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REPORT NO. FAA-RD-76-68

SURVEY OF GROUNDING, BONDING, AND SHIELDING PRACTICES

H. W. Denny
J. A. Woody

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FINAL REPORT

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16. Abstract

In May 1974 detailed surveys were made of the grounding, bonding, shielding, and lightning protection networks in FAA facilities at Hartsfield International Airport, Atlanta, GA and in selected AF facilities at Robins AFB, GA and Aiken AFS, Aiken, SC. At the facilities the earth electrode system, the lightning protection system, fault protection and signal ground networks, bonding practices, and facility shielding were evaluated. Similarly, the equipments in each facility were examined to determine the grounding procedures used for both low frequency and high frequency signals, the type of signal interfacing used, the bonding practices employed, and the type of shielding available for both personnel protection and EMI control. This report presents the findings of the surveys, compares the existing networks and practices with those which have been recommended for new facilities, and suggests corrective measures for the noted deficiencies.

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METRIC CONVERSION FACTORS

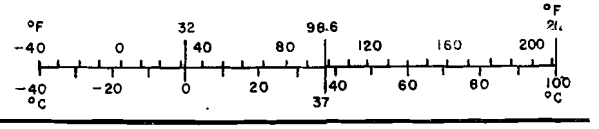
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find
		LENGTH	
mm	millimeters	0.04	inches
cm	centimeters	0.4	inches
m	meters	3.3	feet
m	meters	1.1	yards
km	kilometers	0.6	miles
		AREA	
cm^2	square centimeters	0.16	square inches
m^2	square meters	1.2	square yards
km^2	square kilometers	0.4	square miles
ha	hectares (10,000 m^2)	2.5	acres
		MASS (weight)	
g	grams	0.035	ounces
kg	kilograms	2.2	pounds
t	tonnes (1000 kg)	1.1	short tons
		VOLUME	
ml	milliliters	0.03	fluid ounces
l	liters	2.1	pints
l	liters	1.06	quarts
l	liters	0.26	gallons
m^3	cubic meters	35	cubic feet
m^3	cubic meters	1.3	cubic yards
		TEMPERATURE (exact)	
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature



FOREWORD

This report was prepared by the Electronics Technology Laboratory of the Georgia Tech Engineering Experiment Station for the Federal Aviation Administration under Contract No. DOT-FA72WA-2850 with cosupport from the Air Force Communications Service. Technical cognizance of the program was provided by Mr. Raymond R. Barkalow, ARD-354, of FAA. It was written under the general supervision of Mr. D. W. Robertson, Director of the Electronics Technology Laboratory. The principal author is Mr. H. W. Denny, Senior Research Engineer and Head of the EMC Group.

This report is in response to Paragraph 4.2 of the Engineering Requirement, FAA-ER-650-012a, of the contract which calls for a survey of the bonding, grounding, shielding, and lightning protection networks at the FAA facilities at Hartsfield Airport in Atlanta, Georgia and at selected AF facilities located at Robins AFB, Warner Robins, Georgia and at Aiken AFS, Aiken, South Carolina.

ACKNOWLEDGEMENTS

Most of the detailed inspection and testing of the grounding, bonding, shielding, and lightning protection networks at the various facilities were performed by Mr. J. A. Woody, Research Engineer, and Mr. Richard S. Smith, Assistant Research Engineer, of the EMC Group at Georgia Tech. Mr. Woody did much of the reduction of data and prepared the initial summary of findings. He assisted in the formulation of the overall conclusions and recommendations arising from the surveys and contributed to the writing of this report.

The assistance of Mr. Barkalow, the FAA technical monitor, and Mr. Warren Keller, EPEUM, of Air Force Communications Service in the selection of survey sites, overall planning of the surveys, and administrative coordination of the site visits is acknowledged.

A specific note of appreciation is extended to the several FAA and AF personnel who cooperated in and assisted with the surveys at the various sites. In particular, Mr. C. E. Elmore, ASO-441.6, FAA Southern Regional Headquarters, and Mr. Byron Matthews, Navaids Unit Supervisor, Airways Facilities Section, Atlanta Airport, provided considerable help in the planning and conduct of the surveys at the FAA facilities. Likewise, the assistance provided by Sgt. Hamm of 1926 Communications Squadron at Robins AFB and by Lt. Michael Allen of the 861 Radar Squadron at Aiken AFS was instrumental in assuring the success of the surveys at the AF facilities.

TABLE OF CONTENTS

	Page
1. INTRODUCTION	1
2. SURVEY FINDINGS	1
2.1 Hartsfield International Airport	1
2.1.1 ATCT	2
2.1.1.1 Earth Electrode System	2
2.1.1.2 Safety Grounding	2
2.1.1.3 Signal Grounding	8
2.1.1.4 Bonding and Shielding	10
2.1.1.5 Lightning Protection	12
2.1.2 Airport Surveillance Radar, ASR-7	12
2.1.3 Instrument Landing Systems	16
2.1.4 Remote Transmit/Receive (RTR) Sites	21
2.1.5 VORTAC Site	23
2.1.6 Other Facilities	23
2.2 Robins Air Force Base	24
2.2.1 Communications Center	24
2.2.2 Flight Line Facilities	28
2.3 Aiken Air Force Station	33
2.3.1 AN/FPS-7 Search Radar	33
2.3.2 AN/FPS-26 Height Finder Radar	34
2.3.3 Ground-Air Transmit/Receive (GATR) Site	36
2.4 Summary of Findings	38
3. DISCUSSION OF FINDINGS AND SPECIFIC RECOMMENDATIONS FOR CORRECTIVE ACTION	41
3.1 Earth Electrode Systems	42
3.2 Lightning Protection	44
3.3 Power Safety Grounding	49
3.4 Signal Grounding	51
3.5 Bonding	53
3.6 Shielding	54
3.7 Supplemental Comments	56
4. OVERALL RECOMMENDATIONS	57
APPENDIX A	A-1

LIST OF FIGURES

Page

1. General Plan View of Atlanta's Hartsfield International Airport 3
2. Layout of Earth Electrode System for the Hartsfield Terminal Building. 4
3. Single Line Diagram of Safety Ground Network for Communications Area and ATCT Circuit No. 6 (Atlanta Tower) 5
4. Grounding Network Configuration in Communications Equipment Area (Atlanta Tower) 7
5. ARTS-I Equipment Grounding Scheme 9
6. An Example of Improperly Cleaned (Paint Not Removed) Surface Prior to Bonding. 11
7. Typical Low Frequency Cabling Practices 11
8. Ground Rod Configuration at ASR-7 Site. 13
9. Earth Resistance Curves for ASR-7 15
10. Radar System Interference Arising from Citizens Band Transceiver 17
11. Results of Earth Resistance Measurement at Localizers 9R and 33 . 18
12. Example of An Improper Bond at Glide Slope 33 20
13. Severely Corroded Ground Rod Connection at Glide Slope 33 20
14. Excessively Long Shield Pigtails on Low Frequency Cables at RTR-D 22
15. Severely Corroded Bonds at Compass Locator Site 25
16. An Example of Damage to Unprotected Grounding Wire. 25
17. Configuration of TEMPEST Earth Ground at Communications Center (Robins AFB). 27
18. Logic Ground Configuration in Communications Center 29
19. Inter-Equipment Cabling Practices 30
20. Coaxial Cable Grounding Practices 30
21. Earth Resistance Data for AN/MRN-7 Localizer (Robins AFB) 32
22. Tower Grounding for the AN/FPS-7 Search Radar (Aiken AFS) 35
23. Representative Bond in Equipment Grounding Network in the AN/APS-7 Tower. 35
24. Lightning Arrester Installation on RF Antenna Leadin. 37
25. Damaged Lightning Down Conductor. 37
26. Examples of Good Cable Tray Bonding Practices 39

1. INTRODUCTION

Surveys were conducted at Hartsfield International Airport in Atlanta, GA, at Robins Air Force Base, GA, and at Aiken Air Force Station in Aiken, SC during May 1974. These surveys consisted of an examination of the grounding, bonding, shielding, and lightning protection practices at selected major facilities at each of the above locations. The earth electrode system, lightning protection system, fault protection and signal ground networks, bonding practices, and facility shielding were evaluated in terms of the recommendations contained in Report No. FAA-RD-75-215, "Grounding, Bonding, and Shielding Practices and Procedures for Electronic Facilities and Equipments" (subsequently referred to herein as GBS Practices and Procedures). Similarly, the equipments in each facility were examined to determine the grounding procedures used for both low frequency and high frequency signals, the type of signal interfacing used, bonding practices employed, and the type of shielding available for both personnel protection and EMI control.

As an aid for use during the surveys, a survey form or worksheet was prepared. A copy of the survey form is included as an appendix. This form was employed to help remind the surveyors of topics to cover and things to look for and to provide a convenient place to make notes and to record observations.

2. SURVEY FINDINGS

2.1 Hartsfield International Airport

The air traffic control tower (ATCT) and other major elements which support the control of air traffic in the Hartsfield terminal area were surveyed. The supporting facilities included (1) the ASR-7 airport surveillance radar, (2) one VORTAC, (3) several instrument landing system (ILS) components, (4) one approach lighting system (ALS), (5) two runway visual range (RVR) sites, (6) two remote transmitter-receiver (RTR) sites, and (7) a compass locator site.

2.1.1 ATCT

The Hartsfield control tower which was surveyed is located within the main airport terminal complex* as shown on Figure 1. The equipment rooms, located on the eighth floor of the tower, and the tower cab were included in the survey. The power vault on the ground floor along with selected elements of the terminal's electrical distribution system (city-owned) were also examined.

For the tower proper, the earth electrode system and the lightning protection system were evaluated. Signal and safety grounding practices were analyzed, and measurements of the resistance between selected points on the ground networks in the equipment room were made. Sample measurements were also made of stray current levels in ground safety wires.

2.1.1.1 Earth Electrode System

The grounding network for the tower consists of clusters of three 10-foot ground rods distributed around the entire terminal building as shown on the drawing in Figure 2. This drawing indicates that the earth electrode system for the terminal complex consists of a peripheral loop of No. 4/0 stranded bare copper cable interconnecting a total of 153 3/4 in. x 10 ft. copper clad ground rods. The main I-beams for the tower are bonded to this peripheral ground loop.

The grounding system was not accessible for either inspection or for testing. Risers connected directly to the ground rods and the peripheral cable are accessible, but the soil in the vicinity of the terminal is covered with pavement and is not accessible. Thus, the resistance to earth provided by the tower's electrode system could not be measured.

2.1.1.2 Safety Grounding

The electrical safety grounding network associated with one of the main feeder circuits to the eighth floor is shown in Figure 3. The focal point of the electrical safety ground network is a silver bus bar

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*Shortly after the conduct of this survey, construction of a new control tower was begun.

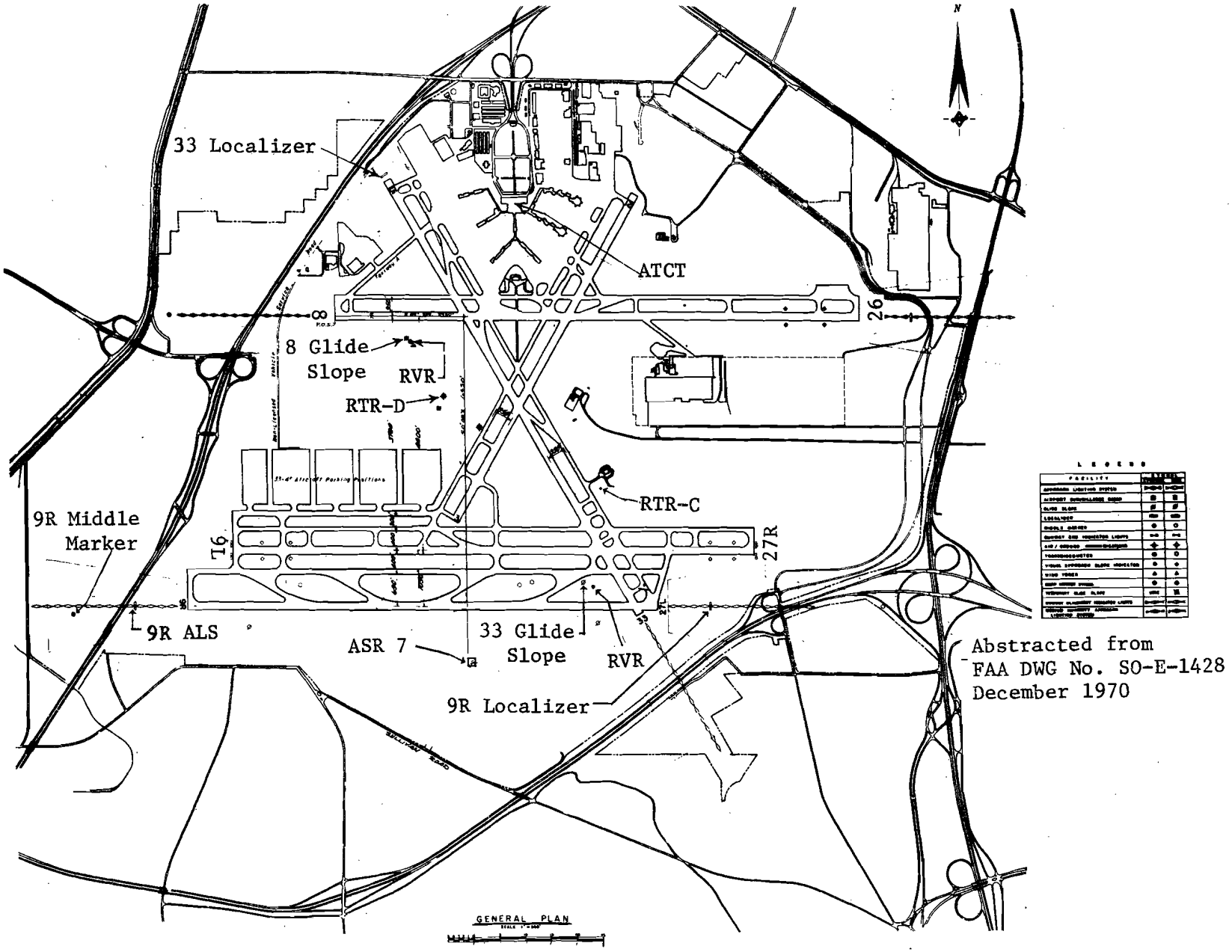
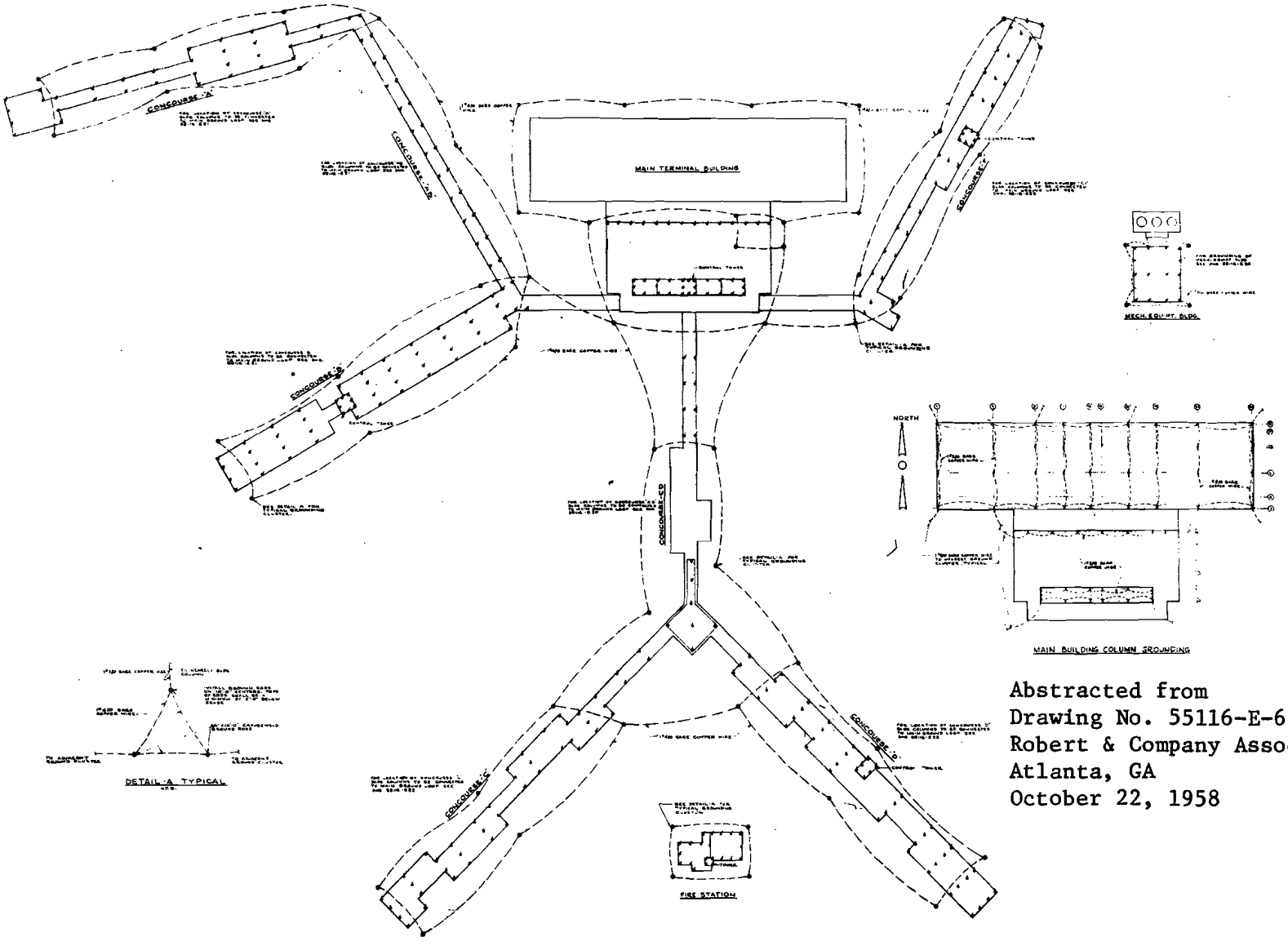


Figure 1. General Plan View of Atlanta's Hartsfield International Airport



Abstracted from
Drawing No. 55116-E-6
Robert & Company Assoc.
Atlanta, GA
October 22, 1958

Figure 2. Layout of Earth Electrode System for the Hartsfield Terminal Building.

