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THE IMPACT OF ELECTROMAGNETIC INTERFERENCE ON SURFACE SHIP ANTENNA PLACEMENT

by

Janice Lai

March 1983

Thesis Advisor: A. W. McMasters

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More and more electronic systems are being added to Naval ships. Many of these systems radiate or receive electromagnetic (EM) energy. They are all vital parts of a ship and it is important that each functions properly if the ship is to accomplish its assortment of missions. However, it is becoming increasingly difficult to place these systems on board a ship without their EM radiation interfering with each other. This thesis analyzes the EM design problem. It concludes that a central clearing house for electromagnetic information is needed which would —

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The Impact of Electromagnetic Interference on Surface Ship Antenna Placement

by

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ABSTRACT

More and more electronic systems are being added to Naval ships. Many of these systems radiate or receive electromagnetic (EM) energy. They are all vital parts of a ship and it is important that each functions properly if the ship is to accomplish its assortment of missions. However, it is becoming increasingly difficult to place these systems on board a ship without their EM radiation interfering with each other. This thesis analyzes the EM design problem. It concludes that a central clearing house for electromagnetic information is needed which would maintain an up-to-date data base on electromagnetic problems and solutions, that shipboard personnel need to be more aware of the EMC problem, and suggests that more frequent updates of model studies and military standards be made.

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LIST OF ABBREVIATIONS

AAW	anti-air warfare
ASUW	anti-surface warfare
ASW	anti-submarine warfare
CFE	contractor furnished equipment
CNO	Chief of Naval Operations
DSARC	defense systems acquisitions review council
ECM	electronic countermeasures
EHF	extremely high frequencies
EM	electromagnetic
EMC	electromagnetic compatibility
EME	electomagnetic environment
EMI	electromagnetic interference
EMV	electromagnetic vulnerability
ESM	electronic surveillance measures
EW	electronic warfare
FYDP	Five Year Defense Plan
GFCS	gun fire control system
GFE	government furnished equipment
HERF	hazards of EM radiation to fuel
HERO	hazards of EM radiation to ordnance
HF	high frequencies
IM	intermodulation
IMI	intermodulation interference
ITU	International Telecommunications Union
JCS	Joint Chiefs of Staff
LF	low frequencies
LOS	line-of-sight
MF	medium frequencies
OPNAV	Naval Operations
OTH	over the horizon
POM	program objectives memorandum
PPBS	planning programming and budgeting system
PPI	plan position indicator

PRR	pulse repetition rate
RADHAZ	radiation hazards to personnel
RF	radio frequency
RF burn	RF burn hazards to personnel
SDM	ship design manager
SECDEF	Secretary of Defense
SEMCIP	shipboard EMC improvement program
SHAPM	ship acquisition project manager
SHF	super high frequencies
TDIET	topside design information exchange team
TGO	time to go
TLR	top level requirements
TESSAC	tactical EM systems study acquisition council
TGM	task group manager
UHF	ultra high frequencies
VHF	very high frequencies
WCAP	waterfront corrective action program

I. INTRODUCTION

As better equipment is developed, more and more electronic systems are being deployed aboard Navy surface ships. Many of these systems require antennas that radiate or receive electromagnetic (EM) energy. As the number of required antennas increases, placement becomes a problem because of the limited amount of space available on a ship, the fact that a certain amount of isolation is needed between the antennas and because other things must be taken into account such as the firing zone of weapon systems. Figures 1.1 and 1.2 from [Ref. 1: p. 26 and 23] illustrate the magnitude of the problem. The placement problem is just as acute on a carrier as on a typical Naval combatant, in fact worse due to the larger requirements and the fact that most of the deck must be kept clear for aircraft operations.

The effects of electromagnetic interference (EMI) on a ship's electronic systems can vary from static on a communications circuit and clutter on a radar scope to the complete disruption of communications, fire control, and electronic warfare (EW) systems [Ref. 2: p. 3].

Directives put out by the Chief of Naval Operations (CNO) give guidance to design engineers on approximately where to put certain high priority systems antennas. Unfortunately, communications systems and their associated antennas are not considered high priority.

The importance of communications to an individual ship, the task group commander, and the other commanders above him cannot be emphasized enough. As Mr. Irving Gottlieb, technical editor of Military Electronics/Countermeasures observed:

> Historians attribute military victories to outstanding generals, to clever strategems, to geographic topography, certainly to esprit de corps of the combative personnel, and perhaps to the fact that the defeated belligerents had the sun in their eyes; they may also allude to weapons superiority, to food supply, and to overall logistics. Strangely, we find scant mention of that element of warfare which, if absent or malfunctioning, can render the other much-quoted attributes partially or disastrously ineffective. This all important element is communications [Ref. 3: p. 42].

Chapter II looks at some of the systems that are especially affected by electromagnetic energy and presents some examples of problems, chapter III will examine the design process that is used to try and ensure electromagnetic compatibility, chapter IV lists some problem areas in the design process, chapter V looks at some of the problems that occur after a ship enters the fleet, and chapter VI offers some recommendations for the various problem areas.

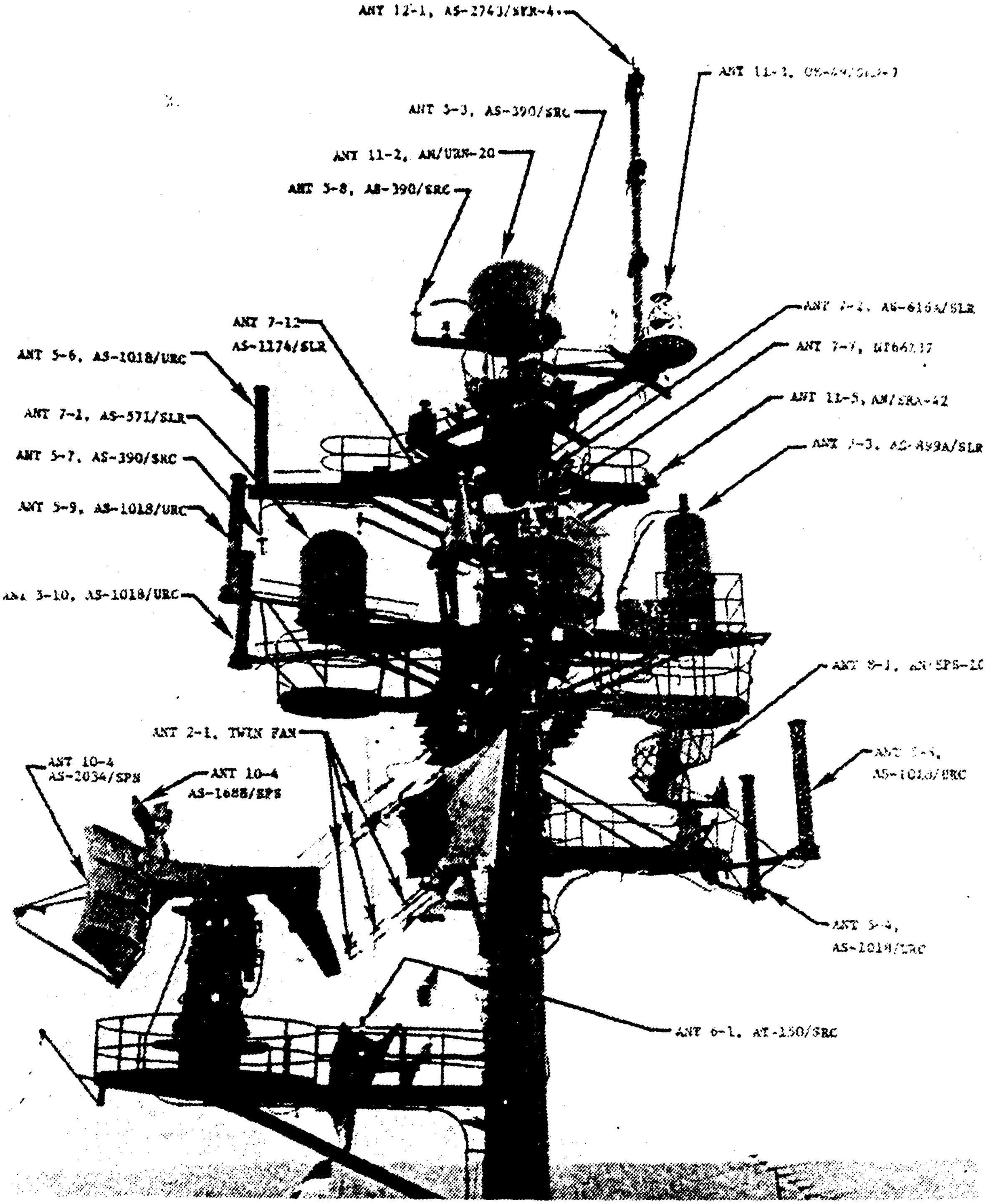

Figure 1.1 Mast Area of a Typical Warship.

