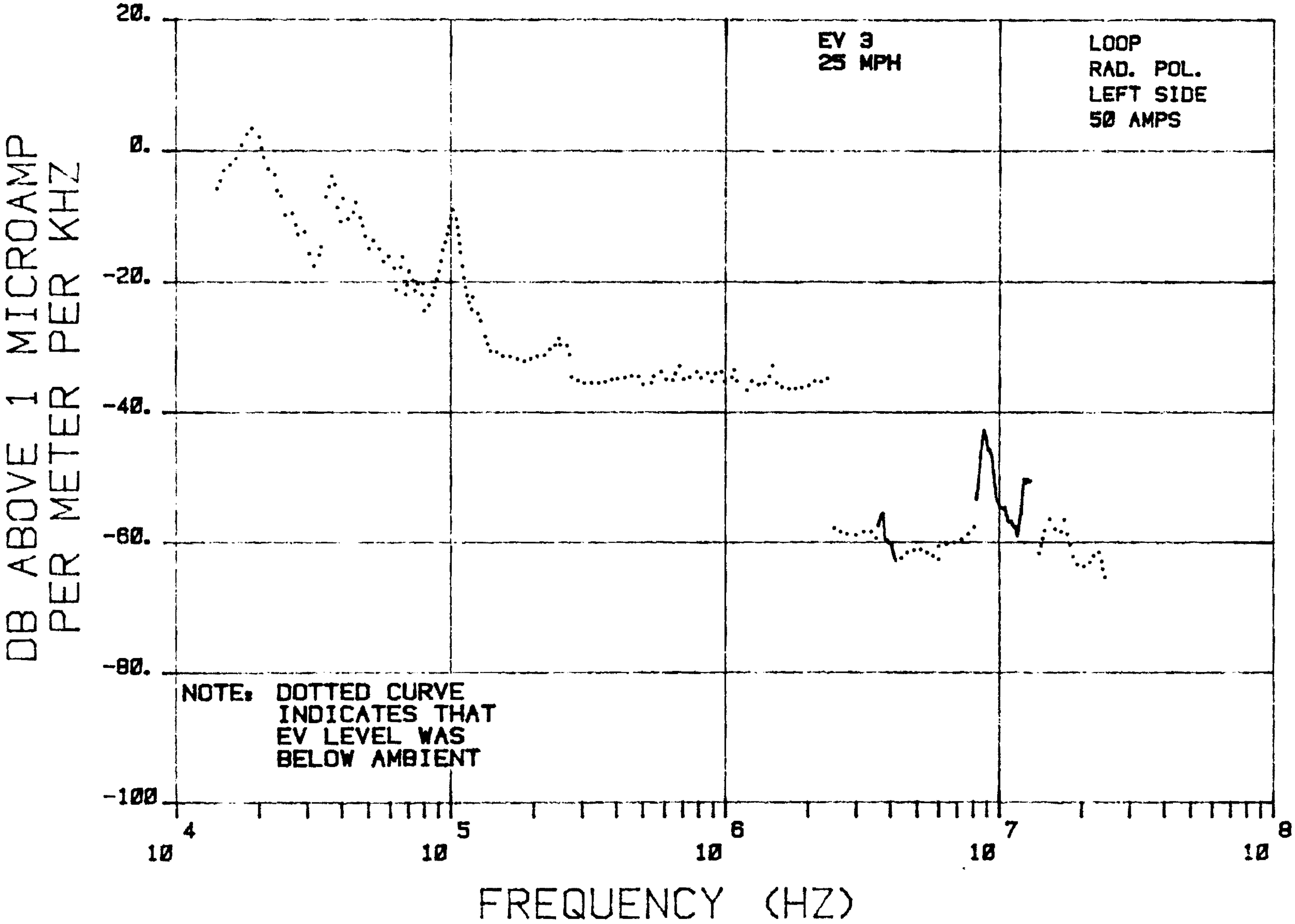


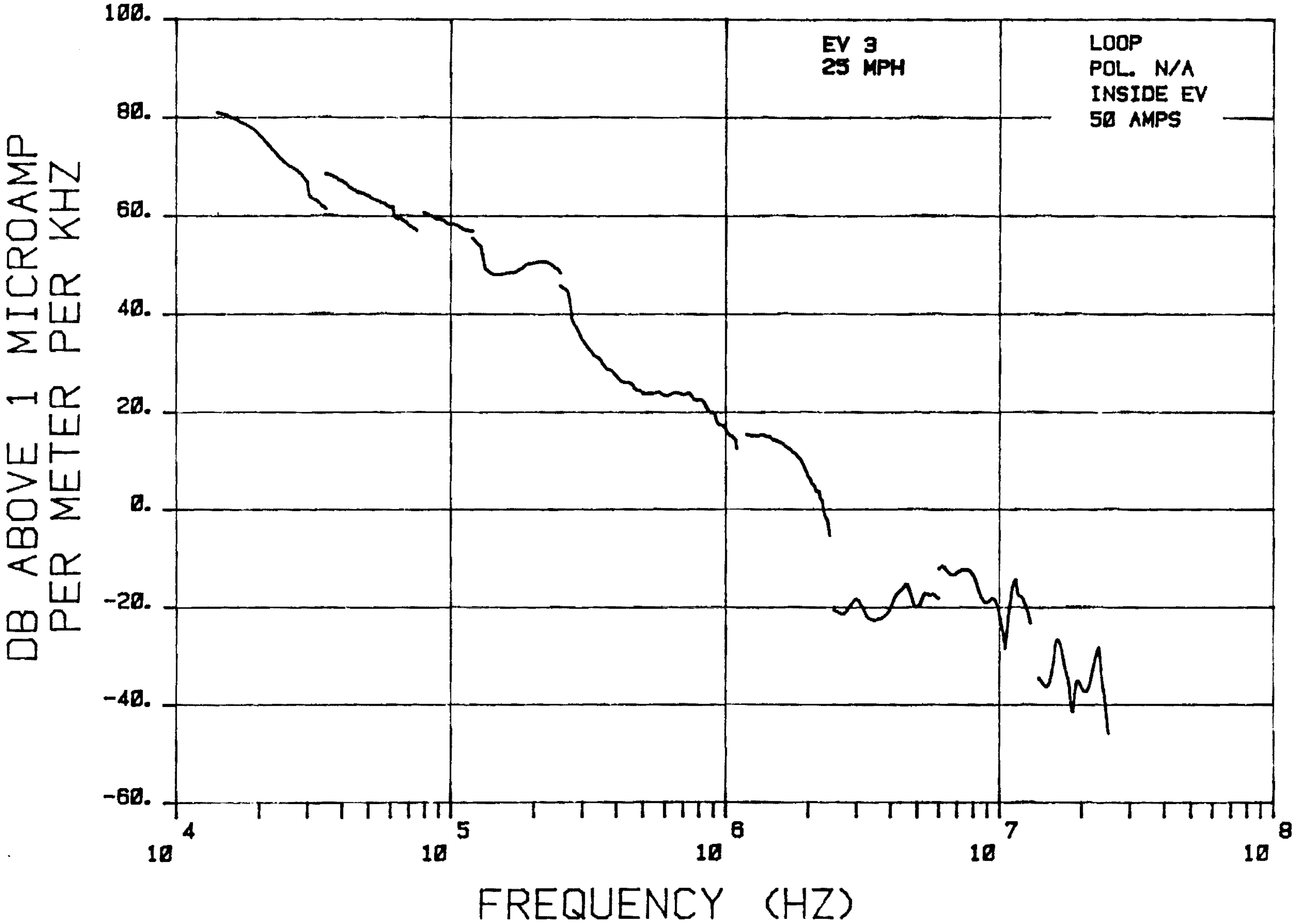
80.
60.
40.
20.
0.
-20.
-40.
-60.
DB ABOVE 1 MICROVOLT PER METER PER KHZ
EV 3
25 MPH
E-FIELD
VERT. POL.
LEFT SIDE
50 AMPS
SAE J551
LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
10^9
FREQUENCY (HZ)


EV 3
25 MPH
LOOP
HOR. POL.
LEFT SIDE
NO LOAD
DB ABOVE 1 MICROAMP
PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
-100
NOTE: DOTTED CURVE
INDICATES THAT
EV LEVEL WAS
BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)


EV 3
25 MPH
LOOP
RAD. POL.
LEFT SIDE
NO LOAD
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
-100
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)


EV 3
25 MPH
LOOP
HOR. POL.
LEFT SIDE
50 AMPS
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER METER PER KHZ
20.
0.
-20.
-40.
-60.
-80.
-100.
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