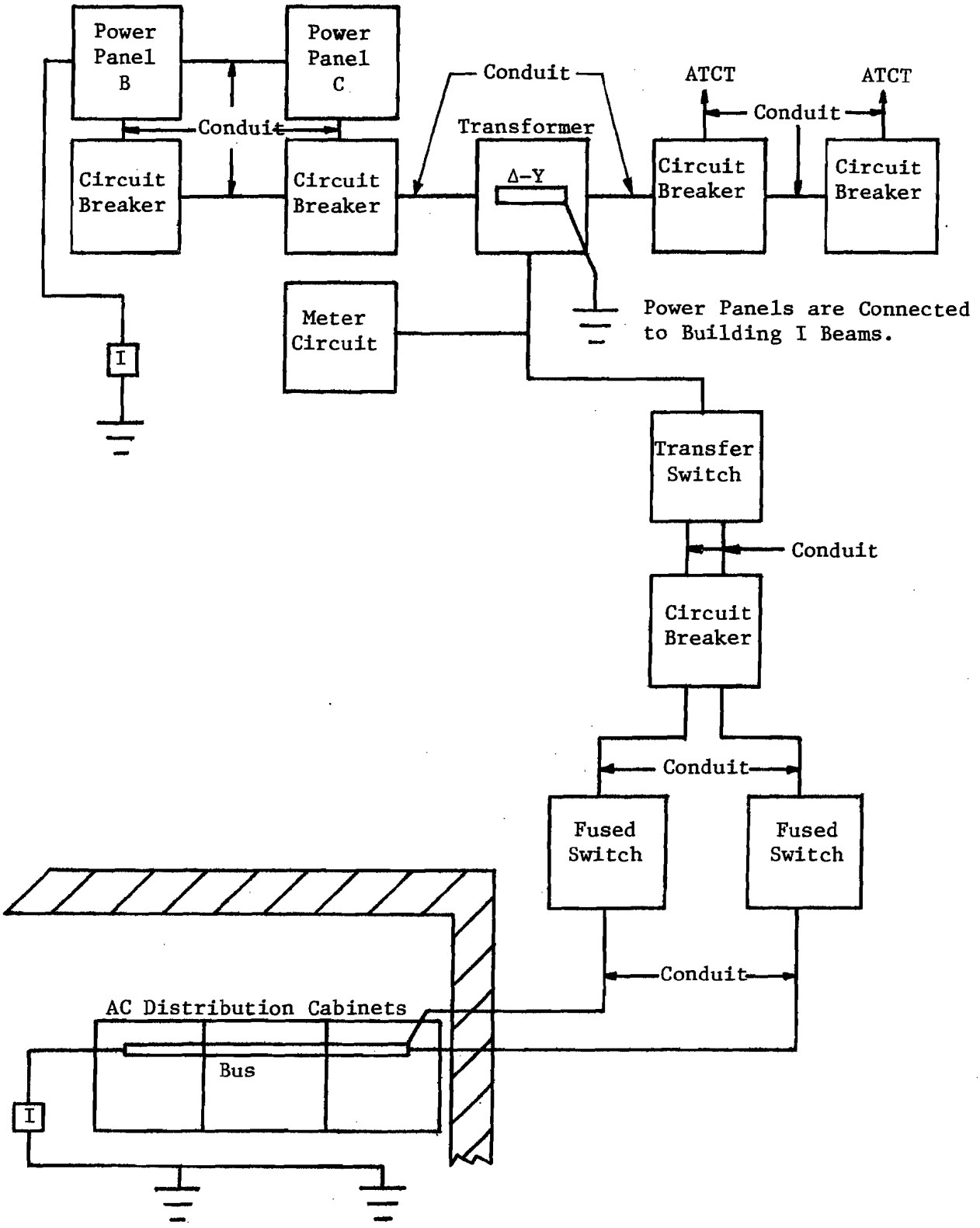


Figure 3. Single Line Diagram of Safety Ground Network for Communications Area and ATCT Circuit No. 6 (Atlanta Tower).

interconnecting the electrical distribution cabinets in the (city-owned) power vault. This bus bar is bonded to a building column and to the peripheral ground loop.

AC power for FAA equipment is delivered to the eighth floor with a pair of three-phase, 400-volt delta circuits. The 4-inch conduit surrounding the circuit conductors is bonded to the silver bus bar located in the power vault. A separate grounding bus is not provided between the power vault and the step down transformers on the eighth floor.

An auxiliary path to earth is shown on facility drawings as being available through structural steel elements, primarily the vertical I-beams. The secondary neutrals of the 440/220 transformers are connected to their respective cabinets. The cabinets in turn are shown on the drawings as being bonded to I-beams on the eighth floor. Thus, an additional fault clearance path back to the power vault ground bus is supposed to be provided by the tower columns. Attempts were made to obtain access to the steel I-beams in the equipment room in order to verify that the connections were, indeed, made between the transformer neutral, i.e., power ground, and the structural elements. These attempts were unsuccessful, and the connections could not be verified.

A No. 4/0 stranded cable provides the grounding connection between the transformer neutral and the main power distribution panels located inside the equipment room. This safety ground connection is extended to equipment racks with a No. 6 bare copper conductor routed through cable troughs and ducts. Typifying this extension is Figure 4 which schematically illustrates the configuration of the network in the communications equipment area.

Sample measurements of stray 60 Hz current levels at various points on the ground conductor network were made. Inside one power distribution panel the No. 6 bare copper conductor leading to two radar equipment bays had 3 amperes flowing in it. Similarly, one ampere was measured on a wire inside the power distribution box in the airport surface detection (ASDE) room. No effort was made to sample every ground wire for stray currents. Spot checks were made, however, of the stray current levels in the bare copper wires in the cable ducts above the equipment racks. No currents large enough to be measured with a clamp-on ammeter were found in these wires.

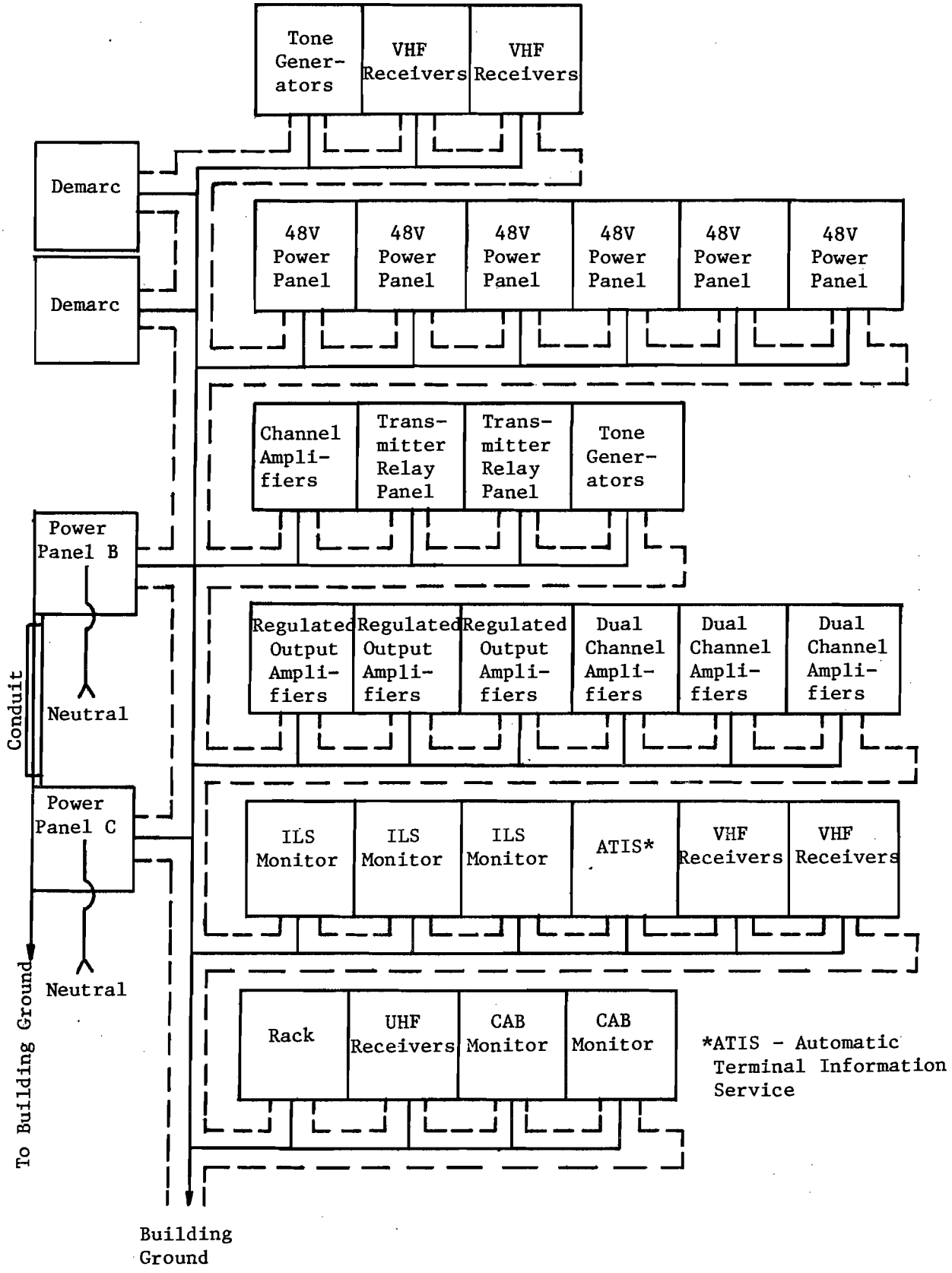


Figure 4. Grounding Network Configuration in Communications Equipment Area (Atlanta Tower).

2.1.1.3 Signal Grounding

Except for the ARTS-I network described in the next paragraph, no identifiable signal grounding networks separate from the safety ground network and the system of interconnected equipment racks were noted. Equipment chassis provide the signal reference points for both low and high frequency signals. For example, low frequency* signals such as those associated with audio communication, monitor, and control circuits are grounded to the chassis internal to the equipments. At the same time, high frequency signals, such as those associated with the RF portions of communications receivers, microwave equipment, etc., are also referenced (grounded) to chassis. The equipment chassis are fastened to the racks. The racks in turn are connected together and to the power panels through the cable ducts and raceways and with the No. 6 bare copper conductor. Thus, this interconnected metallic network serves as the equipment signal ground as well as the equipment safety ground.

A special grounding network configured as shown in Figure 5 has been installed for the ARTS-I system. Insulated No. 4/0 conductors extend from each equipment rack of the ARTS-I system to a common bus. This bus is mounted on insulators in a centrally located box. The No. 4/0 cable indicated in Figure 5 was described by FAA personnel as being connected to the structural steel building frame.**

Unfortunately, the intent of this single-point ground network has been compromised at several points. For example, the ARTS-I equipment cabinets are clustered in groups of three. On two of the three cabinets in a cluster the insulated ground wire is attached to an insulated terminal on the back of the cabinet. At the third cabinet, however, the ground wire is connected directly to an uninsulated stud. All three cabinets in turn are electrically interconnected through mounting bolts and through the cable tray assembly which is fastened to each cabinet. (Thus, the "isolated" ground network is, in fact, interconnected with all other cabinets, frames, ducts, power panels, etc. in the equipment room.)

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*Low frequency signals, as defined in Volume I, Section 7.3.4.3 of GBS Practices and Procedures are those signals below 1 MHz.

**This connection could not be verified.

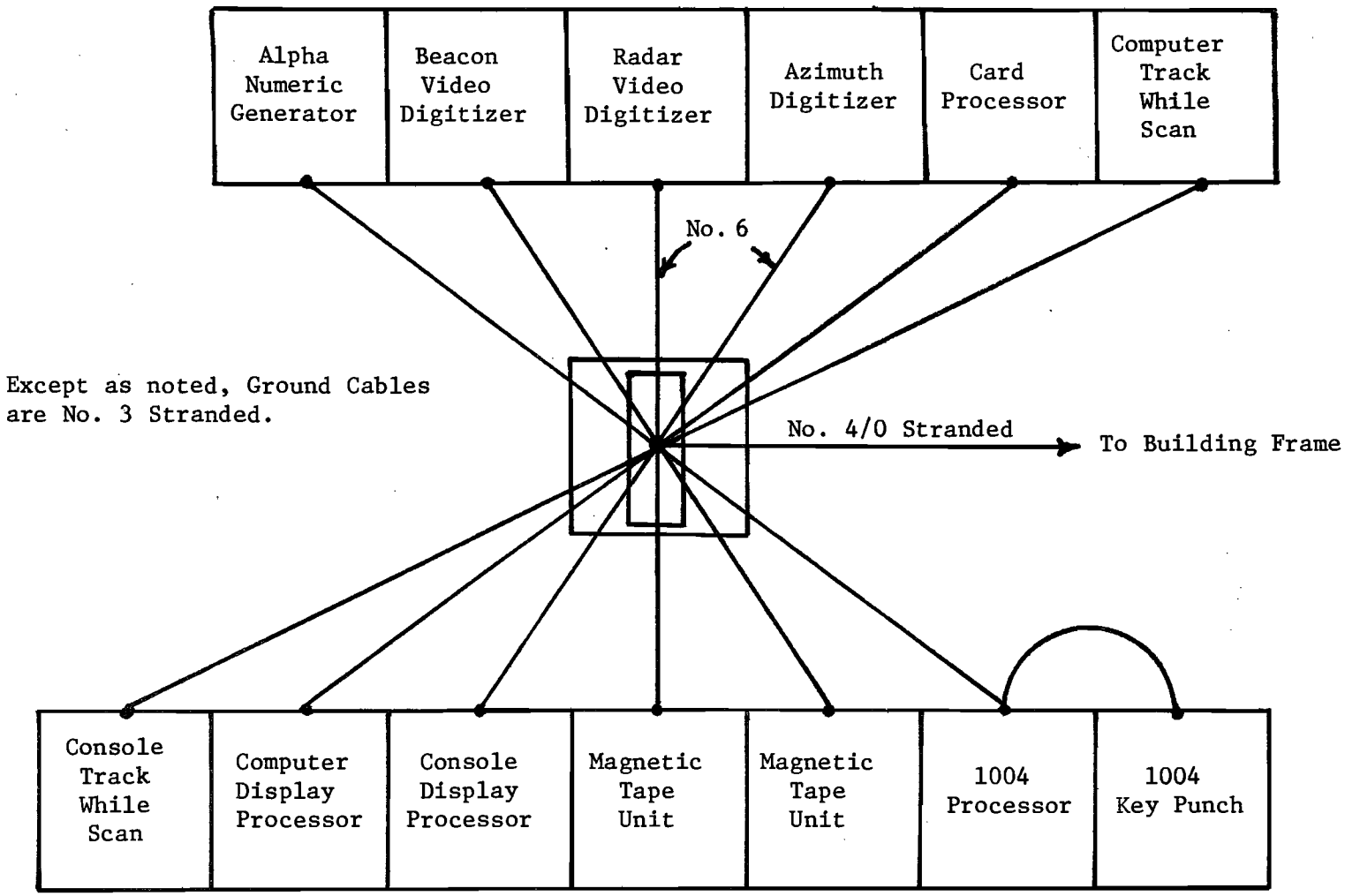

Figure 5. ARTS-I Equipment Grounding Scheme.

2.1.1.4 Bonding and Shielding

Visual inspections and electrical measurements were made on a representative number of bonds, both as implemented with direct metal-to-metal contact and with intermediate conductors such as bare No. 6 copper wires. Only one or two isolated instances were noted of specific deficiencies such as failure to clean surfaces before joining or failure to achieve and maintain adequate tightness at fasteners. As an example, Figure 6 shows a connection in a radar power distribution panel which was not properly cleaned prior to assembly. Several connections to the No. 6 bare copper conductor network described earlier were observed to be soldered. Physically, these and other connections appeared to be in good condition with little or no evidence of corrosion.

The resistance between the No. 4/0 copper building ground cable connection in power panel C and the No. 6 bare copper conductor in the duct above equipment bay No. 4 (see Figure 4) was measured to be 2.3 milliohms. Between this same No. 4/0 cable and an equipment case in Rack No. 3 of Bay 4, the resistance was measured to be 4.75 milliohms.

Equipments located within the ATCT in general are not intentionally designed to provide a high degree of electromagnetic shielding. Although most equipment cabinets and racks are not intentionally RF shielded, there was no evidence that any supplemental shielding was needed. Since all communication transmitters are at the RTR's (located 3/4 of a mile or more from the tower) and since other high power sources such as the ASR-7 transmitter and local commercial radio stations are either oriented away from the tower or are located at some distance away, the threat from high level RF signals is limited.

Most low frequency cable shields are not insulated*, as shown in Figure 7. Signal cable shields were noted to be grounded either to the chassis of the terminating equipment or to a distribution panel ground. Some cables leading to other sites (such as an ILS, the RTR, an RVR, etc.) were observed to have their shields grounded at the tower end while others

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*See discussion in Section 3.6.

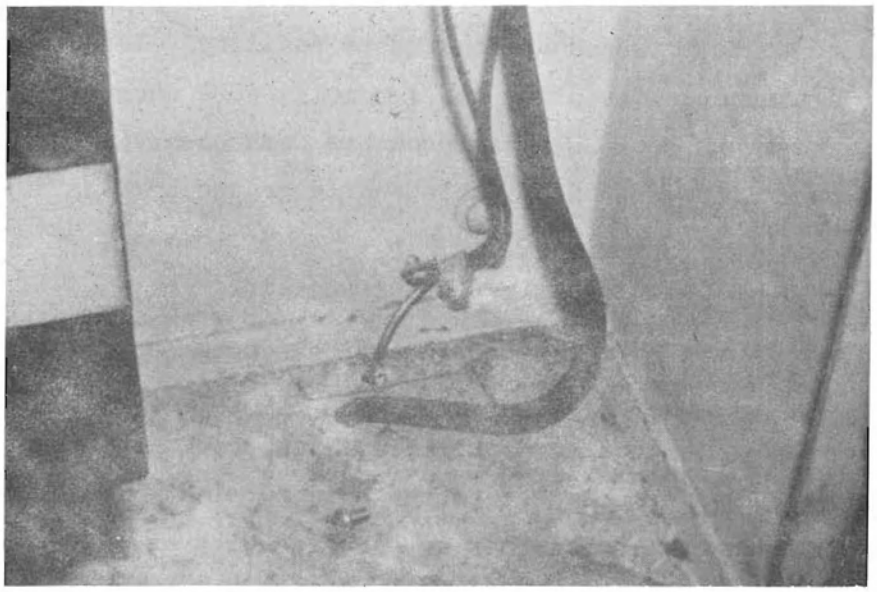

Figure 6. An Example of Improperly Cleaned (Paint Not Removed) Surface Prior to Bonding.