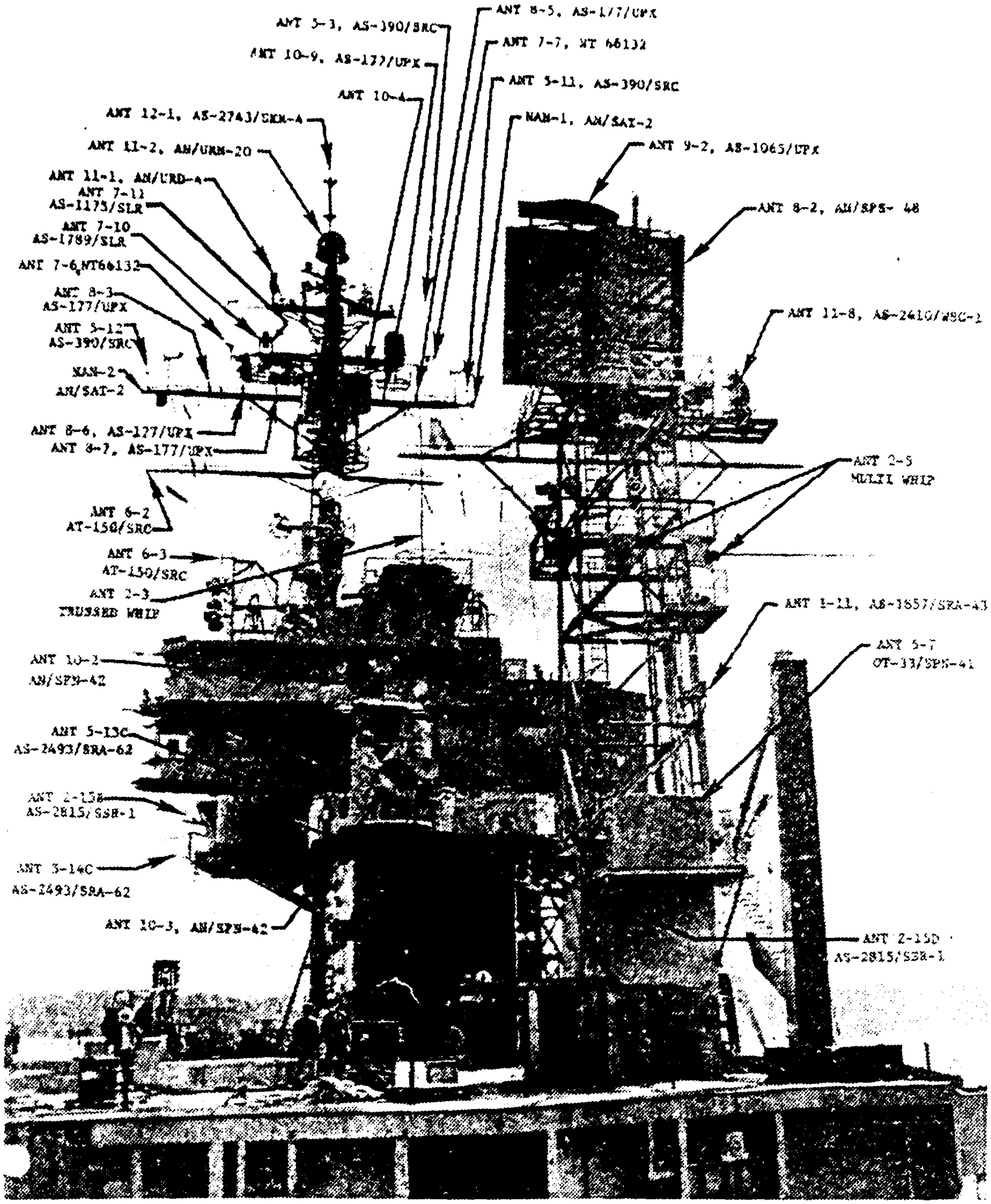

Figure 1.2 Antennas on a Carrier Island.

II. THE SHIP AND ITS ENVIRONMENT

As technology advances, we are able to produce equipments that will do an ever increasing range of things. The 1890's saw the invention of the wireless, the 1930's saw the invention of radar, and the 1970's saw the Navy start to use satellites for communications.

Each system, in its own exclusive environment, performed as was expected of it when developed. However, on board a ship, the many systems that have been brought together by necessity, must share the environment with other systems. The topside of a Navy ship is a conglomeration of many systems including weapon systems, navigation systems, and communications systems that radiate or receive electromagnetic (EM) energy. Electromagnetic Compatibility (EMC) therefore, is becoming an increasing headache for topside design engineers as they try to place an increasing number of EM systems in a limited amount of space.

A. THE ENVIRONMENT

The electromagnetic (EM) environment of a ship can affect the ability of the ship to properly perform its missions. Physical damage can result from the power of transmitting systems such as radars and communications equipment; ordnance can detonate, personnel can be burned and equipment can burn out. The performance of radar equipment can be reduced due to noise which could cause a false target to appear on a screen or equipment to be desensitized because trigger kills or blankers were used in an effort to reduce the effect of noise. Tactical limitations can result if certain sensors must be turned off or operated within very narrow limits in order to avoid mutual interactions.

There are two primary sources of electromagnetic energy which can affect a ship:

1. Natural which includes terrestrial (atmospheric noise and precipitation static) and extra-terrestrial (solar and cosmic noise) sources and
2. Man-made (equipment emanations from electric tools to radar and communications systems) [Ref. 4: p. 1-7].

Only the latter can be controlled by design.

When the electronic systems of a ship are turned on, the ship

> becomes a time-varying electromagnetic system as governed by Maxwell's equations, not approximations for a static operational environment [Ref. 5: p. 57].

The components of a ship (propulsion systems, radars, weapons systems etc), are usually developed with no specific ship in mind.

> In general, subsystem designers do not have a clear understanding of the overall ship design process. In particular, most subsystem designers do not know how their subsystem impacts the physical characteristics and performance capabilities of a ship as a system [Ref. 6: p. 87].

Although EMI became a problem when the first communications equipment started operating, it was not considered a primary problem when compared to accomplishing a mission. More transmitters and receivers were placed on board ships and, by the late 1960's, the problem had become significant enough that Fleet operations had to take EMI into account. For example, during the Viet Nam war

> In some instances, it was standard practice to shut down certain search radars and communications transmitters when missile alert conditions were set in the Gulf of Tonkin [Ref. 7: p. 51].

E. THE EQUIPMENT

1. Communications Systems

In 1899, Marconi demonstrated wireless communications to the U. S. Navy [Ref. 8: p. 41]. Equipment was installed on the USS New York, USS Massachusetts and at a shore station. Since that time, Navy communications requirements have increased to the point where now every Navy ship has multiple communications requirements for voice, data, and message transmissions.

Frequencies are allocated by the International Telecommunications Union (ITU), which allocates the frequency spectrum to the countries of the world. The U. S. in turn allocates frequencies for different uses, such as amatuer bands, citizen's radio, broadcasting, fixed, aeronautical radio navigation, land mobile, meteorological aids, satellites, and government utilization. Formal allocation helps to avoid mutual interference.

Navy ships utilize several different bands of frequencies depending on where a ship wants to transfer information. Because atmospheric attenuation (weakening of signal) increases as frequency increases, lower frequencies such as HF (high frequency) are used for longer range over-the-horizon (OTH) communications. Higher frequencies such as VHF (very high frequency) and UHF (ultra high frequency) are used for shorter line-of-sight (LOS) communications. Table I defines the list of frequency bands [Ref. 9: p. 1-2].

