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THESIS

Comparative Analysis of Passive Communications Satellites Employing the SHF and HF Spectrum for Use in a Strategic Role

by

Giuseppe Donadio

March 1988

Thesis Advisor: Major Thomas J. Brown

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Passive communications satellites were instrumental in the evolution of todays satellite communications networks. However, ever since the successful deployment of the first geostationary satellite, research and development into passive communications satellites has almost come to a halt. In addition to examining the characteristics of the historic passive satellites, this thesis will evaluate the capabilities of a new design approach for a passive system. The passive backscatter array, which was initially proposed by Joseph Yater, was intended to provide an effective communications satellite with a large radar cross section. Primary emphasis is placed upon this system's survivability within a nuclear stressed environment. The effects of a nuclear burst upon the propagation of an electromagnetic signal are evaluated so as to assess systems survivability. Both the advantages and disadvantages of a passive communications satellite are evaluated to

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Comparative Analysis of Passive Communications Satellites Employing the SHF and HF Spectrum for Use in a Strategic Role

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Passive communications satellites were instrumental in the evolution of today's satellite communications networks. However, since the successful deployment of the first geostationary satellite, research and development into passive communications satellites has almost come to a halt. In addition to examining the characteristics of the historic passive satellites, this thesis will evaluate the capabilities of a new design approach for a passive system. The passive backscatter array, which was initially proposed by Joseph Yater, was intended to provide an effective communications satellite with a large radar cross section. Primary emphasis is placed upon this system's survivability within a nuclear stressed environment. The effects of a nuclear burst upon the propagation of an electromagnetic signal are evaluated so as to assess the system's survivability. Both the advantages and disadvantages of a passive communications satellite are evaluated to determine its suitability for use within the Minimum Essential Emergency Communications Network. The concept of developing a passive satellite system that would use the HF spectrum is also explored. It was found that such a system would be untenable due to the large size of the satellite reflector and excessive signal absorption in a nuclear environment. Passive satellites which use the SHF band may prove to be effective for the broadcast of strategic messages provided that the potential problem of orbital instability can be resolved.

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I. INTRODUCTION

A. BACKGROUND

The United States' satellite communication program started in the 1960's with the introduction of the Echo I and II passive satellites. Work on passive satellites continued through 1966 with the introduction of the OVI-8 wire grid sphere. In 1969 the Goodyear Aerospace Corporation completed their study of a passive communications satellite which would be in the shape of a saddle reflector. However, since the successful deployment of the first active geostationary Syncom satellite in 1963 the concept of using passive satellites has fallen into disfavor. Almost instantly active satellites became the panacea for all communication problems.

Recently, doubt has been cast upon the continued availability of active satellites in a hostile environment. These satellites can be easily jammed and are very susceptible to HEMP damage in a post nuclear environment. With this in mind there has been renewed interest in the use of passive satellites. As a result of this interest the Rand Corporation has been commissioned by DARPA to develop a proposal for a PACSAT (Passive Communication Satellite) system. Once again a new idea has its roots firmly planted in the past.

Some of the supposed advantages of a passive satellite system are: increased reliability due to the lack of electronic and moving parts, jamming resistance due to frequency agility over a large transmission bandwidth, lower costs, imperviousness to HEMP, and lower susceptiblity to active countermeasures. Additionally, passive satellites would weigh considerably less than their active counterparts. This may translate to a savings in launch delivery cost while at the same time broadening the set of potential launch vehicles that may be used to place the satellites into orbit. This is particularly important in light of the delay that NASA has experienced with their launch schedule.

B. OBJECTIVES

The primary emphasis will be to determine if a passive communications satellite system may be used effectively in a hostile environment. Also, depending upon the advantages and disadvantages of such a system, what type of mission would it be best suited for, strategic or tactical? In determining mission suitability the proposed system will be evaluated with respect to communications availability, reliability, survivability, interoperability, and graceful degradation.

In keeping with the concept of attaining survivable and effective communications in a hostile environment, increased emphasis has been placed upon improving the capabilities of existing HF communications, to wit the High Frequency Anti Jam (HF-AJ) program and improved HF environmental prediction models. One of the concepts to be examined in this thesis is that of using the HF spectrum in conjunction with passive satellites. By using direct HF line of sight to a satellite the more traditional means of skywave propagation is circumvented.

Of particular concern will be the system's ability to maintain an operational communications link in a post nuclear environment. Both the SHF and HF spectrum will be considered in determining the degree of degradation inherent to a passive communications satellite relay within a nuclear stressed environment.

Cost considerations are always crucial to the development and success of any new communications system. While specific costs for the development and deployment of a passive communications array will not be examined, key factors affecting those costs will be reviewed. To what degree are there common or unique determinants of costs for both a passive and active communications satellite?

Finally, with respect to transmission characteristics, what type of data rates may be sustained by a passive system and what factors affect the data rates and signal to noise ratio of such a system?

C. THESIS OUTLINE

The following chapter will provide the reader with a summary of the United States' communications satellite development program. Starting in the early 1960's with the development and deployment of the Echo series of passive satellites and progressing to the current system of active geosynchronous satellites. That chapter will describe in some detail the communication performance characteristics that were attained with the Echo-II satellite during an experiment conducted between the United Kingdom and the Soviet Union. The closing sections of Chapter II will describe the Passive Communications Satellite Array (PACSAT) that is being studied by the Rand Corporation.

Chapter III deals with the effects of a high altitude nuclear burst upon the ionosphere. It examines the degree of ionospheric deterioration due to the release of both prompt and delayed radiation. Of primary interest is the debilitating effects that a nuclear burst has upon the communications spectrum. Both the HF and SHF spectrum are examined to determine their susceptibility to increases in the amount of atmospheric noise, refraction and absorption resulting from a nuclear blast. A series of graphs are presented to display the effects upon electromagnetic absorption as a function of burst height, yield, and time.

A detailed description of the design and performance characteristics of the PACSAT array is presented in Chapter IV. Both the operating and structural characteristics of the array are examined as well as its orbital placement and required constellation size. The received signal is characterized by its minimum required signal to noise ratio in order to attain the desired probability of error. An example of a "typical" communications link is described with its associated path calculations.

Chapter V presents an analysis of the passive communications satellite with respect to cost and operating efficiency. It describes the determinants of cost for both the active and passive system. A cost model is presented which delineates the determinants of total cost for a passive communications satellite network. The cost efficiency model of an active satellite network is also presented as a means of identifying the measures of capacity that may be important to a passive satellite communications network.

The remaining sections of Chapter V deal with an analysis of the potential survivability of a passive satellite in a hostile environment. Such an environment would be typified by active jamming, anti-satellite weapons, and the possibility of signal propagation being deteriorated by a nuclear burst. Finally, the chapter closes with an evaluation of the passive satellite's suitability for a strategic role, specifically as a part of the Minimum Essential Emergency Communications Network. The final chapter of the thesis presents the author's conclusions and findings.

D. SUMMARY OF FINDINGS

Any use of the HF spectrum in conjunction with a passive communications satellite would be ineffective due to the satellite's size requirements and excessive absorption loss in a nuclear environment. The attenuation caused by suspended particulate matter after a nuclear burst would result in some deterioration of a SHF signal on a passive satellite link.

Due to the limited field of view of any one satellite the role of the passive satellite system would be restricted in scope. Interoperability between services would be restricted due to the limited coverage area. However, the large number of satellites required in any passive communications system would add significantly to the redundancy, survivability, and graceful degradation of the entire network.

Current design specifications for a passive satellite array result in serious deficiencies in orbital stability. The orbital instability of the PACSAT array may result in substantial signal degradation. However, passive satellites have in the past proven themselves to be capable of maintaining an effective communications link. The success of any future passive satellite system would depend upon solving the problem of orbital instability.

II. SATELLITE BACKGROUND

In 1950 the U.S. Navy first utilized the moon as a passive communication satellite in order to transmit communication traffic between Washington, D.C. and Hawaii. Ever since that time communication via satellite has become an integral part of the Navy's day to day operations. Satellite communication has evolved from the rudimentary use of natural satellites as passive reflectors to the use of active satellites that are capable of on board processing and amplification of the received signal.

This chapter will discuss some events that were instrumental in the evolution of the current satellite communication systems. After describing the development and capabilities of some of the active satellites that are currently in existence a detailed examination of one of the first passive satellites will be presented. This will be followed with an introduction to a proposed Passive Communication Satellite (PACSAT). A detailed technical analysis of PACSAT will be included in later chapters.

A. CURRENT SYSTEM OF ACTIVE SATELLITES

The current plethora of active satellites has undergone a tremendous metamorphosis since the first active satellite, Sputnik I was launched in October 1957. Shortly after the successful launch of Sputnik I the United States reciprocated with the Score satellite which was placed into orbit in December 1958. Score became the first artificial satellite to be used to transmit voice communication. President Eisenhower used this satellite to broadcast his 1958 Christmas message. [Ref. Pritchard: p. 3]

Private industry soon joined in the fray when the Bell System developed their first active communication satellite, Telstar I in July 1962. NASA injected the Telstar I into a medium altitude elliptical orbit. While higher altitude geosynchronous orbits had first been proposed by Arthur C. Clark during the 1940's they were not actually attempted until 1963 with the launch of the SYNCOM I satellite. This first attempt at placing a satellite in synchronous orbit resulted in failure. NASA was able to successfully place the SYNCOM II and SYNCOM III in synchronous orbit later that same year. [Ref. Pritchard]

A key piece of legislation which was instrumental to the evolution of the satellite industry was the Communications Satellite Act of 1962. This Act resulted in the formation of the Communications Satellite Corporation (Comsat) and fostered an environment conducive to the development of a truly multinational satellite communications program, Intelsat. In July 1964 one hundred nations joined together to form Intelsat for the purpose of developing an international satellite communication system. Their first active satellite, Early Bird (Intelsat I) was placed into synchronous orbit in April 1965. This series of satellites has evolved from the Intelsat I with a launch weight of 38.6 Kg and a capacity of 240 voice circuits to the Intelsat VI with a weight of 2,004 Kg and a capacity of about 40,000 voice circuits as well as two television circuits.

1. Mission

Satellites have become so entrenched in our daily lives that we often tend to take them for granted. They have been used for everything from voice, data and video communication to earth resource mapping. In short they have become a vital national resource.

With regard to national defense they are employed both strategically and tactically on a daily basis. Both Naval battle groups and Single Integrated Operating Plan (SIOP) forces rely upon satellites for their intelligence gathering as well as relaying their tactical and strategic messages. With the proliferation and miniaturization of earth satellite receivers and transmitters more traditional forms of communication have fallen into disfavor.

While the details and use of any one specific satellite system are varied the generic applications of communication satellites may be broken down into three primary mission areas: [Ref. 1: p. 24]

- Multipoint-to-Multipoint (Multiple access)
- Multipoint-to-Point (Data Gathering)
- Point-to-Multipoint (Broadcast).

In a Multipoint-to-Multipoint system there are a number of earth stations within the satellite's field of view which are using the same satellite to relay information along a two way communication circuit. An example of such a system would be the Navy's Demand Assigned Multiple Access (DAMA) communication system.

With a Multipoint-to-Point system data is gathered by several earth stations and relayed to one central site where it may be processed and analyzed. Finally, in a Point-to-Multipoint system information is transmitted via a one way channel from a central earth transmitter via the satellite to multiple earth receivers. A common example would be the Navy fleet broadcast.

2. Existing Satellites

Many of today's operational satellites are placed in a geosynchronous orbit of approximately 35,786 Km to take advantage of their greater field of view. At this altitude only three satellites are required to provide total earth coverage. An additional advantage to this configuration is that these satellites can maintain a constant position relative to the surface of the earth. This simplifies the task of the earth receiver in both acquiring and tracking the satellite.

While the advantages of a geosynchronous orbit are considerable they do not come without a price. It is much more difficult and costly to place a satellite into geosynchronous orbit vice a medium altitude orbit of say 10,000 Km. A geosynchronous orbit limits both the size of the payload and the type of launch vehicle. Additionally it increases the propagation delay time as well as the amount of signal loss due to spreading.

While Intelsat VI was initially intended to be launched with either the Ariane or the Space Shuttle, the Challenger catastrophe as well as the unavailability of the Ariane (fully scheduled through 1992) has caused Intelsat to seek other means of placing their heavy satellite into orbit. Intelsat and Glavkosmos have drafted a letter of agreement for launching the Intelsat VI on a Soviet Protons rocket. This will most likely be a temporary measure until the United States is able to resume a commercially available heavy launch schedule. [Ref. 2]

Table 1 provides synoptic data on some of the early and current civilian communication satellites. [Ref. 1: p. 4-7]

TABLE 1

CIVILIAN COMMUNICATION SATELLITES

System	Intelsat I	Intelsat VI	Telstar
Number of Satellites	2	5	1
Communication Capacity	240 voice 1 Television	40,000 voice 2 Television	N/A
Number of Transponders	2	46	24
Frequency	C band	C & Ku band	C band
Mass in Orbit	38.6 Kg	2004 Kg	659 Kg
Design Life	18 months	10 years	10 years
Launch Vehicle	3 stage thrust-augmented Delta	Shuttle or Ariane	Delta 3920

Table 2 provides a summary of some of the operating characteristics of several existing military communication satellites. [Ref. 1: p. 14]

TABLE 2
MILITARY COMMUNICATION SATELLITES

System	DSCS-2	DSCS-3	Fleetsatcom
Number of Satellites	8	4	5
Number of Transponders	2	7	12
Frequencies	X band	X & UHF	X & UHF
Transponder bandwidth (MHz)	50 to 185	50 to 85	0.005 to 0.5
Satellite EIRP (dBW)	28 to 40	23 to 40	16.5 to 28
Receive G/T (dB/K)	8.5 to 20	-16 to -1	-16.6
Satellite Mass	500 Kg	816 Kg	1005 Kg
Design Life (years)	5	10	5
Launch Vehicle	Titan III-C	Titan 34-D	Atlas Centaur

3. Operational Frequencies

As can be seen from the above the predominant operating frequencies are in the SHF band of 3 to 30 GHz. While most of the civilian satellites such as Telstar, Intelsat and Satcom use the C band of frequencies (4 to 8 GHz) the military has opted to use the higher frequencies of the X band (8 to 12 GHz) in an attempt to gain access to the greater bandwidth that is available at these frequencies. The UHF frequencies on the DSCS-3 and Fleetsatcom are used primarily for Tracking, Telemetry and Control (TTC) purposes.

Some of the problems inherent to SHF propagation are increased atmospheric attenuation due to the gas and water vapor content within the atmosphere. Generally the higher the frequency the greater the attenuation. Rainfall will also increase the attenuation and background noise of the downlink signal. For example a heavy rainfall (defined as 15.24 mm/hr) will cause a 4 GHz signal to experience an excess path loss of approximately 0.02 dB/Km while a 11 GHz signal will be attenuated by about 0.5 dB/Km. [Ref. 3: p.76]

In later chapters the author will examine the effects that nuclear induced ionospheric disturbances have upon the propagation of these frequencies.

4. Cost per Circuit-Year

As can be seen from the above tables the weight of active satellites has increased with their complexity. The first Intelsat had a beginning of life (BOL) weight of 38.6 Kg. Intelsat VI has a proposed BOL of 2,004 Kg. This increased weight and complexity is translated into higher development and launch costs. For example the budget for strategic and tactical SATCOM (for both satellites and terminals) is in excess of $1 billion dollars annually. [Ref. 4]

While the overall development costs have increased, the enhanced circuit capacity and increased longevity of the satellites have improved efficiency and hence reduced the investment costs per circuit-year. For example when Intelsat I was developed it had a capacity of 240 telephone circuits and a design life of 1.5 years, which translates into an investment cost per circuit-year of $32,500 (total investment cost of about $11.7 million). Intelsat V on the other hand has a circuit capacity of 12,000 with a design life of 7 years which results in an investment cost per circuit-year of only $800 (total investment cost of about $67.2 million). [Ref. 3: p. 116]

5. Vulnerability

With the multiplicity of circuits and the high quality of signal transmission the Navy has come to rely upon active satellites almost to the exclusion of more traditional forms of communication. However, there has been increasing concern of late that vital satellite communication may not be as readily available in a hostile environment. Of particular concern is the degree of communication degradation resulting from jamming of the downlink signal, loss of satellite integrity due to anti-satellite weapons, and degradation of the communication link due to a High Altitude Electromagnetic Pulse (HEMP). While satellites in low to medium altitude orbit are particularly susceptible to anti-satellite weapons, all active satellite communication systems are vulnerable to the destructive effects of HEMP and jamming.

The HEMP effects result from the detonation of a nuclear device within the earth's atmosphere. This detonation releases high energy X-rays and gamma rays. When these energy rays interact with air molecules they produce radially moving electrons and positively charged ions through the Compton effect. These electrons are turned by the earth's magnetic field and create a transverse current density. This in turn produces a fast moving electromagnetic pulse within the line of sight of the nuclear burst. [Ref. 5: p. 5]

Depending on the magnitude of the weapon and the height of burst communication equipment may be damaged or disrupted within a 2,000 mile radius. If a nuclear weapon were to be detonated at an altitude of 500 Km above the center of the United States the EMP effect would blanket the entire country. [Ref. 6: p. 14]

The solid state circuitry that is used in active satellites is particularly susceptible to HEMP damage. While solid state electronics have increased the capabilities and reduced the size of communications systems they are also 1,000 times more vulnerable than the old vacuum tube technology.

B. PASSIVE SATELLITE DEVELOPMENT

As was mentioned at the onset of this chapter the moon was the first operational passive communications satellite. Experimentation in the use of passive communication satellites continued in 1960 with the launch of the Echo I.

In 1963 the Westford experiment was conducted to demonstrate the feasibility of using a large cloud of orbiting metallic strips sized so as to act as half wavelength dipole antennas. This experiment was based on the same principle that is used today in the deployment of "chaff" for electronic countermeasures. These half wavelength dipoles acted as a reflective surface for passive communication signals. The Westford experiment was doomed from the start due to environmental considerations as well as the successful launch of Syncom, the first geostationary satellite. Syncom's success eclipsed the efforts of subsequent attempts at achieving an operational passive satellite system. [Ref. 7: p. 9]

The Westford experiment was followed in 1964 by the launch of the Echo II, a large pressurized balloon that acted as a passive reflector. Finally in 1966 the deployment of the OVI 8, a wire mesh sphere that measured 30 feet in diameter, marked the last experimental effort at producing a passive satellite communication system.

While passive satellites have fallen into disfavor some of their characteristics which were advantageous in the 1960's may still prove to be so today. The supposed advantages include:

- simplicity
- low cost
- survivability in a hostile environment
- ability to operate over a wide frequency range
- simultaneous access by multiple users
- ability to change the operating frequencies, bandwidth and modulation methods once in orbit
- independence from the ionosphere for signal propagation
- resistant to active jamming by hostile forces

The advantages as well as disadvantages will be closely examined throughout the course of this thesis to determine if a passive satellite system may be used effectively in todays strategic environment.