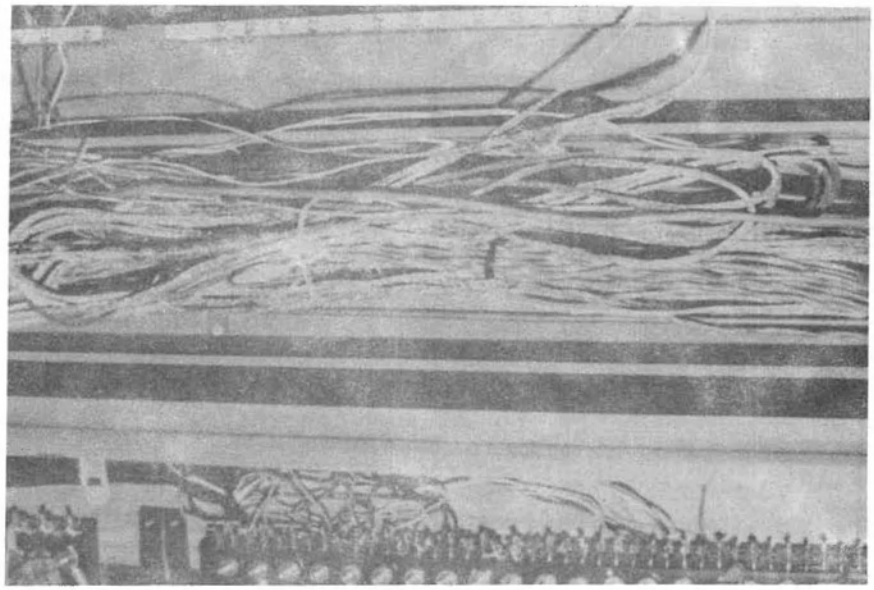

Figure 7. Typical Low Frequency Cabling Practices.

were noted to be grounded at the remote facility. Yet other cables routed between equipments within the tower complex were determined to be grounded on both ends. No serious noise problems were observed to exist as a result of this nonuniform method of cable shield grounding.

2.1.1.5 Lightning Protection

The lightning protection system for the tower consists of 10-inch air terminals distributed around the perimeter of the cab roof and around the edges of the tower building. Construction drawings indicate that these terminals are connected to the structural steel I-beams of the tower. The I-beams are bonded together at the base with No. 2/0 cables and are bonded to the encircling grounding conductor and then to the ground rods.

Gas tubes, such as the commercial NE-2 neon bulb, are used extensively for surge limiting at many terminal strips in the equipment room area. The bulbs are connected between each signal or control line conductor and a common No. 6 bare wire.

2.1.2 Airport Surveillance Radar, ASR-7

The ASR-7 site consists of (1) an antenna tower; (2) the building which houses the radar, beacon, and remote microwave link (RML) equipment; (3) the emergency power generator building; and (4) the commercial power transformer. The site is located on a manmade hill near Runway 9R on the south side of the airport (see Figure 1).

Thirty-eight, 3/4-inch by 10-feet, copper clad ground rods provide the earth electrode system for the site. The ground rods are distributed in the manner shown by Figure 8. They are interconnected with a bare No. 4/0 cable buried three feet deep. Connections are made to this electrode system at the power transformer, at the standby generator, and at one point inside the shelter. Two connections from the antenna tower are also made.

The resistance of this electrode system was measured with a No. 63220 Biddle Megger™ Earth Tester using the fall-of-potential method described in Section 1.7.2, Volume I, GBS Practices and Procedures. Connection to the earth electrode system was made inside the engine/generator van (marked

were noted to be grounded at the remote facility. Yet other cables routed between equipments within the tower complex were determined to be grounded on both ends. No serious noise problems were observed to exist as a result of this nonuniform method of cable shield grounding.

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The lightning protection system for the tower consists of 10-inch air terminals distributed around the perimeter of the cab roof and around the edges of the tower building. Construction drawings indicate that these terminals are connected to the structural steel I-beams of the tower. The I-beams are bonded together at the base with No. 2/0 cables and are bonded to the encircling grounding conductor and then to the ground rods.

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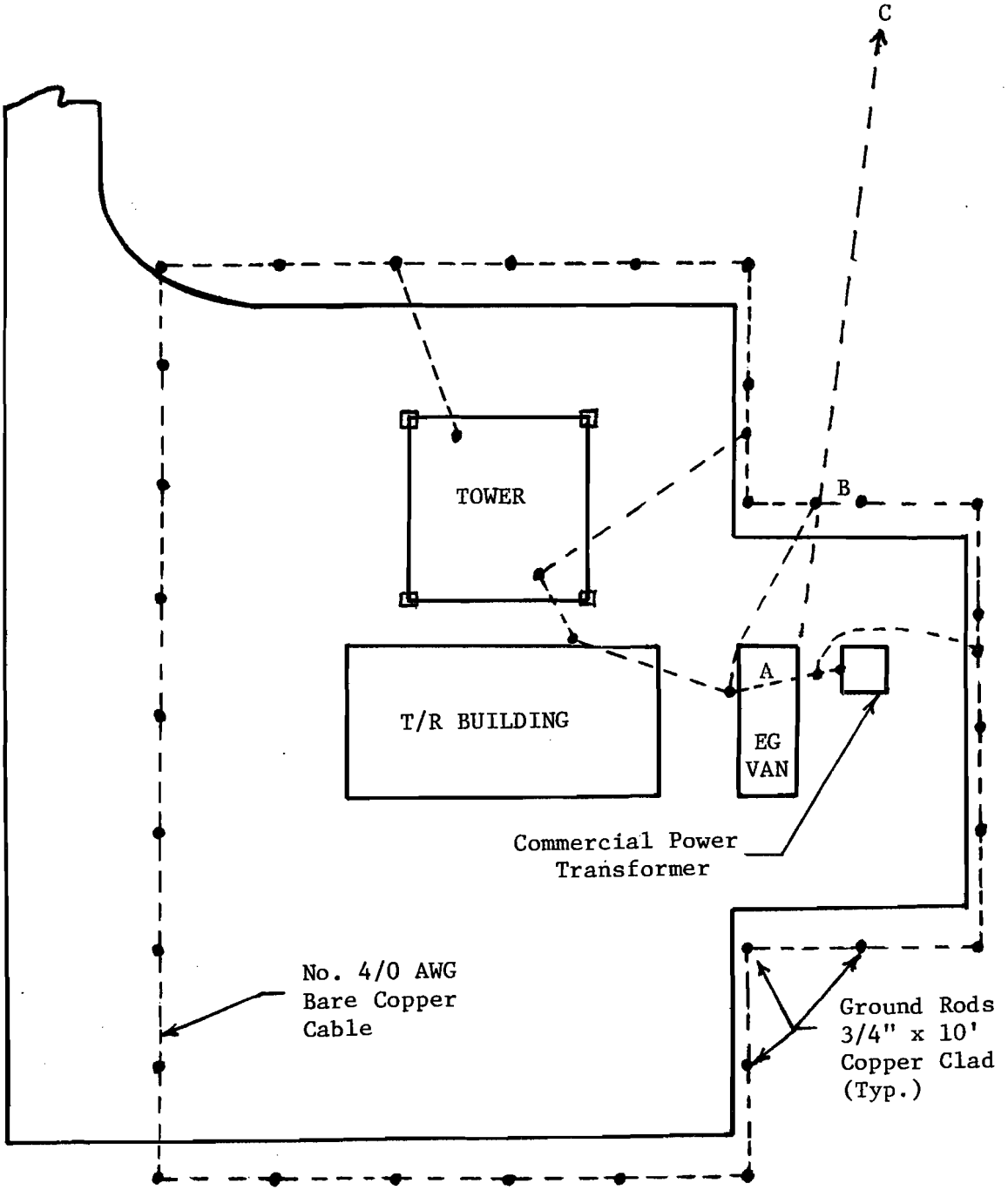

Figure 8. Ground Rod Configuration at ASR-7 Site.

point A on Figure 8). Current probe spacings of 100 feet and 200 feet along line ABC were used. Figure 9 shows the results of these tests.

Lightning protection for the site is provided by 3 air terminals mounted on the antenna platform. These air terminals extend high enough (see Section 2.5.1, Volume I, GBS Practices and Procedures) to provide protection against a direct strike to the radar and beacon antennas, and they simultaneously protect the tower and adjacent structures. One down conductor connects the air terminals to the grounding cable at the base of the tower. The air terminals and the down conductor are bonded to the tower; thus, the tower steel provides supplemental down conductors from the air terminals to earth (see Paragraph 1.3.2.2.2i, Volume II, GBS Practices and Procedures).

Power line surge protection is provided by secondary surge arresters mounted inside the equipment shelter adjacent to the power distribution panel. An arrester is provided for each phase; the three arresters are connected to the system of ground rods with a single No. 6 copper wire.

Standard National Electrical Code practices throughout the ASR-7 provide adequate protection against electrical fault hazards. Additional protection is provided by a 4-inch wide copper strap which interconnects all equipment cabinets of both radar channels with the patch panels and one of the power panels. At the connection between the copper bus and the power distribution panel, paint was not removed from the panel's outer surface prior to bonding.* Thus, the bonding path was made through the body of the bolt rather than between the bonded surfaces.* However, this particular connection exhibited a resistance of about 0.1 milliohm which indicated that an effective bond was made in spite of inadequate prior treatment of the mating surface.

Other representative bonds were checked. Being a new facility at the time of the survey, all bonds inside and not exposed to weather showed no evidence of corrosion.* Checks with a double-balanced bridge (see Section 2.2.2.3.1, Volume II, GBS Practices and Procedures) showed a typical resistance of less than 1 milliohm for bonds inside the structure. Measurements of the resistance across representative structural joints, both welded and bolted, in the tower showed a resistance of less than 0.1 milliohm. However,

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*See Section 1.5, Volume II, GBS Practices and Procedures.

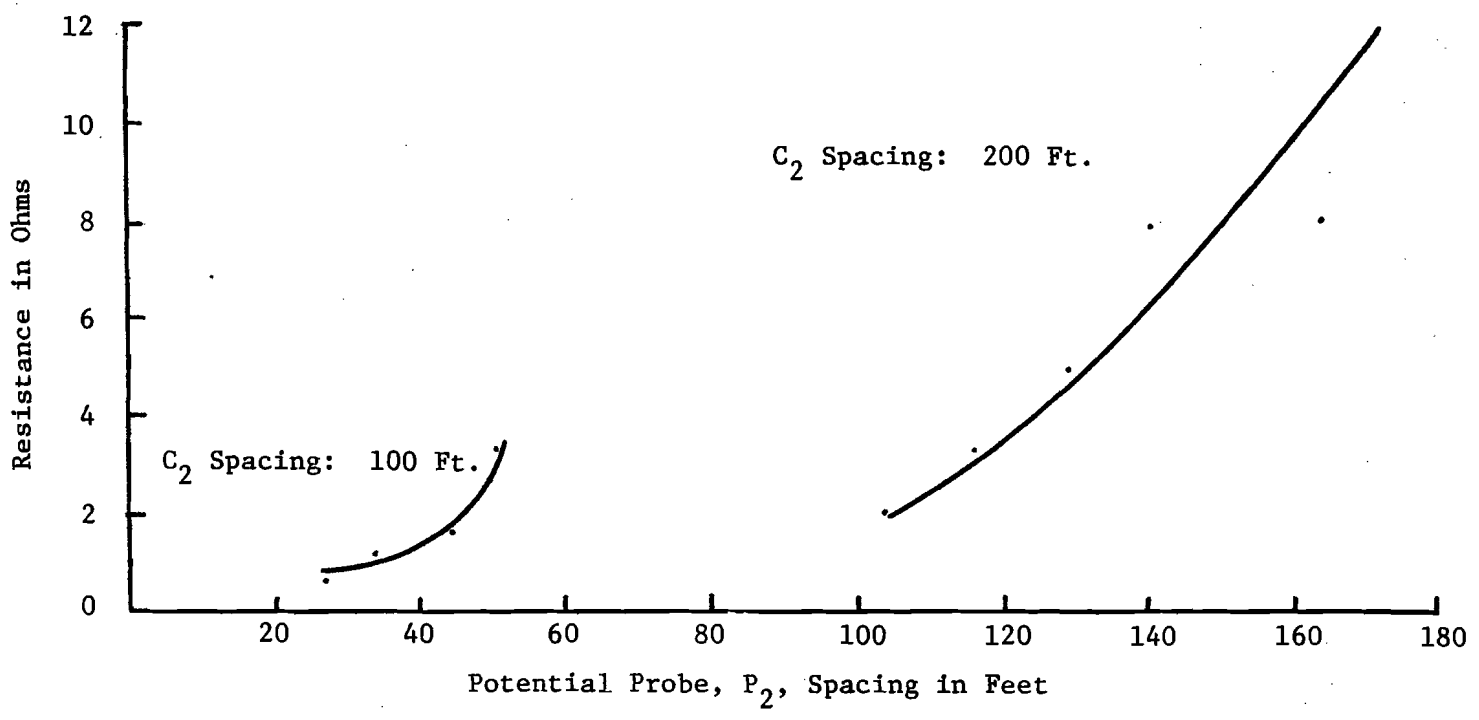


Figure 9. Earth Resistance Curves for ASR-7.

several bonds associated with the lightning discharge path already were showing signs of rusting.

The radar equipment cabinets are well shielded electromagnetically (see Chapter 5, Volume I, GBS Practices and Procedures). Conversations with FAA personnel indicated that the shielding is necessary for reliable operation of the equipment.

A serious interference problem was observed to be caused by a citizens band transceiver used as a local intercom. Being close to the 30 MHz radar IF, the 27 MHz signal readily couples to the radar and effectively obscures the return signal as shown in Figure 10. (The interference was also observed to be plainly evident on the video channel back in the equipment room of the tower.)

2.1.3 Instrument Landing Systems (ILS)

The ILS components surveyed at Hartsfield include the following (the locations of these components are noted on Figure 1):

(a) Localizer and Middle Marker for Runway 9R.

(b) Localizer and Glide Slope for Runway 33.

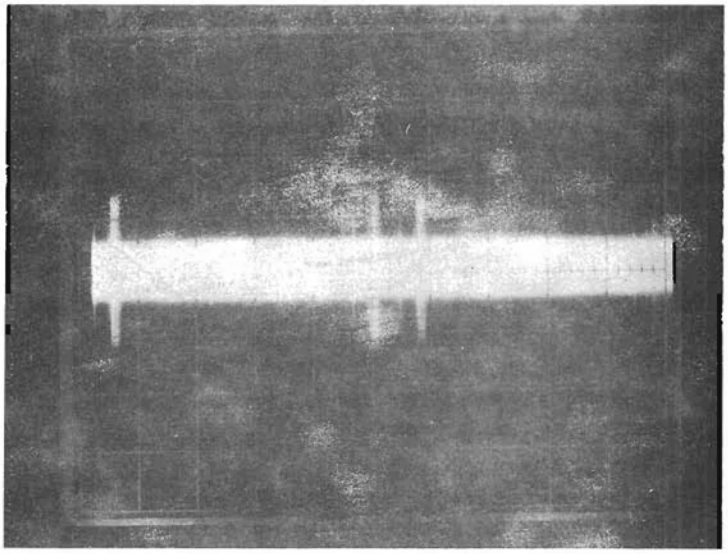
(c) Glide Slope for Runway 8.

(d) Outer Marker (BRU) for Runway 26.

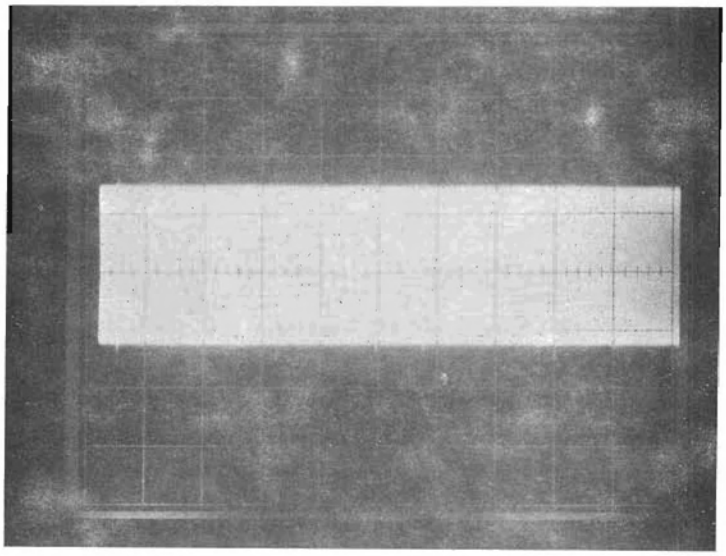
At all sites a representative number of bonds were inspected, equipment and building shields were examined, the lightning protection for equipments and buildings was inspected, and safety/signal ground networks were examined.

The earth electrode systems for the various ILS components consist of from two to eight 3/4-inch x 10-foot ground rods. Supplemental contact with the soil is provided by the additional rod or rods provided by the power company at their transformer. The various rods at the site are all effectively interconnected with conduit and the electrical safety ground wire.

At the two localizers spot check measurements of resistance of the earth electrode systems were made. The results of the measurements are shown in Figure 11. The measurements indicated that the resistance to earth at both locations is on the order of 5 ± 2 ohms.

