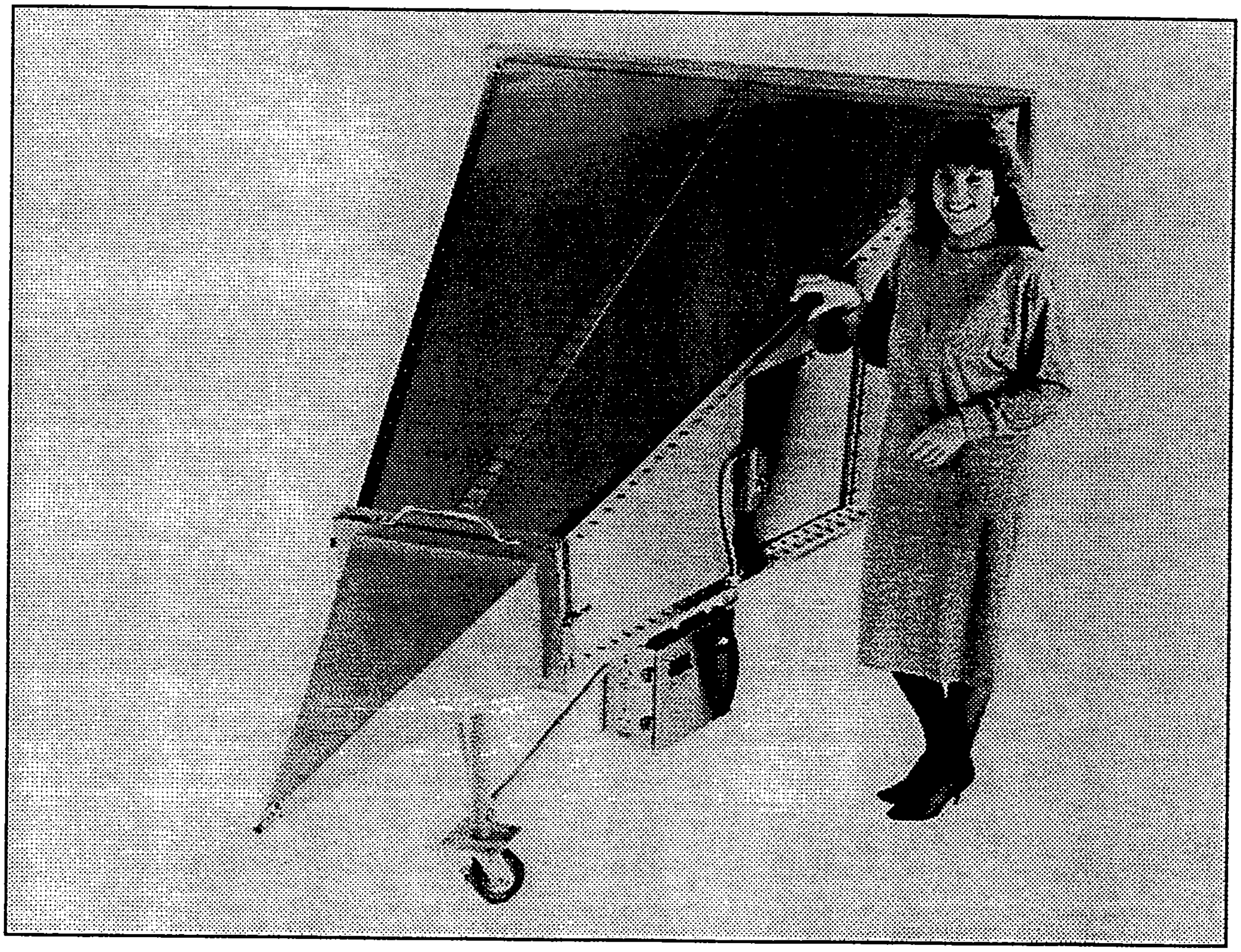
MODEL 5300 SERIES
Gigahertz Tranverse Electromagnetic (GTEM!)

OPERATION MANUAL



The Electro-Mechanics Company

An ESCO Company

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The Electro Mechanics Company
Model 5300 Series
Gigahertz Transverse Electromagnetic (GTEM!™) Cell
Operator's Manual

Part Number: 399169
Revision: B

NOTICE!

This manual describing the operation and use of the Electro-Mechanics Company's Model 5300 Series GTEM! is provided on a preliminary basis. Information presented in the manual is subject to change as additional information becomes available.

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The Electro-Mechanics Company

Model 5300 Series

Gigahertz Transverse Electromagnetic (GTEM!™) Cell

Operator's Manual

Introduction

General Description

The GHz Transverse Electromagnetic (GTEM!™) Cell is a precision EMC test instrument primarily intended for use as an electromagnetic compatibility radiated immunity and radiated emissions test facility. It is intended for installation in a corporate, laboratory or industrial environment, where its unique characteristics allow fast, efficient conduct of electromagnetic compatibility (EMC) radiated tests at a convenient location, without impact of the ambient electromagnetic environment.

The GTEM! is a pyramidally tapered, doubly terminated section of 50 ohm transmission line. At the input, a normal 50 ohm coaxial line is physically transformed to a rectangular cross section. The cross sectional dimensions are a ratio of 3:2, horizontal to vertical cross-sectional dimensions. The center conductor, the septum, is a flat, wide conductor that, when driven by a signal generator, will produce a reasonably sized region of a nominally uniform electric field distribution underneath it. This region of nominally uniform field is the test volume for radiated immunity (susceptibility) testing. By the theory of reciprocity, radiated emissions testing is also conducted in the test volume. The septum is physically located well above the horizontal center line of the cross section, to increase the usable test volume, while maintaining constant characteristic impedance and uniform field distribution. The septum is physically terminated in a resistive array having a total value of 50 ohms, while matching the current distribution in the septum. The fields that are generated in the test volume and that are applied to the immunity test item, or that are produced by the

Equipment Under Test during emissions testing, are terminated in free space RF absorber.

It should be noted that the shape of the test volume is a tapered wedge. The fields generated by application of an RF voltage to the input of the GTEM! propagate from the apex of the GTEM! to the terminations with a spherical wave front.

Acknowledgment

The GTEM! is manufactured by the Electro-Mechanics Company of Austin, Texas, in the United States of America, under license from Asea Brown Boveri Ltd. of Baden Switzerland.

GTEM! Unpacking and Installation

GTEM!s are shipped in one or more plywood crates, or may be shipped partially assembled by custom means. The larger GTEM!s are shipped in multiple crates.

Unpacking the Model 5302

The Model 5302 GTEM! is shipped fully assembled except for the installation of the Type "N" to DIN 7/16 adapter. The Model 5302 should be carefully uncrated. The packing materials must be checked to assure that the adapter and, the manuals and any other components will not be discarded. The packaging materials and container are not reusable, and may be discarded. Instructions for the installation of the Type "N" to DIN 7/16 adapter are found in the section on GTEM Mechanical Information.

After removal from the packing, the Model 5302 should be placed in a convenient location for use. If the primary access to the Model 5302 will be through the door in the side of the GTEM!, it will be convenient to install the GTEM! in a horizontal orientation on a table top. If the primary access to the GTEM is through the hatch on the bottom, a vertical orientation will be the most practical. The Model 5302 can be conveniently handled by two persons.

Unpacking, Assembling and Installing the Model 5305

The Model 5305 is shipped in a single crate that is built around the GTEM! The crate is large but is light for its size and can easily be handled by small lift devices. The shipping crate is not meant to be returned.

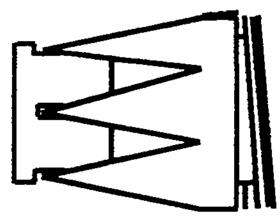
On delivery, have the shipping crate placed in a convenient area for unpacking. Remove the top and sides of the crate. In the crate you will find the GTEM! body, and in four separate packages, the CW Feed Section, the RF Load Boards, Absorber Caps, and a smaller package with the Manuals and Manual Radiated Emissions Software. The Type "N" to DIN 7/16 adapter will be found in the small package containing the Manuals.

Remove the packages containing the RF Load Boards, CW Feed section, Absorber Caps, and set aside. Remove the body of the GTEM from the base of the shipping crate. Discard the shipping crate after making certain that there are no remaining pieces of the GTEM! remaining in the crate or packing materials.

The Absorber Caps are shipped separately and are installed by the customer upon arrival. There will be two Absorber Caps (EMCO Part No. 870071, Absorber Cap Bottom, 432 mm sq. [17 inch sq.] white foam material) shipped with each unit.

Absorber Caps are installed only across the bottom absorbers of the GTEM Model 5305.

As illustrated in the drawing below, caps are to be installed firmly into the absorbers covering the absorber tips. Each Absorber Cap will fit over one section of the absorbers (which are approximately 609.60 mm sq. [24.00 inch sq.]).



Once in place, the Absorber Caps remain installed providing continuous protection of the absorber tips.

Follow the assembly instructions in the section on Mechanical Information to place the GTEM into service. The load boards, the feed section and the Type "N" to DIN 7/16 adapter will need to be installed to complete the installation of the Model 5305.

Installation of the Models 5311 and 5317

The purchaser should not attempt to uncrate or assemble any GTEM! delivered in multiple crates. The purchaser should inspect the arriving shipment for externally visible signs of damage, and notify EMCO immediately if such damage is found.

Since the Model 5311 and 5317 GTEM!s are shipped disassembled, they must undergo detailed assembly. This assembly is accomplished by an EMCO representative. The purchaser should not attempt to assemble these Model GTEM!s. An EMCO representative will arrive to unpack, assemble and place into service the Models 5311 and 5317.

GTEM! Specifications

This section contains the detailed GTEM Specfications. The specifications are shown in Table I. Figures 1 through 6 provide additional information on interpreting the specification, and dimensional information on the several sizes of GTEM!

GTEM! Model 5300 Series Specifications

Usable Frequency Range							
	Radiated Emissions Testing	30 MHz - >= 1 GHz					
	Radiated Immunity Testing	DC - 18 GHz					
Nominal INput Impedance		50 Ohms					
Voltage Standing Wave Ratio		**5302**	**5305**	**5311**	**5317**	**5317H2**	**5317H75**
	At Cell Characteristic Frequency	1.5 : 1	≤ 1.75 : 1	≤ 1.75 : 1	≤ 1.75 : 1	≤ 1.65 : 1	≤ 1.75 : 1
	At All Other Frequencies	1.5 : 1	≤ 1.50 : 1	≤ 1.50 : 1	≤ 1.50 : 1	≤ 1.50 : 1	≤ 1.50 : 1
Maximum CW Input Power: (Higher with Additional Cooling)		50 W	400 W	1 kW	1 kW	2 kW	75 kW
Typical CW Field Strength (At Rear of Test Volume, Increases as Apex Is Approached)							
	Input Power	Field Strength V/m	V/m	V/m	V/m	V/m	V/m
	50 W	≥ 200	≥ 100	≥ 45	≥ 28	≥ 28	≥ 28
	400 W	N/A	≥ 280	≥ 120	≥ 80	≥ 80	≥ 80
	1 kW	N/A	N/A	≥ 200	≥ 125	≥ 125	≥ 125
	2 kW	N/A	N/A	N/A	N/A	≥ 180	≥ 180
	75 kW	N/A	N/A	N/A	N/A	N/A	≥ 1100
Electric Field Uniformity, Ey, As a Function of Frequency (At Center of Recommended Test Volume)							
	DC - 1000 MHz	± 4 dB	± 4 dB	± 4 dB	± 4 dB	± 4 dB	± 4 dB
	1 - 4 GHz	± 5 dB	± 5 dB	± 5 dB	± 5 dB	± 5 dB	± 5 dB
	4 - 18 GHz	± 8 dB	± 8 dB	± 8 dB	± 8 dB	± 8 dB	± 8 dB
Maximum Rated Power Dissipation (Higher with Additional Cooling)							
	RF Power Dissipation	50 W	400 W	1 kW	1 kW	2 kW	75 kW
	EUT Thermal Dissipation	50 W	100 W	1 kW	1 kW	1 kW	1 kW
	Cooling (Add'l. Cooling for Higher Dissipation Available as Option)	None	None	Forced Air	Forced Air	Forced Air	Forced Air
Maximum Pulse Voltage (Peak)		15 kV	15 kV	15 kV	15 kV	15 kV	15 kV

Table 1, Page 1

GTEM! Mechanical Specifications

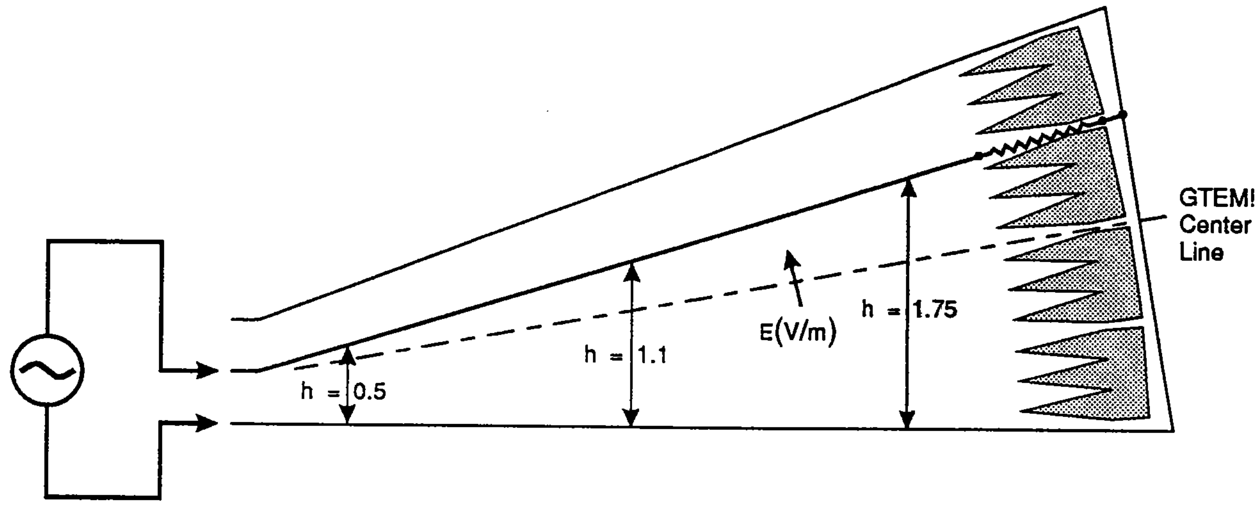
	5302	5305	5311	5317
Door Size	160 x 230 mm	385 x 460 mm	925 x 685 mm	1545 x 1035 mm
Maximum Septum Height at Rear of Test Volume, at Interface to RF Absorber	250 mm	500 mm	1100 mm	1750 mm
Recommended Maximum EUT Test Volume for Emissions at any Frequency	167 mm (h) 167 mm (w) 167 mm (d)	333 mm (h) 333 mm (w) 333 mm (d)	733 mm (h) 733 mm (w) 733 mm (d)	1166 mm (h) 1166 mm (w) 1166 mm (d)
Recommended Maximum EUT Test Volume for Immunity at any Frequency	125 mm (h) 187 mm (w) 1288 mm (d)	250 mm (h) 375 mm (w) 250 mm (d)	550 mm (h) 825 mm (w) 440 mm (d)_	875 mm (h) 1300 mm (w) 875 mm (d)
Outer Cell Dimensions Including Frame	1.4 x 0.75 x 0.52 m	3.0 x 1.6 x 1.2 m	5.4 x 2.8 x 2.0 m	7.7 x 4.1 x 2.8 m
Outer Cell Dimensions (w/ Legs and Casters)	N/A	3.0 x 1.6 x 1.9 m	5.4 x 2.8 x 2.3 m	7.7 x 4.1 x 3.1 m
Minimum Required Area Around Cell for Installation	N/A	4.0 x 2.0 m	7.0 x 4.0 m	9.0 x 5.0 m
Approximate Cell Weight (With Legs and Casters)	40 kG	250 kg	800 kg	1200 kg
Standard Feed Through Connector Panels with 3 ea. Type N and 1 Four-Position F/O Feed Throughs	N/A	1 ea. 304 mm sq.	1 ea. 304 mm sq.	1 ea. 304 mm sq.

Table 1, Page 2

GTEM! Electrical Specifications

Standard GTEM! Power Input Requirements		
(Includes requirements for filtered EUT Power Supply)	US & Canada	120 V, 30 A, 1 Phase, 60 Hz
(Note: Filters produce strong reactive current	European	240 V, 30 A, 1 Phase, 50 Hz
and GTEM! can not be operated on GFI breaker)	Other	As Required
Standard EUT Filtered Power		
(Other ratings or additional	US & Canada	120 V, 20 A, 1 Phase, 60 Hz, 2 Filtered Outlets
filtering available on request)	European	240 V, 20 A, 1 Phase, 50 Hz, 2 Filtered OUtlets
	Other	As Required

Table 1, Page 3



$$E(\text{Field Strength, V/m}) = \frac{V(\text{RF voltage, volts})}{h\ (\text{meters})}$$

Where h = Variable Septum Spacing

P watts (max) from
RF Signal Generator
Produces V RF volts on Septum

$$V\ \max\ (\text{RF voltage, volts}) = \sqrt{P\ \text{watts}\ (\max) \times 50}$$

for	V max(V)	E(V/m) @ h = 1.75 m	E(V/m) @ h = 1.1 m	E(V/m) @ h = 0.5 m
P (max) = 100 W	70.7	40.4	64.2	141.4
1000 W	223.6	127.7	203.3	447.2

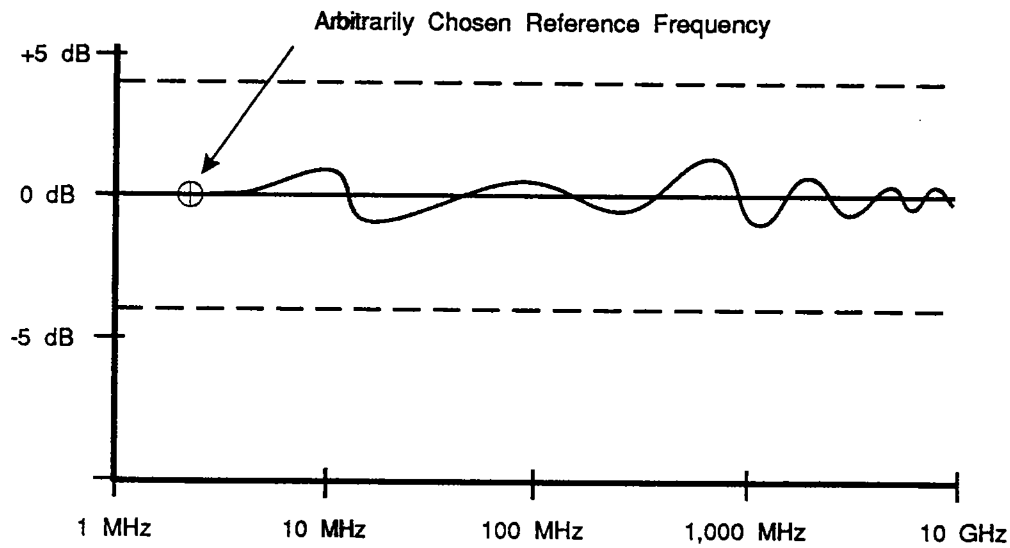
For a Model 5317, 1 kW Input Produces:

447.0 V/m @ Septum Height of 0.5 m (at small door)

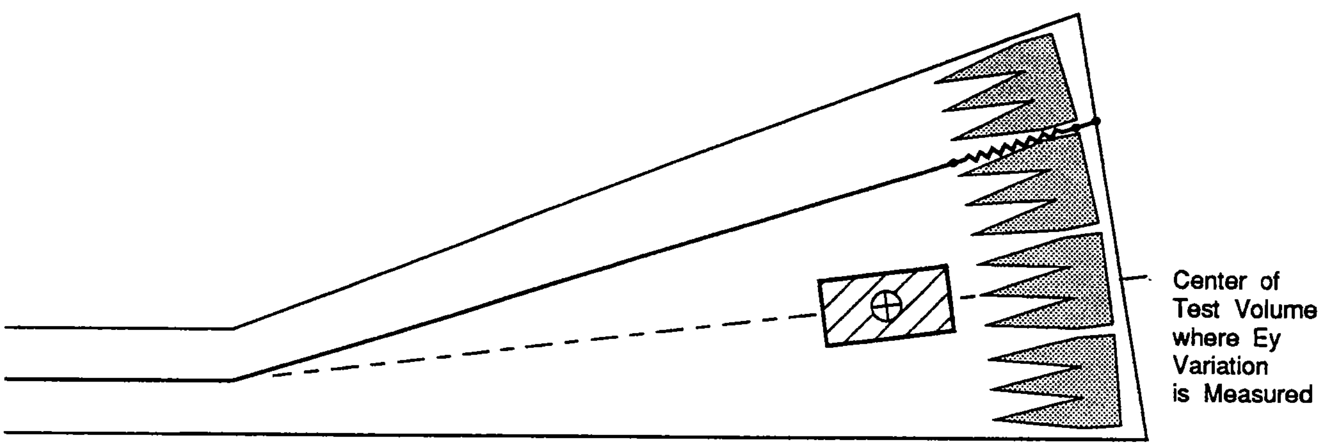
203.0 V/m @ Septum Height of 1.1 m (in front of large door)

127.7 V/m @ Septum Height of 1.75 m (at large door)

Figure 1. CW Field Strengths in GTEM! Model 5317



A. Variation of E_y over Frequency



B. Location of Center of Test Volume
Measurement Device is Centered in Cell

Figure 2. Illustration of the Meaning of E-Field Frequency Response

Model 5302 illustration unavailable at press time.

Figure 3 Model 5302 GTEM!

NOTES:

1. PRIMARY DIMENSIONS SHOWN ARE IN MILLIMETERS; SECONDARY IN BRACKETS ARE IN INCHES.

2. AC POWER INFORMATION
   REQUIRED POWER INPUT SERVICE TO GTEM IS:
   U.S. & CANADA
   -ONE CIRCUIT OF 30 AMPS, 120 V, SINGLE PHASE, 60Hz
   EUROPE
   -ONE CIRCUIT OF 30 AMPS, 240 V, SINGLE PHASE, 50Hz
   GROUNDING
   A LOW IMPEDANCE GROUND OR SEPARATE GROUND REFERENCE MAY BE NEEDED. IF THIS IS IMPLEMENTED, TRANSFORMER ISOLATION FROM MAIN SERVICE MAY BE REQUIRED.
   GENERAL INFORMATION
   THERE SHOULD BE NO GROUND FAULT INTERRUPTER (GFI) IN POWER SERVICE CIRCUIT TO GTEM. REACTIVE CURRENT THROUGH FILTERS COULD INADVERTENTLY TRIP GFI.

3. ESTIMATED TOTAL CELL WEIGHT IS 250 Kg [551 Lbs] DISTRIBUTED ON 3 CASTERS.

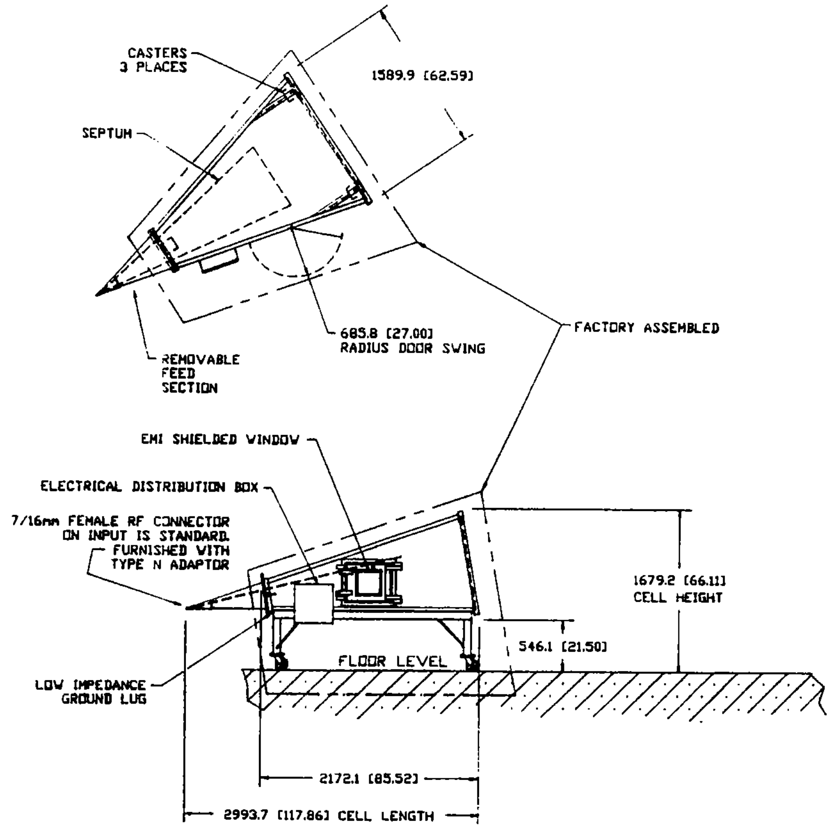
   APPROX CRATE SIZE & QUANTITY

   (1) EA 1727 x 2438 x 1880mm [68 x 96 x 74in]

   TOTAL SHIPPING WEIGHT 450 Kg [990 Lbs] APPROX.

CAUTION

IN ORDER TO ROLL CELL FROM LOADING DOCK TO INSTALLATION AREA, PASSAGEWAYS MUST BE 1651mm [65in] WIDE MINIMUM.



102241	102241	THIRD ANGLE PROJECTION	TOLERANCES-MILLIMETER
NEXT ASSY	USED ON		
APPLICATION			
METRIC			

DRAWN CAC	9/26/91
	9/16/92

THE ELECTRO-MECHANICS COMPANY
AUSTIN, TEXAS

TITLE: INSTALLATION REQUIREMENTS STANDARD GTEM MODEL 5305

SIZE A1 | DWG. NO. 398606 | REV. A | SCALE 1 : 25 | SHEET 1 OF 1

DWG. NO. 398606 | SH 1 | REV. A

NOTES:

1. PRIMARY DIMENSIONS SHOWN ARE IN MILLIMETERS; SECONDARY IN BRACKETS ARE IN INCHES.

2. AC POWER INFORMATION
   REQUIRED POWER INPUT SERVICE TO GTEM IS:
   U.S. & CANADA
   -ONE CIRCUIT OF 30 AMPS, 120 V, SINGLE PHASE, 60Hz
   EUROPE
   -ONE CIRCUIT OF 30 AMPS, 240 V, SINGLE PHASE, 50Hz
   GROUNDING
   A LOW IMPEDANCE GROUND OR SEPARATE GROUND REFERENCE MAY BE NEEDED. IF THIS IS IMPLEMENTED, TRANSFORMER ISOLATION FROM MAIN SERVICE MAY BE REQUIRED.
   GENERAL INFORMATION
   THERE SHOULD BE NO GROUND FAULT INTERRUPTER (GFI) IN POWER SERVICE CIRCUIT TO GTEM. REACTIVE CURRENT THROUGH FILTERS COULD INADVERTENTLY TRIP GFI.

3. ESTIMATED TOTAL CELL WEIGHT IS 1200 Kg (2640 Lbs) DISTRIBUTED ON 12 SWIVEL CASTERS.

4. THE FACILITY FLOOR MUST BE FLAT WITHIN 6.0mm (.24in) FOR ADEQUATE SUPPORT OF THE GTEM.

5. STAGING AREA ADJACENT TO INSTALLATION AREA MUST ACCOMODATE 9 TOTAL SHIPPING CRATES AND A 1.6m x 5.0m WORK AREA.

   APPROX CRATE SIZES & QUANTITIES

   (3) EA 1524 x 2032 x 1168mm (60 x 80 x 46in)

   (1) EA 1524 x 2032 x 1016mm (60 x 80 x 40in)

   (1) EA 1727 x 2438 x 1676mm (68 x 96 x 66in)

   (3) EA 1524 x 2438 x 914mm (60 x 96 x 36in)

   (1) EA 4166 x 203 x 203mm (164 x 8 x 8in)

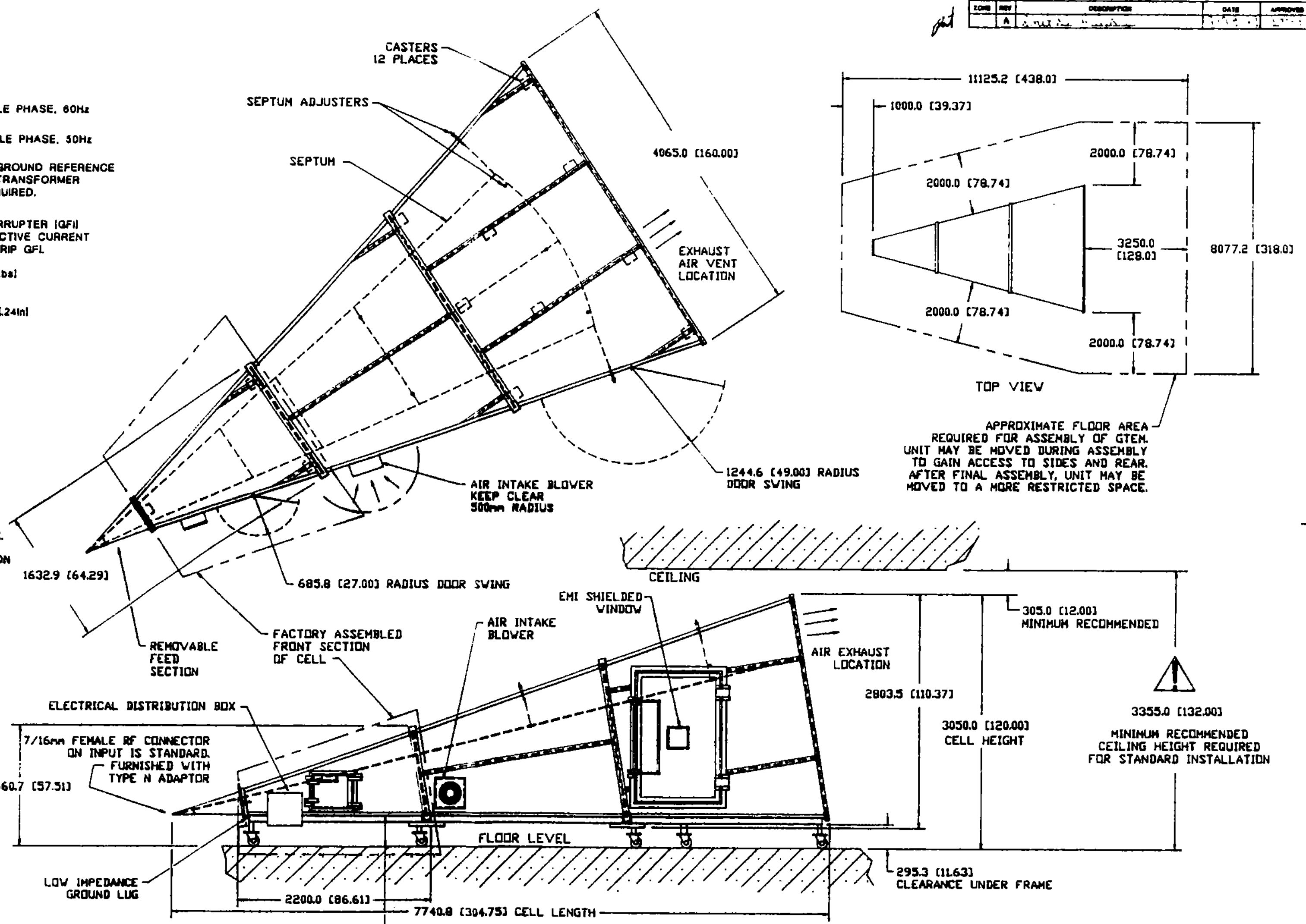
   TOTAL SHIPPING WEIGHT 3600 Kg (7920 Lbs) APPROX.