The higher the frequency used the more data can be transmitted per channel as wider bandwidths are possible at higher frequencies. For instance, the bandwidth between two and three GHz is much wider than the bandwidth between two and three MHz. Data rates can be shown by Shannon's Law :

$$C = 3.32\ H \log (1 + (S/N)), \qquad \text{(Eqn. 2.1)}$$

where C = the maximum number of bits/second;
H = bandwidth; and
S/N = signal to noise ratio.

The Navy uses satellites (satellite use is considered IOS) in order to take advantage of the higher frequency bands, such as UHF and SHF, and the higher data rates possible at these frequencies. Satellites, however, are subject to malfunctions and cannot be depended upon in wartime situations. Therefore, ships carry a variety of communications equipment and antennas in order to use several bands of frequencies at one time. Some UHF and VHF frequencies are utilized within a battle group so that the ships can communicate with each other with a reduced risk of being detected by the enemy. HF is used for longer distances of several hundred miles.

Optimum antenna lengths vary as it depends on the frequency it is being used for. The lower the band of frequency, the longer the antenna length. The length of the antenna is calculated by:

$$\lambda = c/f, \qquad \text{(Eqn. 2.2)}$$

where λ = the wavelength;
c = the speed of light; and
f = the particular frequency in cycles/sec.

TABLE I

Frequency Designations

Band	Range
ELF (extremely low frequencies)	30-300 Hz
VLF (very low frequencies)	3-30 kHz
LF (low frequencies)	30-300 kHz
MF (medium frequencies)	.3-3 MHZ
HF (high frequencies)	3-30 MHz
VHF (very high frequencies)	30-300 MHz
UHF (ultra high frequencies)	300-3000 MHz
SHF (super high frequencies)	3-30 GHz
EHF (extremely high frequencies)	30-300 GHz

The ideal antenna is a quarter-wave vertical antenna. The HF spectrum is from 2-30 MHz so the 2 MHz frequency requires an antenna 123 feet in length and the 30 MHz frequency requires an antenna which is 8.2 feet long. The 123 ft. antenna is too large to realistically place on a ship so the Navy has adopted a 35 foot vertical (whip) antenna as its standard HF antenna. Antennas for other frequencies are of different sizes and shapes, the UHF antenna AN/WSC-3 is a dish type antenna, but they also pose placement problems on board a ship as, if they are an LOS band antenna they must have an unobstructed view of its appropriate target.

2. Radars

Radars have two primary functions, surveillance and tracking. A surveillance or search radar searches a volume of space and reports the detection of targets. A tracking radar determines the time history of a target. It must be given the initial pointing information in order to acquire and lock on a target. The target will then be tracked until it is no longer considered of interest.

There are three types of radars that do both surveillance and tracking:

1. A track-while-scan radar correlates detection reports as the radar continuously scans.
2. A track radar with search capability can search a volume of space and detect a target. If a detection is made, the radar can aim its antenna beam in the direction of the target. This type of system can usually track only one target at a time.
3. Agile beam or inertialess beam steering has the flexibility to schedule its search or track functions in any direction as needed. Its antennas are not constrained to rotate at a fixed rate, hence it can detect tracks anywhere in its detection volume and still perform a surveillance function.

Within the above mentioned types of radars are 2D and 3D radars. A 3D radar measures target range, azimuth, and elevation. A 2D radar measures target range and one angle. For example, a radar that measures range and height is sometimes called a heightfinder.

There are two approaches to identifying targets, Selective Identification Friend/Identification Friend or Foe (SIF/IFF) and Space Object Identification (SOI). An SIF/IFF radar sends out a coded series of pulses that triggers a transponder on the target. The target sends back a reply (if friendly) as to target identification, range and altitude. An air traffic control (ATC) radar is an example of this system. An SOI system uses what is known as a skin return. It illuminates orbiting satellites at a high data rate resulting in an amplitude versus time history of the target. The reflected signal is analyzed to determine target characteristics such as size, shape and tumbling rate.

Radar frequencies are allocated by the International Telecommunications Union (ITU) to the countries of the world. With its allocated radar frequencies, the U. S. controls certain bands for certain purposes so that the different radar equipment do not interfere with each other. These frequencies are specified in chapter 4 of [Ref. 10] and are listed in Table II .

Chapter 5 of [Ref. 10] contains the criteria for certain equipment characteristics to ensure an acceptable degree of EMC among radar and other systems sharing the frequency spectrum. The criteria are combined with operational requirements such as power, sensitivity, pulse repetition rate (PRR), pulse duration, pulse rise time, and range of radio frequency emission to specify the required radar frequencies. Then, depending on the use of the particular radar system (short, medium or long range) other factors must be considered.

TABLE II
Radar Frequency Bands

Band	Frequency	Range
VHF	137-144	MHz
	216-225	MHz
UHF	420-450	MHz
	890-940	MHz
L	1215-1400	MHz
S	2300-2550	MHz
	2700-3700	MHz
C	5255-5925	MHz
X	8.5-10.7	GHz
Ku	13.4-14.4	GHz
	15.7-17.7	GHz
K	23-24.25	GHz
Ka	33.4-36	GHz

Atmospheric attenuation increases as frequency increases due mainly to microwave absorption caused by oxygen and water vapor, so low frequencies (VHF, UHF, and L bands) are used for long range radars (distances greater than 100 nautical miles) while high frequencies are used for medium and short range radars. Medium range radars (50-100 nm) operate in the S and C bands while short range radars (less than 30 nm) use the X and K bands of frequencies

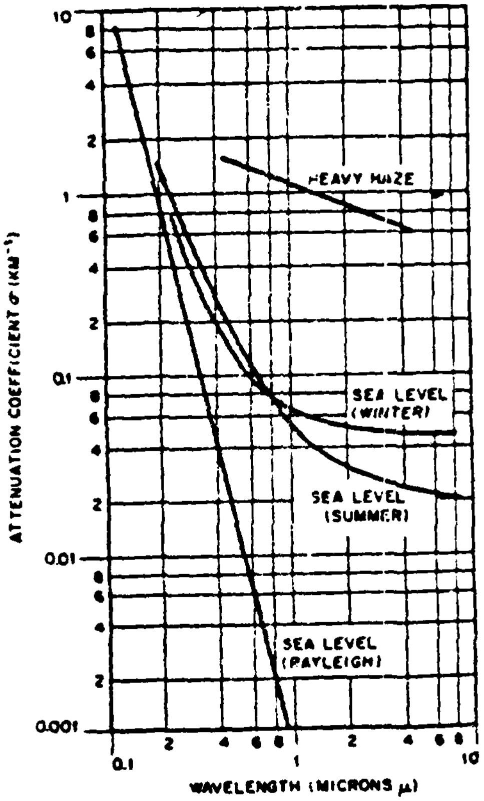

Figure 2.1 Atmospheric Attenuation.

[Ref. 11: p. 14]. Figure 2.1 from [Ref. 9: p. 28-26] shows the atmospheric attenuation coefficients for several conditions as a function of wavelength for window regions of the spectrum. As can be seen, the time of the year will affect the attenuation coefficient.

C. CAUSES OF PROBLEMS

1. Broadband Noise

Broadband noise is generated by the ship's hull and other structures near high power radiating sources such as HF communications transmitters. The noise is characterized by intermittent noise bursts (similar to those generated by electrical storms) that can affect portions of the communications and radar frequency spectrums. Broadband noise can be generated by loose points of contact at metallic junctions that are subjected to radio frequency (RF) currents from transmitting antennas. These currents can cause arcing at the junction. Other sources of noise include metallic objects which carry induced RF currents and which rub or touch each other intermittently while antennas are radiating. When the metallic objects make and break contact, spikes of noise are produced.

2. Intermodulation

It is important to understand a little about intermodulation interference (IMI) because it can cause a considerable amount of problems. Intermodulation interference can disrupt the operation of receivers in three ways:

1. If the IMI amplitudes are higher than what the receivers can optimally handle, the sensitivity of the receiver will be reduced,
2. IMI can mask other communications signals of interest by being on or near the frequency of those signals, and,
3. IMI components can be mistaken for true signals [Ref. 12: p. 209].