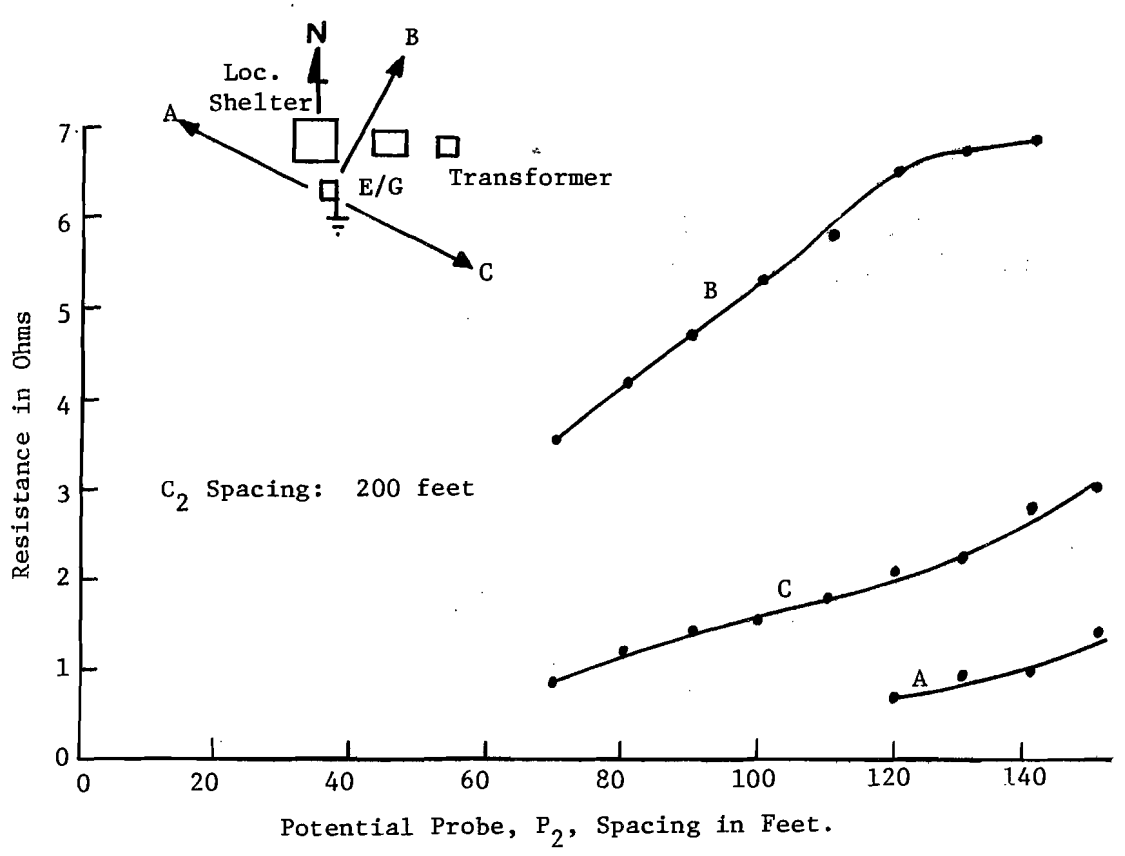


(a) Radar Video with CB Transmitter Off.

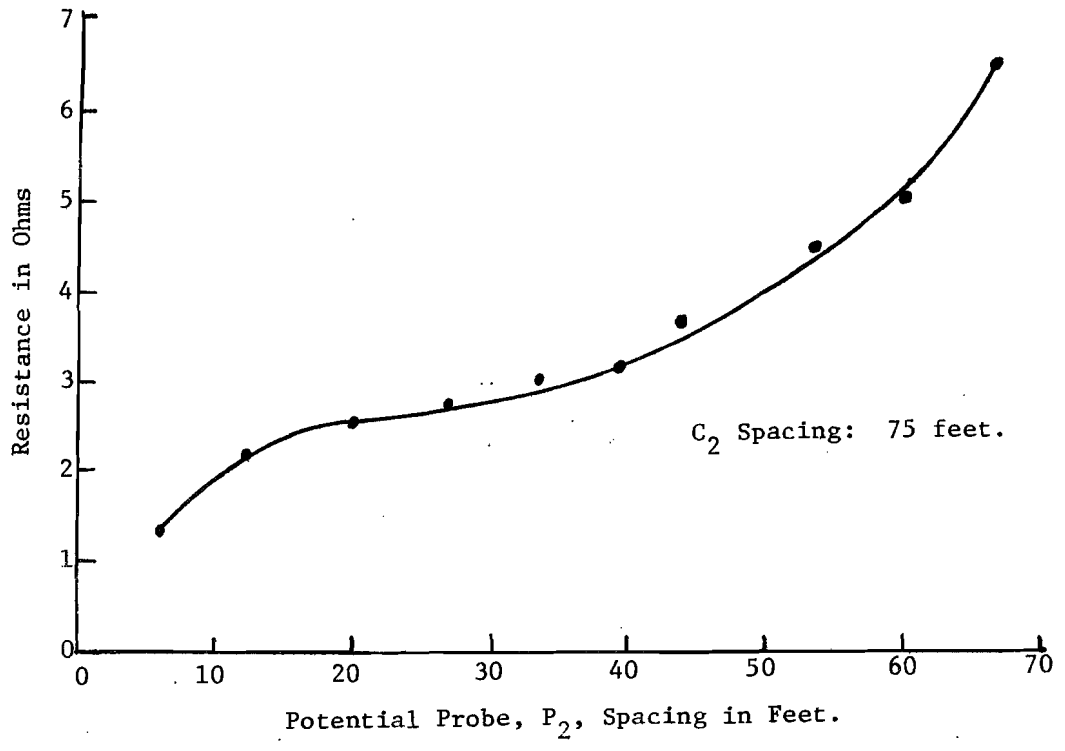


(b) Radar Video with CB Transmitter On.

Figure 10. Radar System Interference Arising from Citizens Band Transceiver.



(a) Localizer 9R.



(b) Localizer 33.

Figure 11. Results of Earth Resistance Measurement at Localizers 9R and 33.

In general, direct lightning stroke protection for ILS components is not provided or, in the case of the glide slopes and the outer marker, is incidentally provided by the associated tower or other metal structure located near the equipment shelter. For example, the middle marker for Runway 9R is located near a tower of the approach lighting system (ALS). The tower is steel and is much taller than the marker structure. The middle marker facility falls within the cone of protection (see Section 2.5.1, Volume I, GBS Practices and Procedures) established (unintentionally) by the ALS tower.

All ILS components have secondary surge arresters installed on incoming commercial power lines. Various types of devices, placed between control lines and ground, have been installed in an attempt to limit lightning surges to nondestructive levels. Carbon block arresters, zener diodes, and neon bulbs were noted at various locations. Surge protectors have not been installed to all control lines, however. For example, at the Runway 33 glide slope no surge arresters were observed.

The safety ground networks at all locations are adequate. National Electrical Code practices appear to have been rigorously applied. Only one example of an improperly color coded wire was noted. A black insulated wire being used for the neutral conductor was found in the power junction box at the base of the antenna tower at the glide slope for Runway 33. Sample measurements of the stray power current levels in ground wires were made in the various ILS facilities, and current levels as high as 1.4 amps were recorded.

Sample measurements and visual inspections indicated that overall bonding practices have generally been implemented well. Resistance measurements directly across joints and between different conductors of each grounding system showed that bonding resistances of less than 3 milliohms are typical. The most serious bonding deficiencies were noted on those connections exposed to weather. Several examples of rusted joints (see Figures 12 and 13) were noted. At one location, the Runway 33 localizer, a clamp used for connecting a ground wire to a ground rod was found to be loose.

Figure 12. Example of An Improper Bond at Glide Slope 33.

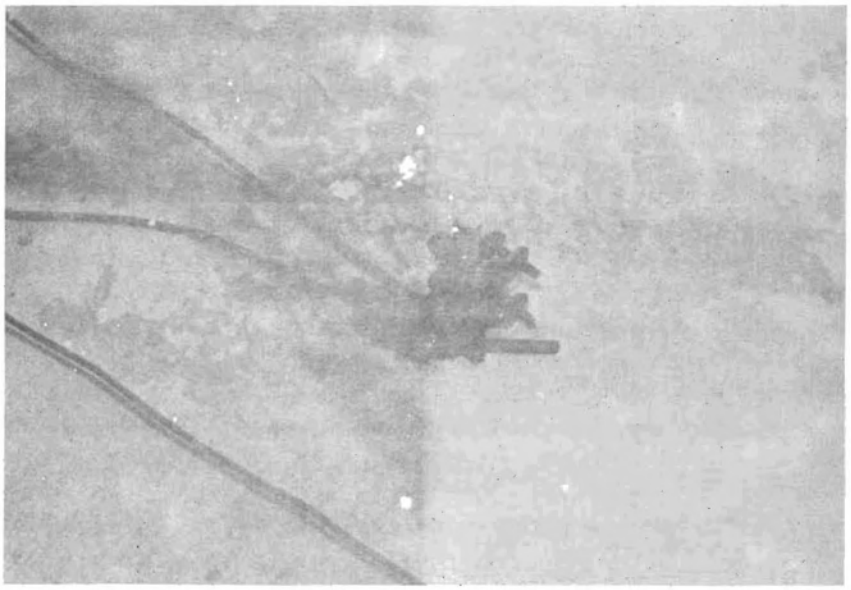


Figure 13. Severely Corroded Ground Rod Connection at Glide Slope 33.

2.1.4 Remote Transmit/Receive (RTR) Sites

All VHF and UHF communications transmitters and several of the UHF receivers are located at two sites which are nearly a mile from the present tower. Both sites, RTR-C and RTR-D, were included in the survey. RTR-C is a UHF and VHF transmitter site containing mainly solid state equipment while RTR-D is a UHF receiver site containing vacuum tube equipment. The VHF receivers are located in the equipment room in the tower.

Many of the observations made at the various ILS components apply also to the RTR sites. For example, lightning protection is provided mainly by the communications antennas. An exception is that one of the antenna mounting poles at RTR-D does have a lightning rod installed on it.

Generally, electrical joints inside and protected from weather were in good condition and exhibited a resistance of less than 5 milliohms. Connections outside, however, frequently showed evidence of excessive corrosion.

The equipment fault protection network consists of a No. 6 bare copper wire interconnecting all equipment racks and cabinets. This interconnected network provides backup protection to the National Electrical Code green wire ground and serves as the signal grounding network as well.

Audio input and output lines from the ATCT enter the RTR structures at an audio junction box. The cable interconnecting the RTR's with the tower is a multiconductor cable containing several pair of shielded, twisted communication lines and several unshielded control cables. The complete cable is provided with an overall shield. At each site this overall shield is grounded to a No. 6 bare wire inside the audio junction box. At the transmitter site (RTR-C) the shields of the separate pairs entering the building from the ATCT are also grounded to the No. 6 wire at the junction box. The cable sections connecting the audio junction box to the separate transmitter inputs are grounded at the transmitter end only. At the receiver site, RTR-D, the interconnecting line shields are grounded at both the receiver and at the junction box. The effectiveness of the cable shields is seriously jeopardized, however, by the excessive (see Section 3.2.1.1.7, Volume II, GBS Practices and Procedures) pigtail lengths used (see Figure 14).

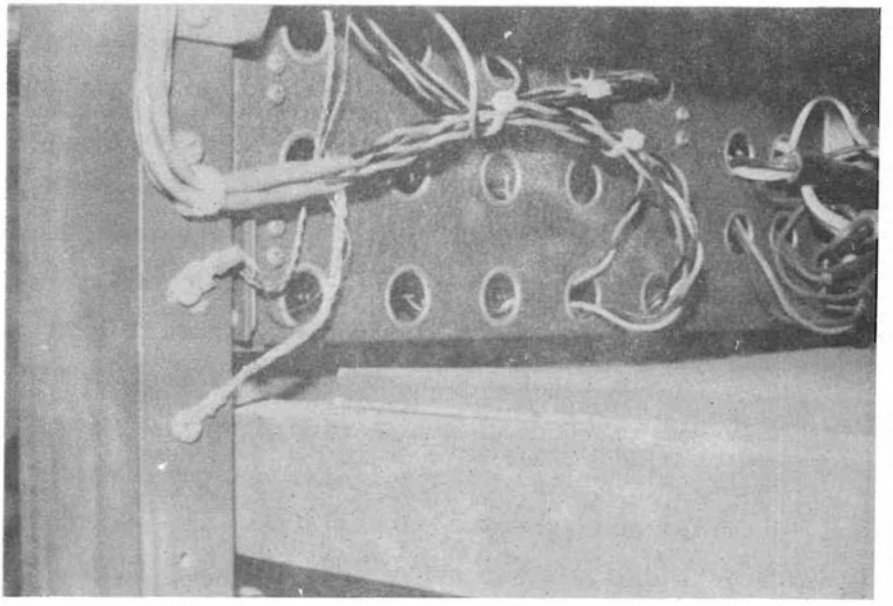


Figure 14. Excessively Long Shield Pigtails on Low Frequency Cables at RTR-D.

The audio lines terminate into balanced transformers; the center taps of the transformers are not grounded, however (see Section 3.2.1.1.6, Volume II, GBS Practices and Procedures). This same practice was observed in the communications equipments located in the tower.

2.1.5 VORTAC Site

The REG VORTAC site located near Rex, GA (approximately 12 miles from the Hartsfield ATCT) was surveyed. The findings at this site are quite similar to those noted previously. For example, protection against direct lightning strokes is provided by the antenna support structure. Where protected from weather, bonds are generally well made; measured bond resistances were typically less than 0.5 milliohms. However, many of the outdoor connections are not adequately protected from the weather and, consequently, showed considerable evidence of corrosion.

The equipment grounding system consists primarily of a No. 6 bare copper wire interconnecting all equipment racks and cabinets with ducts, power panels, and the ground rods. Up to 3 amperes of stray power current were measured in the ground safety wire between the distribution panel and the ac voltage regulator. In the ground wire connecting the distribution panel to the ground rods, the stray current was measured to be 1.2 amperes.

2.1.6 Other Facilities

Other facilities surveyed include the approach lighting system (ALS) for Runway 9R, a compass locator, and two runway visual ranges (RVR).

Each metal tower of the ALS is provided with at least one ground rod. The towers are effectively interconnected with a steel messenger wire. Thus, in effect, the earth electrode system extends over the full length of the light string.

No auxiliary lightning protection in the form of lightning rods is present on the towers. The topmost elements of the towers are interconnected with a bare copper conductor. A single conductor extends down a leg of each metal tower to a point approximately 15 feet above grade level. At this point, another conductor branches off to an adjacent leg to attach

to a second ground rod. This second conductor was apparently installed to achieve the additional connection* to earth that is prescribed by NFPA-78, "Lightning Protection Code".

No intentional lightning protection system is provided for the 120-foot compass locator tower. The metal structure of the tower will thus serve as the down conductor for lightning stroke current. Grounding connections at the base of the tower were in very poor condition; as Figure 15 shows, they were severely corroded. The bare copper conductors used to connect the RVR tower to the ground rods are routed over the outside edge of the tower footings, as shown in Figure 16. In many cases the conductors have been damaged by lawnmowers or other equipment.

2.2 Robins Air Force Base

The survey at Robins was primarily directed at those facilities under the operations and maintenance responsibility of the 1926th Communications Group. These facilities included the communications center (Building 225) and flight line facilities. The telephone switchboard located in Building 214 and the digital subscriber terminal equipment (DSTE) were included with the communications center survey. The flight line facilities surveyed were the: (1) localizer, AN/MRN-7; (2) glide slope, AN/MRN-8; (3) middle marker, AN/GRN-25A; and (4) precision approach radar (PAR), AN/FPN-16. The transmit/receive site and radar presentation facilities located in Building 2 and the ATCT were also examined (both of these facilities are under FAA jurisdiction). The MARS communications site was also surveyed.

2.2.1 Communications Center

The communications center is an automated message handling and routing facility. It accepts messages from local terminals, provides encryption if necessary, and automatically routes them to their proper destination. Inversely, incoming messages are directed to the proper local address. The center also serves as a switching hub for messages traveling

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*This second connection fails to meet the intent of NFPA-78 which is to establish two separate paths over the total discharge distance from the point of impingement of the stroke to the earth.

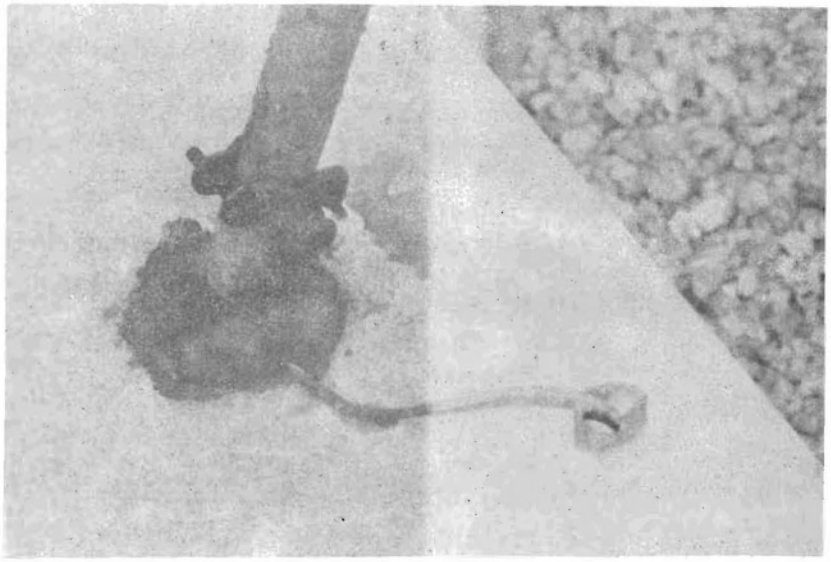

Figure 15. Severely Corroded Bonds at Compass Locator Site.

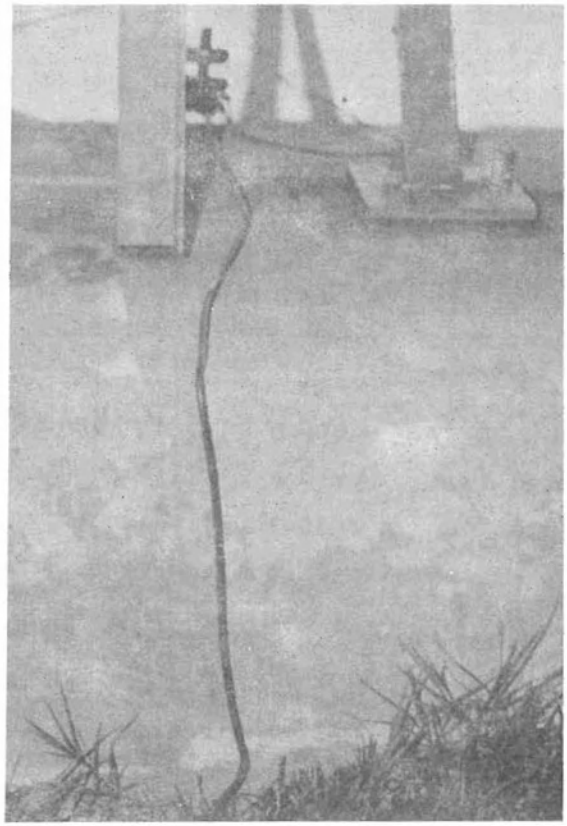

Figure 16. An Example of Damage to Unprotected Grounding Wire.

between other facilities. On-line encoding and decoding equipments are present at the center. Because of the classified nature of much of the traffic through the facility, TEMPEST requirements are imposed.