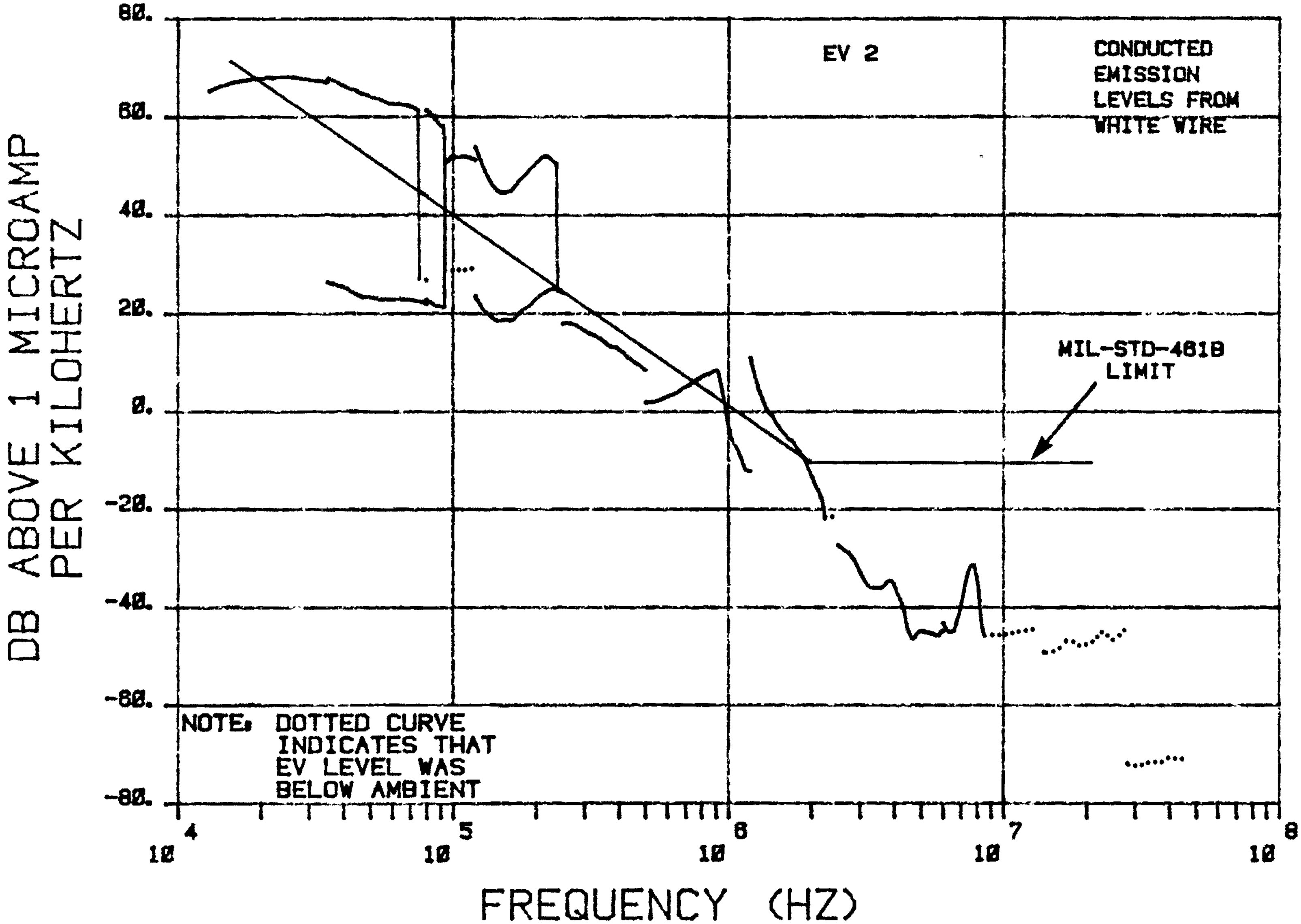

EV 3
25 MPH
LOOP
RAD. POL.
LEFT SIDE
50 AMPS
20.
0.
-20.
-40.
-60.
-80.
-100
DB ABOVE 1 MICROAMP PER METER PER KHZ
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

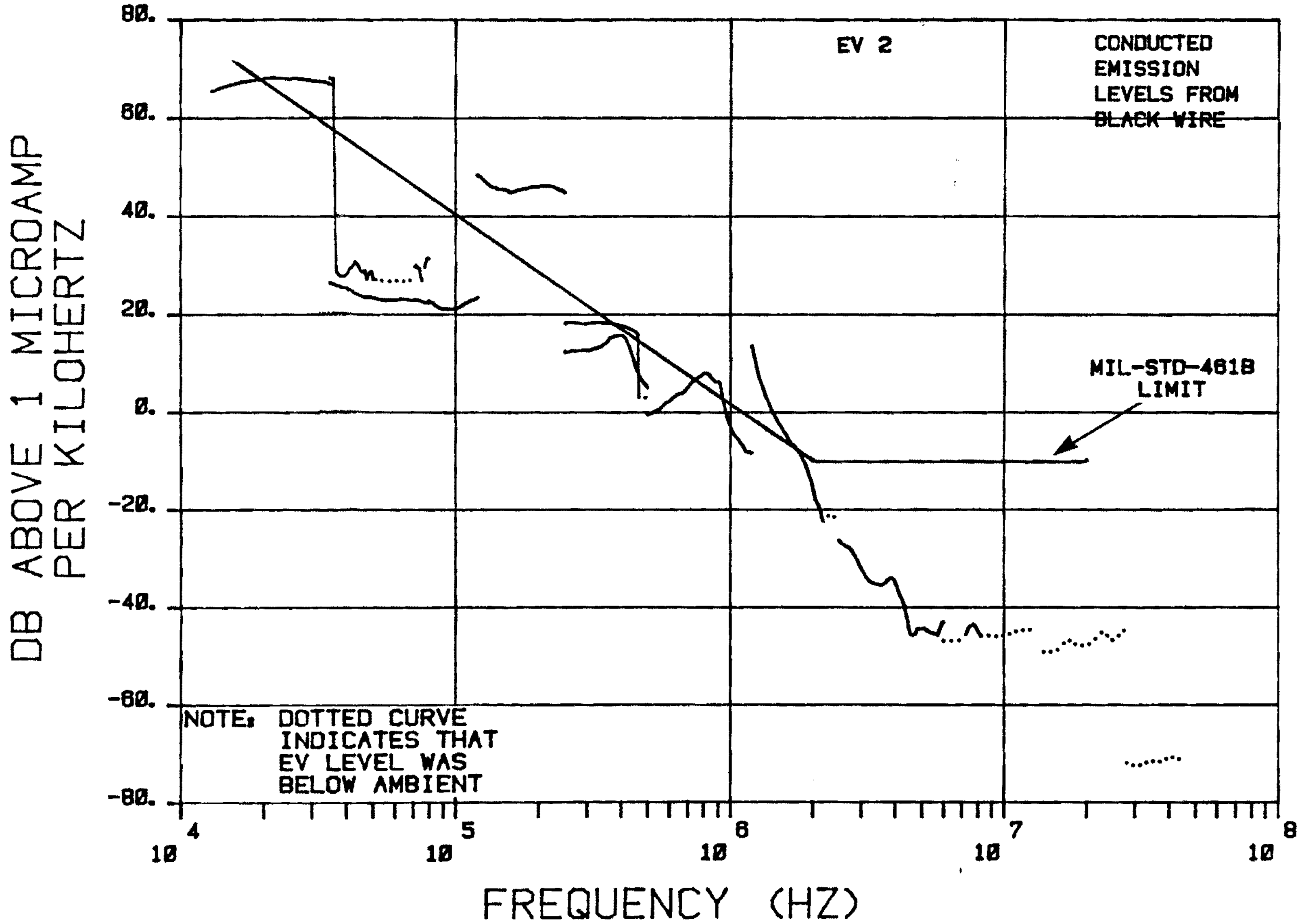

EV 3
25 MPH
LOOP
POL. N/A
INSIDE EV
50 AMPS
DB ABOVE 1 MICROAMP PER METER PER KHZ
100.
80.
60.
40.
20.
0.
-20.
-40.
-60.
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