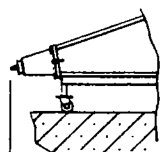
AN IDEAL INSTALLATION WOULD ALLOW TRANSPORTATION OF SHIPPING CRATES TO THE STAGING/INSTALLATION AREA WITHOUT THE NEED FOR CRATES BEING OPENED.

6. PASSAGEWAYS FROM LOADING DOCK TO STAGING AND INSTALLATION AREA ARE RECOMMENDED TO BE 1828mm x 1828mm (72in x 72in) MINIMUM. MINIMUM SIZE PASSAGEWAYS WILL REQUIRE SEPARATE UNPACKING AREA AND PIECE BY PIECE TRANSPORTATION OF ALL COMPONENTS TO INSTALLATION AREA.

CAUTION

IN ORDER TO ROLL FACTORY ASSEMBLED FRONT SECTION OF CELL FROM LOADING DOCK TO INSTALLATION AREA, PASSAGEWAYS MUST BE 1651mm (65in) WIDE MINIMUM. THE FACTORY ASSEMBLED FRONT SECTION OF CELL CAN BE CARRIED ON ITS SIDE THROUGH PASSAGEWAYS 1524mm (60in) WIDE MINIMUM.





7337.7 [288.89] CELL LENGTH

HIGH VOLTAGE FEED OPTION

102519	102519
NEXT ASSY	USED ON
APPLICATION	
METRIC	

THIRD ANGLE PROJECTION

TOLERANCES-MILLIMETER

APPROVALS: CAC 11/19/90; 9/16/92; 9/21/...

THE ELECTRO-MECHANICS COMPANY
AUSTIN, TEXAS

INSTALLATION REQUIREMENTS STANDARD GTEM MODEL 5317

SIZE A1 DWG. NO. 398605 REV. A
SCALE 1 : 25 SHEET 1 OF 1

DWG. NO. 398605 SH 1 REV. A

REVISIONS: ZONE | REV A | DESCRIPTION | DATE | APPROVED

NOTES:

1. PRIMARY DIMENSIONS SHOWN ARE IN MILLIMETERS; SECONDARY IN BRACKETS ARE IN INCHES.

2. AC POWER INFORMATION
   REQUIRED POWER INPUT SERVICE TO GTEM IS:
   U.S. & CANADA
   -ONE CIRCUIT OF 30 AMPS, 120 V, SINGLE PHASE, 60Hz
   EUROPE
   -ONE CIRCUIT OF 30 AMPS, 240 V, SINGLE PHASE, 50Hz
   GROUNDING
   A LOW IMPEDANCE GROUND OR SEPARATE GROUND REFERENCE MAY BE NEEDED. IF THIS IS IMPLEMENTED, TRANSFORMER ISOLATION FROM MAIN SERVICE MAY BE REQUIRED.
   GENERAL INFORMATION
   THERE SHOULD BE NO GROUND FAULT INTERRUPTER (GFI) IN POWER SERVICE CIRCUIT TO GTEM. REACTIVE CURRENT THROUGH FILTERS COULD INADVERTENTLY TRIP GFI.

3. ESTIMATED TOTAL CELL WEIGHT IS 900 Kg (1980 Lbs) DISTRIBUTED ON 7 SWIVEL CASTERS.

4. THE FACILITY FLOOR MUST BE FLAT WITHIN 6.0mm (.24in) FOR ADEQUATE SUPPORT OF THE GTEM.

5. STAGING AREA ADJACENT TO INSTALLATION AREA MUST ACCOMODATE ALL SHIPPING CRATES AND A 1.6m X 5.0m WORK AREA.

APPROX CRATE SIZES & QUANTITIES

(1) EA 1727 x 2438 x 1676mm (68 x 96 x 66in)
(1) EA 1524 x 2438 x 1168mm (60 x 96 x 46in)
(1) EA 1422 x 2438 x 1168mm (56 x 96 x 46in)
(1) EA 508 x 2438 x 1067mm (20 x 96 x 42in)
(1) EA 2921 x 203 x 203mm (115 x 8 x 8in)

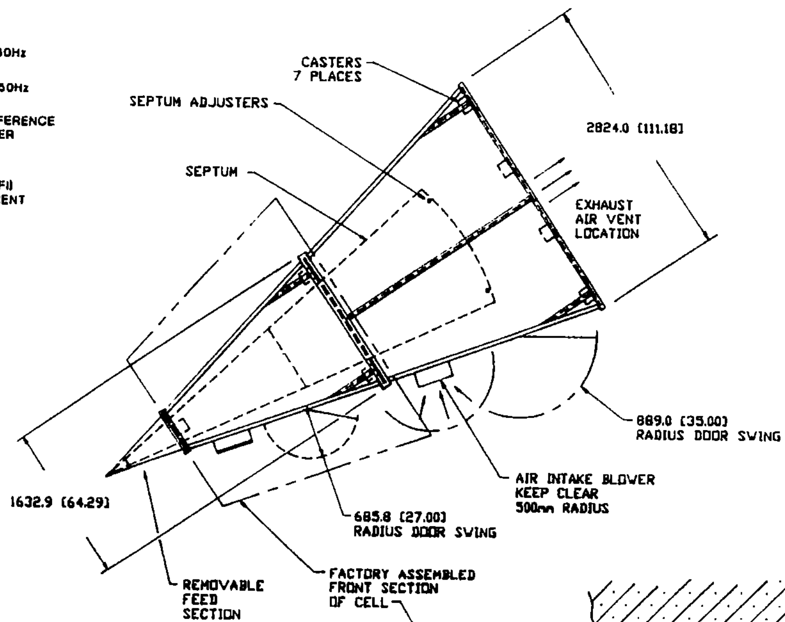
TOTAL SHIPPING WEIGHT 1400 Kg (3080 Lbs) APPROX.

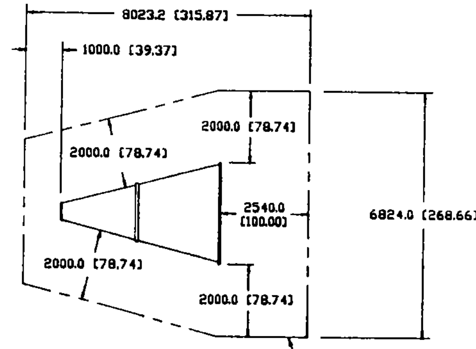
AN IDEAL INSTALLATION WOULD ALLOW TRANSPORTATION OF SHIPPING CRATES TO THE STAGING/INSTALLATION AREA WITHOUT THE NEED FOR CRATES BEING OPENED.

6. PASSAGEWAYS FROM LOADING DOCK TO STAGING AND INSTALLATION AREA ARE RECOMMENDED TO BE 1828mm x 1828mm (72in x 72in) MINIMUM. MINIMUM SIZE PASSAGEWAYS WILL REQUIRE SEPARATE UNPACKING AREA AND PIECE BY PIECE TRANSPORTATION OF ALL COMPONENTS TO INSTALLATION AREA.

CAUTION

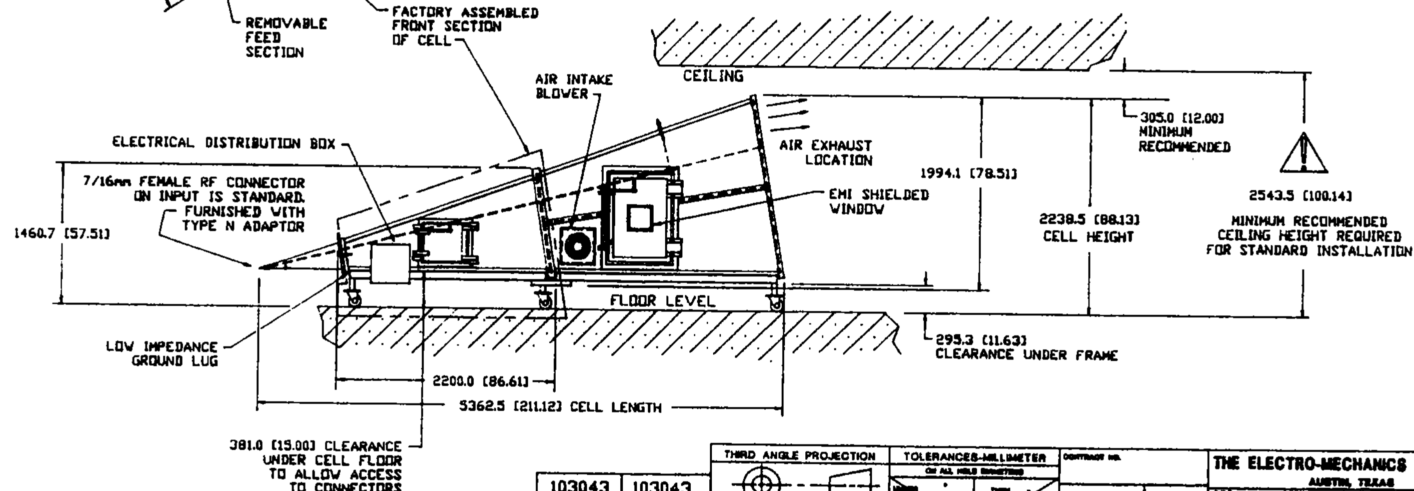
IN ORDER TO ROLL FACTORY ASSEMBLED FRONT SECTION OF CELL FROM LOADING DOCK TO INSTALLATION AREA, PASSAGEWAYS MUST BE 1651mm (65in) WIDE MINIMUM. THE FACTORY ASSEMBLED FRONT SECTION OF CELL CAN BE CARRIED ON ITS SIDE THROUGH PASSAGEWAYS 1524mm (60in) WIDE MINIMUM.

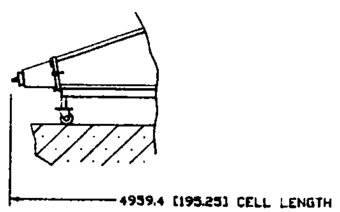




TOP VIEW

APPROXIMATE FLOOR AREA REQUIRED FOR ASSEMBLY OF GTEM. UNIT MAY BE MOVED DURING ASSEMBLY TO GAIN ACCESS TO SIDES AND REAR. AFTER FINAL ASSEMBLY, UNIT MAY BE MOVED TO A MORE RESTRICTED SPACE.





HIGH VOLTAGE FEED OPTION

103043	103043	THIRD ANGLE PROJECTION	TOLERANCES-MILLIMETER
NEXT ASSY	USED ON		
APPLICATION			
METRIC			

THE ELECTRO-MECHANICS COMPANY
AUSTIN, TEXAS

INSTALLATION REQUIREMENTS
STANDARD GTEM MODEL 5311

DRAWN CAC 9/86/91

9/21/96

A1 — DWG. NO. 398604 — REV. A

SCALE 1 : 25 — SHEET 1 OF 1

DWG. NO. 398604 — SH 1 — REV. A

GTEM! Mechanical Information

General

This section describes the mechanical actions that may be required in the normal operation and maintenance of a GTEM!

Installation and Removal of the Feed Adaptor(s)

The GTEM is designed with a DIM 7/16 female connector as the interface to test equipment. Since this is not a standard connector for many RF applications, a Type "N" to DIN 7/16 adapter for the GTEM! input is furnished to allow direct connection to RF equipment.

CAUTION:	The feed section should be installed on the GTEM! prior to the installation of the Feed Adapter.

Installation is straightforward.

1. Unpack the adapter.

2. The large, male end of the adapter is inserted in to the matching female DIN 7/16 on the feed section, and pushed into the 7/16 female connector until resistance is felt.

3. Tighten the knurled knob on the adapter until snugly seated.

CAUTION:	The frequency response of the GTEM! may be impaired if the adapter is installed to loosely or to tightly. Take care not to over tighten!

Installation and Removal of the CW or Other Feed

The CW feed (furnished as the standard feed with all GTEM!s) is removed and replaced as follows:

Removal of CW Feed:

1. Grasp the handle of the CW feed in one hand while facing the GTEM! from the apex (small) end.

2. Unlock the two latches on either side of the GTEM!

3. Allow the apex of the GTEM! CW Feed section to rotate gently down until the septum connection is free. Maintain support of the feed section during this operation.

4. Using the handle, and the CW Feed end, lift the CW feed away from the GTEM!

Replacement of CW Feed (Initial assembly for the Model 5305):

1. Grasp the feed by the handle and place the lower edge of the feed on the small shelf at the bottom of the GTEM!

2. Gently rotate the CW Feed section upward to the point where the septum is about to be engaged. The guides on the sides of the GTEM! body will center the septum in the CW Feed section and provide proper alignment with the septum section in the GTEM!

3. Continue the upward rotation of the CW Feed section while observing to assure the CW Feed section aligns and that the CW Feed section will fit into the GTEM! septum section.

4. When the septum is mated continue the rotation until the upper portions of the CW Feed are in contact with the GTEM!

5. Secure the latches to hold the CW Feed section in place.

Installation and Removal of Load Boards

1. Remove the Load Board Covers on the rear of the cell by loosening the finger screws securing the covers to the GTEM! body. Access to these Load Board Covers in the larger size cells will require a

personnel support device, as they are located a moderate distance from the floor.

CAUTION:	An adequate personnel support device should be used to lift personnel to an adequate height for removal of the RF Load Boards for the Model 5311 and 5317 GTEM!s.

CAUTION:	While removing and replacing the RF Load Boards, personnel may come in contact with finger stock. This material has sharp edges and caution must be used in handling the Load Board Covers and the brackets that secure the Load Boards.

2. With the load board covers removed, the finger screws that secure the Load Boards to the support brackets are accessible by reaching over the back edge of the support bracket. Loosen the finger screws that secure the load boards to the brackets.

3. Remove the brackets from the GTEM!

4. Gently raise the back end of the load boards and pull them from the end of the septum. For the larger sizes of GTEM! a second person inside the GTEM! at the end of the septum is required to support the Load Boards during removal.

5. Remove the Load Boards from the GTEM! Take care to preserve the relative location of the Load Boards to assure that they are replaced in their proper order.

CAUTION:	The Load Boards are not identical. Each board is different, and must be reinstalled in the original location to assure proper operation of the cell.

Replacement of the RF Load Boards

Replacement of the RF Load Boards is the reverse of the above process. There are requirements to meet during the installation. All Load Boards are keyed to assure installation in the proper location. During replacement (installation) assure the alignment of the Load Boards by visually locating the guide pins and assuring that the Load Boards are aligned with the guide pins before seating the boards. Someone should be located inside the larger GTEM! for the installation of the Load Boards to assure proper location. The RF Load Boards are lettered in the sequence A, B, ..., from right to left as seen from the rear of the GTEM!.

There are two load boards in a model 5305 GTEM!, four load boards in a Model 5311 and six load boards in a Model 5317 GTEM!

CAUTION:	The Load Boards are large and have a tendency to flex when handled. Assure that this flexing is kept to a minimum during handling.

Movement of an Assembled GTEM!

Movement of an assembled GTEM! is straightforward.

CAUTION!	Since the object being moved is large and will have inertia, precautions should be taken to assure that the GTEM! is moved safely.

Actual movement of even the Model 5317 GTEM! is possible with as few as three persons. Additional personnel aid in the movement and in assuring that the movement of the test instrument is accomplished without damage.

To move larger GTEM!s on stands:

1. Select the new location for the GTEM!

2. Clear the path between the starting location and the new location. For larger GTEM!s this could involve moving other items of instrumentation, or furniture.

3. Disconnect any instrumentation and / or test cables from the GTEM!

4. Unlock the three casters at the three corners of the GTEM!

5. Push the GTEM! to its new location, using at least one person at each corner of the GTEM!

CAUTION!	Since the GTEM! is a large object, it is mandatory that adequate visibility and communications be maintained during the movement of the cell to prevent damage to the cell or injury to personnel.

6. Engage the wheel locks at the corners of the GTEM!

CAUTION!	The wheels on the corners of the GTEM! are equipped with wheel locks. These should be engaged when the GTEM! is stationary in its desired location.

Relocation of an Assembled GTEM!

When relocating a large GTEM!, particularly a Model 5311 or 5317, to a new building or other site, the factory should be consulted. Often, partial or full disassembly to component pieces is required to allow safe passage through doorways, *etc.* Such disassembly, and the subsequent reassembly, should be accomplished by factory personnel.

GTEM! ELECTRICAL POWER INFORMATION

General

The GTEM! is a simple device from an electrical power standpoint. AC Power control is established at the Power Distribution Panel, normally located on the right front of the GTEM! as seen from the apex. (NOTE: Other locations are possible if custom ordered.)

A view of the Power Distribution Panel is shown in Figure 7.

1. AC Power input is switched by a Main Power Circuit Breaker on the Power Distribution Panel. This switch controls AC power to all GTEM! functions:

    - Unswitched receptacle on the Power Distribution Panel. This outlet is rated at the AC standard input voltage of the GTEM, at 10 A.

    - EUT Power output to the filtered EUT power on the inside of the GTEM! This outlet is rated at the AC standard input voltage of the GTEM, at 10 A.

    - Power to the 24 V DC safety interlolck circuit.

    - AC Power to the Switched receptacle. This power outlet is controlled by the Safety Interlock Circuit. All doors must be closed and the feed section must be in place for the AC power to be available at the switched outlet. For nominal power RF amplifiers, this outlet can be used to power OFF the RF amplifier if one of the GTEM! doors is opened with the RF power applied to the GTEM!

Standard GTEM! Power Input

The Standard GTEM! power ratings are 120 or 240 V AC at 50 or 60 Hz.

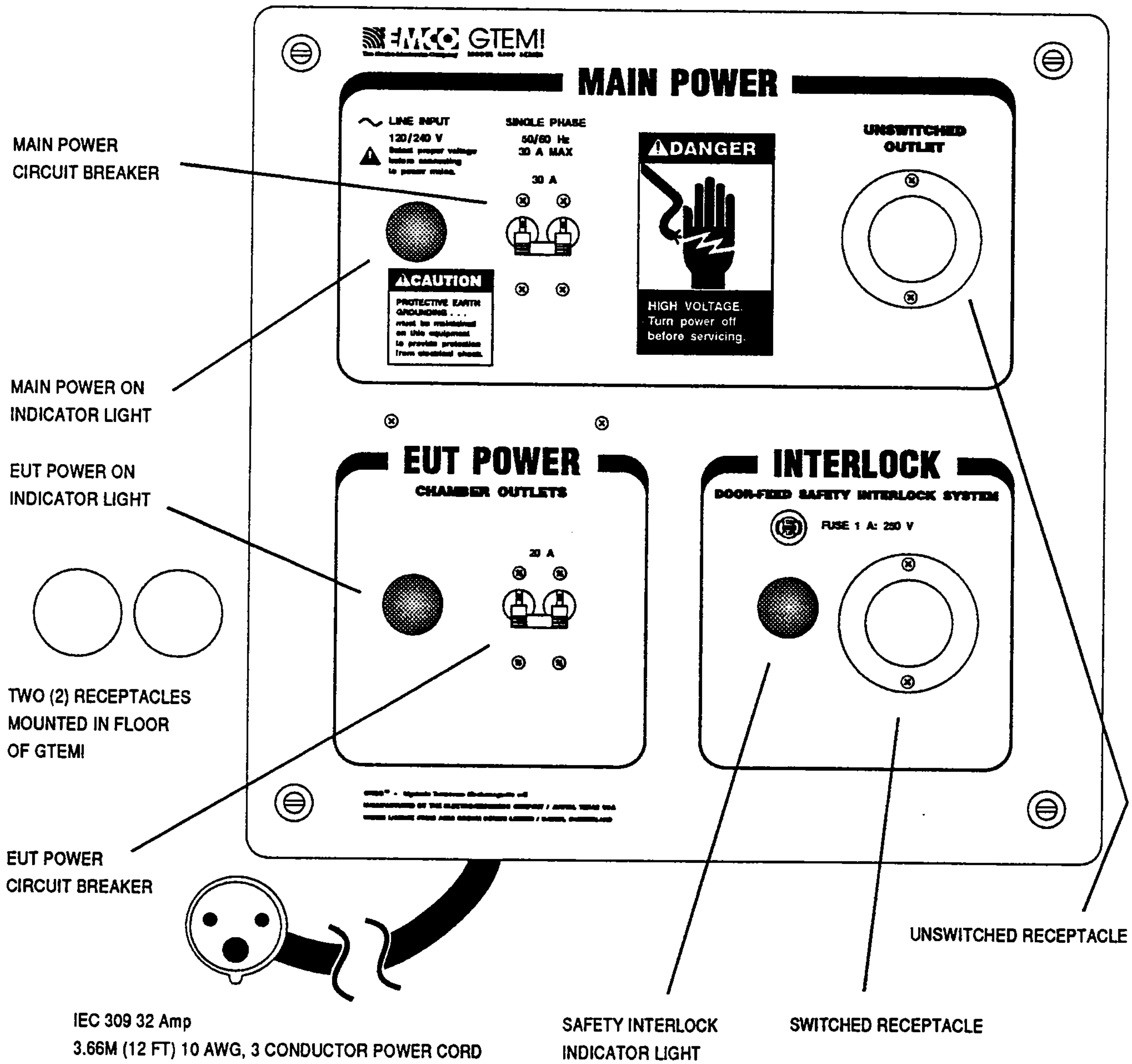


Figure 7. GTEM! Power Distribution Panel

Safety Interlock Circuit

The GTEM! is furnished with a safety interlock circuit. The items on this circuit on a standard configuration GTEM are the two EUT access doors and the feed. All of these items must be closed or in place for AC power to be available to the switched outlet on the Power Distribution Panel.

DANGER:	When performing immunity testing, all access doors must be closed and the feed section must be in place to prevent possible exposure to hazardous RF levels.

Schematic

The schematic for the power distribution is given in Figure 8.

DANGER:	The GTEM! Electrical Junction Box contains high voltages. Switch off the GTEM! and disconnect the GTEM! from the power source before servicing.

Grounding

Standard AC power grounding is shown in Figure 9. As installed on a standard GTEM! configuration, reactive AC currents flow through the capacitive impedances of the power line filters. If the GTEM! power is supplied through a ground fault interrupter circuit, this circuit breaker can be expected to trip when the AC power to the EUT is switched on.

To prevent this from occurring, a solution such as is shown in Figure 10 may be employed. An isolation transformer with the secondary referenced to a separate, locally derived ground system, as shown in this Figure, may be used to prevent tripping of the ground fault interrupter circuit.

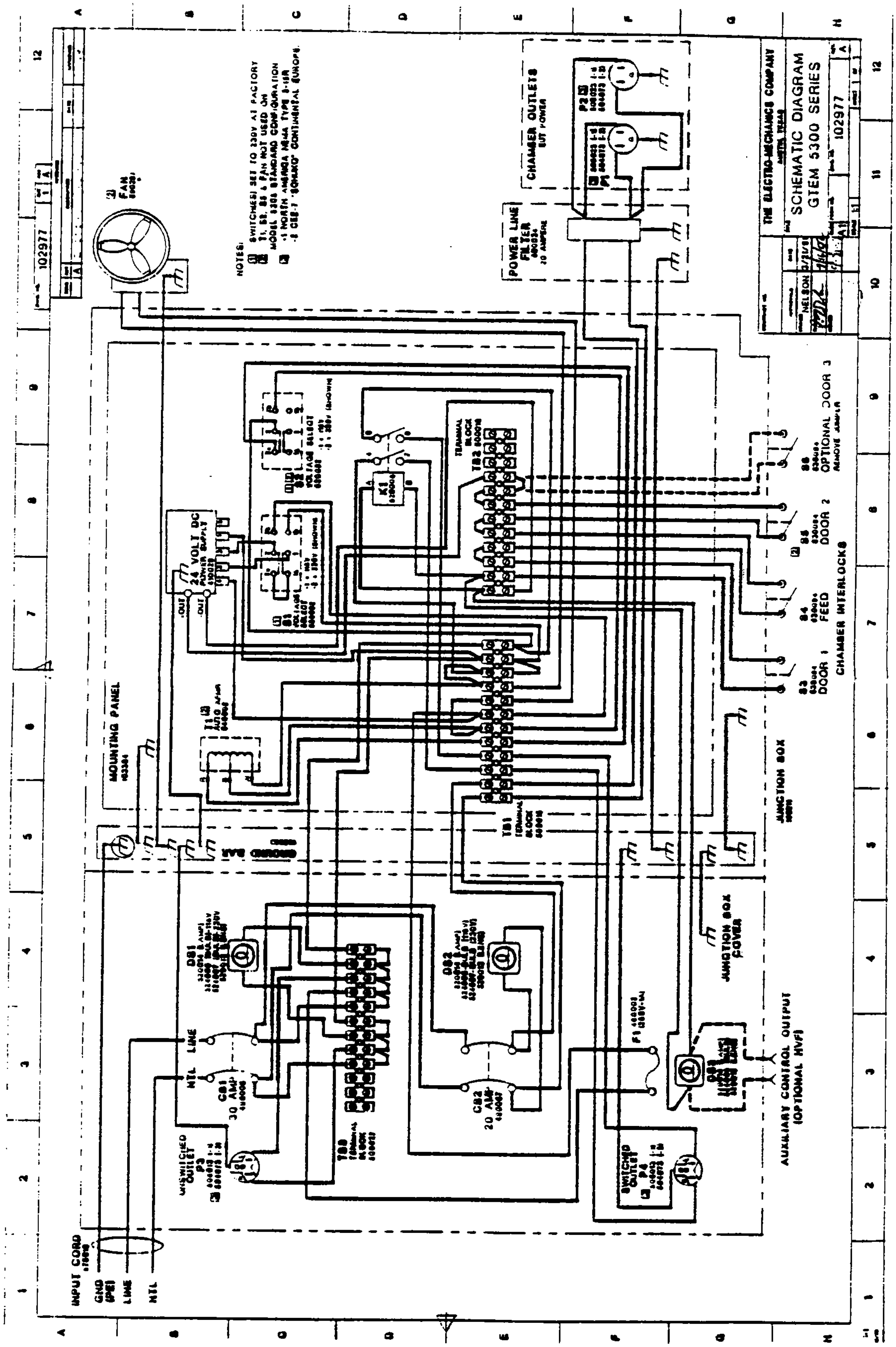


Figure 8. GTEM! Power Distribution Schematic

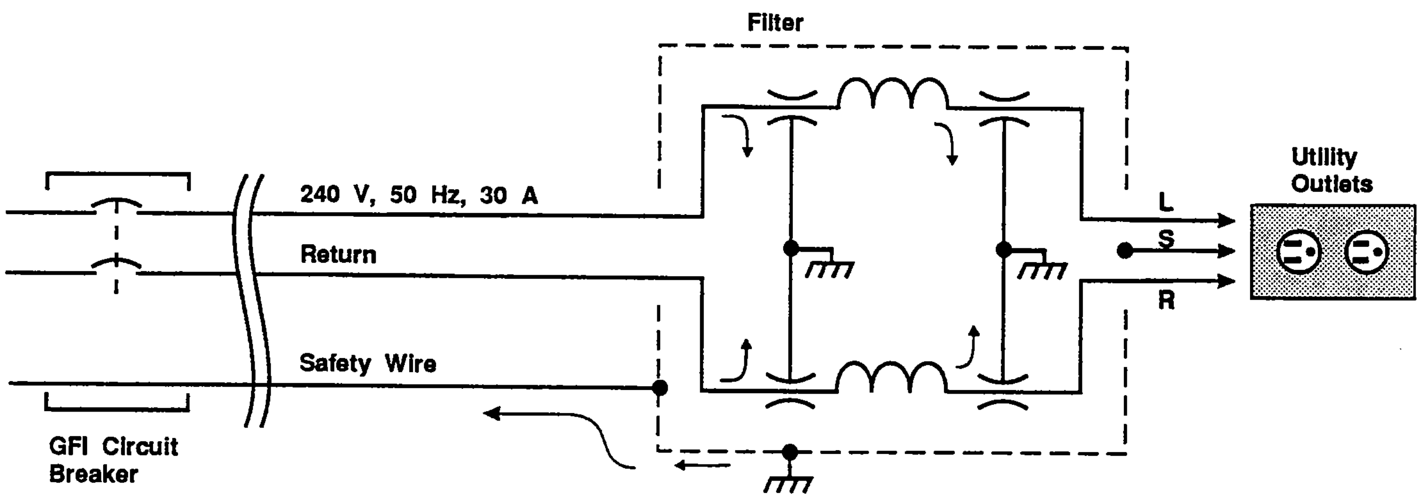


Figure 9. Standard GTEM! Power Grounding

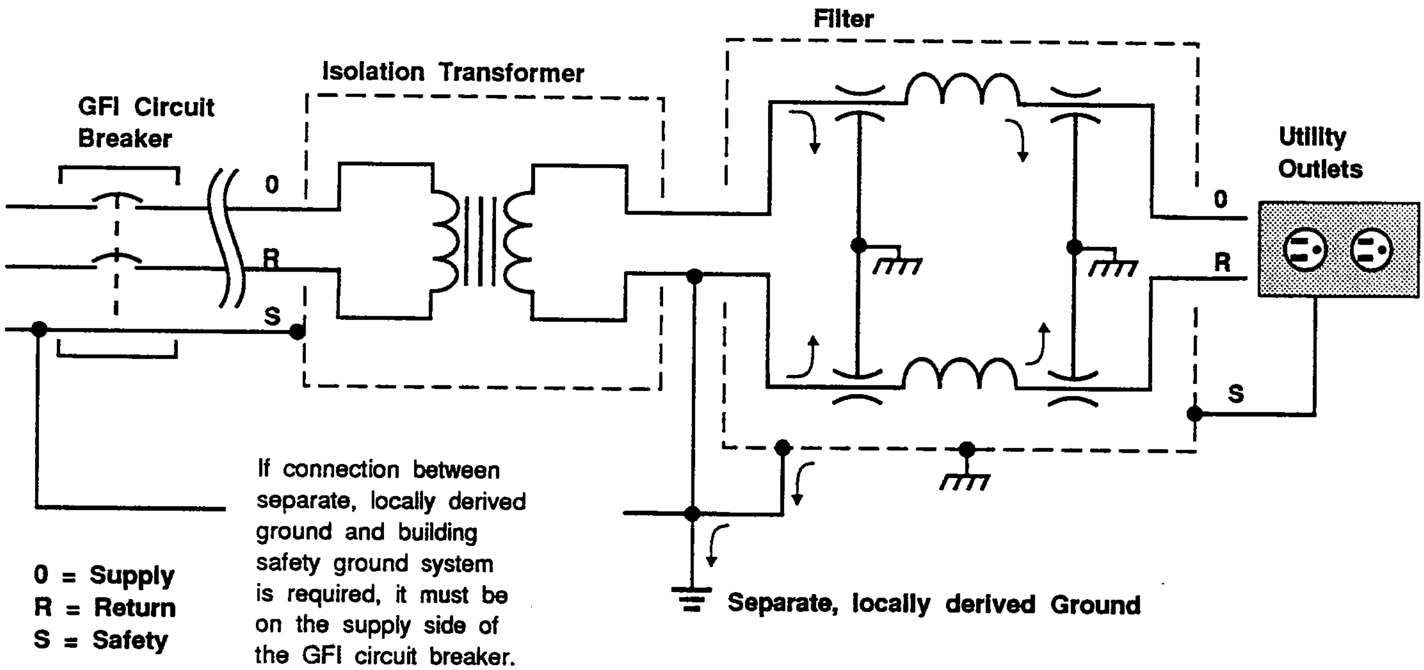


Figure 10. Modified GTEM! Power Grounding for GFI Power Circuits

General Theory of RF Operation

In an RF sense, the GTEM! is a very simple device. It is a terminated transmission line, as far as analysis and development of GTEM! theory are concerned. In practice, it is more complicated in that the actual termination is a dual termination. There is a 50 Ω termination for currents flowing in the septum and a RF absorber termination for electromagnetic fields generated in the GTEM! that are traveling toward the large end of the GTEM!