The TEMPEST earth electrode system consists of a 1-foot by 10-foot copper plate coiled in a 2-foot diameter cylinder as shown in Figure 17. One end of the coil is brazed to a 5/8-inch copper ground rod, and the other end is brazed to a second 5/8-inch copper ground rod which is bent and brazed to the first ground rod. The plate is immersed in a charcoal fill which is saturated with a magnesium sulphate (epsom salts) solution (see Section 1.9.2, Volume I, GBS Practices and Procedures).

Surrounding the ac power transformer cage adjacent to the communications center building are ten 6-foot by 1/2-inch ground rods spaced approximately one rod length apart around the periphery of the cage.* These rods are interconnected with a No. 4/0 AWG copper cable. The transformer neutral and the cage fence are bonded to this earth electrode system.

The conduit surrounding the RED and BLACK ground conductors is bonded to the TEMPEST earth ground near the earth connection. Inside the facility near the equipments this conduit is tied to structural steel and to the ac "green wire" ground. Thus, the TEMPEST earth connection and the ac power ground are common through these conduit connections.

The TEMPEST signal ground networks (both RED and BLACK) are each configured as a tree (see Section 7.3.4.1, Volume I, GBS Practices and Procedures) with no closed loops and with only one connection made to the earth electrode system. Both RED and BLACK ground conductors are insulated and routed in conduit. In the BLACK ground junction box, the ground conductors are fastened with compression lugs to a 10 x 2 x 1/4 inch copper bar (which is insulated from the junction box enclosure). Inside equipments the RED and BLACK ground conductors are insulated from the cases and enclosures.**

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*According to local Air Force personnel, this earth electrode system extends around the periphery of the communications building. Unfortunately, engineering drawings of the entire electrode system could not be obtained, and the exact configuration of this system was not determined.

**Other than these limited visual observations, a more thorough examination of the networks and the performance of measurements was not permitted because of security restrictions.

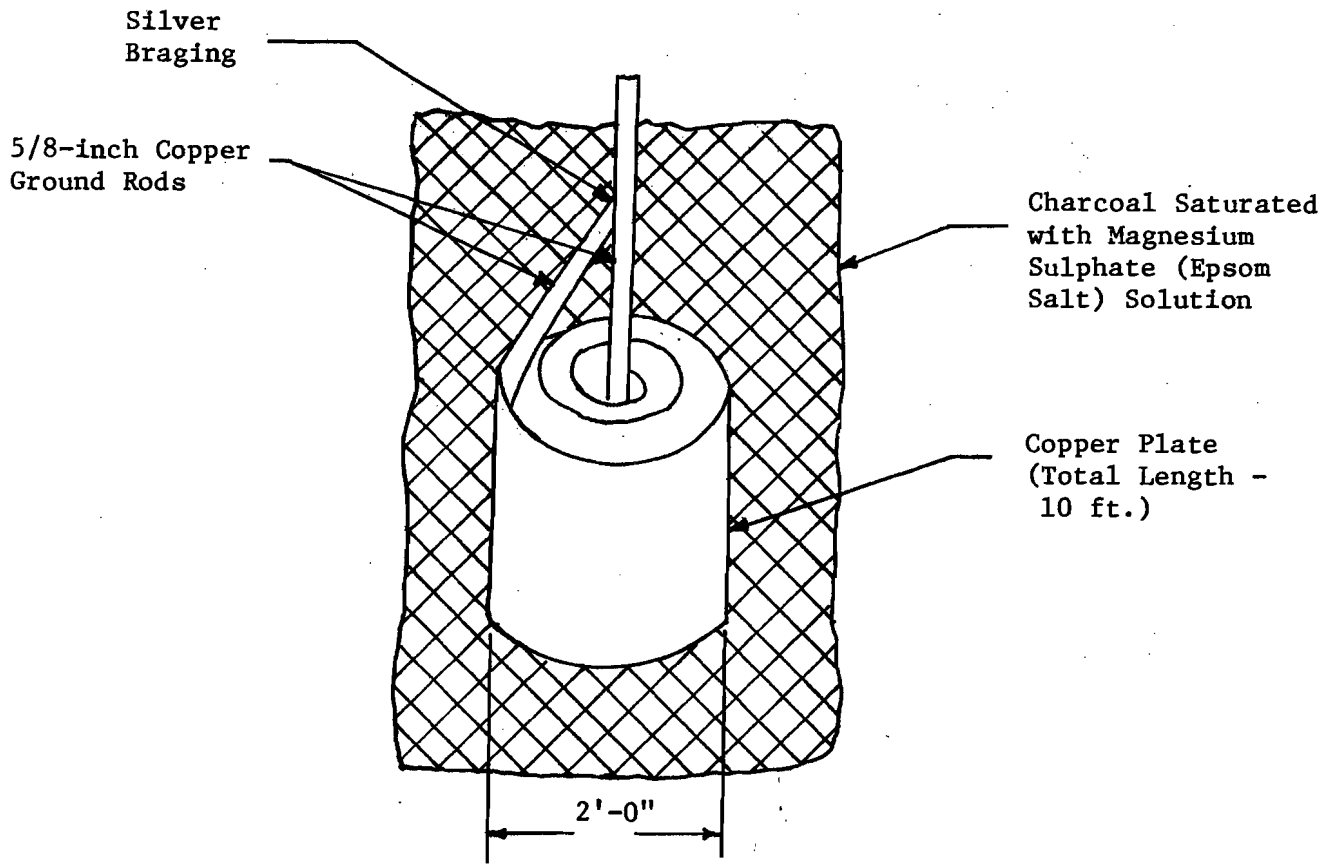

Figure 17. Configuration of TEMPEST Earth Ground at Communications Center (Robins AFB).

The logic ground networks employed in the two Univac 418/3 computers are configured as shown in Figure 18. In the newer equipments logic ground is isolated from the equipment cabinet; it is not interconnected with either the power neutral or with safety ground. In a few older equipments at the installation logic ground is tied to the case. To prevent compromising the isolation (see Section 3.2.1.1.5, Volume II, GBS Practices and Procedures) of the logic ground in the newer equipments, these older equipments have been isolated from structural elements and from the cabinets of the newer equipments.

Signal interfacing between various components of the data processing system utilizes both twisted pair lines (see Section 3.2.1.1.6, Volume II, GBS Practices and Procedures) and coaxial cables. For example, twisted pair lines are used for interconnecting the computer mainframe to peripheral units such as a magnetic tape deck or a high speed printer (DCT 9000). A typical cable arrangement is shown in Figure 19. Between I/O devices such as paper tape readers, card punch machines, and the high speed printer, coaxial cable assemblies of the type shown in Figure 20 are used.

One side of the twisted pair line is connected to logic ground in the peripheral unit through a 10K resistor. The shields of coaxial lines are connected to logic ground on both ends through 27 ohm resistors. The shields of all interconnecting cables are insulated from cabinet or case ground.

2.2.2 Flight Line Facilities

The survey of the air traffic control facilities revealed that the grounding, bonding, shielding, and lightning protection techniques employed are quite similar to those observed at Hartsfield. Consequently, the general descriptions of the Hartsfield facilities apply equally well to those at Robins. For example, practically none of the facilities have protection against direct lightning strikes to the facilities except for the incidental protection provided by nearby antenna supporting structures. However, discussions with the operating personnel indicated that problems related to direct strikes to the facilities are minimal. Some control and signal lines between the various facilities had surge protectors on them, and some did not. For instance, control lines between the localizer and

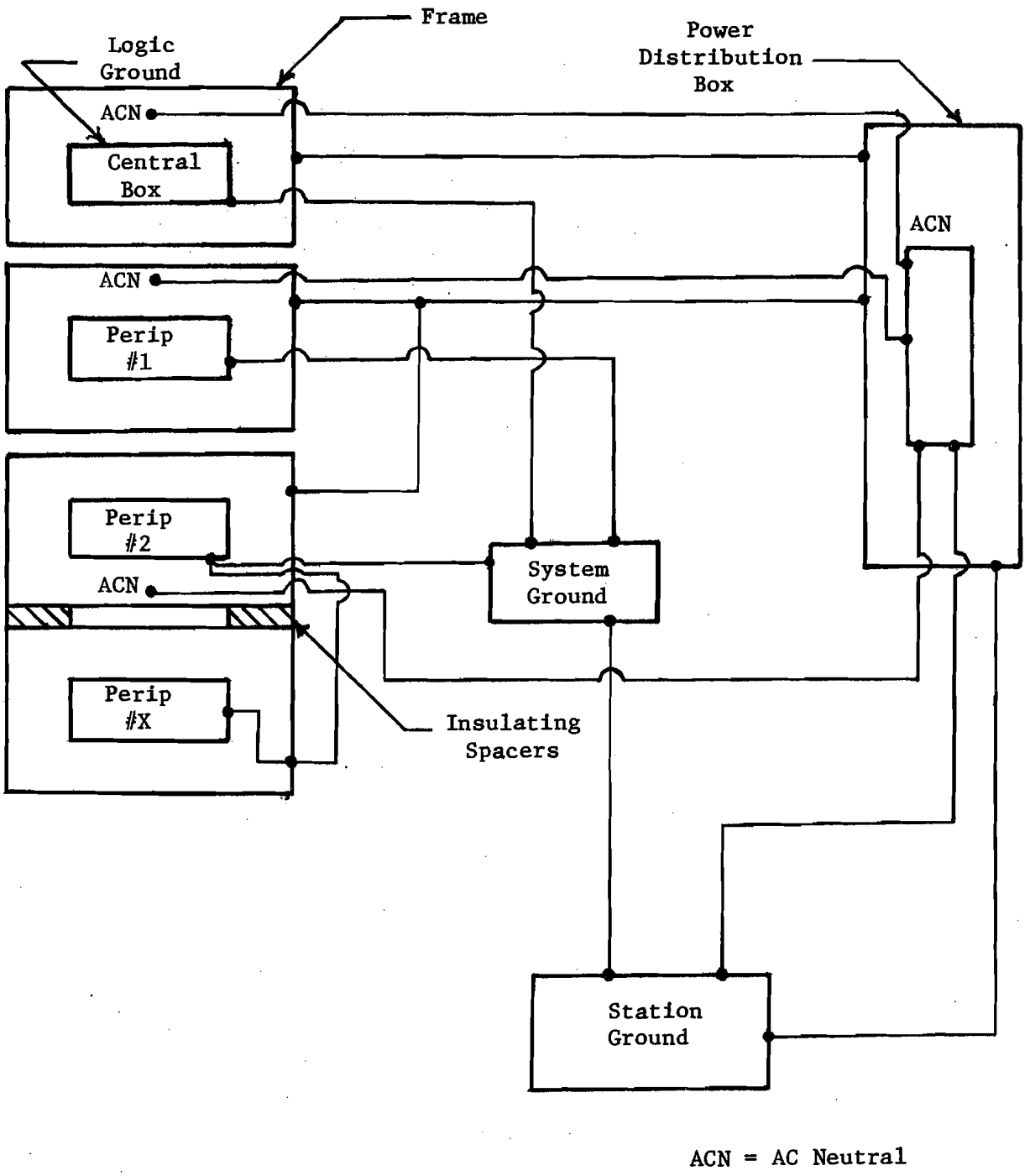

Figure 18. Logic Ground Configuration in Communications Center.

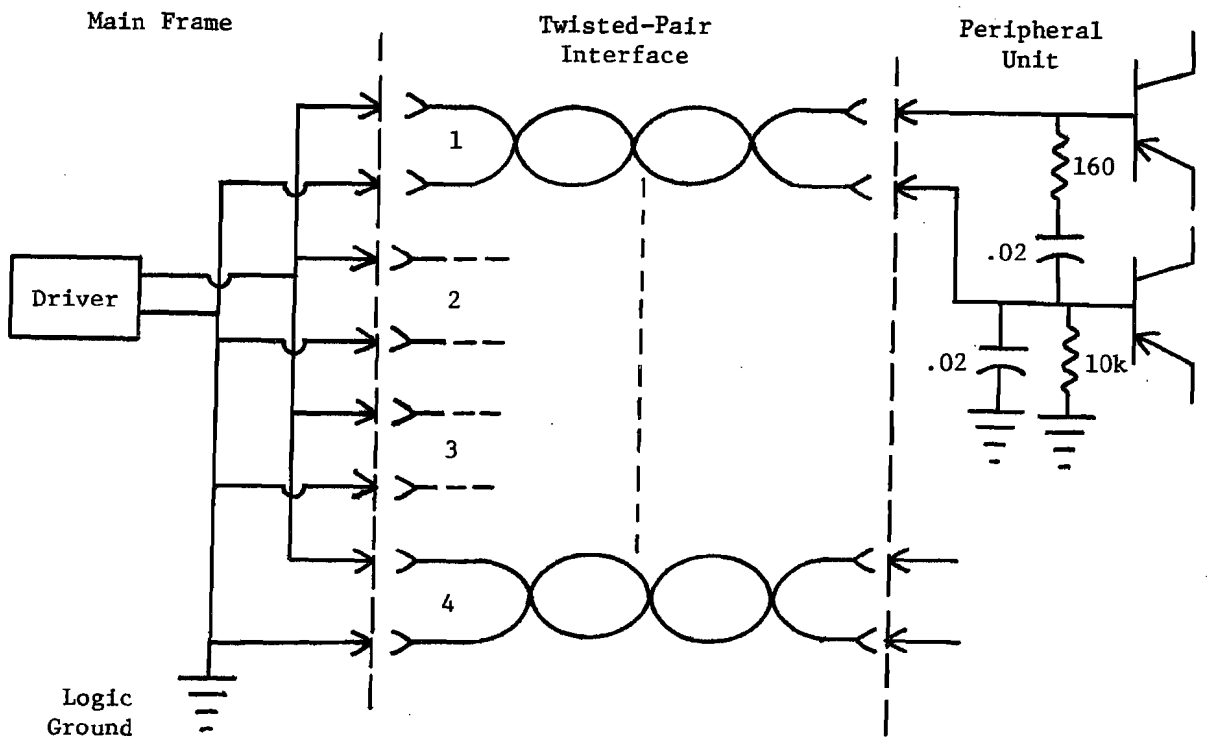

Figure 19. Inter-Equipment Cabling Practices.

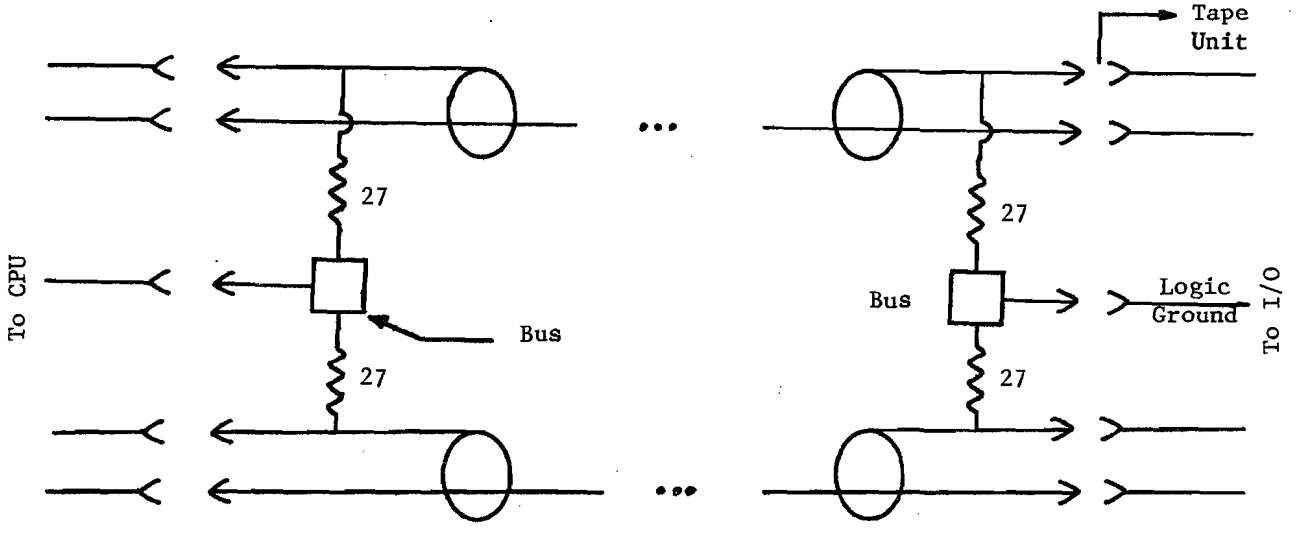

Figure 20. Coaxial Cable Grounding Practices.

the control tower had carbon block arresters on each line while the communications lines between the transmit/receive and radar presentation facility had no surge arresters in evidence. (The communications lines are telephone company lines and may have had surge arresters provided by the phone company.)

At the localizer and the glide slope one ground rod is installed near the equipment shelter, and another ground rod is provided at each antenna. The only apparent connection between the separate ground rods is that provided by the shields on the cables running between the equipment and the antennas.

The resistance to earth provided by the ground rods at the localizer was measured with a Biddle Megger™. A current probe spacing of 105 feet was used. The curve of Figure 21 indicates that the resistance is in the neighborhood of 5 to 6 ohms (see Section 2.2.2.2.1, Volume II, GBS Practices and Procedures).

The safety ground network in the localizer and glide slope equipment shelters is a braided strap which interconnects the equipment enclosures with the ground rods. The metal supporting structure for the localizer course antenna is bonded to a ground rod with a braided strap; the wire mesh between the clearance and course antenna is connected to the ground rod and to the course antenna supporting structure with another braided strap. (In a like manner, the equipment cases in the MARS facility are connected with braided straps to a No. 6 AWG bare copper wire routed around the walls of the equipment room.)

In the other flight line facilities the equipment enclosures are grounded with a No. 6 AWG bare copper wire. In general, the equipment ground networks at these facilities are quite similar to those at Hartsfield, and the descriptions presented earlier apply to these sites also.