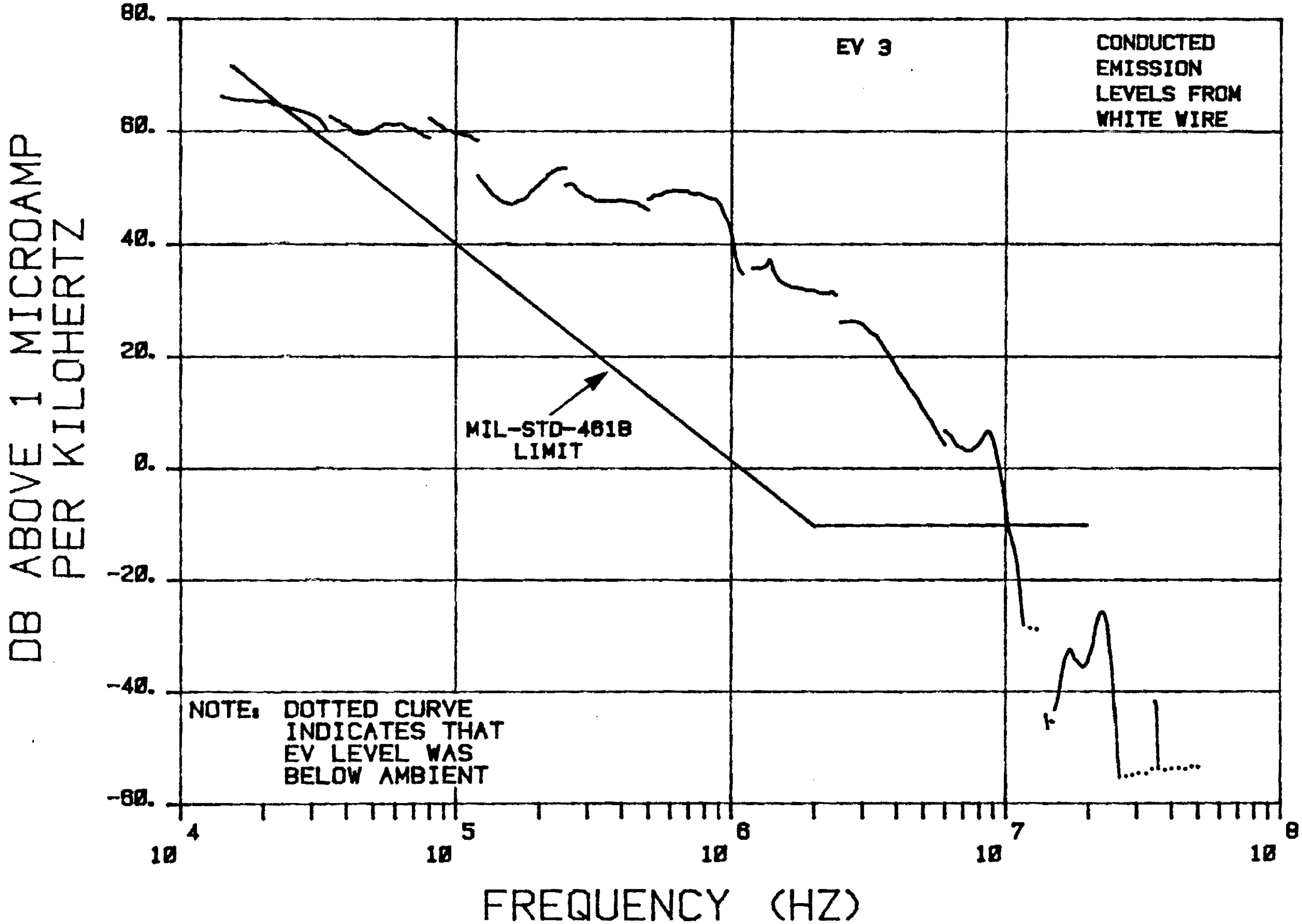
APPENDIX II

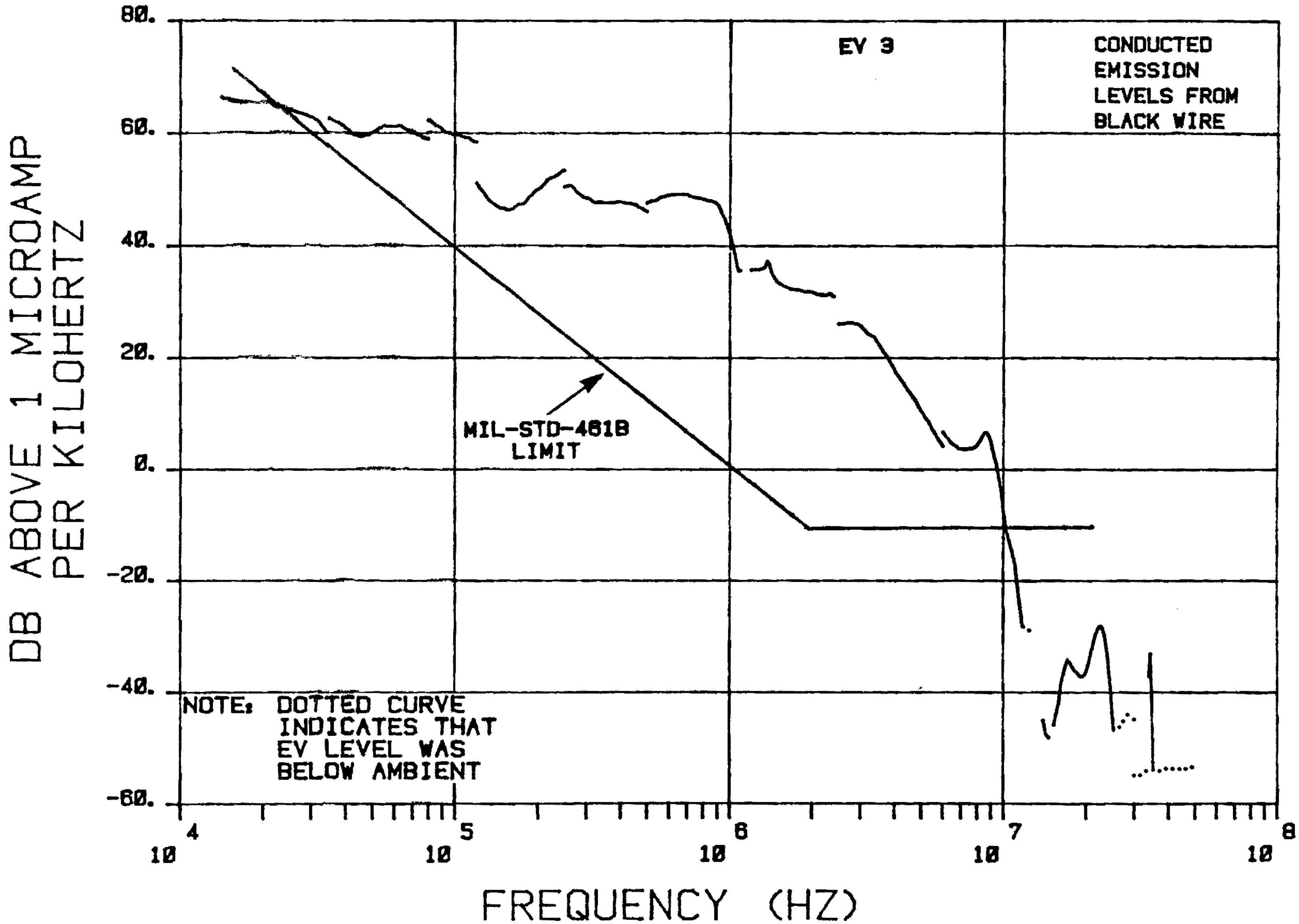
CONDUCTED EMISSION DATA FOR ON-BOARD BATTERY CHARGERS

This appendix includes the emission current levels on both the black (phase) and white (neutral) conductors of the two on-board chargers tested. The same codes as in Appendix I were used. That is, EV2 is the EVA Evcort charger and EV3 is the Unique Mobility Electrek charger.


EV 2
CONDUCTED EMISSION LEVELS FROM WHITE WIRE
MIL-STD-461B LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER KILOHERTZ
FREQUENCY (HZ)
80.
60.
40.
20.
0.
-20.
-40.
-60.
-80.
10^4
10^5
10^6
10^7
10^8


EV 2
CONDUCTED EMISSION LEVELS FROM BLACK WIRE
MIL-STD-461B LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER KILOHERTZ
FREQUENCY (HZ)
80.
60.
40.
20.
0.
-20.
-40.
-60.
-80.
10^4
10^5
10^6
10^7
10^8


EV 3
CONDUCTED EMISSION LEVELS FROM WHITE WIRE
MIL-STD-461B LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
DB ABOVE 1 MICROAMP PER KILOHERTZ
FREQUENCY (HZ)
80.
60.
40.
20.
0.
-20.
-40.
-60.
10^4
10^5
10^6
10^7
10^8



EV 3
CONDUCTED EMISSION LEVELS FROM BLACK WIRE
DB ABOVE 1 MICROAMP PER KILOHERTZ
80.
60.
40.
20.
0.
-20.
-40.
-60.
MIL-STD-461B LIMIT
NOTE: DOTTED CURVE INDICATES THAT EV LEVEL WAS BELOW AMBIENT
10^4
10^5
10^6
10^7
10^8
FREQUENCY (HZ)

APPENDIX III

ANALYSIS OF POTENTIAL IMPACT OF EV EMISSIONS ON STANDARD AM BROADCAST RECEPTION

This appendix contains an analysis which demonstrates the potential impact of EV radiated emissions on the interference-free range of an AM broadcast station.

A 50 kW AM transmitter (Class I or II) operating at 1 MHz was selected for the analysis. The electric field intensity radiated from a vertical tower, insulated from ground, and of a construction commonly used for standard AM broadcasting may be approximated by the following equation [15]*:

$$E_b = \frac{60\ I}{D\ \sin(2\pi h/\lambda)}\left[\frac{\cos[(2\pi h/\lambda)\cos\theta] - \cos(2\pi h/\lambda)}{\sin\theta}\right] \qquad (1)$$

where:

E_b = electric field intensity of broadcast signal in mV/meter,

I = current at base of antenna in amperes,

h = height of antenna,

λ = wavelength in same units as h,

D = distance from antenna in kilometers, and

θ = angle from the vertical.

For a quarter-wave tower ($h = \lambda/4$) and broadside radiation ($\theta = 90^\circ$), Equation (1) reduces to

$$E_b = 60I/D \qquad (2)$$

The current may be approximated to be

$$I = \sqrt{W\eta/R} \qquad (3)$$

*The references in this appendix can be found on page 35 of this report.

where:

W = input power in watts,

η = antenna efficiency, and

R = resistance at base of antenna in ohms.

For a quarter-wave antenna, R is approximately 40 ohms and a typical efficiency is 90 percent, which results in a current of 3.5 amperes. Substituting this current into Equation 2, the field intensity at 1 mile (1.609 kilometers) is approximately 1250 mV/meter. Taking the minimum field intensity for adequate reception (i.e., sensitivity) of an AM receiver to be 100 μV/m meter and assuming typical ground terrain with a conductivity of 0.007 mho/meter and a dielectric constant of 15, the broadcast range* is estimated to be 170 miles [15].

