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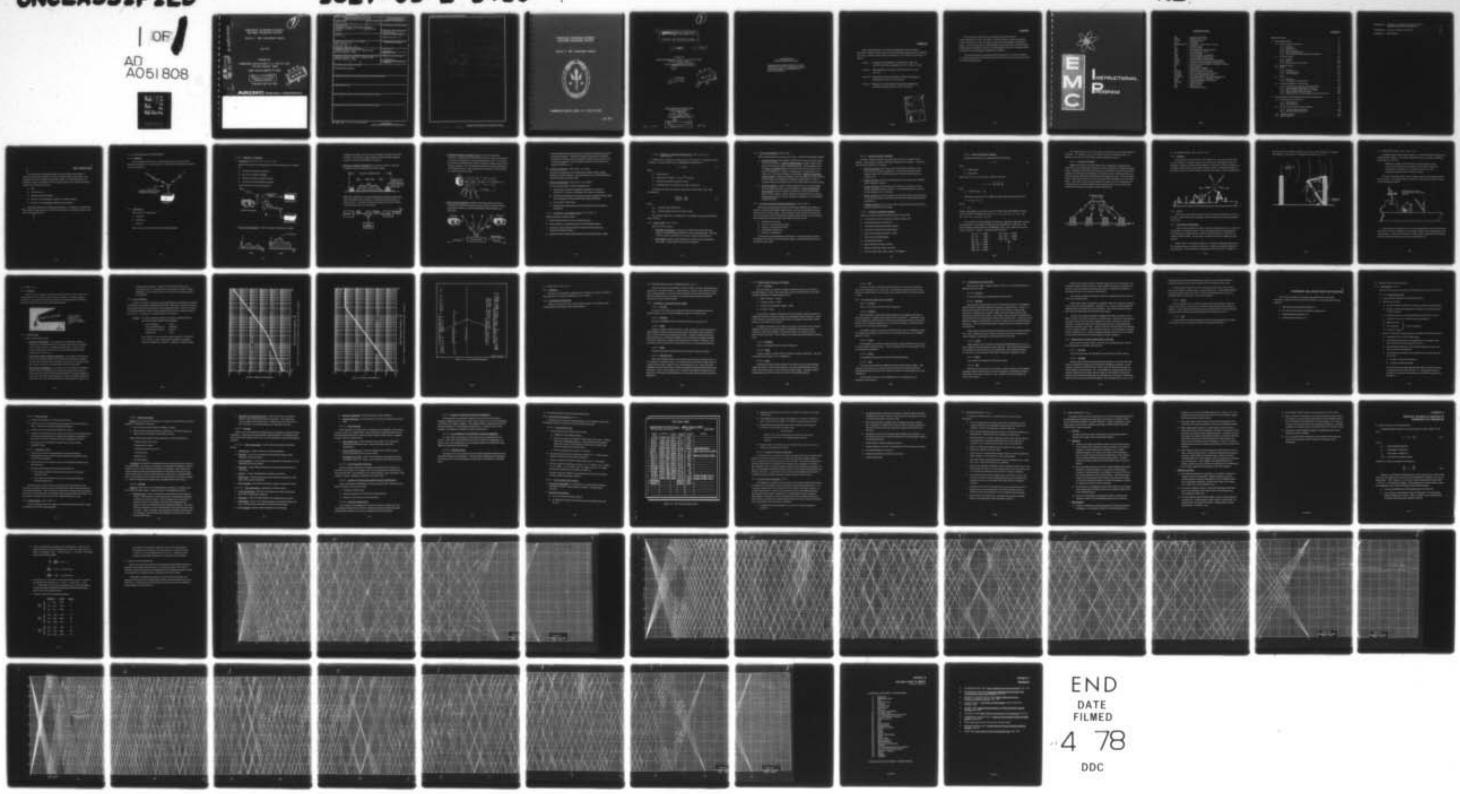

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COMSERVPAC SHIPBOARD ELECTRONIC EQUIPMENT ENGINEERING SUPPORT

Volume II: EMC Instructional Program

June 1975

Prepared for

COMMANDER SERVICE FORCE, U.S. PACIFIC FLEET
FPO San Francisco 96610

Under Contract N66314-74-C-2497

Publication 1627-01-2-1410

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FOREWORD

Under Contract N66314-74-C-2497 with PERA(CSS), ARINC Research Corporation conducted various tasks involving electronic equipment aboard COMSERVPAC ships. Results of these tasks are presented in a four-volume set of reports, as follows:

Volume I – Adequacy and Availability of GPETE Aboard ARS, ATF, and ATS Class Ships, publication 1627-01-1-1409, June 1975

Volume II – EMC Instructional Program, publication 1627-01-2-1410 June 1975

Volume III – Effectiveness of PMS for Shipboard Electronic Equipment, publication 1627-01-3-1411, June 1975

Volume IV – Shipboard Electronic System Configuration Management Analysis, publication 1627-01-4-1412, June 1975

SUMMARY

This document is Volume II of a four-part report produced under Contract N66314-74-C-2497, Task 0002. Presented herein is technical material to serve as the text for a course for ship personnel on electromagnetic compatibility (EMC). Topics covered include electromagnetic interference (EMI), RF burn hazard, radiation hazard (RADHAZ), hazards of electromagnetic radiation to ordnance (HERO), and hazards of electromagnetic radiation to fuel (HERF).

The subject material is recommended and arranged for two-part presentation: 1) a general description of EMI and the four types of hazard, and 2) means of detecting and reducing these factors.

EMC

INSTRUCTIONAL PROGRAM

ABBREVIATIONS

AM	–	Amplitude modulation
ASROC	–	Antisubmarine rocket
AVGAS	–	Aviation gasoline
BW	–	Bandwidth
COMSERVPAC	–	Commander Service Force, Pacific
CW	–	Continuous wave
DF	–	Direction finder
ECM	–	Electromagnetic countermeasure
EED	–	Electroexplosive device
EM	–	Electromagnetic
EMC	–	Electromagnetic compatibility
EMI	–	Electromagnetic interference
FAST	–	Fast automatic shuttle transfer
GPETE	–	General purpose electronic test equipment
HERF	–	Hazards of electromagnetic radiation to fuel
HERO	–	Hazards of electromagnetic radiation to ordnance
HF	–	High frequency
IF	–	Intermediate frequency
IFF	–	Identification, friend or foe
NAVAIR	–	Naval Air Systems Command
NAVORD	–	Naval Ordnance Systems Command
NAVSEC	–	Naval Ship Engineering Center
NAVSHIPS	–	Naval Ship Systems Command Headquarters
NELC	–	Naval Electronics Laboratory Center
PMS	–	Planned Maintenance Subsystem
RADHAZ	–	Radiation hazard
RF	–	Radio frequency
S/N	–	Signal to noise
UHF	–	Ultra high frequency

CONTENTS

1
EMC DESCRIPTION

Electromagnetic compatibility (EMC) is usually defined as the ability of electronic equipment to function in a fixed environment without degradation of performance due to electromagnetic interference (EMI). For present purposes, the definition of EMC is expanded to include personnel safety and a combined personnel/equipment environment subject to:

a. EMI

b. RF burn hazard

c. Radiation hazard (RADHAZ)

d. Hazards of electromagnetic radiation to ordnance (HERO)

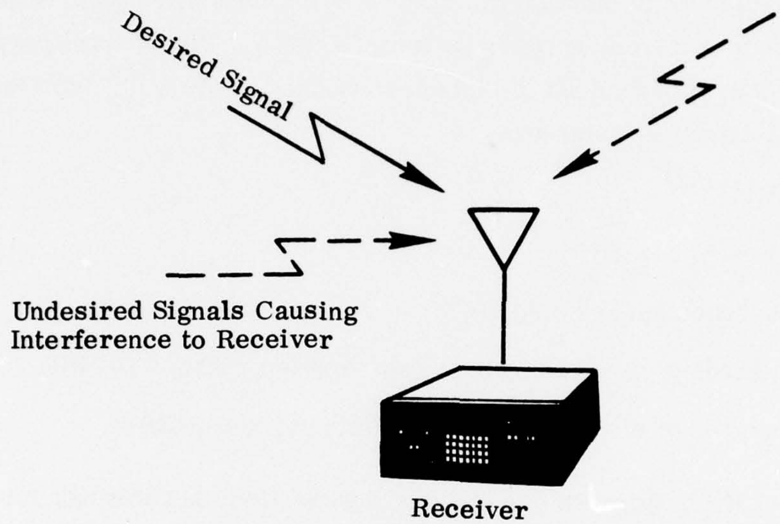
e. Hazards of electromagnetic radiation to fuel (HERF)

These EMC categories are discussed in Sections 1.1 through 1.5, respectively. Since antenna location impacts on all of these categories, a special discussion of that topic is given in Section 1.6.

1.1 ELECTROMAGNETIC INTERFERENCE

1.1.1 Definition

Electromagnetic interference is radiated energy that interferes with the detection and analysis of a desired signal, or which otherwise degrades the performance of an equipment.



1.1.2 EMI Sources

EMI sources are classified as:

a. Equipment

b. Atmosphere

c. Inherent

These sources are discussed in the following paragraphs.

1.1.2.1 EMI Source: Equipment

a. Transmitters – Ref. B, Sec. 3.1.1, 7.1, and 8

Spurious emissions from transmitters (see illustration below) are initiated by:

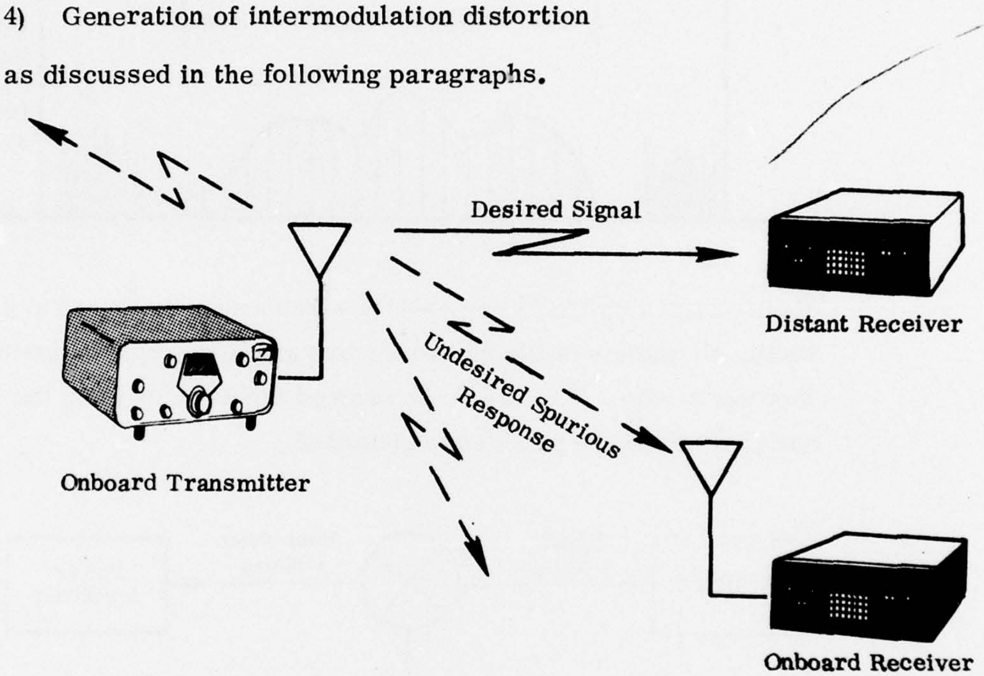
1) Overdriven transmitter amplifiers

2) Excessive modulator bandwidth

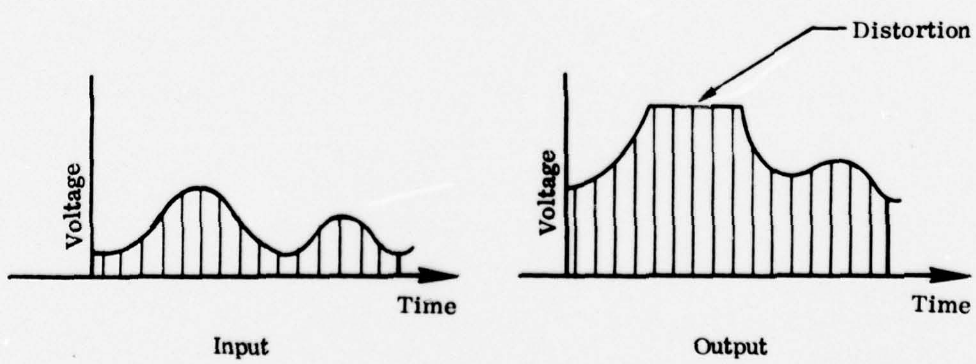
3) Unshielded frequency multiplier stages

4) Generation of intermodulation distortion

as discussed in the following paragraphs.

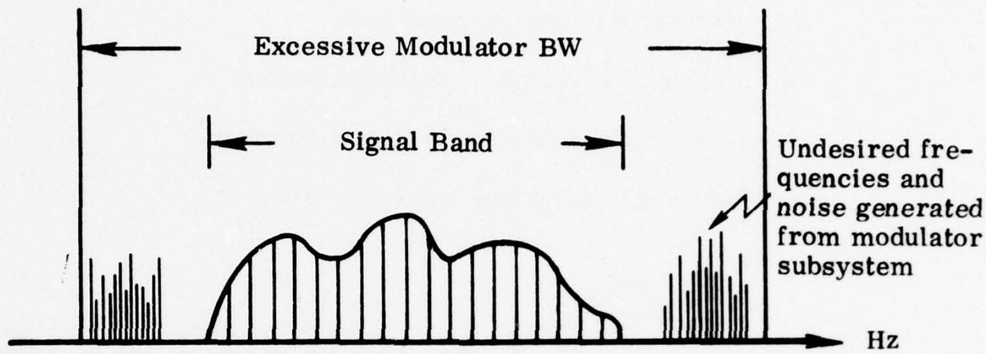


• An overdriven amplifier results in clipping or distortion of a signal:

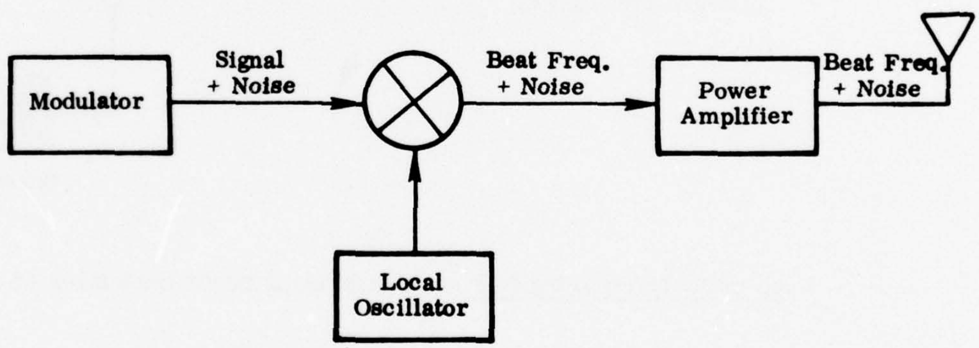


Clipping of the signal waveform causes unwanted spreading of the signal spectrum. Therefore the signal contains a distorted signal frequency spectrum plus unwanted additional frequencies.

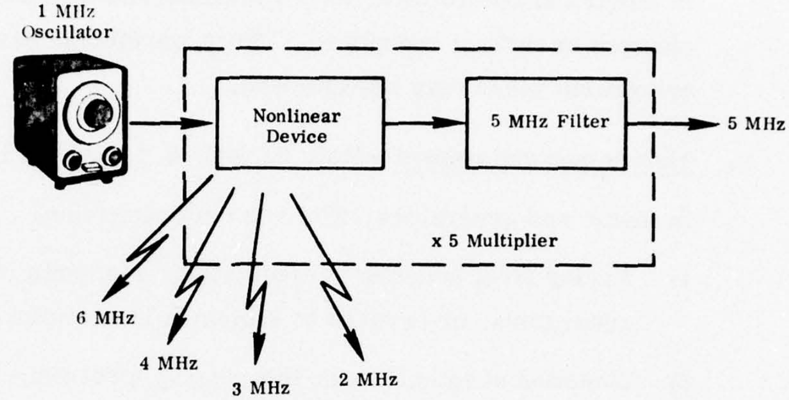
- Excessive modulator bandwidth usually permits passage of undesired frequencies and noise along with the desired signal.