Intermodulation (IM) products are generated when two or more radio transmitters induce RF currents through non-linear junctions in the ship's hull and superstructure such as corroded or rusty joints or bolts. This is commonly called the "rusty bolt" effect. The non-linear junctions create IM products which are reradiated by the ship's structure, this produces undesired frequencies, some of which interfere with signals that the ship wishes to receive.

If f1 and f2 are two fundamental frequencies that are transmitted by the ship, intermodulation products will be generated which are sums and differences of integral multiples of the two frequency sources. Table III shows the frequency combinations possible for the first 5 harmonics. The type of non-linear junctions usually found aboard ship produce odd-ordered harmonic products that are much stronger than those of even-ordered harmonics.

TABLE III

Intermodulation Products

FREQUENCY	PRODUCT ORDER
f1 +/- f2	2
f1 +/- 2f2	3
2f1 +/- f2	3
f1 +/- 3f2	4
2f1 +/- 2f2	4
3f1 +/- f2	4
f1 +/- 4f2	5
2f1 +/- 3f2	5
3f1 +/- 2f2	5
4f1 +/- f2	5

The number of intermodulation products increases as product order and the number of transmitters increase as shown by Table IV from [**Ref. 8: p. 44**].

Even if different equipment operate in different frequency bands of the spectrum, IM products could interfere because harmonics up to the 60th order have been detected

TABLE IV

Products for 1 to 10 Transmitters

NO. OF TRANS-MITTERS	NUMBER OF ODD-ORDER PRODUCTS					
	3	5	7	9	11	13
1	1	1	1	1	1	1
2	6	10	14	18	22	26
3	19	51	99	163	243	339
4	44	180	476	996	1,804	2,964
5	85	501	1,765	4,645	10,165	19,605
6	146	1,182	5,418	17,718	46,530	104,910
7	231	2,471	14,407	57,799	180,775	474,215
8	344	4,712	34,232	166,344	614,680	1,866,280
9	489	8,361	74,313	432,073	1,871,845	6,539,625
10	670	14,002	149,830	1,030,490	5,188,590	20,758,530

with only 2 transmitters radiating. As the product orders increase, the signal strength decreases. But if the decreased signal of a product is as strong as a weak signal being detected (for example SHF communications during inclement weather) the interference problem can only be resolved by removing the source of the interference.

Table V is taken from CINCPACFLT INSTRUCTION 9407.1 of 9 June 1981 and lists some of the typical causes of hull generated IMI.

D. EXAMPLES OF PROBLEMS

This section lists some unclassified examples of problems due to equipment interaction and design, some of which have been solved.

TABLE V

Typical Causes of IMI

accommodation ladders
antenna pedestals
armored cable
awning supports
belaying pins (signal flag halyards)
boat cradles
boat gripes
bolted flanges or panels
bonding and grounding straps (deteriorated)
booms (refueling and cargo)
cable clamps
cabinets
canopy supports
chain safety links
conduit
cover plates
cranes
davits
dissimilar metal joints
doors
drainpipes
expansion joints
ferro-magnetic hardware in antenna systems
flagstaffs
fog nozzles
garbage chutes
gratings
handrails
hoist cables
jackstaffs
ladders
life jacket holders
lifelines
life raft holders and racks
masts
radar waveguide flanges
rigging
rusty or corroded bolts and screws
scuttles
shackles
stanchions
storage racks and bins
swivels
tackle
transmission lines
turnbuckles
waveguides
water washdown systems
wire mesh covers
yardarm rails and footropes

1. The AN/SPS-10 radar, which operates in the C band, causes interference in HF receivers. The interference had the characteristic sound of the AN/SPS-10 (625-650 pulse repetition rate (PRR)) in the 19 MHz to 28 MHz range, **[Ref. 8: p. 46].**
2. Emanations from the Mk 68 gun fire control system (GFCS) of the AN/SPG-53 radar bounced off of its associated topside structure which acted as an HF transmitting antenna, and reradiated the emanations of the GFCS masking incoming low-level communications signals, **[Ref. 8: p. 46].**

3. The AN/SPS-37/43 radar causes interference to the majority of topside electronic receivers. The 37/43 series radar generates broadband energy via an arc discharge occurring in either the antenna rotary joint and/or loose metallic items in the radar's main beam. Arc-type energy is detected on receivers operating above 3.5 GHz. The 43 radar operates at 225 MHz. On at least one ship, energy from the 2-6 MHz HF transmitting antenna caused IM products to be produced off of nearby flight deck flood lights. When the AN/SPS-43 radar was operated in excess of 100 kw, the emanations combined with the IM radiations to cause arcing in all the joints of the flood lights and flood light structures, [Ref. 8: p. 46].
4. Mutual interference between the AN/SPS-37/-40/-43 UHF radars and all UHF communications, such as the AN/SRC-20/-21 and AN/WSC-3, can cause lost messages and prevent effective target detection and tracking, [Ref. 13: p. 8-14].
5. Mutual interference from multiple weapons control radars can cause self jamming to weapons control systems, [Ref. 8: p. 8-16].
6. Pulsed radars can cause an overload on Electronic Warfare (EW) systems operations and interfernce which can prevent detection of signals of interest by electronic surveillance measures/electronic countermeasures (ESM/ECM) systems, [Ref. 13: p. 8-19].
7. Link 11 transmissions and the AN/SPQ-9 (Mk 86) system have been shown to degrade the AN/SPN-35's ability to provide a stabilized precision approach for landing aircraft, [Ref. 13: p. 8-22].
8. The AN/SPS-37/-43 air search radars have caused false alarm shut downs on AN/SPN-41 elevation transmitters,

loss of glide slope display during Automated Carrier Landing System (ACLS) operations by pilots, and spoking interference on the AN/SPN-43 Marshalling radar display scope preventing proper detection and control of aircraft, [Ref. 13: p. 8-24].

9. When a radar is pointing toward a flat surface, energy is reflected from the flat surface to a target which returns to the radar system as a false target in the direction of the obstruction so that the operator sees two targets on his display, only one of which is real, [Ref. 8: p. 47].
10. On some ships the AN/SPS-10 radar is located on the after mast. To see forward it has to look through several obstructions. Also, two communications antennas on either side of the radar interfere with its operation, [Ref. 8: p. 48].
11. There have been cases where radar emissions from ships being replenished at sea have caused the winch-control mechanisms on the replenishment ship to operate independently (out of control), [Ref. 2: p. 3].

The above were recorded examples of EM problems. While most of them did not seem to be life threatening, they could affect the combat capability of a ship. Figure 2.2 from [Ref. 5: p. 62] is from an article on combat capability assessment. The article illustrated the possibility of the electromagnetic environment degrading the tracking ability of an acquisition radar by as much as 20 % if time to go (TGO) was specified as the earliest time to detect a given target and a 50 % probability of acquisition is assumed. The dark right hand curve shows the radar's ability to track in free space and the dotted line depicts the degraded capability. The change due to the EM environment is calculated to be about a 20 % difference.

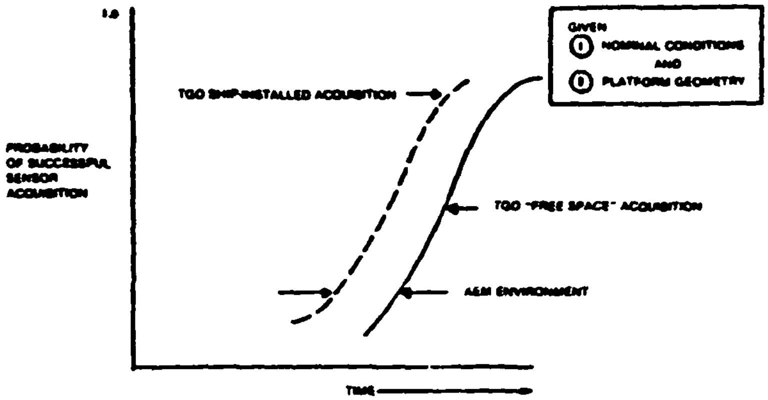

Figure 2.2 EM Environment Effect on Acquisition Radar.