The next few sections will provide a brief description of the Echo I and Echo II systems and then present a description of a new breed of passive communications satellites, PACSAT. A more detailed technical analysis of the PACSAT system will be presented in later chapters.

1. Echo I

The Echo I was designed as a non-stressed spherical system. It was nothing more than an inflatable balloon with a 100 foot diameter. The balloon was placed into orbit in 1960 and was still in orbit in 1965 during the time frame in which the Echo II was tested.

The Echo I was tracked with radar in order to determine its effective backscatter area. Test results indicated that it had a backscatter radiation pattern or radar cross section of 20.6 dB/m^2 as compared to 31 dB for the Echo II. The Echo I suffered from a higher frequency scintillation and a greater signal dispersion than its successor the Echo II.

The overall performance of the Echo I satellite system was dependent upon the surface quality that was presented to a communications or radar signal. This surface quality varied greatly depending upon the surface stress resulting from the satellite's spin and the expansion and distortion that was experienced as a result of thermal stresses. [Ref. 8]

2. Echo II

Echo II was launched on January 25, 1964 into a 800 mile circular orbit with an inclination of 82 degrees. The satellite system was designed to determine how a stressed spherical reflector would perform as a passive communication relay. During the test and evaluation phase one of the key properties that needed to be evaluated was how the satellite's backscatter characteristics or radar cross section affected communications.

a. Physical Characteristics

The satellite was constructed of 106 panels that were composed of intermixed layers of aluminum and Mylar film. The actual structure is depicted in Figure 2.1. [Ref. 8: p. 1]

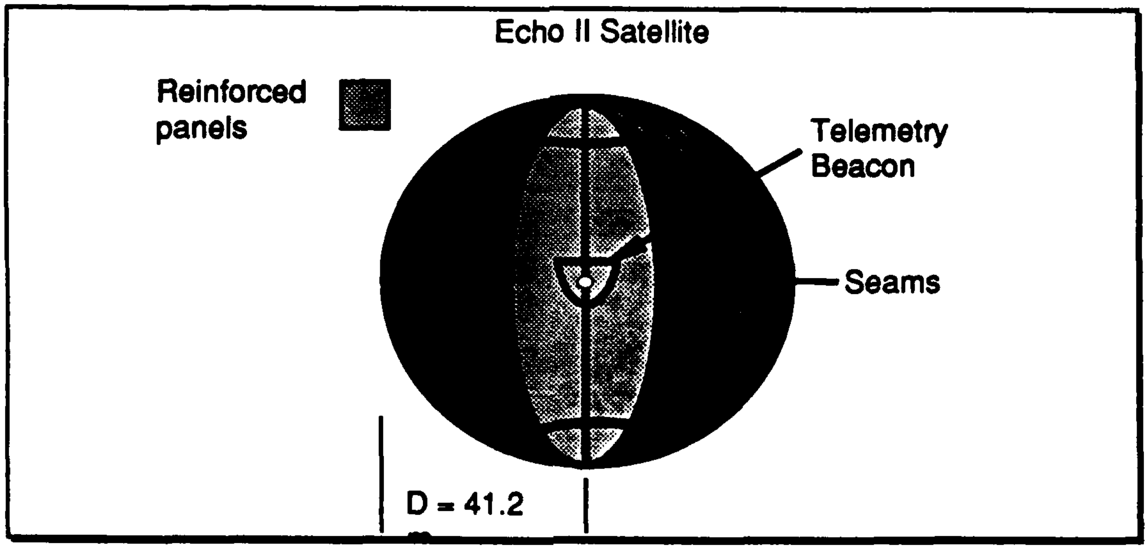


Figure 2.1 Physical Characteristics of the Echo II

During the ground testing phase of the Echo II experiment the balloon was inflated from ambient surface pressures up through 12,000 psi. Measurements of the radar cross section were then taken at 1.7 and 5.85 GHz. It was determined that once launched the satellite would achieve a Radar Cross Section (RCS) of 30 dB.

b. *Operating Characteristics*

Once the Echo II was launched it was tracked by 18 radar facilities to determine its operational RCS. The radar facilities tracked the satellite over a frequency band ranging from VHF up through 10 GHz. Measurements were then taken of the fading rate at a specified carrier frequency as well as the scintillation and RCS.

While the satellite was designed to be stressed in the range of 5,000 to 6,000 psi it was only able to achieve a pressure of 1,000 psi after launch. This resulted in a higher scintillation level than was originally calculated. As was the case with the Echo I the electromagnetic characteristics of the returned signal were dependent upon the surface quality of the satellite.

Empirical data showed a periodic drop in the RCS. It was determined that this drop was the result of an unexpected rotation of the satellite with a spin period of approximately 100 seconds. Additionally the observed scintillation was evaluated as being caused by the reduced skin stress and surface distortions that were caused by the balloon's rotation. [Ref. 8: p. 18]

The fading rates that were calculated were based upon the operation of a high quality voice communication system with a 20 KHz bandwidth. The system parameters were such that it required a signal to noise ratio of 25 dB to operate successfully under FM modulation. The receiving and transmitting antenna had a diameter of 60 feet and the transmitter power (P_t) was rated at 1 Kw. With this configuration the minimum RCS capable of supporting a 25 dB signal/noise figure was a function of the transmission frequency and was approximated by:

$$\sigma_m \approx 10^3 \lambda^2 \qquad \text{(eqn 2.1)}$$

The fading rate, which is defined as the percentage of time that the RCS is below σ_m is summarized in Table 3 [Ref. 8: p. 20]

TABLE 3
FADING RATE

Carrier Frequency	Fading Rate (60 ft. antenna)	Fading Rate (40 ft. antenna)
0.3 GHz	76%	90%
2 GHz	3%	8%
5 GHz	0.05%	0.5%

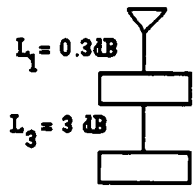
Based upon this the satellite was evaluated to be able to act as an effective communications relay system with frequencies greater than or equal to 2 GHz while employing frequency modulation techniques. Its performance was reduced by scintillation induced noise when amplitude modulation techniques were employed.

c. Communication Test Results

From 21 February to 8 March 1964 a communications experiment was conducted using the Echo II satellite for a communications relay between the Jodrell Bank Observatory in the United Kingdom and Zimenki in the Soviet Union. Based upon a one Kw transmitter operating at a carrier frequency of 162.4 MHz calculations prior to the experiment indicated that the received signal to noise ratio (SNR) should be about 12.2 dB above the receiver threshold. The experiment configuration and calculations are shown in Figure 2.2. [Ref. 8: p. 24]

ASSUMPTIONS: Jodrell Bank Transmits: 1Kw @ 162.4 MHz.
Zimenki receives.

T_R = 423°K = Antenna System Temperature



Paramplifier NF = 3.5dB
G = 20 dB

Receiver NF = 5.3dB (700°K)

T_G = Galactic Temperature

$$\text{Total System Temperature } T_s = T_R + T_G = 423°K + 450°K$$

$$T_s = 873°K$$

SYSTEM PERFORMANCE

Space Loss (2400mi)	- 245.3 dB
P_t (1Kw)	30.0 dBw
G_t (250')	39.5 dB
G_r (45')	24.8 dB
CARRIER LEVEL	- 151 dBw

Total System Noise T (873°K)	29.42 dB
Noise Power Density	- 228.6 dBw/MHz
Noise Power	- 199.18 dBw/MHz

Bandwidth (1KHz)	30.0dB
Noise Level	- 169.18dBw in 1KHz Bandwidth

CARRIER/NOISE (1KHz)	- 169.18 - 151 = 18.18 dB
RECEIVER THRESHOLD 6DB	6.00 dB
CARRIER/NOISE (1KHz)	12.18 dB MARGIN

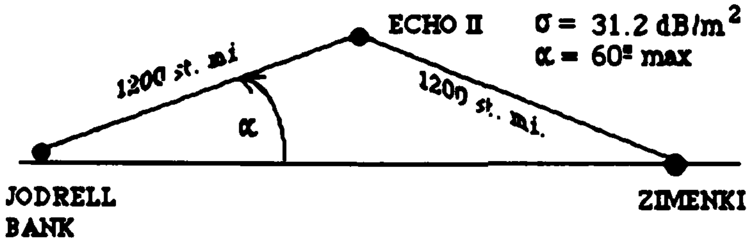


Figure 2.2 Echo II Expected Performance

While expected SNRs were nominally achieved there was considerable variation in signal quality due to scintillation. Best results occurred when both the transmitter and receiver antennas were at maximum elevation angles. Signal degradations became more evident when transmission occurred at low elevation angles and during multipath reception.

C. PACSAT: A NEW DESIGN IN PASSIVE SATELLITES

The Passive Communications Satellite is not an operational satellite system. PACSAT is a research project whose purpose is to design and evaluate a constellation of passive communication satellites. The project is sponsored by the Strategic Technology Office of the Defense Advanced Research Projects Agency (DARPA) and it is being conducted by the Rand Corporation. [Ref. 7]

The following is a brief description of the proposed mission and operational characteristics of the satellite. A detailed discussion concerning the link parameters and path calculations will be presented in later chapters.

1. Mission

The proposed mission for this satellite system would be strategic in nature and categorized as being point-to-multipoint or broadcast in application. PACSAT would be used to augment the existing Minimum Essential Emergency Communication Network (MEECN). Its primary mission would be to transmit an Emergency Action Message (EAM) from the National Command Authority (NCA) to the various Single Integrated Operational Plan (SIOP) forces.

Some of the existing MEECN systems include the Emergency Rocket Communication System (ERCS), the SAC Digital Network (SACDIN) and, the Air Force Satellite Communication System (AFSATCOM). As part of the MEECN system PACSAT would be expected to provide reliable communications in a hostile environment under conditions of active jamming and possible ionospheric disturbances resulting from a nuclear burst.

2. Description

The Passive Communication Satellite is envisioned as being totally passive without any capability of amplifying or processing the received signal. In order to maintain its passive qualities orbital stability will be attained by using the earth's gravity gradients. This will eliminate the need for the transmission of any corrective Tracking, Telemetry and Control (TTC) signal from the earth stations or the satellite.

PACSAT will operate predominantly within the SHF frequency band with a nominal carrier frequency of 8 to 10 Ghz. It will employ frequency hopping over a 360 MHz band of the communications spectrum in order to both steer the return signal and provide jamming resistance. The signal which is returned by the satellite is in the shape of a hollow cone or annulus. One is able to steer the annulus and thereby move the satellite antenna's footprint by selecting the appropriate frequency. The configuration if this return signal is depicted in Figure 2.3. [Ref. 9: p. 2]

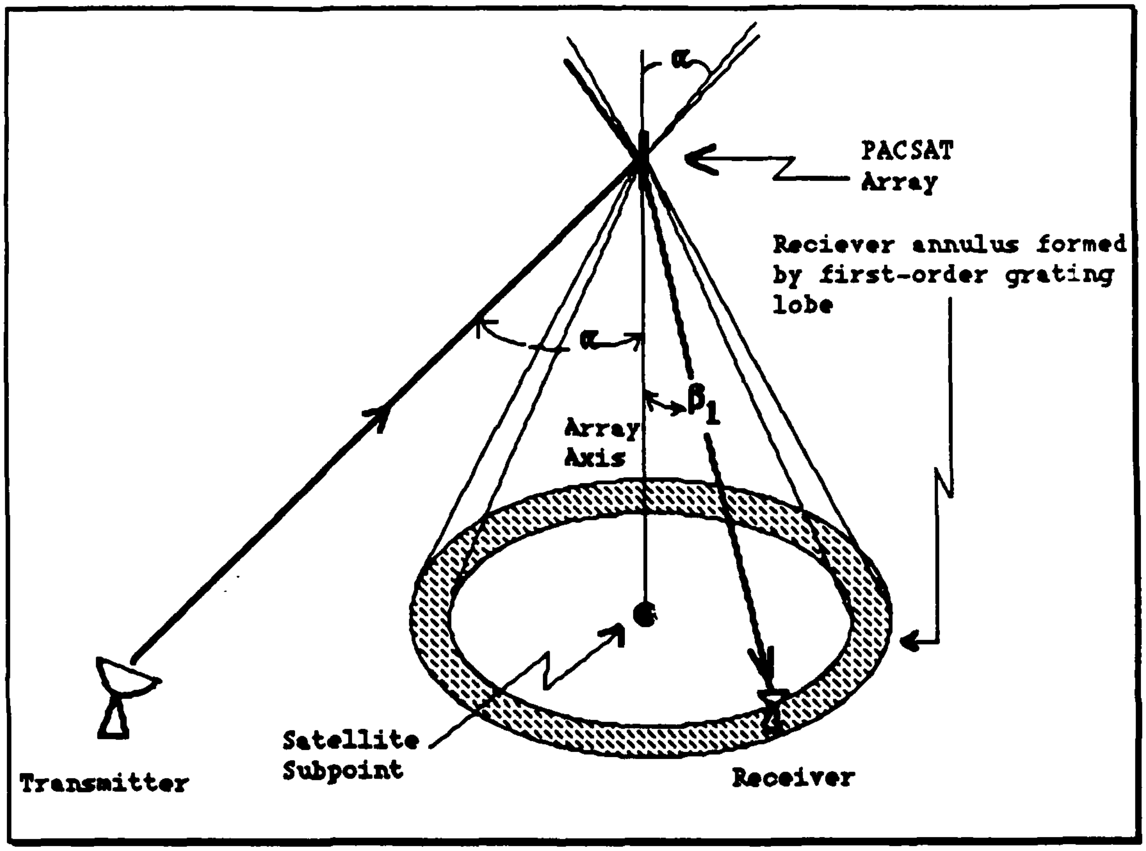


Figure 2.3 PACSAT Link Configuration

The satellite array consists of a long string of spherical scattering elements. Both the size and number of these elements are chosen so as to enhance the backscattering characteristics and therefore the directivity and gain of the entire array. The array may vary in length from 154 meters to 1.5 Km. It may be divided into as few as 100 or as many as 1000 sections each of which is about 1.5 meters long.

3. Orbital Placement

The altitude at which the satellite is placed in orbit will depend upon several factors:

- acceptable signal loss due to propagation
- desired area of coverage
- number of satellites within the constellation
- propagation time
- satellite tracking capabilities of intended earth receivers

The predominant criteria for a passive communication system is the amount of propagation loss which may be sustained without reducing the communication reliability. Because of this PACSAT will not be in geostationary orbit and will most likely operate at an altitude of between 6,000 and 10,000 Km.

The rate of transmission will be predicated upon the acceptable bit error rate for the received message. Generally the slower the transmission rate the better the quality of the received signal.

4. Comparison with Active Satellites

Due to advances in electronic miniaturization, increasingly more complex on board signal processing capabilities have been incorporated into active satellite designs. The increased capabilities of active satellites has decreased the required complexities of earth bound receivers while at the same time reducing the per circuit-year operating costs.

These advances have not come without cost. Due to the sensitivity of the electronic components the satellites have had to be hardened both physically and electronically so as to survive in a hostile environment. Passive satellites, due to their simple design, are less susceptible to physical attack than their active counterparts. Additionally a high altitude electromagnetic pulse will not incapacitate a passive satellite.

Uplink jamming is a significant concern for active satellite systems. Not so for passive satellites. Because a passive system does not amplify the received signal it will not be susceptible to saturation or intermodulation of the traveling wave tube amplifiers (TWTA). The circuit elements are basically linear and hence resistant to uplink jamming. [Ref. 10: p. 2]

Due to the absence of active components, the PACSAT system enjoys the advantages of simplicity, economy, survivability, and reliability. Additionally since there are no active components to wear out or to degrade as a result of radiation damage the passive system should experience an extended operational life.

One of the most significant disadvantages for any passive communications satellite is the weakness of the returned signal. As was stated earlier, this reduced signal strength will affect the design of the satellite's orbit, area of earth coverage and the speed at which the message may be transmitted. These limitations will in turn be a major factor in determining the mission for which this communications platform is best suited.

III. NUCLEAR EFFECTS UPON ELECTROMAGNETIC PROPAGATION

The effectiveness of any military communication system must be evaluated in light of the worst case scenario. Of particular concern is the system's reliability and survivability in a hostile environment. If a passive or active satellite communication system is to operate reliably it must be able to function in an environment stressed by a nuclear detonation.

This chapter will describe some of the environmental perturbations caused by the detonation of a nuclear weapon within the earth's atmosphere. Of particular interest will be the changes in the ionosphere's electron density and ionization level and how this variation from the norm affects the communication spectrum. This chapter will also stress the effects of increased absorption and thermally induced noise upon a satellite link.

While the majority of the existing satellites operate in the SHF band this chapter will explore the possibility of using the HF band for satellite communications. Specifically it will examine the deterioration of the HF band due to increased ionization in both the traditional ionospheric propagation mode as well as a possible satellite communication path.

The majority of the information in this chapter dealing with the analysis and effects of a nuclear blast was derived from Glasstone's book, "The Effects of Nuclear Weapons" [Ref. 11].

A. ELECTROMAGNETIC PULSE

While this chapter is primarily concerned with propagation problems a related affect that is also caused by the detonation of a nuclear weapon within the atmosphere is the generation of an electromagnetic pulse (EMP). This pulse is caused by the prompt release of high energy X-rays and gamma rays. When these high energy rays interact with the surrounding air molecules they produce radially moving electrons and positively charged ions through the Compton affect. These electrons are turned by the earth's magnetic field and create a transverse current density. This current produces a fast moving electromagnetic pulse which can attain a peak energy of about 50 Kv/m within 10 ns [Ref. 5: p. 5].

The EMP poses a threat to satellite communications as it can be coupled to exposed antennas. Once this strong current has been collected by the antenna it may then be transmitted to the receiving equipment via the various power and transmission lines. These cable transients may then cause disruption and/or destructive currents and voltages at the connection pins of the receiving equipment.

Since the main thrust if this chapter deals with propagation problems and due to the scope and complexity of EMP it will not be discussed in any further detail. Also, latter chapters will show that EMP is less of a problem for passive satellites than for active ones.

B. CLASSIFICATION OF A NUCLEAR BURST

Before getting into a detailed description of the effects of a nuclear blast the three classifications of a nuclear burst will be described. Each category will be discussed in light if its ability to generate an electromagnetic pulse.

1. Surface Burst

If the weapon detonation takes place within 2 Km (1.2 mi.) of the earth's surface it is classified as a surface burst. In this situation the range and intensity of the Electromagnetic Pulse will be greatly curtailed due to the absorption of the gamma rays by the earth's surface. The Compton electrons will only travel a short distance in the air before they are absorbed. However, the earth will act as an alternate transmission path for this electron field. The magnitude of this field is inversely proportional to the distance from the blast. Ranges will be dependent upon weapon yield but are generally restricted to 3-6 Km.

Communication interference will occur in the area surrounding the mushroom cloud due to the presence of suspended particulate matter. The suspended debris will tend to disrupt the upper frequency spectrum, VHF and UHF [Ref Hill, C: HEMP paper]. Additionally the sudden release of large amounts of thermal radiation results in an increased ionization of the surrounding atmosphere. This results in increased absorption of the lower communication frequencies [Ref. 11].