The decrease in the effective broadcast range due to radiated emissions from a large population of EV's may be calculated as follows. Since the radiated emission levels for the Electrek and the Electrica were much higher than that of the Evcort,two cases will be considered. First, as a worst case, assume for the moment that the Electrek and the Electrica are representative of the EV population in terms of their emission levels. Using an average value of 25 dBμV/m/kHz for the radiated emission levels from these two EV's in the AM broadcast band (535 kHz to 1.605 MHz) and assuming a 10 kHz bandwidth, the "total" field intensity in the receiver bandwidth due to a single EV is 45 dBμV/m. The emissions from different EV's are assumed to be uncorrelated (incoherent) and the radiated power levels will consequently be summed. Assuming 4 EV's at a 10 meter distance from the receive antenna, the total resultant field is 51 dBμV/m (45 dBμV/m + 10 $\log_{10} 4$) or 355 μV/m. Assuming that an interference condition exists when the total (peak) field radiated from EV's is equal to the broadcast signal level (i.e., 0 dB signal-to-noise ratio), the broadcast range is subsequently reduced to approximately 115 miles. If the interfering vehicles are taken to be only 5 meters from the receive antenna and if the field levels are assumed to vary as the reciprical

*The range was calculated assuming ground-wave propagation, which is a good assumption for day-time broadcasts. An entirely similar analysis can be performed assuming sky-wave propagation, with an increase in the resultant range. However, the reduction in range due to EV interference will be of approximately the same relative magnitude as before.

of separation distance, the total field radiated from the EV's would be 57 dBμV/m (51 dBμV/m + 20 $\log_{10}2$) or 708 μV/m. The resulting interference-free range would be approximately 85 miles, i.e, the effective range would be reduced by a factor of 2 from the interference-free case.

Next, a similar analysis may be performed assuming that the Evcort radiation levels (which are much lower than those of the Electrica or Electrek) are representative of the EV population as a whole. Using a value of 10 dBμV/m/kHz** for the radiated emission levels from this vehicle in the AM band and making the same assumptions as above, the effective interference-free range was again calculated. With 4 EV's at a 10 meter distance from the receive antenna, the effective range remains unchanged. With 4 EV's at a 5 meter EV-to-antenna spacing, the effective range would be reduced from 170 miles to about 165 miles, a reduction of only about 3 percent.

**The levels radiated from the Evcort in the AM band were below the ambient levels, an average value of which is approximately 20 dBμV/m/kHz. Since the actual values for this vehicle are unknown, a value 10 dB below the average ambient level was chosen for the purposes of these calculations.

APPENDIX IV

RECOMMENDED PERFORMANCE LEVELS AND METHODS OF MEASUREMENT OF RADIATED EMISSIONS FROM ELECTRIC VEHICLES (14 kHz - 1000 MHz)

Appendix IV is composed of two parts. Part 1 includes the recommended performance levels and methods of measurement of radiated emissions over the 14 kHz to 20 MHz frequency range. Part 2 presents the recommended performance levels and methods of measurement of radiated emissions over the 20 MHz to 1000 MHz frequency range.

RECOMMENDED PERFORMANCE LEVELS AND METHODS OF MEASUREMENT OF RADIATED EMISSIONS FROM ELECTRIC VEHICLES (14 kHz - 1000 MHz)

Part 1: Recommended Performance Levels and Methods of Measurement of Radiated Emissions (14 kHz - 20 MHz).

1. Purpose - The purpose of these test procedures is to provide guidance in the measurement of electromagnetic radiation from an electric vehicle (EV). Recommended performance levels are given in order to establish uniform requirements and to minimize the likelihood of large populations of electric vehicles interfering with equipment or communication services.

2. Scope - The test procedures and limits cover the measurement of radiated emission levels from EV's over the frequency range of 14 kHz to 20 MHz.

3. Equipment[1]

3.1 Accuracy - The measurement instrumentation shall be capable of measuring impulse electric and magnetic field intensity over the frequency range of 14 kHz to 20 MHz with an amplitude error of no greater than ± 5 dB and a frequency error of no greater than ± 3 percent.

3.2 Receivers

3.2.1 Spectrum Analyzer - Used for preliminary scanning purposes only.

3.2.2 Electromagnetic Interference (EMI) Receiver - Used for measuring absolute field intensity levels. The EMI receiver shall have peak or quasi-peak detection capabilities over the frequency range of 14 kHz to 20 MHz. The nominal input impedance shall be 50 ohms with a voltage standing wave ratio (VSWR) of less than 2.0:1 over the applicable frequency range. The impulse bandwidth must be known and shall not exceed 10% of the frequency at which measurements are being made.

---

[1] If measurements are made outdoors, the test equipment should be protected from direct sunlight and/or extreme temperatures. Environments which are significantly different from normal indoor lab environments may degrade equipment performance and cause erroneous results.

3.3 Scanning Plotter - The sine wave response at 1.25 cm (0.5 in) peak-to-peak shall not be down by more than 3 dB at 10 Hz from the 1 Hz response.

3.4 Calibrated Signal Source, Impulse Generator, Precision Attenuator, and Frequency Counter - Used for calibration purposes.

3.5 Antennas - The receive antennas to be used are the loop (electrostatically shielded) and the rod above a ground plane, each equipped with switchable impedance matching networks.

3.6 Transmission Line - It is recommended that double shielded coaxial cable be used between receive antenna and receiver. The characteristic impedance of the transmission line shall be 50 ohms (nominal).

4. Equipment Calibration

4.1 Receiver Calibration

4.1.1 Frequency Calibration - Frequency calibration shall be accomplished with a signal source and a frequency counter using standard techniques.

4.1.2 Amplitude Calibration - Amplitude calibration shall be made in one of two ways. The first method involves calibration of the receiver at the arithmetic center frequency of the band being measured by using the standard signal substitution method. If this method of calibration is used, a bandwidth calibration factor (BF), determined in Paragraph 4.1.4, must subsequently be applied. The second method involves the use of a calibrated impulse generator. An impulse signal of known level is injected into the receiver input, so that the receiver can be calibrated (via a look-up table or other suitable method) in terms of dBμV/kHz. Use of the latter method precludes the need for a separate bandwidth calibration.

4.1.3 Bandwidth Calibration - The impulse bandwidth of the receiver must be known for each frequency band. Published data should be used if available. If unavailable, receiver impulse bandwidth shall be measured using standard techniques.

4.1.4 Bandwidth Calibration Factor - The bandwidth calibration factor, BF, shall be calculated for each frequency band according to the relationship:

$$BF = 20 \log_{10} [BW_i] \text{ dB}$$

where: BW_i = Impulse bandwidth in kHz.

4.2 Scanning Plotter Calibration - Calibrate the scanning plotter with a signal source, precision attenuator, and frequency counter using standard techniques.

4.3 Antenna Calibration

4.3.1 Antenna Factor - The antenna factor for a rod antenna (in m^{-1}) is defined to be the ratio of the incident electric field intensity (in μV/m) to the voltage delivered to a 50 ohm load (in μV). The antenna factor for a loop antenna (in mhos/m) is defined to be the ratio of the incident magnetic field intensity (in μA/m) to the voltage delivered to a 50 ohm load (in μV). The antenna factor shall include the effects of baluns, impedance matching networks, and mismatch losses. Antenna factors are normally supplied by the manufacturer of EMC antennas. If unknown, determine using standard techniques (e.g., SAE ARP 958).

4.4 Transmission Line Calibration

4.4.1 Insertion Loss - The insertion loss of the transmission line used to connect the receive antenna to the receiver shall be measured as a function of frequency over the frequency range of interest using standard techniques.

5. Test Site Conditions

5.1 Field Site - An outdoor field site may be used for vehicle testing provided that it is free from metallic surfaces within a circle of 30 m radius (minimum) measured from a point midway between the EV and antenna. The ground surfaces shall be natural to the vehicle (e.g., asphalt or concrete). All surfaces shall be dry during testing.

5.2 Indoor Test Site - A shielded enclosure or an anechoic chamber may also be used for vehicle testing provided that the vehicle-to-antenna spacing and the antenna height is preserved. In addition, the antenna-to-wall and the EV-to-wall separation distances shall be at least one meter. The chamber or enclosure floor shall have electrical constants (dielectric constant, conductivity, etc.) approximating the average surface of an outdoor site.

6. Preliminary Scan Procedure

6.1 Elevate the drive wheels using jack stands as supports.[2]

6.2 Use a rod antenna mounted above a ground plane and tuned to approximately 500 kHz.

6.3 Establish steady-state condition of 25 mph (40 kph) in high gear.

6.4 Beginning with the base of the rod antenna one meter above the ground and one meter away from the nearest part of the front end of the vehicle, scan the radiated emission levels from 0-20 MHz. Use a spectrum analyzer as the receiver with the following settings:

Center Freq.: 10 MHz	RF Attn: 0 dB
Scan Width: 2 MHz/div.	Video Filtering: none
Scan Time: 500 ms/div.	IF Bandwidth: 100 kHz

6.5 Take photographs of the display (or tabulate the data in sufficient detail) in order to characterize the received power levels over the 0-20 MHz frequency range for both vertical and horizontal antenna polarizations.

6.6 Repeat Paragraphs 6.3-6.5 for the other three sides of the vehicle.

[2]If operation of the vehicle in the unloaded state would cause damage to the propulsion system, an absorption-type (i.e., non-electrical) dynamometer should be used.

6.7 Determine the direction of maximum radiation based upon the results of Paragraphs 6.1 - 6.6. This determination should be based on the larger of the two levels obtained for vertical and horizontal polarizations. If the levels are approximately equal for two different sides of the vehicle, either of these sides may be selected as the direction of maximum radiation.

6.8 With the antenna positioned and oriented for maximum received signal (i.e., the side and polarization determined in Paragraphs 6.1-6.7), repeat Paragraphs 6.4-6.5 for steady-state conditions of 10 mph (16 kph) and 40 mph (64 kph) in order to determine the speed of maximum radiation.