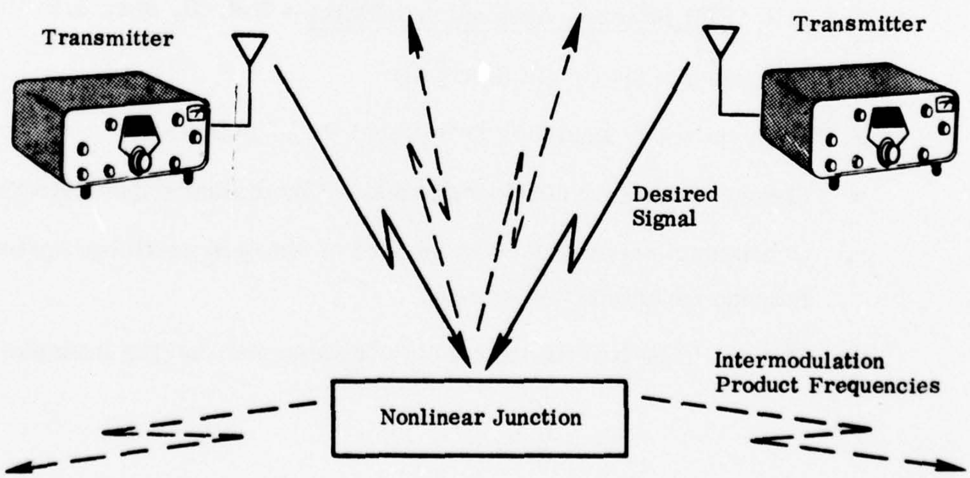
Since power amplifiers are usually wideband with respect to signal bandwidth, all signals in the modulator are amplified and transmitted (see diagram below). Therefore if unwanted frequencies from the modulator are present, these are also transmitted.



• Unshielded frequency multiplier stages are sources of spurious harmonics. Multiplication of frequencies involves not only the generation of the desired frequency, but many unwanted ones as well. For example the frequency multiplication of 1 MHz to 5 MHz (see figure below) involves driving a nonlinear device to obtain all harmonics of 1 MHz and filtering out the fifth harmonic. If the multiplier is not shielded, other harmonics are radiated and become EMI.



• Intermodulation distortion products are generated when two or more transmitters illuminate a nonlinear junction (usually a metallic junction that displays nonlinear electrical input/output characteristics); see illustration.



Intermodulation products can exist at many different frequencies than the transmit frequencies. When these unwanted frequencies fall within the passband of a nearby receiver, the ability of that receiver to function can be seriously degraded. A more detailed discussion of this EMI source appears in Section 1.1.5.

b. Electrical controllers – Ref. B, Sec. 3.1.2 and 6

In electrical controllers, on-off make/break contact results in sharp changes in current waveform. These waveforms have broadband frequency spectrums which may become EMI.

c. Motors and generators – Ref. B, Sec. 3.1.3 and 6.1

In motor and generators, EMI can originate from:

1) Arcing from brushes to commutator segments in dc motors or generators, or brushes to sliprings in ac motors or generators.

2) Induction of interference into nearby electronic equipment from the high energy magnetic fields associated with rotating machinery.

3) DC generator output ripple.

4) Slot harmonics appearing as harmonic frequencies in the output of generators.

1.1.2.2 EMI Source: Atmospheric Noise – Ref. B, Sec. 3.2

EMI of atmospheric origin includes:

a. High-intensity impulses from local thunderstorms.

b. Steady rattling or crackling produced by distant thunderstorms.

c. Continuous noise caused by impact of charged particles against an antenna (precipitation static).

d. Steady, hiss-type static (at high frequencies) having interstellar origin.

1.1.2.3 EMI Source: Inherent (Thermal Noise) – Ref. B, Sec. 3.3; Ref. D, Ch. 8

Thermal noise is caused by random motion of electronics in a conductor of finite resistance. This phenomenon can be mathematically expressed as:

$$N = kTB \tag{1}$$

where

N = Thermal noise

k = Boltzmann's constant: 1.38×10^{-23} joule/deg

T = Absolute temperature (degrees Kelvin)

B = Bandwidth (Hz) over which noise voltage is measured

Thermal noise affects the receiver input signal-to-noise (S/N) ratio in the following way:

$$\left(\frac{S_{in}}{N_{in}}\right) = \frac{S_{in}}{kTB} \tag{2}$$

where

S_{in} = Available input signal power

N_{in} = Available input noise power (equal to kTB)

As seen from equation 2, as temperature or bandwidth increases, the input S/N ratio decreases.

1.1.3 Types of EMI – Ref. B, Sec. 4

EMI is of two basic types:

a. Wideband or broadband, usually a part of the RF spectrum wider than either the assigned frequency channel or the receiver bandwidth. This type of EMI is usually caused by arcs, corona, or short-duration pulses.

b. Narrowband, usually a single frequency or a narrow band of frequencies that occupy a small portion of the receiver passband.

1.1.4 EMI Coupling Methods – Ref. B, Sec. 5

EMI is transmitted from its origin in two ways: conducted and radiated coupling.

a. Conducted coupling is the transfer of EMI from its source by means associated with hard-wiring. Typical conduction paths are power supply cables, control and accessory cables, grounding systems, and transmission lines. The degree of coupling depends on the frequencies involved, power level, amount of capacitive or inductive coupling, types of circuit (pulse, CW, audio, etc.), lead dress, filtering, and shielding. Methods of containing conducted EMI are filtering; shielding; proper grounding of circuits, shields, and interconnecting cabling; use of isolation transformer for circuit or ground isolation; and separation of low-level signal cables from other cables.

b. Radiated coupling is transfer of EMI through space by an electromagnetic field according to the laws of wave propagation. Factors affecting EMI field strength include the amount of current flow in the conductor from which the field radiates, and the efficiency of the conductor as an antenna. Containment factors are usually confinement techniques, such as shielding around the source.

1.1.5 Hull-Generated Intermodulation Interference – Ref. B, Sec. 8

Ship topside equipment and structures have always exhibited some degree of nonlinear electrical input/output characteristics, and thus intermodulation product frequencies have always existed. These frequencies were not serious interference sources in the past, but this situation has changed with the advent of new communications technology and requirements, particularly with increases in:

a. Sensitivity of receivers
b. The use of the frequency spectrum
c. Number of antennas aboard ship
d. Transmitter output power
e. Number of transmitters

Hull-generated intermodulation interference is caused by nonlinear junction formations, the primary cause of EMI aboard ships. That phenomenon will now be discussed in some detail.

1.1.5.1 Nonlinear Junction Formation

Nonlinear metallic junctions form when metal junctions are exposed to the weather. These junctions corrode and display nonlinear characteristics. The following are major categories of corrosion:

a. Galvanic corrosion occurs when a more noble metal is joined to a less noble metal (see listing, Appendix B). The more noble metal remains unharmed while the less noble experiences a high corrosion rate (e.g., a battery cell).

b. Fatigue corrosion results from the breakdown of protective film on metals due to bending or vibration.

c. Crevice corrosion occurs because of the tendency of fissures to collect liquids, including corrosive solutions. The resulting differences in metal ion concentration lead to corrosion.

d. Stress corrosion occurs when metals are exposed to either excessive stress, or a corrosive medium; or when the base metal has an improper structural configuration.

e. Welding corrosion occurs in areas where variations of grain size have been produced by the heat from welding.

1.1.5.2 Locations of Nonlinear Junctions

Typical areas where nonlinear junctions can be found include:

a. Loose metallic items in topside area (pipes, chains, etc.)

b. Rusted pinned joints, sister hooks

c. Corroded stanchions and metallic lifelines

d. Corroded door hatches and scuttle hinges

e. Rusty anchor chains and metallic cables

f. Booms and associated rigging

g. Accommodation ladder

h. Safety chains and metallic lifelines

i. Metallic safety nuts, chain, and cable

j. Corroded mast items (cable, armor, and hangers)

1.1.5.3 Theory of Nonlinear Junctions

A nonlinear junction may be characterized by the equation,

$$y = e^x \tag{3}$$

where

y = Output signal

x = Input signal

Expressing e^x as a series expansion, equation 3 becomes:

$$y = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} \tag{4}$$

where

$N! = (N)(N-1)(N-2)\ \ldots\ (1)$

If the input comprises two CW signals, the input signal may be expressed as

$x = \cos \omega_1 t + \cos \omega_2 t$

where

$\omega = 2\pi f$

and the output signal (y) will equal a series of cosine terms representing all combinations of signals of frequency ω_1 and ω_2, i.e., $2\omega_1 - \omega_2$, $2\omega_2 - \omega_1$, $2\omega_1 - 2\omega_2$, $2\omega_2 - 2\omega_1$, $3\omega_1 - 2\omega_2$, $3\omega_2 - 2\omega_1$, etc.

As an example of intermodulation frequency (or "intermod") generation, assume that transmitter 1 is operating at 5 MHz (f_1) and transmitter 2 at 6 MHz (f_2). The intermodulation products include all combinations of $Af_1 + Bf_2$, where A or B is any integer, positive or negative. Examples of intermods are:

$|f_1 + f_2| = 11$ MHz

$|f_1 - f_2| = 1$ MHz

$|f_2 - f_1| = 1$ MHz

$|2f_1 - f_2| = 4$ MHz

$|2f_1 + f_2| = 16$ MHz

$|2f_2 - f_1| = 7$ MHz

$|2f_2 + f_1| = 17$ MHz

$|2f_1 + 2f_2| = 22$ MHz

$|2f_2 - 2f_1| = 2$ MHz

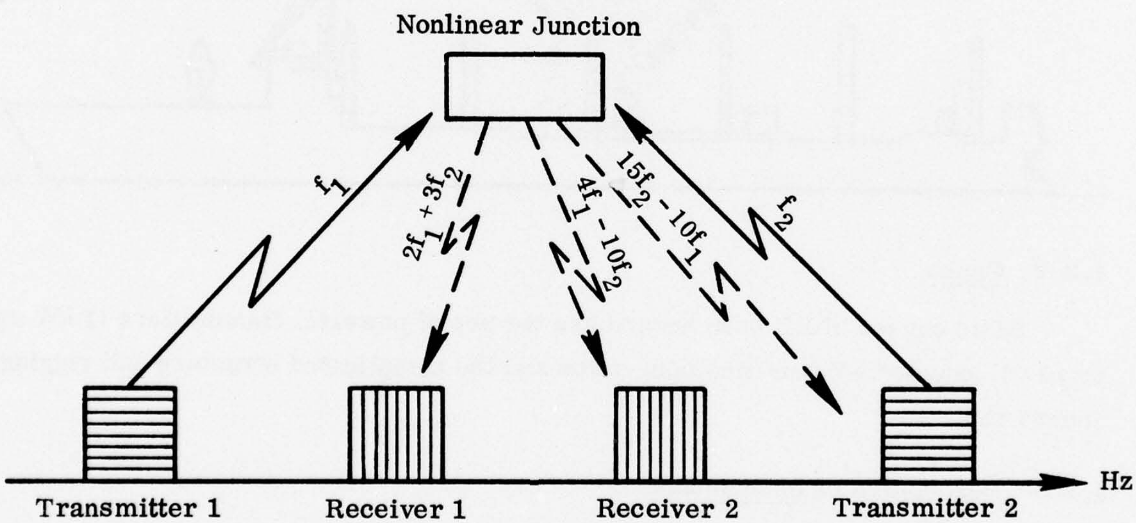
$|2f_1 - 2f_2| = 2$ MHz

etc.

The coefficients of f_1 and f_2, when added, gives the order of the intermodulation frequency. For example, $3f_1 - f_2$ is a fourth-order intermodulation product. In general, as the order is increased the signal magnitude decreases.

1.1.5.4 Summary of Problem

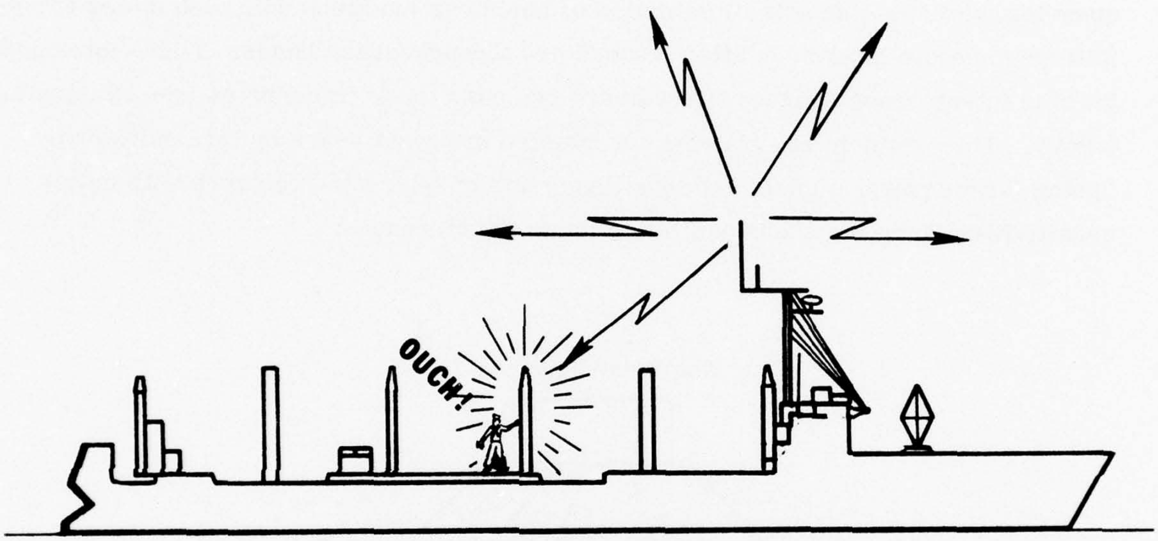
Shipboard electronic operations often involve simultaneous transmission by radio and/or radar equipments in addition to receiver operation on different frequency bands. Although the transmitted frequencies are spectrally far from the received frequencies, the simultaneous illumination of nonlinear junctions with high power transmitters generate intermodulation frequencies throughout the bands. These intermods become interference sources if receivers can pass these frequencies (see illustration below). This problem has become accentuated in recent years by transmitters producing larger power signals and thus larger intermods, and receivers with better sensitivities being more susceptible to these interferences.



1.2 RF BURN HAZARD – Ref. A, Sec. 1 and 2

1.2.1 Definition

RF burn hazard is the existence of RF voltages on a ship at places where they are not intended nor normally expected. The level of RF voltage that creates this hazardous condition is defined as that sufficient to cause pain, visible skin damage, or involuntary reaction upon contact with the charged surface. NAVSEC has defined as hazardous an open-circuit RF voltage at 140 volts on an object in an RF radiation field.



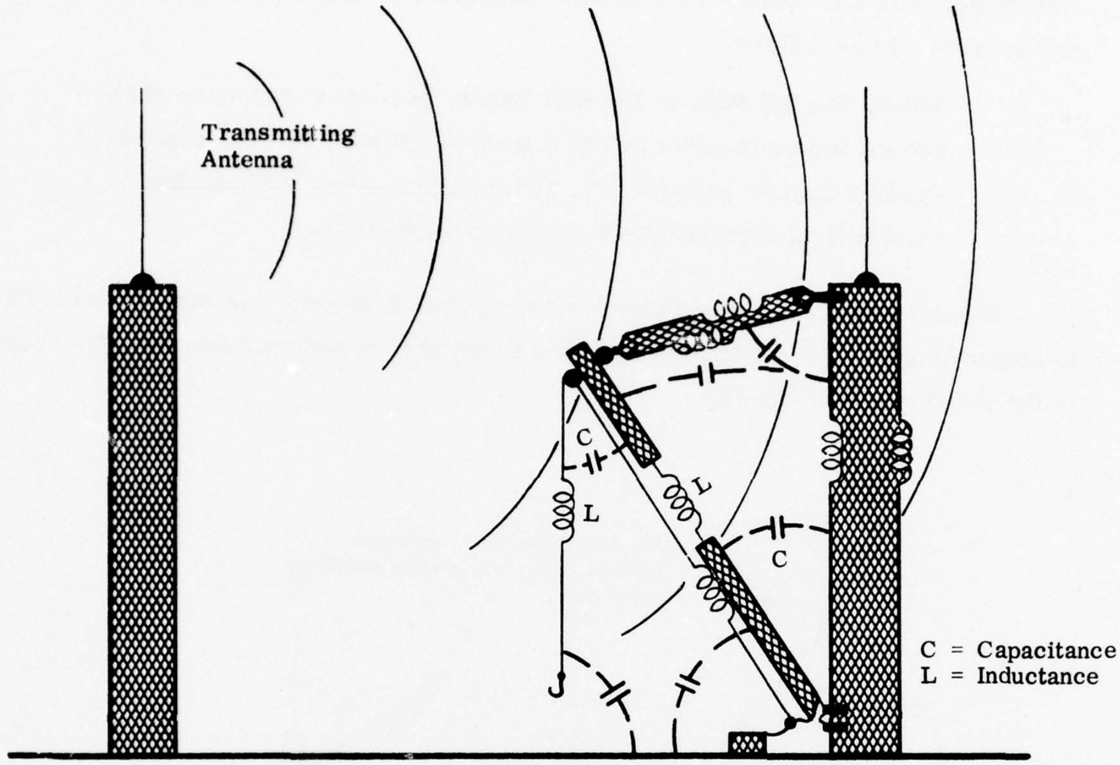
1.2.2 Cause

Basic causes of RF burn hazard are the use of powerful transmitters (1 kW and greater), coupled with antenna congestion and the complicated structure and rigging aboard ship.