2. Air Burst

An air burst will be produced when detonation occurs within 2 - 20 Km (1.2-12.4 mi.) of the earth's surface. Due to the relatively high air density within this altitude range, gamma rays and Compton electrons will only travel short distances. The net EMP effect is even less than that in the surface burst scenario due to the fact that the earth no longer provides a transmission path for the free flowing electrons.

As in the previous case communication difficulties arise when the transmission path traverses the area of the burst [Ref Hill, C: HEMP paper].

3. High Altitude Burst

A high altitude burst is the result of a weapon detonating 20 Km or more above sea level. When the gamma rays which are emitted in a downward direction encounter regions of denser atmosphere (at about 20 Km) Compton electrons are produced.

Detonation of a large yield nuclear weapon above 20 Km will produce the most sever EMP effects.

C. IONOSPHERIC EFFECTS

The effects of a nuclear blast on a satellite communication system is a function of the blasts yield, altitude, distance from the communication path and the time after the detonation. The geometry between the detonation site and the communication path also comes into play. The severity of signal attenuation is not only affected by the distance from the blast site but also by the number of times that the propagation path intersects the disturbed regions of the ionosphere.

The effects of a nuclear detonation are not homogeneous throughout the ionosphere. There is a great deal variability due to the different levels of ionization within the various regions or layers of the atmosphere. These layers are discussed below.

1. Ionospheric Layers

The various layers within the ionosphere have been designated D, E, F_1, F_2 and have been categorized according to their maximum levels of ionization. The ionization within a docile environment is primarily due to high energy ultraviolet radiation from the sun striking the upper regions of the atmosphere and liberating electrons and positive ions from the air molecules. Under normal conditions the electron density varies inversely with the angle of the sun with greater levels of ionization occurring at equatorial latitudes. The ionization level is also a function of the sunspot cycle and the solar flare activity. The ion density is greater for all layers during the daylight hours. As we will see the ion density is primarily responsible for the attenuation or refraction of an incident electromagnetic wave.

The D region is the closest layer to the surface of the earth with an average altitude of 70 to 90 Km above sea level (ASL). The level of ionization in this region is dependent upon the angle of incidence of the sun and is therefore at a maximum at local noon and disappears during the night. As can be seen from Figure 3.1 [Ref. 11: p. 463] the D region has the smallest electron density of any of the other layers. Under normal atmospheric conditions this region will affect the communications spectrum by absorbing low frequency signals. However, with certain combinations of weapon yield and detonation altitude, this region will experience a large change in electron density.

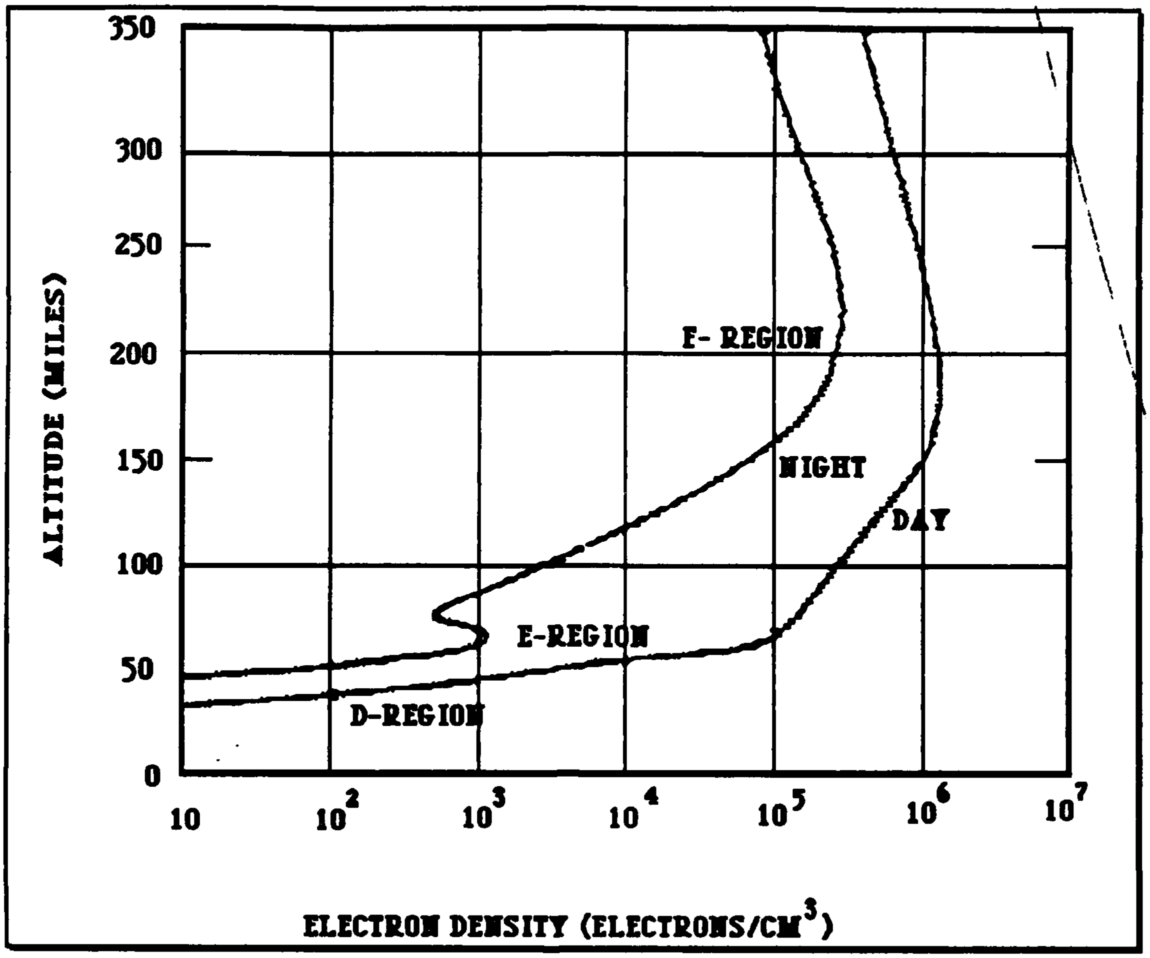


Figure 3.1 Electron Densities in D, E and F Regions

The E layer is the next region in the ionosphere and varies in altitude from 100 to 200 Km. It has a higher level of ionization than the D layer but it too is highly dependent upon the sun's activity and demonstrates distinct seasonal and diurnal changes. Its maximum ionization occurs at local noon and will dissipate shortly after sunset.

A transitory phenomena known as the Sporadic E may also occur. The exact causes for the Sporadic E layer are not known but it has been associated with large squall line thunderstorms, meteor showers, and auroral substorms. The Sporadic E is an area of very high electron density which may extend over hundreds of kilometers. On occasion a Blanketing Sporadic E layer may develop an electron density high enough to prevent electromagnetic transmissions from reaching the F layer above it. [Ref. 12: p. 22]

The highest layer, designated as the F layer, extends upward from about 300 Km. However, during the day the ionization level increases to the point that it separates into two distinct layers. The lower layer, the F_1 layer starts at about 175 to 250 Km while the upper layer, F_2 starts at about 300 Km ASL. The actual altitude of the F_2 layer varies with the season and is actually higher in the summer than the winter. The two layers combine at night at a lower altitude of about 150 to 250 Km.

As can be seen from Figure 3.1 the F layer contains the greatest electron density. The electron density at the Control Point, that region of the ionosphere that is encountered by a transiting electromagnetic wave, is responsible for the refraction of some HF band transmissions below a specified critical frequency.

2. Scintillation Affects

Scintillation is caused by a non homogeneous ionosphere and irregular F region. These irregularities result from disturbances in the ion density that align themselves along the earth's magnetic lines of flux. The disturbances are roughly cylindrical in shape with diameters of 100 to 1000 feet and may affect an area of the ionosphere from 25 to 2000 miles in diameter [Ref. 13]. In the presence of scintillation electromagnetic signals experience random variations in both amplitude and phase. This results in an enhancing and fading effect upon HF, VHF, and UHF transmissions.

Under normal atmospheric conditions scintillation is a function of the latitude, season, time of day and sun spot activity. The most pronounced effects occur approximately one to two hours after sunrise with activity increasing during the spring and fall equinox. As we will see, the focusing and defocusing of the electromagnetic spectrum due to scintillation may also be produced by a nuclear detonation.

3. Prompt Radiation

As much as three quarters of the energy released by a nuclear detonation is expended by ionizing the surrounding atmosphere. Ionization may be caused by the interaction of surrounding atmosphere with the gamma rays, neutrons or X-rays that are released at the onset of the nuclear burst. It may also result from residual radiation that is released from beta particles, gamma rays and, positive ions from the weapon debris itself. The ultraviolet component of thermal radiation will also cause an increase in the ionization surrounding the fireball. [Ref. 11: p. 466]

The increased ionization will gradually dissipate in one of two ways, attachment with neutral particles or recombination with other ions. Attachment is the primary means of dissipation at lower altitudes where neutral particles, primarily molecular oxygen, are in greater abundance. For surface bursts and low altitude air bursts the relatively high air density prevents the widespread dispersal of atomic debris thereby containing the ionization levels. Free ions in the upper atmosphere are removed by combining electrons with positive ions.

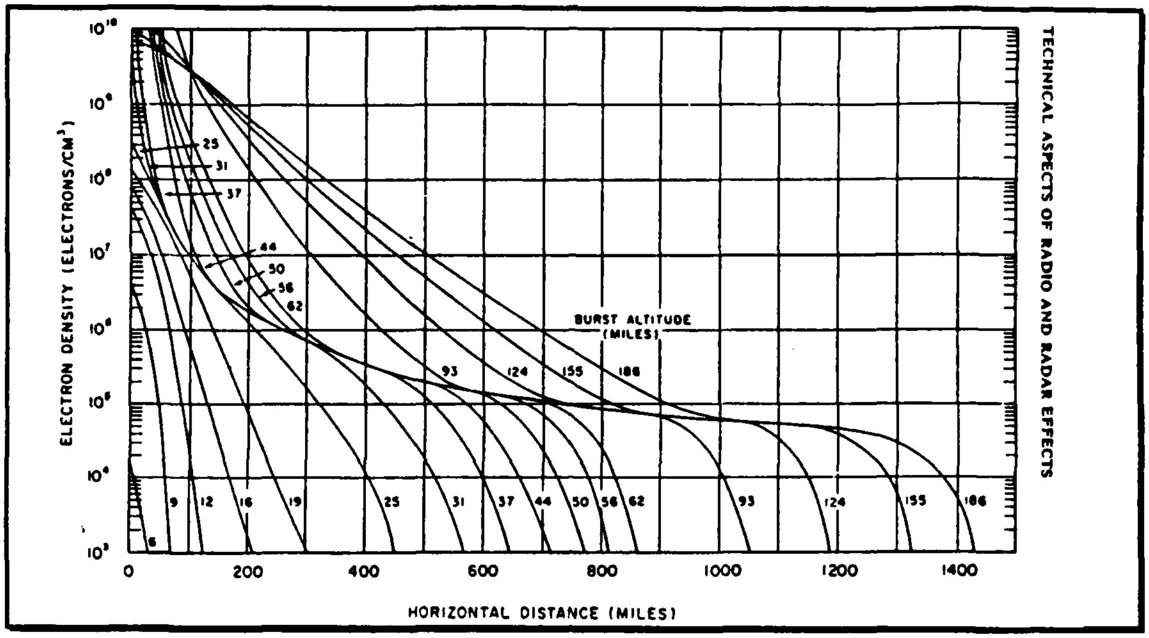
The electron density of the D layer will increase dramatically if the ionizing radiation and the positive ions of the weapon debris can reach its altitude. Because of its low atmospheric density and the dearth of positive ions within the D layer the resulting ionization will dissipate very slowly. The greatest effects will be evident in a 10 mile band centered around an altitude of 40 miles ASL.

The primary components of prompt radiation are X-rays which account for 70% of the explosive energy released as prompt radiation and neutrons which account for 1% of the energy; a negligible portion (3/10%) are the result of gamma rays. This in turn will produce a total electron density (N_e) which may be approximated by equation 3.1. [Ref. 11: p. 496]

$$N_e \approx 2.4 \times 10^{18} \left[\frac{kW}{D^2}\right] \rho F(M) \qquad \text{(eqn 3.1)}$$

In equation 3.1 the weapon yield in kilotons is designated as W, D is the distance of the observation point from the detonation, ρ is the air density in grams per cubic centimeter, k is the energy constant associated with the type of radiation (i.e. 0.7 for X-rays) and F(M) is the effective mass absorption coefficient which is a function of the radiations penetration mass (the air mass per unit area that lies between the blast and the observation site).

Figure 3.2 [Ref. 11: p. 499] shows the result of equation 3.1 once the electron densities (N_e) have been summed for the various types of radiation energy. The electron densities shown are for the D region (approximately 40 miles ASL) of the ionosphere and are the result of the prompt radiation produced by a one megaton blast detonated at the altitudes indicated alongside the various curves.



TECHNICAL ASPECTS OF RADIO AND RADAR EFFECTS

Figure 3.2 Electron Density From Prompt Radiation

As can be seen in equation 3.1 the electron density resulting from prompt radiation is directly proportional to the yield (W) of the weapon. With this in mind once the burst altitude and the horizontal distance from the burst site have been established, the N_e can be derived from Figure 3.2 for any size yield.

For example, if a 500 kiloton blast is detonated at an altitude of 20 miles to what extent will the D layer experience an electron density equal to 10^5? The desired N_e must first be scaled by the appropriate weapons yield as is shown in equation 3.2.

$$N_e(1MT) = \frac{N_e(W)}{W} = \frac{10^5}{0.5} = 2 \times 10^5 \text{ electrons/CM}^3 \qquad \text{(eqn 3.2)}$$

Entering Figure 3.2 with the value from equation 3.2 we see that it intersects the curve approximating the 20 mile burst altitude at approximately 190 miles. [Ref. 11: p. 498]

While the normal electron density for the D layer is approximately 10^3 electrons/CM^3 during the day and zero at night, Figure 3.2 shows that N_e can attain levels in excess of 10^9 electrons/CM^3. N_e values in excess of 10^4 are sufficient to cause increased attenuation of the electromagnetic spectrum.

The rate at which the electron density is removed from the D region may be approximated by the following equations [Ref. 11: p. 501]:

$$N_e(t) \text{ at 40 miles} \approx \frac{1}{3}\left[\frac{N_e(0)}{1 + 10^{-7}N_e(0)t}\right] \text{(daytime)} \qquad \text{(eqn 3.3)}$$

$$N_e(t) \text{ at 55 miles} \approx \left[\frac{N_e(0)}{1 + \{2 \times 10^{-7} N_e(0)t\}}\right] \text{(nighttime)} \qquad \text{(eqn 3.4)}$$

As can be seen from the above, the electron density remaining is inversely proportional to the product of the initial electron density, $N_e(0)$ and the elapsed time in seconds after the burst. The result of equations 3.3 and 3.4 is that regardless of the value of $N_e(0)$ the electron density in the D region caused by prompt ionization will drop below 10^3 electrons/cm^3 within three hours of the blast. This relationship is depicted in Figure 3.3. It must be stressed that Figure 3.3 shows the ionization decay resulting only from the prompt radiation effects. It does not take into account the affects of delayed radiation. [Ref. 11: p. 503]

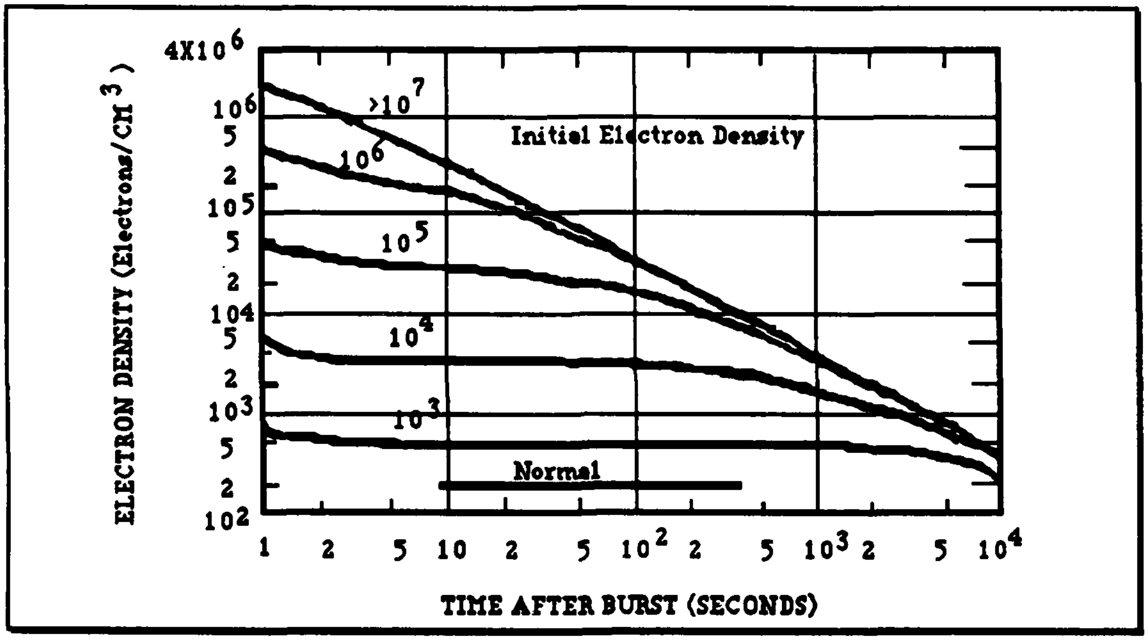


Figure 3.3 Electron Density Decay

The burst altitude will determine to a large extent the degree to which the various atmospheric layers are affected by prompt radiation. If an air burst occurs below 10 miles altitude the majority of the blast energy will be deposited within the vicinity of the fireball. This will cause the electron density within the fireball to exceed 10^9 electrons/cm^3 for up to 3 to 4 minutes. Temperatures in excess of 2,500°K will also cause thermal ionization of the surrounding atmosphere. The D region will remain unaffected by prompt radiation. This is due to the fact that the burst is well below the stopping altitude of X-rays (35-55 miles), and neutrons and gamma rays (15 miles). Any ionization of the D region at this burst altitude will be due to the effects of delayed radiation.

With a nuclear detonation occurring between 10 to 40 miles altitude the X-rays produced by the prompt radiation will primarily be confined to the fireball. Ionization of the surrounding atmosphere and the D region will be caused by the release of neutrons. The fireball itself will be ionized to a level of 10^7 electrons/cm^3 for up to 3 minutes. The area affected by this level of ionization will be greater than in the previous case but its spread will be limited by the curvature of the earth. For example a one megaton blast detonated at 40 miles ASL will produce an electron density of between 10^4 and 10^5 electrons/cm^3 up to a horizontal distance of about 550 miles [Ref. 12: p. 33].