The GTEM! as a Terminated Transmission Line

The GTEM! is essentially a section of asymmetric rectangular transmission line with unique, tapered geometry and a dual termination. Its RF performance is that of a terminated transmission line. The geometry of the GTEM! is shown in Figure 11. An RF signal applied to the center conductor creates a uniform field directly below the flat septum, between the septum and the bottom of the TEM Cell.

Due to the geometry, there is a vertical and horizontal gradient in the electromagnetic field distribution inside the GTEM, just as there is in a coaxial transmission line.

Historically, the center third, vertically and horizontally, of the volume below the septum is of sufficiently uniform distribution to allow use of the GTEM for immunity testing. In actuality, the test volumes producing accurate results for radiated emissions testing may be as large as two-thirds of the vertical and horizontal dimensions. In the case of radiated immunity testing, the "uniform field" may not be as large, but it does exceed the one-third by one-third traditionally stated value. (See Section on measured GTEM! Performance.)

Since the GTEM! provides a matched termination for input signals, there are no severe VSWR problems as there are when using antennas, particularly lower frequency antennas. It is easy to produce low frequency intense electromagnetic fields. In fact, using summing techniques, emulations of complex electromagnetic environments are possible. The capability of a GTEM! to operate without size or scaling problems well into the GHz frequency range allows the testing of items without the need for frequent antenna changes. This allows the generation of a test electromagnetic environment for frequencies well in excess of 1.0 GHz. (See the measured data in the section on Measured GTEM! Performance.)

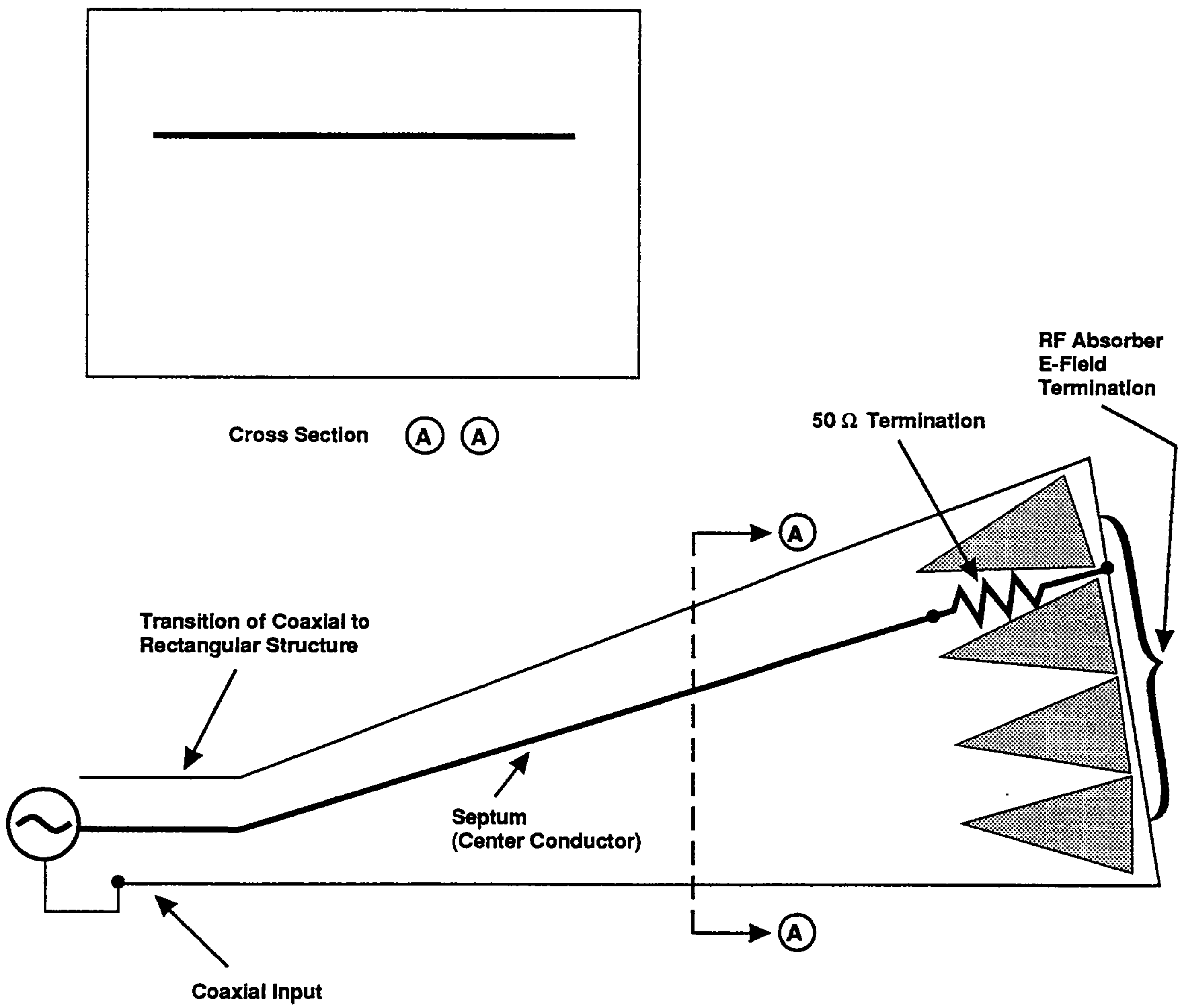


Figure 11. GTEM! Geometry

Coaxial Transmission Line Analog

For many analysis purposes the GTEM! may be considered as a special case of a coaxial transmission line.

Characteristic and Field Impedances of a GTEM!

The characteristic impedance of the GTEM is set by its internal dimensions. The width of the septum and its location, in combination with the cross sectional dimensions of the GTEM!, set the characteristic impedance of the cell. Since it is an asymmetric transmission line, the derivation is complicated, but follows the same approach as that used for a coaxial transmission line. For brevity and simplicity, the derivation of the impedances of a coaxial line is shown, instead of that of a GTEM!

Traditional coaxial transmission line such as is shown in Figure 12, with inner conductor of radius *a*, and radius of the inside of the outer conductor of *b*, has per unit length values of capacitance and inductance of:

$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)} \qquad \text{and} \qquad L = \frac{\mu_0}{2\pi}\ln(b/a),$$

where ε_0 and μ_0 are the permittivity and permeability of the material between the conductors. For this derivation free space is assumed. The characteristic impedance of the transmission line is then:

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{\ln(b/a)}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}} = 60\ln(b/a)$$

The magnitude of the electric and magnetic field strengths between the conductors is given as:

$$E = \frac{V}{\rho\ln(b/a)} \qquad \text{and} \qquad H = \frac{I}{2\pi\rho}$$

where: V = Voltage on the Septum (Volts)

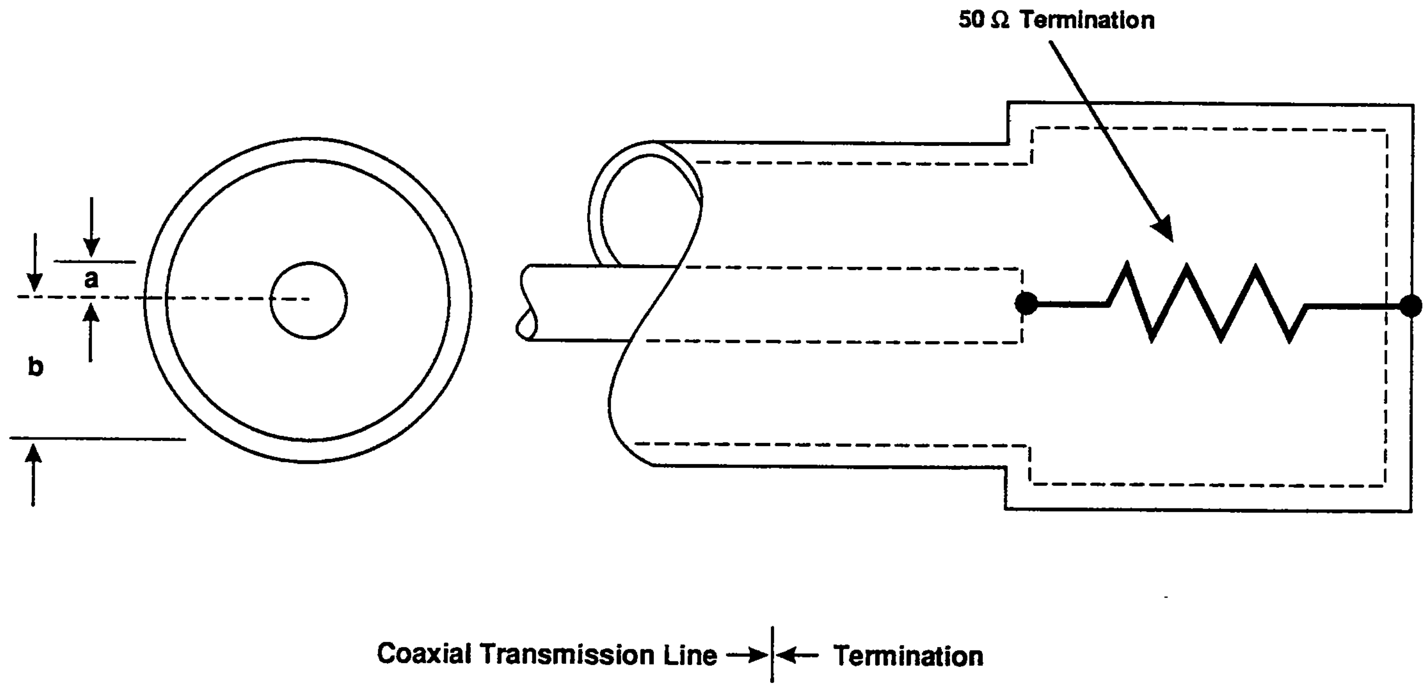


Figure 12. Terminated Transmission Line

I	=	Current in the Septum (Amps)
ρ	=	Distance from center, but between the conductors,(m)

The field impedance is given by the relationship of *E/H:*

$$\eta = \frac{E}{H} = \frac{V}{\rho \ln(b/a} \frac{2\pi\rho}{I} = \frac{V}{I} \frac{2\pi}{\ln(b/a)}$$

remembering that:

$$\eta = Z_0 = 60 \ln(b/a)$$

Then:

$$\eta = Z_0 \frac{2\pi}{\ln(b/a)} = \frac{2\pi 60 \ln(b/a)}{\ln(b/a)} = 120\pi$$

Note that the value of the ratio of b/a can be selected to give a characteristic impedance of 50 Ω, while the impedance of the field remains at 377 Ω between the conductors. This is a condition for transverse electromagnetic mode (TEM) operation.

While the geometry and the calculations are more complex, the same conditions hold true for the GTEM!, that is that the characteristic impedance of the GTEM! is set by the cross-sectional dimensions at a value of 50 Ω, while maintaining TEM operation with field impedance values of 377 Ω.

Termination Characteristics

Having derived the transmission line characteristics of the a coaxial transmission line, it is stated that the characteristics of a GTEM! match those of the coaxial line. The characteristic impedance is 50 Ω and the TEM mode exists. The next step, the description of the performance of the terminations, follows. It was stated above that the GTEM! is a dually terminated device, The two terminations are:

1.) Resistive to match the currents flowing in the septum, and

2.) RF absorbers to "terminate" (absorb) electromagnetic fields propagating to the termination.

The performance of these two terminations are discussed separately and then in combination.

Load Boards - The GTEM employs load boards to hold a large number of carbon resistors that compose the resistive termination. The resistive distribution and the wattage distribution of the carbon resistors are chosen to match the non-uniform current distribution in the septum. Figure 13 shows the performance of the load boards as one of the plots in Figure 13(a). This Figure shows return loss in dB versus frequency. Return Loss is shown as a negative number in dB since a small value of Return Loss (less than one) as a low walue of Return Loss (in negative dB) is the desired performance.At low frequencies, where the match of the load boards is excellent, the return loss is of the load boards by themselves is low. As frequency increases, the resistive distribution parasitic elements degrade the load boards performance as does the parallel termination of the RF absorbers that appears as a capacitive element, causing the return loss to increase.

RF Absorber - The second termination for the GTEM! is the array of RF absorbers The absorbers cover the end of the GTEM! in a spherical array, matching the arriving wave front, when generated by application of a signal to the apex of the GTEM!. At low frequencies, the RF absorber shows very low return loss as seen in Figure 13(a). As frequency increases, however, the match to the RF absorber improves until the return loss due to the absorber is quite low.

Combined Performance - When taken together, the two terminations appear to be in parallel. The measured combined response is as shown in Figure 13(a). The load boards dominate the response at low frequencies while the RF absorbers dominate the response at higher frequencies. The transition between the responses shows as an increase in the return loss at what is termed the critical frequency of the GTEM! this critical frequency also is found as an increase in the VSWR of the GTEM!, as shown in Figure 13(b). The critical frequency varies with the size of the GTEM! as well as with the individual GTEM!. This variation is attributed to the variations in the RF absorber.

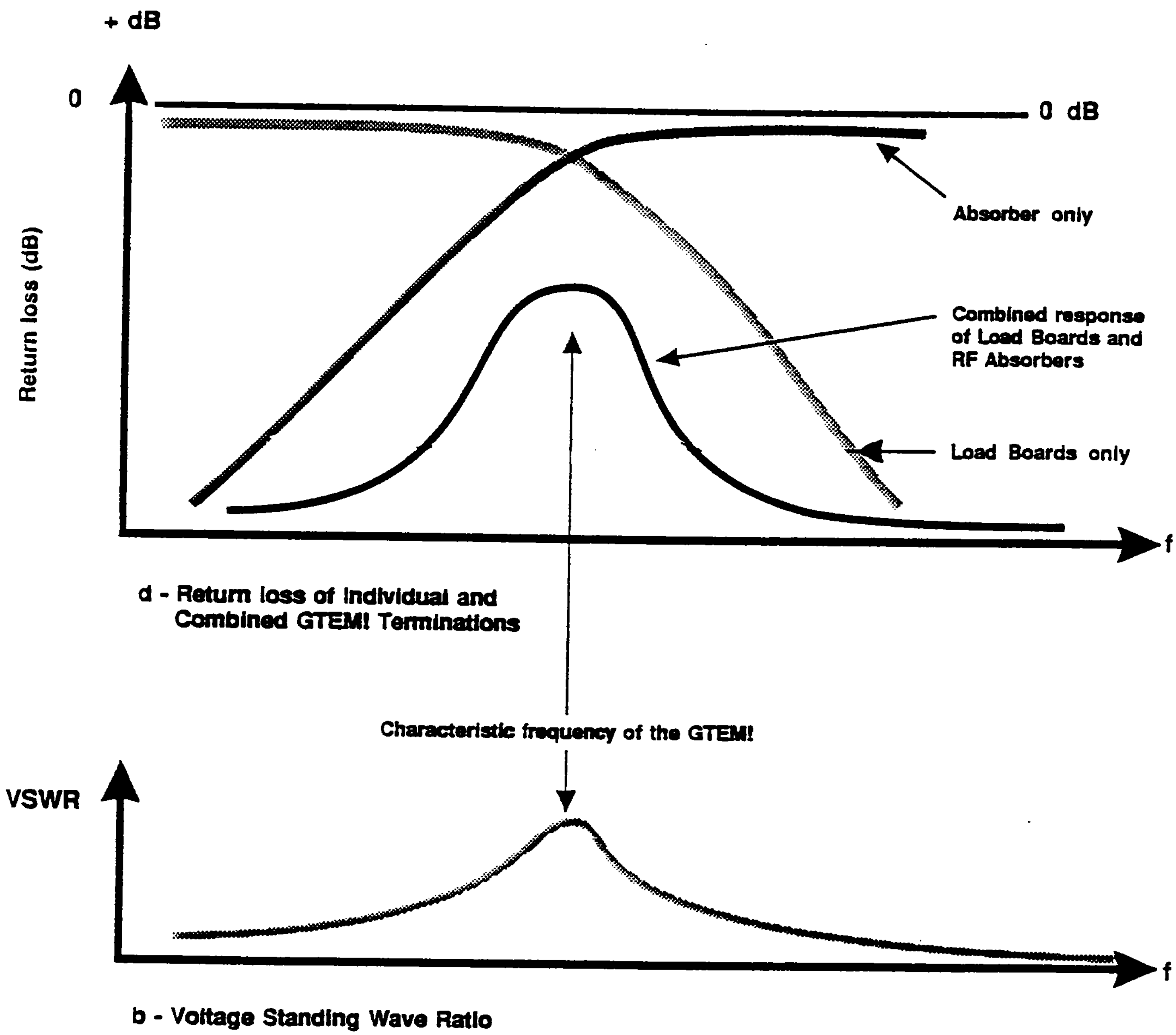


Figure 13 Explanation of GTEM Characteristic Frequency

Measured GTEM! Performance

There are several different measurable quantities that illustrate the performance of a GTEM!. Typical measurements are discussed in this section.

VSWR

The Voltage Standing Wave Ratio (VSWR) of a terminated transmission line is one of the fundamental measurements of transmission lines. Since the value of the VSWR reading is a measure of mis-match, it completely defines the capability of a GTEM! to work with interconnected 50 Ω RF equipment.

GTEM! Performance Quantification - VSWR

The VSWR is the quantifying measurement for GTEM!s. It is a straightforward measurement and it defines the GTEM! as a transmission line. All GTEM!s are assembled at the factory and the VSWR measured. The GTEM!s are not shipped until satisfactory values of this measurement are obtained.

Example VSWR

The VSWR of a typical GTEM! Model 5317 is shown in three segments in Figure 14, from 40 MHz to 1 GHz.; Figure 15, from 1 to 10 GHz; and Figure 16 from 10 to 20 GHz. The peak VSWR at the critical frequency is 1.785:1 at 46 MHz. The data was taken by a Wiltron Model 360. At all other frequencies, the VSWR is less than the specificationvalue of 1.5:1.

Shielding Effectiveness of the GTEM!

The shielding effectiveness of a GTEM! is difficult to measure, due to both the size of a GTEM! and the angles of the construction of the walls and other surfaces. An alternative method has been developed that is described in the measurement procedure included in Appendix D. The primary technical issue in the development of the measurement is the choice of signal inside the GTEM!. Due to size constraints, normal antennas cannot be used to generate the signal inside the GTEM!. In addition, the variation of electric field intensity along the GTEM! can cause a variation of more than 20 dB from apex to load. The more fundamental power basis was chosen for the measurement.

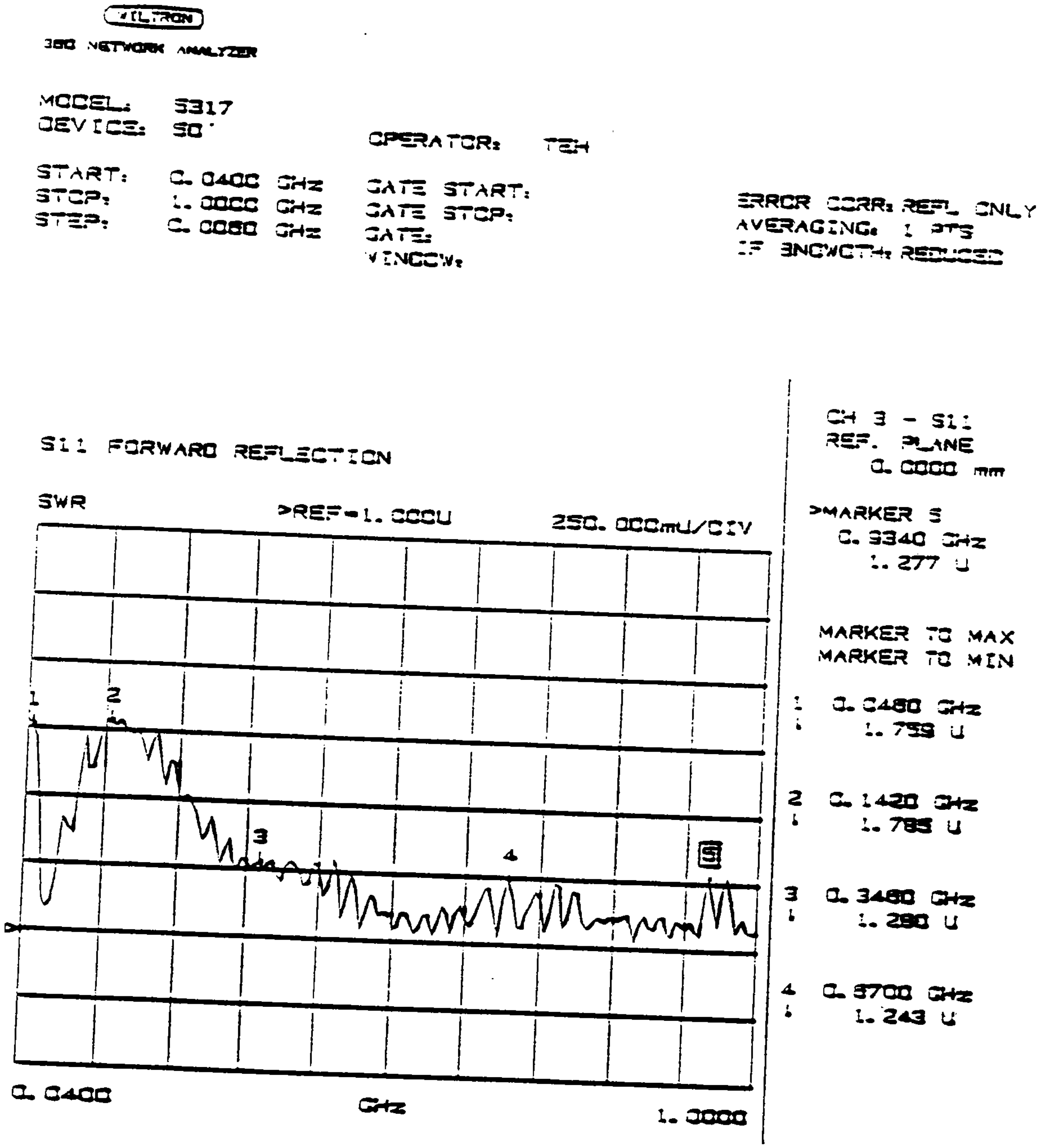


Figure 14 Model 5317 VSWR, 40 MHz to 1.0 GHz

WILTRON

360 NETWORK ANALYZER

MODEL: 5317
DEVICE: 30

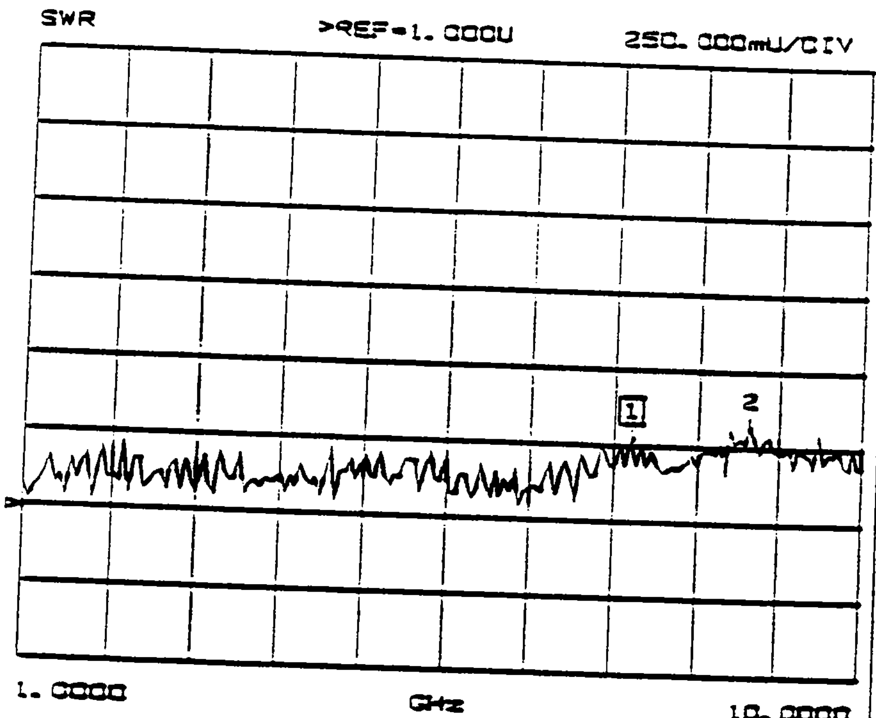
OPERATOR: TEH

START: 1.0000 GHz
STOP: 10.0000 GHz
STEP: 0.0540 GHz

GATE START:
GATE STOP:
GATE:
WINDOW:

ERROR CORR: REFL ONLY
AVERAGING: 1 PTS
IF BANDWIDTH: REDUCED

S11 FORWARD REFLECTION



CH 3 - S11
REF. PLANE
0.0000 mm

>MARKER 1
7.4800 GHz
1.275 U

MARKER TO MAX
MARKER TO MIN

2 8.7780 GHz
1.314 U

Witnessed By:
C. Garrison
[illegible]

Figure 15 Model 5317 VSWR, 1.0 GHz to 10.0 GHz

WILTRON

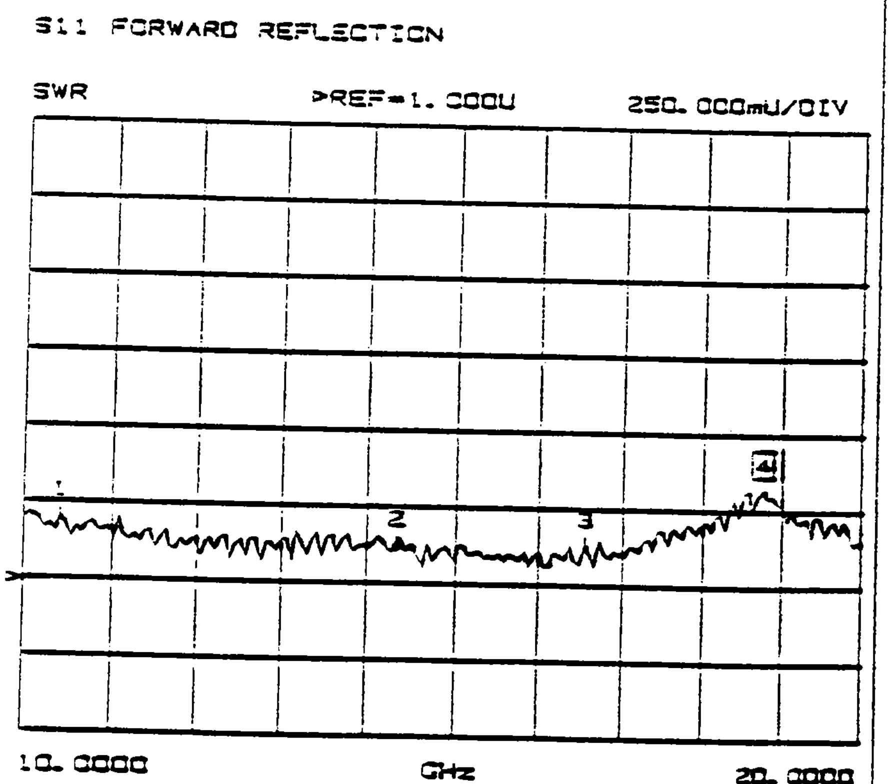
360 NETWORK ANALYZER

MODEL: 5317
DEVICE: 50
OPERATOR: TEH

START: 10.0000 GHz
STOP: 20.0000 GHz
STEP: 0.0200 GHz

GATE START:
GATE STOP:
GATE:
WINDOW:

ERROR CORR: REFL ONLY
AVERAGING: 1 PTS
IF BNDWDTH: REDUCED



CH 3 - S11
REF. PLANE
0.0000 mm

>MARKER 4
18.7800 GHz
1.318 U

MARKER TO MAX
MARKER TO MIN

1 10.4200 GHz
1.197 U

2 14.3200 GHz
1.122 U

3 16.5400 GHz
1.127 U

Figure 16

Figure 16 Model 5317 VSWR 10.0 GHz to 20.0 GHz

Shielding Effectiveness Measurements of the GTEM!

The shielding effectiveness of the GTEM! is measured at a minimum of 15 positions around the GTEM, at a selection of frequencies from 15 kHz to 17 GHz. There are 15 readings for each frequency. The limitation in measurement is the leakage from the signal generation equipment primarily the RF amplifier at about 20 W output, and the cable to the GTEM! input. This leakage has limited the measurement capability by limiting the maximum value of shielding effectiveness that can be detected at 900 MHz and 17000 MHz, at some locations around the GTEM. Additional refinement of the measurement procedure is required to increase the range of the measurement..

Example Shielding Effectiveness Data

Example shielding effectiveness plots on a Model 5317 are shown in Figures 17 and 18. Figure 17 shows the Vertical Polarization SE measurements while Figure 18 shows the horizontal polarization measurements. Note that there are no horizontal polarization measurements below 350 MHz as only vertically polarized antennas are available from 15 kHz to 15 MHz.

Electromagnetic Fields Performance

Characterization of a GTEM! for immunity testing straightforward The measurements are not difficult, but they are time consuming.

Definitions

The definitions below are included to assure generated electric field performance discussions are conducted using standard terms.

Electric Field Uniformity -- The electric field uniformity of a GTEM! is defined as the measured electric field value at a specific location (not the reference location) at any specific frequency, compared to the electric field value at that same frequency at the reference location, expressed in decibels.

The Electric field uniformity is reported in deciBels. It may be measured over a plane, as for determination of calibration for IEC 801-3, or over a volume.

The reference location may be arbitrarily chosen such as the center of the test volume or the bottom of the reference plane (as for IEC 801-3 calibration measurements).