In several instances, the braided straps are bonded with a bolt passing through the wire strands of the strap. The remaining bonds between the braided strap and the No. 6 copper ground wire use split bolt connectors. These bonds are well made and exhibit a low (less than 1 milliohm) dc resistance. In general, bonds inside buildings and not exposed to weather were in good condition. Many of the exposed bonds, however, were excessively corroded. (Some of the exposed connections have been painted, but most bonds have no protection at all.)

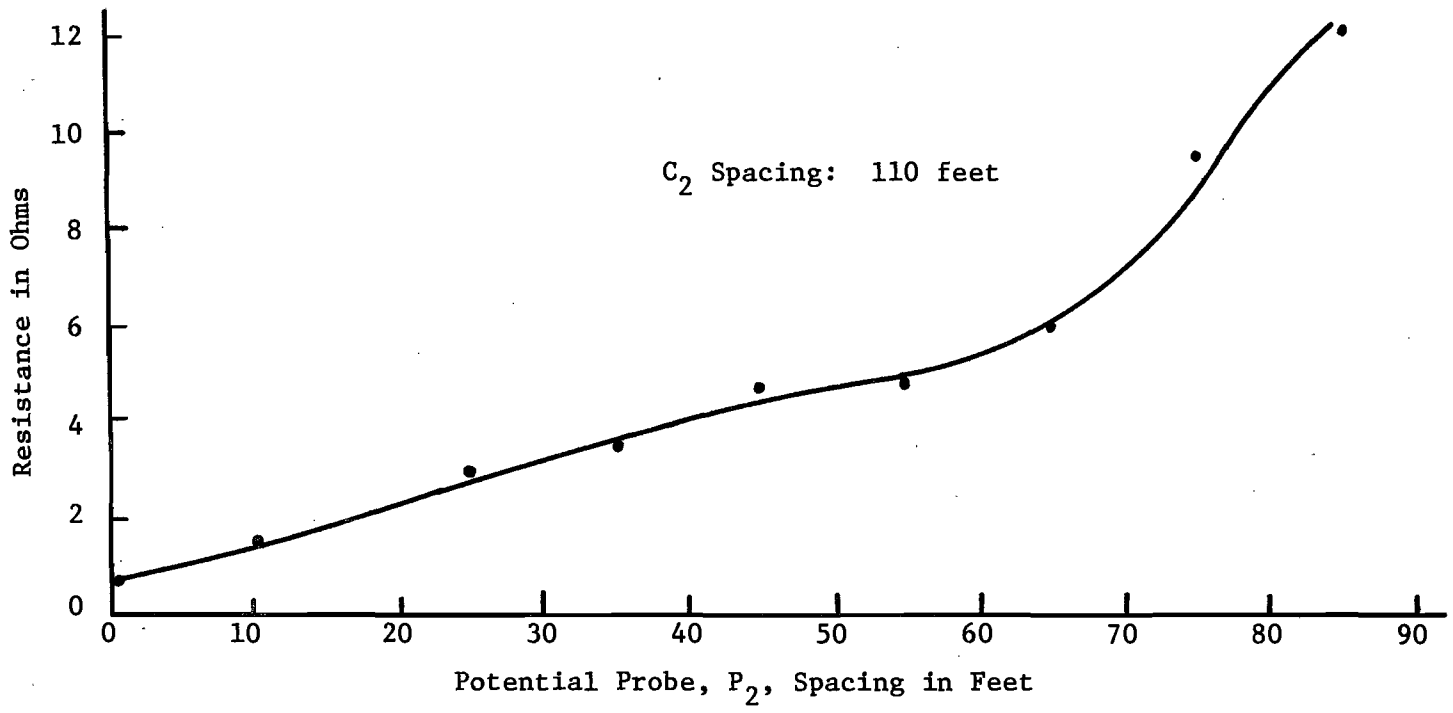

Figure 21. Earth Resistance Data for AN/MRN-7 Localizer (Robins AFB).

Except for one system, flight line facilities do not have signal ground networks installed that are distinct from the safety ground. The circuit signal ground inside each equipment is connected to the equipment chassis (and the enclosure). Thus, the equipment ground network provides the signal ground network. The exception is the Brite System located in the transmit/receive and radar presentation site. The signal ground network for this system was intended to be an isolated single-point ground network. Each equipment ground is routed to an isolated metal plate. A connection is then made between this plate and the building/safety ground network and thence to the earth electrode system. Unfortunately, the individual units of equipment of the system are interconnected with coaxial lines. The shields of these coaxial cables are connected to the equipment cases which defeats the purpose of the isolated ground network.

2.3 Aiken Air Force Station

The heavy duty radar installation at Aiken Air Force Station, Aiken, SC was the third major facility surveyed. Included in the survey were an AN/FPS-7 search radar, an AN/FPS-26 height finder, and a ground air transmit/receive (GATR) site.

2.3.1 AN/FPS-7 Search Radar

The AN/FPS-7 antenna radome is equipped with a single lightning rod mounted on top. The down conductor from this rod is routed over the outside of the radome.*

The lightning down conductor and the tower columns are grounded to an earth electrode system composed of four buried copper plates. These plates each have an area of 6 square feet. A 2-inch wide, 16 gauge flat copper strap connects the four plates together. Similar straps are used to bond the tower columns to the plates as shown in Figure 22.

The equipment grounding system for the AN/FPS-7 is the best of any facility surveyed. A typical example of the practices is illustrated in

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*The actual installation could not be inspected in detail because the radar was operating at the time of the survey.

Figure 23. The equipment enclosures are interconnected with a wide copper strap. At each connection the bond surfaces showed evidence of careful cleaning to remove all foreign, nonconducting material (see Section 1.5, Volume II, GBS Practices and Procedures). Joints in this strap are brazed; the strap itself is brazed to the tower structure. Joints in support columns are jumpered with wide copper straps which have been brazed to the structural member on each side of the joint. A typical example of one of these bonds exhibited a resistance of approximately 0.5 milliohm.

An undesirable practice was noted at the AN/FPS-7 site in that three 3-phase voltage regulators are interconnected with two No. 2/0 cables which also are attached to the equipment ground strap. Apparently these No. 2/0 cables serve as the neutral conductor between the regulators because current measurements with a clamp-on ammeter showed a current of 23 amperes in one No. 2/0 cable and 16 amperes in the other. Such large currents* can pose a severe noise threat to wideband video systems (see Section 3.2.1.2.1, Volume II, GBS Practices and Procedures).

Most bonded joints which are exposed to weather have been painted. Those which have not been painted showed extensive corrosion.

The high voltage power supply, the radar modulator, and most other equipment enclosures are well shielded.

All gaskets appeared to be well maintained and in good physical condition.

2.3.2 AN/FPS-26 Height Finder Radar

The AN/FPS-26 has a number of features quite similar to the AN/FPS-7. For example, lightning protection consists of a single lightning rod located on top of the radome. A braided strap connects the lightning rod to a stranded rope-lay cable which runs around the antenna pedestal; this cable is connected to a bare solid conductor extending vertically down the tower to the earth electrode system.

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*Steps should be taken to assure that a current path other than through these ground cables is provided between the regulators.

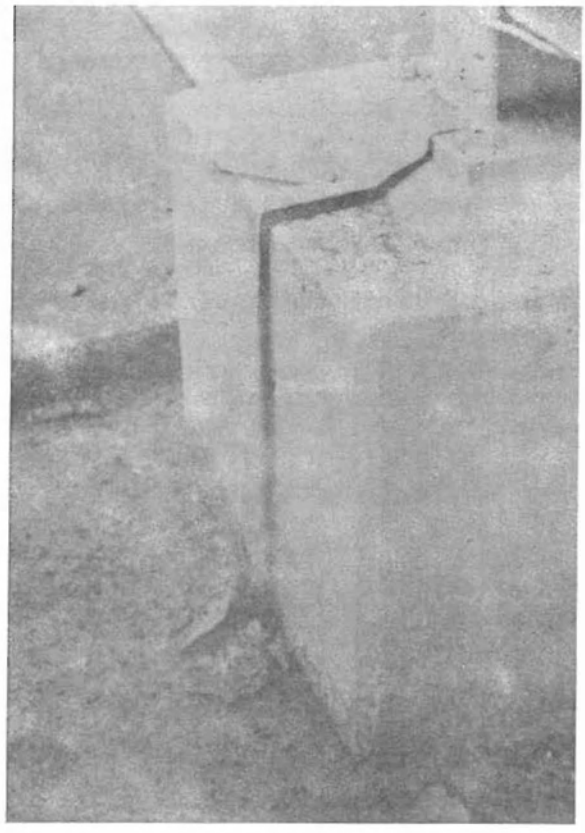

Figure 22. Tower Grounding for the AN/FPS-7 Search Radar (Aiken AFS)

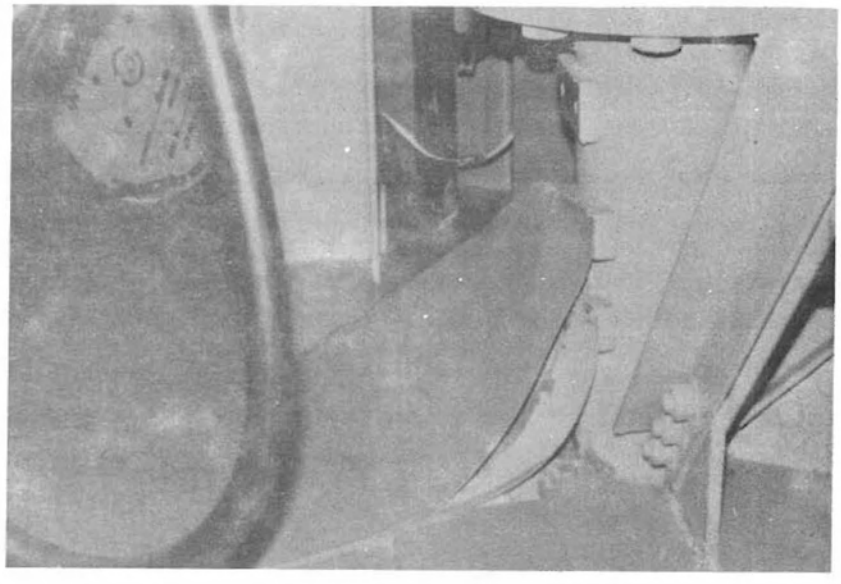

Figure 23. Representative Bond in Equipment Grounding Network in the AN/APS-7 Tower

Flat copper plates like those used for the AN/FPS-7 provide contact with the soil underneath the tower. These plates are connected together and to the tower legs with No. 4/0 solid copper conductors. Stray power currents in the ground wires between structural steel members of the tower and the earth electrode connections were measured at levels ranging from 0.6 amperes to as much as 9 amperes.

No separate, isolated grounding network is provided for signal referencing purposes.

In general, bonds were excellent; many connections utilize exothermically welded bonds. As was observed in the AN/FPS-7 tower, equipment shielding is very well done.

2.3.3 Ground-Air Transmit/Receive (GATR) Site

Lightning protection for this site is that incidentally provided by the antennas and their supporting structures. The RF cables to the antennas do have lightning arresters provided as shown in Figure 24. The arresters are grounded directly to the earth electrode system.

Ground wires are provided on each antenna pole. Since no mechanical protection such as guards or conduit have been provided, some of the wires have suffered severe damage as shown in Figure 25.

The audio signal cables associated with the transmitters and receivers are terminated in transformers whose center tap is not grounded. The practice is similar to that employed in the communications equipment at Hartsfield.

Equipment enclosures and racks are connected with a braided strap to a copper cable in a cable trough under the floor. This copper cable connects to the earth electrode system.*

The interconnected enclosures and racks are used as ground for both low and high frequency signals (see Section 7.3.4.2, Volume I, GBS Practices and Procedures). Supplemental grounding is provided by a copper bar bolted to cable trays (see Figure 26(a)). Braided straps extend from this bar to

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*No information was available on the earth electrode system itself.

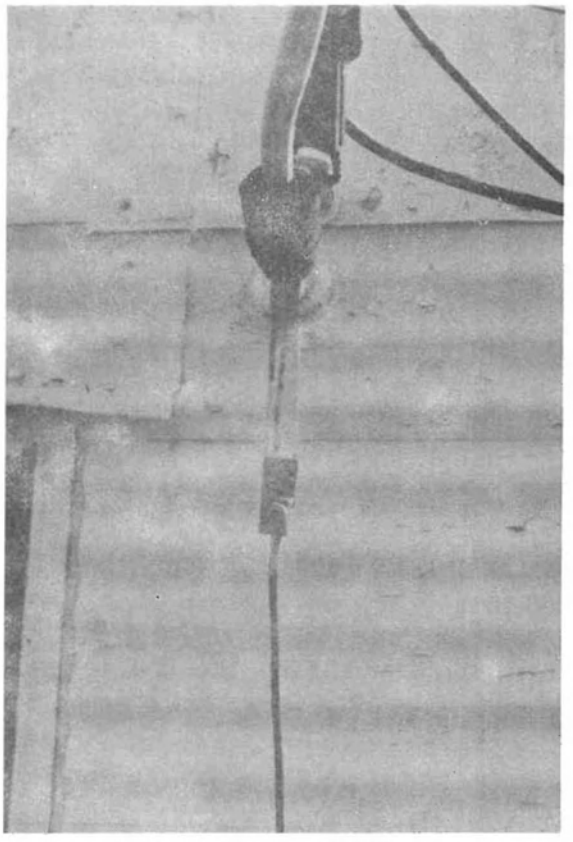


Figure 24. Lightning Arrester Installation on RF Antenna Leadin.

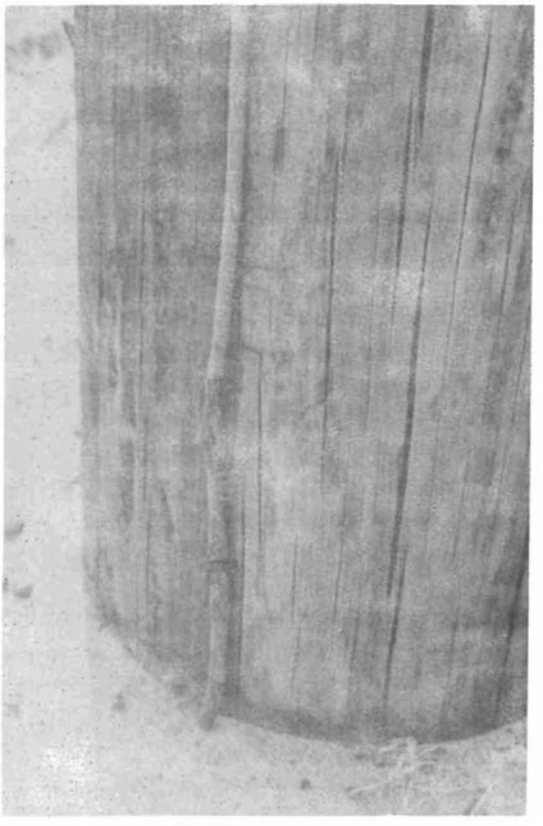


Figure 25. Damaged Lightning Down Conductor.

signal distribution cabinets. Cable tray sections are bonded together with a jumper cable in the manner shown in Figure 26(b).

2.4 Summary of Findings

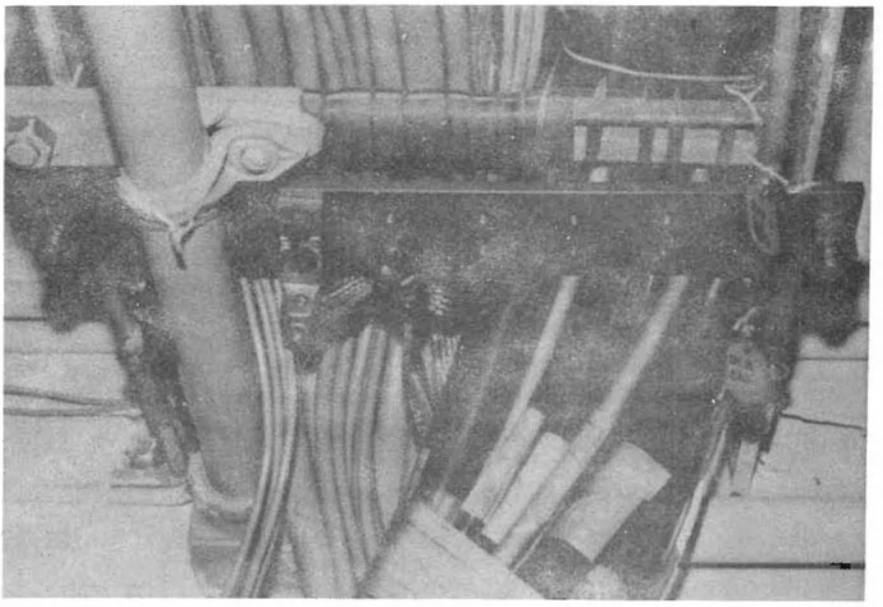
A. Most of the bonds which were inspected and/or measured are considered adequate for their intended functions. The dc resistances of single connections were measured to be typically less than 1 milliohm, and many resistances were less than 0.5 milliohm. Most mating surfaces had been cleaned to bare metal before the bond was made. In some instances the cleaned area was approximately the same size, though sometimes smaller, than the area of the mating surfaces; in a very few specific instances it was doubtful that the mating surfaces had been cleaned. In general, however, bonds were found to be physically tight and to exhibit a low dc resistance.

B. Many bonds which are outdoors and exposed to the weather are not properly protected and exhibited serious corrosion. This corrosion will eventually destroy the bonds.

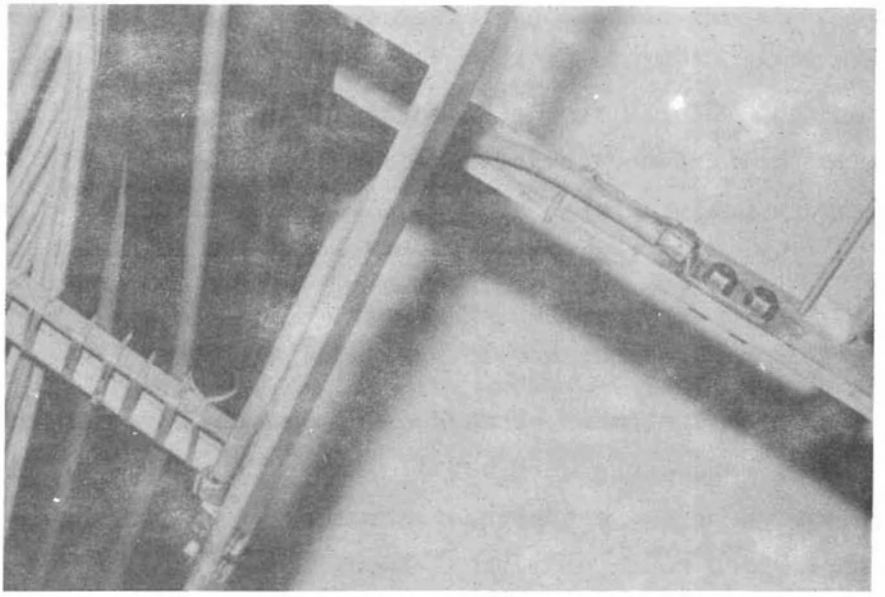
C. Many bonds are located in inaccessible locations such as in building walls and below the earth's surface. Some of these bonds utilize bolts or clamps for fasteners. Because of their inaccessibility, the physical condition and resistance of the bonds could not be checked.