7. Measurements

7.1 Frequency Range - Measurements shall be performed over the frequency range of 14 kHz to 20 MHz. This range shall be divided into a minimum of 10 bands with approximately one band per frequency octave. Each band shall be scanned either manually or automatically to determine the radiated field strength as a function of frequency. As an example, one possible band selection would be:

Band 1:	14 kHz - 30 kHz	Band 6:	500 kHz - 1.1 MHz
Band 2:	30 kHz - 60 kHz	Band 7:	1.1 MHz - 2.4 MHz
Band 3:	60 kHz - 120 kHz	Band 8:	2.4 MHz - 5.0 MHz
Band 4:	120 kHz - 250 kHz	Band 9:	5.0 MHz - 10.0 MHz
Band 5:	250 kHz - 500 kHz	Band 10:	10.0 MHz - 20.0 MHz

Spot frequency measurements, although not recommended, shall be considered sufficient provided that a minimum of two frequencies are measured per octave and the ratio of successive frequencies does not exceed 1.6.

7.2 Sweep Rate - Either manual or automatic frequency scanning may be used, provided the scanning is sufficiently slow to ensure that the peak field intensities have been measured. As a check, fix tune the receiver to a frequency in the band in question and observe the measured level. Then reduce the scan rate for that band until the detected level approximates (within 1 dB) the fix-tuned level at that particular frequency.

7.3 Operating Conditions - All of the following radiated emission measurements should be made with the EV's drive wheels elevated and supported by jack stands[3]. The EV shall be operated at the speed of maximum radiation (determined in Paragraph 6.8) during all of the testing.

7.4 Vehicle and Antenna Positions (See Figure 1) - Locate the vehicle and the antenna such that all test site conditions are satisfied as stated in Section 5.

7.4.1 Antenna Position - Position the receive antenna: (1) on the side of the EV found to emit maximum radiation (as determined in Paragraph 6.7) and (2) with the electrical center of the antenna (considered to be the base of the rod or the center of the loop) 10 m from the closest part of the vehicle at a height of 3 m above ground level (or above the bottom of the tires if ground is unlevel).

7.4.2. Antenna Polarization - Both vertical and horizontal components of impulse electric and magnetic field strengths shall be measured. The polarization for a magnetic loop antenna is referenced to an imaginary axis perpendicular to the plane of the loop. In the case of horizontal polarization, for example, the imaginary axis would be horizontally oriented in the plane transverse to the direction of propagation.

7.5 Measurement Instrumentation - The measurement instrumentation must be located within the permitted regions shown in Figure IV-1.

7.6 Measurement Procedure

7.6.1 Ambient Measurements - The purpose of these measurements is to determine the levels of ambient noise and RF carriers. The measurements shall be

---

[3]If Note 2 applies or if desired, measurements may be made using an absorption dynamometer to load the EV at the zero-grade road load for the particular speed determined in Paragraph 6.8 to yield maximum radiation levels.

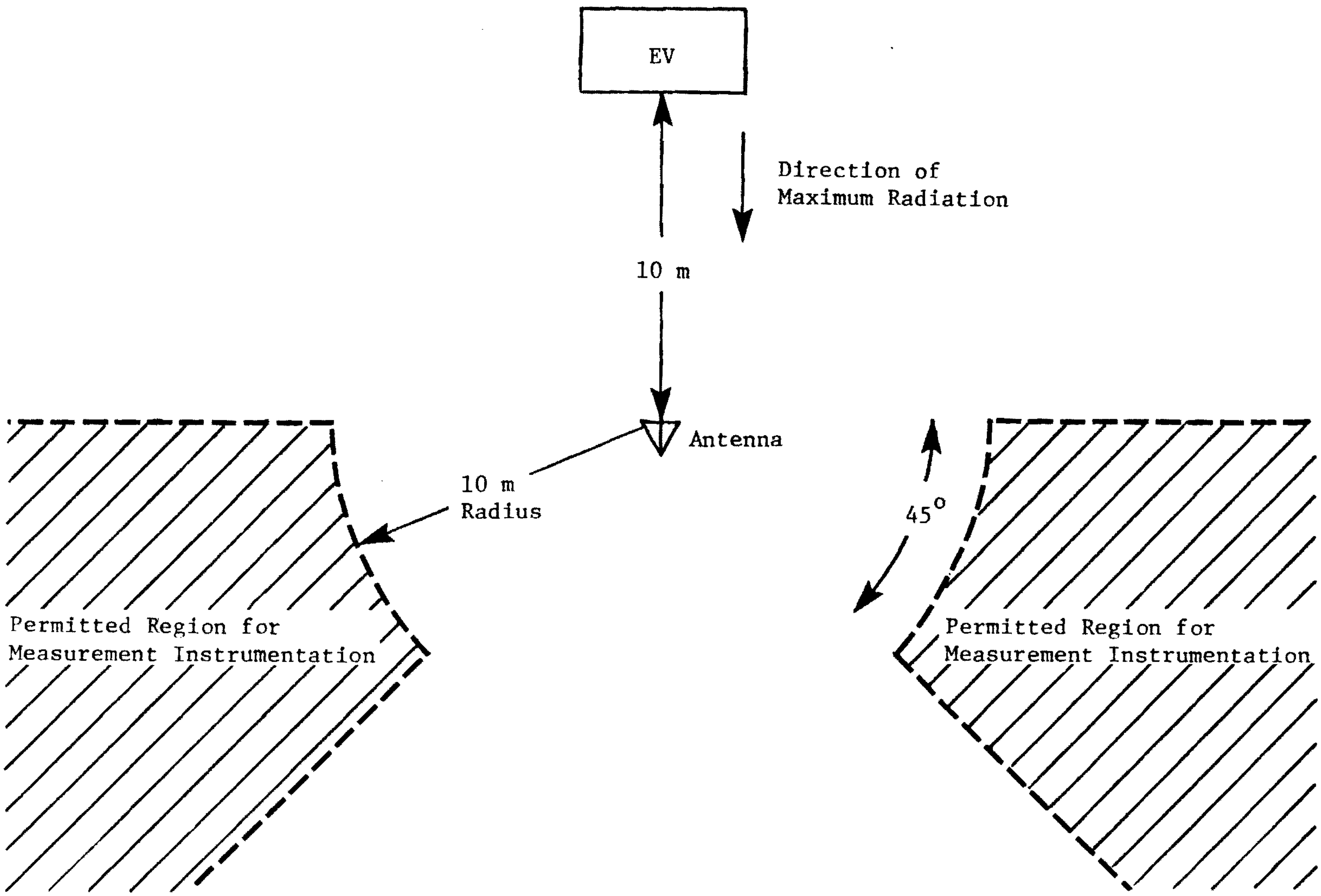


Figure IV-1. Vehicle and Antenna Positions for Radiated Emission Measurements.

made over the applicable frequency range for both the electric and magnetic field tests. Ambient measurements shall be made for each band with the vehicle completely inoperative and shall be made immediately before the vehicle measurements. Data shall be recorded in terms of received voltage (in either dBμV or dBμV/kHz) versus frequency.

7.6.2 Vehicle Measurements - The EV shall be measured for each band as stated in the previous paragraph except that the vehicle will be operative as specified in Paragraph 7.3. Data shall be recorded in terms of received voltage (in either dBμV or dBμV/kHz) versus frequency.

8. Data Reduction - The impulse electric field intensity and the impulse magnetic field intensity shall be calculated from the received voltage levels as measured in Paragraph 7.6.2.

8.1 Impulse Electric Field Intensity - Impulse electric field intensity shall be expressed in units of decibels above one microvolt per meter per kilohertz bandwidth (dBμV/m/kHz). If the receiver has not been calibrated with an impulse generator, the equation relating impulse magnetic field intensity to the received voltage level is:

$$E_i = V_r + AF_r + TL - BF$$

where: E_i = Impulse electric field intensity in dBμV/m/kHz,
V_r = Received voltage level in dBμV,
AF_r = Antenna factor for rod antenna in dB (see Paragraph 4.3.1),
TL = Transmission line insertion loss in dB (see Paragraph 4.4.1), and
BF = Bandwidth calibration factor in dB (see Paragraph 4.1.4).

If the receiver has been calibrated with an impulse generator, the equation which should be used is:

$$E_i = V' + AF_r + TL$$

where V' is the receiver reading in dBμV/kHz.

8.2 Impulse Magnetic Field Intensity - Impulse magnetic field intensity shall be expressed in decibels above one microampere per meter per kilohertz bandwidth (dBμA/m/kHz). If the receiver has not been calibrated with an impulse generator, the equation relating impulse magnetic field intensity to the received voltage level is:

$$H_i = V_r + AF + TL - BF$$

where: H_i = Impulse magnetic field intensity in dBμA/m/kHz and
AF = Antenna factor for loop antenna in dB (see Paragraph 4.3.1).

If the receiver has been calibrated with an impulse generator, the equation which should be used is:

$$H_i = V' + AF + TL.$$

9. Assessment of Results

9.1 Characteristic Level - The characteristic level for each band (used for the purpose of comparison with the recommended level) is defined to be the maximum measured value obtained for that band for both polarizations. The characteristic level shall be compared to the recommended performance level at the arithmetic center frequency of the band. Known ambient carriers and broadband noise shall be ignored in determining characteristic levels.

9.2 Recommended Performance Levels - The recommended performance levels, based on peak measurements, are given in Attachment I. The corresponding quasi-peak levels are 20 dB lower than the peak levels.