III. TOPSIDE DESIGN

This chapter begins with an overview of the design process for the topside configuration of a surface ship.

A. THE DESIGN PHASE

Before a ship is built, there must be a need for it, the Navy cannot arbitrarily ask for a ship without a specific purpose. This first step is illustrated in figure 3.1 and begins when the Joint Chiefs of Staff (JCS) issue the Joint Strategic Planning Document (JSPD) which

> provides the advice of the JCS to the President, the National Security, and the Secretary of Defense (SECDEF) on the military strategy and force structure required to attain the national security objectives of the United States [Ref. 14: p. A-11].

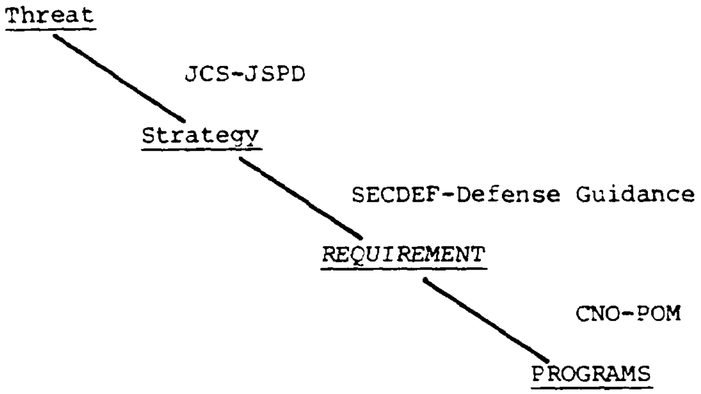

Figure 3.1 Planning Phase of the PPBS.

The SECDEF later issues the Defense Guidance, a document which provides the guidelines that must be observed by the JCS, the Military Departments and Defense Agencies in the formulation of force structures and the Five Year Defense Plan (FYDP), especially with respect to fiscal constraints. This guidance is based upon the JSPD, as amended, to reflect decisions made by the President or those made by SECDEF. Along with the other services, the Navy submits its Program Objectives Memorandum (POM) which expresses the Navy's requirements in terms of force structure, manpower, material and costs to satisfy all assigned responsibilities and functions during the period of the FYDP.

1. CNO Level Planning

After considering the Navy's requirements over the FYDP, the Chief of Naval Operations (CNO) matches his assets to the requirements by assigning specific missions to his platforms (ship, submarines and aircraft). If it is discovered that a new platform is needed, i.e. a ship, the initial design process begins. The mission and requirements for the desired ship are defined and an Operational Requirement (OR) or a Required Operational Capability (ROC) is issued.

A feasibility study is done to determine if a ship can be designed that will meet the OR/ROC and other constraints such as size, cost, manning and propulsion. The study also identifies the major technical risks associated with alternative designs and provides the basis for setting a design to cost target.

Next a conceptual design is done to develop a Conceptual Baseline (CBL) Package which includes design rationale, weight estimates, weapons equipment list, manning list, electronics space, general arrangements drawings and topside arrangements among its 16 areas of coverage. A draft Top Level Requirement (TLR) is another conceptual design product and defines the operational requirements of the ship to be produced, the ship's mission, configuration constraints, manning limitations, maintenance and supply concepts, and minimum operational standards.

> It defines what the user (OPNAV) expects from the product as obtained from the producer, the Naval Material Command (NAVMAT) [Ref. 15: p.66].

This corresponds to block 1 of figure 3.2 from [Ref. 15: p. 66].

Refinement of the TLR occurs through an iterative process involving OPNAV, NAVMAT and the Naval Sea Systems Command (NAVSEA) to ensure that there is a clear understanding of the requirements, that they can be met, and that the ship can be produced with present technology and resources in a timely manner (block 2 of figure 3.2).

Conceptual design is followed by the preliminary design whose objectives are :

1. to achieve a complete engineering description of an integrated ship system such that the basic ship size and definition will not change during contract design;
2. to achieve a functional definition of integrated subsystems selected for optimization of total ship performance and cost;
3. provide a technical baseline called a Functional Baseline (FBL) for the Defense Systems Acquisition and Review Council (DSARC) II process;
4. to assure definition of the ship to the level required for a Class C cost estimate (lowest budget quality estimate);
5. to select final design criteria for characteristics such as noise and ship protection consistent with cost and performance optimization of the total ship;

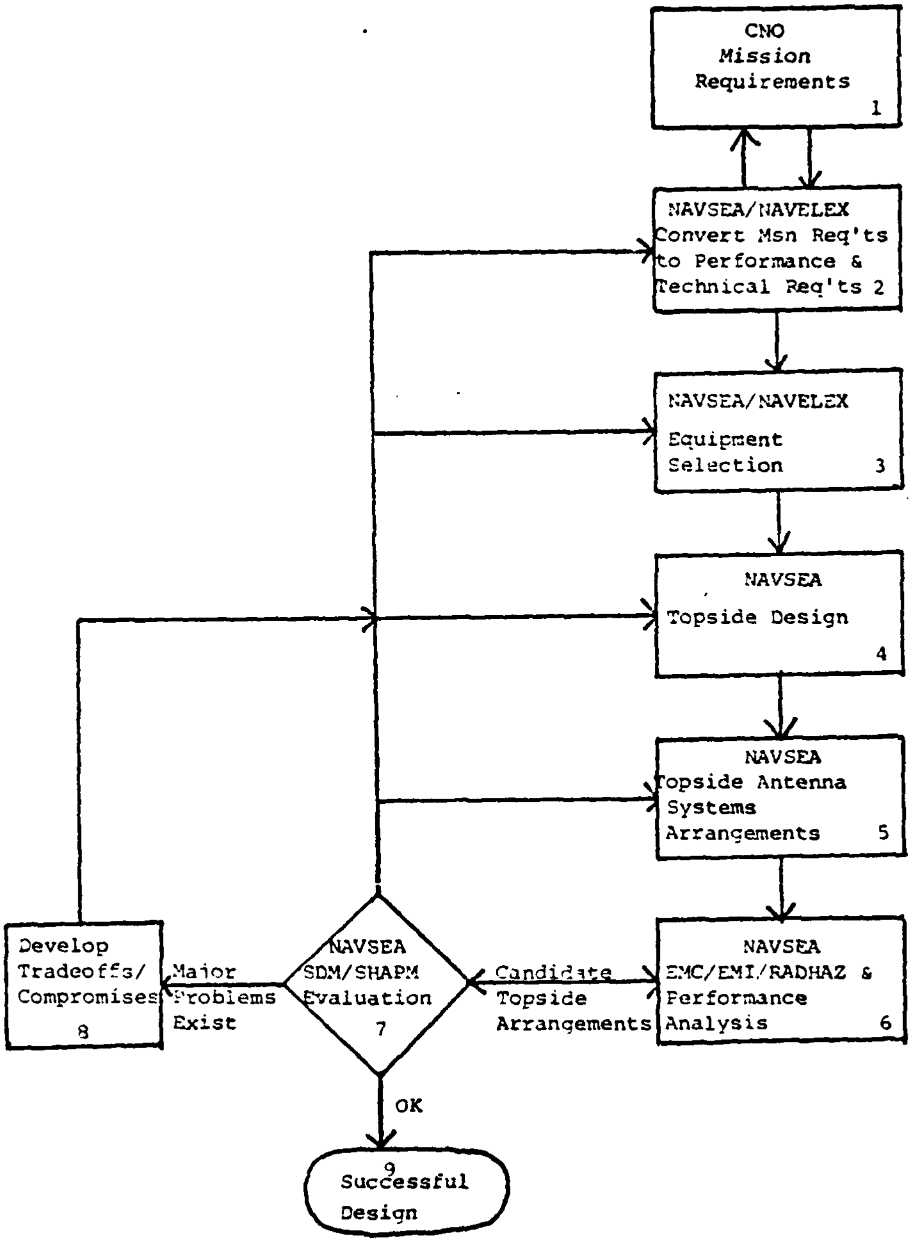

Figure 3.2 EM Systems Portion of the Ship Design Process.