1.2.3 Description of Phenomenon

A ship's superstructure has reactive electrical characteristics, i.e., capacitive and inductive (see diagram below). If the transmitted frequency illuminating the superstructure corresponds to the electrical resonant frequency, energy will be coupled to this structure. The structural members then become potential RF burn hazards.

Additionally, if a structural member is of a physical length approaching that of the radiating antenna, the member may become a radiator and display antenna-like characteristics. This situation also represents an RF burn hazard. Potential RF burn hazards include ASROC launchers, aircraft on carrier flight decks, kingposts with outriggers, cargo booms, long lengths of metallic cables, etc.

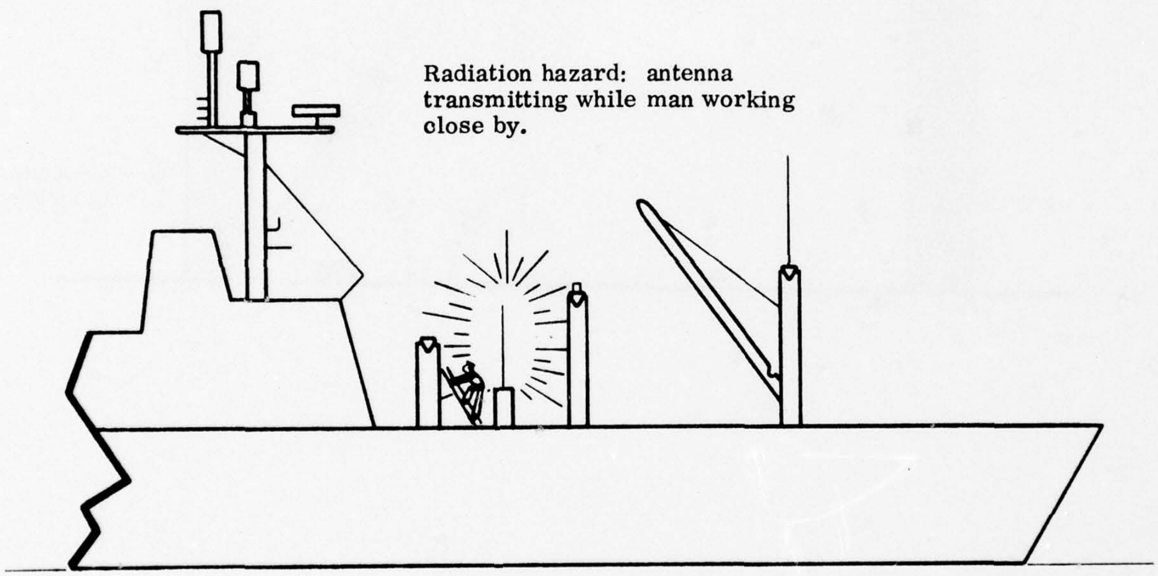


1.3 RADIATION HAZARD – Ref. E, Sec. 1.2.2

A radiation hazard exists when personnel are directly illuminated by high-power electromagnetic radiators. Safe limits established by the U.S. Bureau of Medicine and Surgery are as follows:

> Within the 100 MHz to 100 GHz range, personnel exposure shall not exceed an incident power density of 10 mW/cm^2 for exposures greater than 30 seconds; or, 300 millijoules/cm^2/30 sec for intermittent exposure between 3 and 30 seconds.

For power levels above these limits, radiation exposure is considered harmful to human tissue. EM radiation burns are thermal in nature and are directly related to the incident power density.

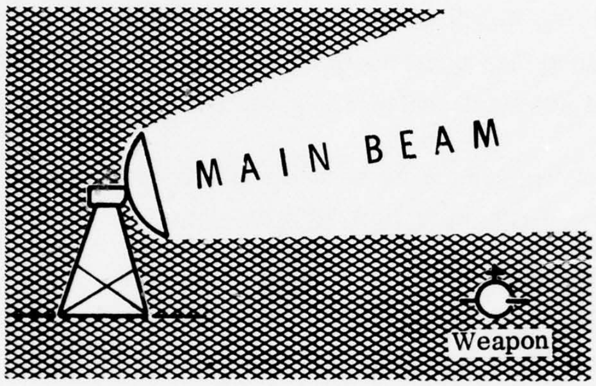


If an individual is exposed to UHF or x-ray transmissions on an area of his body where there are no nerve endings, he could suffer internal burns without being aware of the problem. Organs such as the liver, kidneys, heart, and lungs can be damaged before an individual realizes he has been in a hazardous area.

1.4 HERO – Ref. C

1.4.1 Definition

Hazards of electromagnetic radiation to ordnance (HERO) are due to the use of electroexplosive devices (EEDs), such as fuses or squibs, in ordnance systems. The EEDs can be prematurely actuated or degraded by high intensity RF fields produced by modern radio and radar transmitting equipment.



HERO condition: Main beam of antenna in vicinity of weapon containing EED.

1.4.2 Classifications

HERO classifications include:

a. HERO SAFE ORDNANCE. Any ordnance item sufficiently shielded or otherwise so protected that all EEDs contained by the item are immune to adverse effects (safety or reliability) when the item is employed in its expected shipboard RF environments, provided that the general HERO requirements are observed.

b. HERO SUSCEPTIBLE ORDNANCE SYSTEM. Any ordnance system proven (by tests) to contain EEDs that can be adversely affected by RF energy to the point that the safety and/or reliability of the system is in jeopardy when the system is employed in expected shipboard RF environments.

c. HERO UNSAFE ORDNANCE. Any ordnance item is defined as being HERO UNSAFE when its internal wiring is physically exposed; when tests are being conducted on the item that results in additional electrical connections to the item; when EEDs having exposed wire leads are present, handled, or loaded; when the item is being assembled or disassembled; or when it is in a disassembled condition. Ordnance items that fall into the above classification may be exempted from being classified as HERO UNSAFE ORDNANCE as the result of HERO tests conducted to determine specific susceptibility.

1.4.3 Power Densities

Figures 1-1 and 1-2 give the worst-case field intensity restrictions for all HERO SUSCEPTIBLE and UNSAFE ORDNANCE SYSTEMS. These may be used to determine the maximum allowable field intensity for any so-defined system. However, it should be noted that individual ordnance data specifications may be less restrictive than the given curves. An example of a typical problem is given below.

Problem: We wish to determine whether a hazardous condition exists for the following HERO SUSCEPTIBLE situation:

Radar frequency:	10 GHz
Average radiated power:	1000 watts
Distance from ordnance:	400 feet
Antenna gain:	37 dB

From Figure 1-3, the main beam power density is 2.8 mW/cm^2. From Figure 1-1, the average power density for a potentially hazardous condition is 5 mW/cm^2. Therefore, no hazard exists.

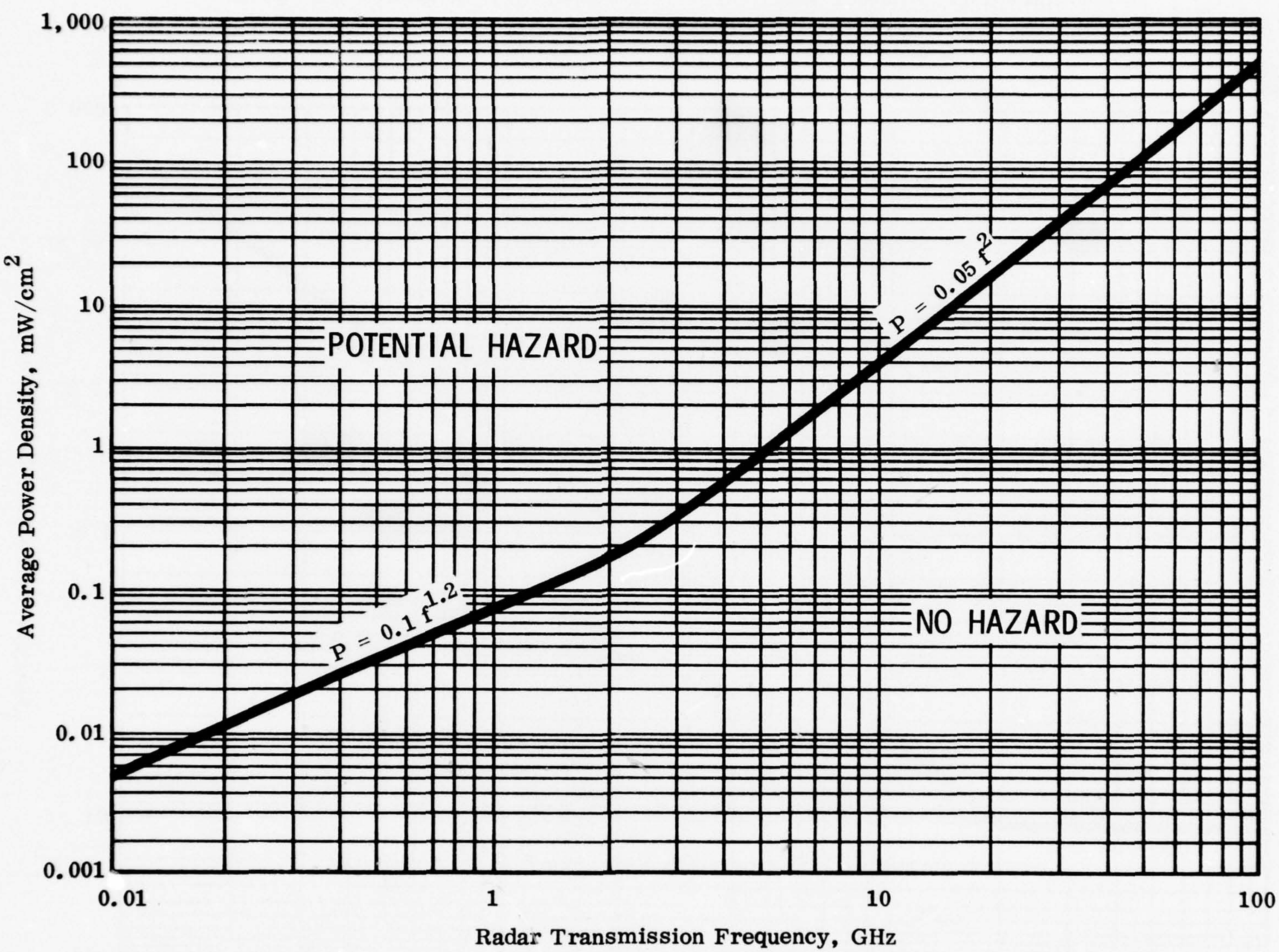


Figure 1-1. Maximum Safe Power Density for HERO SUSCEPTIBLE ORDNANCE

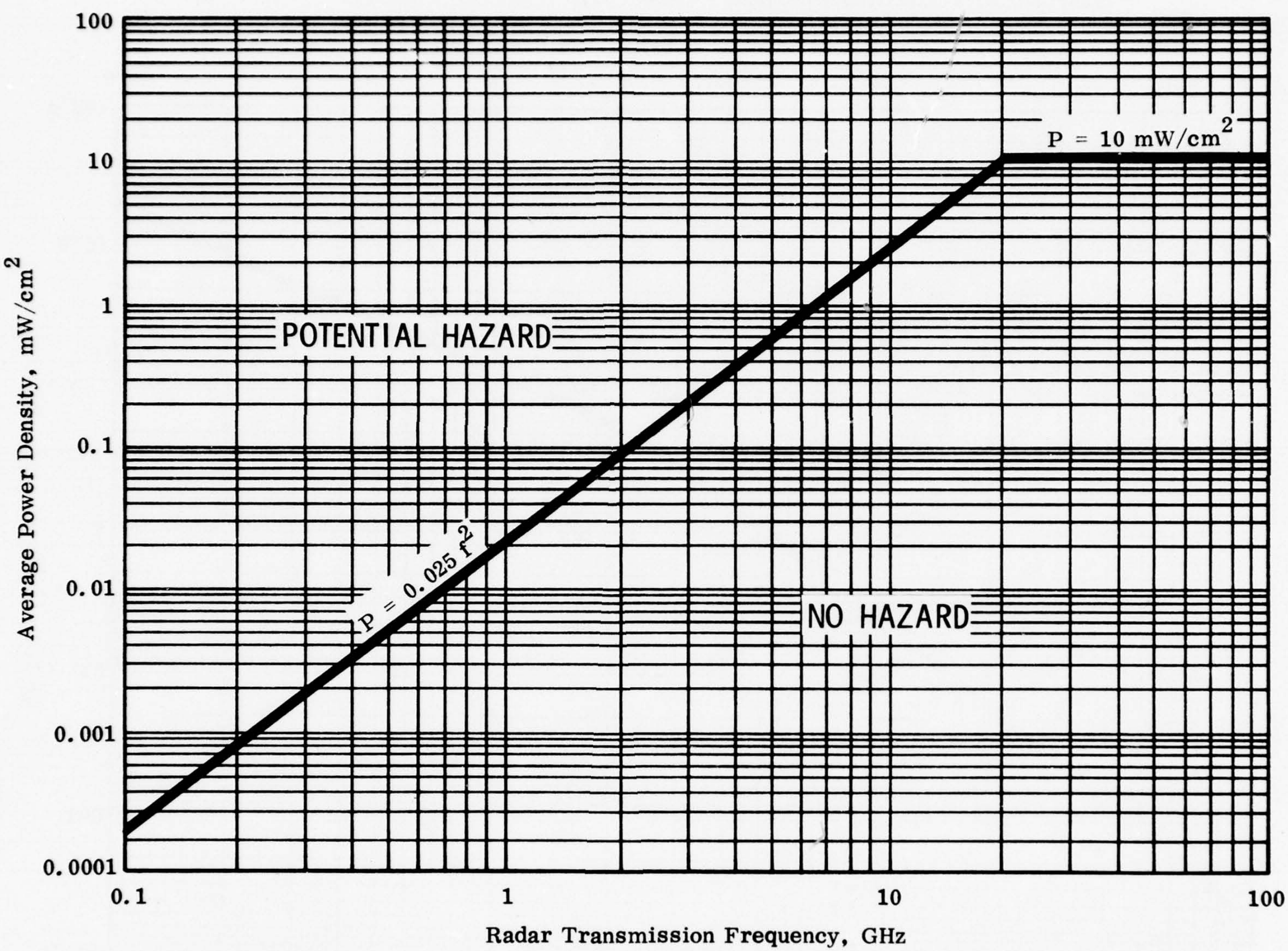


Figure 1-2. Maximum Safe Power Density for HERO UNSAFE ORDNANCE

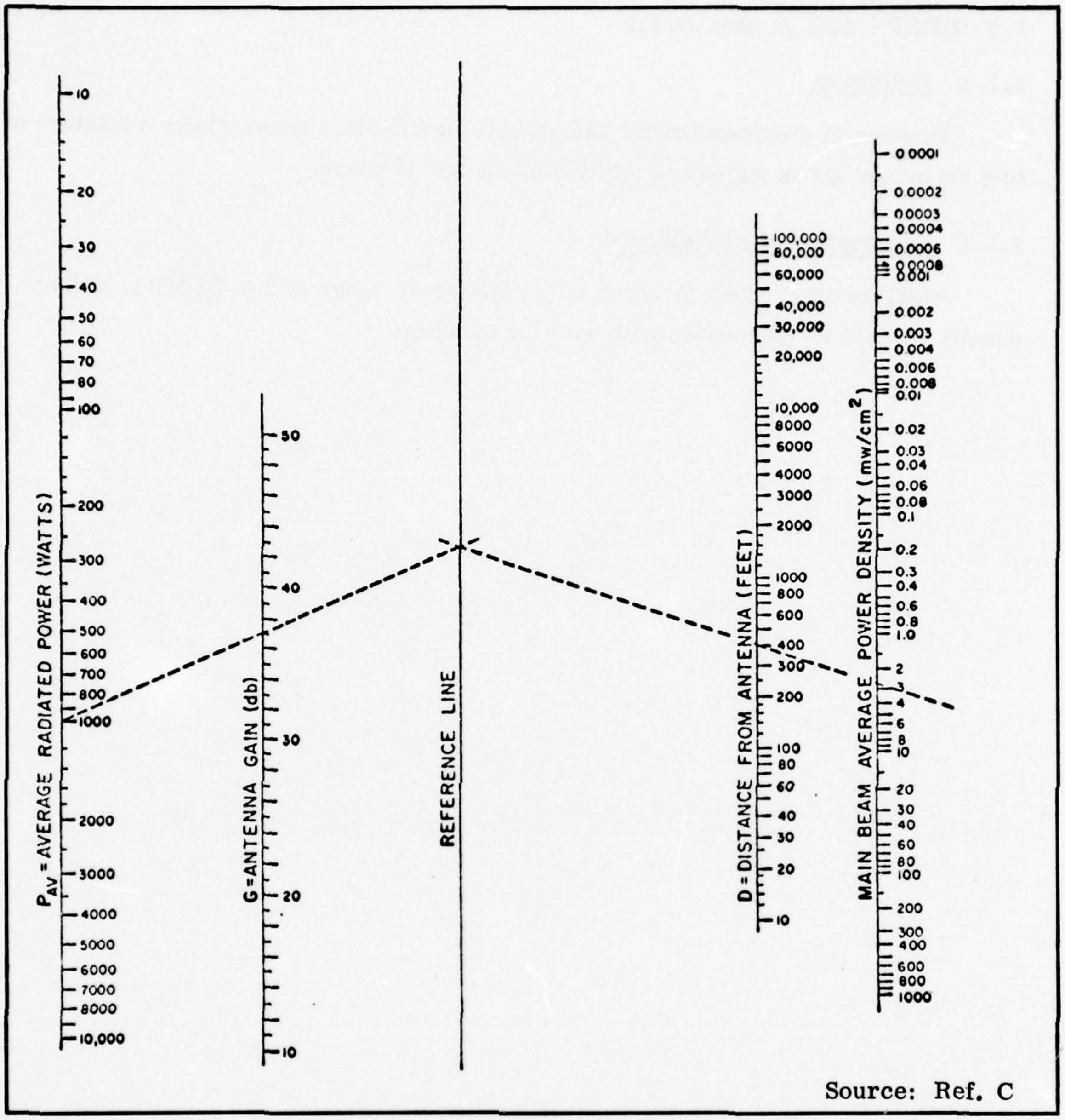


Figure 1-3. Power Density Nomograph

1.5 HERF – Ref. E, Sec. 2.2.2

1.5.1 Definition

Hazards of electromagnetic radiation to fuel (HERF) occur where a mixture of fuel vapor and air is subject to ignition by an arc or spark.