D. The installation of lightning protection systems on structures to provide protection against direct lightning strikes appears to be sporadic. In some instances where lightning protection systems are installed, the tips of the lightning rods are at the same level of, or even lower than, the highest object on the structure; and, thus, the rods are of little use. However, examination of the structures and discussion with the operating personnel indicate that there have been no major problems associated with direct lightning strikes to the structures.

E. The safety grounds examined at each facility appear to have been installed in accordance with the requirements of the National Electrical Code and to have been maintained in satisfactory condition. These grounds are considered adequate to provide personnel and equipment protection against hazardous voltages due to power faults.



(a) Bonding via a Copper Bar.



(b) Bonding via a Jumper Cable.

Figure 26. Examples of Good Cable Tray Bonding Practices.

trode systems are adequate since no problems could be directly attributed to them. Because of inherent problems with the measuring techniques, however, the true value of the earth resistances of large earth electrode systems is hard to determine. Those resistances that were (and have been) measured may or may not be related to the actual effectiveness of the earth electrode systems.

K. In general, it appears that no supplemental facility electromagnetic shielding is needed. At some facilities where nonmetal buildings are used, auxiliary shields of screen wire have been installed to prevent interference to equipment in these facilities. The use of metal buildings at these specific sites could have eliminated the need for auxiliary shields; however, the screens provide the required degree of shielding and are considered adequate at present.

L. Only a few equipment enclosures were designed to provide a high degree of shielding. In several of these enclosures the shielding effectiveness of the door gaskets was questionable since these gaskets did not fit tightly against the mating surface except near the hinges and the fasteners. In general, however, it did not appear that the lack or deterioration of equipment shielding has caused serious EMI problems.

3. DISCUSSION OF FINDINGS AND SPECIFIC RECOMMENDATIONS

The objective of these surveys was to define the nature of the existing grounding, bonding, and shielding practices in order to determine their conformity with the recommendations and criteria of the previously referenced report (FAA-RD-75-215) and with the requirements set forth in two proposed FAA standards.*

The major thrust of the Standards and the report is toward practices and procedures for new facilities, either new structures or major additions

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*"Buildings and Structures, Grounding, Bonding, and Shielding Practices, General Requirements," FAA-Std- , July 31, 1973, and "Electronic Equipments, Grounding, Bonding, and Shielding Practices, General Requirements, FAA-Std- , July 31, 1973, prepared under Contract No. DOT-FA72WA-2850 by the Engineering Experiment Station, Georgia Tech, Atlanta, GA 30332.

to existing structures. In the preparation of these documents existing practices and procedures were considered; they did strongly influence the content of the Standards and the report. However, by virtue of the thrust toward what should be in a facility rather than what is in a facility, some of the more significant practices and procedures called for in these documents were not in evidence in the facilities surveyed. The difficulty arose because the recommended networks and systems either did not exist in the facilities examined or the existing ones could not be segregated from other networks and systems to see if the requirements and recommendations were indeed met.

However, as illustrated in the remainder of this section, the existence of a deficiency per se does not necessarily mean that an immediate rework of the facility is in order. Although frequently a surveyed practice was noted to be not in conformance with a particular requirement or recommendation, in many situations there was a lack of corroborating evidence of operational problems of a magnitude sufficient to justify the expenditure of funds that would be required. Those areas where corrective action is recommended are identified in Section 4 of this report. The considerations leading to these recommendations are presented in the remainder of this section.

3.1 Earth Electrode Systems

The earth electrode systems installed for grounding purposes at the facilities vary in size and configuration depending on the size of that particular facility. At many small facilities the system consists of only one ground rod. On the other hand, the earth electrode system at the relatively large facilities consists of several interconnected ground rods or buried plates. Because of the numerous interconnections with supplementary earth connections such as buried cable counterpoises, cold water pipes, and the power company's grounds, typically the earth electrode system at each facility is effectively much larger than just the rods or grid installed for the structure.

Generally, the earth electrode systems and the interconnections with other buried metals are physically inaccessible except for power ground

and lightning down conductor risers. The entire system at most facilities is completely buried in the earth and at a few facilities is located underneath the building or structure. The existing configurations had to be determined from available drawings.

One criterion for determining the adequacy of an earth electrode system is its resistance to earth. Resistance measurements of the systems have either not been made in the past; or if measurements have been made, the readings are questionable. Supplemental measurements were made at several sites using the fall-of-potential method (see Section 1.7.2, Volume I, GBS Practices and Procedures). The results of the measurements are shown in Section 2, "Survey Findings". The shape of the curves (Figures 9, 11, and 21) of resistance-versus-potential-probe-spacing do not permit a distinct determination of resistance to be made at most locations. Not only is the flat portion of the curve indistinguishable, measurements made along different directions (for example, see Figure 11A) produce quite different results. Such indefinite results are a clear indication that even though current probe (C_2) spacings of up to 180 feet were used the spacings were not sufficient to get beyond the area of influence of the electrode systems. The results of these measurements imply that the resistance to earth at the sites measured is near or below the 5 ohms recommended in the Handbook; however, the overall test results indicate that the standard measurement techniques are of limited applicability to large interconnected electrode systems.

Although no quantitative data is available or obtainable to indicate the grounding resistance of the large electrode systems such as those of the Hartsfield tower or Building 225 at Robins AFB, overall the systems as installed are considered to be rather good. For example, the rod configuration at Hartsfield provides a large number of contacts with the earth. The clusters of rods are separated sufficiently to maximize the effectiveness of each cluster.

Being located near a river bed, the soil in the vicinity of the Hartsfield terminal building can be expected to offer a reasonably low resistivity. Assuming a resistivity even as high as 10,000 ohm-cm, the resistance of each cluster of 3 rods is projected to be 13.4 ohms using the nomographs of

Figures 1-4 and 1-5 of Volume II, GBS Practices and Procedures. By extrapolation, Figure 1-6 (also Volume II) was used to estimate the effective resistance of the total system to be in the neighborhood of 0.6 ohm. These rods are further paralleled by the grounding connections provided by water mains and other utility pipes and by the power system grounds. Thus, the net effective resistance to earth provided by the tower's earth electrode system is conservatively estimated to be less than 0.5 ohm.

The apparent effectiveness of the Hartsfield electrode system is high; few, if any, equipment or power-related problems attributable to earth grounding system inadequacies were mentioned by either FAA or City of Atlanta personnel. Operational experience with the system has been good.

The exact configuration of the earth electrode system for Building 225 (Communications Center) at Robins AFB is less definable than that at Hartsfield. From conversations with local personnel and from the available drawings, it was concluded that the signal ground connection and power/building ground were, in fact, common. This commonality could not be verified, nor could definitive earth resistance measurements be made.

Resistance measurements have been made routinely by the Robins base civil engineering personnel using standard commercial procedures. The tabulated data were reviewed by the survey team; the data were found to contain several entries indicating "zero" resistance and some entries of hundreds of ohms. Such variations should not be encountered in except very unusual circumstances, and thus the tabulated data were considered as unreliable.

In spite of such difficulties both in obtaining an accurate picture of the electrode configuration or its resistance, no major rework effort is recommended because the system appears to be adequate for the needs of the particular facility.

3.2 Lightning Protection

Lightning protection for equipments and facilities consists of both lightning protection networks (air terminals and down conductors) on the facility structures and surge arresters on signal, control, and power lines.

The air terminal/down conductor network minimizes the possibility of structural damage from direct strikes to the facility whereas the surge arrresters are intended to minimize the damage from lightning-induced currents on intersite lines.

Many facilities such as the components of the ILS systems at Hartsfield and the communications center at Robins have no air terminal networks. Other facilities, including one RTR-D antenna pole and the RVR towers at Hartsfield and the two radar towers at Aiken, have a single air terminal or lightning rod. On a few facilities, e.g., the ATCT and the ASR-7 radar tower at Hartsfield, an interconnected network of lightning rods is installed for direct strike protection. Thus, the degree of protection from direct lightning strokes varies drastically from one facility to another.

Several facility buildings which have no air terminal/down conductor network on them are located near an antenna tower or pole or some other type of metal tower. At Hartsfield the glide slope equipment buildings are all located adjacent to the glide slope antennas; the ASR-7 building is adjacent to the radar tower; and the middle marker building for Runway 9R is near an ALS tower. In each case these metal towers are taller than the adjacent structures and thus provide protection against direct lightning strikes to them. However, most of these towers do not have air terminals to prevent direct strikes to the antennas or equipment that might be mounted on them.

In several instances, even on facilities with lightning protection networks, the adequacy of protection against direct strikes to the facility is questionable. The ATCT at Hartsfield has an extensive lightning protection network on its roof; however, the network serves only a limited function. Other metal objects such as antennas, ladders, and guardrails extend higher in the air than do the air terminals. An impending lightning stroke would strike one of the higher objects before striking an air terminal.

The RVR towers do have a single lightning rod provided; however, the usefulness of this rod is questionable because the RVR's surveyed are located near glide slopes which have an antenna structure that is taller than the RVR tower. Similarly, the top of the lightning rod on one of the RTR-D antenna poles at Hartsfield is approximately the same height as the antenna.

Even though many facilities have no lightning protection networks or the usefulness of the networks are doubtful, an inspection of some of the rod tips and discussion with the operating personnel indicate that there are very few, if any, lightning-related problems caused by direct strikes to the facilities, including the control tower.

Using the procedure given in Sections 2.4 and 2.5, Volume I, GBS Practices and Procedures, an estimate of the expected frequency of a lightning strike to the Hartsfield tower was made. First, the height, h, was estimated at approximately 150 feet, or 45.7 meters. Then, the attractive radius, r_a, was calculated as follows, using Equation 2-4 from Section 2.5:*

$$r_a = 80\sqrt{h}\left(e^{-0.02h} - e^{-0.05h}\right) + 400\left(1 - e^{-0.001h^2}\right)$$

$$= 80\sqrt{45.7}\left(e^{-0.02(45.7)} - e^{-0.05(45.7)}\right) + 400\left(1 - e^{-0.001(45.7)^2}\right)$$

$$= 161.8 + 75.5$$

$$= 237.3 \text{ meters.}$$

The attractive area, A_a, for the tower was determined from

$$A_a = \pi r_a^2 \quad \text{(Equation 2-6, Section 2.5)}$$

which calculates to be

$$1.77 \times 10^5 \text{ m}^2 = 0.177 \text{ km}^2.$$

The average number of thunderstorm days per year, T_y, for the Atlanta area was estimated from Figure 2-2* to be 56. Then, substituting 56 into Equation 2-1* for T_y, i.e.,

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*Equation and figure numbers refer to Volume I of GBS Practices and Procedures.

$$\sigma_y = 0.007\ T_y^{\ 2} = .007(56)^2,$$

the average number of lightning flashes per square kilometer per year was calculated to be 21.9 for the Atlanta area. Atlanta being located at 33.6 degrees longitude means that 22.6 percent (see Equation 2-2)* of the flashes are to earth. In other words, approximately 5 lightning strokes per square kilometer per year are roughly characteristic of the Hartsfield area. Thus, the expected strike frequency is:

$$\text{Number of strikes/year} = 5\ \text{strokes/km}^2 \times 0.177\ \text{km}^2$$
$$= 0.89\ \text{strokes/year}$$

or one lightning stroke very 13-1/2 months.

This estimate would appear to indicate that some evidence of lightning stroke effects (burning or pitting) should have been evident on some of the metal antennas and antenna masts on the cab roof. But no such evidence was found. FAA personnel were not aware of any particular lightning problems with the communications equipment utilizing the antennas. This anomaly was not resolved.

An analysis of the expected lightning threat to Building 225 at Robins AFB was made, also using the above procedure. The roof of the communications center building is flat with what appears to be a smoke stack extending approximately 11 feet above the roof. There is no lightning protection network on the roof or the smoke stack to intercept direct strokes to the building. There are no other tall objects such as trees or utility poles nearby. By assuming the total height of the smoke stack to be 23 feet above the ground, the likelihood of a direct strike to the communications center in a given year is calculated to be approximately 1 in 50, i.e., on the average a direct strike can be expected once every 50 years. Discussions with the Air Force personnel indicate that direct lightning strikes to the building have not been a problem.

Another consideration in evaluating the need for an air terminal/down conductor network is the damage that would result from a lightning strike to

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*See footnote on preceding page.

the building (see Section 2.8, Volume I, GBS Practices and Procedures). If lightning does strike the communications center, the building material surrounding the structural steel at the point of impingement will be physically damaged. The entire facility including the equipment will instantaneously rise to a high potential. This large instantaneous potential is not likely to cause any problems inside the facility, but it may cause electrical breakdown in the power transformer or in the signal lines to and from the facility if they are not adequately protected. However, with adequate surge arresters on the power transformer and on the signal lines, the likelihood of severe damage to the system is very low. With a low probability (only 1 in 50 years) of a direct strike to the facility and with the low likelihood of severe damage, the addition of an air terminal/down conductor network to the communications center is probably not necessary.

At most facilities the major lightning threat is not the direct strike to the structure. Rather, almost all of the lightning related problems appear to be the following:

(a) direct strikes to power distribution lines which interrupt commercial power,

(b) lightning surges on commercial power distribution lines which cause equipment malfunction or destruction,

(c) cloud-to-cloud strikes which induce sufficiently large currents into intersite signal and control lines to produce malfunctions or damage sensitive equipments.

For example, although little evidence of direct lightning strikes to structures was noted, lightning-induced surges on signal and control lines has historically been a chronic problem at Hartsfield. In particular, the lines to ILS components experience frequent voltage surges during thunderstorms. These surges pose a severe threat to electronic components, a problem which has become worse with the installation of the solid state equipment on Runway 9R.

Some of the intersite signal and control cables have surge arresters on them. For example, in the ATCT at Hartsfield many control lines have NE-2 neon bulbs to ground to provide some surge protection; the middle marker for

Runway 9R has carbon block arresters and 1N4752 diodes on the control lines to the ATCT; and at the glide slope for Runway 33 the control cables to the nearby RVR have neon bulb surge arresters. Similarly, many of the power distribution lines have surge arresters near the point where they enter the facility. The ASR-7 radar facility has a secondary surge arrester on the incoming power lines; the middle marker for Runway 9R has a three-electrode surge arrester; and the power transformer at the glide slope for Runway 33 has pellet-type arresters on both its primary and secondary. Even with these surge arresters on many of the signal, control, and power lines, the problems related to lightning-induced surges still exist and are presently being studied.* Progress is being made toward solving these problems, but further work remains to be done taking into account the specific characteristics of each facility before these lightning-related problems will be solved.

3.3 Power Safety Grounding

The power safety grounding function in many of the facilities included in this survey is provided by both the safety grounding (green) conductor as required by the NEC and by an equipment ground network. In the majority, if not all, of the facilities, a safety grounding conductor to provide power line fault protection is routed with the ac power line to the equipment. This conductor is bolted to the equipment cabinet and to the service entrance disconnect switch enclosure with compression clamps. It appears to have been sized and installed in accordance with the requirements of the NEC and, generally, appears to have been adequately maintained.

An auxiliary equipment ground network in addition to the safety grounding conductor is also installed in several of the facilities. This equipment ground network usually consists of either a No. 6 AWG copper wire, a copper strap, or both. For example, the equipment ground networks in the equipment room of the ATCT at Hartsfield and in the VORTAC near Rex, GA consist of a

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*These efforts are being conducted through the Post Doctoral Program, Rome Air Development Center, Rome, NY under Contract No. DOT-FA72WAI-356.

No. 6 AWG copper wire. The ASR-7 radar at Hartsfield and the AN/FPS-7 radar at Aiken, SC employ copper straps for the equipment ground network. On the other hand, the glide slope facilities for Runways 8 and 33 at Hartsfield use both a No. 6 AWG copper wire and a copper strap for the equipment ground network. A few facilities such as the GATR site at Aiken and the MARS facility at Robins employ braided straps instead of wires or copper straps.

The conductors of the equipment ground network are bonded to each piece of equipment, to the metal structural elements of the facility, and either directly or indirectly to the facility's earth electrode system. The copper wires and braided straps are usually bolted to the equipment cabinets with compression clamps, whereas the copper straps are bolted and/or soldered to the cabinets.

In almost all of the facilities surveyed the electrical supporting structures such as conduit, cable trays, etc. are interconnected with the equipment cabinets. These metal elements of the facility form extra parallel paths in the equipment ground network and, thus, lower its impedance. With all of these interconnections between the equipment cabinets, the metal elements of the facility and the earth electrode system, the power safety grounding is considered adequate in the facilities surveyed.

In several of the power safety grounding conductors, relatively large 60 Hz currents were measured. For example, at Hartsfield there was 0.3 amperes of 60 Hz current in the ground conductor from the power distribution panel to the equipment cabinets in the glide slope for Runway 33, and there were 1.2 amperes and 3 amperes in two different ground conductors leaving the ac power breaker box at the VORTAC. At Aiken the 60 Hz currents varied from 0.6 amperes to 9 amperes in the ground conductors located in the crawl space under the AN/FPS-26 tower. Since these 60 Hz currents are flowing in the power safety ground/equipment ground network and since this ground network also functions as the signal ground network (see next section), the currents can be conductively coupled into signal circuits to create interference. At these locations and any others where large currents are found to be flowing in the safety/equipment ground network, steps should be taken to determine the source of the stray current and implement the necessary measures to eliminate it.

3.4 Signal Grounding

As a general rule, a separate network for signal grounding is not installed in the facilities surveyed. The return side of the signal circuits is usually grounded to the equipment chassis, and the chassis are all bonded to the equipment rack or enclosure. The racks or enclosures are then in turn connected to the equipment ground network (building ground) which forms a part of the power safety ground. Thus, the equipment ground network functions as the power safety ground and the signal ground network.