If the burst altitude is between 40 to 65 miles X-rays will cause the majority of the prompt radiation. This is due to the fact that the blast altitude is greater than the stopping distance for X-rays. Since X-rays account for up to 70% of the energy released by prompt radiation the D region will be affected to a much greater extent.

At burst altitudes in excess of 40 miles the E region will be irradiated by the X-rays released from the prompt radiation. This will result in the rapid ionization of the E region with a rather prolonged recovery time. The overall effect will be similar to the sporadic E mentioned above.

4. Delayed Radiation

Delayed radiation is the result of energy being emitted in the form of beta and gamma radiation from the radioactive debris of the nuclear explosion. This delayed radiation will then proceed to cause an increase in the ionization of the surrounding atmosphere in much the same manner as described above. The duration of the ionization as well as the area affected is dependent upon the yield and the burst altitude of the weapon.

If the burst altitude is below 10 miles the cloud of radioactive debris will remain fairly close to the fireball. Due to the high air density in this region of the atmosphere the life expectancy of free electrons is short. This is primarily due to their high rate of attachment to neutral particles. Upper regions of the ionosphere are not affected unless the fireball pushes the radioactive debris above the 15 mile stopping altitude of gamma radiation. If this should occur then there would be an increase in the D layers ionization.

Delayed radiation becomes significant if the burst altitude is between 10 to 40 miles. At this altitude the atmosphere is thin enough so that the fireball can propel radioactive debris up to 20 miles above the blast point. The radius of the debris cloud will then increase at a rate of approximately 100 miles per hour [Ref. 14: p. 285].

If the debris is below 35 miles gamma rays will be the primary cause for the ionization of the D layer. Below this altitude the secondary source of delayed radiation, beta particles, are prevented from expanding beyond the debris area.

Once the debris reaches an altitude in excess of 40 miles the electrically charged beta particles will spiral along the earth's geomagnetic field into the opposite magnetic hemisphere and irradiate the conjugate area of the ionosphere. The total level of ionization caused by the beta particles is equally distributed between the blast site and the conjugate area. Meanwhile gamma rays are not restricted by the earth's magnetic lines of flux and will continue to spread about the blast site. The ionization caused by the gamma radiation is less intense than the beta particles and dissipates with increased altitude. This situation is depicted in Figure 3.4 [Ref. 11: p. 473].

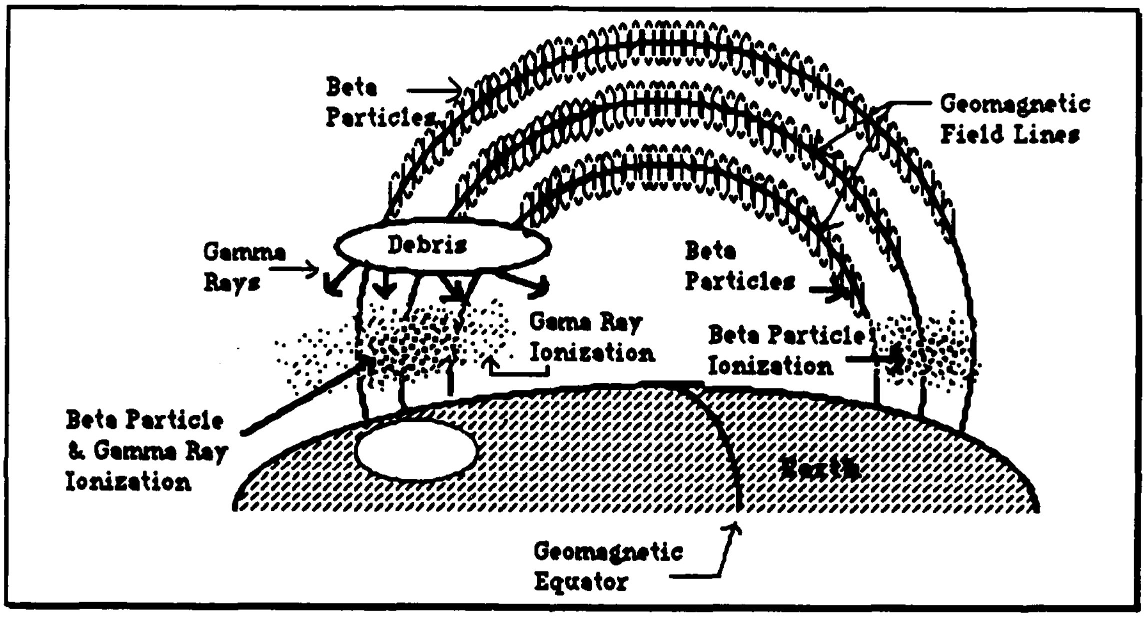


Figure 3.4 Dispersal of Beta Particles

As the beta particles are spread along the earth's magnetic lines they cause irregularities in the surrounding ionosphere. These irregularities will form arcs or tubes of varying electron densities similar to those resulting from the natural forces that can create scintillation affects.

If the detonation occurs above 70 miles radioactive debris can be propelled hundreds of miles above the blast point. At extreme altitudes the electrically charged debris can cause the geomagnetic field to stretch before it. The debris may continue to expand for hundreds of miles before it is stopped by the pressure of the magnetic field. It will then proceed to fall and irradiate the D region from above. Additionally beta particles which have been trapped by the earth's magnetic field will continue to irradiate the area between the blast site and the conjugate area. As these field lines move eastward they will within a few hours form a shell of high energy beta particles (electrons) around the entire earth [Ref. 11: p. 478].

The rate at which the electron density is dissipated is dependent upon the time of day and the altitude and yield of the weapon. In general the electron density will be higher for a blast that occurs during the day than at night. Additionally while the area affected is larger for a high altitude burst (40 - 70 miles) the electron density of the D region is less than would be the case if the burst altitude was between 10 to 40 miles. Figures 3.5 and 3.6 show the electron density of the D region and the debris radius over time for a one megaton explosion [Ref. 12: p. 36]. In Figure 3.5 the blast altitude is in the range of 10 to 40 miles and in Figure 3.6 the blast altitude is between 40 and 70 miles.

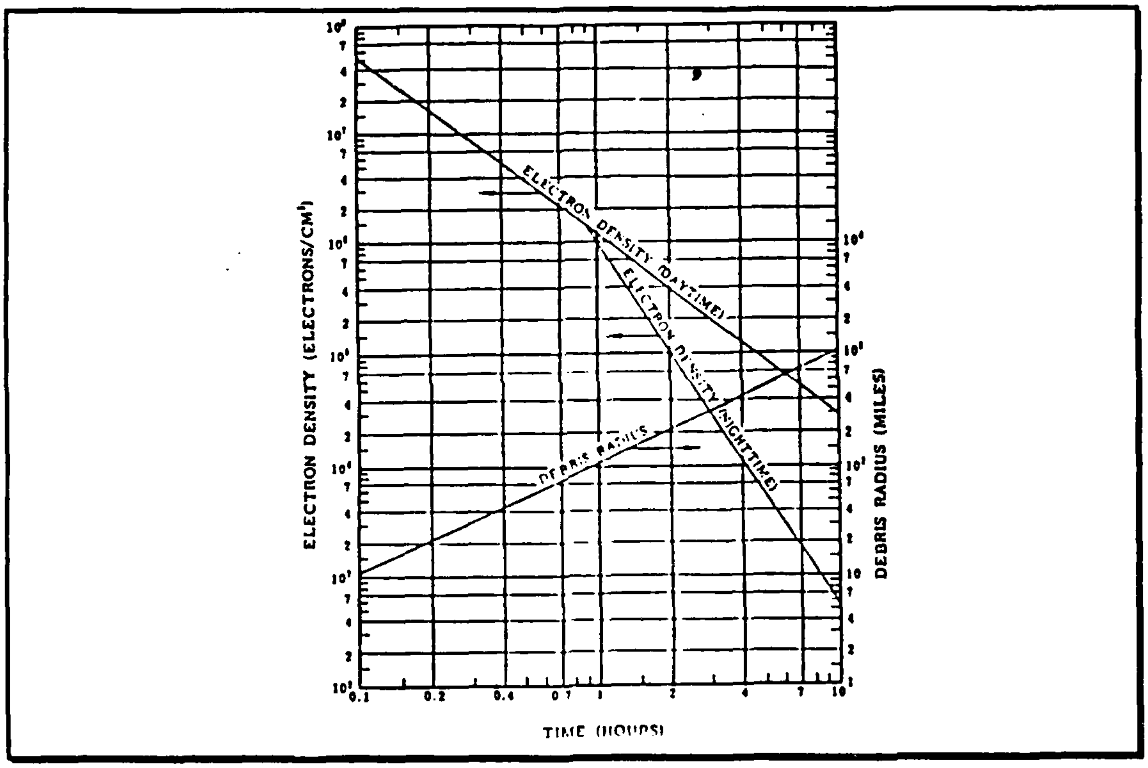


Figure 3.5 Delayed Radiation Affects on D Region Burst 10-40mi.

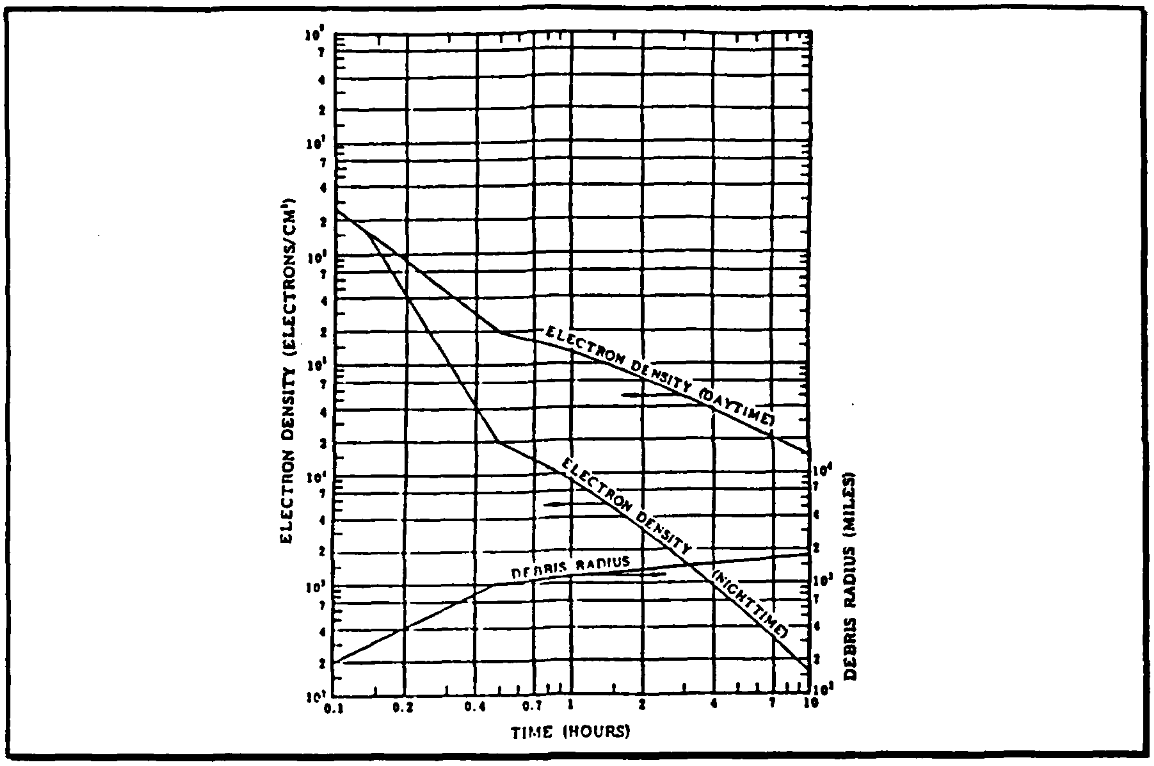


Figure 3.6 Delayed Radiation Affects on D Region Burst 40-70 mi.

Direct ionization is not the only means by which the ionosphere's electron density may be affected. The hydrodynamic (shock) and hydromagnetic effects of a nuclear blast will change the electron density of the E and F region of the atmosphere. As the shock wave propagates through the atmosphere it ionizes the surrounding air. During the compression stage of the shock wave the electron density increases due to the decreasing volume. However as the air expands due to the heating caused by compression, an expansion phase may cause the electron density to be reduced below normal levels. This was evident during the TEAK megaton range burst that was detonated at an altitude of 40 miles. As the shock waves from the blast encountered the E and F regions the electron density was observed to first increase and then decrease below normal until after sunrise. [Ref. 11: p. 478]

D. EFFECTS UPON THE COMMUNICATION SPECTRUM

A nuclear blast will have several debilitating effects upon the communications spectrum. Foremost of these is attenuation via absorption. There will also be an increase in both the level of atmospheric noise and the degree of refraction and scattering of the communication signal.

1. Noise

Thermal radiation from the nuclear blast is the primary cause for the increased atmospheric noise. The temperatures generated around the fireball may remain in excess of 1,000º K for several minutes. This may result in a significant contribution to the overall system temperature (noise level) of a low temperature satellite receiver system particularly if the directive antenna is aimed at the region of the fireball.

A secondary source of atmospheric noise is synchrotron radiation. This radiation is the result of beta particles that are trapped along the earth's magnetic lines of flux. As these particles travel between the conjugate and the blast site they will generate synchrotron radiation at right angles to their line of propagation. The intensity of this radiation is inversely proportional to frequency. While less intense than thermal radiation, synchrotron radiation noise may cause significant deterioration of low frequency communications systems. [Ref. 11: p. 480]

2. Refraction and Scattering

According to Snell's law as an electromagnetic wave passes through a plane of differing densities it will be refracted back toward the area of higher density. The index of refraction (n) is inversely proportional to the velocity of the electromagnetic wave through a medium. The index of refraction has been defined as unity in a vacuum and approximately 1.0003 for normal ambient air. This index may be approximated by equation 3.5 [Ref. 11: p. 493]

$$n \approx \left[1 - \frac{N_e}{10^4 f^2}\right]^{1/2} \qquad \text{(eqn 3.5)}$$

As can be seen from the above n is directly proportional to the electron density and inversely proportional to the square of the frequency. In a highly ionized atmosphere this may result in n being significantly less than unity. In such a situation the electromagnetic wave will be refracted back toward the region of higher n. If the satellite uplink frequency passes through a heavily ionized region of the D layer it may be refracted back toward the surface of the earth. The same situation may arise with respect to the satellite downlink frequency. Since the satellite downlink is normally transmitted at a lower frequency it is more susceptible to changes in the index of refraction. In extreme cases this reduced index may result in the downlinked frequency being bent back toward free space. The net result will be a shadow zone around the D layer. This area would be relatively impermeable to certain radio frequencies due to its low index of refraction (high electron density). Such a shadow zone is depicted in Figure 3.7.

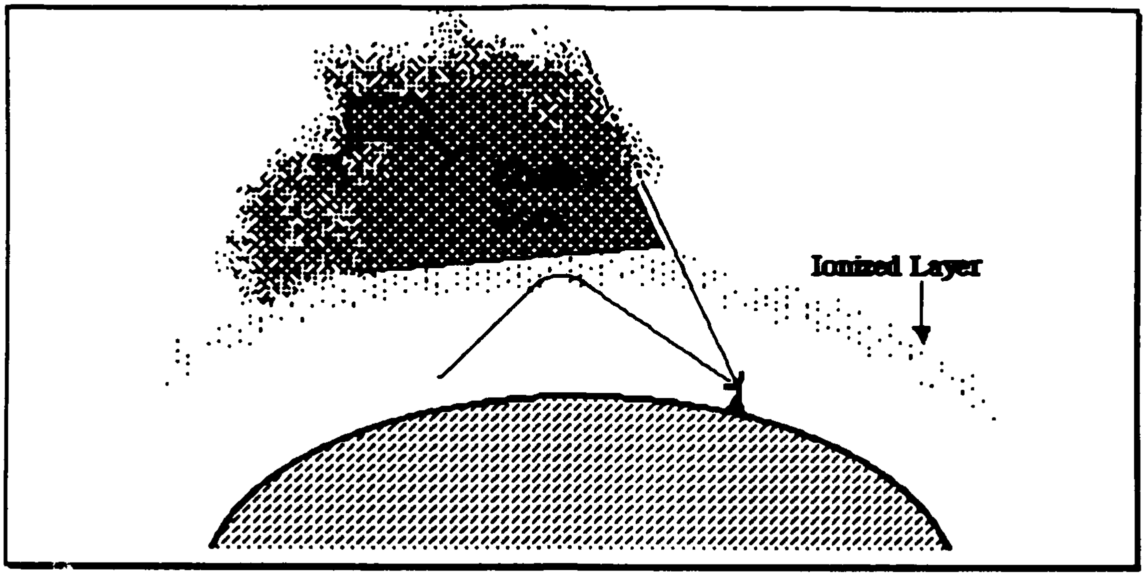


Figure 3.7 Shadow Zone

Equation 3.5 may be manipulated so as to determine the highest frequency which will be refracted by a given electron density. This critical frequency in megahertz is approximated by equation 3.6 [Ref. 11: p. 493].

$$f_{cr} \approx 10^{-2}\sqrt{N_e}\sec\phi \qquad \text{(eqn 3.6)}$$

Where ϕ is the communications transmission angle measured from the vertical. The critical frequency increases as the transmission angle is displaced from the vertical . This is significant for terrestrial communications systems and satellite systems that are not in geosynchronous orbit.

The critical frequency is also directly proportional to the electron density. As the electron density increases due to either prompt or delayed radiation a larger portion of the communication spectrum will be refracted back toward the surface of the earth. Even if the electron density is not sufficient to totally refract the electromagnetic wave back toward the surface of the earth it may be high enough to bend it from its original path. This may result in an increased pointing error and a reduced signal to noise ratio in satellite communication systems.

The D layer may become so ionized that HF frequencies which are normally refracted at the much higher F layer may in fact be refracted at the lower altitude of the D layer. This reduced refraction altitude will cause a disruption of established terrestrial communications systems.

After a nuclear detonation the increase in electron density is not distributed uniformly throughout the affected area. As was mentioned above the immediate area of the burst will be affected by prompt radiation and the thermal radiation within the fireball and will therefore exhibit the highest electron density. Areas surrounding the blast site as well as the conjugate area will be affected by the rate of dispersal of the radioactive debris. These irregularities in the electron density may result in the scattering of the communications signal. If the signal's propagation path traverses areas of varying electron density the signal may be refracted to varying degrees resulting in the scattering of the signal and a reduction of the overall signal strength. Scattering will often occur when the signal's transmission path passes through one of the earth's magnetic lines of flux which have been charged by the spiraling beta particles depicted in Figure 3.4. When this occurs the signal will undergo random changes in amplitude and phase similar to the scintillation effect discussed earlier.

Scattering of the communication signal may also result in multipath interference at the receiver. This interference is accentuated by the fact that the received signal will undergo phase changes as it is being refracted. Random changes in the received signal's phase will induce added noise into the receiving equipment; reducing the signal to noise ratio.