1.5.2 Description of Phenomenon

HERF is most likely to occur in the frequency range of 2 to 32 MHz, and is usually limited to association with aviation gasoline.

1.6 ANTENNA INSTALLATION CONSIDERATIONS – Ref. E

As has been pointed out frequently in the preceding discussion, ship antennas are a major source of EMC problems. Their location to minimize such problems is therefore of vital importance. This discussion of antenna locations points out how various types of antennas and various ranges of incident frequencies impact on the EMC categories covered in this document.

1.6.1 Low/Medium Frequency (250 kHz-1 MHz)

1.6.1.1 RF Burn

RF burn is not a danger from shipboard transmitters operating at these frequencies because of their long wavelength and usually low radiated power.

1.6.1.2 RADHAZ

There is no RADHAZ problem at these frequencies (see Section 1.3).

1.6.1.3 HERO

Relative to HERO, antenna location is of little importance at these frequencies. HERO UNSAFE ordnance must not be handled above deck under any circumstances with even the lowest power transmitter operating. Ordnance handling restrictions specify that there be a minimum separation of 10 feet between an antenna radiating more than 5 watts and an ordnance item being handled or loaded. Therefore, most transmitter antennas must not be located within 10 feet of a fixed-location launcher.

1.6.1.4 HERF

Potential fuel hazards attributable to this frequency range are minimal.

1.6.1.5 EMI (Receiver)

EMI in this frequency range is not a major problem except in special cases. In most instances, transmitter power is less than 500W and utilization is light compared to that in the HF bands. Sparks or arcs, dirty insulators, etc., can produce both broadband and narrowband noise, the latter consisting of intermodulation products and harmonics. There are not specific cures available to the antenna arranger; the only approach is to attempt to keep antennas as far as possible from potential topside noise generators.

1.6.2 Medium/High Frequencies (2-32 MHz)

1.6.2.1 RF Burn

RF burn voltages are induced in shipboard metallic objects at or near their resonant frequency. Some of the objects upon which measurements have been made and their approximate resonant frequencies are:

a. ASROC launcher: 12 MHz

b. 3"/50 gun mount: 14 MHz

c. Underway replenishment rigging: 4 MHz

d. 35' whip: 6 MHz

In most cases a minimum separation of at least 50 feet is required to achieve a significant reduction in induced voltages into surrounding metallic structures. Some of the structures requiring special consideration are kingposts, gunmounts, ASROC launchers, and ready service lockers.

Broadband fan antennas (2 to 6 MHz) are preferred from an RF burn-reduction standpoint since they are usually located in conjunction with masts and superstructures, which tend to diffuse or spread the energy over a greater area and thereby reduce the hazard. Their locations are usually away from normally accessed areas.

1.6.2.2 RADHAZ

There is no radiation hazard at these frequencies.

1.6.2.3 HERO

Antenna location is of little HERO consequence at these frequencies. The same comments given in Section 1.6.1.3 apply here.

1.6.2.4 HERF

Potential fuel hazards aboard ship are most likely to occur in this frequency range, and usually involve aviation gasoline. The same phenomena that cause RF burns will produce sparks or arcs in moving metallic objects. Therefore, transmitting antennas should be located away from AVGAS handling stations.

1.6.2.5 EMI

To minimize EMI, transmitting antennas should be located as far as feasible from receiving antennas (at least 30 feet). Transmitting antennas should be located away from running rigging or areas where loose metallic objects are normally stored or used.

1.6.3 UHF Communications (225 to 400 MHz)

1.6.3.1 RF Burn

There is no RF burn problem at these frequencies.

1.6.3.2 RADHAZ

UHF transmitters using nondirectional antennas and operating at 100 watts or less cannot exceed a radiated power density level of 10 mW/cm^2. Transmitters such as the AN/SRC-31, operating at 1000 watts into a nondirectional antenna, can produce 10 mW/cm^2 at a maximum distance of 3.5 feet from the antenna. Any transmission line loss will reduce the hazard distance.

Directional antennas increase the chances that there will be a RADHAZ problem. For example the AN/WSC-1 system, with a 3 dB transmission loss, has a RADHAZ distance of 7 feet.

1.6.3.3 HERO

UHF antennas are normally mounted as high as possible; little more can be done to reduce possible HERO problems. Very few ordnance items are susceptible to UHF communication transmitters.

1.6.3.4 HERF

No significant HERF problem exists in this frequency band.

1.6.3.5 EMI

The most serious problem is EMI from radars in this frequency range. This problem is due primarily to receiver front end overload, and can be reduced by providing additional protection to the receiver by means of a multicoupler such as the AN/SRA-33.

Intermodulation between UHF transmitters can be remedied by use of appropriate multicouplers.

1.6.4 Search Radars (200-6500 MHz)

Search radars, with a rotating antenna or beam, have the following impact on personnel safety and EMI.

1.6.4.1 RF Burn

No RF burn problems are attributable to search radars.

1.6.4.2 RADHAZ

Search radars are the primary source of RADHAZ problems; see NAVSHIPS 0900-005-8000 for RADHAZ distances and maximum exposure times. Table 1-1 of that document indicates that none of the radars are hazardous as long as their antennas are rotating and/or scanning. Many radars can radiate with the beam stationary and thereby be hazardous. Some radars have pitch-and-roll stabilization circuits that will permit the beam to be depressed as much as 30°. In this case, even though the antenna is mounted high, some areas of the deck can be illuminated by the main beam. This is an operational problem beyond the control of antenna arrangement planners.

Radars using computerized beam positioning should be given special consideration, since a malfunction of the computer program could cause the main beam to remain stationary long enough to exceed the exposure time limit.

1.6.4.3 HERO

Many ordnance items are listed as being HERO SUSCEPTIBLE and a few are HERO UNSAFE at radar frequencies above 200 MHz. While HERO should therefore be considered, other factors will in all probability govern the antenna location. OP 3565 (Ref. C) gives minimum HERO SAFE distances for shipboard radars.

1.6.4.4 HERF

Fuel hazards are unlikely in this frequency range.

1.6.4.5 EMI

EMI between search radars is not usually a problem because of the frequency separation between radar types, but vertical separation is important to prevent a main beam-to-main beam condition. Such a condition would likely destroy the receive-mode diodes.

Search radars usually interfere with ECM equipment on an in-band basis, and sometimes when harmonically related. Spatial antenna decoupling is desirable, but will not completely eliminate the interference effects. Blanking via AN/SLA-10 equipment provides some easement of the problem.

Low frequency radards can interfere with UHF communications since they are in the same frequency band.

Pulsed radar energy can penetrate susceptible cables if the cables are exposed to the main beam; and preamplifiers, converters, etc., that are located high in the superstructure may suffer from case penetration. Every effort should be made to assure that the radar beam will not strike these objects.

Arcing in such metallic hardware as rigging and ladders can produce severe EMI. Arcing is one of the worst sources of interference, regardless of the frequency causing it, since it usually contains frequencies covering a broad part of the RF spectrum. Arcing may result when metallic objects close to a radar antenna are exposed to the radar's main beam. Radars in the 225 to 390 MHz band are frequently a source of these problems. Some solutions include the use of nonmetallic equipment (ladders, lifelines, etc.), corrective bonding techniques, and the use of cam outlets to prevent the radar beam from illuminating the metallic hardware.

1.6.5 Missile and Fire Control Radars (2500-15,000 MHz)

Missile and fire control radars, with slow-moving antenna beams, have the following impact on personnel safety and EMI.

1.6.5.1 RF Burn

No RF burn problems are attributable to missile and fire control radars.

1.6.5.2 RADHAZ

Missile control radars present the greatest RADHAZ of all radars since they utilize a combination of high power transmitters with high gain antennas. Power densities as high as 300 mW/cm^2 may result, which is 30 times greater than the defined danger level (see Section 1.3). The antennas are normally located to give maximum unobstructed coverage; however because of the weight of these driven antennas, their placement height above the superstructure is limited. Most missile control directors can be positioned throughout a 360° azimuth and from -25° to +90°

elevation; thus some means of protection is required, such as cutout switches or protective shields, to prevent the main beam from irradiating manned areas.

Gun fire control radars offer some of the same problems as missile control radars except that the radiated power is considerably lower. The RADHAZ distances for gun fire control radars vary from 0 to 100 feet depending upon the radar; see NAVSHIPS 0900-005-8000 (Ref. I) for specific distances.

1.6.5.3 HERO

Several ordnance items are listed as being HERO SUSCEPTIBLE in this frequency range, but few if any of these are likely to be handled while these radars are radiating. Most potential HERO problems can be handled without adversely affecting ship operation by imposing the appropriate HERO restrictions (see Ref. C).

1.6.5.4 EMI

EMI problems involving the guidance radars have been experienced, but these are basically related to frequency-selection or operational situations.

2
INTERFERENCE AND HAZARD REDUCTION GUIDELINES

This section presents test procedures and guidelines for reducing the interference and hazard factors discussed in Section 1. Described on the following pages are:

a. EMI Detection and Reduction (Section 2.1)

b. RF Burn Hazard Detection and Reduction (Section 2.2)

c. RADHAZ Reduction (Section 2.3)

d. HERO Reduction (Section 2.4)

2.1 EMI DETECTION AND REDUCTION

2.1.1 EMI Detection – Ref. F

To locate EMI sources aboard ship, the following test plan can be carried out.

2.1.1.1 Preparation for Test

a. Remove topside materials not normally found there.

b. Obtain required tools:

1) 10-digit electronic calculator to compute transmitter test frequencies

2) 50 ohm, 1 dB-per-step attenuator to attenuate strong signals leading to the DF receiver

3) Damped audio meter for hearing intermods from the DF receiver

4) Portable DF receiver to detect intermods electrically

5) Signal generator
6) Noise generator
7) Frequency counter

} to verify frequencies

c. Select CW transmitter test frequencies according to the following criteria:

1) Frequencies to be in the 2-30 MHz range

2) Intermodulation frequencies of transmitters to be detectable in the 550 to 1600 kHz band (as suggested by NELC)

3) Intermodulation frequencies to be detected should be at least 5 KHz from the next nearest intermod

4) The appropriate transmitter test frequencies may be selected in one of two ways:

a) Greatest common factor approach

b) Graphical selection approach

The greatest common factor approach (developed at NELC/San Diego) is documented in NELC/TD-335 (Ref. F). The graphical solution approach is not formally documented and is therefore summarized in Appendix A.

2.1.1.2 Test Procedure

a. Energize transmitters at selected test frequencies.

b. Tune DF receiver to high-order expected intermod in the 550-1600 kHz band. Verify receiver tuning using signal generator.

c. If signal is present, locate source using DF receiver.

d. If signal is not present, tune DF receiver to next lower order intermod and try to detect and locate source. Repeat until intermod is detectable or intermod to be tried is less than 7th order (as suggested by NELC).

e. Repeat test for all transmitter frequency pairs selected during preparation stage.

2.1.1.3 Evaluation of Data

a. Review data and make recommendations concerning reducing or eliminating EMI sources detected and considered to be harmful to shipboard receiver operation.

b. If test results are not absolutely clear, select additional frequency pairs and repeat test.

c. Intermod characteristics that should be noted include:

1) The signal strength of an intermod increases with decreasing intermod order.

2) The number of intermods per order increases significantly for each increasing order.

With these facts in mind, a 30th-order intermod that is the greatest order detectable represents a much more serious problem than a 20th-order intermod that is the highest detectable. This is true since a 30th-order detectable intermod implies that all lower order intermods are detectable (and potential interference sources), and the number of intermod orders from 1 to 30 is greater than from 1 to 20.

2.1.2 EMI Reduction – Ref. B, Sec. 10

The most common means of reducing or eliminating EMI in the vicinity of ships are discussed in the following paragraphs.

2.1.2.1 Bonding/Grounding

Bonding is the process of providing a low-impedance union between two metallic conductors. Bonding is of two types:

a. Direct metal-to-metal contact by welding or brazing.

b. Indirect metal-to-metal contact via a bond strap. The bond strap may be either welded at both ends or removable at one end.

Typical metal items bonded to other metal items to reduce EMI include:

- Flush-mounted locker doors
- Watertight door hinges
- Bulkhead mounted locker doors
- Liferaft holders
- Scuttle covers
- Standing rigging

Grounding is the process of providing a common reference point with regard to electric potential. The purpose of grounding is to establish and maintain a reference potential for all system electrical and structural components. This common reference potential prevents any EMI generated by one unit of the system from being transferred through a common ground impedance to other units. If potential differences are not allowed to exist, interference current cannot flow and spurious signals can neither be radiated nor conducted to the susceptible parts of the system.

2.1.2.2 Shielding

Shielding is the process of preventing EMI from entering, or keeping it confined within, specific regions. Important factors in shielding efficiency are:

a. Reflection loss – Losses incurred when an incident plane wave contacts a shield. The largest loss occurs where there is the greatest impedance mismatch (free space to metal). Since free space has an impedance of about 377 ohms, it is desirable to have the metal impedance much greater or much less than that value for maximum mismatch. The easier of these alternatives is to have the impedance of the shield much less than 377 ohms. Copper, aluminum, and magnesium have high conductivity and low impedance, and therefore offer the highest reflection loss and make the best EMI shields.

b. Absorption loss (penetration loss) – Losses incurred as a wave passes through a metal shield between the two boundaries. The largest loss occurs in high-permeability material. Magnetic materials such as iron and "mumetal" are good EMI shields at low frequencies (<60 Hz).

2.1.2.3 Filtering

Filters are circuit components designed to pass or attenuate currents at certain frequencies. Filters operate by introducing a high impedance to all frequencies outside of the desired frequency band, and a very low impedance to frequencies within the passband.

2.1.2.3.1 Filter Terminology – Terms commonly associated with filters include:

a. Insertion loss – Input-to-output loss within the passband.

b. Mismatch – Loss due to mismatch between the filter and the circuit component connected to filter.

c. Cutoff frequency – Usually defined as the frequency for which there is 3 dB attenuation below the passband.

d. Bandwidth – Usually defined as the band of frequencies between the two 3-dB points.

e. Q-factor – A factor describing the selectivity of the filter.

f. Shape factor – Usually defined as the ratio between the passband at 3 dB points to the band at 60 dB points

g. Power handling – The ability of the filter to handle certain power levels.

2.1.2.3.2 Filter Applications – Applications of filters include:

a. Power line filtering – Prevents an HF signal from being conveyed by a power line to vulnearable equipment.

b. Bypassing – Filters out high frequencies by shunting them to ground.

c. Feedthrough – Allows a low-frequency signal to be passed through a wall (e.g., bulkhead) while bypassing or blocking HF interference.

d. Wave trapping – Rejects certain frequencies (if Hi-Q design).

e. Harmonic suppression – Reduces harmonic signal magnitude.

f. Duct/shaft filtering – Prevents signal from leaving or entering via duct and shaft.

2.1.2.4 Cable Separation

Cable separation is placing cables at a distance from equipment or other cables in order to reduce or eliminate EMI. Such separation prevents high-energy circuits from interfering with medium- and low-energy circuits by either direct or inductive coupling. Types of cables include:

a. Active (high level) – Radar modulator pulse cables, radio transmitter antenna and transmission lines, sonar transducing leads (when transmitting).

b. Passive (medium level) – Power and lighting cables, control cables, intercommunication and fire control cables.

c. Susceptible (low level) – Radio receiving antenna and transmission lines, hydrophone cables, IFF cables, sonar transducer leads (when receiving).

2.1.2.5 Use of Nonmetallic Materials

Since nonmetallic materials are essentially transparent to RF energy, and therefore do not absorb or re-radiate, their use aboard ship reduces the chances of hull-generated EMI. Such materials can be used in lifelines, guys, mast items, whip antennas, life nets, flag boxes, stanchions, and utility boxes.