9.3 Method of Checking for Compliance with Recommended Limits - Results from a single vehicle may be used to determine compliance provided that the vehicle tested is representative of production-line vehicles. Measurements may also be made on a sample of six or more vehicles and statistical analysis applied to the characteristic levels in order to determine compliance. In this case, the characteristic levels shall be evaluated as given in Attachment II.

Part 2: Recommended Performance Levels and Methods of Measurement of Radiated Emissions (20 MHz - 1000 MHz).

The recommended performance levels for electric vehicles over the 20 MHz to 1000 MHz frequency range are identical to that given in SAE J551 (JUN 81). The following test conditions are recommended:

(1) The EV shall be operated with the drive wheels elevated (unloaded) unless such operation is likely to cause damage to the vehicle. If operation in the unloaded state would cause damage, the vehicle should be operated on an absorption-type dynamometer at a load corresponding to the zero-grade load at a given speed.

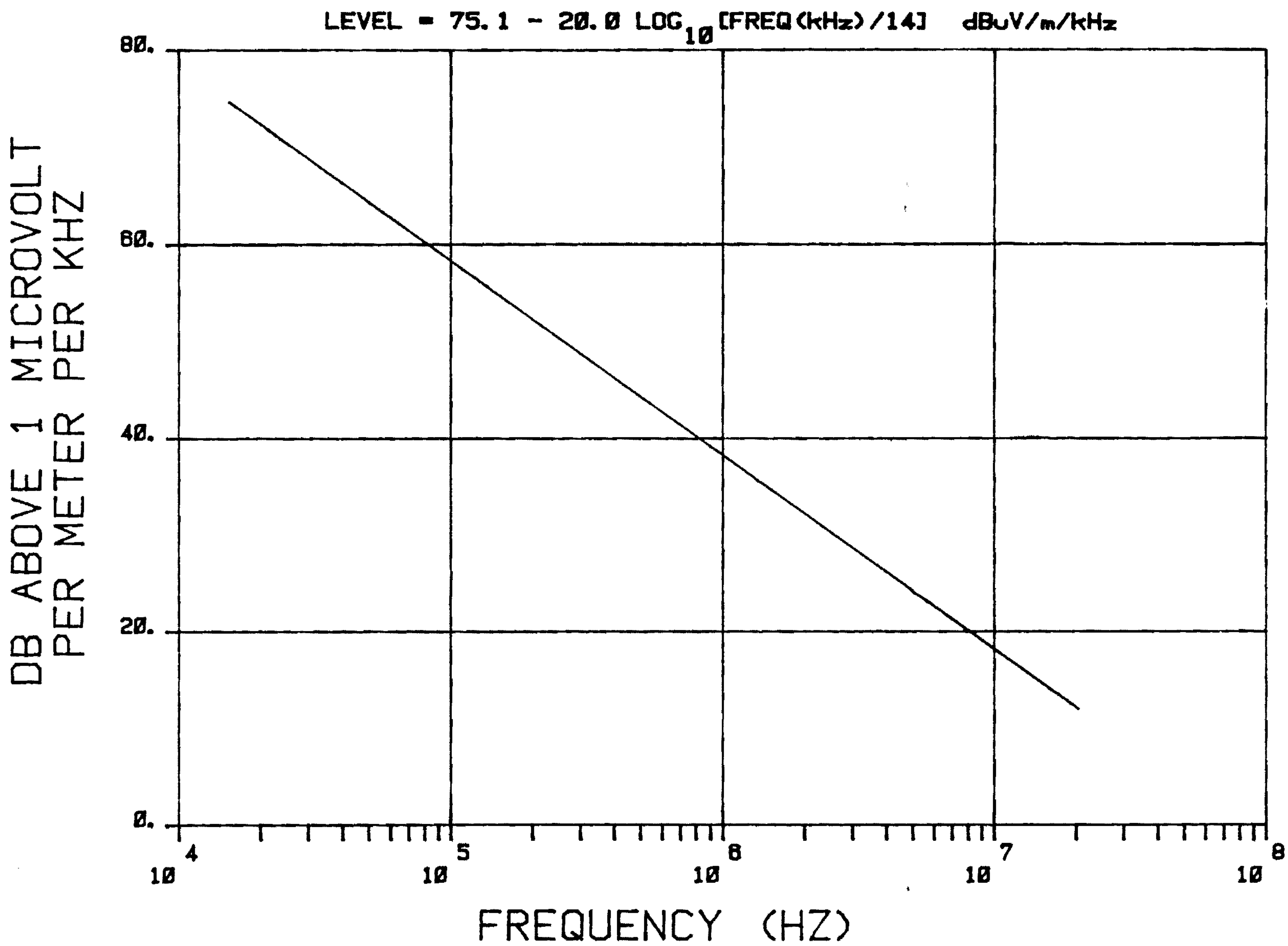
(2) A preliminary test shall be made to determine the vehicle speed which produces maximum radiation levels.

(3) Final testing shall be conducted on all four sides of the vehicle at the speed which produces maximum radiation levels.

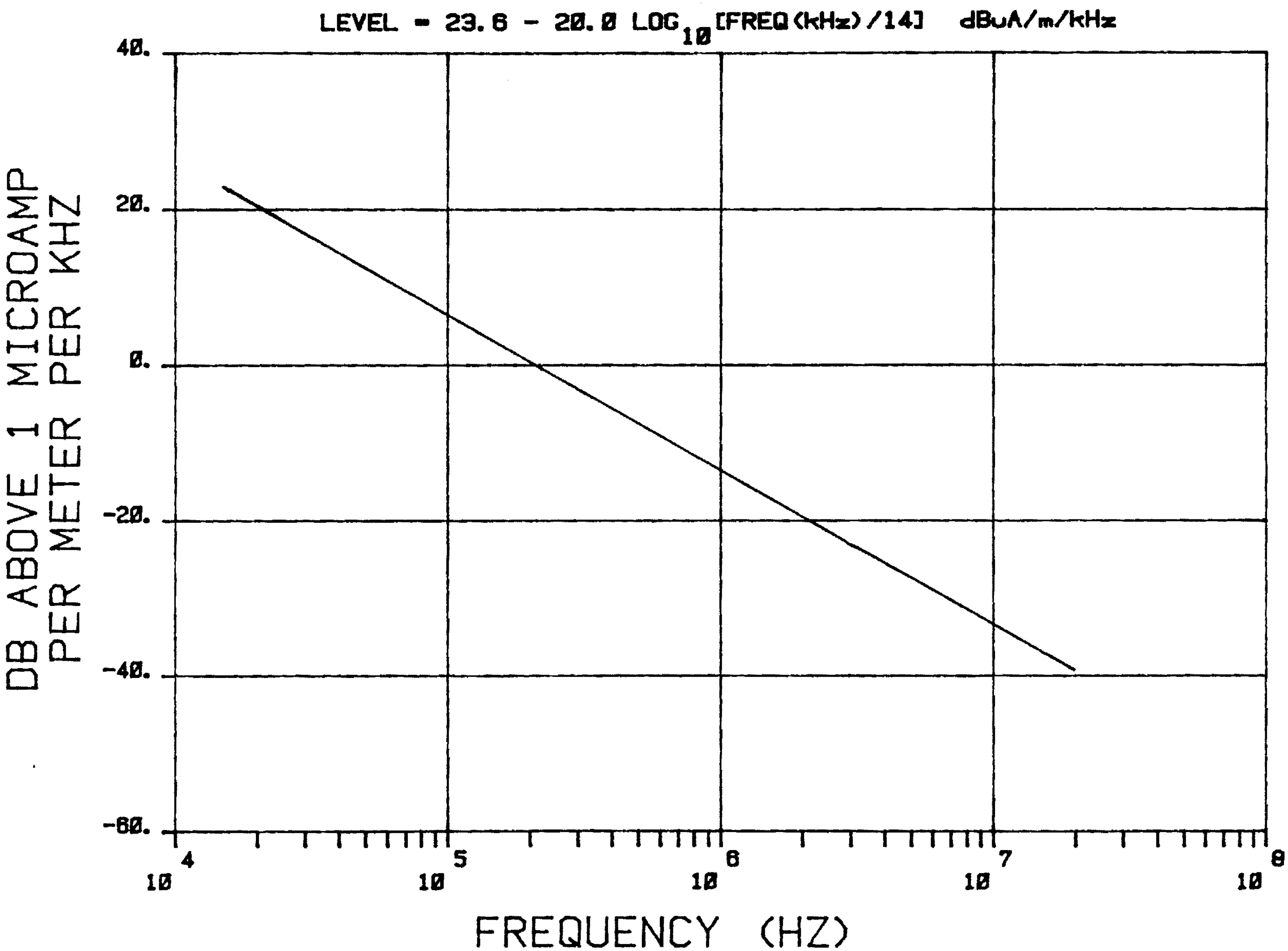
Radiated testing of on-board battery chargers is not required. All other requirements of the SAE standard shall apply.

ATTACHMENT I

RECOMMENDED PERFORMANCE LEVELS FOR RADIATED PEAK IMPULSE ELECTRIC AND MAGNETIC FIELD INTENSITY



Recommended Performance Levels For Peak Impulse Electric Field Intensity.



Recommended Performance Levels For Peak Impulse Magnetic Field Intensity.

ATTACHMENT II

STATISTICAL ANALYSIS OF MEASUREMENT RESULTS ON SIX OR MORE VEHICLES

The criteria to be used is 80% conformance with 80% confidence. The following condition must therefore be satisfied:

$$\bar{x} + kS_n \leq L$$

where: $\bar{x}$ = Arithmetic mean of the results on n vehicles,

k = Statistical parameter dependent on n,

S_n = Standard deviation of results on n vehicles,

L = Recommended performance level, and

$\bar{x}$, S_n, and L are all expressed in the units used for the recommended performance levels.