6. to confirm the design-to-cost goal, and;

7. validation of selected subsystems [Ref. 16: p. 29].

2. NAVSEA Level Planning

The Top Level Specification (TLS) (block 2 of figure 3.2) is an output of the preliminary design and states what NAVSEA as the cognizant producer (for NAVMAT), intends to provide as a solution to OPNAV.

Once the preliminary design is approved, it is translated into a contractual package and put out to bid.

3. NAVELEX Input

Although NAVSEA is the responsible producer (designer and manager) for NAVMAT for the overall ship, the Naval Electronics Systems Command (NAVELEX) is responsible for the interiors of the communications, electronics countermeasures (ECM) and intelligence spaces as well as the associated antennas.

CNO documents such as the TLR or the OPNAV approved Ship Characteristics will state specifically each antenna that will be used by surface and air search radars, navigation, ECM, target illumination/tracking, identification friend or foe (IFF) and so on. These antennas can be specified because they are the latest generation available. If an antenna is in the research and development (R&D) phase, that is taken into account and its anticipated space and weight are allotted on the shipboard material listing and topside design analysis so that the new antenna can be used when it becomes available. (block 3 of figure 3.2).

The selection of communications equipment is made by NAVELEX utilizing guidance from documents such as NWP (Naval Warfare Publication) 11-1, "Characteristics and Capabilities of US Navy Combatant Ships" and NWP (Naval Warfare Publication) 4, "Basic Operational Communications Doctrine".

A ship's mission areas are evaluated and the appropriate communication system needed to support each area is selected. A circuit analysis is done to categorize each circuit as to usage, frequency range, transmit/receive, emmission mode, simplex/duplex and so on. In addition, circuits are looked at in terms of which need dedicated equipment and which might be able to share equipment. Once the needed circuits have been established, equipment such as tuners, patching equipment, antennas, multicouplers, transmitters and receivers are chosen to satisfy the circuit requirements and block 3 of figure 3.2 is completed. NAVSEA prepares a preliminary topside configuration complete with the placement of radar systems and forwards this to NAVELEX for their recommendations on the placement of communications antennas (block 4 of figure 3.2).

After NAVELEX determines the communications equipment that will be used, the Naval Ocean Systems Center (NOSC) in San Diego, California or Chu Associates in El Cajon, California is tasked with building a 1/48th scale brass model of the proposed ship from the waterline up based on Molded Offset Drawings for actual hull configuration and Compartment and Access (C&A) Drawings for actual superstructure configuration. All structures that could affect the electromagnetic (EM) environment in the high frequency (HF) spectrum are modeled.

During the construction of the brass model, engineering judgement is used to select feasible locations for communications antennas using preliminary NAVSEA topside drawings.

When the brass model has been completed, the actual placement of broadband HF antennas is started. The process involves measuring antenna impedance to establish adherence to associated equipment requirements. When an acceptable design is achieved, actual impedance matching components can be calculated for actual ship installation.

These tests are done on a model range with the brass model placed on a rotatable 20-foot diameter platter capable of simulating different sea states. Based on test measurements, changes in antenna location can be made fairly easily on the topside structure of the model. Eventually, an optimum antenna placement arrangement may be obtained.

According to [Ref. 17: p.40] brass modeling

> will accommodate any degree of superstructure detail without a corresponding increase in the cost or complexity of measuring the performance of individual antennas. Also, once a detailed brass model is in inventory, the model measurement approach is a quick, reliable and accurate means of determining the impact of proposed alterations to the ship topside structure or antenna arrangement

Once a model has been built, other benefits can be achieved including verification of weapon firing cut-out zones, acceptability of radar locations as related to turn radius, potential radiation hazards (RADHAZ) solutions, and identification of intermodulation interference (IMI) problems. An electromagnetic compatibility (EMC) analysis can be done if proposed communications equipments are known, to identify required intersystem isolation.

The model range can only make measurements for the placement of HF antennas. The measured data is extrapolated in order to acquire data for antennas of other frequency spectrums, such as VHF and SHF. The extrapolated data has proven to be accurate enough to continue using this means of measurement.

The NOSC inventory of models presently represents about 95% of the active fleet by ship class.

The data obtained from the model range studies is used by NAVELEX to help provide an external communications arrangement sketch to NAVSEA in its task of accomplishing the ship topside design and topside antenna systems arrangements (blocks 4 and 5 of figure 3.2). At this point, the placement of weapon systems, the location and form of stacks, the quantity and structure of the masts, etc., can still be changed by NAVSEA.

Some of the things that NAVSEA must keep in mind when doing a topside antenna arrangement (block 5 of figure 3.2) are:

1. weapon systems locations and the resultant firing cut out zones of guns and missiles
2. radar antenna placement
3. propulsion exhaust stacks
4. TACAN and other aircraft related systems
5. mast and yardarm configurations
6. deck house locations
7. cargo handling equipment, ladders, lifelines, and stanchions
8. HF and UHF transmit and receive antenna locations
9. ESM antennas
10. working zones which must be kept clear such as aircraft takeoff and landings, boat handling and replenishment

The antenna placements must meet necessary EMC standards of EMI, radiation hazards to personnel and ordnance (HERO), electromagnetic pulse (EMP), electromagnetic environment (EME), and electromagnetic vulnerability (EMV) (block 6 of figure 3.2).

The various NAVSEA functional codes (specifications coordination, hull, ship, and combat systems) and a recent addition, an EMC task group manager (TGM) (see Figure 3.3 from **[Ref. 18: p. 56]**), work together utilizing tradeoff studies to determine topside configurations that come closest to meeting the specified requirements.

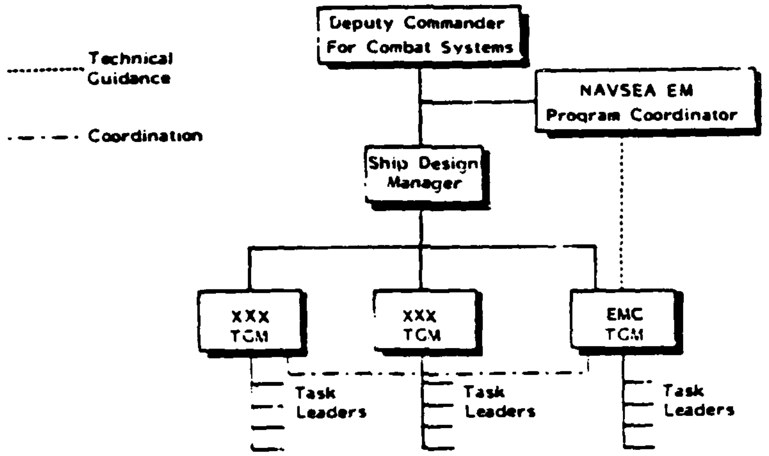

Figure 3.3 NAVSEA Organizational Structure.

Alternatives, along with the risks and deficiencies of the different configurations are given to the Ship Design Manager (SDM) (block 7 of figure 3.2) or Ship Acquisition Project Manager (SHAPM), who has the prerogative of accepting the proposed arrangement or reallocating space, weight and power to achieve a certain performance level. The SDM's choice of configuration becomes the Baseline Arrangement Drawing. It is refined (block 8 of figure 3.2) with necessary changes due to policy decisions concerning ship cost, size and manning. Other system commands such as the Naval Air Systems Command (NAVAIR) and NAVELEX either participate in the configuration refinements, mainly through Topside Design Information Exchange Team (TDIET) meetings, or are kept advised of the impacts on their respective subsystems.

Revised and updated topside configuration drawings are passed out to all cognizant NAVSEA codes for assessment, to NAVAIR for input on aircraft operations and to NAVELEX for comments. The approved final drawings are included in documentation that is used for ship acquisition (block 9 of figure 3.2). Future revisions or changes during shipbuilding or modernization such as ECP's (engineering change proposals) are reflected on these finalized drawings as they occur.

IV. PROBLEM AREAS IN THE DESIGN PHASE

Now that the design process has been reviewed, some problem areas will be discussed.

Present CNO directives give priority to virtually all systems but communications. While it is true that communications as such are not a main mission of a ship when compared to anti-air warfare (AAW), anti-submarine warfare (ASW), or anti-surface warfare (ASUW), a commander cannot perform his command and control function without proper communications support.