2.1.2.6 Treatment of Miscellaneous Metal Objects in Topside Areas

Loose metal items in intermittent contact can generate EMI. Steps that can be taken to minimize such contact include:

a. Installation of bond straps.

b. Isolation (insulation) of loose items from the ship hull.

c. Stowage of loose items in below-deck areas.

2.1.2.7 Insulation of Small Items

Dog wrenches, fire extinguishers, fog and fire nozzles, and the like can be isolated from the ship hull to prevent corrosion and nonlinear junction formation. Heat-shrinkable tubing can be used on mounting brackets for insulation.

2.1.2.8 Computer Prediction for Frequency Assignments

An appropriately programmed computer may be used to select transmit-frequency assignments on the basis of time of day, distance to be covered, geographical location, and weather conditions. The assigned receive frequencies provide for minimum harmonics or intermodulation interference. Command levels use this technique for planning in an attempt to minimize interference.

2.1.2.9 Use of Multiplex to Avoid Multiple Frequency Assignments

To reduce EMI, many channels of information can be transmitted via one carrier. This can be accomplished by any of three methods of multiplexing: frequency, time, or time-frequency, thus reducing the number of transmitted carrier signals and consequent EMI problems.

2.1.2.10 Blanking Devices

Blanking devices can be utilized to turn off EMI-susceptible equipment during operation of high power transmitters. This has limited applications in a shipboard environment, since certain equipments are required to be operational at specified times.

2.2 RF BURN HAZARD DETECTION AND REDUCTION

2.2.1 RF Burn Hazard Detection – Ref. A

The following test and measurement techniques can be applied to detect and recommend corrective actions for RF burn hazards aboard ship.

2.2.1.1 Preparation for Test

a. Select measurement locations and test items.

   1) Identify HF transmitting antennas.

   2) Select test locations and items on which tests will be made – metallic lines near transmitting antennas, vertical metallic lines (inhauls, span lines, hooks of cargo booms), FAST heads, and other items that have antenna-like characteristics.

   3) Select operating position of item to be tested.

b. Prepare test data sheets as illustrated in Figure 2-1. A separate sheet should be filled out for each item to be tested.

c. Ready test equipment (Hewlett Packard 410B, 410C, or equivalent).

d. Note the primary frequencies to be used: 2.2 ± 0.2 MHz, 4.0 ± 0.3 MHz, 6.0 ± 0.5 MHz, 8.0 ± 0.5 MHz, 12.0 ± 0.5 MHz, and 15.0 ± 0.5 MHz. Select exact frequencies from JANAP 195 (Ref. J).

e. Establish rapid and reliable communications between the measurement locations and the transmitter operator.

2.2.1.2 Test Personnel and Procedure

a. Personnel requirements – Test director, two measurement personnel, transmitter operator, cargo equipment operator, communications personnel.

b. Measurement procedure –

   1) All test personnel take their stations.

   2) All equipment required by test plan is made operational and ready for test.

TEST DATA SHEET

KINGPOST 8 OUTHAUL	MAIN DECK FR147	1
TEST ITEM (NAME OR DESCRIPTION)	LOCATION	SHEET NUMBER

	FREQUENCY (kHz)	TRANSMITTER	POWER (WATTS)	ANTENNA NUMBER	MEASURED VOLTAGE	COMMENTS
1	2150	URT-23	950	2-1	80	
2	2150	URT-23	950	2-2	105	
3	2150	URC-32	450	2-3	30	
4	4146	URT-23	950	2-1	100	
5	4146	URT-23	950	2-2	220	HAZARDOUS
6	4146	URC-32	450	2-3	100	TEST WITH 2-2 AT 2180
7	6217	URT-23	980	2-1	70	
8	6217	URT-23	950	2-2	130	TEST WITH 2-3 AT 4146
9	6217	URC-32	480	2-3	80	
10	8317	URT-23	950	2-2	60	
11	8317	URT-32	480	2-3	20	
12	12468	URT-23	950	2-2	40	
13	12468	URC-32	500	2-3	5	
14	16146	URT-23	980	2-2	15	
15	16146	URC-32	450	2-3	3	
16	3230	URT-23	950	2-2	150	ADDED TO TEST PLAN
17	5150	URT-23	950	2-2	145	ADDED TO TEST PLAN
18	2150/4146			2-2/2-3	130	
19	4146/6217			2-3/2-2	160	
20						
21						
22						
23						

Figure 2-1. Test Data Recording, Sheet 1

3) Equipment operator places test item in position for testing in accordance with test plan.

4) Transmitter operator energizes transmitter in accordance with the test plan. Operation of transmitter is verified by measurement personnel.

5) Measurement personnel make open-circuit voltage measurements on test item and enter data on test data sheet.

PRECAUTION

Hold the case of the test probe and touch the tip of the probe on the item under test. No additional probe ground is required.

6) Measurements on each test item are continued until all items have been tested in accordance with test plan.

2.2.1.3 Example of Analysis of Test Data

A review of the RF burn hazard test data may indicate the need to conduct further testing. As shown in Figure 2-1, for example, the "Measured Voltage" entry on line 5 exceeds NAVSEC-defined hazard level of 140 volts. The 220-volt measurement was taken while there was radiation from antenna 2-2 at a frequency of 4146 kHz. Since neither of the two adjacent frequencies (lines 2 and 8) produced a hazardous voltage, two additional test frequencies (lines 16 and 17) were added to define the RF burn problem more fully. Lines 18 and 19 were added to test simultaneous transmitter operation because of the high measured voltage indicated on lines 6 and 8.

2.2.2 RF Burn Hazard Reduction - Ref. H

The magnitude of potential RF burn hazard at a particular location depends upon the distance in wavelengths between that location and the transmitting antenna. It is essentially independent of the antenna type or its location on the ship's structure. A conductor approximately a quarter-wavelength long at the transmitting frequency, spaced away from the ship's structure by a certain integral number of quarter-wavelengths, is required to convert a potential hazard into an actual burn hazard. Based on these considerations, and the physical nature of RF burn hazard, the magnitude of that problem can be reduced on a ship by:

a. Locating transmitting antennas as far away from metallic rigging as practical.

b. Arranging conductors that must be handled so that the length between the attachment to the ship's structure to the point of human contact is as short as possible (preferably less than 10 feet).

c. Decreasing the effective length of long conductors by using a "ground clip" consisting of a length of wire rope less than 6 feet long connected to the ship's structure at one end, and with a spring-loaded clamp at the other end.

d. Learning to check for burn hazards before handling long conductors. An RF burn may usually be avoided by making first contact through a metallic object held in the hand.

e. Using insulators between riggings and hooks.

f. Using nonmetallic materials for applications where RF burn is a problem.

g. Relocating antennas as necessary.

h. Changing operational procedures as necessary.

i. Using warning signs.

2.3 RADHAZ REDUCTION – Ref. G

To minimize radiation hazards, personnel should take the following precautions:

a. Do not visually inspect feed horns, open ends of waveguides, or any opening emitting RF electromagnetic energy unless the equipment is definitely secured for the purpose of such an inspection.

b. Park aircraft employing high power radars, or orient their antennas, so that the beam is directed away from personnel working areas.

c. When operating or servicing a shipboard radar, ensure that the radar is operating in such a manner that personnel on deck or in the superstructure are not subjected to hazardous levels of RF radiation.

d. Observe warning signs that point out the existence of RF radiation hazards in a specific location or area.

e. Ensure that radar antennas that normally rotate are rotated continuously while radiating, or are trained to a known safe bearing.

f. Train and elevate nonrotating antennas away from inhabited areas, ships, piers, etc., while these antennas are radiating.

g. Where the possibility of accidental exposure might still exist, have a man stationed topside within view of the antenna (but well out of the beam), and in communication with the operator while the antenna is radiating.

h. Ensure that radiation hazard warning signs are available and used, not only where required to be permanently posted but also for temporarily restricting access to certain parts of the ship subject to hazardous radiation.

i. Construct an RF screen or shield in areas where personnel must frequently pass near an antenna known to produce hazardous levels of radiation and it is not practical to secure radiation from the antenna.

j. Do not start any task unless fully cognizant of the potential RADHAZ danger and the applicable safety precautions required.

2.4 HERO REDUCTION – Ref. C

The general HERO reduction guidelines given in the following paragraphs should be implemented when handling any of the three classifications of ordnance (HERO SAFE, HERO SUSCEPTIBLE, and HERO UNSAFE). Greater restrictions, as indicated, apply to the presence, handling, and loading of HERO UNSAFE and HERO SUSCEPTIBLE ordnance systems.

a. Aircraft

Prohibit all radio and radar transmission by aircraft being loaded or unloaded with ordnance that is electrically initiated.

b. Shipboard

1) Conduct all handling and loading operations so that the nearest part of the ordnance (air launched or surface launched) or any metallic structure or object attached to the ordnance (e.g., aircraft, handling equipment, tow vehicle, gun mount, missile launchers, etc.) is a least 10 feet from the nearest extremity of any communications antenna radiating more than 5 watts of power. Aircraft loaded with ordnance must not be parked within 10 feet of any such antenna.

2) When deck edge antennas are lowered, conduct handling and loading operations so that the ordnance or nearest part of any metallic structure or object attached to the ordnance is at least 10 feet from the vertical projection of the lowered antenna. The nearest part of a loaded aircraft (includes towing vehicle) may be parked to within 5 feet of the vertical projection of a lowered whip antenna, provided all loading procedures have been completed.

3) When antenna are radiating less than 5 watts of power, the ordnance of the nearest part of loaded aircraft may be parked to within 5 feet of the radiating antenna.

4) If the above safe distance requirements must be violated for any ordnance operation, the transmitting antenna must be silenced.

c. Shore Stations

1) Conduct all handling and loading operations so that the nearest part of ordnance, or any metallic structure or object attached to the

ordnance (e.g., aircraft, handling equipment, tow vehicle, etc.) is at least 25 feet from the nearest extremity of any communication antenna radiating more than 5 watts of power.

2) If the safe distance requirements in the previous paragraph must be violated for any ordnance operations, silence the transmitting antenna.

3) While transporting ordnance on a shore station, practice the same safety requirements and field intensity restrictions as specified for that particular item during normal handling operations. Ordnance packages in its approved shipping configuration/container is generally considered HERO SAFE and may be safely transported in trucks equipped with transceivers and portable executive telephones. However, the transmitting antenna must not be placed closer than 10 feet to any HERO SAFE ordnance.

4) When ordnance systems are disassembled or when they have exposed EEDs, exposed firing circuits, or exposed wiring during the transport operation, HERO UNSAFE restrictions apply. Refer to NAVORD OP 3565/NAVAIR 16-1-529, Chapter 3, for safe distances for communication transmitters. HERO UNSAFE and HERO SUSCEPTIBLE ordnance systems may be protected from hazardous field intensities by use of metal containers that completely enclose the ordnance.

d. Shipboard and Shore

1) Plan ordnance operations so that there is a minimum of exposure of ordnance to the RF environment. Whenever possible, perform sensitive phases of ordnance deployment, such as continuity checks where specifically authorized, warhead replacement, fuze setting, etc., below deck or in RF shielded areas.

2) Do not alter ordnance systems, especially when firing circuit hardware or RF shielding is concerned, unless such alterations have been specifically authorized.

3) Avoid touching any exposed firing contact, wiring, or other exposed circuitry (e.g., contact buttons, primer buttons, contact band, etc.) with the hand or any metallic structure or object such as a metal steering hook, screwdriver, etc.

4) Do not handle umbilical cables and cable connectors unnecessarily.

5) Make no electrical connections to air launched ordnance systems before the ordnance is racked to the aircraft unless the field intensity restrictions of NAVORD OP 3565/NAVAIR 16-1-529, Chapter 3, are observed, or unless such procedures have been specifically authorized. Electrical connections to ordnance are the most likely paths for RF energy to enter.

6) Transport all HERO UNSAFE ordnance in completely enclosed metal containers whenever possible.

7) Cover all open electrical connectors on the ordnance with nonmetallic caps to prevent the pins of these connectors from being touched accidentally.

APPENDIX A

GRAPHICAL APPROACH TO SELECTION OF TRANSMITTER TEST FREQUENCIES

A.1 SELECTION OF TEST FREQUENCIES

An intermodulation frequency can be represented by a linear equation of the form:

$$f_3 = Af_1 + Bf_2 \tag{A-1}$$

where

f_3 = Intermodulation frequency

f_1 = Transmitter frequency #1

f_2 = Transmitter frequency #2

A, B = Any positive or negative integer

Equation A-1 can be normalized by dividing by f_1:

$$\frac{f_3}{f_1} = A + \frac{Bf_2}{f_1} \tag{A-2}$$

Equation A-2 can then be plotted with f_2/f_1 as the x-axis and f_3/f_1 as the y-axis. Each line on the graph will now represent an intermodulation frequency, the order of which is $|A| + |B|$. Figures A-1, A-2, and A-3 show all intermods for the orders 1 to 30 (i.e., 10 intermods per figure). These graphs may be used directly to select test frequencies in the manner illustrated in the following example:

a. Let the f_3 bandwidth be the AM broadcast band, 550-1600 kHz

b. Let f_1 and f_2 be any frequency in the 2-30 MHz band. For convenience select frequency pairs in the 2-6 MHz, 4-12 MHz, and 10-30 MHz bands. At least five frequency pairs should be selected.

c. Let f_1 be any frequency normally used in transmission. Select f_2 to be another frequency in that frequency band (2-6 MHz, 4-12 MHz, or 10-30 MHz). For example, let $f_2 = 2380$ kHz and $f_1 = 5410$ kHz. We can then obtain the following quotients:

$$\frac{f_2}{f_1} = \frac{2380}{5410} = 0.44 = x$$

$$\frac{550}{5410} = 0.101 = y_1 \text{ lower band}$$

$$\frac{1600}{5410} = 0.296 = y_2 \text{ upper band}$$

d. On Figures A-1, A-2, and A-3, draw a line from (x, y_1) to (x, y_2); for this example, the lines from $(x = 0.44, y = 0.101)$ to $(x = 0.44, y = 0.296)$ apply, and are shown as dashed lines on each of the figures. All intermod lines crossing this vertical line represent intermod frequencies in the AM broadcast band.

e. List these intermods in the following manner:

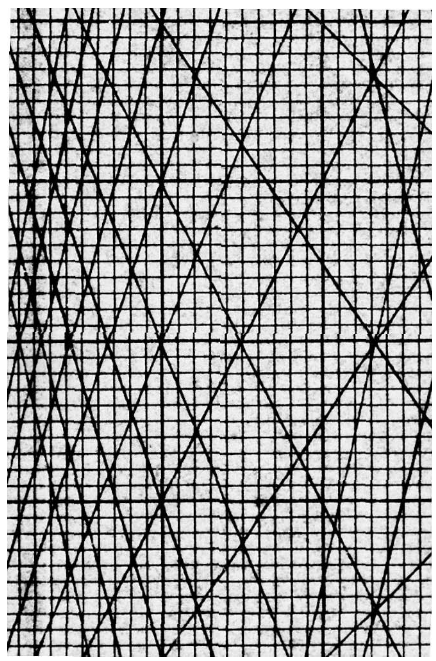
	Intermod	f, kHz	Order
Fig. A-1	$f_1 - 2f_2$	650	3
	$-2f_1 + 5f_2$	1080	7
	$2f_1 - 4f_2$	1300	6
Fig. A-2	$5f_1 - 11f_2$	870	16
	$6f_1 - 13f_2$	1520	19
	$-5f_1 + 12f_2$	1510	17
Fig. A-3	$-6f_1 + 14f_2$	860	20
	$9f_1 - 20f_2$	1090	29
	$-9f_1 + 21f_2$	1290	30

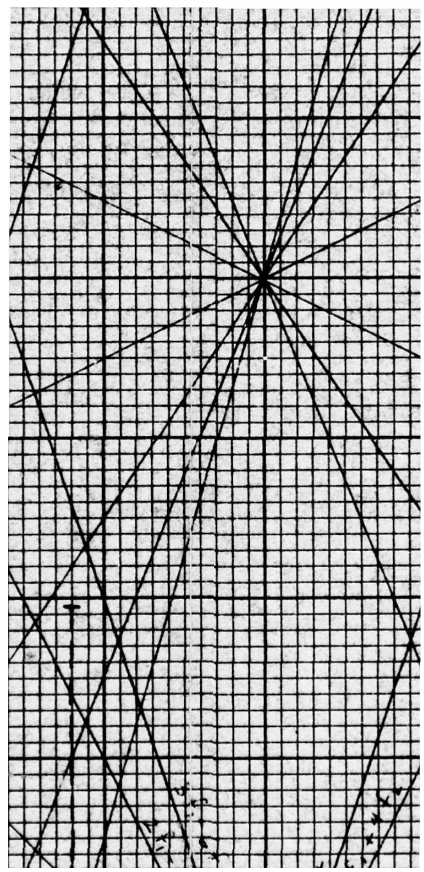
Transmitter test frequencies should be selected such that intermod frequencies to be detected are not spectrally close to other intermods (± 5 kHz, or the IF bandwidth of the DF receiver). Adherence to this guideline will eliminate ambiguity as to which intermod is detected.