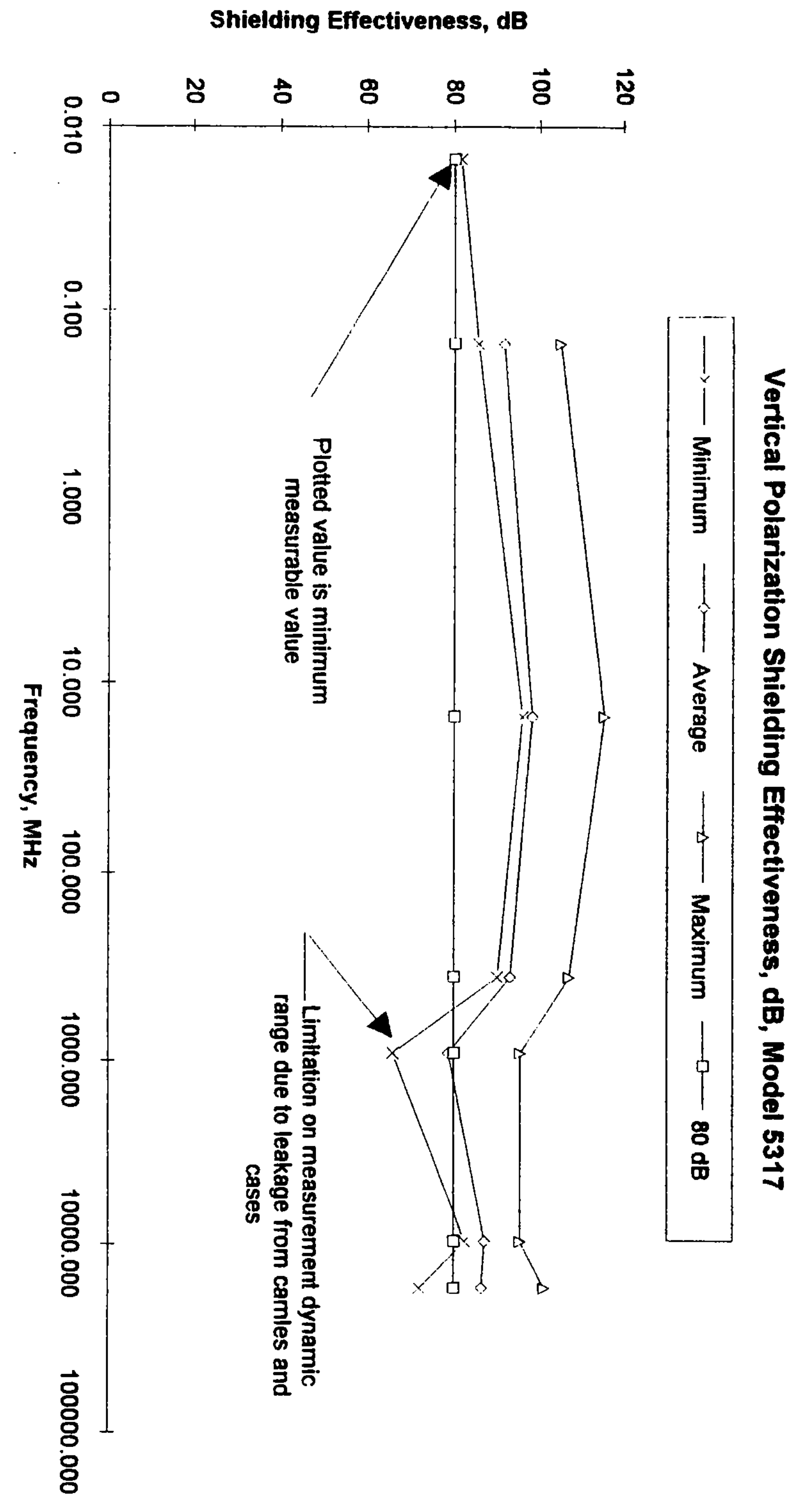


Figure 17 GTEM Model 5317 Shielding Effectiveness, Vertical Polarization

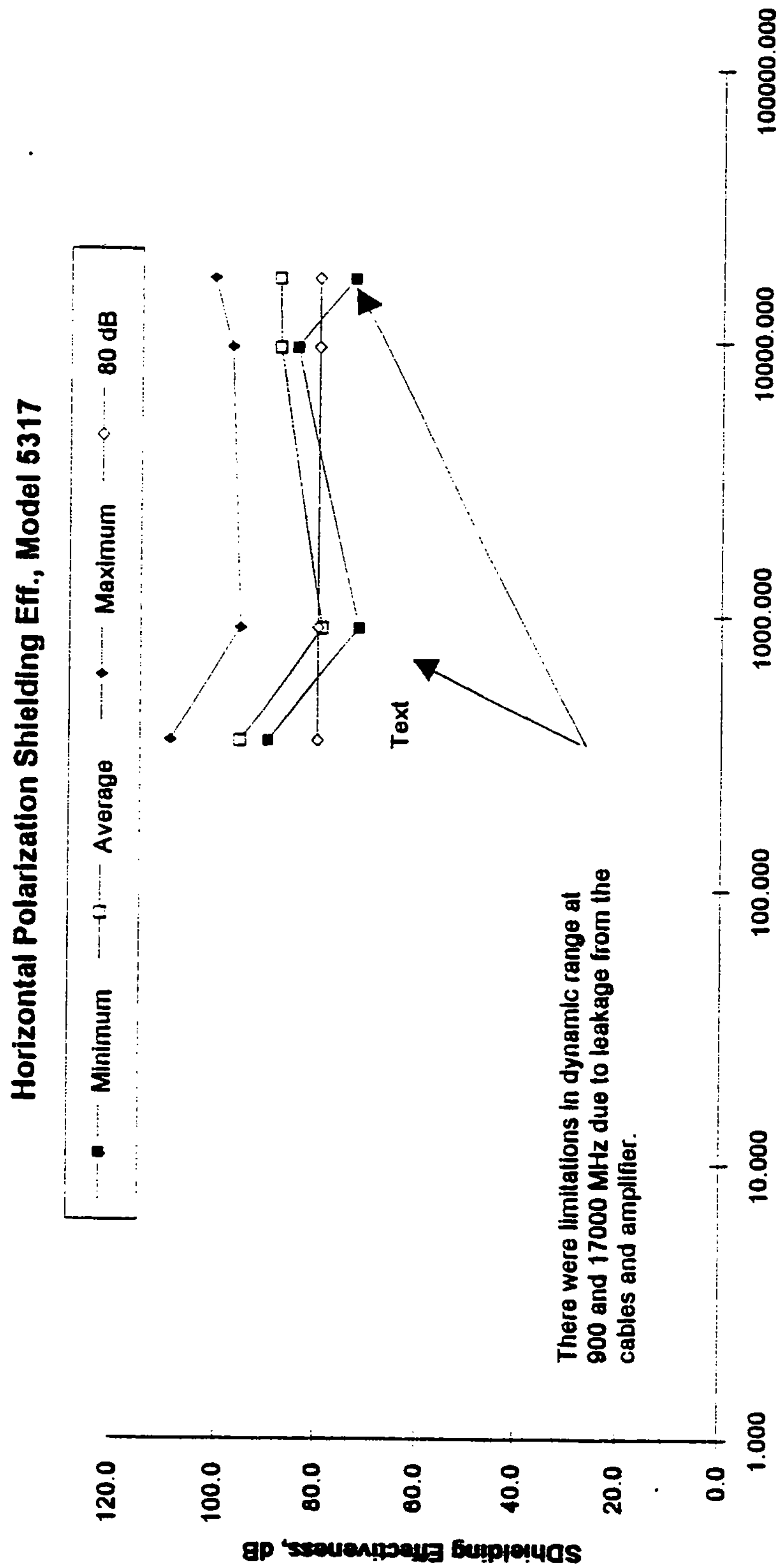


Figure 18 GTEM Model 5317 Shielding Effectiveness, Horizontal Polarization

$$E_{Unif} = 20\log_{10}\left[\frac{\vec{E}_{y,locn}(f)}{\vec{E}_{y,ref}(f)}\right]$$

Electric Field Frequency Response - The measured electric field strength frequency response of the GTEM. The frequency response is measured with the input voltage to the GTEM! held constant over the frequency range to be measured. The voltage is chosen to develop an arbitrarily selected electric field strength value at an arbitrarily selected reference frequency. The electric field strength value is determined at the center of the test volume by taking the ratio of the RF voltage on the septum to the height of the septum where the electric field strength estimate is required. The electric field response shall be reported as a fractional difference from the reference level.

$$E(f) \equiv \frac{\left|\vec{E}_y(f_{ref})\right| - \left|\vec{E}_y(f)\right|}{\left|\vec{E}_y(f_{ref})\right|}$$

Example Field Uniformity

The electric field uniformity of a Model 5317 as measured to IEC 801-3 requirements is shown in Figure 19. These data were taken with the Automated Radiated Immunity software using the precalibration function for a reference position and run precalibrated test for all other positions. Data were taken over a reduced dimension plane in the GTEM!, of 0.75 by 0.75 m,. at a total of nine positions. In accord with the requirements of IEC 801-3 one data point was discarded at one frequency and two data points were discarded at a second frequency. Nowhere were any points discarded in excess of the 25 % criteria of IEC 801-3. As can be seen in Figure, 19, the actual performance is less than the - 0 dB, + 6 dB requirement.

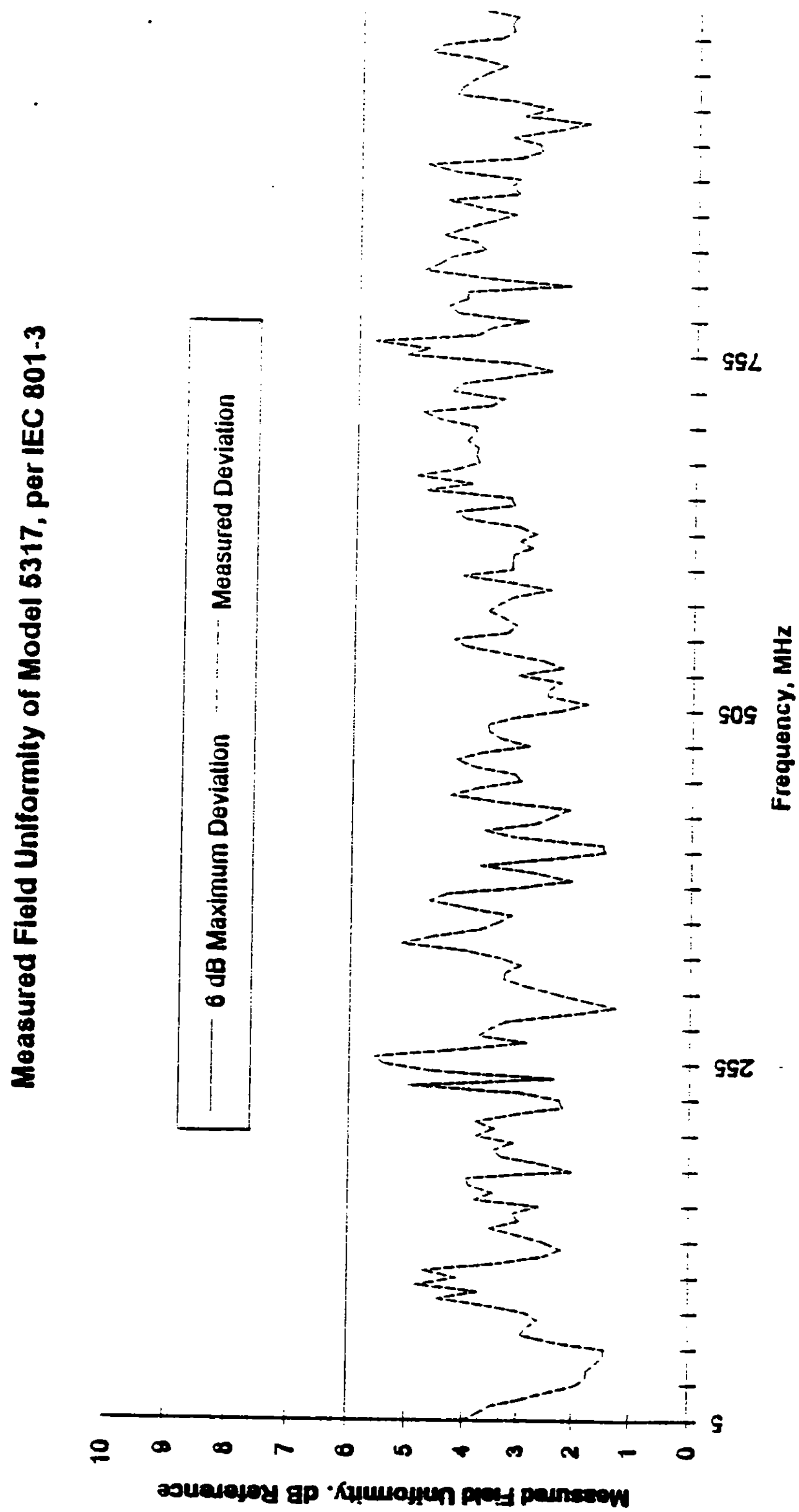


Figure 19 Electric Field Uniformity of a Model 5317, per IEC 801-3

Emissions Testing Characterization

The radiated emissions comparison of a GTEM! measurement to an OATS Measurement is reported in detail in Appendix C. Another comparison is shown here to place all measured data in one place for easy comparison.

Example Comparison

Figure 20 shows a graphical representation of a tuned resonant dipole comparison between a GTEM! Model 5317 and an OATS. There are three plots in the Figure, each of the Measured E-field values and their difference. If these measurements are examined statistically, the mean difference of the readings over frequency is +1.79 dB with the GTEM! measuring higher values than the OATS. The standard deviation of the measurements is 1.2 dB.

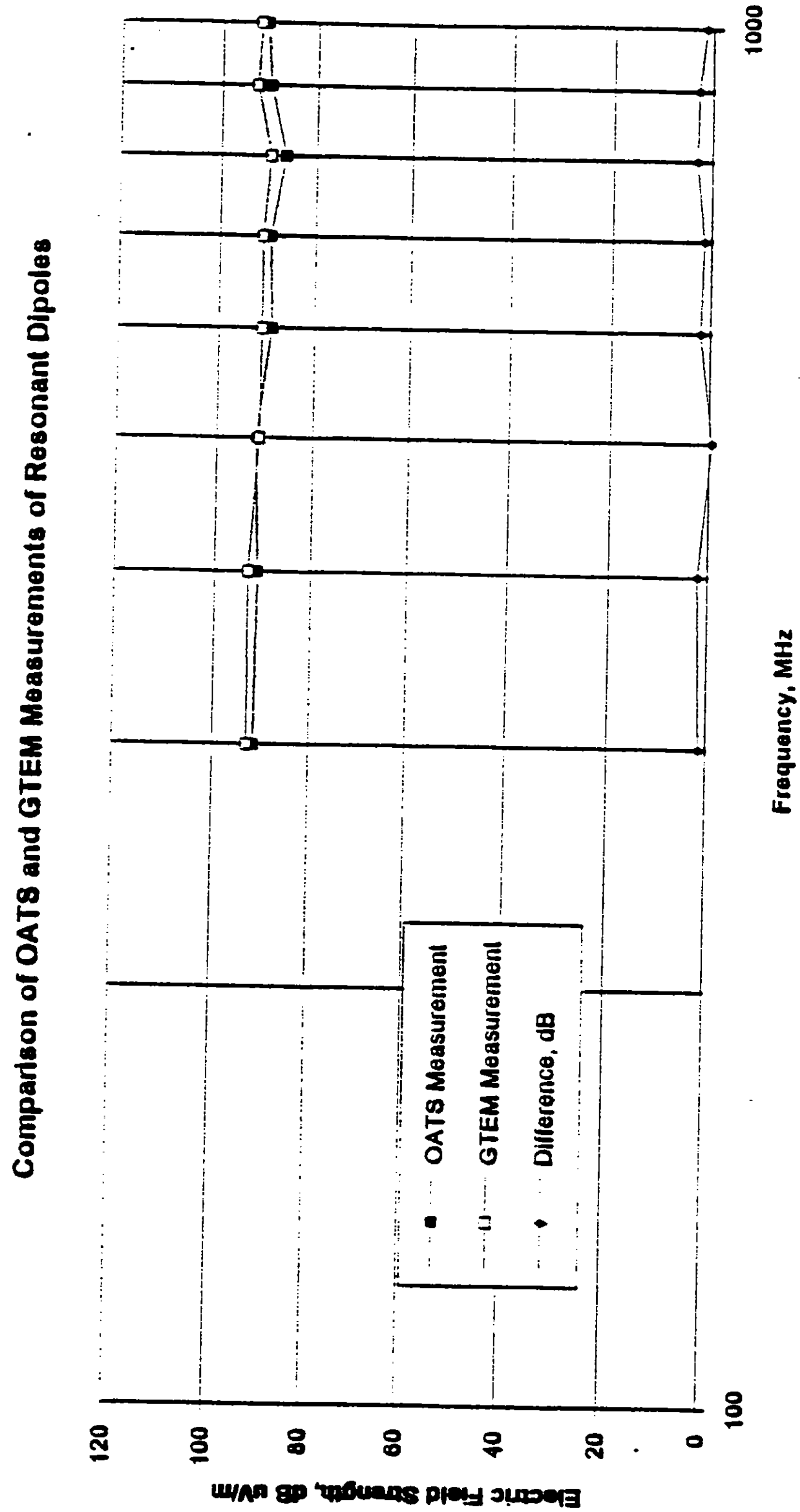


Figure 20 Comparison of OATS and GTEM Measurements of a Resonant Dipole

USE OF A GTEM!

The intended use of the GTEM! is radiated immunity testing and radiated emissions testing. The following sections on GTEM! usage provide a general overview of these uses. Note that the user must plan and implement the testing of all devices as thoroughly as in any other facility to assure repeatable results.

Radiated Immunity Testing

Radiated immunity testing is conducted to ascertain if the equipment under test (EUT) will respond to radiated energy in the electromagnetic ambient in a deleterious manner. The GTEM! provides an ideal facility for the accomplishment of such tests in a laboratory environment.

Immunity (susceptibility) testing is straightforward, and driving the GTEM! is simple. All that must be done is to connect the output of the 50-ohm power amplifier to the input of the GTEM!. The standard RF power handling capability of the larger GTEM!'s is in excess of 1 kW. Greater power handling capabilities are possible if modified load boards are ordered. Field intensities in excess of 200 V/m can be generated, if adequate power is available. The GTEM! can simultaneously dissipate 1 kW of EUT power, with the 1 kW (standard rating) of RF power.

Estimation of RF Input Power Required for a Given Field Strength

The determination of the power required for obtaining a given field strength is easy.

Beginning from basics, the estimated field strength halfway between the septum and the floor of the GTEM! is given by the ratio of the RF voltage on the septum to the spacing of the septum above the floor of the GTEM!, or:

$$E \text{ (Volts/metre)} = V \text{ (Volts)} / h \text{ (metres)}$$

In addition the RF voltage on the septum is a function of the power drive available, from:

$$P_{in} \text{ (Watts)} = V^2 \text{ (Volts}^2\text{)} / Z_0 \text{ (Ohms)}$$

where :

$$P_{in} = \text{Input RF Power (Watts)}$$

V = RF Voltage on the Septum at height h

Z_0 = Characteristic Impedance of the GTEM! = 50 Ohms

For a simple solution(s):

$$E = (1/h)\,(P \times Z_0)^{1/2}$$

and:

$$P = (E\,h)^2 / Z_0.$$

Completing the determination of required input power is accomodating for the input VSWR of the GTEM. All GTEM! devices have an input VSWR of less than 1.2:1. At a value of 1.2:1, approxamately 8 % of the input power is reflected. The estimated RF power from the above calculations should be increased by at least 8 % to assure that the desired field values can be generated.

The expressions in the above two equations can be used for first order estimates of field strength given power or power required given field strength.

The absence of shielded enclosure resonances and reflections, and removal of high power handling antennas from the test setup allows precise application of test signal levels.

Figure 21 shows a typical setup for the conduct of radiated immunity testing using manual control techniques. A signal generator is shown with an external modulation source so that the modulation characteristics can be matched, if desired, to signals internal to the Equipment Under Test. The output of the signal generator is applied to a RF power amplifier, which in turn drives the GTEM!. Application of the signal to the GTEM! input produces the test signal between the septum and the floor of the GTEM!. Internal to the GTEM!, an optional broad band, high level isotropic probe monitors the level of the applied signal. One to eight probes with individual metering units may be used to sense the applied field at different locations and present actual electric field

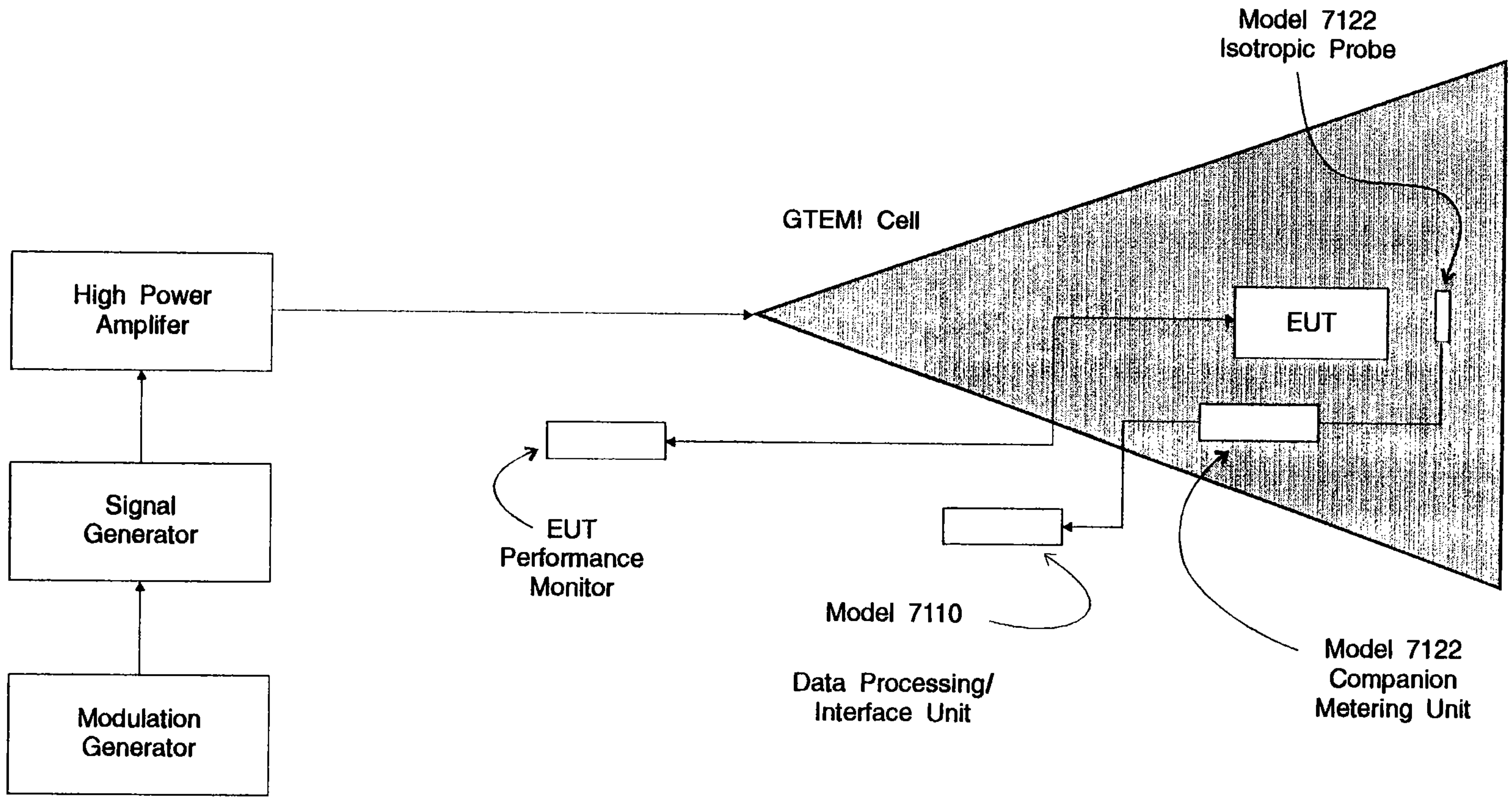


Figure 21. Manually Controlled Radiated Immunity Test Setup

strength values to the Processing Interface Unit. Field strength value(s) are displayed by the Processing Interface Unit.

The EUT is installed in the GTEM! in the approximate center of the test volume. Monitoring of EUT performance is via a cable to externally located monitor unit. Typical precautions, such as are used in a shielded enclosure with EUT performance monitors, must be taken. An example would be grounding the shield of the cable to the performance monitor to the bottom of the GTEM! Once the setup is complete, the signal generator is tuned over the test frequency range while monitoring the performance of the EUT for response to the applied test signal. The levels of the test signal are adjusted by controlling the signal generator output while monitoring for the minimum field level at the location of the isotropic probes.

The linear nature of the GTEM!, and not having to change antennas, allows automation of EMC testing to a degree not previously possible. An example block diagram for automated immunity testing is shown in Fig. 22. This setup is very similar to the manual test. All that has been added is the controlling computer and the GPIB controlling bus. Testing can be completely automated if it is possible to define test signal response from the EUT that can be sensed by the controlling computer. The GPIB is chosen as the control bus for the system to match that presently available in many EMC test laboratories. Testing proceeds as described above except for the automation of the testing.

Note that the electric field strength and the sweep speeds are often set by the test requirements document(s). Care should be taken to not exceed specified sweep speeds. An additional factor is that, with the availability of automated testing, it is possible to sweep at the specification required speed without consideration of the performance of the EUT. If the EUT must be stepped through a number of modes at "each frequency" then even slower sweep speeds may be needed.

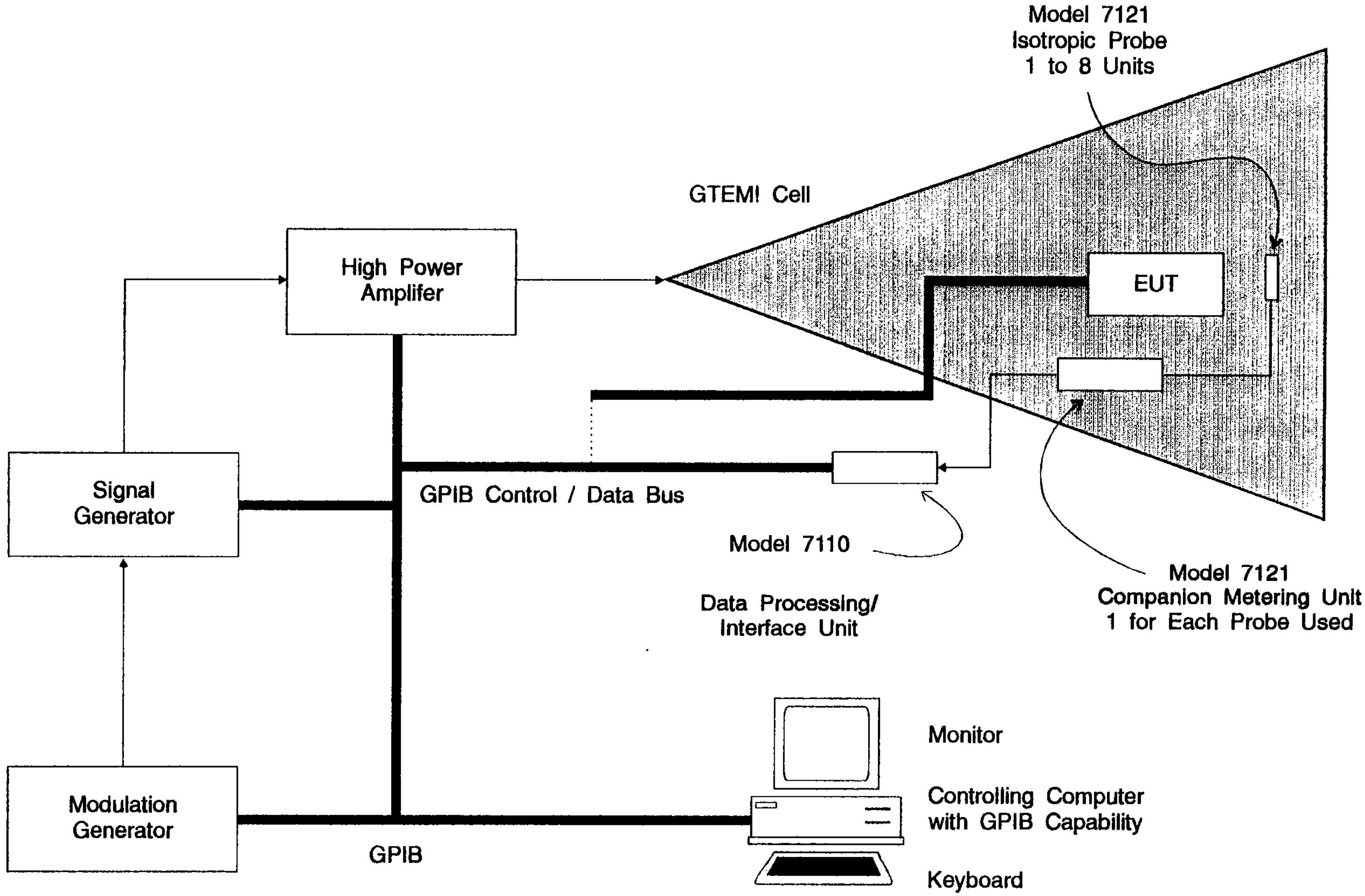


Figure 22. Automatically Controlled Radiated Immunity Test Setup

Radiated Emissions Testing - General

In addition to immunity testing, the GTEM! may also be used for radiated emissions testing. An item placed under the septum in the test volume can be evaluated for radiated emissions as easily and as simply as the immunity test is accomplished. By the Theory of Reciprocity, if the application of a RF voltage generates a field, then the introduction of a device that generates a field in the volume under the septum will produce a RF voltage at the connector. The voltage produced will be proportional to the intensity of the radiated field.

Only recently has the use of the GTEM!, as an alternative to radiated emissions measurements on an OATS, been seen as a practical choice. This change has been brought about by additional developments in the theory of this device, such that a direct comparison can be made to the results obtained from an OATS. The main contribution that has brought the GTEM! forward as a practical radiated emissions device has been in the theoretical development of a mathematical model allowing the direct comparison of data taken in a GTEM! to data acquired on an OATS.

The voltages appearing at the connector of the GTEM! produced by radiated emissions from the EUT at each of three orthogonal axes are measured. Then, at each frequency, an equivalent set of monopole antennas that would produce the same voltages at the GTEM! connector are defined via computer computation. Once these equivalent antennas are defined, the field intensities for comparison to the given specification limit are computed from the set of equivalent dipoles at each frequency, given the separation and geometry of the test setup.

Radiated Emissions Measurements

Hardware Requirement - Measurement of radiated emissions requires the use of a frequency selective microvolt meter (EMI Meter). For manual use, any calibrated receiver typically used for EMC measurements is acceptable so long as the measurement specification requirements for the measurement device are met.

EUT Orientation for Testing - Proper orientation of the EUT in three orthogonal axes is necessary for the accurate conduct of radiated emissions measurements. The method of performance of the rotations necessary to achieve the proper orientations requires an explanation of the definition of the three primary axes of the GTEM!, and the EUT, and a description of how the three rotations are to be accomplished. The development of the theory of the mathematical model for the correlation to an Open Area Test Site and the need of the three orthogonal rotations is described in Appendix A, *Theory of GTEM! Correlation*.

The three reference orthogonal axes of the GTEM! are shown in Figure 23. The positive **Z** axis is to the feed, the positive **Y** axis is up, and the positive **X** axis is toward the right of the cell as seen from the apex. Note that this is a positive right-handed rectangular coordinate system, *i. e.* **X** rotated into **Y**, in a **right handed** sense, gives a positive **Z**. In this discussion the primary reference axes of the GTEM! will be denoted by capitol letters **X, Y, Z.**

The three reference orthogonal axes for the EUT are shown in Figure 24. As shown, they align with the GTEM! axes. They are also right-handed, and are denoted as **x, y, z.**

The mathematical formulation of the GTEM! model for determining the OATS equivalent value of radiated emissions requires three measurements of voltage produced by the EUT, in three orthogonal axes. The rule for the rotation is that the three positions must have the axes replace the previous axes as follows:

Position 1	GTEM! axes	**X Y Z**
	EUT axes	**x y z**
Position 2	GTEM! axes	**X Y Z**
	EUT axes	**y z x**
Position 3	GTEM axes	**X Y Z**
	EUT axes	**z x y**

In position 1, the EUT axes are aligned with the GTEM! axes, that is the axes coincide, as shown in Figure 25. In this Figure, the EUT array, a PC system installed on a plywood panel per the requirements of ANSI 63.4-199-2, is shown with the **x, y, z** EUT axes aligned with the **X, Y, Z** GTEM! axes.