The statistical parameter k is determined using the following table:

n =	6	7	8	9	10	11	12
k =	1.42	1.35	1.30	1.27	1.24	1.21	1.20

The standard deviation, S_n, is determined by the following equation:

$$S_n = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}$$

where x_i is the individual result for the i^{th} vehicle tested.

APPENDIX V

RECOMMENDED PERFORMANCE LEVELS AND METHODS OF MEASUREMENT OF CONDUCTED EMISSIONS FROM ELECTRIC VEHICLE ON-BOARD BATTERY CHARGERS (14 kHz - 20 MHz)

This appendix recommends performance levels and test procedures for conducted emission measurements over the 14 kHz to 20 MHz frequency range.

RECOMMENDED PERFORMANCE LEVELS AND METHODS OF MEASUREMENT OF CONDUCTED EMISSIONS FROM ELECTRIC VEHICLE ON-BOARD BATTERY CHARGERS (14 kHz - 20 MHz)

1. Purpose - The purpose of these test procedures is to provide guidance in the measurement of conducted emission levels from electric vehicle (EV) on-board battery chargers. Recommended performance levels are given in order to establish uniform requirements and to minimize the likelihood that conducted levels on ac power leads (from on-board battery chargers) will interfere with potentially susceptible equipments which are connected to the same mains supply.

2. Scope - The test procedures and performance levels cover the measurement of conducted emission levels from on-board battery chargers on ac power leads over the frequency range of 14 kHz to 20 MHz.

3. Equipment[1]

3.1 Accuracy - The measurement instrumentation shall be capable of measuring impulse current levels over the frequency range of 14 kHz to 20 MHz with an amplitude error of no greater than ±3 dB and a frequency error of no greater than ±3 percent.

3.2 Electromagnetic Interference (EMI) Receiver - The EMI receiver shall have peak or quasi-peak detection capabilities over the frequency range of 14 kHz to 20 MHz. The nominal input impedance shall be 50 ohms with a voltage standing wave ratio (VSWR) of less than 2.0:1 over the applicable frequency range. The impulse bandwidth must be known and shall not exceed 10% of the frequency at which measurements are being made.

3.3 Scanning Plotters - The sine wave response at 1.25 cm (0.5 in) peak-to-peak shall not be down by more than 3 dB at 10 Hz from the 1 Hz response.

[1] If measurements are made outdoors, the test equipment should be protected from direct sunlight and/or extreme temperatures. Environments which are significantly different from normal indoor lab environments may degrade equipment performance and cause erroneous results.

3.4 Calibrated Signal Source, Impulse Generator, Precision Attenuator, and Frequency Counter - Used for calibration purposes.

3.5 EMI Current Probe - The current probe shall be free of resonances at frequencies below 20 MHz and the saturation current rating for the probe at the power-mains frequency shall exceed the maximum rated charger supply current by at least 10 amperes. The transfer impedance must be known from 14 kHz to 20 MHz.

3.6 Line Impedance Stabilization Networks (LISN's) - a 50 μH/50 ohm LISN (free of resonances at frequencies below 20 MHz) is required for each current carrying conductor of the ac power line.

3.7 50 Ohm Resistive Terminations - A termination shall be used on the receiver output port of each LISN. Each termination shall have a voltage standing wave ratio (VSWR) of less than 1.3:1 over the applicable frequency range.

3.8 Transmission Line - It is recommended that double shielded coaxial cable be used between the current probe and the receiver. The characteristics impedance of the transmission line shall be 50 ohms (nominal).

3.9 Audio Isolation Transformer - Used for preventing radio frequency (RF) ground currents from flowing in the EMI receiver chassis ground.

3.10 Power Cables (2) - Two short sections (1 m or less) of power cable shall be made up with a connector on one end of each cable. One connector shall be a male plug and the other shall be a female receptacle. The outer sheath shall be removed from a short section (30 cm or less) of each cable at the end opposite from the connector in order to allow the conductors to be separated at this end. The power cable with the male connector will subsequently be identified as PCM and the power cable with the female connector will be identified as PCF.

4. Equipment Calibration

4.1 Receiver Calibration

4.1.1 Frequency Calibration - Frequency calibration shall be accomplished with a signal source and a frequency counter using standard techniques.

4.1.2 Amplitude Calibration - Amplitude calibration shall be made in one of two ways. The first method involves calibration of the receiver at the arithmetic center frequency of the band being measured by using the standard signal substitution method. If this method of calibration is used, a bandwidth calibration factor (BF), determined in Paragraph 4.1.4, must subsequently be applied. The second method involves the use of a calibrated impulse generator. An impulse signal of known level is injected into the receiver input, so that the receiver can be calibrated (via a look-up table or other suitable method) in terms of dBμV/kHz. Use of the latter method precludes the need for a separate bandwidth calibration.

4.1.3 Bandwidth Calibration - The impulse bandwidth of the receiver must be known for each frequency band. Published data should be used, if available. If unavailable, receiver impulse bandwidth shall be measured using standard techniques.

4.1.4 Bandwidth Calibration Factor - The bandwidth calibration factor, BF, shall be calculated for each frequency band according to the relationship:

$$BF = 20 \log_{10}[BW_i] \text{ dB}$$

where: BW_i = Impulse bandwidth in kHz.

4.2 Scanning Plotter Calibration - Calibrate the scanning plotter with a signal source, precision attenuator, and frequency counter using standard techniques.

4.3 Current Probe Calibration

4.3.1 Transfer Impedance - The transfer impedance, Z_t, for a current probe (in ohms) is defined to be the ratio of the voltage delivered to a 50 ohm load (in μV) to the current passing through the probe (in μA). Transfer impedance is a function of frequency and, therefore, must be known over the entire frequency range of interest. The transfer impedance shall include the effects of impedance mismatch. Transfer impedances are normally supplied by the manufacturer. If unknown, determine by measuring the probe output voltage with a 50 ohm receiver for a known injected current level and then calculating the transfer impedance according to the relationship:

$$Z_t(f) = 20 \log_{10}\left[\frac{V(f)}{I(f)}\right]$$

where: $Z_t(f)$ = Transfer impedance (in dB) at frequency f,
$V(f)$ = Probe output voltage amplitude (in μV) at frequency f, and
$I(f)$ = Injected current amplitude (in μA) at frequency f.

4.4 Transmission Line Calibration

4.4.1 Insertion Loss - The insertion loss of the transmission line used to connect the current probe to the receiver shall be measured as a function of frequency over the frequency range of interest using standard techniques.

5. Test Site Conditions - Any test site may be used provided that sufficient space is available to extend the ac power cord (provided with the battery charger) such that the cord is uncoiled and does not lie within 10 cm of any metallic surface. All surfaces shall be dry during testing.

6. Measurements

6.1 Frequency Range - Measurements shall be performed over the frequency range of 14 kHz - 20 MHz. This range shall be divided into a minimum of 10 bands with approximately one band per frequency octave. Each band shall be scanned either manually or automatically to determine the conducted current level as a function of frequency. As an example, one possible band selection would be:

Band 1:	14 kHz - 30 kHz	Band 6:	500 kHz - 1.1 MHz
Band 2:	30 kHz - 60 kHz	Band 7:	1.1 MHz - 2.4 MHz
Band 3:	60 kHz - 120 kHz	Band 8:	2.4 MHz - 5.0 MHz
Band 4:	120 kHz - 250 kHz	Band 9:	5.0 MHz - 10.0 MHz
Band 5:	250 kHz - 500 kHz	Band 10:	10.0 MHz - 20.0 MHz

Spot frequency measurements, although not recommended, shall be considered sufficient provided that a minimum of two frequencies are measured per octave and the ratio of successive frequencies does not exceed 1.6.

6.2 Sweep Rate - Either manual or automatic frequency scanning may be used, provided the scanning is sufficiently slow to ensure that the peak current levels have been measured. As a check, fix tune the receiver to a frequency in the band in question and observe the measured level. Then reduce the scan rate for that band until the detected level approximates (within 1 dB) the fix-tuned level at that particular frequency.

6.3 Operating Conditions - All of the following conducted emission measurements shall be made while the batteries are at less than 80% energy capacity and with the battery charger operating in the charge mode.

6.4 Measurement Setup - Position the EV and associated measurement equipment such that the test site conditions given in Section 5 are satisfied. Hook up the equipment as shown in Figure V-1. Connect the ground leads of PCF and PCM to the "ground" connector (or its equivalent) of one LISN. Keeping the leads as short as possible, connect the "ground" connector(s) of the other LISN(s) together (see Figure V-1). Connect each current carrying conductor of PCF to the "test sample" connector (or its equivalent) of an LISN. Next, connect each current carrying conductor of PCM to the corresponding "power source" connector (or its equivalent) of an LISN. Connect the ac power cord (provided with the battery charger) to the PCF such that both cords are uncoiled and do not lie within 10 cm of any metallic surface. Measurements shall be made on each current carrying conductor of PCF by clamping the current probe around the appropriate conductor.