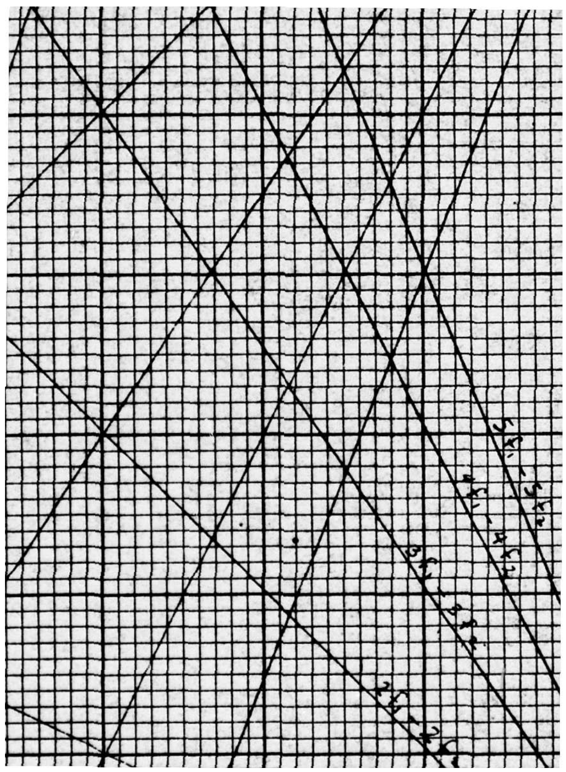
A.2 USE OF TEST FREQUENCIES

The DF receiver should be tuned to each of these intermodulation frequencies starting from the highest order intermod – in the above example, 30th order at 1290 kHz. (Intermod frequencies coinciding with local AM station frequencies should be eliminated due to possible receiver saturation by the local station.)

Transmitter test frequencies should be chosen such that transmitter frequencies across the band are sampled along with the intermods between the 1st and 30th orders. If intermods of orders greater than 30 are desired for investigation, similar graphs may be constructed.







$5\xi_1 - 5\xi_2$
$4\xi_1 - 4\xi_2$
$3\xi_1 - 3\xi_2$
$2\xi_1 - 2\xi_2$

4

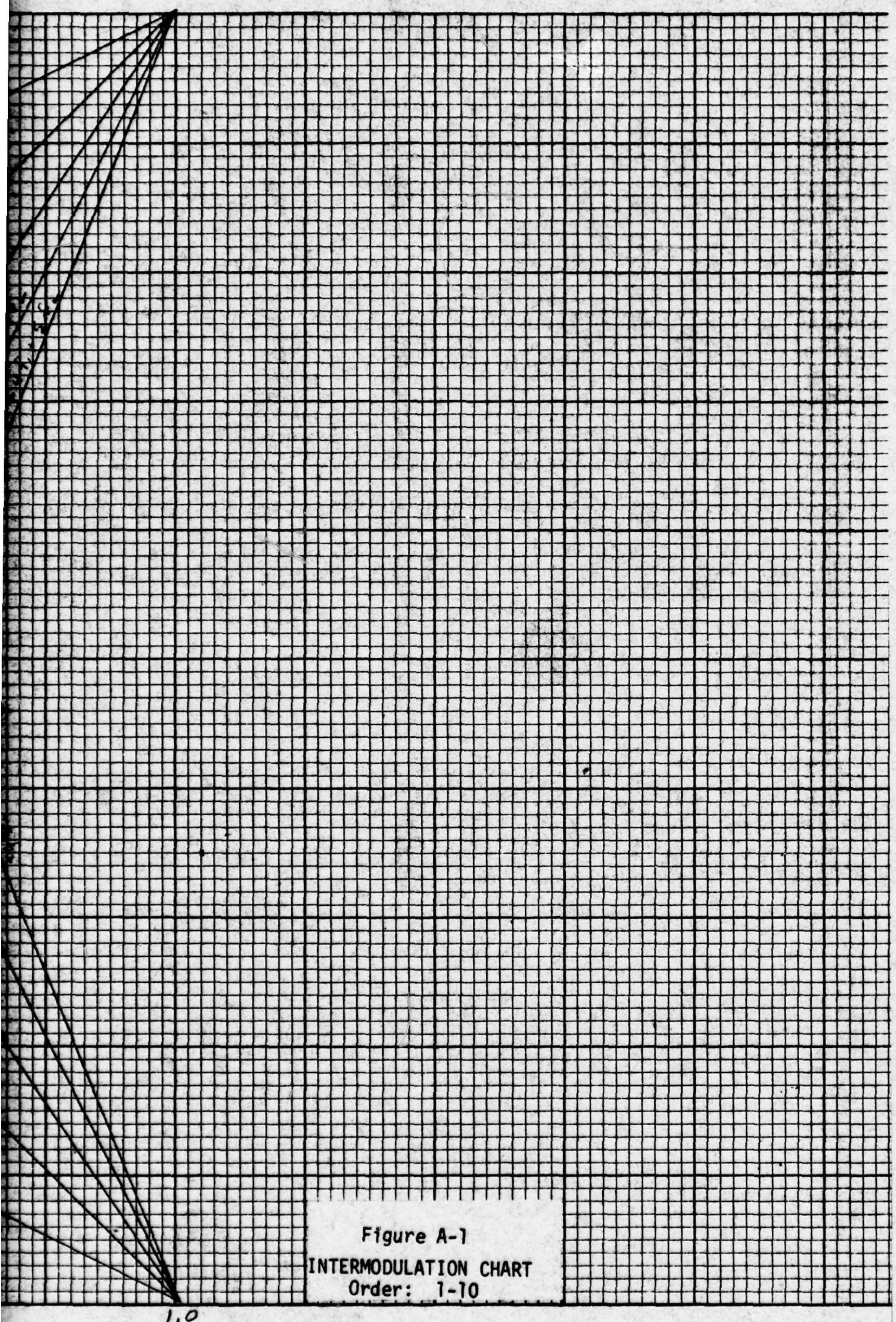
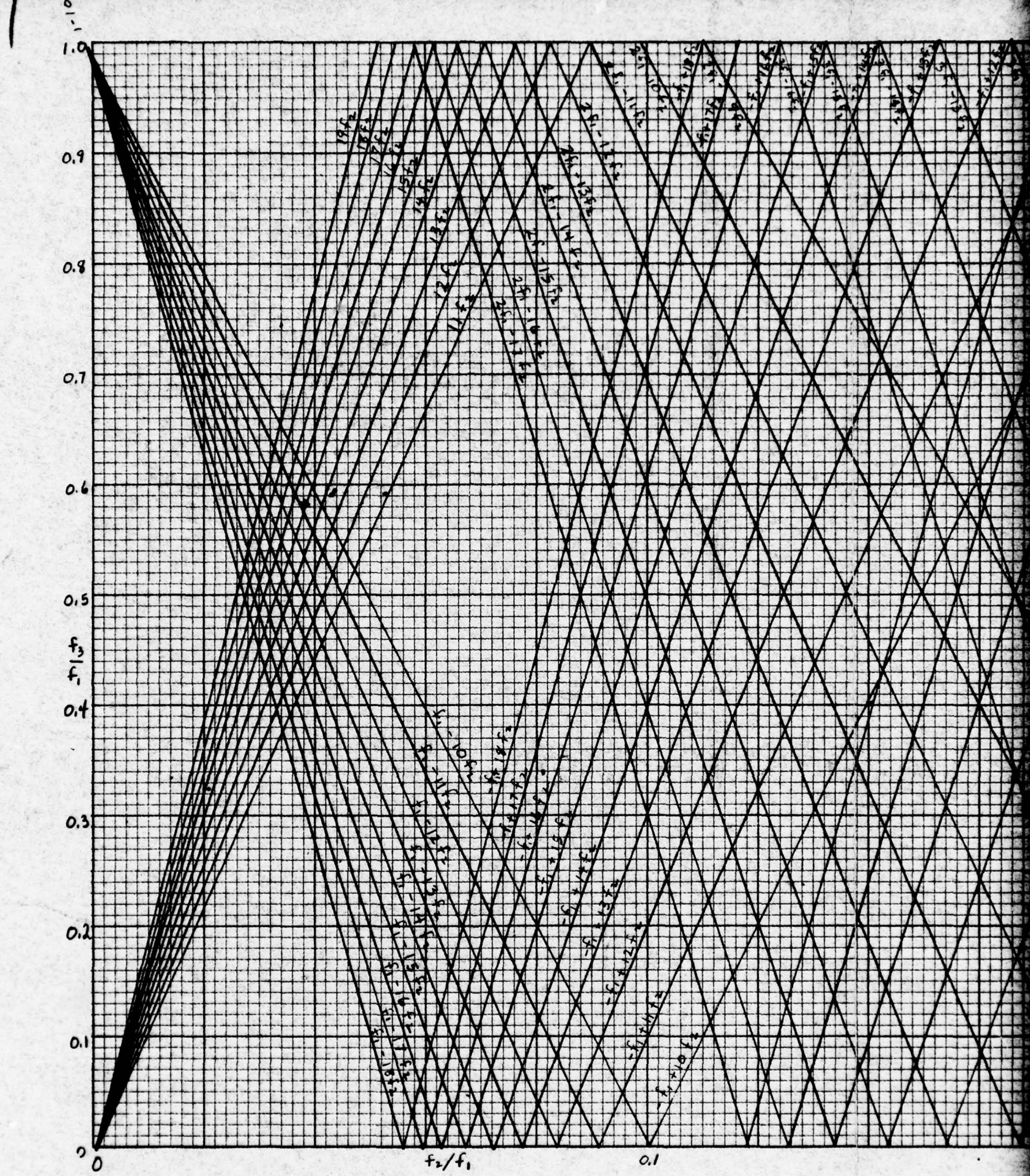
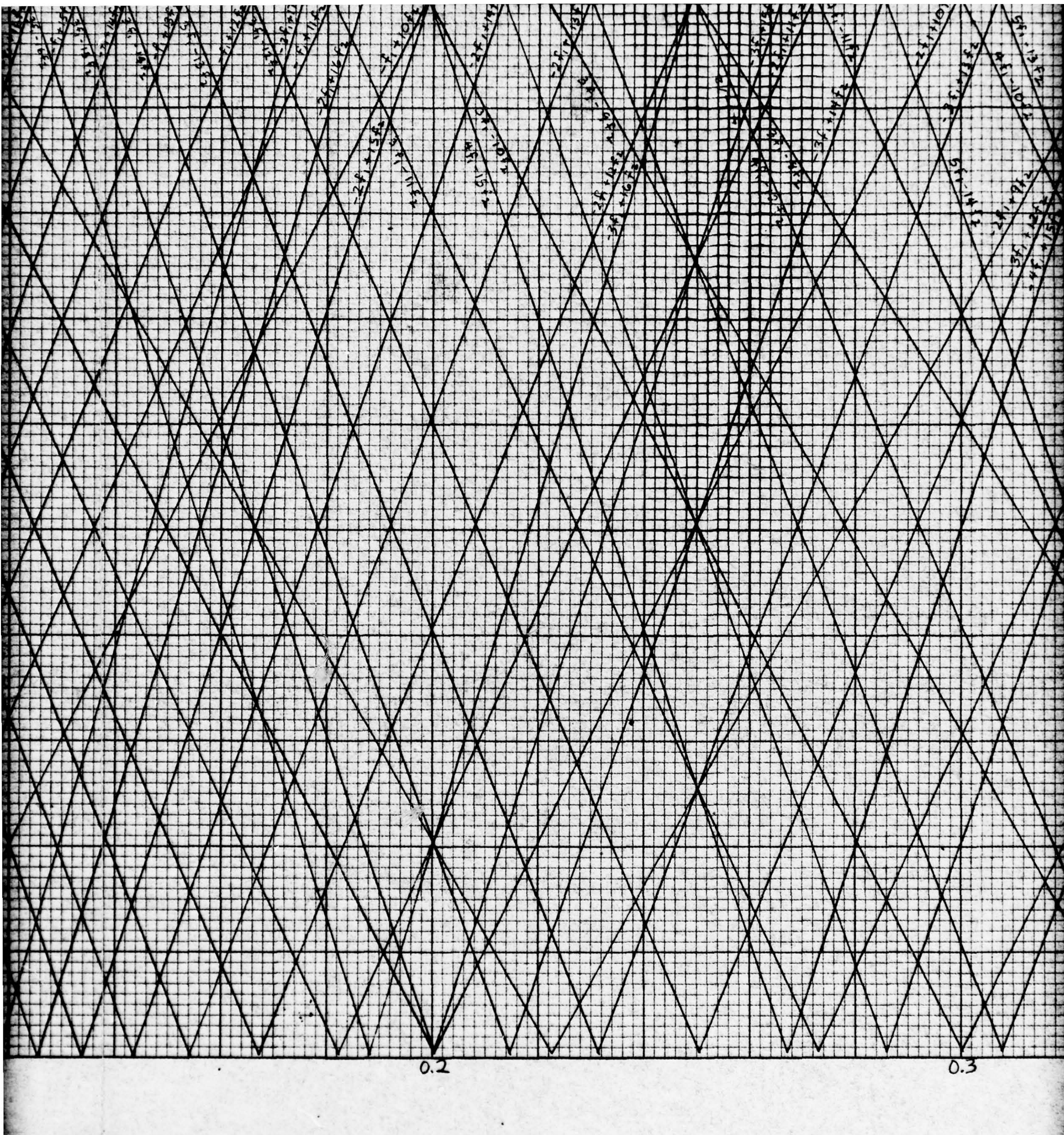


Figure A-1
INTERMODULATION CHART
Order: 1-10

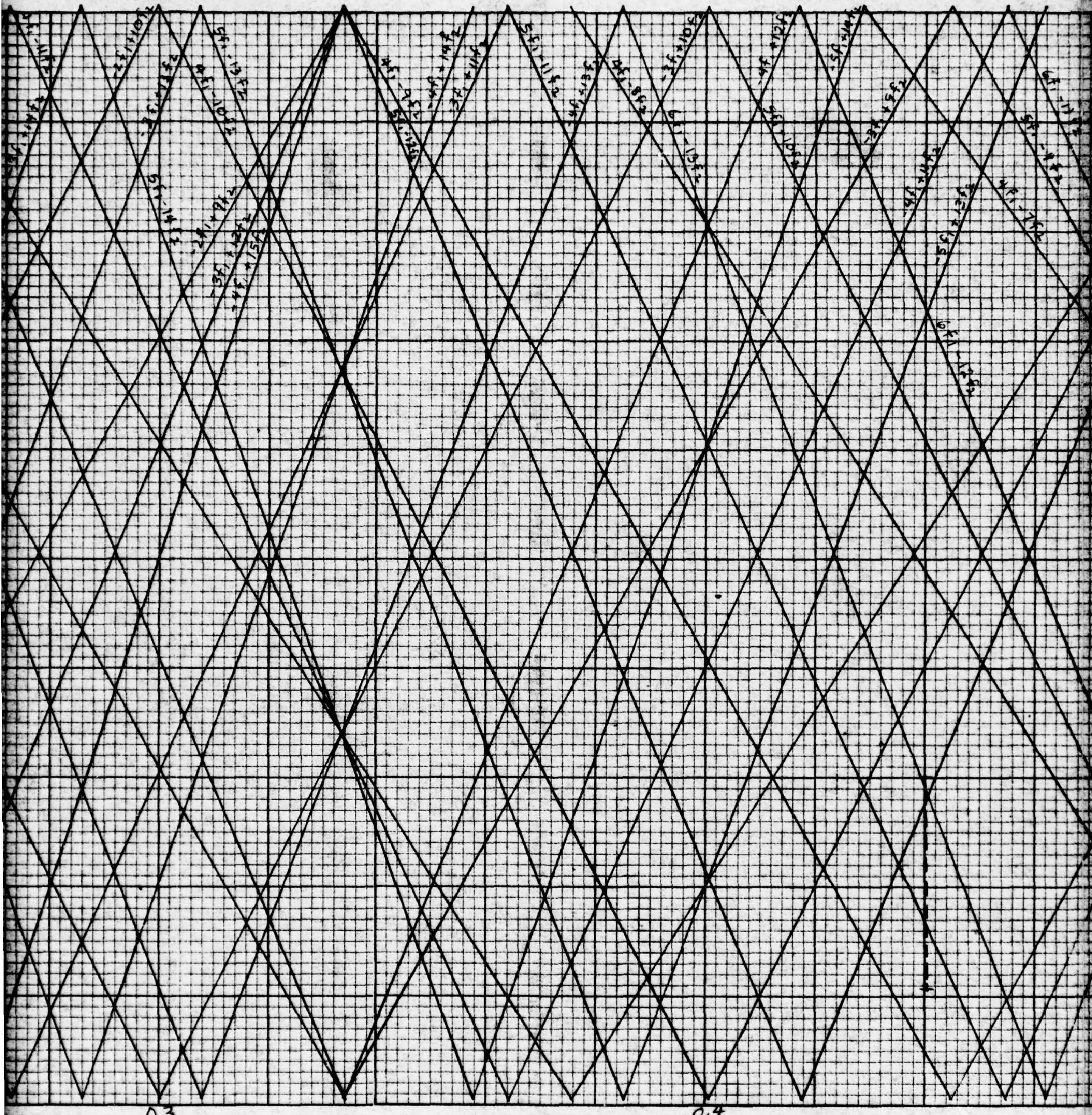


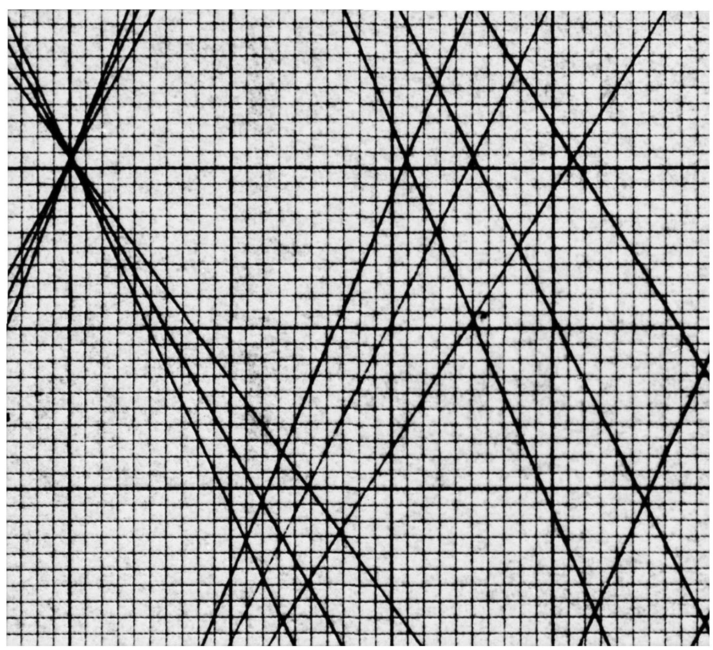
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
f_3/f_1
0
f_2/f_1
0.1