The major problem in placing communications antennas on a ship is the limited amount of real estate that can be used. On land, a Naval Communications Station (NAVCOMMSTA) could have its receiving and transmitting antennas separated by miles of land. A Navy ship does not have such freedom so places must be found amid the other ship illuminators and obstructions to place communications antennas in a least compromising area.

There appear to be no limits of degradation specified if an object is placed somewhere in the beam pattern of an illuminator. A general limit of so many degrees from the main beam or other point of departure is used but it is not always clear if this limit was chosen on the safe side or if it is a critical limit. A few degrees may not matter to the actual beam pattern of an illuminator but it could have a major impact on where the illuminator or an object such as an antenna may be placed. As an example, if a radar has a specified clearance of 40 degrees on either side of its main beam but the best that can be found is a place with 38 or 39 degrees of clearance, either a new site must be found or a compromise agreed on. Mr. Visvaldis Mangulis, who conducted system analyses of the AEGIS combat system including computer simulation of radar blockage by ship's superstructure aboard the CG-47, CSGN, CGN-9, and CGN-42, suggests that

> During ship design one may have to decide between several fire control radar configurations in which one or more of the radars are blocked. Consequently, it is necessary to develop methods by which the blockage can be graded [Ref. 19: p.77].

Prior to a brass model being built, it appears that a ship's topside configuration has already been settled on by NAVSEA such that the only thing that can be done by NAVELEX is to place the communications antennas around them as NAVELEX's brass model study is done using the initial topside configuration done by NAVSEA. However, several iterations may take place before a final design is agreed upon as in blocks 4-7 of figure 3.2, the NAVSEA design team or the SDM/SHAPM can move elements around such as propulsion stacks, weapons launchers and ladders. Therefore, the final topside design could vary markedly from the configuration used for the model study. Although calculated impacts may be done, one of the reasons for the brass model study is its history of fairly accurate measurements.

Brass model studies model the lead ship of a class. These studies are not usually redone if only so called minor topside changes are made or planned. This is especially true when follow-on ships of a new class get minor changes made to them. It is hard to believe that every ship in a particular class has a topside configuration so close to that of the lead ship that follow on model studies are not required.

The SHAPM/SDM does not have to use any of the recommended topside configurations given to him. Though so much effort was expended on careful tradeoffs and compromises into the present design, it may be changed to suit someone's idea of what the ship should look like.

The TDIET meetings are an important arena in which to discuss possible problems. Design teams from different NAVSEA groups (such as hull, machinery, weapons, and combat systems) and NAVELEX (representing the intelligence, ECM, and communications systems) try to determine if all systems are placed compatibly. If a possible conflict arises between two systems, the system with the higher priority will usually win out. This may not always be the best way to solve things . Some of the conflicts should be investigated to determine the extent of the problem before a final decision is made.

Though figure 3.2 shows the general steps taken in the topside design process, there appears to be no check off list or formal agreement on how things get done. Whatever is done is accepted as "standard practice". This may work as long as there are people at NAVSEA and NAVELEX who have many years of experience but what will happen when they leave? According to Dr. R. Leopold [Ref. 20: p. 41], from 1951 to 1952 the Bureau of Ships (BUSHIPS) (from which evolved NAVSEA) hired 250 engineers from 58 universities, many of whom are in leading positions with NAVSEA. In 1977, NAVSEC (the ship design arm which merged into NAVSEA in 1979) could only hire 25 Engineers in Training (EITs).

There seems to be a de-emphasis on in-house technical work with 72% of the work being contracted out in 1978-79 [Ref. 21: p. 105]. The in-house people have had to manage the outside contractors as well as do their own technical work with the result being that only about 10% of the work done in-house was of a technical nature. There may be no problem presently if experienced people are doing the managing, but how will the new people who are coming in each year, as small as their numbers are, gain technical expertise with so much concentration on outside contracting and the management of it. There will soon be a lack of competent NAVSEA managers who possess the technical know how and experience required of today's managers. Commenting on the Navy's ability to design ships, Mr. William H. Hundley of CDI Marine Co. stated that

> In 1970, when the design that became the FFG-7 was first being considered, the Navy in-house ship design organization had not designed a surface combatant for 10 years. The single package procurement process was still very much in vogue, and preparations were being made to procure the new PF by the same process [Ref. 22: p. 106].

Mr. Hundley was acting Chief Naval Architect at the time and went on to say

> After 10 years of Fleet support engineering and monitoring of designs being performed by other agencies, it was becoming very apparent that unless the procurement process was changed and the Navy's ships designed in-house again, the ship design capability of the Navy would be rapidly lost.

Military Standards (MIL STD's) need quicker and more frequent up dating in certain areas. [Ref. 23: p. 2-9] states that the MIL-STD-461A Characteristics Requirements for Equipment revision was started in May 1970. The B version was scheduled to be out 29 Jan 1978, after more than 7 1/2 years of revision. It was finally published in April 1980. One noted reason for delay is that if an activity is unable to resolve a disagreement, the problem is forwarded to a higher authority which could add six weeks to the schedule.

NELC TD 356 (Naval Electronic Laboratory Center Technical Document-the command is now known as the Naval Ocean System Center, NOSC) of 1 Sep 74 is one document that could use an update as it is a primary source of guidance for placing shipboard antennas.

Government Furnished Equipment (GFE) versus Contractor Furnished Equipment (CFE) could be a problem as the contractor sometimes has the latitude of selecting equipment other than GFE. This may lead to future EMI problems if maintenance is difficult or equipment malfunctions and spares are not available.

According to [Ref. 23: p. 2-12] there is no one source that has all the EMI data on GFE, it is scattered throughout activities. On the F-18 aircraft program, data on the 31 major GFE's had to be collected from 7 Navy technical activities. Valuable time can be wasted trying to locate what facility has what data. The longer it takes to acquire the needed information, the longer it will be before productive work can be started.

V. PROBLEMS OCCURRING AFTER THE START OF OPERATIONS

In spite of the painstaking effort expended in developing the topside design configuration of a ship, problems can easily arise after the ship has been placed in operation. Most of these problems are due not to design but to a lack of knowledge on the part of the users of the various communications and radar systems.

One source of IM problems arises from the trash left on decks. Things such as soda cans and foil wrappers can cause havoc when transmitting systems are turned on; especially when the ship is operating in less than ideal sea state and weather conditions. Reflections off of moving objects, such as rolling soda cans, can cause false or inaccurate readings on receiving systems.

Maintenance, or the lack of it, is a primary cause of problems. Personnel assigned to do the job are not always the brightest of people and their attitude toward the assigned chores may not enhance a ship's electronic capability. If careful monitoring is not done, even a well-intentioned effort may have no positive effect. For example, one ship traced its problem to the topside antenna system. An inspection showed the main wires to the fan antenna to be in very good condition but the associated shorting wires had been neglected for some time. Maintenance personnel did not think the shorting wires were part of the antenna system.

Some equipment, especially those with EMI shielding inside the case, are held together with a large number of screws. Often when maintenance or a repair action is done on the piece of equipment, not all of the fasteners are replaced.

> the practice of fastening only one or two retainers on a door or drawer, or of tightening only one or two screws to hold a side or back panel, will invariably result in a loss of effective EMI shielding, both from within, and into, the equipment [Ref. 13: p. 6-4].

When a ship has what it thinks is an EMC-related problem that ship's company cannot solve, assistance can be sought from the type commander (TYCOM) or a nearby mobile technical unit (MOTU). This can be done on as informal a basis as a telephone call. If the source of the problem is found, recommendations are made to the ship on how best to proceed.

If a piece of equipment is recommended to be reported defective via a casualty report (CASREPT), the ship must take the initiative in sending out the message. However, according to personnel associated with the waterfront corrective action program (WCAP) at MOTU 5 located in San Diego, California, some commanding officers are reluctant to send out CASREPTs unless the ship cannot function properly without the piece of equipment. In contrast, if a propeller shaft or boiler were defective and the ship could not carry out its assigned missions, those problems would be reported. But, if a piece of communication equipment were only partially defective and the ship could still carry out its primary missions, the communications equipment would not be reported.