Figure 26 shows this same alignment as seen from the apex of the GTEM!. Note that the EUT and GTEM! axes are shown in alignment at the top, right sides and bottom of the Figure. At the bottom of the Figure

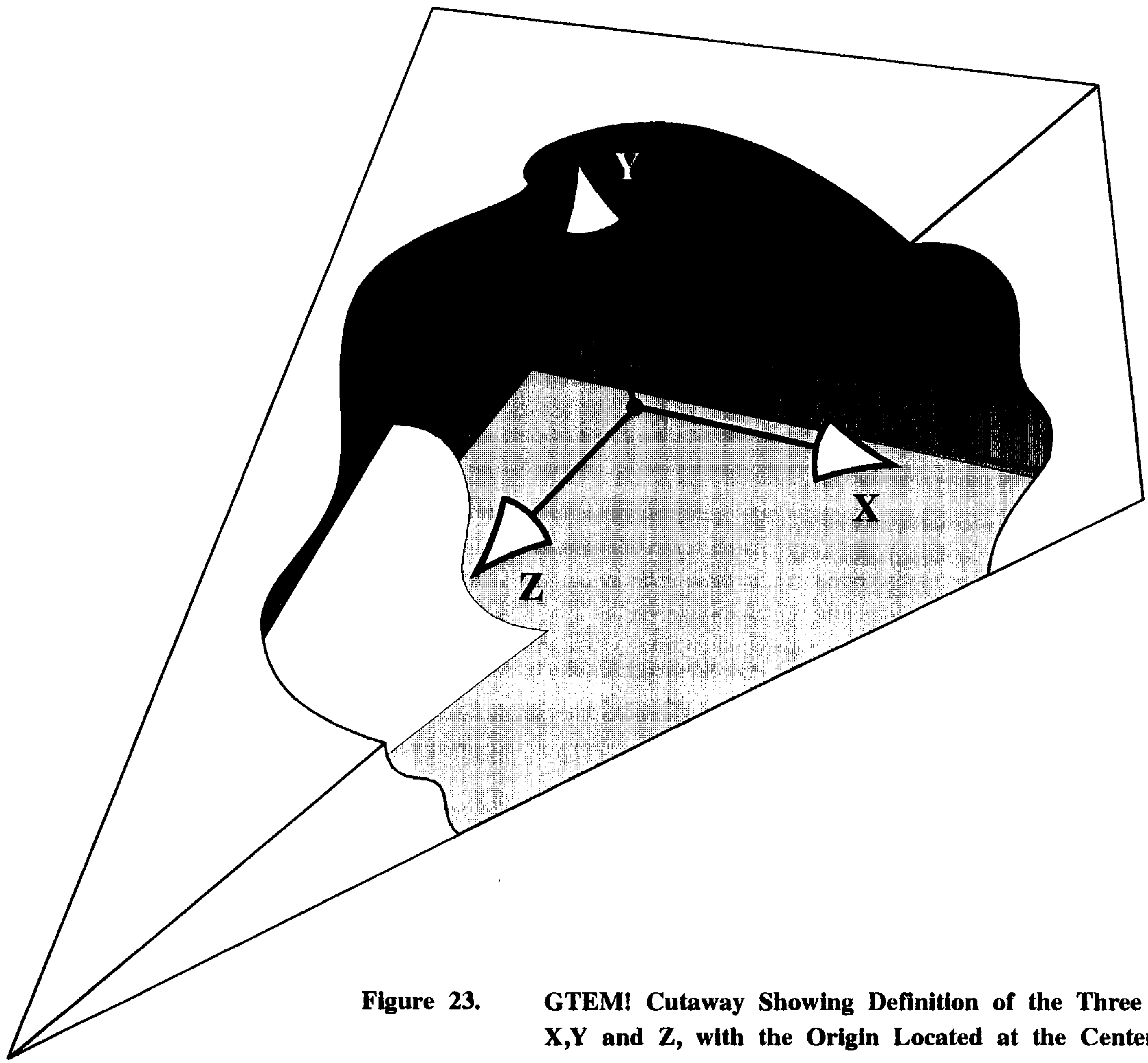


Figure 23. GTEM! Cutaway Showing Definition of the Three GTEM! Axes X,Y and Z, with the Origin Located at the Center of the Test Volume

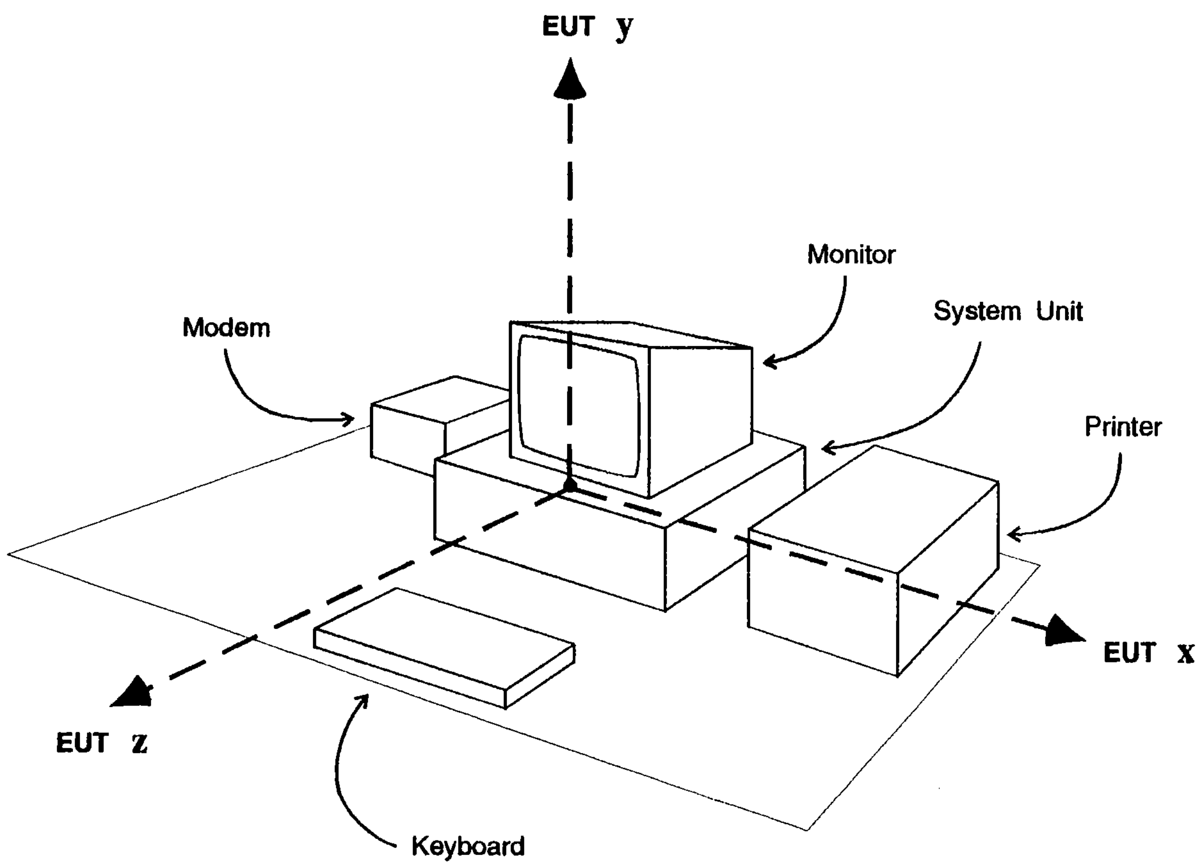


Figure 24. **Example of Equipment under Test (EUT) System, installed per ANSI 63.4-1992 on Reference Board, Defining EUT Axes**

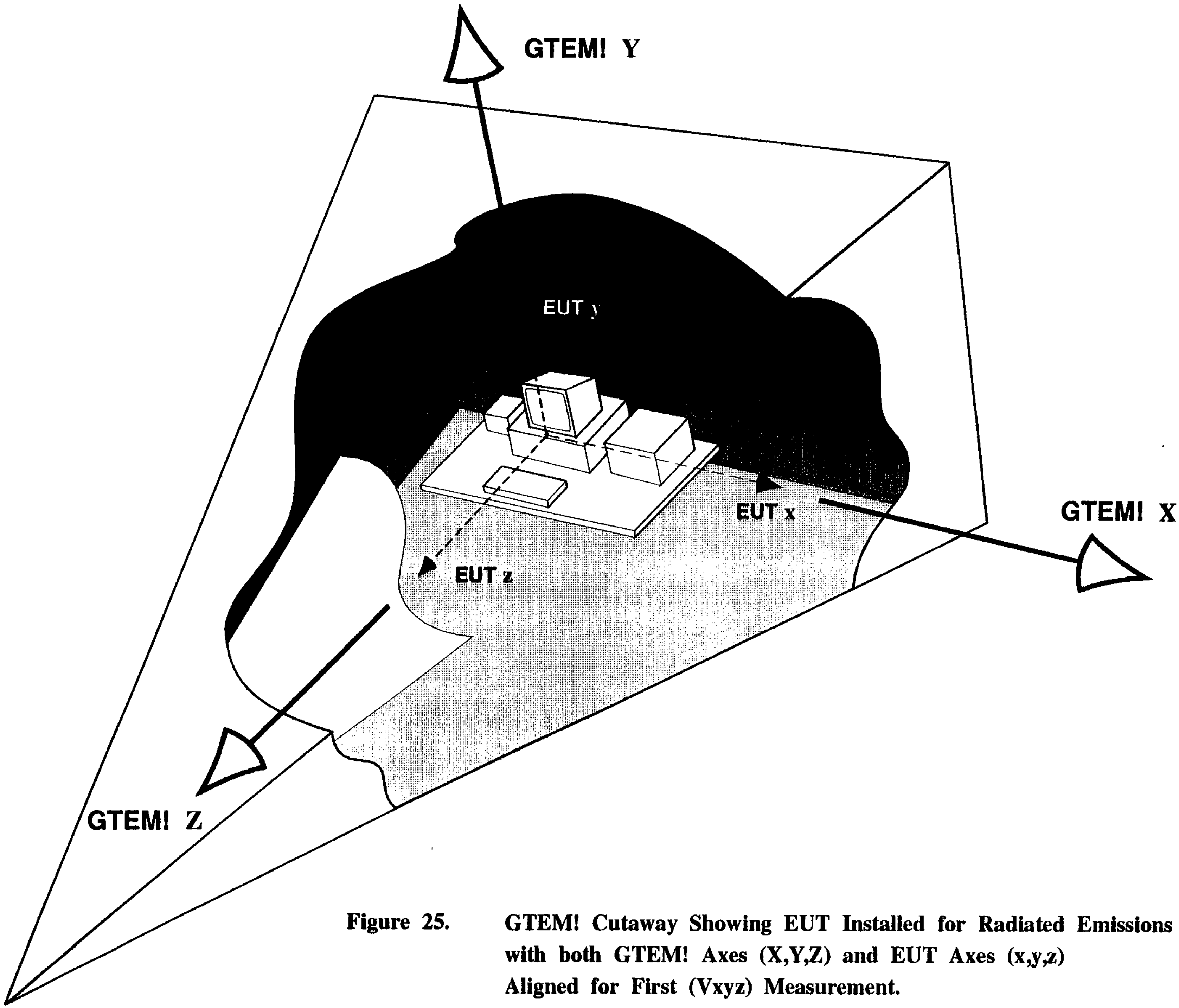


Figure 25. GTEM! Cutaway Showing EUT Installed for Radiated Emissions with both GTEM! Axes (X,Y,Z) and EUT Axes (x,y,z) Aligned for First (Vxyz) Measurement.

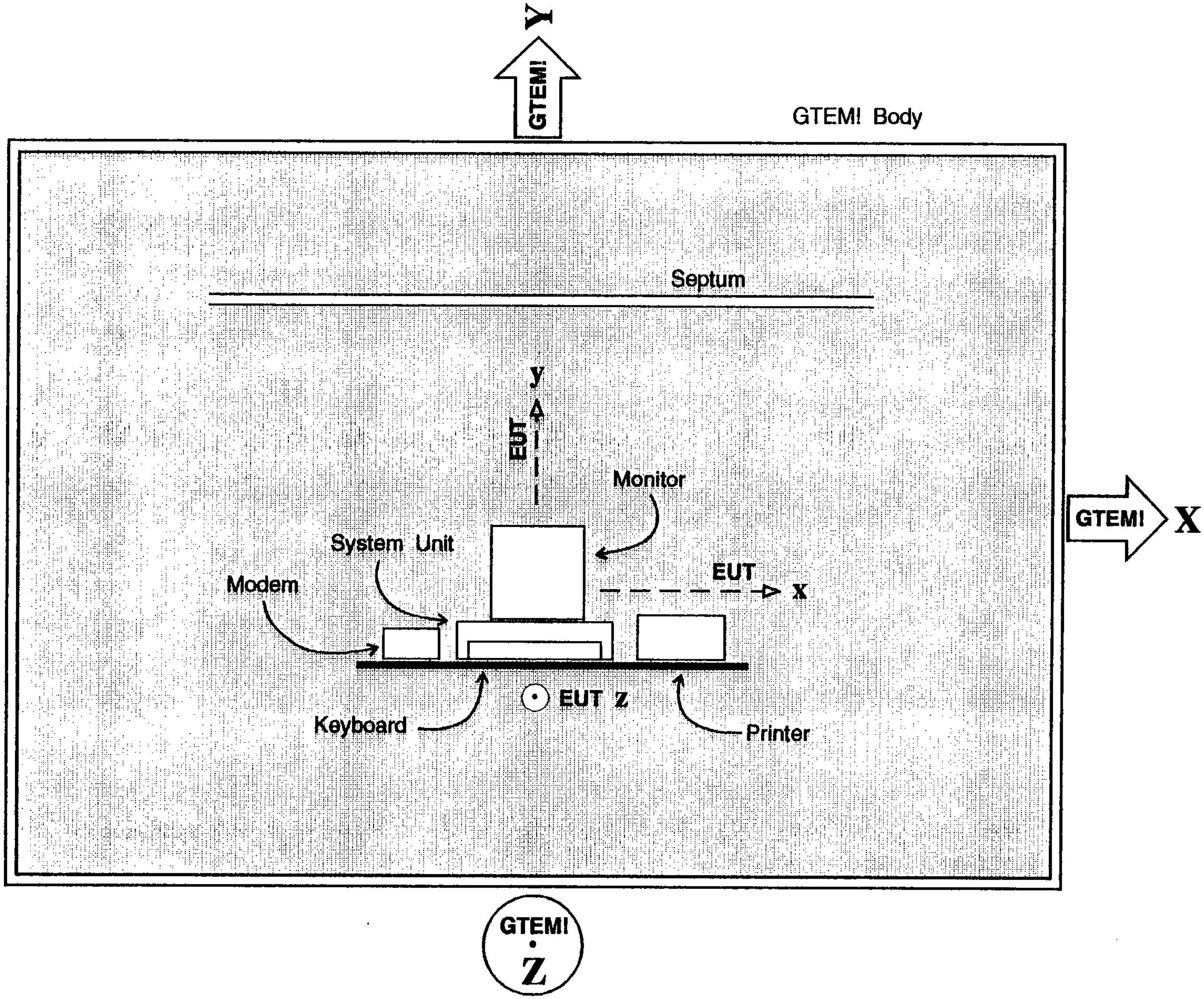


Figure 26. **View of EUT System Installed in GTEM! (as seen from apex) with GTEM! (X,Y,Z) and EUT (x,y,z) Axes Aligned for 1st Measurement, V_{xyz}**

the circle with the dot at the center is to be understood as the point of the arrowhead pointing out of the page.

In position 2, the EUT has been rotated in a manner such that the **y** axis aligns with the **X** axis, the **z** axis aligns with the **Y** axis and the **x** axis aligns with the **Z** axis.

Figure 27 shows this orientation as seen from the same point of view as the previous figure. Again, the Figure shows the alignment of the GTEM! and EUT axes for this rotational position.

In position 3, the EUT has been rotated in a manner such that the **z** axis aligns with the **X** axis, the **x** axis aligns with the **Y** axis and the **y** axis aligns with the **Z** axis. Figure 28 shows the third position, again as seen from the apex of the cell.

Measurement Procedure - The following general procedure should be used to perform radiated emissions measurements in a GTEM! This procedure is written for manually performed measurements.

1. Install the EUT in the center of the test volume of the GTEM! with a reference orientation, as shown in Figure 26 and as described above for the first position.

2. Measure the RF voltages emanating from the EUT as a function of frequency over the desired frequency range. Depending on the measurement device used, either peak, quasipeak or average measurements may be made. These measurements are collectively referred to as V_{xyz} vs frequency.

3. Rotate the EUT through two successive 90^{o} right hand rotations, such that the **x** axis is replaced by the **y** axis, etc., as shown in Figure 27.

4. Measure the RF voltages emanating from the EUT as a function of frequency over the desired frequency range. Depending on the measurement device used, either peak, quasi peak or average measurements may be made. Note that if peak , quasi peak and average measurements were made for any signal on the previous axis they should be repeated at the same frequency on the second axis to assure that complete data set has been obtained. If new signals are

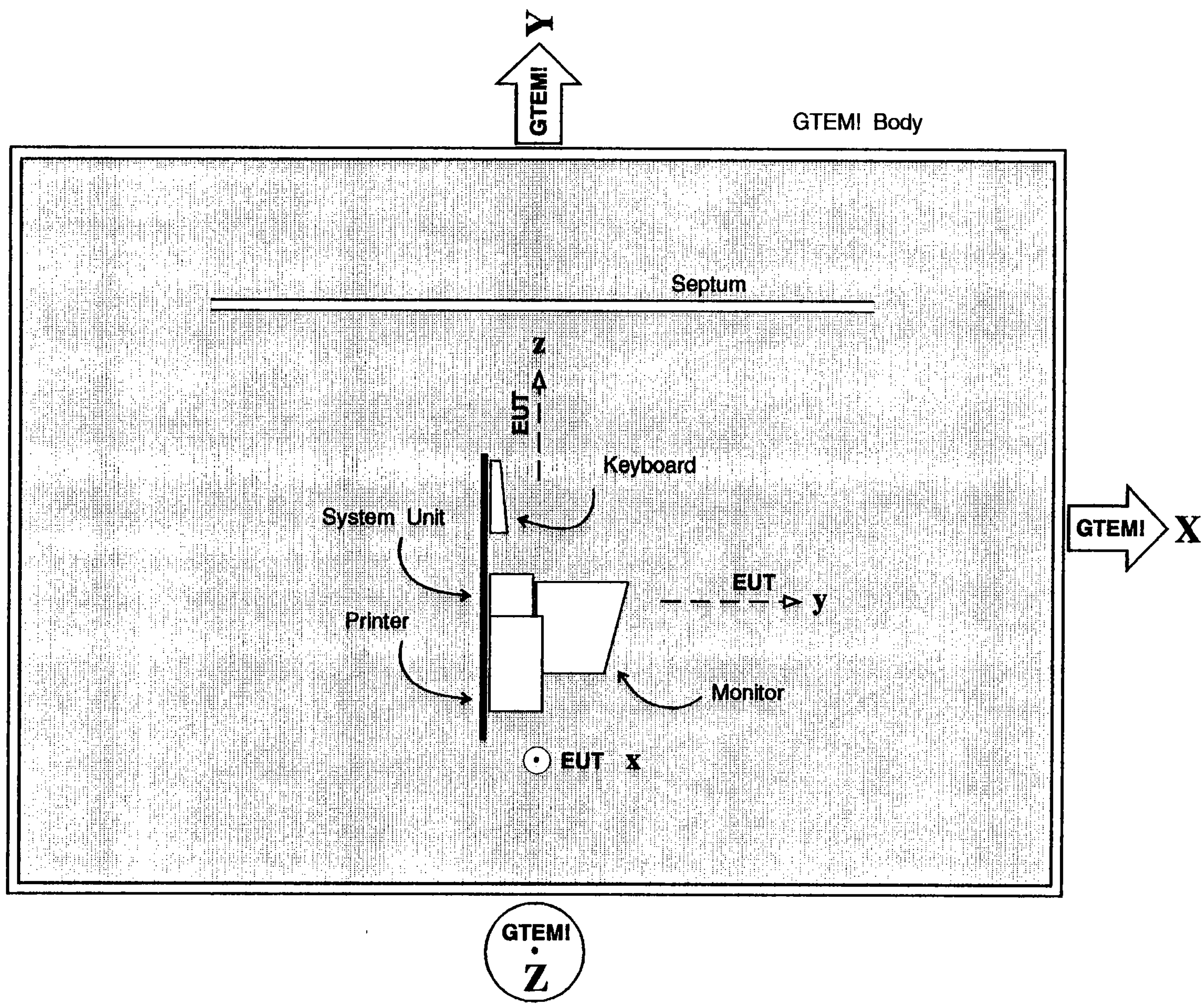


Figure 27. View of EUT System Installed in GTEM! (as seen from apex) with GTEM! (X,Y,Z) and EUT (x,y,z) Axes Aligned for 2nd Measurement, V_{yzx}

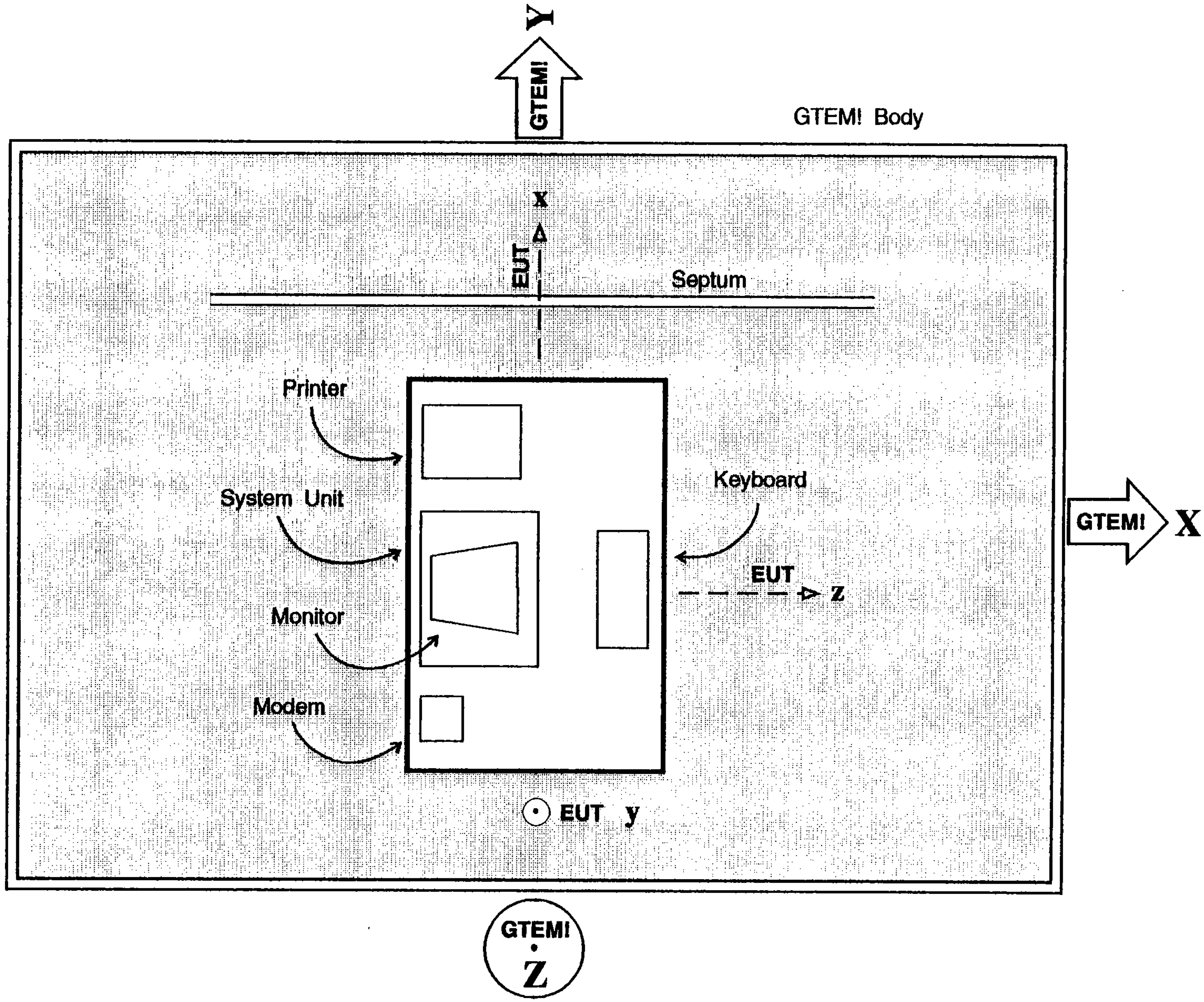


Figure 28. View of EUT System Installed in GTEM! (as seen from apex) with GTEM! (X,Y,Z) and EUT (x,y,z) Axes Aligned for 2nd Measurement, V_{zxy}

identified on this axis where measurements were not made on the previous axis, the previous axis must be repeated to complete the set of data for the correlation. These measurements are referred to as V_{yzx} vs frequency.

5. Rotate the EUT through two additional successive 90^o right hand rotations, such that the **y** axis is replaced by the **z** axis, etc., as shown in Figure 28.

6. Measure the RF voltages emanating from the EUT as a function of frequency over the desired frequency range. Depending on the measurement device used, either peak, quasi peak or average measurements may be made. Note that if peak , quasi peak and average measurements were made for any signal on the previous two axis they should be repeated at the same frequency on the third axis to assure that complete data set has been obtained. These measurements are referred to as V_{zxy} vs frequency.

At the completion of these measurements, the tester should have a matrix of measurements that consists of a frequency and three associated RF voltage measurements all made with the same detector function. Note that if a signal was found on the second or third axis measurement, that was not found on the first axis measurement, that measurement would have to be repeated on the other axes to assure a complete data set, i. e. that no measurable directional component of the signal was missed. A value for the noise measured at a given frequency where signal components were measured may be necessary to complete the measurement set.

Appendix B, *Practical Measurement Tips*, describes the accuracy of the measurement as a function of the emission levels measured.

A software program is furnished with the GTEM! that performs the correlation computations for the data taken as described above. This software must be used as the computations are too complex to be performed by hand in any reasonable amount of time.

Software Computations - The software implementation for the GTEM! accomplishes the following, given three voltage versus frequency measurements V_{xyz}, V_{yzx} and V_{zxy} for three orthogonal orientations of the equipment under test (EUT) in the GTEM!

At each frequency:

- Performs a root sum of the squares summation of the three orthogonal voltages,
- Computes the total power emitted by the EUT as determined from the summation of the three voltages and the TEM mode equations for the GTEM!,
- Computes the current excitation of an equivalent tuned, half wave Hertzian dipole when excited with that input power,
- Computes the field intensity at appropriate height intervals over the total, operator selected scan height, either 1 to 4 metres or 2 to 6 metres for both vertical and horizontal polarizations of the receive antenna when the equivalent tuned resonant dipole is placed at an appropriate height over a perfect ground plane,
- Selects the maximum field strength (larger) value of the horizontal or vertical polarizations,
- Presents this maximum value for comparison to the chosen EMC specification limit.

The voltages appearing at the connector of the GTEM! produced by radiated emissions from the EUT at each of three orthogonal axes are measured, then at each frequency, an equivalent set of fixed dipole antennas that would produce the same voltages at the GTEM! connector are defined via computer computation. Once these equivalent antennas are defined, the field intensities for comparison to the given specification limit are computed from the set of equivalent dipoles at each frequency, given the separation and geometry of the test setup.

The accuracy of the measurement is of prime importance. A report on the relative accuracy of the GTEM! for radiated emissions measurements is given in Appendix C, *Radiated Emissions Test Performance of the GHz TEM (GTEM!) Cell.*

MAINTENANCE

Periodic maintenance will assure the continued performance of the GTEM! There are several areas to be considered.

Periodic Performance Monitoring

VSWR measurements are performed at the conclusion of installation procedures for the Model 5311 and 5317. They are also performed at the factory for all GTEM!s. A satisfactory VSWR measurement is necessary before any GTEM! can be shipped. Determination of continued performance to specified parameters may be assured by periodic measurement of the VSWR. Periodic VSWR measurement will detect any change in performance parameters that would signal unacceptable performance. The VSWR measurement should be performed on a schedule as recommended by the customer's Quality Engineering. The default time period between such evaluations (this is not a calibration) would be six months.

Periodic Owner / Operator Maintenance Items

Finger Stock - There is a large amount of finger stock used in the construction of the GTEM! Some of this finger stock is accessible in the normal course of GTEM! operation. Periodic visual inspections should be made to determine if there is need to clean the finger stock or if damaged replace it. Replacement finger stock for the doors is available from the factory (PN:890XXX). Replacement finger stock for the connector panels and the load board access panels is also available (PN:890258). Finger Stock may be cleaned by using an aerosol lubricant such as WD-40 to loosen the debris and then low pressure air or another aerosol to remove excess lubricant.

CAUTION:	Working with finger stock in cleaning should be done with care. There are numerous sharp edges on the finger stock material and a cautious approach is needed to assure safe completion of the task.

Air Vents - The air vents on the Model 5311 and 5317 GTEM!s should be checked to be sure that there is free airflow to assure optimum cooling. A small soft brush may be used to clean the honeycomb.

Floor Panels - The connector feed through panels in the floor of the GTEM!s will attract small particles of dirt or other debris. Inspection of their continuity on a periodic basis is necessary to assure continued shielding. To inspect for an accumulation of dirt, the panels should be removed and the opening and the flange should be inspected and any accumulated dirt or debris removed. The finger stock should be inspected at this time, and cleanse or replaced if required (PN: 890258).

Connectors - The RF and other connectors are somewhat delicate in their floor mounted position. Periodic examination of these connectors for damage should prevent use of a connector with damaged pins or other connections, assuring proper operation of the connectors. During use, care should be taken to protect these connectors if they are not in use.

Absorber Tips - The RF absorber tips are fragile and are easily broken off. They may be easily replaced with almost any contact cement or with rapid curing epoxy cement. If the tips are too damaged to reuse, they may be replaced by cutting off the entire tip at a point where the absorber body is about 10 cm by 10 cm and replacing the entire tip. Extra absorbers are available from the factory (PN: 920080). Replacement of an entire absorber block by an owner is not possible. If this is required, please contact the factory. Absorber tip protectors are installed for GTEM!s where personnel access inside a GTEM is expected. These tip protectors are cut from block expanded polystyrene. They will protect the tips from casual contact. Extra or replacement tip protectors are available from the factory (P/N:870071).

Shielded Viewing Windows - The shielded viewing windows (if the GTEM! is so equipped) are fabricated from an acrylic plastic material. Cleaning may be accomplished with a plastic cleaner such as Novus Plastic polish.

CAUTION!	Do not use petroleum products, abrasives or solvents, as damage to the acrylic material could result.

GTEM! Cleaning - Overall cleaning of the GTEM! stainless steel surfaces may be accomplished by the use of standard non-abrasive cleaners. Periodic cleaning of the interior with a vacuum cleaner will reduce the possibility of debris build-up in the connector panel area.

CAUTION!	Care in cleaning in the vicinity of the RF absorbers will preclude damage to their tips.

Load Boards - Load Boards should not require periodic maintenance other than periodic inspection and cleaning of contact surfaces, to prevent the occurrence of any film or corrosion. Any foreign substance that is found on the boards or connector surfaces should be removed

Other Maintenance - Other maintenance on the GTEM! is not required. Factory engineering personnel should be consulted in the event of damage or failure to operate properly after maintenance procedures.

No Scheduled Factory Maintenance Required - There is no scheduled factory maintenance required.

In Case of Damage - If severe damage occurs to a GTEM!, please contact the factory for guidance. Please have ready a description of the nature and scope of the damage.

GTEM! Options

There are many optional features for a device such as the GTEM! This section describes those that can be obtained and installed by the purchaser. Additional options are available through factory installed options. The options discussed in this section are available for customer installation. Please contact the factory for details.

Standard Options

A number of optional features are available for the GTEM! An incomplete list is shown here, as standard options that are available as original order options or field installable upgrades.

Pulse Feed Section - A change of the feed section will allow the application of pulsed signals of extremely brief duration and extremely high amplitude. This makes the GTEM! a practical selection for the conduct of lightning and NEMP testing, given appropriate signal generation capabilities.

Pulse feeds must be designed to interface with customer supplied signal generators. Contact the factory for details..

Additional Blank Feed Thru Panel - Additional 304 mm square blank, removable panels (PN: 15346) are available to replace any panels furnished with the unit to accommodate additional cable entries to the GTEM!. These are interchangeable with the panels furnished with the GTEM! In addition, blank panels are available for the bottom mounted access plate for the Model 5302.