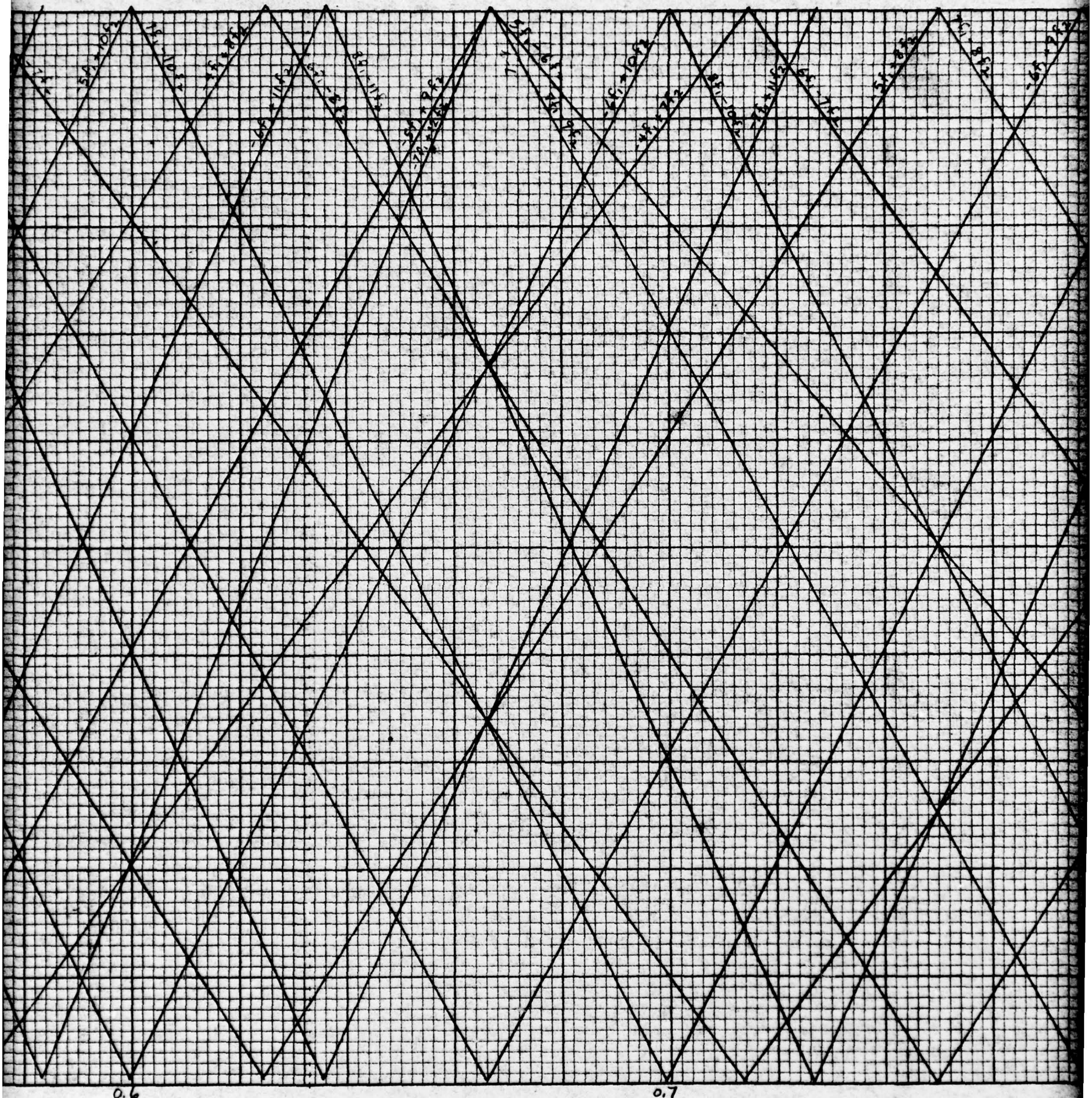
0.2
0.3

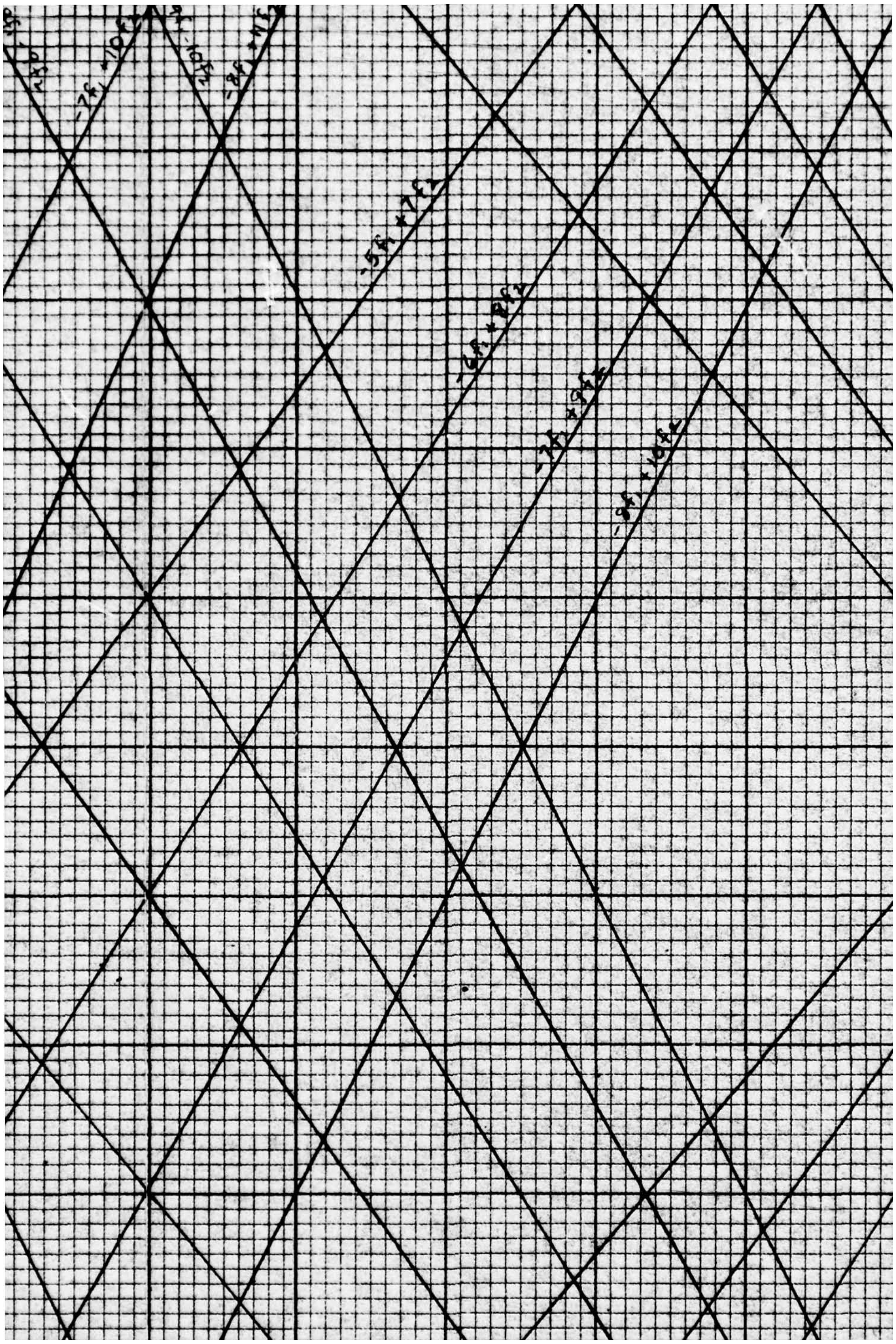
3





5





-7f1 +10f2
-8f1 +11f2
-5f1 +7f2
-6f1 +8f2
-7f1 +9f2
-8f1 +10f2

7

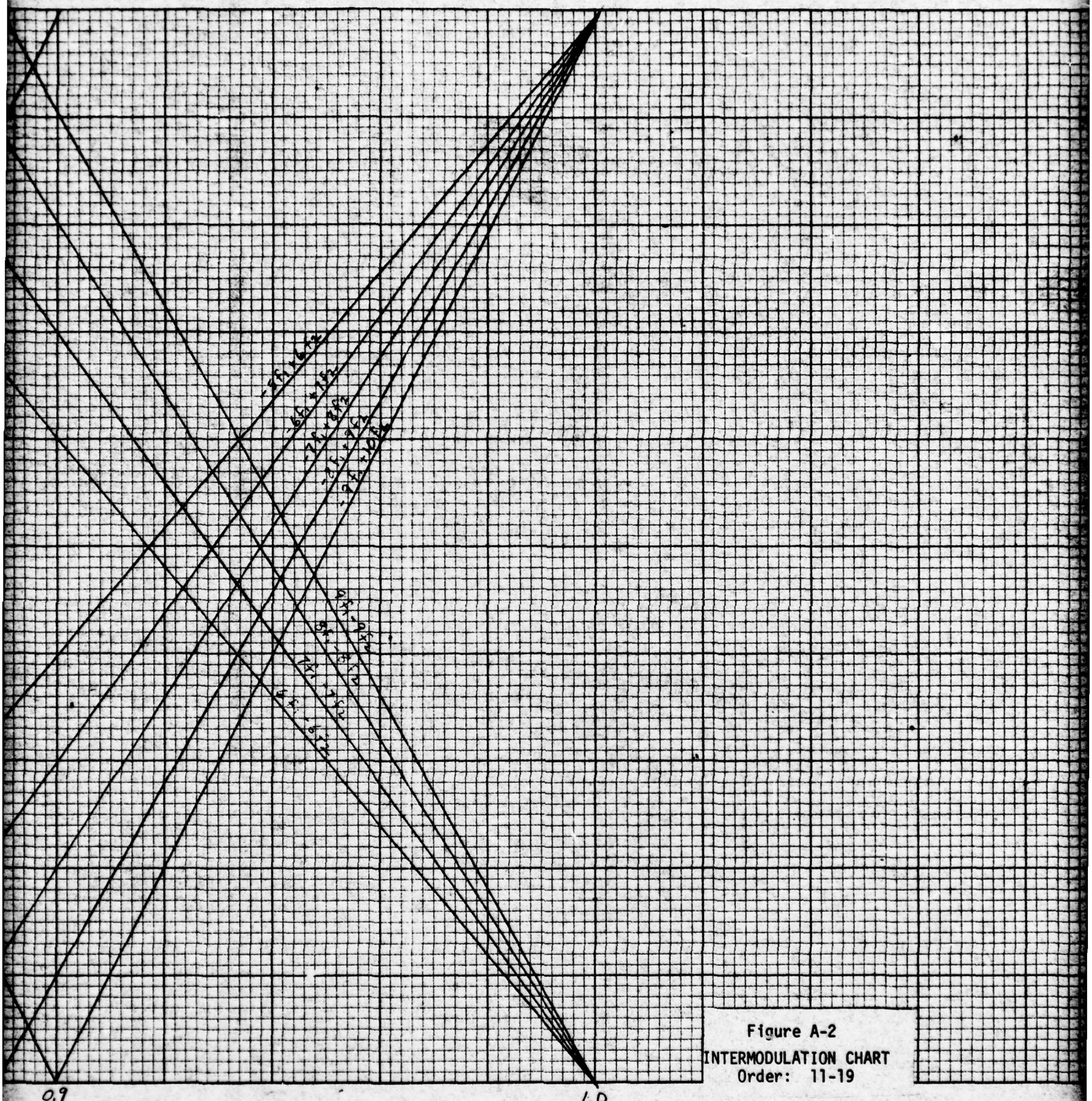


Figure A-2
INTERMODULATION CHART
Order: 11-19

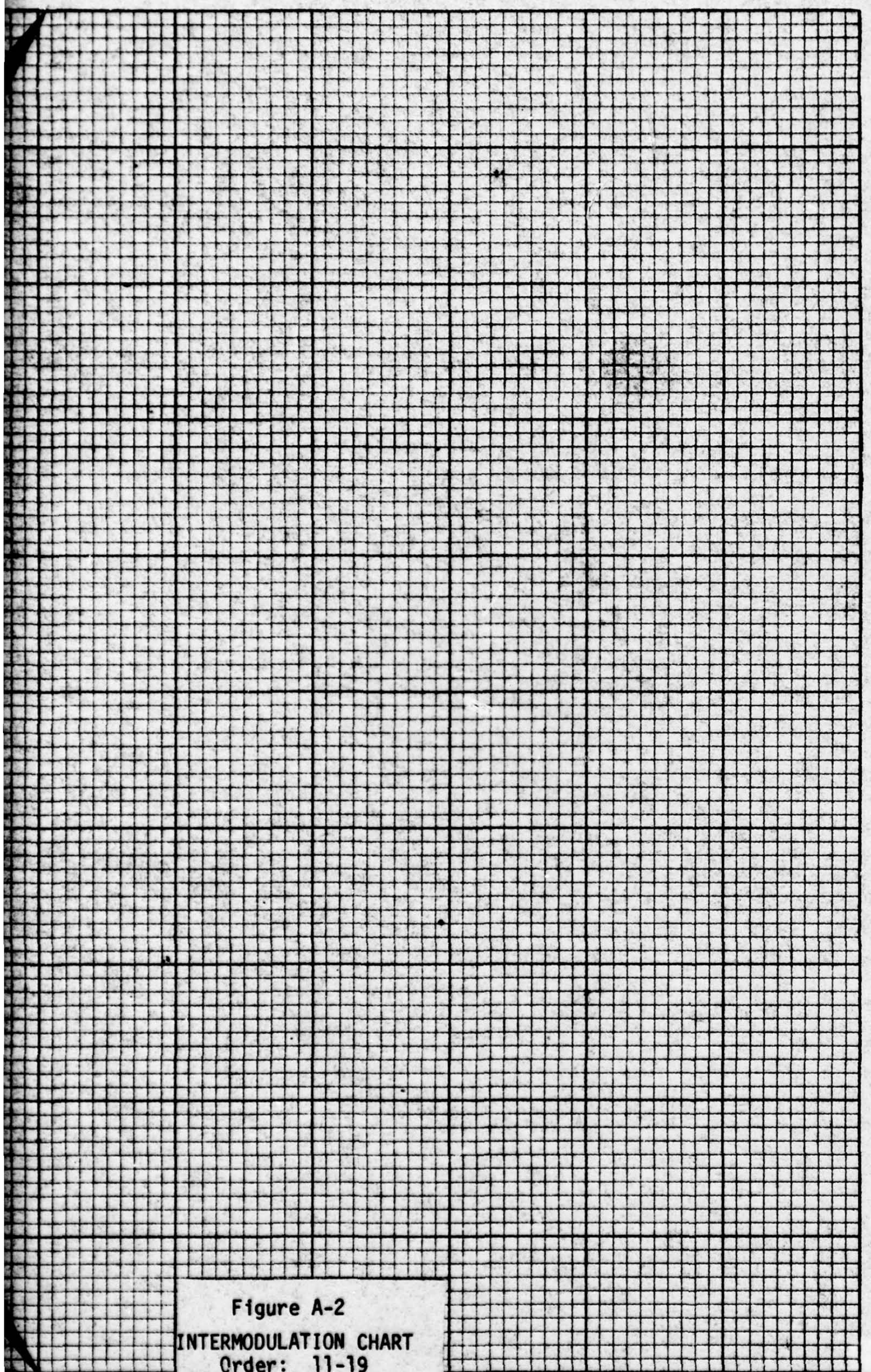
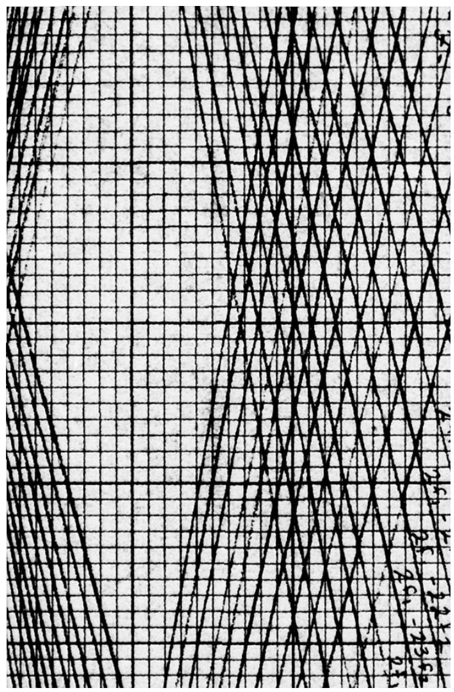
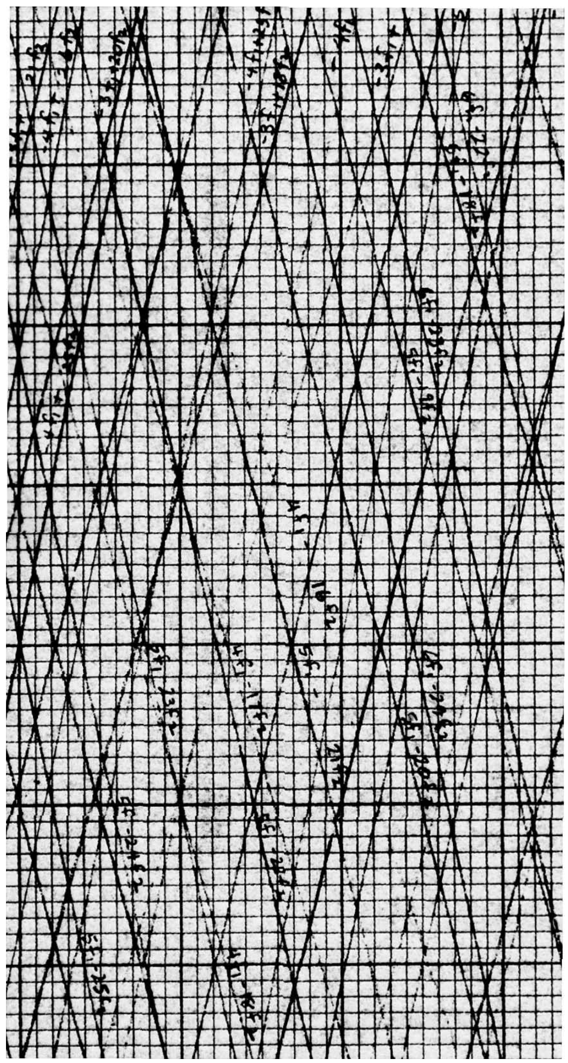
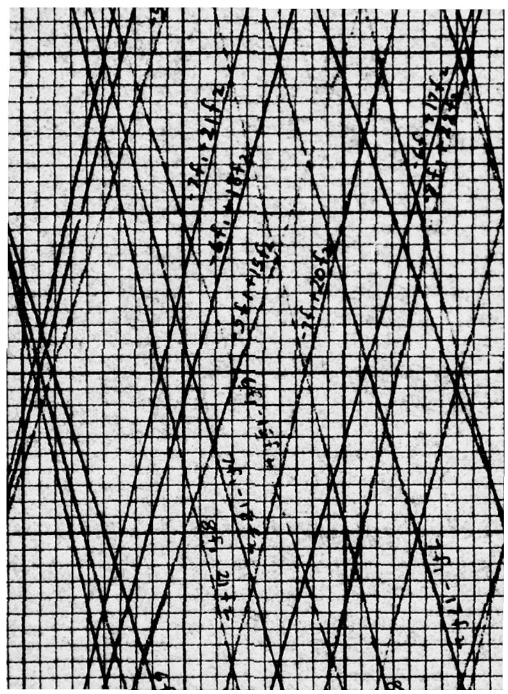
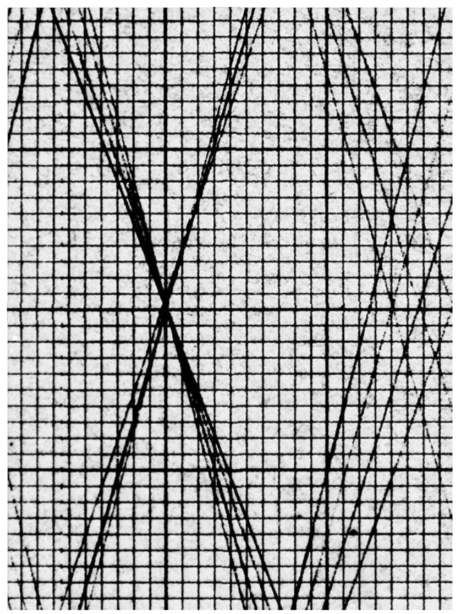


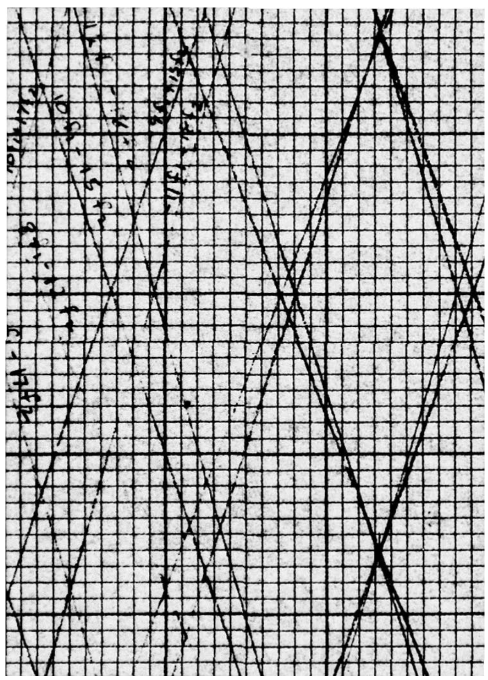
Figure A-2
INTERMODULATION CHART
Order: 11-19

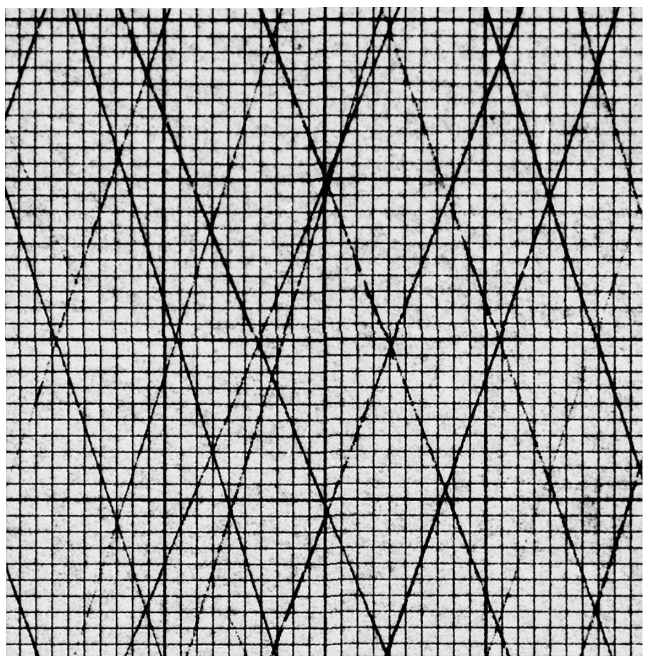












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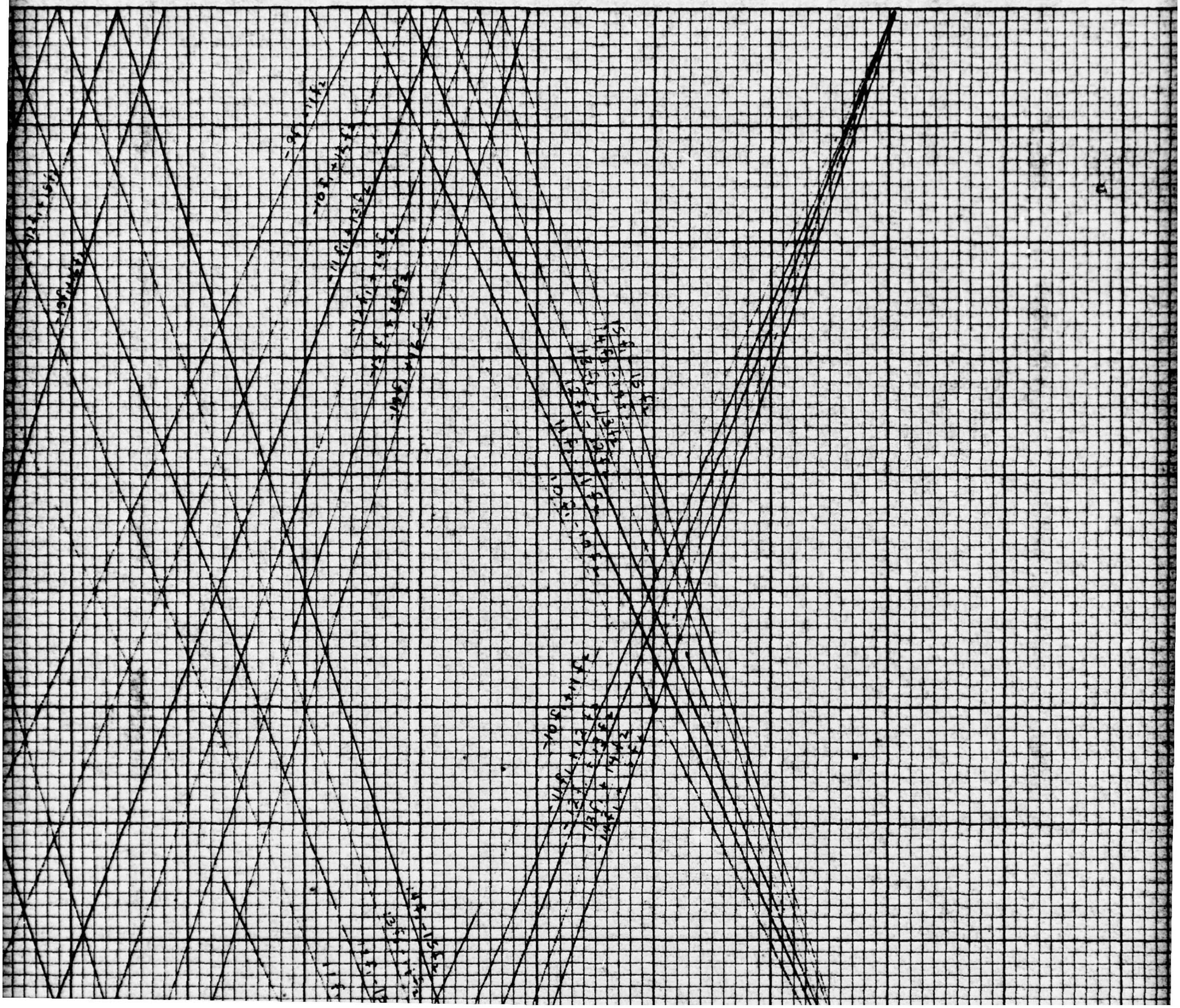

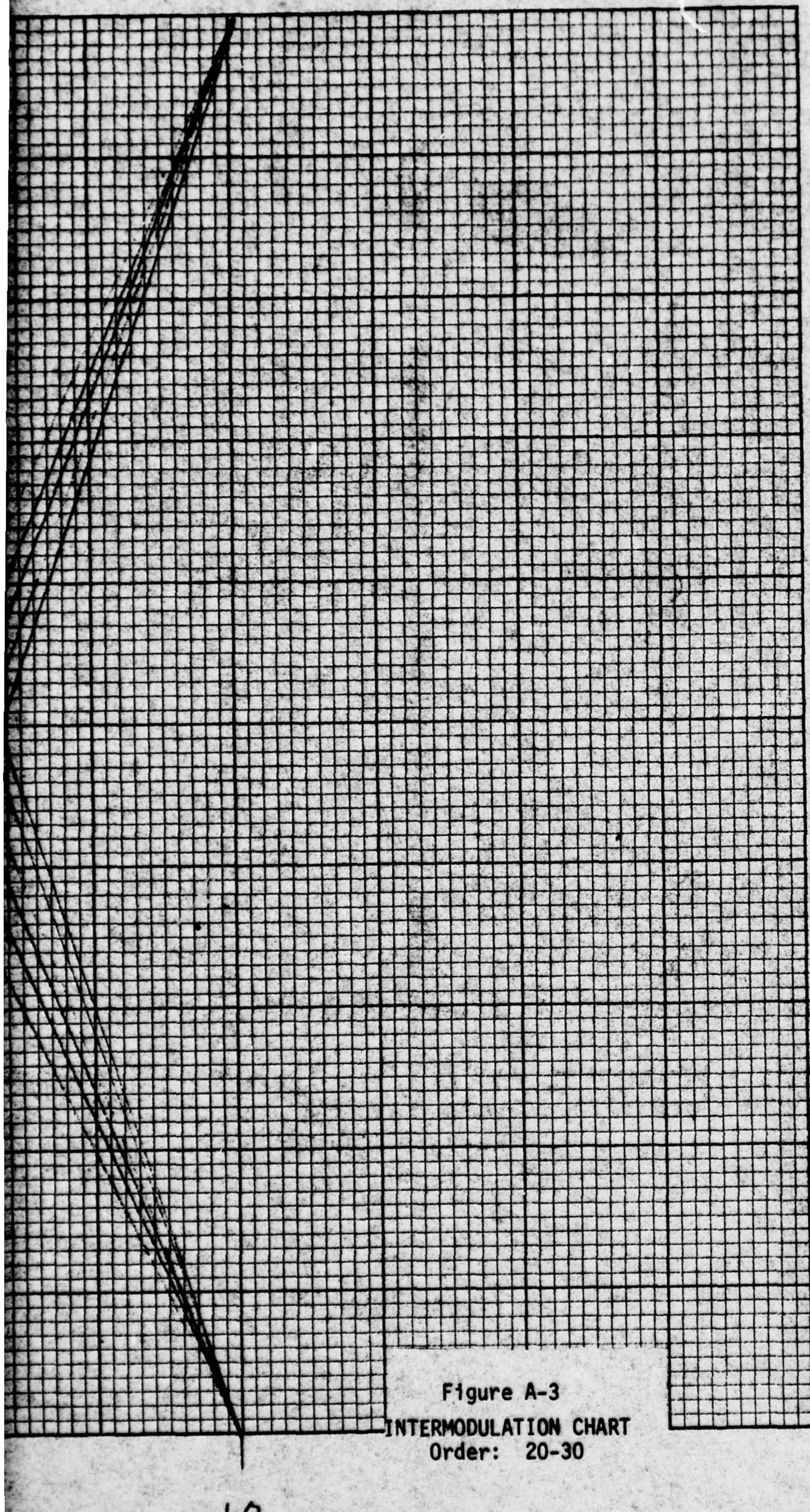

Figure A-3
INTERMODULATION CHART
Order: 20-30

APPENDIX B

GALVANIC SERIES OF METALS

(Ref. B, Table 8-1)

- CORRODED END (ANODIC, OR LESS NOBLE)

1. Magnesium
2. Magnesium alloys
3. Zinc
4. Aluminum 1100
5. Cadmium
6. Aluminum 2017
7. Steel or iron
8. Cast iron
9. Chromium iron (active)
10. Ni-resist. irons
11. 18-8 Chromium-nickel iron (active)
12. 18-8-3 Cr-Ni-Mo-Fe (active)
13. Lead-tin solders
14. Lead
15. Tin
16. Nickel (active)
17. Inconel (active)
18. Hastilloy C (active)
19. Brass
20. Copper
21. Bronze
22. Copper-nickel alloys
23. Monel
24. Silver solder
25. Nickel (passive)
26. Inconel (passive)
27. Chromium iron (passive)
28. Titanium
29. 18-8 Chromium-nickel iron (passive)
30. 18-8-3 Cr-Ni-Mo-Fe (passive)
31. Hastilloy C (passive)
32. Silver
33. Graphite
34. Platinum

- PROTECTED END (CATHODIC, OR MORE NOBLE)

APPENDIX C

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