The feeling appears to be that if everything that was defective was reported via a CASREPT, there would be so many that it would look bad for the ship. This appears to be the reason that some commanding officers try to minimize the number of CASREPTs sent out. As a result, some pieces of equipment may never function properly because they never receive the appropriate attention given a CASREPT.

Additional equipment that was not taken into account for during the design phase is often added to the ship for short periods of time. This could cause EMI problems due to reflections off of the added equipment or degradation in existing systems due to blockages caused by the additional equipment.

When a ship is designed, it is done with just a general plan in mind. Designers are far removed from the process which determines which ship serves in the Atlantic or Pacific area. Depending on which coast a ship is homeported to, different external pieces of gear may be added.

For example, ships serving on the Atlantic coast make deployment tours to the Mediterranean area. One of the requirements when in a Mediterranean port is to hang strings of lights from the bow up the mast and down to the stern of the ship. These are called Med lights and are put up only when in port and taken down when the ship leaves port. During the time a ship is in port the strings of wires used for the MED lights can cause problems for a ship's communications systems. As they are in effect another antenna, they can reradiate transmissions the ship may send out and may interfere with the original transmissions.

When Marines are embarked on amphibious ships, they have their own communications requirements. Sometimes the host ship will not have enough assets to cover the Marine requirements so the Marines ask for permission to add their own gear to that of the ship's. When permission is received from the appropriate authority, UHF and VHF equipment may be added to that of the ship's existing inventory of equipment. It is not hard to conceive of the possible problems that may occur.

Broadband communication antennas are modeled prior to installation on board ships but, as changes are made to a ship superstructure, the data obtained from the model study is no longer valid for placing the antennas.

For a variety of reasons, individual ships have not been modeled on a regular basis. Classes of ships have been

> modeled but quite often the model that is prepared reflects proposed modernization or proposed Shipalt (ship alteration) packages which are not completed in total or are deferred, with the end result that the ship and the model no longer agree [Ref. 24: p. 43].

Two classes of ships which have had problems with their twin-fan antennas are the CG-27 and DDG-2 classes. The brass models of these classes were updated in order to develop new impedance matching requirements or a new antenna design.

> However, because both of these ships were also slated for major modernizations, the impedance matching requirements were modeled against the future configuration of the ship. As a consequence, the ships entered industrial upkeep periods and had their poorly operating twin fan antennas restored to like new condition and returned to the fleet with poorly matched impedance. The net result to the ship was degraded operation which limits long haul communication capability [Ref. 24: p. 43].

In spite of the careful process used in the design phase for placing systems and their antennas on board a ship, sometimes non-electromagnetic requirements are compromised. In addition, changes can be made to a design without NAVSEA knowledge. The following examples illustrate the broad nature of the problem.

1. A PG class ship (This ship is no longer in service) was modified by someone who thought it would look more streamlined if the whip antenna in front of the propulsion stack was to tilt back slightly like the stack. The design change worked as long as the ship was in forward motion but problems occurred when the ship was at a standstill. Then the hot exhaust rising from the stack would heat the antenna to temperatures over 500 degrees causing breakage. The problem was solved by going back to the original design.

2. On cruisers of the Leahy Class, (CG 16 to 24); the Truxtun Class, (CGN 35); and the California Class (CGN 36-37), bow mounted discone antennas were placed in such a position that they obstructed the forward missile launcher, [Ref. 25: p. 3].
3. The USS Bainbridge, (CGN 25), was fitted with a pedestal-mounted receiving antenna which was directly located in front of its forward missile launcher, [Ref. 25: p. 3].
4. The Belknap Class cruisers (CG 26 to 34), were fitted with a trussed-whip antenna on the fantail that violated the clear space requirement of the 5-inch gun located aft of the helo deck, [Ref. 25: p. 3].

VI. RECOMMENDATIONS/CONCLUSIONS

The ever increasing magnitude of the EMI problem requires that if we are to have a properly functioning ship for the fleet, we must find the funds to do whatever is necessary to ensure an environment in which deployed equipment can operate as they were intended.

Funds are needed for an all-encompassing EMI data base to store and update EMC related problems. Time would be saved by many activities in being able to retrieve information from the one data base. NAVSEA already has a SEMCIP data base of reported fleet EMI problems so an expansion of that is a possibility. With other EMI information, such as that on GFE, added to it, the SEMCIP data base could be a one stop clearing house of EM information. However, funding will be needed to expand the data base, keep it up to date, and to make the information more readily available to activities closer to the fleet such as the MOTUs and Naval shipyards. Since many of the problems would be of a classified nature, it may be necessary to establish a small secure network, possibly using the proposed Defense Data Network (DDN), that would enable the MOTUs ready access 24 hours a day to the EMI data.

Budget limitations have prevented updates to specifications. These updates are important because current ones are out of date [Ref. 26: p. 2-4]. At present, acquisition managers cannot rely on the military standards to adequately control EMI design on new procurements. Funding is needed both to update military standards and keep them up to date.

Most of the problems that occur after a ship has been built could probably be solved by training and education. NAVSEA is leading the way with programs like SEMCIP but training is a never ending process that the Navy must expand up on. It should include everyone on board ship since each individual can have a detrimental effect on the electronic systems of the ship without being conscious of it. Adequate funds must be provided so that all personnel will receive the proper training.

Additional funds for studies of possible problem areas which are identified at the TDIET meetings should be made to provide actual data on which to base decisions. An example of this is the study done on the USS Long Beach (CGN-9), where NAVSEA recently tasked Johns Hopkins University Applied Physics Lab to assess the interference effects of the AN/SRC-16 fan antenna with each of the subsystems of the AN/SPG-55E radar. This ship was selected for the study because it was undergoing an overhaul at the time.

Brass model studies should be utilized more often in initial design and to evaluate later changes to the topside configuration. This would help ensure EMC requirements are being met.

As has been shown earlier, the emanations from communications systems can seriously affect other systems and vice versa, therefore it is important that communications be treated as a system on an equal basis with other systems instead of being just added on where ever possible. Therefore use of the knowledge gained by NOSC from model studies should be expanded. If advice is sought from NAVELEX/NCSC earlier in the design phase, (much before the initial configuration is used for the brass model study) the communications antennas could be better integrated into the placement process.

Following the recommendations of Mr. Mangulis in **[Ref. 19]**, methods to grade all types of radar blockage should be developed. The blockage criteria could then give design engineers a better idea of how the placement of systems impacts on the operational capability of a system.

Since the final design depends on the SHAPM/SDM, he should be brought into the process earlier so that when recommended configurations are forwarded, the likelihood of approval will be enhanced. This should also help speed up the design process by reducing the number of iterations after the SHAPM receives the result.

A greater emphasis should be put on in-house design and the training needed to accomplish it while knowledgeable personnel are still in government service.

A checkoff list should be developed so that no area of design is left out of the decision process. For example, [Ref. 27], suggests that

> Prior to NAVSEA 06 approval of a topside design/antenna arrangement for New Construction, Conversions, and Modernizations of surface ships as recommended by NAVELEX/NCSC, a review of the recommended design (should) be conducted by both NAVSEA Code 61 (Combat Systems Engineering Group) and NAVSEA Code 62 (Surface Warfare Systems Group). This method would permit discovery of potential degradation problems early on and potentially reduce cost and schedule impacts.

Having this checkoff list signed by the head of each group would ensure that groups whose systems are involved in the topside configuration of a ship would be aware of each step of the design process. Hopefully, better system interaction at lower costs should be a major result.

Unfortunately, not much can be done about the limited amount of space on board a ship. It is, however, possible to either lower the requirements for smaller ships such as giving up an ASW or AAW capability or, if that proves infeasible, to expect to build ships that are large enough in length to accommodate the required systems.

GFE should be specified in all ships in order to minimize future EMI problems. As an alternative, very strict control contractors might be appropriate.

Degradation caused by the placement of extra equipment on ships after they have become operational should be minimized. Because so many ships may have such equipment added to their topside decks, it may behoove the design engineers to consider the possibility and to allow space for additional temporary equipment in an area that will have the least impact to the present configuration.

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