Operational Software - In addition to the Manual Correlation Software that is furnished with the GTEM!, optional, fully automated measurement software is available to allow rapid, automated measurements of emissions or immunity of the EUT.

<u>Radiated Emissions Software</u> - EMCO offers an optional Microsoft Windows 3.X™ based radiated emissions measurement software package which will run on an IBM PC-AT or equivalent. This package requires a National Instruments AT-GPIB card with a driver package compatible with Microsoft Windows 3.0™. The package is furnished with Microsoft Windows 3.X™ (PN: 15349).

Radiated Immunity Software - EMCO offers an optional Microsoft Windows 3.X™ based radiated immunity measurement software package which will run on an IBM PC-AT or equivalent. This package requires a National Instruments AT-GPIB card with a National Instruments driver package compatible with MicrosoftWindows 3.0™. The package is furnished with Microsoft Windows 3.X™ (PN: 15350).

Higher Power Ratings - The standard power ratings for any sized GTEM can be increased by modifications to the load boards and increasing the air flow through the GTEM! These changes are customer installable and available by special order.

Internal EUT Manipulator - A multi position EUT manipulator is available for the GTEM! to position the EUT for completely automated radiated emissions testing.

Turntable - A turntable is available for installation in the GTEM!

Custom Signal Filters - For users with unique signal input and output requirements, custom designed filters are available mounted to penetration panels.

Custom Power Filters - For additional EUT power input requirements, a number of single and three phase input power filters are available to provide almost any input power requirement to EUT in a GTEM! These power inputs are independently switched, *i.e.*, they are not controlled via the main power switch on the Power Distribution Panels.

High Visibility Windows - When immunity testing a visual display device, high clarity shield windows are available for the GTEM! These high visibility windows allow undistorted viewing of the EUT and can be used for visual or video monitoring of the EUT. They provide a minimum of 90 dB shielding in contrast to the 100 dB of the normal window.

Non-Standard Options

It is recognized that every application for a GTEM! in EMC testing will be unique, or may have unique requirements. If there is a modification to the GTEM! that will accelerate test performance, contact the factory. Most of the standard options listed above are field installable and can retrofitted after delivery.

FACTORY SUPPORT

The equipment described in this manual is straightforward in use, and should require little support. In the event that you have questions or require additional information, contact the Electro-Mechanics Company in Austin, Texas, USA at:

In the USA:	(800) 253-3761	Phone
	(512) 835-4729	FAX
International:	USA + (512) 835-4684	Phone
	USA + (512) 835-4729	FAX

WARRANTY

The Electro-Mechanics Company (EMCO) warrants that our GTEM! will be free of defects in materials and workmanship from a period of two years from the date of first use following installation and acceptance. If you notify us of a defect within the warranty period, we will, at our option, either repair or replace the defective portion.

There will be no charge for warranty services performed at the location we designate. You must, however, prepay inbound shipping costs and any duties or taxes. We will pay outbound shipping costs for a carrier of our choice, exclusive of any duties or taxes. You may request warranty services to be performed at your location, but it is our option to do so. If we determine that warranty service can only be performed at your location, you will not be charged for our travel related costs.

This warranty does not apply to;

1. Normal wear and tear of materials.
2. Consumable items such as fuses, resistors, lights, etc.
3. Anechoic and finger stock material (limited to the warranty supplied by the original manufacturer).
4. Software (warranted separately).
5. Damage caused by improper use and maintenance.
6. Operation outside of specifications.
7. Modification without written authorization.

THIS WARRANTY IS EXCLUSIVE. NO OTHER WARRANTY, WRITTEN OR ORAL, IS EXPRESSED OR IMPLIED, INCLUDING BUT NOT LIMITED TO, THE IMPLIED WARRANTY OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE.

THE REMEDIES PROVIDED BY THIS WARRANTY ARE YOUR SOLE AND EXCLUSIVE REMEDIES. IN NO EVENT ARE WE LIABLE FOR ANY DAMAGES WHATSOEVER, INCLUDING BUT NOT LIMITED TO DIRECT, INDIRECT, SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES WHETHER BASED ON CONTRACT, TORT, OR OTHER LEGAL THEORY.

Please contact our offices regarding any questions you may have regarding use and maintenance.

Please contact our offices, Sales Department, for a Return Material Authorization Number before shipping equipment for repair. Failure to do so could cause delay.

Appendix A

Theory of GTEM! Correlation

by

Dr. Perry F. Wilson

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Baden, Switzerland

6. Theory of GTEM Correlation by Dr. P.F.Wilson

6.1 Multi-Pole Radiation in Free Space and over a Ground Screen

A radiation source (DUT) in free space is depicted in figure A1. A spherical coordinate system (r, θ, φ) is centered at the source. Observation points will be designated by the vector $\bar{r}$ Source points will be designated $\bar{r}'$. We will restrict our attention to the far-field zone where $|\bar{r} - \bar{r}'| \approx r - \hat{r} \cdot \bar{r}'$, $r = |\bar{r}|$, and ^ denotes a unit vector. This both simplifies the analysis and represents the primary case of interest.

The electric $\bar{E}(\bar{r})$ and magnetic $\bar{H}(\bar{r})$ fields due to a current density $\bar{J}(\bar{r}')$ distributed over a volume V may be determined from the usual vector potential formulation;

$$\bar{A}(\bar{r}) = \frac{\mu_0}{4\pi} \int_V \bar{J}(\bar{r}') \frac{e^{-jk_0|\bar{r}-\bar{r}'|}}{|\bar{r} - \bar{r}'|} dv',$$
$$j\omega\varepsilon_0 \bar{E}(\bar{r}) = \nabla x \bar{H}(\bar{r}), \text{ and}$$
$$\mu_0 \bar{H}(\bar{r}) = \nabla x \bar{A}(\bar{r}), \tag{A.1}$$

where ε_0 and μ_0 are the free space permittivity and permeability, k_0 is the free space wave number, and an $\exp(j\omega t)$ time convention is assumed. In the far-zone, the exponent may be approximated as described above and the source to observation point distance in the denominator replaced by r. Thus,

$$\bar{A}(\bar{r}) \approx \frac{\mu_0}{4\pi} f(r) \int_V \bar{J}(\bar{r}') e^{jk_0 \hat{r}\cdot\bar{r}'} dv', \text{ where}$$
$$f(r) = \frac{e^{-jk_0 r}}{r}. \tag{A.2}$$

If the current source is electrically small, then the exponential in the integral may be expanded in a Taylor series about $k_0\hat{r} \cdot \bar{r}'$ Retaining only the leading two terms yields

$$\bar{A}(\bar{r}) \approx \frac{\mu_0}{4\pi} f(r) \int_V \bar{J}(\bar{r}')\left[1 + jk_0\hat{r} \cdot \bar{r}'\right]dv'$$
$$= \frac{\mu_0}{4\pi} f(r) \int_V \left\{\bar{J} + \tfrac{1}{2}k_0\left[(\bar{r}'x\bar{J})x\hat{r} + (\hat{r} \cdot \bar{r}')\bar{J} + (\hat{r} \cdot \bar{J})\bar{r}'\right]\right\} dv'. \tag{A.3}$$

Defining the electric dipole moment $\bar{P}$, the magnetic dipole moment $\bar{M}$, and the electric quadrupole dyadic $\bar{\bar{Q}}$ in the usual fashion [8], we find that

$$\bar{A}(\bar{r}) = \frac{\mu_0}{4\pi} f(r) \left\{ \bar{P} - jk_0\bar{M} + \frac{1}{2}jk_0\bar{\bar{Q}}\bar{r} \right\} \tag{A.4}$$

This basic derivation appears in [3]. The various multi-pole moments are allowed to be complex to account for possible phase differences between the individual components.

We will next consider the far-zone radiation due to $\bar{P}$ and $\bar{M}$. The quadrupole contribution is expected to be small and will be neglected for reasons discussed in Appendix B.

We begin with an analysis of the fields due to the electric dipole. Equation (A.4) indicates that as the frequency approaches zero ($k_0 \to 0$) the electric dipole will represent the dominant contribution. We derive only the radiated electric field since this is the usual field quantity measured; the magnetic field may be found via the wave impedance (far field).

The electric dipole contribution to the potential $\bar{A}(\bar{r})$ is given in (A.4) in terms of spherical coordinates. The resulting electric field may be found from (A.1). However, the result is best expressed in rectangular coordinates since this will facilitate the introduction of a ground screen. Performing the required vector algebra we find that in the far field,

$$\bar{E}_p(\bar{r}) = -j\frac{k_0\eta_0}{4\pi} f(r)\bar{F}_p(\bar{r},\bar{P}) \tag{A.5}$$

where now $\bar{r} = (x,y,z)$, $\bar{P} = (P_x, P_y, P_z)$, $\eta_0 = 120\pi$, $\rho^2 = (x^2 + y^2)$, and

$$\begin{aligned}\bar{F}_p(\bar{r},\bar{P}) = {} & \hat{x}\left[P_x\left(\frac{x^2}{\rho^2}\frac{z^2}{r^2} + \frac{y^2}{\rho^2}\right) - P_y\frac{xy}{r^2} - P_z\frac{xz}{r^2}\right] \\ & + \hat{y}\left[-P_x\frac{xy}{r^2} + P_y\left(\frac{y^2}{\rho^2}\frac{z^2}{r^2} + \frac{x^2}{\rho^2}\right) - P_z\frac{yz}{r^2}\right] \\ & + \hat{z}\left[-P_x\frac{xy}{r^2} - P_y\frac{yz}{r^2} + P_z\frac{\rho^2}{r^2}\right].\end{aligned} \tag{A.6}$$

It is now a relatively easy matter to introduce a ground screen. Referring to figure A.2, let the dipole $\bar{P}$ be at a height h above a perfectly conducting ground screen located in the z=0 plane. This requires that z be replaced by z-h in the expression for $\bar{F}_p$. The field point will again be designated $\bar{r}$. The fields at $\bar{r}$ will be due to both the real source and an image source located a distance h below the ground screen. The vector paths between the observation point and the source and image points are designated $\bar{r}_1$ and $\bar{r}_2$ respectively. The source dipole components are (P_x, P_y, P_z). The image of a positive charge about a perfectly conducting ground screen is a negative charge. Thus, the image of a perpedicular electric dipole is in the same direction while the image of a parallel dipole is reversed. As a result, the image source $\bar{P}_I$ will have dipole components $(-P_x, -P_y, P_z)$ and the electric field due to the image source is given by $F_p(\bar{r}_2, \bar{P}_I)$. Combining results the total electric field $\bar{E}_p(\bar{r})$ may be written

$$\bar{E}_p(\bar{r}) = -j\frac{k_0\eta_0}{4\pi}\{\bar{F}_p(\bar{r}_1, \bar{P})\, f(r_1) + \bar{F}_p(\bar{r}, \bar{P}_I)\, f(r_2)\} \quad (A.7)$$

where

$$\bar{r}_1 = (x, y, z-h),\ r_1 = |\bar{r}_1|, \qquad (A.8)$$
$$\bar{r}_2 = (x, y, z+h),\ \text{and}\ r_2 = |\bar{r}_2| .$$

The magnetic dipole case may be similarly analyzed. One finds that

$$\bar{E}_M(\bar{r}) = \frac{k_0^2\eta_0}{4\pi} f(r)\, \bar{F}_M(\bar{r}, \bar{M})$$

(A.9)

where $\bar{M} = (M_x, M_y, M_z)$ and

$$\bar{F}_M(\bar{r}, \bar{M}) = \hat{x}\left[M_y\frac{z}{r} - M_z\frac{y}{r}\right] + \hat{y}\left[-M_x\frac{z}{r} + M_z\frac{x}{r}\right] \quad (A.10)$$
$$+ \hat{z}\left[M_x\frac{y}{r} - M_y\frac{x}{r}\right].$$

Mimicking the electric dipole analysis, we now introduce a ground screen at a height h below the magnetic dipole. The ground screen is located in the z=0 plane as before. The direct magnetic-dipole far-zone electric field may be found from eqs. (A.9-A.10) simply by replacing z with z-h. The ground screen will also introduce an image source. If we think of the dipole as due to ficticious magnetic charges which retain their polarity when imaged about a perfectly conducting ground screen, then the image dipole $\bar{M}_I$ will have components $(M_x, M_y, -M_z)$ respectively. Thus, the electric field due to the image dipole may be found from $\bar{F}_M$ by replacing z with z+h and $\bar{M}$ with $\bar{M}_I$. The total electric field $\bar{E}_M(\bar{r})$ due to a magnetic dipole over a ground screen is thus;

$$\bar{E}_M(\bar{r}) = \frac{k_0^2\eta_0}{4\pi}\{\bar{F}_M(\bar{r}_1, \bar{M})\, f(r_1) + \bar{F}_M(\bar{r}_2, \bar{M}_I)\, f(r_2)\}.$$

(A.11)

Combining results we find that the total far-field electric field due to the electric and magnetic dipoles is

$$\bar{E}(\bar{r}) = \bar{E}_P(\bar{r}) + \bar{E}_M(\bar{r}) \tag{A.12}$$

One may also show that the total power P_0 radiated by this source approximation is

$$P_0 = 10k_0^2 \left\{ |\bar{P}|^2 + k_0^2 |\bar{M}|^2 \right\} \tag{A.13}$$

6.2 Multi-Pole Radiation and Determination in a GTEM Cell

Given a current source, in a GTEM cell shown in figure B1, the fields $\bar{E}^{\pm}$ and $\bar{H}^{\pm}$ excited in the waveguide may be expanded in terms of the normalized waveguide modes $\bar{E}_n^{\pm}$ and $\bar{H}_n^{\pm}$;

$$\bar{E}^{\pm} = \sum_n \left(\frac{a_n}{b_n}\right) \bar{E}_n^{\pm} \quad \text{and} \qquad \text{(B.1)}$$

$$\bar{H}^{\pm} = \sum_n \left(\frac{a_n}{b_n}\right) \bar{H}_n^{\pm}$$

where $\pm$ indicates the direction of propagation from the source, and a_n, b_n are the forward (+) and backward (-) excitation coefficients respectively. Let z be the direction of propagation and let z=0 be referenced to some suitably chosen origin in the source volume. The normalized waveguide modes may be written

$$\bar{E}_n^{\pm} = (\bar{e}_{nt} \pm \hat{z}e_{nz})e^{\pm jk_n z}, \quad \text{and} \qquad \text{(B.2)}$$

$$\bar{H}_n^{\pm} = (\pm \bar{h}_{nt} + \hat{z}h_{nz})e^{\pm jk_n z},$$

where k_n is the propagation constant of the nth mode. The transverse field components $\bar{e}_{nt}$ and $\bar{h}_{nt}$ are related via the admittance dyadic $\bar{\bar{Y}}_n$,

$$\bar{h}_{nt} = \bar{\bar{Y}}_n \cdot \bar{e}_{nt} \quad \text{and} \quad \bar{\bar{Y}}_n = \frac{1}{Z_n}(\hat{y}\hat{x} - \hat{x}\hat{y}) \quad ; \qquad \text{(B.3)}$$

where Z_n is the wave impedance of the nth mode. The orthonormal condition takes the form

$$\int_S [\bar{e}_{nt} x \bar{h}_{mt}] \cdot \hat{z} ds = \delta_{mn} \quad , \qquad \text{(B.4)}$$

where the integration is over the cross section S of the waveguide and δ_{mn} is the Kronecker delta function.

The excitation coefficients are related to the current source via

$$\left(\frac{a_n}{b_n}\right) = -\frac{1}{2}\int_V \bar{J}(\bar{r}) \cdot \bar{E}_n^{\mp}(\bar{r}) dv', \qquad \text{(B.5)}$$

where $\bar{J}$ is the current density. The excitation coefficients may be simplified for application here based on two conditions; 1) the source is electrically small and 2) the modes of interest are nearly uniform over the source volume. The former restriction justifies retaining only the leading multi-pole terms. The latter condition allows us to expand $\bar{E}_n^{\pm}$ in terms of a Taylor series about the source volume origin and keep only the first derivative correction;

$$\bar{E}_n^{\pm}(\bar{r}) = \bar{E}_n^{\pm}(\bar{o}) + \bar{r}\cdot\nabla\bar{E}_n^{\pm}(\bar{o}) \quad . \tag{B.6}$$

Here, $\bar{o}$ denotes an origin chosen in a coordinate system r local to the source volume. It may or may not coincide with the waveguide coordinate system. Subject to this approximation, the excitation coefficients become

$$\begin{pmatrix} a_n \\ \overline{b_n} \end{pmatrix} = -\frac{1}{2}\left\{\bar{E}_n^{\pm}(\bar{o}) \cdot \int_V \bar{J}(\bar{r})\,dv + \int_V \left[\bar{r}\cdot\nabla\bar{E}_n^{\pm}(\bar{o})\right]\cdot\bar{J}(\bar{r})\,dv\right\} \quad . \tag{B.7}$$

The first integral may be recognized as the electric dipole moment $\bar{P}$. One may show that the second integral is related to the magnetic dipole moment $\bar{M}$ and the electric quadrupole moment $\bar{\bar{Q}}$ [3,8], with the result that

$$\begin{pmatrix} a_n \\ \overline{b_n} \end{pmatrix} = -\frac{1}{2}\left\{\bar{E}_n^{\pm}(\bar{o}) \cdot \bar{P} - jk_0\eta_0\,\bar{H}_n^{\pm}(\bar{o}) \cdot \bar{M} + \frac{1}{2}\nabla\bar{E}_n^{\pm}(\bar{o}) : \bar{\bar{Q}}\right\} \quad . \tag{B.8}$$

If the electric field is perfectly uniform over the source volume, such that $\nabla E(\bar{o}) = 0$, then the electric quadrupole moment is not needed and will be ignored here for simplicity.

We are primarily interested in the dominant TEM mode (n=0). For the TEM mode both e_{0z} and h_{0z} are zero and the the wave impedance takes the free space value η_0. Expanding the various field terms we find that

$$\bar{E}_0^{\pm}(\bar{o}) = \hat{x}e_{ox}(\bar{o}) + \hat{y}e_{oy}(\bar{o}), \tag{B.9}$$

$$\bar{H}_0^{\pm}(\bar{o}) = \pm\hat{x}e_{oy}(\bar{o}) \pm \hat{y}e_{ox}(\bar{o}) \quad \text{or} \pm\left(\hat{x}e_{oy}(\bar{o}) - \hat{y}e_{ox}(\bar{o})\right) \quad .$$

Substituting these results into (B.8) yields

$$\begin{pmatrix} a_o \\ \overline{b_o} \end{pmatrix} = -\frac{1}{2}\{[P_x \pm jk_0M_y]\,e_{ox}(\bar{o}) + [P_y \pm jk_0M_x]\,e_{oy}(\bar{o})\} \quad . \tag{B.10}$$

This result is perhaps more general than needed here. Typically, the DUT will be located centrally in the test chamber (x=0, see fig. B.1). In this case $e_{ox}(\bar{o}) = 0$ and (B.10) reduces to

$$\begin{pmatrix} a_o \\ \overline{b_o} \end{pmatrix} = -\frac{1}{2}[P_y \pm jk_0M_x]\,e_{oy}(\bar{o}) \quad . \tag{B.11}$$

Because of the particular normalization chosen, the powers carried by the TEM mode in the forward and backward directions are simply $|a_0|^2$ and $|b_0|^2$ respectively. It is, in fact, the power that is actually measured in the proposed scheme to determine the dipole moments.

Each of the three complex components of $\bar{P}$ and $\bar{M}$ represent two unknowns. Thus, we need to determine a total of 6 complex quantities or 12 unknowns, in order to fully specify our two term multi-pole expansion. Clearly, a number of GTEM measurements are required to generate sufficient independent equations.

Similar measurement procedures have been developed for a standard TEM cells [3-5]. The basic approach is to rotate the DUT about an axis, typically the longitudinal axis (direction of TEM mode propagation), through a sequence of $\pi/4$ angular steps. A local coordinate system (x',y',z') is assigned to the DUT and in turn each local axis is aligned with the TEM cell longitudinal axis. In this manner, each of the dipole moments is at some position strongly coupled to the vertical component of the electric field or the horizontal component of the magnetic field. Clearly, this approach generates numerous equations; solving these for the individual moment components, magnitude and phase can be tedious.

This paper will assume that the dipole moments are in phase. In general, this should not be an unrealistic restriction. Unintentional radiators are not likely to be designed such that they act as highly directive antennas, or such that they have complicated phase differentiation in their radiation patterns. More typically, we expect a box with possible seams and protrusions but with the currents basically in phase.

In a mathematical sense, rotations about any of the axes are equally simple. One need only introduce a rotation angle and perform the necessary bookkeeping. However, physically it is easiest to rotate about the vertical axis, especially when dealing with bulky DUTs. Unfortunately, the electric field in a GTEM cell is primarily vertical as well. Thus, a rotation about the vertical axis only weakly changes the electric field coupling. Consequently, previous TEM cell schemes have used longitudinal axis rotations.Nontheless, rotation about the vertical axis will be considered here.

The TEM mode will be excited according to eq. (B.11). The apex will be chosen as lying in the forward direction; thus, we need to consider the effect of a rotation on a_0. We first introduce a primed coordinate system which is referenced to the DUT. The rotation angle is designated α . In terms of the DUT primed local coordinates, the GTEM coordinate multi-pole moments become

$$M_x = M_{x'} \cos\alpha + M_{z'} \sin\alpha, \text{ and } P_y = P_{y'} . \qquad \text{(B.12)}$$

Thus, as a function of α, $a_0(\alpha)$ is given by

$$a_o(\alpha) = -\frac{1}{2}\left\{P_{y'} - jk_0 M_{x'} \cos\alpha - jk_0 M_{z'} \sin\alpha\right\} e_{oy}(\bar{o}) \quad . \text{(B.13)}$$

The power measured by at the cell apex will thus be

$$\left|a_o(\alpha)\right|^2 . \tag{B.14}$$

We take measurements at four positions (multiples of $\pi/4$);

$$\begin{aligned}
\left|\bar{a}_o(0)\right|^2 &= P_{y'}^2 + k_0^2 M_{x'}^2 , \\
\left|\bar{a}_o(\tfrac{\pi}{4})\right|^2 &= P_{y'}^2 + \tfrac{1}{2}k_0^2 M_{x'}^2 + \tfrac{1}{2}k_0^2 M_{z'}^2 + k_0^2 M_{x'} M_{z'} , \\
\left|\bar{a}_o(\tfrac{\pi}{2})\right|^2 &= P_{y'}^2 + k_0^2 M_{z'}^2 , \text{ and} \\
\left|\bar{a}_o(\tfrac{3\pi}{4})\right|^2 &= P_{y'}^2 + \tfrac{1}{2}k_0^2 M_{x'}^2 + \tfrac{1}{2}k_0^2 M_{z'}^2 - k_0^2 M_{x'} M_{z'} ,
\end{aligned} \tag{B.15}$$

where $\bar{\ }$ denotes normalization by $-\frac{1}{2}e_{oy}(\bar{o})$.

If we subtract the last two we additionally have

$$\frac{1}{2}\left\{\left|\bar{a}_o(\tfrac{\pi}{4})\right|^2 - \left|\bar{a}_o(\tfrac{3\pi}{4})\right|^2\right\} = k_0^2 M_{x'} M_{z'} . \tag{B.16}$$

The notation xx' is introduced to denote the axis alignment; also let

$$\begin{aligned}
M_{1xx'} &= P_{y'}^2 + k_0^2 M_{x'}^2 , \\
M_{2xx'} &= P_{y'}^2 + k_0^2 M_{z'}^2 , \quad \text{and} \\
M_{3xx'} &= k_0^2 M_{x'} M_{z'} .
\end{aligned} \tag{B.17}$$

In this case the x' axis is aligned with the x (GTEM cell) axis. For the cases where the y' and z' axes are aligned with the GTEM cell x axis we find that

$$\begin{aligned}
M_{1xy'} &= P_{z'}^2 + k_0^2 M_{y'}^2 & \qquad M_{1xz'} &= P_{x'}^2 + k_0^2 M_{z'}^2 \\
M_{2xy'} &= P_{z'}^2 + k_0^2 M_{x'}^2 & \qquad M_{2xz'} &= P_{x'}^2 + k_0^2 M_{y'}^2 \\
M_{3xy'} &= k_0^2 M_{y'}^2 M_{x'} \text{ , and} & \qquad M_{3xz'} &= k_0^2 M_{z'} M_{y'} .
\end{aligned} \tag{B.18}$$

These equations may now be used to solve for $\bar{P}$ and $\bar{M}$, beginning with $\bar{M}$. We find that

$$M_{x'} = \frac{M_{3xx'}\ M_{3xy'}}{k_0^2 M_{3xz'}} \qquad M_{y'} = \frac{M_{3xy'}\ M_{3xz'}}{k_0^2 M_{3xx'}}, \text{ and}$$

$$M_{z'} = \frac{M_{3xz'}\ M_{3xx'}}{k_0^2 M_{3xy'}} \quad . \tag{B.19}$$

Having found the $\bar{M}$ components we may solve for $\bar{P}$;

$$\begin{aligned} P_{x'} &= M_{1xz'} - k_0^2 M_{z'}^2 = M_{2xz'} - k_0^2 M_{y'}^2, \\ P_{y'} &= M_{1xx'} - k_0^2 M_{x'}^2 = M_{2xx'} - k_0^2 M_{z'}^2, \text{ and} \\ P_{z'} &= M_{1xy'} - k_0^2 M_{y'}^2 = M_{2xy'} - k_0^2 M_{x'}^2 \quad . \end{aligned} \tag{B.20}$$

A difficulty is that some of the $\bar{M}$ components may be zero in which case (B.19) would involve dividing by zero. Thus a program to solve for $\bar{M}$ must first check to see if any of the $\bar{M}_{3\alpha\beta}$ values are zero. If so the equations simplify and the solution is not difficult. We also note that in the notation just developed the total radiated power P_0 (no quadrupole contribution) is given by

$$\begin{aligned} P_0 &= 10k_0^2\left\{M_{1xx'} + M_{1xy'} + M_{1xz'}\right\} \\ &= 10k_0^2\left\{M_{2xx'} + M_{2xy'} + M_{2xz'}\right\} \quad . \end{aligned} \tag{B.21}$$

Appendix B

Practical Measurement Tips

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7. Practical Measurement Tips

The GTEM Cell software allows the operator to take RE (radiated emission) test data for the EUT in only one position, if desired, and still obtain a correlation to any of the included EMI standards. For example, the operator may have foreknowledge that a particular EUT radiates strongly from one direction. The operator can perform one scan on the EUT in that one position in the GTEM cell, then fill all three data files with this "worst case" scan data, and obtain a correlation against a standard. This allows the operator to get an accurate measure of the RFI output of an EUT by scanning it in only one or two positions.

Using the formulae in Chapter 6 (C.18), (C.19), the error estimation table (Figure 7.1.1) shown below was constructed. Example data are tabulated for an EUT which radiates 40 dBuV in all 3 (X-Y-Z) positions. One can see that the error introduced by taking data in only one position is small. The first line shows that, if the RFI is measured at 40 dBuV only in position 1 (X,Y,Z), then the resulting correlation is low by 4.77 dB. If measured in two positions, as in line 4 of the table, then the correlation would be low by only 1.55 dB.

Figure 7.1.1: Error Estimation Table:

Vx in dBuV	Vy in dBuV	Vz in dBuV	Fehler in dB
40	0	0	-4.77dB
40	20	0	-4.32dB
40	20	20	-3.98
40	40	0	-1.74dB
40	40	20	-1.55
40	40	40	0 <------
40	40	60	6.02
40	60	60	8.45
40	40	80	15.32
40	60	80	15.68
40	80	80	18.26

Appendix C

Radiated Emissions Test performance of the GHz TEM (GTEM!) Cell

RADIATED EMISSIONS TEST PERFORMANCE

OF THE GHz TEM CELL

Abstract

The GHz TEM (GTEM!) Cell has recently been recognized as a competing technology for the accomplishment of electromagnetic compatibility (EMC) radiated emissions testing for the demonstration of compliance with commercial specifications. As a competing technology, the direct comparison of the performance of a GTEM!, for such compliance measurements, to the results obtained from an Open Area Test Site (OATS), are an obvious and necessary step. This paper describes the direct comparison of results of two series of tests. Two differing comparisons are described; three separate sets of reference dipole comparison measurements, and two full Personal Computer systems tested per the requirements of ANSI 63.4, Draft 11.4 [1] on an OATS and in a GTEM! In addition to a direct comparison, the resultant data has also been subjected to statistical analysis. The statistical analysis was performed on maximum electric field strength data comparing GTEM! calculated levels with open area test site (OATS) measured levels. Pearson's correlation coefficient and Student's-t distribution were used to analyze the data. Good agreement of results, both by direct comparison and by the statistical analysis have been found, and are described.

Introduction

The GHz Transverse Electromagnetic (GTEM!) Cell, Figure 1, has existed in conceptual form, and as a practical device, for some time [2]. Only recently has the use of this device, as an alternative to radiated emissions measurements on an OATS, been seen as a practical choice [3], [4]. This change has been brought about by additional developments in the theory of this device, such that a direct comparison can be made to the results obtained from an OATS. The main contribution that has brought forward the GTEM! as a practical radiated emissions device has been in the theoretical development of a mathematical model allowing the direct comparison of data taken in a GTEM! to data acquired on an OATS. The software implementation for the GTEM! accomplishes the following, given three voltage versus frequency measurements V_{xyz}, V_{yzx} and V_{zxy} for three orthogonal orientations of the equipment under test (EUT) in the GTEM!