Not only is the signal to noise ratio reduced but for wide bandwidth communications systems the effective bandwidth could also be reduced. In a wide bandwidth system the phase of the various frequencies which make up the bandwidth may be randomly changed due to refraction and scattering. Since changes in the index of refraction (n) over time will change the velocity at which the signal is propagated, a wideband signal passing through a region of fluctuating n will undergo a shift in frequency due to the Doppler effect; thereby causing interference with adjacent channels.

3. Absorption

Absorption of electromagnetic energy is the primary cause for signal attenuation after a nuclear burst. As we will see absorption is directly proportional to the electron density and inversely proportional to the square of the frequency. Because of this signal attenuation is more significant for low frequency communications systems. Electron densities in excess of 10^4 electrons/cm^3 are sufficient to cause degradation of the lower frequencies of the HF band. As can be seen in Figure 3.3 densities in excess of 10^4 which were caused by prompt radiation alone may be expected to last for approximately 5 minutes. Figures 3.5 and 3.6 show that electron densities above this level may be maintained for several hours after the blast. Due to the intense ionization of the atmosphere within the fireball, this region may be rendered essentially opaque to all electromagnetic transmissions below 10 Ghz for several minutes [Ref. 11: p. 488].

The D region will cause the greatest attenuation of an electromagnetic signal after a nuclear detonation. The reason for this is that the rate of free electron removal via attachment and recombination is lower here than in any of the layers above or below it. Within the F layer there are a greater number of free flowing ions to recombine with the released electrons and in the lower atmosphere the atmospheric density is greater so that attachment becomes an effective means for electron removal.

An additional factor which affects the rate of absorption is the frequency at which the electrons collide with other particles, i.e., ions, molecules or atoms. This frequency or 'V' is proportional to the air density. The atmospheric density decreases with altitude in accordance with the following approximation:

$$\rho(h) \approx \rho_0 e^{-h/4.3} \text{ g/cm}^3 \qquad \text{(eqn 3.7)}$$

In equation 3.7 $\rho(h)$ is the air density at altitude h and ρ_0 is the air density at sea level. The value 4.3 is the scaling factor for altitudes less than 60 miles. If 'e' in equation 3.7 is converted to base 10 ($10^{-2.3}$) a simple rule of thumb may be used to approximate the changes in air density below 60 miles, for every 10 mile increase in altitude the air density is reduced by a factor of 10. At an altitude of 40 miles the air density will be 10^{-4} times that at sea level. With this in mind we see that the collision frequency will decrease exponentially with altitude. [Ref. 11: p. 491]

The function that describes absorption is depicted in equation 3.8 [Ref. 11: p. 491].

$$a = 7.4 \times 10^4 \left[\frac{N_e V}{\omega^2 + V^2} \right] \text{ in dB/mi.} \qquad \text{(eqn 3.8)}$$

By virtue of the fact that the collision frequency (V) is represented in equation 3.8 in both the numerator and the denominator it will reduce the absorption value at both altitude extremes. If the collision frequency is high, which is the case at lower altitudes then the V^2 term in the denominator will cause 'a' to be small. If V is very small (high altitude, low atmospheric density) then the V in the numerator will be predominant and cause 'a' to be small. Therefore, once again the region of the atmosphere which is most affected by absorption is the D region.

If the frequency of transmission is greater than 10 MHz then $\omega^2 >> V^2$ and the V^2 term may be dropped from the denominator. Additionally, since our primary concern will be the level of absorption within the D layer, we can use the fact that at an altitude of 40 miles $V = 2 \times 10^{-7}$ collisions/sec. Converting the frequency in radians to megahertz the absorption values may then be approximated by equation 3.9 [Ref. 11: p. 492]. This equation was used in constructing the absorption curves shown in Figure 3.8.

$$a \approx 4 \times 10^{-2}\left[\frac{N_e}{f^2}\right] \text{ in dB/mi. per MHz} \qquad \text{(eqn 3.9)}$$

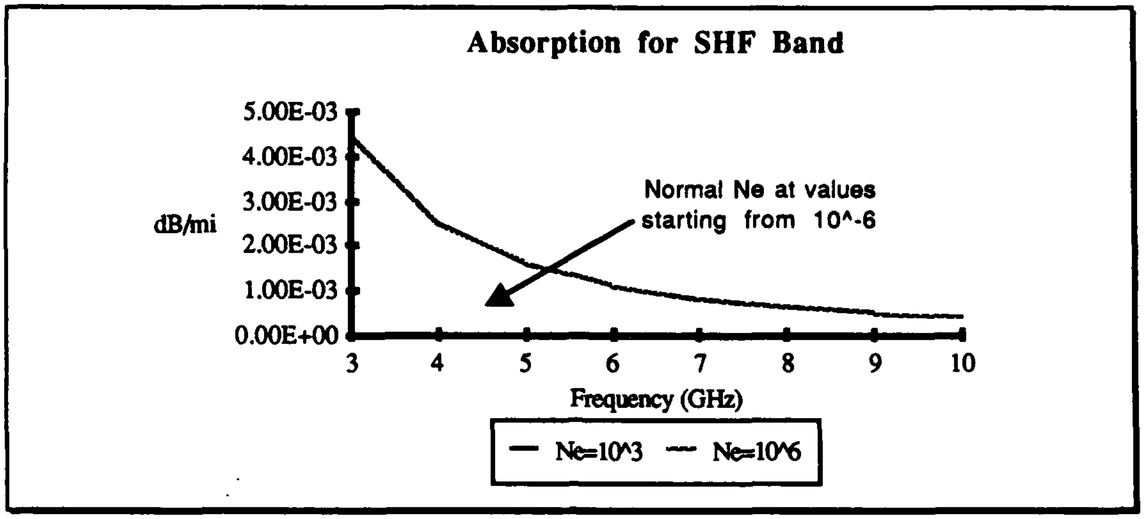


Figure 3.8 D-Region Absorption

In equation 3.9 if the quotient $\left[\frac{N_e}{f^2}\right]$ is sufficiently large then the electromagnetic wave may be both attenuated and refracted. The predominant affect will be dependent upon the ratio of the rate of change in N_e with altitude (Z) and the collision frequency: $\frac{\delta Ne/\delta Z}{V}$. If the ratio is large then refraction will be predominate but if it is small, as is the case at low altitudes, then signal attenuation will be the primary affect.

E. EFFECTS UPON THE HF SPECTRUM

Under normal ionospheric conditions the maintenance of a successful HF terrestrial link is dependent upon two things, the Maximum Usable Frequency (MUF) and the Lowest Usable Frequency (LUF). These two quantities form an upper and lower bound respectively upon the usable frequencies. The MUF is a function of the critical frequency and the angle of transmission while the LUF is a function of absorption. Both quantities will vary during the day with their highest values occurring between the hours of sunrise and sunset. This is due to the normal increase in the electron density caused by the sun's rays. The dependency of the MUF and the LUF on the electron density may be seen by reviewing equations 3.6 and 3.9 respectively.

Normal operating conditions dictate that an HF ionospheric communications link would be maintained at a frequency near the MUF. Communications links at this frequency would reduce the probability of multipath interference while still using a frequency that is capable of being refracted back to the earth by the higher electron densities of the F layer.

In a nuclear environment the electron density of the F layer is first increased and subsequently reduced. This is especially true when a large yield weapon is detonated at night above 65 miles in altitude [Ref. 11: p. 486]. This reduction in ionization will prohibit a HF signal from being bent back to the surface of the earth. Rather than being refracted by the F layer it will continue to propagate out into free space. This may prove useful if an HF link was used for satellite communications. However, prior to arriving at the F layer the communications signal must first transit the highly ionized D region. Figure 3.5 shows up to one hour after the blast $N_e \approx 10^6$ electrons/cm^3. Assuming a worst case situation with a communication satellite in a non geosynchronous orbit and requiring a maximum transmission angle of 23º, equation 3.6 shows that the transmission frequency would have to be greater than approximately 10.9 MHz in order to pass through the D region.

Another factor that must be taken into account is the degree of degradation of the signal to noise ratio due to attenuation. During high sun spot activity in a non nuclear environment, the LUF may be increased to the point that it exceeds the MUF. In these situations there is a total blackout for normal ionospheric propagation of the HF band. A similar situation arises immediately after a nuclear burst. Figure 3.2 shows that the prompt radiation released after the burst may cause the electron density to increase beyond 10^9 electrons/cm^3. This in turn would cause a blackout within the area of the burst.

Returning to our original example, if an HF satellite communications link at a frequency of 10.9 MHz passes through the 10 mile thick D region one hour after the burst it would be attenuated by 3657 dB. Even a 30 MHz signal would be attenuated by 482 dB up to one hour after the burst. Using Figure 3.5 we see the N_e would have to be reduced to about 5.5×10^3 before the 10.9 MHz signal would experience even a 20 dB reduction in its signal to noise ratio. This value would not be attained until approximately 5 hours after the burst and then only at night. It is obvious from the forgoing examples that an HF satellite communications link would not be reliable in a nuclear environment.

IV. SATELLITE PERFORMANCE CHARACTERISTICS

Since there has never been an operational passive communications satellite system, many of the performance characteristics that will be discussed in this chapter are theoretical rather than empirical. The only empirical information concerning passive satellites was derived from the early ECHO satellites. These satellites were designed solely for experimental purposes and were not intended to be a communications prototype.

The Passive Communication Satellite (PACSAT) is the most recent attempt to examine the feasibility of using a constellation of passive satellites for strategic communications purposes. The concept of a passive communications array was first introduced by Joseph Yater in the early 1970's. He envisioned an extremely long (4 x 10^4 ft) array of dipoles strung along a vertical filament and maintained in orbit via radiation pressure at radio frequencies that would be generated from ground facilities. [Ref. 15]

Yater's original proposal was thoroughly examined by the Rand Corporation under DARPA contract . This chapter will describe PACSAT's operating characteristics in light of an example of a two way aircraft-to-aircraft link. It will also delineate the system's deficiencies with respect to orbital and structural characteristics.

A. PACSAT OPERATION

The Passive Communication Satellite is envisioned as being totally passive without the capability of amplifying or processing the received signal. In order to maintain its passive qualities orbital stability will be attained by using the earth's gravity gradients. This will eliminate the need for the transmission of any corrective Tracking, Telemetry and Control (TTC) signal from either the earth or the satellite. This differs from Yater's original proposal which suggested that the array's orbital position be corrected by the use of radiation pressure from radio frequencies generated by earth tracking stations.

PACSAT will operate predominantly within the SHF frequency band with a nominal carrier frequency of 8 to 10 Ghz. Not only is the satellite operable over a broad range of frequencies but its area of coverage is also frequency steerable. [Ref. 10: p. 13]

B. PACSAT STRUCTURE

The array consists of a long string of spherical scattering elements. Both the size and number of these elements are chosen so as to enhance the backscattering characteristics and therefore the directivity and gain of the entire array. A schematic of one section of the array is shown in Figure 4.1 [Ref. 10: p.6].

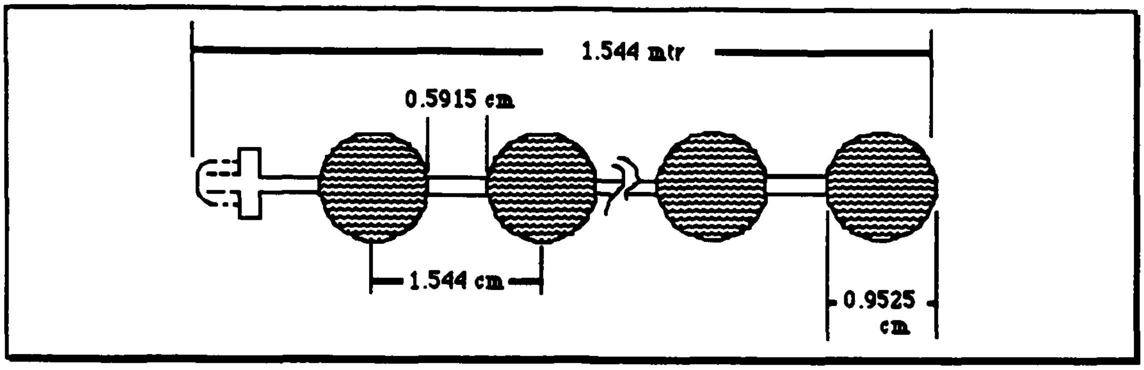


Figure 4.1 Section of PACSAT Array

The array may be composed of as few as 100 and as many as 1,000 sections each of which will contain 99 spheres for a total length of 1.54 meters. The spheres are constructed of nickle plated brass and have a diameter of approximately 1 centimeter with a spacing of about 6/10 of a centimeter. The spacing (s) of the spheres is dependent upon the fundamental design frequency (f_l) of the array in accordance with equation 4.1 [Ref. 16: p. 5].

$$f_l = \frac{c}{2s} \qquad \text{(eqn 4.1)}$$

By restricting the sphere spacing to between $\lambda/2$ and λ the signal returned to the earth is limited to the first grating lobe. Additionally, the backscatter radiation returned towards the earthbound receiver is maximized if the satellite operates within the vicinity of the first resonance which occurs when $K_0\, a = 1.0$ to 1.1, where:

$$K_0 = \frac{2\pi}{\lambda} \qquad \text{(eqn 4.2)}$$

and a = sphere radius. [Ref. 9: p. 12]

C. ORBITAL PLACEMENT

The selection of the orbital altitude is dependent upon a myriad of variables, primary among these is the intended area of coverage and the required field of view for the satellite. The area of coverage is in turn dependent upon the satellite's primary mission which, in this case, is to establish emergency communications with U.S. strategic forces based within the continental United States. The satellite must be placed in a circular orbit if it is to take advantage of gravity gradient stabilization. Because of near-field phase errors the selected orbit must not be less than one earth radius in altitude. [Ref. 9]

For illustrative purposes the satellite array will be injected into a circular polar orbit at an altitude of 10,000 Km. The actual altitude will depend upon the desired satellite footprint as well as the acceptable amount of signal loss due to propagation. As can be seen in Figure 4.2, at an altitude of 10,000 Km the satellite's field of view will be 0.4995 steradians with a worst case one way propagation distance of about 15,423 Km. In order to provide coverage of all areas above 30ºN latitude a minimum of 26 satellites would have to be placed into orbit. This would enable the earth station to see the satellite through 14º of its orbit. [Ref. 10: p. 14]

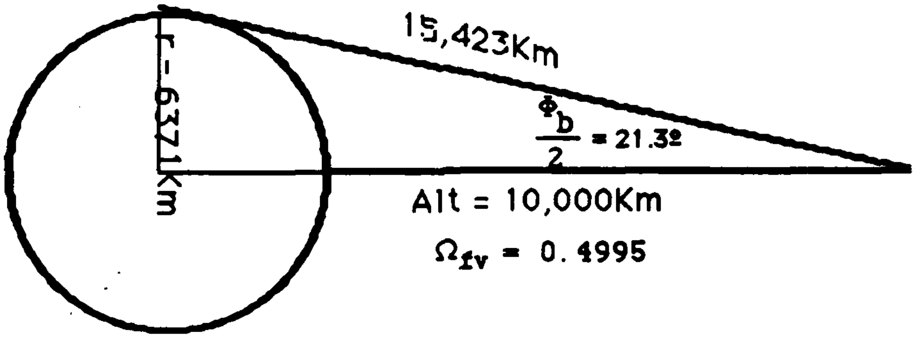


Figure 4.2 PACSAT Field of View

D. RETURN SIGNAL

The signal which is returned by the satellite is centered upon the satellite's subpoint and is shaped like a hollow cone or annulus. This link configuration is shown in Figure 2.3. The angle of the returned signal (β_1) is dependent upon the wavelength of the transmitted frequency, and the transmission angle (α) according to the following function [Ref. 7: p. 13]:

$$s(\cos\alpha + \cos\beta_1) = \lambda \qquad \text{(eqn 4.3)}$$

As can be seen from equation 4.3 one is able to steer the antennas footprint by selecting the appropriate operating frequency.

The solid angle occupied by the satellite's radiation pattern is determined by:

$$\Omega_{ann} = 2\pi \sin\beta(d\beta) \qquad \text{(eqn 4.4)}$$

where β is the angle of the returned signal and $d\beta$ is the 1/2 power beamwidth of the satellite's re-radiation. When the angle of transmission (α) is equal to β at 23º and $f_c = 8$ Ghz then the size of the annulus may be approximated by:

$$\frac{2\pi(0.886)\lambda}{L} = 1.39 \times 10^{-4} \text{ steradians} \qquad \text{(eqn 4.5)}$$

where L equals the array length of 1.5 Km. [Ref. 10: p. 17]

To determine the physical size of the annulus we must convert the result obtained in equation 4.5 from steradians into radians using:

$$\left[1 - \frac{\Omega_{ann}}{2\pi}\right] \cos^{-1} = \frac{\Phi_b}{2} \qquad \text{(eqn 4.6)}$$

Substituting 1.39×10^{-4} steradians for Ω_{ann} we get 6.652×10^{-3} radians or 0.38º. Assuming a satellite altitude of 10,000 Km the actual size of the annulus is then found to be approximately 100 Km.

The gain that may be realized within this annulus is a function of the radar cross section of the satellite and is proportional to the square of the array's length. This radar cross section may be approximated by:

$$\sigma \approx 0.6L^2 \qquad \text{(eqn 4.7)}$$

This in turn is approximately equal to a 61 dB enhancement for a typical array length of 1,500 meters. [Ref. 9: p. 76]

All of the returned energy is concentrated within this 100 Km annulus. While this allows for a great deal of signal directivity it also places the added burden upon the receiver to search for and lock onto the correct carrier frequency.

E. EARTH TRANSMITTER/RECEIVER

The receiver and transmitter specifications which are set forth in Table 4 are those which are proposed by Frankel as being demonstrative of a normal operational link configuration between two aircraft. These same parameters are used in the following sections to determine the path calculations and the carrier to noise ratio which may be expected in an operational PACSAT link. [Ref. 10: pp. 13-18]

TABLE 4

EQUIPMENT PARAMETERS

	Transmitter	**Receiver**
Power	20 Kw	1 Kw
Antenna Size	D = 1.5 mtr	[3x3mtr] $1/\sqrt{2}$
Antenna Area (Ae)	1.767	6.36
Antenna Efficiency (η)	0.55	0.55
Antenna Gain	39.4 dB	6.5 dB
Receiver Syst. Temp		182ºK

The receiver system temperature is based upon a receiver temperature of 75º K and a line loss leading into the receiver of 2 dB. The total system temperature is calculated below.