In a few facilities there are exceptions to the customary convention of using the equipment ground network for signal grounding. The ARTS I computer system in the ATCT at Hartsfield and the data processing computer and the TEMPEST grounds in the Communications Center at Robins all have single point signal ground networks. The signal grounds in the ARTS I system equipment are connected to the equipment chassis and enclosures; the equipment enclosures are then connected each with a single conductor to a copper plate which is connected to the building ground. The equipment enclosures are supposedly isolated from the metal parts of building and the power safety ground network in order to prevent compromises in the single point ground configuration. However, the usefulness of this single point signal ground network is questionable since the equipment enclosures are connected to the cable trays which are interconnected with the power safety ground network (see Section 2.1.1.4). Because of the interconnections, the separately installed signal ground no longer has a single point ground configuration.

Other than that associated with the ARTS-I system, no other isolated grounding network is used for establishing a signal reference. Low frequency signals (i.e., those below 1 MHz, as defined in Section 7.3.4.3, Volume I, GBS Practices and Procedures) such as those associated with audio communications circuits, monitor and control circuits, etc. are referenced to chassis internal to equipments.

The logic ground for the data processing computers in the Communications Center at Robins is a single point signal ground network. A single connection is provided by a ground conductor which is said to be connected to the earth electrode system. The logic grounds in the newer equipments are isolated from the equipment chassis and enclosures. A few of the older equipments

have the logic ground directly connected to the equipment chassis and enclosure. To prevent compromises in the single point ground configuration, the enclosures of these older equipments are insulated from other nearby cabinets and from building or structural ground. As far as could be determined, the single point logic ground is isolated from the equipment ground network although the isolation may be less than the 1 megohm recommended in Section 3.2.1.1.5, Volume II, GBS Practices and Procedures because of circuit resistances between grounds in the equipments (see Section 2.2.1 under Survey Findings).

Even though the logic ground is installed in a single point ground configuration, there are apparently some compromises in this configuration because of the signal lines between the units of equipment. Several of the signal leads between equipments are coaxial lines. The shields on these coaxial signal lines are insulated from the equipment chassis and enclosures, i.e., the power safety/equipment ground networks; however, these shields are grounded at both ends of the signal lines to the logic ground network. As a specific example, the coaxial signal lines between the processor and the line receiver/driver amplifiers in the DCT 9000 high speed printer are grounded to the logic grounds at each end. Thus, the logic ground network is no longer a single point ground configuration and, thus, does not conform to the recommendations presented in Section 7.3.4.1, Volume I, GBS Practices and Procedures for the low frequency signal ground network.

Single point ground networks are also employed for the TEMPEST signal grounds in the Communications Center. These grounds were described as being isolated from the metal parts of the building and from the equipment enclosures. These grounds were verified to be isolated from the conduit and their distribution boxes; however, because of the limited access to these grounds, the isolation at other places could not be determined.

The interfaces between almost all of the susceptible low frequency equipments are balanced lines. Since neither side of these lines is connected to ground, 60 Hz and other low frequency noise current cannot be conductively coupled into the signal interface lines to create interference. However, in all equipment with balanced inputs and outputs, the center tap of the balancing transformer is not grounded. Thus, the balanced nature of

the signal interfaces may, or may not, be with respect to ground and its usefulness in minimizing inductive, capacitive, and radiated coupling is questionable.

In conclusion, except as noted, an isolated signal grounding network does not exist for either high or low frequency equipments. The grounding network for the ARTS-I system was apparently originally intended to be an isolated, single point network; however, subsequent changes have obviously compromised this intent. In addition to the ARTS-I system, several other pieces of equipment in the facilities fall within the definition of low frequency equipment. To retrofit all this equipment to be compatible with the low frequency grounding practices set forth in Section 3.2.1.1, Volume II, GBS Practices and Procedures would be very expensive. Practically all, if not all, equipments would require drastic modifications. Discussions with FAA and Air Force personnel failed to identify major, continuing problems with noise and interference on the low frequency equipments, and thus a strong justification for major renovation was not noted. Consequently, a large scale modification program to implement the total low frequency signal ground concept in facilities surveyed is not recommended.

3.5 Bonding

The electrical bonds inspected during this survey included clamped, bolted, soldered, brazed, welded, and Cadwelded™ bonds. Each of these types of bonds apparently have been used in particular applications where that method is necessary and/or is the most practical technique for making the required electrical connection. In general, most of the bonds examined were in good electrical condition and were physically tight. A few bonds were found to be loose; these were noted under "Survey Findings".

It was noted in Section 2.1.1.4 that several connections to the No. 6 supplemental grounding conductor have been made with soft solder. Although the primary purpose of this network is not fault protection, in the event of a fault, the heat generated by the fault current could cause the solder to melt and flow from the junction. Once the solder is gone, the continuity of the bond could be broken. With no overt indication that the bond has

deteriorated, a potentially hazardous situation could be created if another fault should subsequently occur.

The dc resistance measurements of several typical bonds gave a strong indication that the bonds were in good electrical condition. The dc resistances of the majority of the single bonds which were measured were less than 1 milliohm, and many of the resistances were less than 0.5 milliohms. Most connections generally conformed to the resistance requirements set forth in Section 4.3, Volume I, GBS Practices and Procedures.

At Hartsfield most exterior bonds, i.e., the ones exposed to the weather, have not been properly refinished and are, or are in the process of becoming, seriously corroded. By contrast, most of the exterior bonds at Robins and Aiken were painted at the time they were made; the paint has prevented moisture from getting to the bonded members and has minimized corrosion. Resistance measurements were made of several of the corroded connections; the measurements indicated that the mating surfaces still make good electrical contact. If the corrosion continues, however, the bonds will eventually be destroyed both electrically and physically.

Many bonds could not be examined because they were located in inaccessible locations, e.g., bonds to building structural steel are inside building walls and bonds to the earth electrode systems are buried below the earth's surfaces. Inaccessible connections such as these should be permanently bonded by welding or brazing and must be carefully protected from corrosion. Because of their inaccessibility, the integrity of such bonds cannot be routinely checked; thus, it is highly important that they maintain their tightness and low resistance.

3.6 Shielding

Most of the ILS components are housed in shelters covered with a thin metal skin of either steel or aluminum. The shielding capabilities of this metal skin are not used to advantage, however. No particular effort has apparently been made to achieve an effective electrical bond at joints between panels. The enclosures of the equipments housed within the shelters were not designed to be RF-tight. As a result, undesired coupling has created problems between the glide slope equipments and the associated

antennas. To solve this problem an auxiliary screen has been installed in each glide slope shelter on the wall nearest the antenna. The screen is bonded together well and connected with either 2-inch wide copper straps or No. 6 wire to ground rods outside the shelter. Equipment racks inside the shelter are bonded together with a No. 6 copper wire and to the metal screen.

The equipment shelter for the ASR-7 at Hartsfield is constructed of a type of fiberglass. As a result, the shelter offers essentially no shielding to electromagnetic fields. The equipment racks and cabinets do exhibit a high degree of care in their construction to achieve effective shielding. However, high level signals from sources such as the citizens band transmitter used for intercom purposes (see the next section) couple to cables, ground straps, and into the equipment and cause serious interference problems. Other transmitting systems could conceivably cause similar problems at other locations. A shelter using a properly bonded metal skin would have been a better choice for this shelter.

Shields of signal cables are grounded to chassis or distribution panel grounds. Available evidence indicates that some shields are grounded at the transmitter, or source, end; some are grounded at the receiver, or load, end; and some shields are grounded on both ends. In the event of noise problems on cables, this mixed method of shield grounding makes troubleshooting of the system very difficult. Consequently, a shield grounding procedure should be standardized and implemented.

For optimum effectiveness, the shields of signal cables should be insulated from each other and should be protected from unintentional contact with equipment and building grounds (see Section 3.2.1.1.7, Volume II, GBS Practices and Procedures). This shield-to-shield contact between signal lines can produce crosstalk between channels or circuits and is not desirable. During any future additions or modifications to systems where uninsulated shielded cables are now in use, the installation of properly insulated cables is strongly recommended.

3.7 Supplemental Comments

Survey team access to the Communications Center at Robins AFB was restricted rather severely. No photographs could be made, and only visual inspection of the exteriors of equipments, conduit, and raceways were permitted in the crypto area. As a result, the survey findings tended to be quite limited. In the event of any future surveys of this type, access requirements should be carefully defined and agreed upon in advance between the survey team and the center operational personnel so that a thorough evaluation can be made.

In several instances the opinions of site personnel were solicited relative to known operational problems with some of the networks, primarily the earth electrode system, lightning protection system, and equipment signal grounding. Generally, as noted, the response was negative. This response can be interpreted as either, indeed, the systems and networks are adequate; or operational deficiencies are not recognized as being related to bonding, grounding, and shielding or to the adequacy of the lightning protection system. For example, a high resistance earth electrode system could cause problems to arise from lightning surges, yet the earth electrode system not be recognized as being deficient. Also, noise problems in signal systems can be the result of inadequate or improper grounding and not be recognized as such.

Paradoxically, experience indicates that the inverse situation is also commonly encountered (though not at the particular facilities surveyed under this effort). Many times "poor grounds" are blamed for a wide range of problems that may or may not be related to or curable by "good grounds". Thus, operational problems should be treated only as substantiating evidence of possible deficiencies rather than as proof that "the grounding is wrong".

On a separate matter, the differential time domain voltage measurements showed that the 27 MHz signal produced by the citizens band transmitter appears on the power lines and on the video channel of the ASR-7 at Hartsfield. Steps should be taken to remove this transmitter from the radar site. If the intercom capability is absolutely required, the transmitter portion of the radio should be remotely located at another site or at least the antenna

should be moved. A separation distance of 100-200 feet for the antenna may be adequate--the exact distance will have to be determined experimentally.

During the survey the Survey Form given in the Appendix proved too long and too general. As a result, the survey and inspection forms included in Volume II of GBS Practices and Procedures were shortened and were arranged in a manner to solicit specific comments, observations, and data on the grounding, bonding, and shielded networks being surveyed. The revised form should be more helpful in guiding the survey itself and provide more definite and meaningful data on which to evaluate the facility surveyed.

4. OVERALL RECOMMENDATIONS

Based on the findings of this survey, the following general corrective measures are recommended:

RECOMMENDATION NO. 1: Facility Drawings and Other Documentation Should Be Updated and Kept Current

RATIONALE: Documentation such as architectural and engineering drawings, contractor compliance data, and other information describing the facility as originally constructed was found to be very sketchy, hard to locate, or nonexistent. This information should be gathered, if available, and filed with the other basic documentation associated with the facility. Existing drawings and manuals should be redlined to accurately reflect the current installation. Up-to-date documentation is vital to the assessment or appraisal of the networks in a facility; it is also necessary for troubleshooting purposes. The primary costs associated with this recommendation are the time charges of the personnel to gather the documents and update them. In the long run, the effort should more than pay for itself.

RECOMMENDATION NO. 2: A Regular Inspection and Maintenance Program Should Be Initiated for All Facilities

RATIONALE: At present the condition and performance of the existing bonding, grounding, shielding, and lightning protection networks are not really known by site personnel. Thus, there is little capability for recognizing system operational problems as being either related to or not related to deficiencies

in or deterioration of these networks. A program patterned after the one set forth in Chapter 2, Volume II, GBS Practices and Procedures is suggested. As with Recommendation No. 1, the costs associated with the implementation of an inspection and maintenance program are recognized; however, the long term benefits are considered to be sufficient to justify the expense.

RECOMMENDATION NO. 3: Bonds in Grounding and Lightning Down Conductors in Exterior Locations Should Be Inspected, Redone (if necessary), and Properly Sealed Against Moisture and Corrosion

RATIONALE: During the survey the most common deficiency noted was loose and corroded connections in grounding conductors and in lightning discharge paths. Corrosion seemed to be a problem mainly in outdoor locations. The primary cause appears to be the result of dissimilar metals in contact and exposed to moisture. This problem could be alleviated through the use of the same metal types (for example, don't bond copper or aluminum to steel in an outdoor location), proper use of galvanizing to protect ferrous objects, or replacement of unplated nuts, bolts, and washers with galvanized, nickel plated, or cadmium plated ones. Bonds should be moisture sealed with petroleum or silicone (more permanent) grease, pitch or tar, oil-based paint, or epoxies.

To implement this recommendation, each site should be initially surveyed for bonding deficiencies of the type noted herein. Where surfaces have not been cleaned as recommended in GBS Practices and Procedures, they should be properly cleaned; fasteners should be of the same material as the joined members, or they should be plated with a noncorrosive material; fasteners should be securely tightened; any broken or corroded welded or brazed joints should be redone; the resistance of the bond should be verified to be less than 1 milliohm; and the assembled bond should be thoroughly sealed against moisture.

At most sites this recommendation can be implemented at moderate costs. If routinely inspected on a regular basis, the bonds at a given facility could be kept in an excellent condition with minimal costs.

RECOMMENDATION NO. 4: A Thorough Survey Should Be Made to Determine the Magnitude of Stray Power Currents on Equipment Ground Wires, Then A Program to Identify the Source and Reduce the Amplitude of Any Stray Currents Greater than 1 Ampere Should Be Undertaken

RATIONALE: To date stray currents have appeared to of little concern except in cases of sparking or noticeable heating effects. However, these currents can be a serious source of noise ("hum") in audio and digital systems. Several instances of unacceptably high stray current levels were noted. Steps to locate the source(s) of these currents should be undertaken, and measures to reduce them are highly recommended. Possible sources (or causes) of high stray current levels are: interchanged white/black power conductors; unnecessarily large or leaky power line filter capacitors; and heavily unbalanced loads between the phases of a three-phase power supply. The implementation of this recommendation, particularly for large facilities such as a control tower, could involve considerable expense in rework, equipment modifications, etc. Consequently, it may have to be defined as a long range goal to be sought as the facility goes through an evolutionary upgrading process.

RECOMMENDATION NO. 5: Shelters of Metal or Metal-Sheathed Construction Should Be Used in Preference to Fiberglass or Wood Construction for Radar, ILS, and Communications Facilities

RATIONALE: These facilities can be expected to experience EMI problems if adequate electromagnetic shielding is not provided. The inherent shielding properties of metals should be used to advantage to alleviate potential problems. Although the initial cost may be greater for metal shelters, the overall advantages outweigh the possible price differential.

RECOMMENDATION NO. 6: Exposed Lightning Down Conductors and Grounding Conductors Should Be Rerouted or Nonmetallic Guards Should Be installed to Provide Adequate Physical Protection

RATIONALE: Several instances of mechanical damage to these conductors were noted. The installation of guards or rerouting to a more protected location would prevent further damage of this type from occurring. The cost to achieve this protection is expected to be minimal.

RECOMMENDATION NO. 7: Insulated, Shielded Cabling Should Be Used for Low Frequency Interequipment and Intersystem Circuits. A Controlled Method of Signal Shield Grounding Should Be Formulated and Implemented

RATIONALE: The basis for this recommendation is to lessen the likelihood of crosstalk between circuits and systems arising from shield contact. A prescribed system for shield grounding will help to regiment the practices and make troubleshooting easier. Because of the potential cost of the cable changeover, it will probably be desirable to delay this measure until a major upgrading or modification of the facility is done.

RECOMMENDATION NO. 8: Improved Protection Against Lightning and Other Transients on Outdoor (Buried or Overhead) Wires and Cables Is Needed, Particularly on Those Wires and Cables Feeding Solid State Equipments

RATIONALE: A significant effort is already underway to implement this recommendation, particularly within FAA. Several factors must be considered, and the possible cost is high. However, because of the strong need for the protection, these efforts are encouraged.

APPENDIX A

SURVEY FORM

FACILITY _____

1. Earth Electrode System

Configuration:

No. Rods _____

General Layout: (diagram)

Details

Interconnections with other systems?

_____

_____

Cable size _____ Rod size _____

Bonding? _____

Depth below grade _____

Number risers _____

Measured Resistance _____

General Earth Properties:

Damp or Dry	Clay
Rocky	Subsoil/Topsoil
Sandy	Other

Other Observations:

Lightning Protection System

Air Terminals

Location: (Diagram)

Height _____

Interconnections

Cable Size _____

Routing (on diagram)

Bonds: Type _____

Evidence of Corrosion _____

General Comments: _____

_____

_____

Down Conductors

Location _____

_____

Cable Size _____

Method of fastening _____

Guards _____

_____

Lightning Protection System (Con't)

Bonds _____

Bond Corrosion _____

Use of Structural Steel for Down Conductor _____

_____

_____

Connection to Ground Rods _____

_____
(where and how many)

Other Comments _____

_____

_____

Lightning Arresters

Type (signal and power) _____

_____

_____

Location _____

_____

_____

Method of Grounding _____

_____

_____

Safety Ground

Transformer Neutral _____

_____

_____

_____

_____

Equipment Safety Ground

Wire Size _____

Method of connection _____

Conduit? _____

_____

_____

Current measurements _____

_____

_____

Ground lug on Conv. Receptacles _____

_____

_____

Bonds _____

Other Observations _____

_____

_____

_____

_____

Signal Grounding

General Approach _____

_____

_____

Wire or bus size _____

_____

Routing _____

_____

Primary frequencies used in system (RF)(IF)(Baseband) _____

_____

_____

_____

Low Frequency Networks

Isolation _____

Balanced _____

Shield grounding _____

High Frequency Networks

Noise Problems _____

AC Current of cable shields _____

Shield termination coax or pigtails? _____

Point-to-point resistance _____

Connectors _____

_____

_____

Bonds _____

_____

_____

Signal Grounding (Cont'd)

Interface with Safety Ground _____

_____

_____

Noise Measurements _____

_____

_____

Other Comments _____

_____

_____

_____

Bonding

Types _____

_____

Tightness _____

_____

_____

Surface Cleaning _____

_____

Evidences of Corrosion _____

_____

_____

Protection _____

_____

Resistance Checks _____

_____ _____

_____ _____

_____ _____

Jumpers _____

Length _____

Material _____

Solid/Braided _____

Where Used _____

Shielding

Structural _____

_____

_____

Screens _____

Bonds _____

Equipment

Doors _____

Gaskets _____

Bonds across hinges _____

Etc.

Connectors _____

_____

_____

Cables _____

_____

_____

Other Comments _____

_____

_____

_____