At each frequency:

Performs a vector summation of the three orthogonal voltages

Computes the total power emitted by the EUT as determined from the summation if the three voltages and the TEM mode equations for the GTEM!,

Computes the current excitation of an equivalent tuned, resonant dipole when excited with that input power,

Computes the field intensity at appropriate height intervals over the total scan height, either 1 to 4 metres or 2 to 6 metres for both vertical and horizontal polarizations of the receive antenna when the equivalent tuned resonant dipole is placed at an appropriate height over a perfect ground plane,

Selects the maximum field strength (larger) value of the horizontal or vertical polarizations,

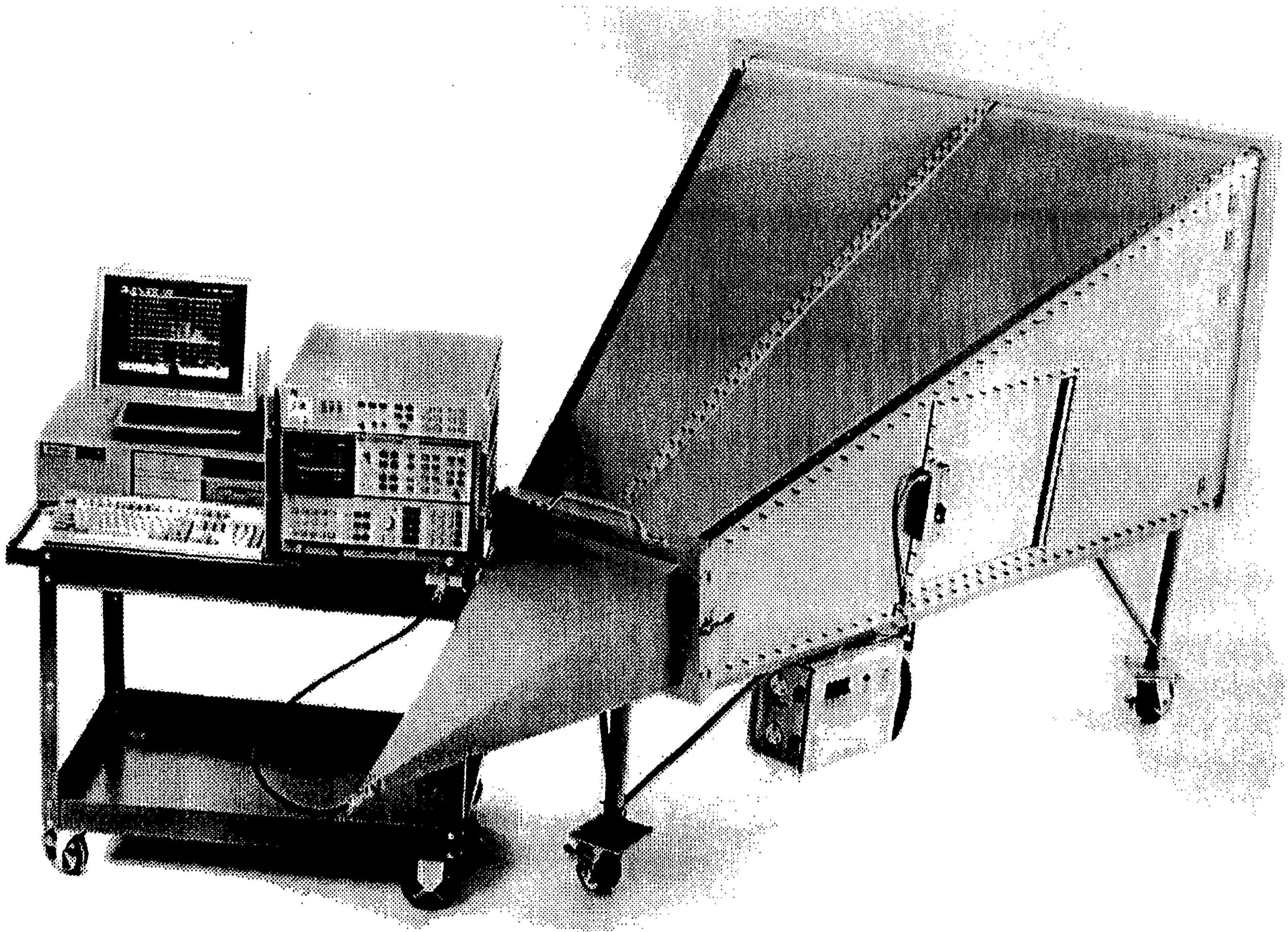

Figure 1. GTEM! Model 5305 with Radiated Emissions testing equipment.

Presents this maximum value as compared to the chosen EMC specification limit.

The augmentation of the GTEM!, a device which presents many of the advantages of both semi-anechoic chambers and traditional TEM cells without accompanying disadvantages, by sophisticated software is a significant technical advancement. This allows the direct comparison of test results from radiated emissions testing in the GTEM! to test results from more traditional test methods

Goals of Testing and Analysis

The purpose of these tests was to develop a valid, direct comparison of the performance of the GTEM! to the performance of an OATS. Thus the goals of testing were:

Provide directly comparable sets of high quality test data from the GTEM! and the OATS.

Develop a simple, direct comparison of the results of these diverse tests.

Provide analytical result of the difference in the GTEM! and OATS performance that is capable of being succinctly stated, yet remains complete.

Provide a supplement to the direct comparison by a statistical analysis that provides a more sophisticated and meaningful comparison of the measurements.

Provide a statistical measure of quality of the compared measurements other than a direct statement of difference of the measurements.

Design of Testing

The development of the specific test approaches was based on the requirements of ANSI 63.4. Since this document will, in time, become the test requirements document for commercial EMC testing in the United States [5], it was selected as the basis for testing.

General

There is provision in ANSI 63.4, for the development of data for the qualification of Alternate Test Sites. While this requirement is directed to the qualification of semi-anechoic chambers for radiated emissions testing, it was felt that there were technical features in this approach usable for GTEM! comparison measurements. ANSI 63.4 requires the development of Normalized Site Attenuation data, in both vertical and horizontal polarizations, from a number of specified locations on the included turntable at the equipment under test (EUT) location in the semi-anechoic chamber. In the ANSI documents, these measurements are made with a broadband antennas such as biconical and log periodic antennas.

A test object produces a certain amount of radiated energy. Some of this energy may be directed up or down depending on the sources of radiation and the coupling among the cables interconnecting the PC system components. In customary traditional EMI tests on OATS, individual units and cables are moved to try to cause as much of the energy as possible to be radiated at a height around the PC such that it can be picked up in the height scan of the measurement antenna, e.g., one to four metres.

In the GTEM!, three orientations of the test object are needed, so that all three components of the total radiation vector can be picked up. It was hypothesized that the GTEM! should predict the maximized field strength that could be measured on an OATS since it picks up the total radiation vector from the test object.

In order to accommodate the size of the planned EUT's, a GTEM! Model 5317 was used. The external dimensions of this device are given in Figure 2.

Reference Dipole Antenna Testing

Equivalence testing for the GTEM! was planned using tunable dipole antennas, The tunable antennas can remain comparatively small over the majority of the frequency range of interest, and dipole antennas are the reference antennas constructed as described in ANSI 63.5 [6], preferred for the resolution of conflicting measurements. The dipoles can be easily placed in the center of the test volume and three orthogonal measurements made to satisfy the requirements for GTEM! testing. They are also easily transferred to the OATS for the comparison testing. When the dipole antennas begin to become large with respect to the size of the GTEM! test volume, they were used as short dipoles with the dipole elements set to a fixed frequency compatible with the size of the test volume.

The resonant dipoles were installed on an OATS with the feed point of the dipole directly over the center of the turntable, The dipole was driven at many frequencies, as appropriate, to 1000 MHz. The test procedure of ANSI 63.4, was used. This procedure requires that the measurement be made at the maximum of the emanation at each frequency. This in turn requires searching the receive antenna in height, and rotation of the turntable to establish the maximum value of the emanation. Measured values were corrected to field strength values by adding cable loss and antenna factors.

The resonant dipoles were then transferred to the test volume of the GTEM! Voltage measurements were made in three orthogonal orientations, and the test control software was used to process the three orthogonal measurements into field strength versus frequency data. These values are directly comparable to those taken at the OATS.

Personal Computer Testing

The second test series involved comparison testing of two different small, desk top Personal Computer systems. They were installed secured to a piece of plywood with the subsystem components and interconnecting cables strapped to the plywood with nylon strapping. The strapping was firm since the entire EUT installation would be rotated to allow three orthogonal axes voltage measurements. Each personal computer system consisted of a system unit, monitor, keyboard, parallel device (printer), mouse and a serial device (printer or modem). These items were installed as shown the figures distributed in ANSI 63.4. These figures require the installation of the EUT on a 1 x 1.5 metre table. In the testing described in this paper a 1 x 1.5 metre piece of 12 mm plywood was used. The system unit was installed with the back edge of the chassis aligned with the back edge of the plywood base and centered. The monitor was centered on the system unit. The printer (required parallel peripheral) was installed to the right of the system unit at a distance of 10 cm. The modem (required serial peripheral) was installed 10 cm to the left of the system unit. The back edges of all of these units were aligned with the back edge of the plywood. The keyboard was centered and aligned with the front edge of the plywood. The mouse was installed 10 cm from the right edge of the keyboard and aligned with the back of the keyboard. All items were secured to the plywood. The plywood array was then transferred into the test volume of the GTEM! used for this testing.

The three orthogonal measurement alignments are shown in Figure 3, showing the orientation for V_{xyz} testing, Figure 4, showing the orientation for V_{yzx} testing and Figure 5, showing the orientation for V_{zxy} testing. The relative position of the subsystem components are shown in these figures. Also shown in the Figures are the calculated field uniformity contours for • 1 dB, • 2 dB, •3 dB and • 4 dB field uniformity referenced to the center of the test volume. Figures 3, 4 and 5 are oriented for the view to be from the apex of the GTEM! cell. To maximize the measured emission values, the draping of the

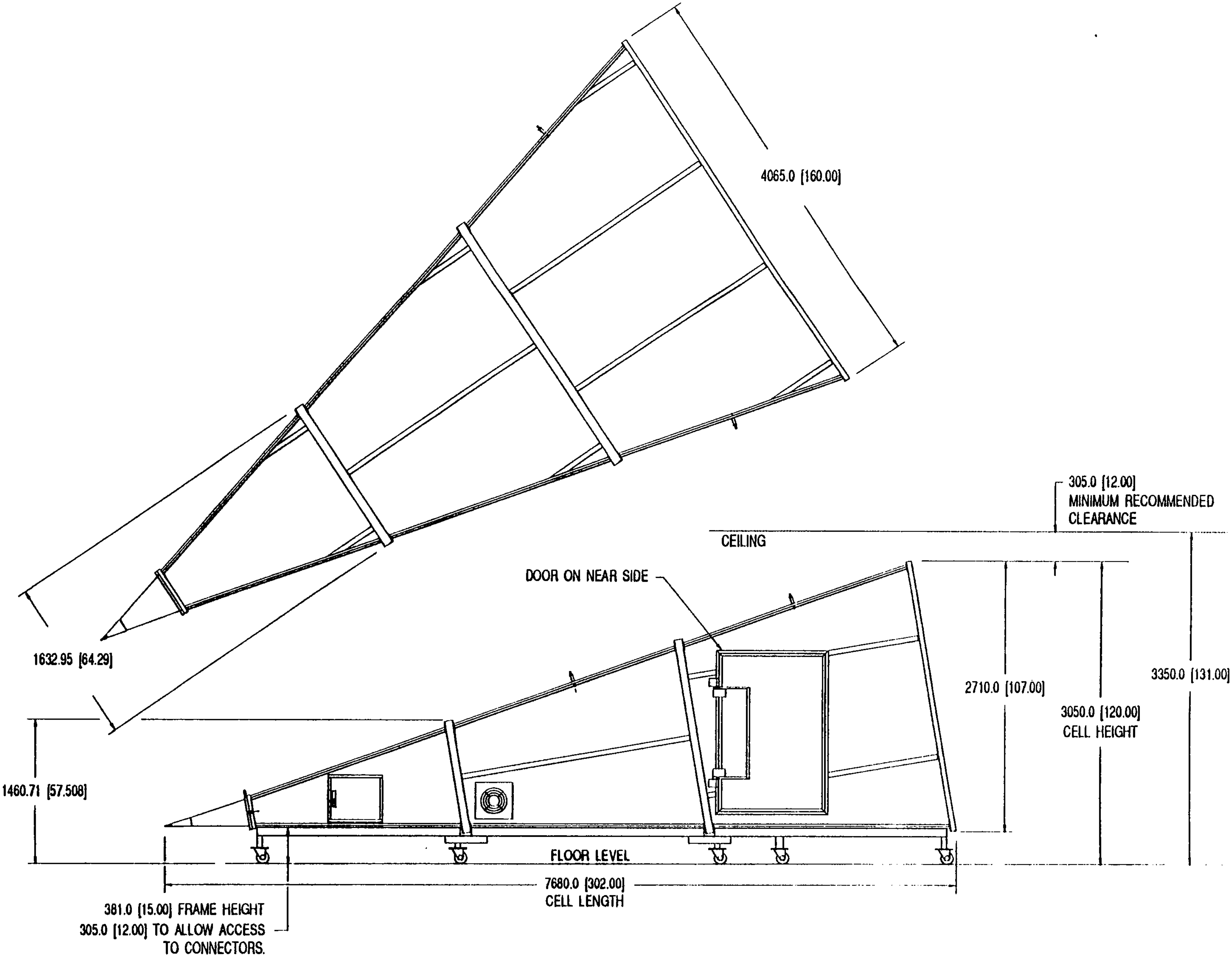

Figure 2. Dimensions of Model 5317 GTEM!

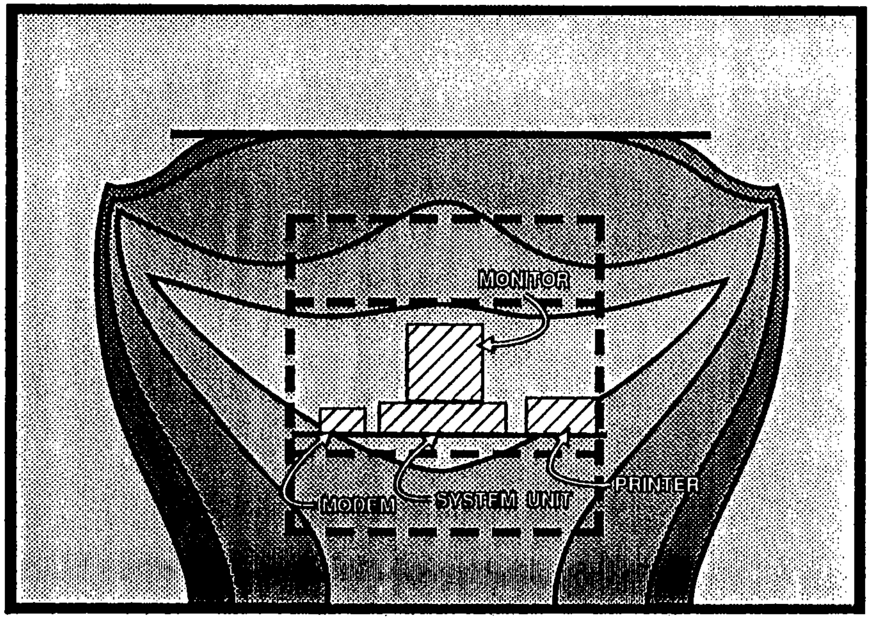

Figure 3. **PC System installed for V_{XYZ} measurement as seen from apex.**

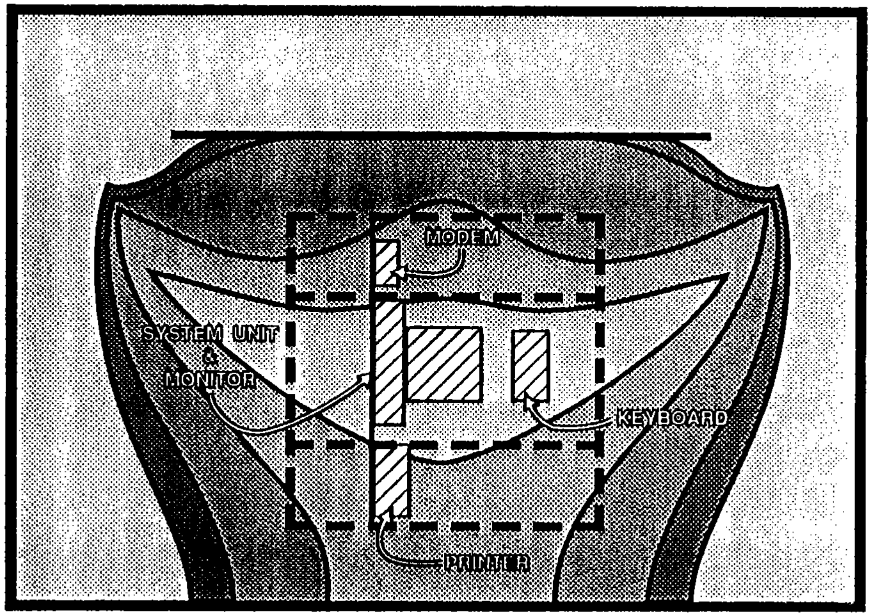

Figure 4. PC System installed for V_{YZX} measurement as seen from apex.

cable from the first position measured was preserved for a minimum of 30 cm from the back edge of the table.

After testing in a GTEM! the plywood sheet with the EUT's secured to the sheet was transferred to the OATS for comparison testing. The five highest frequencies detected in the GTEM!, from each PC array, were evaluated at the OATS using the procedures of ANSI 63.4.

Design of Data Analysis

The consideration of how to compare the data between the two types of test facilities, the GTEM! and an OATS is less straightforward than may seem. Two types of analysis of the comparative data were performed, direct and statistical comparisons.

Direct Comparisons

The first comparison of the data is the direct subtraction of the OATS measurement of a signal at any frequency from the GTEM! measurement at the same frequency. This gives a quantitative analysis of the direct difference of the measurements. By subtracting the OATS reading from the GTEM! reading, a positive value indicated that the GTEM! measured signal is larger than the OATS measured signal. Conversely, a negative value indicates that the GTEM! is measuring the emanation lower than the OATS.

The second direct comparison of the data is the determination of the mean and standard deviation of the differences for all data points in a single data set. An upper bound of the difference of the GTEM! and OATS measurements may be set statistically from the standard deviation data.

Statistical Comparisons

Pearson's Correlation Coefficient - Pearson's correlation coefficient [7] and linear regression equation coefficients [8] were calculated for data (the first three sets of dipole data and the first two sets of PC data) in which values from different distances were combined for overall evaluation. The correlation helps to show when the data are not independent and can properly be combined for further analysis.

Meaning of the Value of Pearson's Correlation Coefficient - Values of Pearson's correlation coefficient between +0.6 and +1, and regression line slopes between +0.5 and +1.5 indicate a strong relationship between the samples of data.

Student's-t Statistic - Student's-t statistic for paired, sample variables was used to analyze the comparison data for both the dipoles and the PCs. This approach allowed testing the null hypothesis for the difference between the GTEM! data and the OATS data.

Meaning of Student's-t Statistic. The interval of Student's-t distribution between -t and +t represents a region in which with a specific probability, all sets of samples of data are from the same population, and therefore are the same even though their means and sample variances appear to be different. The hypothesis that the sample mean is no different than the population mean is called the null hypothesis, H_0, and it is accepted or rejected by virtue of whether the sample mean lies within the interval of -t to +t. The confidence that the sample mean and the population mean are the same is 100(1-a) per cent. If T lies outside of the interval -t to +t, the null hypothesis must be rejected.

Student's-t statistic is tabulated for various degrees of freedom (d.f.). The tabulation must be entered with the d.f. and the confidence level to find the limits of the interval t to be used. For paired,

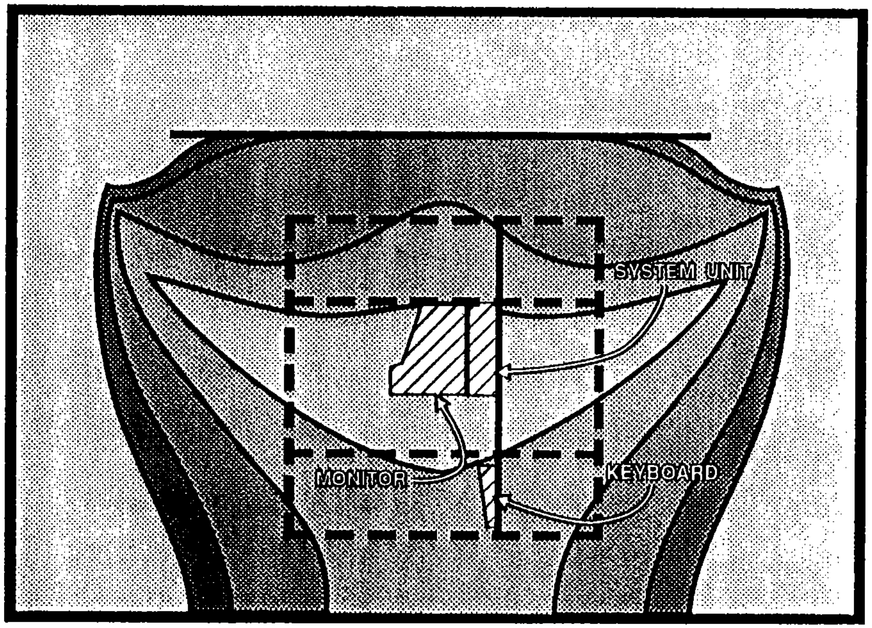

Figure 5. PC System installed for V_{ZXY} measurement as seen from apex.

related data, the d.f. are one less than the number of pairs of data; and for paired independent data, the d.f. are one less than the sum of the number in each set of sample data, *i.e.*:

$$m_x = n_x - 1, \ m_y = n_y - 1, \text{ and d.f.} = m_x + m_y.$$

Student's-t Statistic for *non-independent* (related) paired sample variables [9] was used for the first two sets of PC data since the same test object and configuration were used for measurements both in the GTEM! and on the OATS.

Student's-t Statistic for *independent* paired sample variables [10] was used for the first three sets of dipole data, since a different signal generator was used on the OATS from that used in the GTEM! measurement.

Test Series 1 - Dipole Testing

A series of three tuned dipole measurements were accomplished under slightly different circumstances. The three sets of measurements are as follows:

A set of measurements were performed using only tuned resonant dipoles covering the frequency range of 500 to 1000 MHz. The measurements were conducted at three distances, 3, 10 and 30 metres, corresponding to the three measurement distances common in international commercial EMC specifications. The measurements were made in a GTEM! and the field strength calculation was performed at the three measurement distances. The same dipoles were then transferred to the OATS and comparison measurements performed. The results of these measurements are shown in Tables I, II and III.

Table I
Tuned Resonant Dipole Measurements at 3 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
500.0	92.6	93.4	-0.8
600.0	92.3	93.7	-1.4
700.0	91.5	94.2	-2.7
800.0	90.4	92.2	-1.8
900.0	92.3	92.8	-0.5
1000.0	92.2	90.9	+1.4

The average difference between the GTEM! and the OATS is -1.97 dB, and the Standard Deviation is 1.39 dB

Table II
Tuned Resonant Dipole Measurements at 10 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
500.0	83.7	83.2	+0.5
600.0	82.1	83.6	-1.5
700.0	81.9	84.4	-2.5
800.0	80.6	82.2	-1.6
900.0	82.5	84.8	-2.3
1000.0	84.1	83.9	+0.2

The average difference between the GTEM! and the OATS is -1.2 dB, and the Standard Deviation is 1.26 dB.

Table III
Tuned Resonant Dipole Measurements at 30 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
500.0	74.0	73.3	+0.7
600.0	73.5	75.8	-2.4
700.0	72.4	72.6	-0.2
800.0	71.2	71.7	-0.5
900.0	73.0	73.4	-0.1
1000.0	74.6	73.3	+1.3

The average difference between the GTEM! and the OATS is -0.25 dB, and the Standard Deviation is 1.27 dB.

The second set of dipole measurements were made over the frequency range of 400 MHz to 1000 MHz. Tuned resonant dipoles were also used for this testing.

Table IV
Resonant Dipole Data, GTEM! vs OATS at 3 Meters

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
400.0	93.5	93.7	+0.2
500.0	93.7	92.9	-0.8
600.0	91.1	93.0	+1.9
700.0	89.8	92.2	+2.4
800.0	92.5	92.3	-0.20
900.0	90.3	93.7	+3.40
1000.0	90.3	91.9	+1.6

The average difference between the GTEM! and the OATS is +1.21 dB, and the Standard Deviation is 1.52 dB.

The third dipole test was performed in the same manner as the first, with the exception that an extended frequency range of the evaluation was desired. Where only resonant dipoles were used in the first evaluations, short dipoles were added to allow the extension of the evaluation down to 50 MHz. This was accomplished by tuning the resonant dipole to 230 MHz, and lowering the frequency of excitation in steps to 50 MHz. The dipoles were tuned to resonance at 230 MHz and above. The data is summarized in Table V. Note that these data were acquired with different instrumentation, at different test sites using a different GTEM!, making them an independent set of data.

Table V
Resonant Dipole Data, GTEM! vs OATS at 3 Meters

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
50.0	45.8	45.0	-0.8
100.0	69.3	73.1	+3.8
200.0	88.5	84.4	-4.1
230.0	96.0	88.7	+7.7
250.0	92.7	91.9	-0.8
300.0	99.8	97.3	-2.5
400.0	100.3	100.5	+0.2
500.0	101.3	100.7	-0.6
600.0	98.3	98.1	-0.2
700.0	99.7	96.8	-2.9
800.0	99.8	99.5	-0.3
900.0	100.2	97.3	-2.9
1000.0	99.6	97.3	-2.3

The average difference between the GTEM! and the OATS is -1.62 dB, and the Standard Deviation is 2.68 dB.

Test Series 2 - Personal Computer Testing

Test results for the testing of the two Personal Computer systems are shown in Tables VI, VII and VIII.

Table VI
Personal Computer System 1, OATS vs GTEM! at 3 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
35.32	64.4	63.6	+0.8
70.65	62.1	54.0	+8.1
141.5	45.2	45.2	+0.0
160.5	46.1	45.7	+0.4
186.1	45.0	38.4	+6.6

The average difference between the GTEM! and the OATS is +3.18 dB, and the Standard Deviation is 3.85 dB.

Table VII
Personal Computer System 1, OATS vs GTEM! at 10 Metres

Frequency (MHz)	GTEM! Computed Field Strength (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
35.3	54.4	57.7	-3.3
70.6	52.1	42. 8	+9.3
141.6	35.2	34.2	+1.0
160.5	36.1	35.0	+1.1
186.1	35.0	32.2	-2.8

The average difference between the GTEM! and the OATS is 2.18 dB, and the Standard Deviation is 4.57 dB.

Table VIII
Personal Computer System 2, OATS vs GTEM! at 3 Metres

Frequency (MHz)	GTEM! Correlated Field Data (dB uV/m)	OATS Measured Field Data (dB uV/m)	Difference (dB)
140.0	28.74	27.5	+1.24
182.0	26.00	28.0	-2.00
185.0	30.20	28.6	+1.60
233.0	28.91	27.8	+1.11
320.0	24.69	27.6	--2.91

The average difference between the GTEM! and the OATS is -0.19 dB, and the Standard Deviation is 2.10 dB.

The data is summarized in Tables IX and X. Note that these data were acquired with different instrumentation, at different test sites using a different GTEM!, making them an independent set of data.

Discussion of Test Results

This section describes the results of the analysis performed on the data, and provides commentary about the results.

Results of Comparative Analysis

The test series reported show good agreement between GTEM! measurements and OATS measurements. It is interesting to note that the sets of dipole measurements, summarized in Table IX, show reasonably consistent results.

Table XI shows Pearson's correlation coefficient and the regression coefficients for the first three sets of dipole measurements and the first two sets of PC measurements. The correlation is good enough that, while these results came from measurements in which certain parts of the process were different, they can be combined with the rest of the data for further analysis.

Table IX
Summary of Dipole Measurements

Data Set	Average Difference (dB)	Standard Deviation (dB)
Dipole Data 1 at 3 Metres	-0.97	1.39
Dipole Data 1 at 10 Metres	-1.20	1.26
Dipole Data 1 at 30 Metres	-0.25	1.27
Dipole Data 2 at 3 Metres	-1.21	1.52
Dipole Data 3 at 3 Metres	+1.59	2.6

A similar summary for the personal computer data is shown in Table X.

Table X.
Summary of Personal Computer Measurements

Data Set	Average Difference (dB)	Standard Deviation (dB)
PC 1 at 3 Metres	3.18	3.85
PC 1 at 10 Metres	2.18	4.57
PC 2 at 3 Metres	0.19	2.09

The personal computer data is again in reasonably good agreement between the GTEM! and the OATS measurements. There is a difference between the first two data sets and the third that is in part attributable to the improvement in test procedures as the learning curve flattened. The last data set is felt to be representative of the measurement capability of the GTEM! much more than the first two.

As can be seen by comparing the data between Tables IX and X, there is a larger deviation in Personal Computer data and dipole data. This is felt to be related to the difference in the type of EUT from dipoles to a Personal Computer system. Dipoles are "strongly" polarized in that the two planes that are orthogonal to the plane of polarization show radiated emission levels that are low with respect to the primary plane. The Personal Computer system shows much smaller differences in the three orthogonal measurements. It is suspected that this difference as related to the characteristic of the personal computer array to radiate more equally in three orthogonal directions.

Results of Statistical Analysis

The general results of the statistical analyses are shown in Tables XI and XII.

Table XI
Correlation of Data from the First Three Dipole Measurements and First Two PC Measurements

Coefficient	Dipole 1 (Tables I, II, III)	PC 1 (Tables VI, VIII)
r	0.941	0.988
a	-2.36	+3.30
b	+1.00	0.95

Table XII shows the results of the Student's-t comparisons between the several sets of data and the null hypothesis test. D is the standard mean difference of the data sets, S_D is the standard deviation of the mean differences, t is the interval from the Student's-t distribution for a 95% confidence, and T is the deviation of the difference of the sample means from zero normalized to Student's-t distribution.

Table XII
Summary of Statistical Analysis on All Measurements
$\alpha = 0.05$, H_0: $\mu_D = 0$

Data Set	Dipole 1 (Tables I, II, III)	Dipole 2 (Table (IV)	Dipole 3 (Table V)	PC 1 (Tables VI, VII)	PC 2 (Table VIII)	All Dipoles	All PC's	All Data
D	-0.8	+1.2	-1.6	+2.7	-0.2	-0.7	+1.7	-0.02
S_D	2.7	2.3	7.2	4.0	4.4	4.5	13.6	8.1
n	36	7	13	10	5	38	15	53
d.f.	34	6	12	9	4	37	14	52
t	+/-2.030	+/- 2.447	+/- 2.179	+/- 2.262	+/- 2.776	+/- 2.029	+/- 2.145	+/- 2.008
T	-0.295	+1.388	-0.812	+2.107	-0.097	-0.980	+0.489	-0.022
H_0	Accept	Accept	Accept	Accept	Accept	Accept	Accept	Accept

Summary of Statistical Findings

The results show that there is no significant difference between the samples of data and we can accept the null hypothesis. That is, the GTEM! measurement is the same as the OATS measurement. The results also show that for the PCs, the field strength measured in the GTEM! without cable manipulation are essentially the same as those on the OATS with cable manipulation. This implies a much faster and more consistent measurement.

Measurement Error, Precision and Repeatability

The overall absolute rss error in the test instrumentation was 2.5 dB, and the probable instrumentation error was 1.7 dB. The precision of the measurement was 0.1 dB. From the descriptive statistics of the dipole-to-dipole OATS measurements, the probable variation of repeatability was 0.7 dB.

CONCLUSIONS

The following conclusions are drawn after the conduct of the testing described and after review and analysis of the test results.

Test Procedure Specific Conclusions

Must Control EUT Configuration - There are several issues connected with this statement. An early procedure tried for the three orthogonal rotations was to rotate each component in place. This was quickly discarded in favor of maintaining right relative positions of the components in an EUT like a Personal Computer System.

Must Manage Cable Placement - The relative positions of the interconnecting and power cables should be managed to maintain the EUT configuration to provide the highest levels of emanations from the EUT array.

Must Manage EUT Performance by Operating Software - The GTEM! may be scanned in frequency at rates much much higher than are normally associated with commercial EMC testing. The exercising software must be written with this in mind. For example, the optimal software approach in a GTEM! test is to write a single "H" to the screen and the printer, not a string of 80 "H's".

Must Use Precision Methods for Conduct of Measurements - The care that is normally taken by conscientious test personnel is adequate. For GTEM! to OATS testing it was found that it is necessary to characterize measurement accessories such as preamplifiers and coaxial cables to a precision of 0.1 dB, to achieve meaningful results.

More General Conclusions

Direct comparison of dipole and personal Computer measurements indicates a successful comparison measurement program.

Statistical analysis indicates comparison of GTEM! data and OATS data from a variety of devices and conditions indicates that the direct comparison is statistically valid.

The GTEM! is a viable alternative facility for the conduct of radiated emissions testing.

The time savings in the conduct of testing can be more than 8:1 in favor of the GTEM! This indicates that a higher test efficiency will allow substantially more testing to be done in the same amount of time, so long as this is possible in a practical sense.

The characteristics of the GTEM! allow its operation in a corporate location with a rather high electromagnetic ambient environment, rather than a remote site like a OATS. This allows increased efficiency in that travel time and possibly external test costs can be avoided. This makes the GTEM! ideal for EMC engineering development work.

The GTEM! will have future applicability as a qualification facility for new products. The amount of data collected to date has shown that the differences in GTEM! data and OATS data are not statistically different. Additional statistical data is probably needed to establish a larger data base, but it seems that this will be possible in the not too distant future.