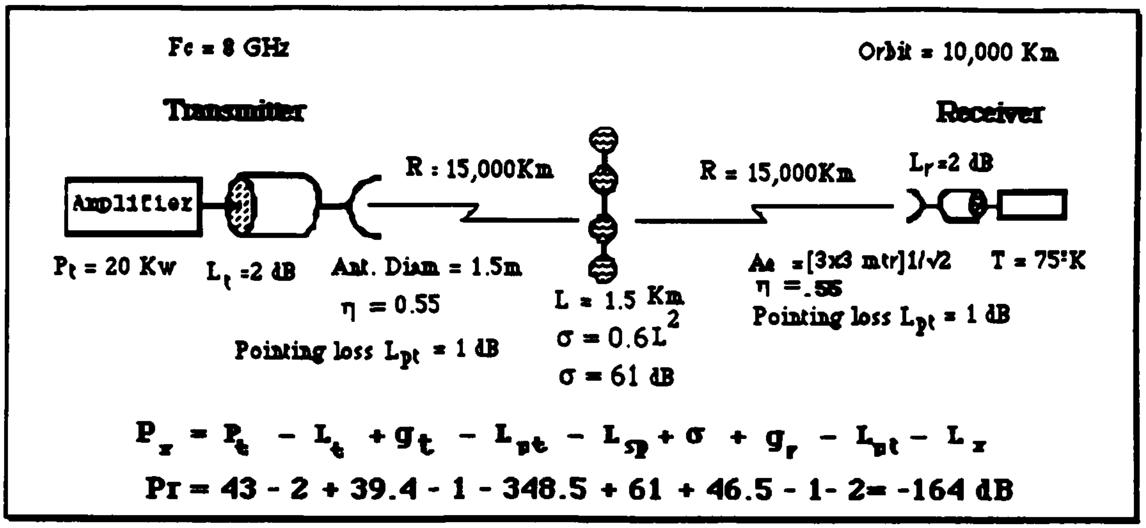
$$T_S = \left[1 - \frac{1}{1.58}\right]290 + 75 = 182^{\circ}K \qquad \text{(eqn 4.8)}$$

1. Path Calculations

The path calculations for the satellite are presented in Figure 4.3. The total spreading loss for a passive satellite at an altitude of 10,000 Km is -348.5 dB and is based upon the following:

$$L_{sp} = \frac{(4\pi)^3 R^4}{\lambda^2} \qquad \text{(eqn 4.9)}$$

where R = 15,000 Km distance from the transmitter or receiver to the passive array. As can be seen in Figure 4.3 the total received signal strength (P_r) is equal to -164 dB.



$$P_r = P_t - L_t + g_t - L_{pt} - L_{sp} + \sigma + g_r - L_{pt} - L_r$$

$$Pr = 43 - 2 + 39.4 - 1 - 348.5 + 61 + 46.5 - 1 - 2 = -164 \text{ dB}$$

Figure 4.3 PACSAT Path Calculations

2. Message Characteristics

While a $P_r = -164$ dB may appear to be excessively small the reception may be improved by using Viterbi encoding with a $K = 5$ and a rate of $R = 2/3$. The primary performance criteria for the received digital signal is the bit error rate (P_e). Assuming a minimum acceptable error rate of one in a thousand ($P_e = 10^{-3}$) then with the Viterbi encoding there must be a minimum signal to noise ratio of 4 dB in order to provide the required error rate. This signal to noise ratio may be attained by reducing the speed of transmission (R_{Bps}). Equation 4.10 shows that the signal to noise ratio (E_b/η_o) is inversely proportional to the rate of transmission:

$$\frac{E_b}{\eta_o} = \frac{P_r T_b}{kT_s} = \frac{P_r}{kT_s R_{Bps}} \qquad \text{(eqn 4.10)}$$

where k = Boltzmann's constant (1.38×10^{-23} joules/kelvin), T_s is the system temperature, and T_b is the time to transmit one bit of data ($T_b = 1/R_{Bps}$). Solving for RBps while at the same time converting to logarithmic form provides us with:

$$R_{bps} = P_r - k - T_s - \frac{E_b}{\eta_o} \qquad \text{(eqn 4.11)}$$

After substituting the appropriate values into equation 4.11 the maximum data rate that can support a signal to noise ration of 4 dB is 3162 Bps. [Ref. 10: p. 16]

With respect to the transmitted message, each EAM (Emergency Action Message) is assumed to be 400 bits long and will be transmitted in equally sized packets of 200 bits each. In order to ensure that each message packet is received by all stations within the satellites field of view each packet must be transmitted a total of 3600 times. The reason for this is that while the PACSAT $\Omega_{fv} \approx 0.5$ steradians the field of view of the transmission annulus is only $\Omega_{ann} = 1.39 \times 10^{-4}$ steradians therefore:

$$\frac{0.5}{1.39 \times 10^{-4}} = 3{,}600 \text{ repeats} \qquad \text{(eqn 4.12)}$$

The time to transmit the entire message is:

$$3600 \text{ repeats} \times \left[2 \times \frac{200 \text{ bits}}{3162 \text{Bps}} \right] = 7.8 \text{ min} \qquad \text{(eqn 4.13)}$$

3. Frequency Hopping

The system will use a quasi random frequency hopping technique using 3600 frequencies over a total bandwidth of 360 MHz. The bandwidth of each of the selected frequencies will be 100 MHz. The 100 MHz bandwidth is limited by the physical size of PACSAT array. The changes in frequency will steer the returned signal in 3 dB bandwidth hops so as to cover the entire field of view of the satellite. The time that will be required to transmit the 3600 frequencies is 3.9 minutes.

4. Jamming Resistance

The jam resistance that is inherent in this technique results in a processing gain or jammer penalty of 360 MHz/3 Khz = 51 dB. Additionally the dwell time per frequency is only 200 bits/3162 Bps = 0.063 seconds.

F. PACSAT DEFICIENCIES

While the foregoing discussion has provided a fairly comprehensive view of PACSAT's operating parameters under ideal operating conditions it has not dealt with some of the system's deficiencies. Some of the problems that will be discussed are the near-field effect, carrier frequency search and acquisition, limited coverage area, and orbital stability.

1. Near-Field Effect

When the PACSAT array is placed in an orbit that is less than one earth radius (6,371 Km) altitude the returned signal will suffer from phase errors due to the large number of reflectors used in the array. The amount of phase distortion is proportional to the number of elements in the array and is inversely proportional to the orbital altitude. When an array of 1,500 meters is placed in a low earth orbit the receiver will no longer be in the far-field of the reflected wave and may experience a loss of up to 3.4 dB due to the phase error of the near-field effect. This loss may be further aggravated if the array is not aligned vertically with the earth. [Ref. 16: p. 28]

The near-field affect may be ameliorated by using pseudo-noise modulation on the carrier. The array is in effect spatially subdivided into subarrays each containing 4,000 elements. This is accomplished by using a pseudo-noise code with a period that spans the 4,000 elements. Each correlation of the returned signal "...produces a weighted sum of the dephased returns...." [Ref. 16: p.32]. In this way the loss suffered from the near-field effect may be reduced to less than 0.2 dB.

2. Carrier Frequency

As we saw from the previous discussion the returned signal has a very narrow beamwidth which is aimed by selecting the appropriate frequency in accordance with equation 4.3. The problem that arises is that while the transmitter may know the exact angle of transmission (α) and angle of reception (β) from an a priori list, the transmission angle remains unknown to the receiver. The receiver is therefore required to search for the appropriate carrier frequency. This may be corrected if the carrier frequency is varied in discrete intervals over a predefined range. [Ref. 16: pp. 11-16]

Since the receiver knows the reception angle (β) either through a priori knowledge or through direct measurement it may determine a range of corresponding transmission angles (α). It then cycles through the range of frequencies dictated by α. The spacing between frequencies is selected so as to steer the reflected beam in 3 dB beamwidth increments. This is the beamwidth which corresponds to a 3 dB reduction from the peak returned signal. [Ref. 16: p. 16]

One of the drawbacks of this process is that the number of frequencies that must be scanned is proportional to the number of elements in the array as well as the sum of the cosines of the transmission and reception angles. In an array of about 80,000 elements this translates into a total of 1,355 different frequencies each separated by 101.3 KHz. A formidable task for any receiver. However, by increasing the frequency detection time the number of detector channels can be reduced from 1,355 to 49. [Ref. 16: p. 22]

While this system may work well for transmitting information to stationary strategic forces it would severely restrict the mobility of naval forces. Depending upon the operating environment it may not always be feasible for the transmitting station to know the intended receiving units actual position to the degree of accuracy required by this frequency steering technique.

3. Coverage Area

A basic limitation of this system is that the area of coverage is limited by the amount of signal loss that can be sustained. There is a basic trade-off between the satellites field of view and the signal to noise ratio. As the satellite's altitude increases the field of view increases but the signal to noise ratio decreases due to increased spreading losses.

Equation 4.9 shows that the loss due to spreading increases as the fourth power of the distance from transmitter/receiver to the satellite. The spreading loss incurred as a function of orbital altitude for an 8 GHz signal is shown in Figure 4.4.

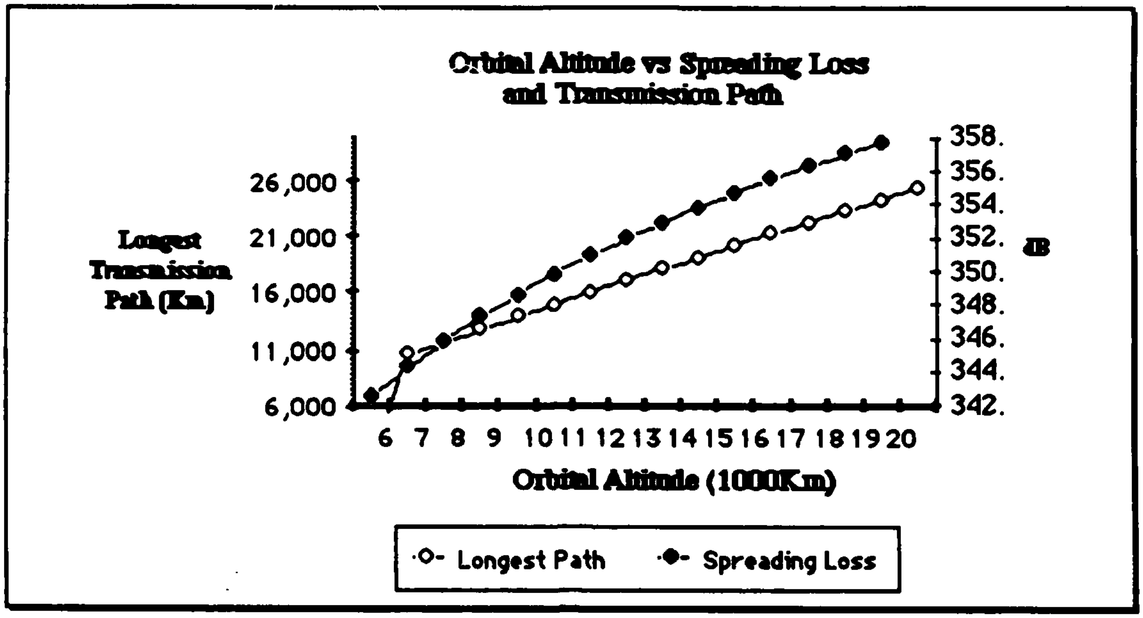


Figure 4.4 Spreading Loss vs Orbital Altitude

In Figure 4.4 the spreading loss in dB was computed for the longest transmission path that would exist for the orbital altitude indicated. The length of this transmission path is computed from the transmitter to the midpoint of the antenna array using equation 4.14:

$$L^2 = Re^2 + (Re + h)^2 - 2Re(Re + h)\cos\theta \qquad \text{(eqn 4.14)}$$

where Re = one earth radius (6371 Km), h = array's orbit altitude, and θ is the polar angle formed by the transmitter and the array [Ref. 9: p. 39]. The polar angle used in computing Figure 4.4 is the maximum angle at which the observer is able to see the array. This occurs when the observer is located on the horizon.

As the satellite's orbit is reduced to the lower limit of one earth radius the number of satellites required to provide continuous coverage increases while their field of view decreases. The minimum number of satellites in a constellation is a function of the type of orbit, i.e, polar or equatorial, and the arc of mutual visibility between the transmitting and receiving stations.

4. Orbital Stability

One of the most stringent constraints placed upon PACSAT is the need for the array to remain erect within it's orbit. If the loss in the radar cross section is not to exceed 1 dB then the amount of libration (tilt away from vertical) must be less than 1.5º and the flexure (curvature of the array) must be limited to a fraction of the operating wavelength. At a carrier frequency of 8 GHz the array must not flex more than 5 mm. The array flexural requirements are depicted in Table 5. [Ref. 17: p. 2]

TABLE 5

PACSAT FLEXURAL REQUIREMENTS

Reduction in Cross Section (dB)	Departure from Vertical (deg)	Maximum Parabolic Displacement (λ)
1	1.5	.127
3	2.0	.217
10	2.7	.401

Some of the forces that will affect the array's libration and flexure while in orbit are:

- earth's gravitational field
- elastic forces of tension and bending
- perturbations in the initial launch condition
- ellipticity of orbit
- earth oblateness effects
- solar and lunar gravity
- solar radiation pressure
- micrometeoroid impacts
- thermal bending

Of these forces, those which have the greatest effect upon the departure from vertical are earth oblateness, ellipticity of orbit and the initial launch condition. Even though dampening devices are attached to both ends of the array, major perturbations in the initial launch condition will have a lasting affect upon the satellite. The initial condition as well as the amount of thermal bending and micrometeoroid impact significantly affect the flexure of the array. Solar and lunar gravity as well as solar radiation pressure have the least affect upon the array's condition. [Ref. 17: p. 3]

Thermal bending is the result of differential expansion caused by solar heating. This expansion causes the array to bend away from the sun. In order for the thermal bending to be reduced to within acceptable limits the absorptivity of the array material must be below 0.0007. As was stated by Sollfrey in his investigation of the flexure characteristics of the array, "Thermal bending effects will excite resonant oscillations of large amplitude and are so severe that it is highly unlikely that they can be overcome." [Ref. 17: p. 110]

5. Transmission Rate

As was shown earlier the transmission rate (Bps) is varied so as to attain the required signal to noise ratio. The problem with this approach is that since the received power is so low any further reduction will have a significant affect upon the transmission rate. For example, the link parameters given in Figure 4.3 result in a received power (Pr) of -164 dB. If this power drops by one dB the transmission rate would have to be slowed from 3162 Bps to 2512 Bps and thereby increasing the transmission time for a 400 bit message from 7.8 to 9.5 minutes.

Within a non-stressed environment signals within the SHF band may be attenuated by rainfall. The amount of attenuation is proportional to the carrier frequency and the rainfall rate. In a heavy rainfall of about 15 mm/hr a 8 GHz signal will be attenuated in excess of 0.1 dB/Km [Ref. 3: p. 78].

The situation is analogous to a HF link where the capacity of the link will vary over time as a function of the signal to noise ratio. This relationship is show in equation 4.15 where: C = channel capacity, B = bandwidth in Hz, s(f) and n(f) are the signal and noise power density function respectively [Ref. 18: p. 254]

$$C = \int_0^B \log_2\left[1 + \frac{s(f)}{n(f)}\right] df \text{ Bps} \qquad \text{(eqn 4.15)}$$

Figure 4.5 shows the reduced transmission rate that results from the signal transiting a 10 Km area with the rainfall rate as indicated. All parameters have remained the same as depicted in Figure 4.3 with the addition of added attenuation due to rainfall. The times shown are the total time required to transmit a 400 bit message.

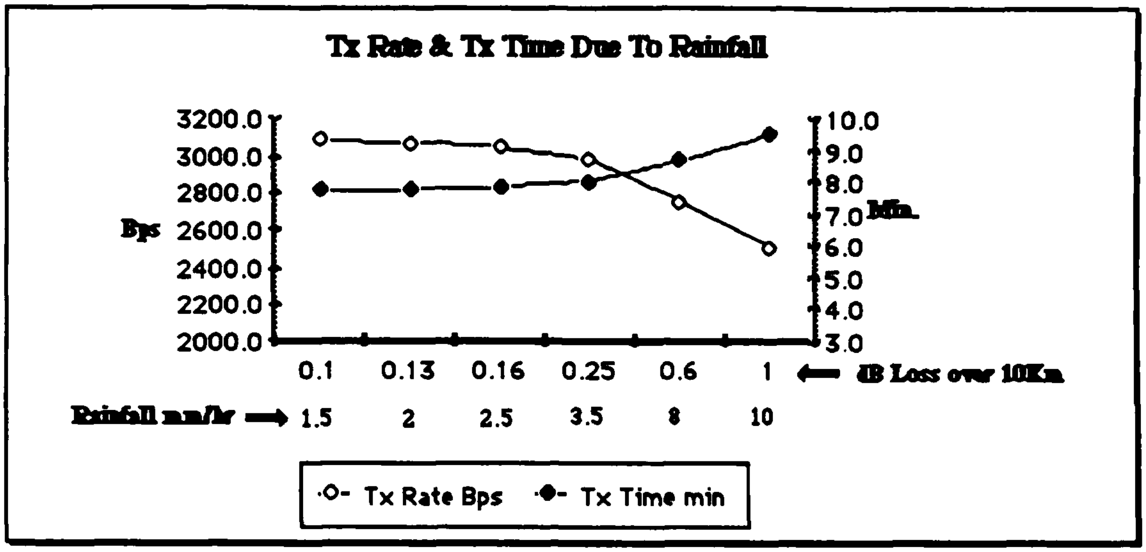


Figure 4.5 Transmission Rate vs Attenuation Loss

In an environment stressed by a nuclear detonation the attenuation affects may be even more pronounced. While absorption is not a significant factor for frequencies within the SHF band, attenuation due to suspended particulate matter becomes a significant concern. The amount of attenuation will depend upon the weapon yield, height of burst, time after burst, and the propagation path. Additionally, nuclear induced scintillation will cause an increase in the signal attenuation.

As can be seen from the above, the variations in the quality of the transmission path will require an inordinate degree of coordination between the transmitter and the receiver if the rate of transmission is expected to match the quality of the transmission media.

V. ANALYSIS

This chapter will attempt to analyze the effectiveness of passive communications satellites in light of the previous discussions dealing with nuclear survivability and satellite design characteristics. It will examine the advantages and disadvantages of a passive system with respect to the satellite's operating environment. We will also examine the problems inherent to using the HF spectrum in conjunction with a passive satellite communications system.

In addition to evaluating the operational aspects of the communications system, this chapter will start with an examination of some of the factors affecting the cost of both active and passive satellite networks.

A. COST COMPARISON

This section will not attempt to provide a definitive analysis of all the operating and development costs of an active or passive satellite rather, it will identify some of the factors influencing the total cost equation. It will also distinguish between total system cost and cost efficiency over time.

1. Launch Cost as a Function of Weight

Some factors affecting the satellite's launch cost are the orbital altitude, payload weight, and satellite size. The anticipated weight of a 1500 meter PACSAT array with an operating frequency of 8 GHz is only 200 Kg [Frankel p.9]. The DSCS-II satellite on the other hand has a beginning of life (BOL) weight of 500 Kg. The intended launch vehicle for PACSAT is the Titan-III C, the same launch vehicle which was used for DSCS-II. In 1970 the launch cost for a Titan-III booster depended upon it's payload. Prices started at $8.4 million for 455 Kg and went up to $18.1 million for 1364 Kg [Ref. 19].

Using existing chemical rocket technology, it currently costs between $4,000 to $10,000 per kilogram to ferry payload mass into low earth orbit via the space shuttle [Ref. 20]. This translates into a shuttle launch cost for PACSAT of $800,000 to $2 million.