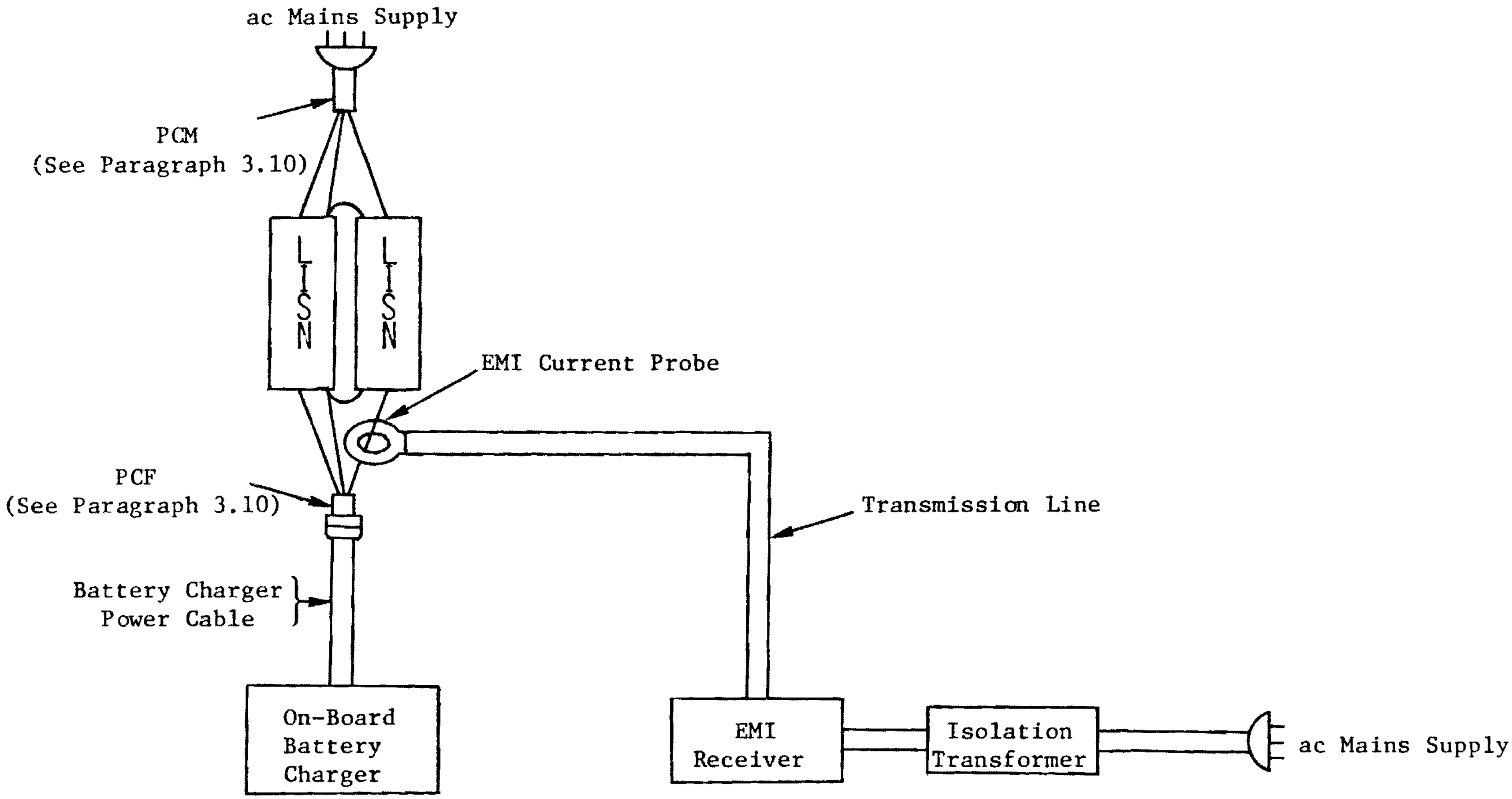


Figure V-1. Block Diagram of Conducted Emission Measurement Setup.

If the receiver has been calibrated with an impulse generator, the equation which should be used is:

$$I_i = V' + TL - Z_t$$

where V' is the receiver reading in dBμV/kHz.

8. Assessment of Results

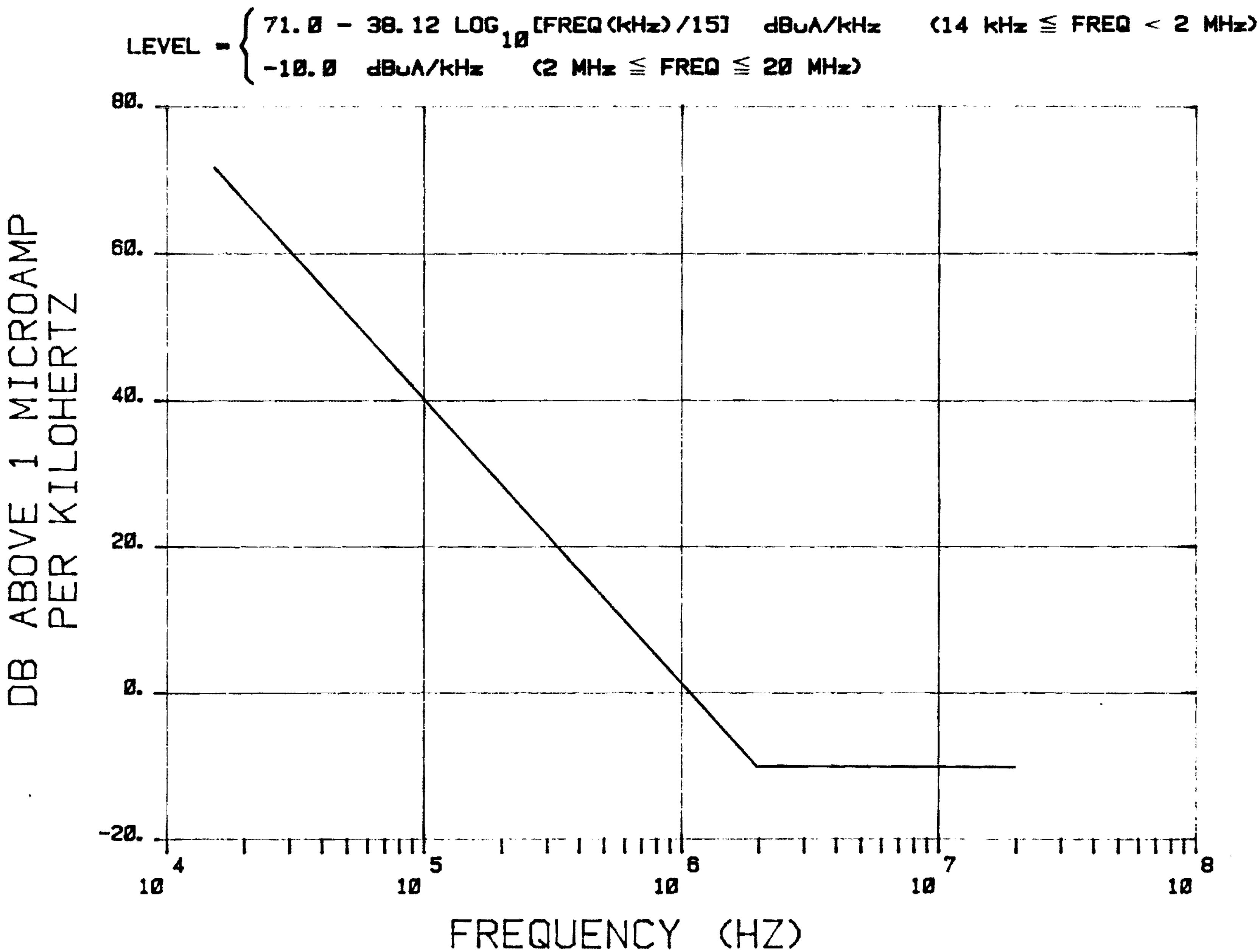
8.1 Characteristic Level - The characteristic level for each band (used for the purpose of comparison with the recommended level) is defined to be the maximum measured value obtained for that band for all leads tested. The characteristic level shall be compared to the recommended performance level at the arithmetic center frequency of the band. Known ambient carriers and broadband noise shall be ignored in determining characteristic levels.

8.2 Recommended Performance Levels - The recommended performance levels, based on peak measurements, are given in Attachment I. The corresponding quasi-peak levels are 20 dB lower than the peak levels.

8.3 Method of Checking for Compliance with Recommended Limits - Results from a single battery charger may be used to determine compliance provided that the battery charger tested is representative of production-line battery chargers. Measurement may also be made on a sample of six or more chargers and statistical analysis applied to the characteristic levels in order to determine compliance. In this case, the characteristic levels shall be evaluated as given in Attachment II.

ATTACHMENT I

RECOMMENDED PERFORMANCE LEVELS FOR CONDUCTED PEAK IMPULSE CURRENT AMPLITUDE



Recommended Performance Levels For Conducted Peak Impulse Current Amplitude.

ATTACHMENT II

STATISTICAL ANALYSIS OF MEASUREMENT RESULTS ON SIX OR MORE BATTERY CHARGERS

The criteria to be used is 80% conformance with 80% confidence. The following condition must therefore be satisfied:

$$\bar{x} + kS_n \leq L$$

where: $\bar{x}$ = Arithmetic mean of the results on n battery chargers,

k = Statistical parameter dependent on n,

S_n = Standard deviation of results on n battery chargers,

L = Recommended performance level, and

$\bar{x}$, S_n, and L are all expressed in the units used for the recommended performance levels.

The statistical parameter k is determined using the following table:

n =	6	7	8	9	10	11	12
k =	1.42	1.35	1.30	1.27	1.24	1.21	1.20

The standard deviation, S_n, is determined by the following equation:

$$S_n = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n}$$

where x_i is the individual result for the i^{th} battery charger tested.