Acknowledgements

The GTEM was developed by Asea Brown Boveri of Baden Switzerland, and is licensed for production by the Electro-Mechanics Co. The technical content of this paper was prepared for presentation at the 1991 IEEE EMC Symposium.

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Appendix D

GTEM! Shielding Effectiveness Measurement Procedure

GTEM SHIELDING EFFECTIVENESS (SE) TEST METHOD

22 Apr. 93
(File: SE-Test7)

Introduction

Traditional shielding effectiveness (SE) test methods for shielded enclosures, such as those found in IEEE Std 299, define SE as the ratio of the coupling between two antennas without the shield to the coupling between them with the shield intervening. In these traditional test methods, two antennas are set up a certain distance apart, one is driven by a signal generator, the other is connected to an AC or RF voltmeter, and the coupling loss between them is measured. The antennas are then set up again the same distance apart, with one inside and the other outside of the shielded enclosure, and the coupling loss between them is again measured. The SE is then found as the ratio of the first measurement to the second measurement. These traditional methods require that the enclosure have minimum dimensions two or three times those of the antennas used in the measurement, which for room-sized enclosures is not a problem. Traditionally, shielded enclosures are intended to separate the electromagnetic environment inside the room from that outside the room; the processes going on in the room being essentially independent of the room itself.

For the broadband TEM cell, the GTEM cell, the process going on inside the cell is a function of the cell itself rather than being an independent process. The cell must provide both the process and the shielding for it. Furthermore, the space inside of the GTEM cell is restricted by the presence of the septum, the load resistors, and the absorbing material; thus leaving little room for typical antennas that might be used to assess its shielding effectiveness. These constraints lead to the need for a different method to measure or assess the SE of GTEM cells. In the method described by the procedure given below, the coupling between the septum and a measurement antenna is calculated as if the walls and ceiling of the GTEM cell were not in place, and this is compared to the measured coupling between the septum of the cell surrounded by its walls and ceiling as is normal in its construction. The calculation determines what the power output from the test antenna would be, based on the power input to the cell, if the septum were not shielded by the cell walls and ceiling. This gives the free space path loss between the septum and the test antenna. The power output from the antenna during the measurements, in which the cell is driven by a known power level, is divided by this free space path loss. The antenna factor or gain of the measurement antenna is stated separately in the calculations so that calibrated antennas from various manufacturers may be used in the measurements.

The procedures in this method are designed to conform, in so far as is possible, with the traditional procedures in IEEE Std 299-1991. This IEEE standard represents the consensus of shielding experts in North America, and will soon replace the much older MIL-STD-285 for military shielding effectiveness measurements. Since there was no CISPR standard on shielding effectiveness measurements, this transnational IEEE standard was selected as a model. In several places in the following procedure, "(IEEE Std 299)" designates when some IEEE Std 299 procedure, method, or concept was used.

Procedure

1. The SE is defined as the ratio of the net power input into the GTEM cell to the power delivered by an antenna placed near the cell in various locations, adjusted for the free-space path loss and the gain or antenna factor of the measurement antenna. The assumptions in this approach are:

   a. Below 30 MHz, the current flowing on the GTEM septum induces an electric field adjacent to it, which could be measured with an electric antenna, and a magnetic field around it, which could be measured with a magnetic (loop) antenna, if these fields were not enclosed within the walls of the cell; and,

   b. Above 30 MHz, the GTEM septum acts as a traveling wave antenna producing an electromagnetic field around it which could be measured with a dipole or horn antenna if it were not enclosed within the walls of the cell.

2. The results of the SE measurements shall be displayed as two values: One, the worst-case (least) SE; and two, the average of all values of SE. (IEEE Std 299)

3. One frequency in each of the following bands shall be tested using the antenna listed. Usually the center frequency of each band is used; the range being allowed to avoid local ambient interference. (IEEE Std 299)

Band	Range	Antenna
1	14 - 16 kHz	1 m rod w/counterpoise & 0.3 m shielded loop
2	140 - 160 kHz	1 m rod w/counterpoise & 0.3 m shielded loop
3	14 - 16 MHz	1 m rod w/counterpoise & 0.3 m shielded loop
4	300 - 400 MHz	Log-Periodic Array
5	800 - 1000 MHz	Log-Periodic Array
6	8.5 - 10.5 GHz	Horn
7	16 - 18 GHz	Horn

4. The rod and loop antennas shall be placed 0.5 m from the cell in the locations specified below. The Log-Periodic Dipole Array (LPA) and horn antennas shall be placed 1.0 m from the cell as measured from the tip of the LPA or the aperture of the horn, in the locations specified below.

5. Figure 1 shows the block diagram of the test. Figures 2 and 3 show test locations for a standard configuration GTEM.

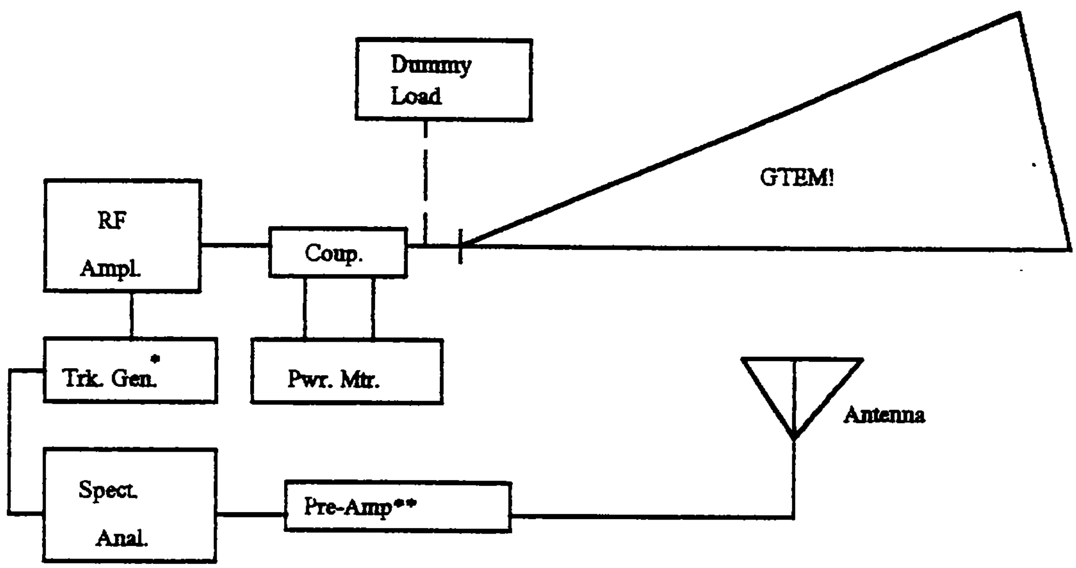
6. Preliminary Tests.

a. First, using a small hand-held shielded loop probe about 6 cm in diameter, search for emissions on the outside of the GTEM cell along seams, door frames, access panels, vents, etc. Perform this search at 15 to 16 MHz. Note any positions which have strong leakage and test these positions in addition to those shown in Figures 2 and 3.

b. Test first at each location with the amplifier terminated in a dummy load but occupying the exact position it will have during the SE tests. Strap the shell of the dummy load coaxial connector to the shell or frame of the GTEM feed connector. This will establish a baseline of amplifier and cable leakage. This value is later called P_b.

Note: This baseline of amplifier and cable leakage is coherent with the leakage from inside the GTEM, and thus must be subtracted from the antenna output on a voltage basis rather than on a power basis to separate the actual shield leakage from the baseline energy on the framework and outside surfaces of the GTEM. This is done in equations (2), (3), (6), and (7) below.

7. Test each location recording the power output from the antenna. Use both polarizations of the LPA and Horn antennas, use vertical polarization of the rod (monopole) antenna, and use the polarizations shown in Figure 2 for the loop antenna.



* May be manually tunable generator

**If needed

Figure 1. Block Diagram of Test Set up.

8. Reduce the measured data to SE by using the following equations.

a. Below 30 MHz:

$$SE = P_T - A_o - AF - P_a, \ dB \tag{1}$$

$$P_a = 20 \log (10^{0.05Pm} - 10^{0.05Pb}), \tag{2}$$

if P_b is above noise floor of analyzer.

Otherwise,

$$P_a = 10 \log (10^{0.1Pm} - 10^{0.1Pn}), \tag{3}$$

if P_n (noise floor) is within 10 dB of P_m.

If $P_m = P_n$, then $P_a = P_m$,

and the resulting "SE" value is recorded as "limited by dynamic range."

Note: Since the shield leakage is not discernible above the ambient noise, this measurement does not represent the true shielding effectiveness of the GTEM and should not be recorded as such.

In the above and subsequent equations:

P_T is the net power into the GTEM in dBm;
A_o is the normal space attenuation (defined in Appendix B) in dB;
AF is the antenna factor or the rod in dB(1/m), or the loop in dB(S/m), as appropriate;
P_a is the corrected antenna power output, dBm;
P_b is the baseline power output from the antenna, dBm; and,
P_m is the power output from the antenna during SE measurements, dBm.

$$SE_{avg} = P_T - A_o - AF - 10 \log \sum_{i=1}^{n} (p_a)_i/n \tag{4}$$

where: $(p_a)_i$ is the ith position corrected antenna output in mW.

A_o = -8 dB for electric field measurements; and,
A_o = 44 dB for magnetic field measurements.

b. Above 30 MHz:

$$SE = P_T + G_r - A_o - P_a \tag{5}$$

where: G_r is the gain of the antenna.

$$P_a = 20 \log (10^{0.05Pm} - 10^{0.05Pb}), \tag{6}$$

if P_b is above noise floor of analyzer.

Otherwise,

$$P_a = 10 \log (10^{0.1Pm} - 10^{0.1Pn}), \tag{7}$$

if P_n (noise floor) is within 10 dB of P_m.

If $P_m = P_n$, then $P_a = P_m$,

and the resulting "SE" value is recorded as "limited by dynamic range."

Note: Since the shield leakage is not discernible above the ambient noise, this measurement does not represent the true shielding effectiveness of the GTEM and should not be recorded as such.

$$SE_{avg} = P_T + G_r - A_o - 10 \log \sum_{i=1}^{n} (p_a)_i/n \tag{8}$$

Freq.	350 MHz	900 MHz	9.5 GHz	17 GHz
A_o	17 dB	22 dB	40 dB	44 dB

c. Data Reduction Note: When the measurement instrument noise floor or the base-line power P_b is equal to the measured power P_m, use only the level which sets the noise or base-line level as P_a in equations (1) and (5). If the base-line level is higher than a clearly measured P_m, use the measured value of P_b in place of P_a in equations (1) and (5).

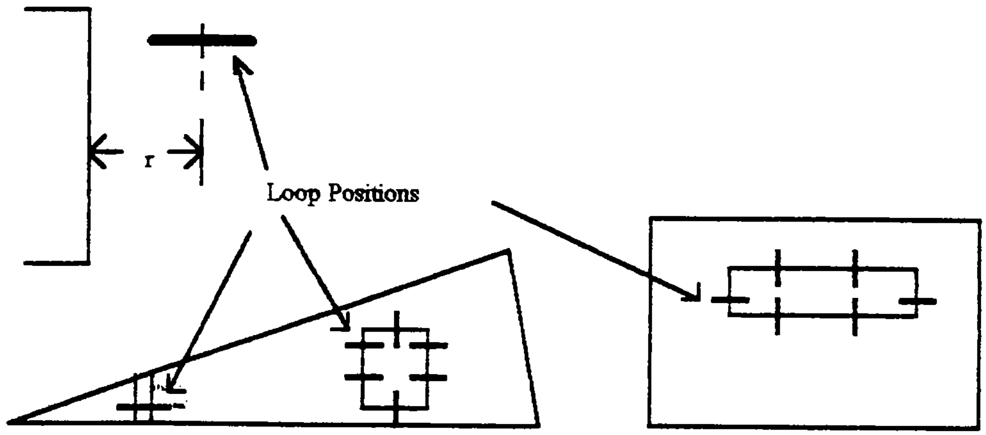
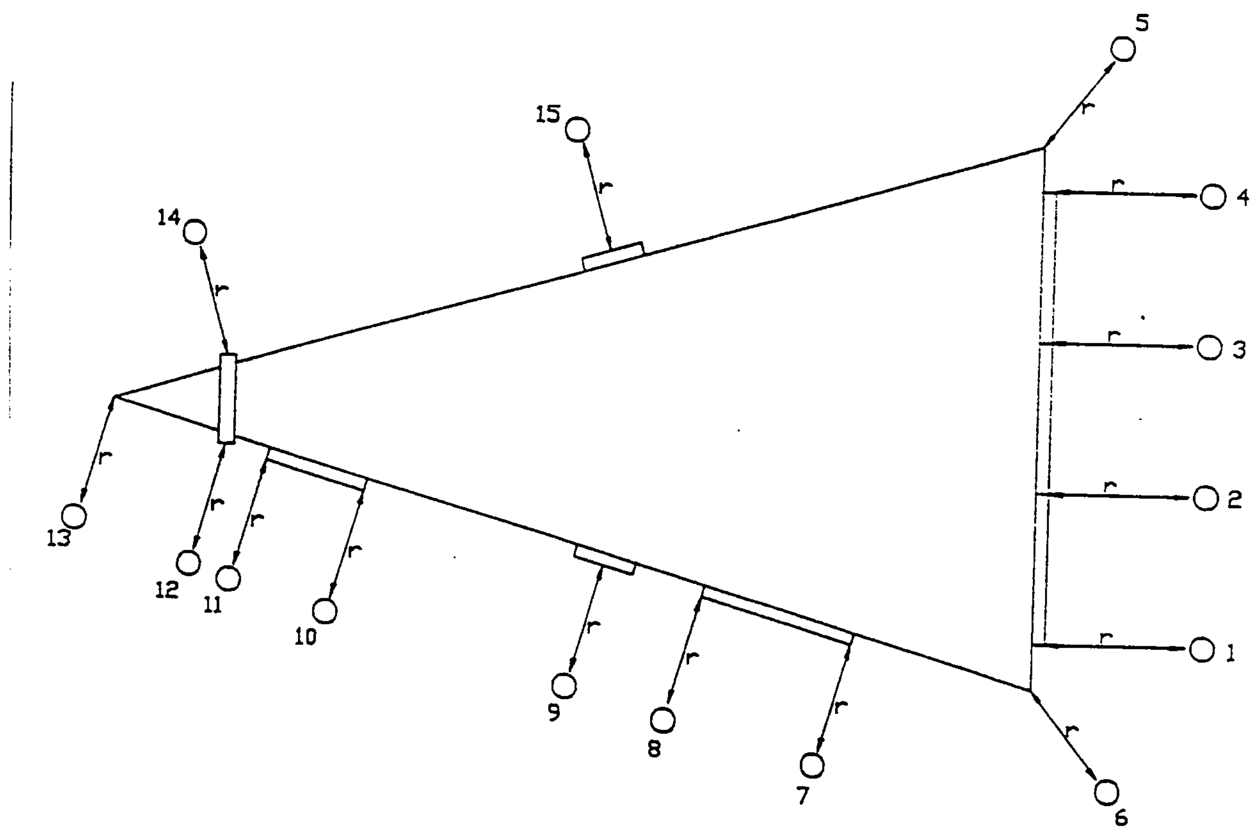


Figure 2. Positions of loop antennas. Position the loop with its plane both perpendicular to and parallel with the cell wall. Use similar positions around all doors, windows, vents, and other access panels in the sides of the cell. r = 0.5 m



Note: Positions found in step 6.a. should also be used, including positions on the top and bottom of the cell, if accessible by the antennas.

Figure 3. Positions around GTEM for rod, LPA, and horn antennas. For the LPA and horn antennas, r = 1 m; for the rod antenna, r = 0.5 m.

APPENDIX A

Instrument Sensitivity Needed For Measuring 100 dB Of Shielding Effectiveness

This tabulation is based on amplifiers which will provide 400 W from 10 kHz to 1 MHz, 50 W from 1 MHz to 1 GHz, and 10 W from 1 GHz to 18 GHz. In the equation below, all values are in dBm or dB. The factors in the equation are the power available for transmission, the effective initial path loss between the septum and the measurement antenna, the desired 100 dB of shielding effectiveness, and 6 dB of signal to noise ratio.

$$P_{sens} = P_T - SE_o - 100 - 6, \text{ dBm}$$

Frequency	P_T	SE_o	P_{sens}	HP 856x Sens.
15 kHz	400 W	H: 57 dB E: 73 dB	H: -106 dBm E: -123 dBm	-109 dBm in 3 kHz -129 dBm in 30 Hz
150 kHz	"	H: 43 dB E: 52 dB	H: -92 dBm E: -102 dBm	-104 dBm in 10 kHz
15 MHz	50 W	H: 26 dB E: 15 dB	H: -85 dBm E: -104 dBm	-104 dBm in 10 kHz
350 MHz	"	13 dB	-71 dBm	-94 dBm in 100 kHz
900 MHz	"	16 dB	-74 dBm	-94 dBm in 100 kHz
9.5 GHz	10 W	28 dB	-101 dBm	-82 dBm in 1 MHz
17 GHz	"	31 dB	-104 dBm	-82 dBm in 1 MHz

A low-noise preamplifier will be needed for measurements at 9.5 GHz and 17 GHz to measure shielding effectiveness values of 100 dB. If preamplifier/spectrum analyzer has a total noise figure of 6 dB, the sensitivity will be -108 dBm. This can be achieved with a preamplifier having a noise figure of 3.7 dB and a gain of 30 dB. If only 80 dB of shielding effectiveness is to be measured, a preamplifier will not be needed.

An improvement in sensitivity can also be achieved by using the "max hold" feature of the spectrum analyzer. This can improve the sensitivity by several decibels, but the total amount of improvement is dependent on the characteristics of the ambient noise. Sensitivity can be improved as much as 10 dB, 20 dB, or more by using a tracking generator or a very stable signal generator and narrowing the bandwidth of the spectrum analyzer.

APPENDIX B

Development of A_0 and Other Factors for GTEM Cell SE Measurements

Magnetic Field

The current on the septum of the GTEM cell induces a magnetic field about it. If the septum were not contained within the walls of the cell, one could place a loop antenna near the septum and measure the magnetic field. However, the walls provide shielding for the septum. The magnetic field induced around the septum by the current on it induces voltage across the walls. This voltage in-turn induces a current on the outside of the walls due to the transfer impedance of the material from which the walls are made. This current on the outside surfaces of the cell then induces a magnetic field around it. The ratio of the magnetic field which could be measured without the walls to the field which is actually measured with the walls is the shielding effectiveness of the cell. The loop antenna used for the measurements would normally be placed about 0.5 m from the septum, if there were no walls and ceiling, and it is placed 0.5 m from the outside surfaces of the cell in the measurements.

The procedure, then, depends upon the calculated value of the magnetic field near the septum and the measured magnetic field outside of the cell. The necessary constants and coefficients are developed below.

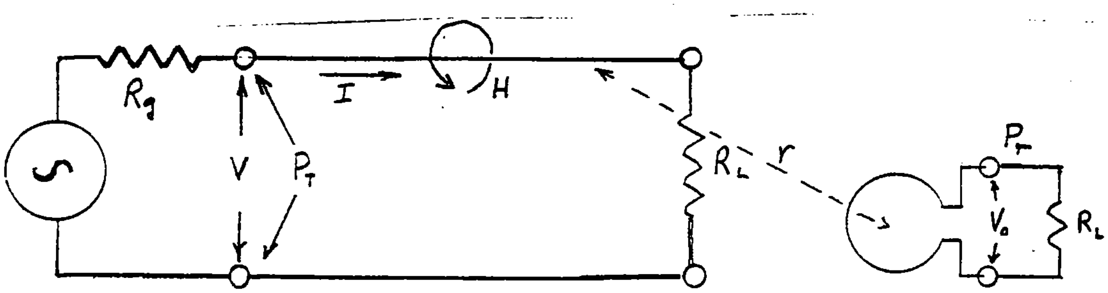


Figure B1. Circuit Model for Magnetic Field SE Measurements

For Transmit:

$I = \sqrt{(p_T/R_L)}$, for $R_L = R_g$

$H = I/(2\pi r)$

For Receive:

$p_r = V_0^2/R_L$

$V_0 = H/af_H$

af_H is the loop antenna factor in S/m

The power that would be received in absence of the cell walls and ceiling is defined by:

$$p_r = (H/af_H)^2 \bullet 1/R_L = I^2/(2\pi r)^2 \bullet 1/R_L \bullet 1/af_H^2$$

$$p_r = p_T/R_L \bullet 1/(2\pi r)^2 \bullet 1/R_L \bullet 1/af_H^2$$

Defining a_o:

$$p_T/p_r = R_L^2 (2\pi r)^2 af_H^2 = a_o af_H^2$$

$$\therefore a_o = R_L^2 (2\pi r)^2$$

Defining unshielded path loss, se_o:

$$se_o = a_o af_H^2$$

Define shielding effectiveness (se = shielded path loss ÷ unshielded path loss) from power transmitted and power actually received with GTEM cell walls and ceiling in place.

$$se = p_T/p_a \bullet 1/se_o$$

In dB,

$$SE = 10 \log[p_T/p_a] - 10 \log[se_o], \text{ or}$$

$SE = P_T - P_a - A_o - AF_H$, which allows different loop antennas to be used.

Note: Capital letters designate values in dB, e.g., $P_T = 10 \log[p_T]$ in dB(W). Units must agree, i.e., if P_a is expressed in dBm then P_T must also be expressed in dBm.

Using EMCO Models 6511 and 6512 passive loop antennas at a distance of r = 0.5 m, and assuming the nominal 50 Ω GTEM cell impedance, the following table is produced for A_o and SE_o.

FREQ. Hz	AF_H dB(S/m)	A_o dB	SE_o dB
15 k	13	44	57
150 k	-1	44	43
15 M	-18	44	26
Calc.:	Col. 2 + Col. 3 = Col. 4		

Electric Field

Similar arguments are made about the electric field shielding effectiveness of the GTEM cell. The current on the septum of the cell induces an electric field adjacent to it. If the septum were not contained within the walls of the cell, one could place an electric antenna near the septum and measure the electric field. However, the walls provide shielding for the septum. The electric field induced adjacent to the septum by the current on it induces a current in the walls. This current in turn induces a voltage on the outside of the walls due to the transfer impedance of the material from which the walls are made. This voltage on the outside surfaces of the cell then induces an electric field adjacent to it. The ratio of the electric field which could be measured without the walls to the field which is actually measured with the walls is the shielding effectiveness of the GTEM cell. The electric (rod or monopole) antenna used for the measurements would normally be placed about 0.5 m from the septum, if there were no walls and ceiling, and it is placed 0.5 m from the outside surfaces of the GTEM cell in the measurements.

The procedure, then, depends upon the calculated value of the electric field near the septum and the measured electric field outside of the cell. The necessary constants and coefficients are developed below.

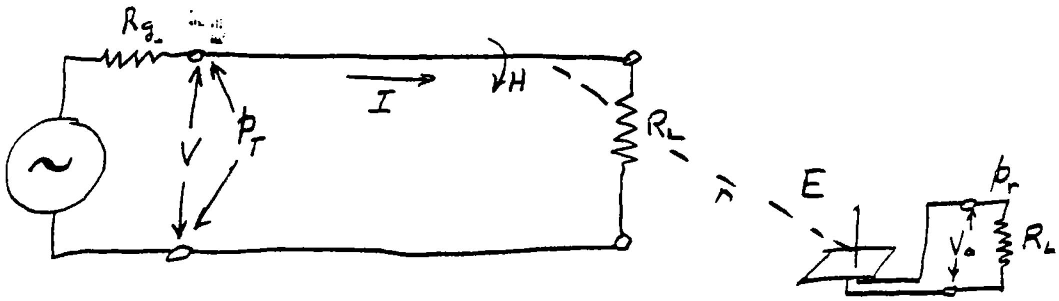


Figure B2. Circuit Model for Electric Field SE Measurements

For Transmit:

$I = \sqrt{(p_T/R_L)}$, for $R_L = R_g$

$E = H\eta = I\eta/(2\pi r)$, $(\eta = \sqrt{120\pi})$

For Receive:

$V_o = E/af_E$

$p_r = V_o^2/R_L$

Define power that would be received in the absence of GTEM cell walls and ceiling:

$$p_r = I^2\eta^2/[(2\pi r)^2\, af_E^2\, R_L]$$

$$p_r = (p_T/R_L)\,\{\eta^2/[(2\pi r)^2\, af_E^2\, R_L]\}$$

Define unshielded path loss:

$$p_T/p_r = [R_L^2(2\pi r)^2/\eta^2] \bullet af_E^2$$

Define se_o and a_o for E-Field measurement:

$$a_o = [R_L^2(2\pi r)^2/\eta^2]\text{, and}$$

$$se_o = a_o \bullet af_E^2$$

Define shielding effectiveness (se = shielded path loss ÷ unshielded path loss) from power transmitted and power actually received with GTEM cell walls and ceiling in place.

$$se = (p_T/p_a) \bullet 1/a_0 \bullet 1/af_E^2$$

In dB:

$$SE = P_T - P_a - A_0 - AF_E,$$ which allows different rod antennas to be used.

Using EMCO Model 3303 passive rod antenna at a distance of r = 0.5 m, and assuming the nominal 50 Ω GTEM cell impedance, the following table is produced for A_0 and SE_0.

FREQ. Hz	AF_E dB(1/m)	A_0 dB	SE_0 dB
15 k	81	-8	73
150 k	60	-8	52
15 M	23	-8	15
Calc.:	Col. 2 + Col. 3 = Col. 4		

Plane Wave (Above 30 MHz)

In this case, the septum is treated as a traveling wave (beverage-type) antenna. In this frequency range, the Friis transmission equation describes the power transfer between two antennas. The ratio of power which would be received without the walls and ceiling of the GTEM cell to power received in actual measurements is the shielding effectiveness.

$$p_r/p_T = (\lambda/4\pi r)^2 g_T g_r,$$ (Friis equation)

Define for plane waves:

$$a_0 = (4\pi r/\lambda)^2/g_T$$

Define the unshielded path loss:

$$se_0 = p_T/p_r = a_0/g_r$$

Define shielding effectiveness (se = shielded path loss ÷ unshielded path loss) from power transmitted and power actually received with GTEM cell walls and ceiling in place.

$$se = p_r/p_a = (p_T/p_a)(g_r/a_0)$$

In dB:

$$SE = P_T - P_a + G_r - A_0$$

Using EMCO Model 3115 double ridged guide antenna at a distance of r = 1.0 m, and assuming the nominal 50 Ω GTEM cell impedance, the following table is produced for A_0 and SE_0. The values of G_T are for a beverage-type long wire antenna as a model for the septum of the cell.

Freq. MHz	AF dB(1/m)	G_r dB	G_T dB	A_0 dB	SE_0 dB
350	18	4	6	17	13
900	24	6	11	21	15
9500	38	12	12*	40	28
17000	42	13	12*	45	32

* Gain of a beverage antenna tends to stabilize or drop off at higher frequencies, and is not likely to be higher than the gain of the horn antenna. G_T was calculated on basis of 4 m long septum. A_0 for several lengths of septum is shown in the graph in Figure 4. $SE_0 = A_0 - G_r$

Gain of Septum above 30 MHz

The gain of the septum of the GTEM cell is based upon the gain of a Beverage traveling wave (type of long-wire) antenna. A graph of A_0 versus septum length is shown below. The high limiting value of A_0 is based on the assumption that the septum has gain no greater than a resonant dipole, while the low limiting value is based on the assumption that the gain of a Beverage antenna is not greater than about 12 dB referenced to isotropic. The two limiting curves are 12 dB apart, asymptotically.

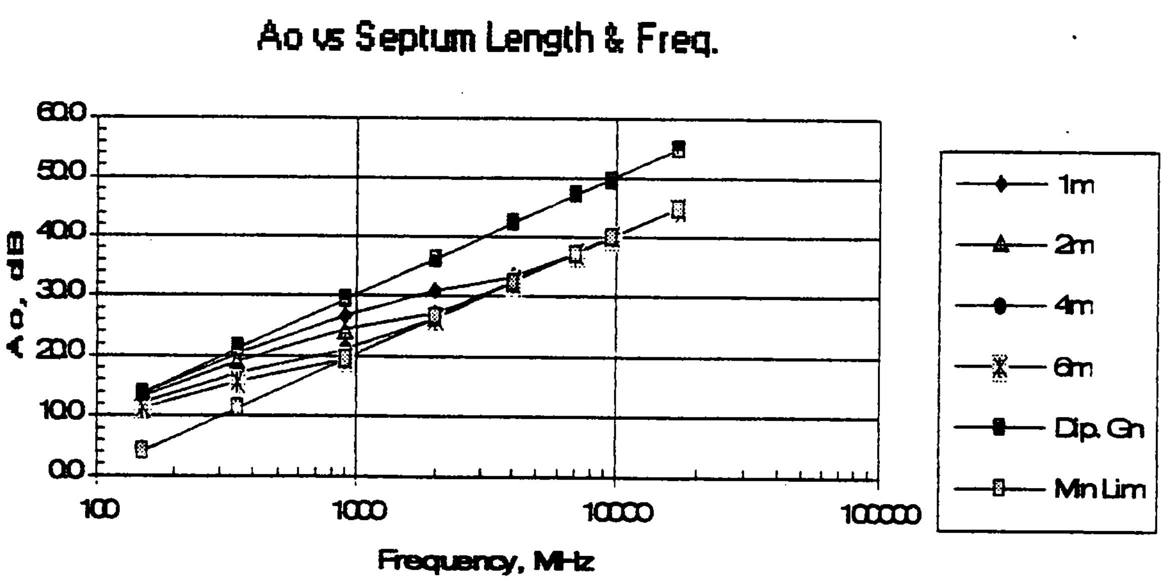


Figure 4. Values of A_0 versus Septum Length, and Limiting Values of A_0.

Amplifier Leakage onto Frame of GTEM Cell

The shielding effectiveness of TEM cells of any kind is generally superior to that of the power amplifiers which are likely to be used in the shielding effectiveness measurements. Thus, correction must be made for the extraneous fields caused by the leakage of RF from the amplifier onto the outside of the shielded cable and then onto the outside surface of the GTEM cell. Since the signal on the outside of the cell, the baseline signal p_b or v_b, is coherent with any signal leaking from inside of the cell, this baseline signal must be subtracted on a voltage basis from the signal measured during the test to correct for the amplifier leakage. Development of this subtraction equation is shown below.

$$v_a = v_m - v_b$$

$$v_m = 10^{V_m/20}$$

V_m is converted from dBm to dB(μV) in 50 Ω by:

$$V_m = P_m + 107$$

$$v_m = 10^{(P_m+107)/20} = 10^{P_m/20} \bullet 10^{107/20}$$

$$v_b = 10^{V_b/20} = 10^{(P_b+107)/20} = 10^{P_b/20} \bullet 10^{107/20}$$

$$v_a = 10^{107/20}[10^{P_m/20} - 10^{P_b/20}]$$

$$p_a = (v^2 \bullet 10^{-12}/50) \bullet 10^3 = v_a^2 \bullet 10^{-9}/50\text{, in mW}$$

$$P_a = 10\log[p_a] = 20\log[v_a] + 107$$

$$P_a = V_a + 107 = 107 + 20\log[10^{P_m/20} - 10^{P_b/20}] - 107$$

$$\therefore P_a = 20\log[10^{P_m/20} - 10^{P_b/20}]$$

If the baseline radiation is included in the spectrum analyzer noise floor, then a power addition of p_b and p_n must be made.

$$p_{amb} = p_n + p_b$$

$$P_{amb} = 10\log p_{amb}$$

$$p_a = p_m - p_{amb} = p_m - p_n - p_b$$

$$P_a = 10\log[10^{P_m/10} - 10^{P_b/10} - 10^{P_n/10}]$$