The loss of the Challenger space shuttle in August 1986 left a void in the United States' satellite launch capability. This void is rapidly being filled by other nations, primarily by the European's Ariane booster and the Soviet Union's Soyuz and Proton rockets. At the 1986 International Aeronautical Federation (IAF) meeting in Budapest, representatives from the Soviet "civilian" space agency Glavkosmos, announced that they would provide launch services to other nations via the SL-4 Soyuz and the SL-12 Proton rockets. The cost for placing a 300 Kg payload into low earth orbit aboard the SL-4 would be 8 million Swiss francs ($5.4 million U.S. dollars). The Proton rocket could be used at a cost of 40 million Swiss francs ($27 million U.S. dollars) with a 100,000 deposit. The SL-4 is capable of lifting 2,000 Kg into geosynchronous orbit or 20,000 Kg into a low earth orbit. Intelsat has already scheduled the launch of the Intelsat 6, a 2000 Kg communications satellite for the Proton in 1989. The Europeans on the other hand are charging $80 million per launch for the Ariane booster. [Ref. 21].

The launch costs as a factor of weight for a PACSAT system would only be about 1/5 of those for a Fleetsatcom satellite which weighs in at approximately 1000 Kg. The negative side of this argument is that after taking into consideration the total of 26 satellites required for the PACSAT constellation, the aggregate weight for the passive system is about equal to that of the 5 satellites required for Fleetsatcom (see Table 2).

With regard to orbital altitude the passive satellite system has a distinct advantage over the active systems. Placing a constellation of 26 satellites into low earth orbit would allow for one launch vehicle to deploy multiple satellites. This would in effect reduce the launch cost per satellite.

An additional concern is the availability of launch vehicles for a passive satellite system. Since such a system would not contain sensitive components such as on-board processing equipment, there would be little reason to prevent the system from being launched by other nations. Therefore, even if payload space aboard the space shuttle is preempted by higher priority shipments, the passive satellites may still be deployed by other U.S. launch vehicles (Titan-III) or even by other nations.

2. Satellite Design Factors

Pritchard has indicated that the determinants of satellite cost are dependent upon the desired carrier to noise density ratio (C/N_0) and the coverage area (A_{cov}). The exact relation is indicated in equation 5.1. The left side of this equation describes the desired information capacity for a specified area, while the right side is composed of the system parameters that are the primary determinants of cost. D is the diameter of the earth station antenna, T_s is the overall receiver system temperature, P_t is the transmit power, and K is a constant composed of Boltzmann's constant, π, and antenna efficiency (η). [Ref. 1: p. 58]

$$A_{cov}\left[\frac{C}{N_0}\right] = KP_t\left[\frac{D^2}{T_s}\right] \qquad \text{(eqn 5.1)}$$

For an active satellite system there exists a trade-off between the satellite's transmission power and the size and capability of the ground stations. If there are many users that access the satellite system, the overall network costs may be reduced by increasing the relay capability of the satellites rather than boosting the size and power of all the earth stations. Therefore, based upon the total size of the network there exists some optimum value for satellite capacity with respect to cost.

In the case of a passive satellite system with a specified coverage area and a minimum signal to noise density ratio, the limiting factor will be the size and power of the ground stations. Since there is no on-board processing or amplification of the received signal the carrier to noise density ratio will be determined by the transmitting site. This in effect will require that all transmitting sites be larger in both power and size than would normally be the case for an active satellite.

Rather than being able to increase the capacity of a limited number of components, i.e., the satellites themselves, the power, size, and system temperature of each of the ground stations would have to be enhanced. Ameliorating this is the fact that it is far easier to improve the capabilities of the ground facilities than those of the satellites.

Due to size constraints the mobility of the transmitters would be greatly reduced. It is very unlikely that these transmitters can attain the degree of portability that is evident in the current inventory of communication satellite transmitters.

3. Active Satellite Cost Efficiency Model

While the total development costs for communications satellites has increased, the cost per circuit-year has gone down with time. In 1984 Namkoong performed a statistical analysis on 13 series of commercial communication satellites to determine the primary factors that influence cost efficiency over time. The data was pertinent only for mature technologies and for existing active satellite systems. He did not include in his sample the first of a new series of satellites due to the high development costs involved with a prototype system. Once again, the emphasis was on mature existing technologies and as such may not be totally applicable for a passive communications system. [Ref. 22]

The primary variables taken into consideration were the satellite's beginning of life (BOL) weight and bandwidth-years. This is defined as the amount of bandwidth used by the satellite over it's expected design life. Both of these variables are considered to be a measure of the satellite's capacity. The former is a physical measure while the latter is a functional measure of capacity. [Ref. 22]

The general telecommunications cost model which was developed by L. W. Ellis and later modified by Namkoong is depicted in equation 5.2:

$$C = Ke^{(-\psi(t-t_0))}X^aV^cD^d \qquad \text{(eqn 5.2)}$$

where C = cost, ψ is the annual exponential rate of technological change, X = capacity, D= distance, and V relates to the efficiencies gained by changing the slope of the learning curve through increased production runs. The exponents a, c, and d are indicative of the economies of scale while K is an unspecified constant. Finally $t\text{-}t_0$ represents the time in years from the first procurement.

Since distance only determines the initial costs associated with satellite placement and does not effect the continuing costs of the network, it was removed from the equation.

'V' was also considered to be an insignificant determinant of cost and, therefore, it too was dropped from the equation. The rational being that production runs are very limited in size and, therefore, do not significantly change production efficiency. Also as the satellite series matures new technology with different production runs may be used in subsequent satellites thereby further reducing the effects of production efficiency upon cost. [Ref. 22]

In an attempt to determine the cost per unit of capacity (UC) both sides of equation 5.2 were divided by X resulting in:

$$UC = Ke^{(-\psi\Delta t)}X^{-n} \qquad \text{(eqn 5.3)}$$

where $\Delta t = t\text{-}t_0$ and $-n = a-1$. In this form either satellite weight or bandwidth-years could be substituted for X as a measure of satellite capacity. [Ref. 22: p. 2]

a. Cost Efficiency and BOL Weight

A least squares analysis with 10 degrees of freedom was conducted on the collected data. The coefficient of determination (R^2) was found for each formulation of the efficiency function. In the case of satellite mass the R^2 value was only equal to 0.101, with a t-statistic of -0.78 for X (BOL weight) and -0.46 for Δt. It was therefore concluded that mass is an insignificant determinant of decreasing satellite cost. [Ref. 22: p. 5]

b. Cost Efficiency and Bandwidth-Year

When the log form of equation 5.3 was used to analyze bandwidth-years as a determinant of unit cost it was found to be statistically significant. The coefficient of determination for this case was equal to 0.732 (0.678 after being adjusted for the appropriate degrees of freedom). There was a t-statistic of -2.51 for Δt and -0.98 for X (Bandwidth-years). Therefore there is a stronger correlation for economies of scale for technological changes in bandwidth-years than there is for satellite weight. [Ref. 22: p.5]

While these results relate specifically to active communications satellites, one may assume that satellite capacity as measured in terms of bandwidth-years will also have a significant affect upon the economies of scale and marginal cost's of passive satellites.

4. Passive Satellite Costs

Since passive communications satellites have never been used operationally there is no empirical data relating to the systems development and operating costs. This section however will attempt to identify some of the factors that must be considered in the development of such a system.

a. Goodyear Cost Model

In the late 1960's NASA commissioned the Goodyear Aerospace Corporation and the Stanford Research Institute to study the feasibility of using a saddle reflector as a passive communications satellite. During the course of this study they developed a cost model for the total system cost per year. This model is shown in equation 5.4. [Ref. 19: p. 23]

$$C_{T/A} = [C_{rdg}+C_{eg}+C_{rds}+N_e(C_{ls}+K_eC_s)]\left[\frac{i}{1-(1+i)^{-n}}\right]+[C_{mg} + N_m(C_{ls}+K_mC_s)] \qquad \text{(eqn 5.4)}$$

Where:
C_{rdg} = Cost of initial R & D for ground subsystem
C_{eg} = Cost of establishing the ground subsystem
C_{rds} = Cost of the initial R & D for the orbiting subsystem
N_e = Number of launches needed to establish the space segment
C_{ls} = Total cost of the booster and launch services
$K_{e,m}$ = Number of satellites per booster
C_s = Cost of individual satellite
i = Annual rate of return on invested capital (i.e., the interest rate)
n = Number of years to recover the capital expenditures (satellite operating life)
C_{mg} = Annual operating and maintenance costs for the ground segment
N_m = Number of launches required per year to replenish the satellites

As may be seen from the above, the actual cost of the satellite itself is just a small portion of the total costs that are incurred by this communications system. In the case of the saddle reflectors the actual cost of the satellite is dependent upon the desired reflector gain, satellite weight, and diameter. Figure 5.1 graphically depicts the trade-off between these values . As the satellite gain or radar cross section goes up the antenna diameter must be increased with a corresponding increase in the satellite's unit and development costs. [Ref. 19: p. 5]

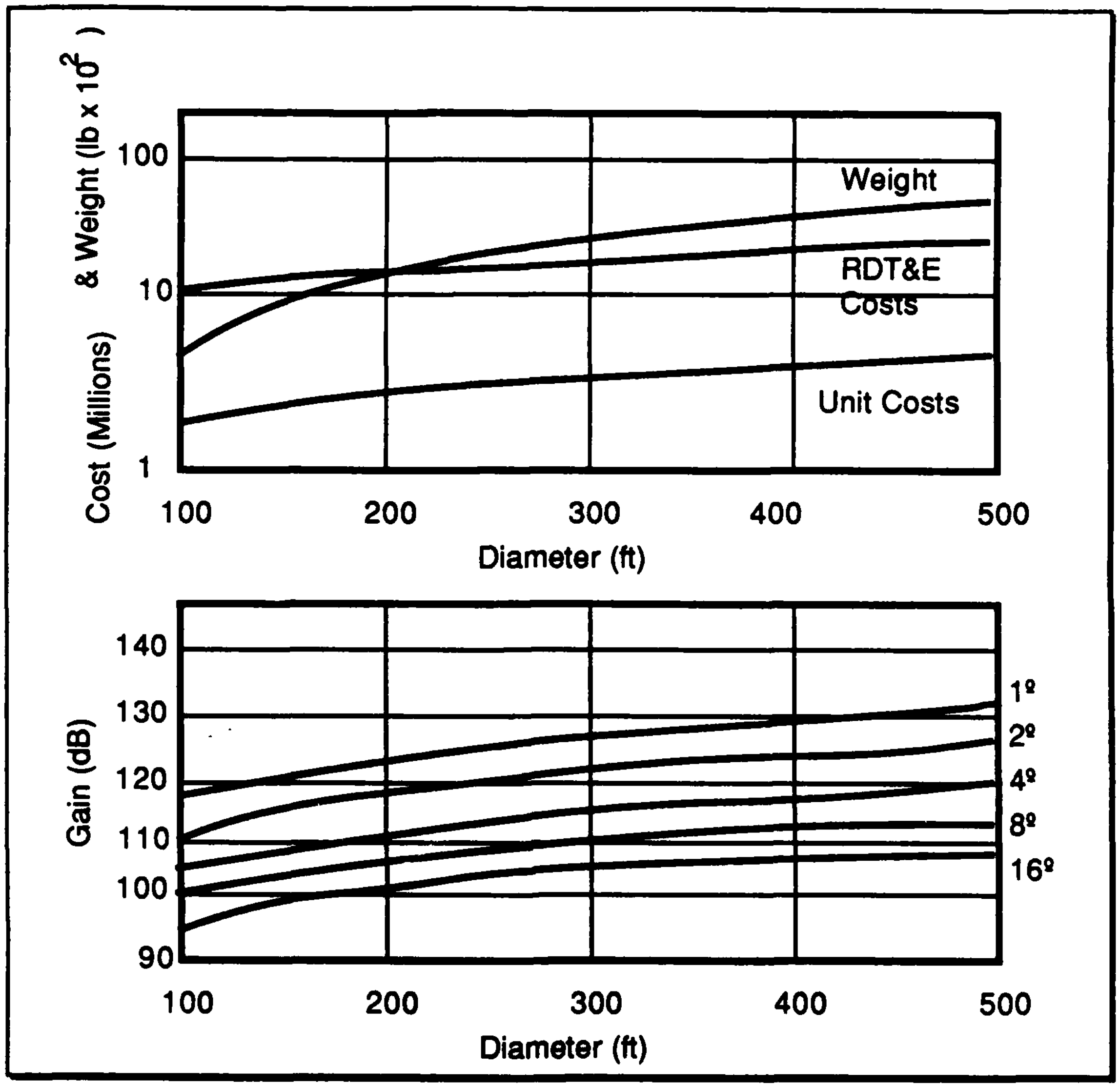


Figure 5.1 Saddle Reflector Costs

The same situation is true for the PACSAT array. Equation 4.7 shows that the radar cross section of the array is proportional to the square of the array's length. One would expect that the size of the satellite would have a direct effect upon the system's development, production, and launch costs. The larger the array the fewer the satellites that can be simultaneously launched from one launch vehicle, therefore, increasing the number of boosters required to deploy the initial constellation. Assuming that the type of launch vehicle remains the same, an increase in the satellite's radar cross section would cause a corresponding increase in the following values: C_{rds}, N_e, $K_{e,m}$, and C_s.

b. PACSAT Cost Considerations

Equation 5.1 showed that as the intended area of coverage is increased for an active satellite system there must necessarily be a corresponding increase in the size of the earth stations. This is particularly true for a passive satellite system where the ground station determines the probability of error of the received signal.

For PACSAT to cover an area the size of the continental United States a minimum of 26 satellites would be required. The same area can be covered with more satellites in a lower orbit with smaller ground stations. Since signal power is attenuated at the fourth power of the distance traveled there would be significantly less loss at the lower orbital altitudes. Depending upon the number of ground stations and the magnitude of their development, establishment, and maintenance costs (C_{rdg}, C_{eg}, C_{mg}), it may be less costly to deploy more satellites than to bear the costs of the larger ground stations.

c. Echo Satellite Cost Factors

As we have already seen weight, size, and bandwidth or channel capacity play a key role in determining the cost of both active and passive satellites. While the Echo II was only designed for research purposes it was used for up to a year for communications experiments. Table 6 provides a clear indication of why this type of satellite was not feasible for operational purposes. It provides a listing of the weight and size required for an Echo II type satellite to intercept one watt of power at the indicated altitude. Table 6 also shows the channel capacity availadle if that one watt is radiated isotropically. [Ref. 23: p. 18]

TABLE 6

ECHO II CHANNEL CAPACITY

Altitude (nmi)	Balloon Diameter (ft)	Weight (lb)	Channel Capacity
1000	932	39,400	500
2000	1227	76,950	222
3000	1506	132,000	135
5000	1778	194,000	68
10000	3094	872,000	22

It should be fairly obvious from the above why the decision was made to pursue other technologies (i.e., saddle reflectors and scattering arrays) for the construction of passive communication satellites.

B. PASSIVE HF SATELLITES

There have been recent proposals suggesting the use of the HF band for passive satellite communications [Ref. 24]. This proposal will be evaluated in light of the information presented in chapters three and four.

1. Satellite Size Requirements

In order to enhance the radar cross section of any dipole antenna the antenna length must be some fraction of the selected wavelength. This poses a particular problem for the HF spectrum where the wavelength is 150 to 10 meters.

In the case of Yater's array of passive dipole reflectors the spacing between the scattering elements is determined by equation 4.1. If the array's optimal design frequency (f_1) is selected so as to fall within the upper limit of the HF band i.e., $f_1 = 30$ MHz, then the spacing between elements will be approximately 5 meters.

The size of the scattering elements themselves may be determined by using equation 4.2. In order to return the maximum backscatter radiation toward the earth, the product K_0a must be approximately equal to 1.0. With a design frequency of 30 MHz each of the scattering elements would then be about 1.6 meters in diameter. Based upon a 30 MHz design frequency and the above proportions, each 99 sphere section of the array would be about 653.4 meters long. This does not compare favorably with the dimensions shown in Figure 4.1 for SHF operation.

Equation 4.7 shows that the radar cross section (RCS) of the passive array is proportional to the square of its length. While an array of the same length for both SHF and HF design frequencies would yield the same RCS, the HF array would be so bulky, because of the size of the scattering spheres, that it could not be easily deployable.

2. SNR of an HF Dipole Satellite

In a benign environment the signal to noise ratio will be primarily affected by the amount of spreading loss due to propagation. Equation 4.9 shows that the loss is inversely proportional to the square of the wavelength. In this respect HF communications have an advantage because the longer wavelengths are less effected by propagation loss.

Using the same design configuration shown in Figure 4.3 but with an operating frequency of 30 MHz the total spreading loss is 320 dB. This is approximately 28 dB less than the loss incurred by the 8 GHz configuration. While this may seem substantial at first it is not sufficient to provide a minimum SNR of 4 dB while maintaining a high data rate. The reason for this is that the gain that may be attained from an HF transmit/receive antenna is not as great as that from a SHF antenna.

For example, a log periodic HF antenna, which is considered to have a high gain over a large range of frequencies, has a gain of only about 15 dBi. Substituting this value for both g_t and g_r in the calculations shown in Figure 4.3, and using a spreading loss of 320 dB we get a P_r of -192 dB. The calculations are shown in equations 5.5 and 5.6.

$$P_r = P_t - L_t + g_t - L_{pt} - L_{sp} + \sigma + g_r - L_{pt} - L_r \text{ in dB} \qquad \text{(eqn 5.5)}$$

Where:
P_r = Received power in dB
P_t = Transmitted power in dB
L_t = Line losses at the transmitter
g_t = Transmit antenna gain in dB
L_{pt} = Loss due to pointing errors
L_{sp} = Propagation loss due to spreading in dB
σ = Radar Cross section
g_r = Receive antenna gain
L_r = Line losses at the receiver

$$P_r = 43 - 2 + 15 - 1 - 320 + 61 + 15 - 1 - 2 = -192 \text{ dB} \qquad \text{(eqn 5.6)}$$

Equation 5.6 allowed for a radar cross section of 61 dB solely for the purpose of comparing this result with the calculations in Figure 4.3. Given the required dimensions calculated above it is very unlikely that this RCS would be attained.

The value attained in equation 5.6 was used to determine the maximum transmission rate as defined by equation 4.11. The result was a transmission rate of about 1082 Bps. While this rate provides the minimum SNR of 4 dB, it also increases the time it takes to transmit a 400 bit message to all receiving units within the coverage area to 22.2 minutes (see equation 4.13).

One component that was left out of equation 5.5 is the amount of loss due to atmospheric absorption (L_a). This value becomes especially significant when transmitting in the HF band in an environment disturbed by a nuclear detonation. As we saw in chapter three the amount of absorption is inversely proportional to the frequency of transmission.

Figure 3.5 shows that even one hour after a nuclear burst the electron density is still in excess of 10^6 electrons/cm^3. Using this value in conjunction with equation 3.9 we see that the absorption loss for a carrier frequency of 30 MHz is equal to 44 dB/mile. This would effectively preclude the use of the HF band for any form of passive satellite communication in such an environment.

3. Unreliable Propagation Paths

The use of the HF spectrum for satellite communications would also introduce the problem of erratic and unreliable propagation paths. As we saw in chapter three HF transmissions bend away from highly ionized layers. Increased ionization of the various layers within the atmosphere occurs regularly due to solar storms and increased sun spot activity. This can result in the bending of the signal as it passes through the sporadic E layer or when it encounter the F layer. The resulting shadow zones may eliminate some transmitter or receiver sites from the communications link.

4. Multipath Interference

Unlike the deficiencies noted above, there is little likelihood that multipath interference would pose a serious problem for HF satellite communications. In a benign environment under normal operating conditions HF skywave communications operates at or near the Maximum Usable Frequency (MUF). Operating at this frequency assures the greatest range for skywaves while at the same time reducing the likelihood that a distant receiver site will receive both the ground wave and the skywave component of the signal. Basically, the ranges for direct path line of sight propagation are inversely proportional to the transmitting frequency.

If the HF band were to be used for satellite communication the transmitter would have to operate above the MUF in order for the signal to propagate through the F layer and on out into space. This, therefore, would further limit any multipath interference at the receiver.

5. Frequency Availability

Under normal HF propagation the transmission frequency is chosen so as to lie between the Lowest Usable Frequency (LUF) and the MUF. During high sunspot activity or a particularly strong solar flare the LUF may spike above the MUF. In these cases there is a total blackout of the HF frequency band. The same results would occur even if the mode of transmission was via satellite. Therefore there would be times when a portion if not all of the HF band is unusable.

Additionally, since satellite transmissions would always require the use of frequencies above the MUF the lower range of the HF band would be unavailable. In a hostile environment this makes the job of a potential jammer that much easier. He no longer has to search the entire frequency band but only those frequencies above the MUF.

C. PASSIVE SHF SATELLITES

The following is an analysis of some of the characteristics of a passive SHF satellite system. Particular emphasis is placed upon the operating characteristics within a hostile environment and the satellite's ability to maintain a communications link.

1. Nuclear Environment

As can be seen in Figure 3.8 the increased ionization from a nuclear burst will have little effect upon the absorption of an 8 GHz carrier frequency. The added loss due to absorption at this frequency is less than 1 x 10^{-3} dB/mile. Absorption within the SHF band becomes significant only when the signal traverses the fireball cloud. Complete absorption may occur due to the very high electron densities within the cloud. Additionally, the increased thermal noise from within the fireball will cause a reduction in the quality of the received signal. However, this is only significant if the transmit or receive antenna is pointed directly at the fireball. The noise caused by synchrotron radiation is much weaker and will have a greater effect upon signals at the lower frequencies. [Ref. 11: p. 480]

Of greater concern is the amount of particulate matter suspended in the atmosphere after a nuclear burst. The more particulate matter the greater the degradation in the received power (P_r). An analogy may be drawn with the rainfall rate and signal degradation. Figure 4.5 shows that the communications transmission rate is inversely proportional to the rate of rainfall. In order to maintain the required signal to noise ratio the bit rate must be reduced so that the signal density (P_rT_b) remains the same.

2. PACSAT Orbital Stability

In Yater's original proposal [Ref. 15] for a passive satellite array, one of the arguments he used to gain support for his concept was that the array's signal power to weight ratio was very low. He argues that a passive scattering array would have a greater relayed signal power per weight than an active satellite. If one compares the ideal PACSAT array with a radar cross section of 61 dB and a mass of only 200 Kg to the military communications satellites described in Table 2, one can see that this statement is quite true. However, the magnitude of the returned signal, i.e., RCS, is very much dependent upon the orbital stability of the array.

The most serious problem faced by PACSAT and any other unsupported scattering array is the amount of flexure and libration. As was pointed out by Sollfrey, the array must remain within 1.5º of vertical and may not flex more than 5 mm if it is to maintain the required RCS. Gravity gradient forces alone are not sufficient to prevent the excessive flexure of the unsupported PACSAT array. [Ref. 17]

A means of preventing the flexure of the unsupported array is by increasing the tension on the array. Since the amount of flexural displacement is inversely proportional to the tension on the array it may be possible to stabilize it by attaching trusses made of dielectric members. Another alternative is to use bow-like supports to hold the array between their tips. [Ref. 7: p.26]

The early Echo satellites also encountered a similar problem with orbital instability. Since the satellites exhibited a large surface area to mass ratio they were greatly effected by atmospheric drag. At low orbital altitudes they encountered a relatively dense atmosphere which caused the orbit to deteriorate. This problem was solved by the OVI-8 grid sphere satellite.

PasComSat as it was called, was 30 feet in diameter and was fabricated by joining a total of 162 pentagonal and hexagonal panels into a geodesic pattern. The total weight of the sphere was only 23 pounds. Once the sphere was inflated in orbit ultraviolet radiation from the sun caused photolyzation of the film like skin thereby leaving only the metal grid frame. The satellite remained in orbit for 12 years even though it's orbital altitude was only 500 miles. [Ref. 23: p. 20] Further study would have to be conducted to determine if such a system could be effectively used to construct an entire constellation of passive communications satellites.

3. PACSAT Alternatives

The majority of the research in recent years has been dedicated to the development of active communications satellite systems. While PACSAT represents one of the more recent attempts at developing a passive system it is not the only system that has been studied. As we saw in earlier chapters the original Echo system was able to maintain an effective two way communications link between two stations separated by more than 2,000 miles. Prior to the advent of the geosynchronous satellite, Project Rebound was designed to encircle the earth with a ring of passive balloon satellites [Ref. 23: p. 16]

A passive communications satellite based upon orbiting saddle reflectors was studied by the Goodyear Corporation in 1970. This system proposed using an orbital reflector in conjunction with one or more master ground terminals. These terminals were to be located between the primary transmitter and receiver in order to act as a relay station. The satellite itself was a planar array that generated a fan beam that could be frequency steered in one angle while being spin stabilized. The spin would cause the beam to scan across the earth in the other angle. [Ref. 19]

The OVI-8 was successful in correcting one of the major flaws of the early Echo satellites, orbital instability. Similar grid spheres were also used in 1971 to conduct experiments investigating the near earth environment. They were also used to calibrate earth radars. [Ref. 23: p. 21]

A modified version of PACSAT, similar to the one discussed above, may prove to be a viable alternative. Table 7 provides a summary of some of the advantages and disadvantages that are unique to a passive communications satellites using either the SHF or HF bands. It does not mention those characteristics which are common to both bands, i.e., frequency agility.

TABLE 7

HF/SHF ADVANTAGES & DISADVANTAGES

HF

- Large satellite reflectors
- Low gain earth transmit/receive antennas
- Slower transmission rate
- Excessive signal absorption in a nuclear environment
- Unreliable propagation paths
- Restricted frequency band

SHF

- Poor orbital stability
- Large radar cross section
- Susceptible to scintillation in both nuclear and benign environments
- Small scattering spheres
- High gain earth transmit/receive antennas

D. SUITABILITY FOR MEECN

Through the course of this discussion we have seen that a passive communications satellite would be ill suited for a tactical mission. In order to select the appropriate transmit frequency the transmitter must have an a priori knowledge of the receiver's position. This would not always be possible in a tactical environment. Also the size of the transmitter sites and the constraints placed upon the receivers mobility would be excessively restrictive.

However the avowed mission for the PACSAT system is strategic in nature, it is intended to be part of the MEECN system. As part of this system the passive satellite would act in a broadcast mode so as to transmit the emergency action message from one central position to many receiver sites. In order to successfully accomplish this mission any communications system must, to one degree or another, exhibit the following characteristics: redundancy, graceful degradation, flexibility, survivability, reliability, and interoperability. This section will attempt to evaluate how well the PACSAT system, and passive satellites in general fulfill these requirements.

1. Satellite Redundancy

The large number of satellites required to maintain a fully functional communications constellation is both a boon and a bane. Many satellites allow for a certain degree of redundancy as well as graceful degradation. The elimination of one or two satellites either through downlink jamming or through direct removal will not completely disrupt the entire constellation. At worst it will cause temporary blank spots within the coverage area. Additionally, since these satellites are in low earth orbit and are light in comparison to most active satellites, replacements may be launched with relative ease.

The primary difficulty arises in the initial installation of the constellation. Once the large number of satellites have been installed further launches would only be required for replacement purposes or as a means of increasing the system's redundancy and flexibility.

An additional problem caused by the low earth orbit is the need for the earth stations to continuously track the satellites and switch to new satellites as they drop below the horizon. However, depending upon the satellites altitude and the amount of longitude that separates the transmitter and receiver sites, mutual viewing times in excess of 60 minutes can be readily attained. [Ref. 9: p. 64]

2. Flexibility

One of the mixed blessings of a passive satellite system is that the available signal power is not restricted by the on-board satellite amplifiers. The negative aspect is that the signal experiences an absorption loss proportional to the fourth power of the range (R^4). The absorption loss in an active system on the other hand is proportional to the square of the range (R^2). The positive side is that since the receive power is determined by the transmitter site, adverse environmental conditions could be compensated for by increasing the transmit power.

Due to the low orbital altitude of a passive satellite system the coverage area of the constellation is far more restricted than that of a geosynchronous satellite. In the case of the PACSAT system, if the constellation is placed in an equatorial orbit it would cover the continental United States at the expense of the polar regions. This would severely restrict the operating area of the strategic units and thereby limit their overall flexibility.

3. Survivability

Low orbital altitudes also pose a problem for satellite survivability. With the advent of more sophisticated anti-satellite weapons capable of reaching these low orbital altitudes, passive satellites run an increased risk of being neutralized by hostile forces. Compensating this is the fact that there are so many satellites in orbit. The elimination of a few satellites would not completely incapacitate the system.

Passive satellites would tend to be more resilient in a nuclear environment then their active counterparts. While the atmospheric effects of a nuclear blast would have the same debilitating effects upon both satellites, passive satellites would not be as susceptible to HEMP damage.

The sensitive electronic circuitry required for an on-board processing satellite is subject to damage from high transient voltages caused by an electromagnetic pulse. Since there are no on-board electronics in a passive satellite, there would be no damage due to the HEMP effect. The only nuclear induced damage that could be sustained by a passive satellite would be orbital displacement due to the shock wave or blast overpressure.

A passive satellite would also be more resistant to active jamming. Since there is no travelling wave tube amplifier (TWTA) any attempt at uplink jamming would be unsuccessful. In the case of downlink jamming frequency hopping over a very wide frequency band would limit the effectiveness of this form of countermeasure.

The PACSAT system demonstrated that operating over a bandwidth of 360 Mhz with a signal bandwidth of only 3 KHz imposed a 51 dB penalty on the potential jammer. Additionally, the narrow beamwidth of the PACSAT system would make it very difficult for the jammer to be within the same satellite footprint as the receiver. [Ref. 10: p. 20]

4. Reliability

Continued reliability is the major problem faced by a passive satellite system. In the case of the PACSAT system orbital instabilities are such that continued reliability and availability is questionable. For any passive system to be effective in a strategic role there can be no doubt about the systems reliability.

An additional problem is that of signal attenuation due to rainfall or particulate matter. In the previous chapter we saw that the probability of error for the received signal was maintained by adjusting the rate of transmission. Should the attenuation increase there would be a corresponding increase in the amount of time required to transmit the EAM. Figure 4.5 graphically depicts the affects of attenuation upon transmission rates.

5. Interoperability

A passive satellite system as described in the PACSAT proposal would have limited interoperability between services. Due to the limited geographic coverage the system would not be available to all of the strategic forces. The transmitter station would have to know the position of the strategic unit in order to select the appropriate transmission frequency. As we saw in the previous chapter the beamwidth of the returned signal is only about 200 Km wide. This would make sustained two way communications with any one specific unit of unknown position rather unwieldy.

This system would be best suited for a broadcast mode to units that have restricted geographic positions. Strategic naval forces would not be able to avail themselves of this system because of the mobility restrictions as well as the time required to transmit any one message. In a benign environment it can take up to 8 minutes to transmit a message. This time requirement may be greatly increased depending upon the degree of environmental degradation. Prolonged transmission times would increase the naval unit's risk of detection by hostile forces.

VI. CONCLUSIONS

The development and implementation of an operational passive satellite system can prove to be a valuable asset to MEECN, provided that the selected design is able to overcome the problem of orbital instability. Like the nuclear triad, the introduction of a passive satellite system will add redundancy while complicating the enemy's decision process.

The primary advantages with regard to a strategic role are its survivability in a hostile environment and its graceful degradation. The major disadvantages of the system as envisioned in the PACSAT design, is its questionable availability and reliability. An additional problem for any passive satellite system is its limited coverage area per satellite. While this adds to the redundancy of the system by requiring more satellites it also reduces the system's interoperability.

Due to the restrictions placed upon a passive satellite system by propagation loss and the limited field of view its overall role would necessarily be restricted in scope. While sustained two-way communication would not be impossible it would certainly be unwieldy. Therefore passive communications satellites would best be suited for a point-to-multipoint mission in a restricted geographic area.

Both the power and satellite tracking requirements placed upon the transmitter sites would increase their complexity as well as their costs as compared to those associated with an active satellite system. The mobility of the receiver sites would be restricted by the need of the transmitter to have an a priori knowledge of their positions in order to successfully establish a communications link.

The overall cost effectiveness of a passive satellite system remains in doubt. While the costs associated with the actual satellites themselves will most certainly be less than that of an active satellite, the entire cost of the network depends to a great extent on the size and number of both transmit and receive sites. The number of satellites and their selected orbital altitude will greatly affect the costs of the ground stations. Unlike the active system where the capabilities and costs of the ground stations may be balanced against the capacities of a few satellites, a reduction in the costs of the ground stations in a passive system may only be attained by increasing the number of satellites in orbit.

Any use of the HF band in conjunction with a passive satellite system would be ineffective. The size requirements for an HF passive satellite would make its development and deployment improbable. Additionally, such a system would be unreliable in a benign environment and unsurvivable in a hostile one. Signal absorption due to high electron densities caused by a nuclear detonation would deny the use of the HF spectrum for prolonged periods of time. Such an interdiction of a critical communications link at such a crucial time would be unacceptable at best and fatal at worst.

A passive satellite system that uses the SHF band would not necessarily be totally incapacitated in a nuclear environment. Such a system would suffer from the same problems of signal attenuation and absorption that effect an active satellite system. However, due to the low received power of a passive satellite signal they will be more susceptible to the increased environmental noise caused by a nuclear burst. Unlike an active communications system signal degradation in a passive system may be compensated for by increasing the signal power at the transmitter site. Also, they are not susceptible to HEMP damage as are active satellites.

The probability of downlink jamming of passive satellite communications may be lessened by using frequency hopping techniques. The design specifications for the PACSAT system showed that the downlink could be rendered relatively immune to jamming by employing frequency hopping and focusing the signal within a narrow beamwidth. Unlike an active satellite, a passive satellite is impervious to uplink jamming.

While passive satellites may be resistant to both jamming and HEMP damage, their low orbital altitude reduces their chances of survival in a hostile environment. Even though the survival of any one satellite remains in question, the survival of the entire network is virtually assured against anything short of an all-out threat. The large number of satellites increase the redundancy of the system and assures the graceful degradation of the network.

Before a definitive decision may be made, important questions concerning overall system costs and orbital placement and stability must be answered. If orbital stability can be assured through an alternate design approach, i.e., OVI-8 grid sphere, the addition of a passive communications satellite may prove to be a valuable enhancement to the existing MEECN system.

APPENDIX A:
GLOSSARY OF ACRONYMS

ACRONYM	DEFINITION
AFSATCOM	Air Force Satellite Communications System
ASL	Above Sea Level
BOL	Beginning Of Life
Bps	Bits per second
COMSAT	Communications Satellites
DAMA	Demand Assigned Multiple Access
DARPA	Defense Advanced Research Projects Agency
DSCS	Defense Satellite Communications System
EAM	Emergency Action Message
EMP	Electromagnetic Pulse
ERCS	Emergency Rocket Communications System
FM	Frequency Modulation
GHz	Gigahertz
HEMP	High-altitude Electromagnetic Pulse
HF	High Frequency
HF-AJ	High Frequency Anti Jam
KHz	Kilohertz
LUF	Lowest Usable Frequency
MEECN	Minimum Essential Emergency Communications Network
MHz	Megahertz
MUF	Maximum Usable Frequency
NCA	National Command Authority
NF	Noise figure
PACSAT	Passive Communications Satellite
RCS	Radar Cross Section
SACDIN	Strategic Air Command Digital Network
SATCOM	Satellite Communications
SHF	Super High Frequency
SIOP	Single Integrated Operating Plan
SNR	Signal to Noise Ratio
TTC	Tracking, Telemetry & Control

TWTA	Traveling Wave Tube Amplifier
UC	Unit Cost
UHF	Ultra High Frequency
VHF	Very High Frequency

APPENDIX B: GLOSSARY OF SYMBOLS

SYMBOL	DEFINITION
a	Radius of PACSAT scattering element
A_{cov}	Coverage area
$\frac{C}{N_0}$	Carrier to noise density ratio
D	Distance from observer to detonation point in miles
$\frac{E_b}{\eta_0}$	Signal to noise ratio
f	Frequency
f_{cr}	Critical frequency
$F(M)$	Effective mass absorption coefficient
f_1	Fundamental design frequency for PACSAT array
G	Gain in dB
G_r, g_r	Gain of the receive antenna
G_t, g_t	Gain of the transmit antenna
h	PACSAT array's orbital altitude
K	Constant
k	Boltzmann's constant, $1.38\text{x}10^{-23}$ joules/kelvin
L_{pt}	Signal loss due to antenna pointing error
L_r	Signal loss line losses at the receiver
L_{sp}	Signal loss due to spreading
n	Index of refraction
N_e	Electron density
$n(f)$	Noise power density function
P_r	Total received signal power
P_t	Transmitter power
R	Distance from the transmitter/receiver to the satellite
R_{Bps}	Transmission rate in bits per second
R_e	Earth's radius, approximately 6,371 Km
s	Spacing between scattering elements in the PACSAT array
$s(f)$	Signal power density function
T_b	Time to transmit one bit of data
T_r	Receiver temperature

T_s	Total system temperature
V	Electron collision frequency
W	Nuclear weapon yield in kilotons
α	Transmission angle from the earth transmitter to the PACSAT array
β, β_1	Angle of the returned PACSAT signal
δN_e	Rate of change in electron density
δZ	Rate of change in altitude
φ	Transmission angle measured from the vertical
λ	Wavelength
θ	Polar angle formed between the transmitter and the PACSAT array
ρ	Air density in grams per centimeter cubed
σ	Radar cross section
σ_m	Minimum radar cross section
ω	Frequency in radians
Ω_{ann}	Field of view of the PACSAT array's annulus in steradians
Ω_{fv}	Satellite's field of view in steradians
ψ	Annual exponential rate of technological change

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