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THESIS

FEASIBILITY OF METEOR BURST BUOY RELAY
AS A
COMMAND AND CONTROL ASSET

by

Dana A. Williams

March, 1992

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Meteor burst communication is currently being researched as a survivable, backup means to long-range communications due to a perceived vulnerability to HF and satellite communications. A specific hypothetical link that is analyzed in this thesis is that of a meteor burst relay network. The network consists of fixed land facilities, permanently moored ocean buoys, and air-deployable buoys, all in support of deployed submarines. The advantage of such a system for the submarine fleet is that it would allow the ability of establishing communications while maintaining a covert posture on-station. This is due to the meteor burst phenomenon of scattering, where a meteor trail projects a small ground illumination footprint, as compared to HF communications. As a result, a meteor burst channel has inherent characteristics that are resistant to ground-based interception and jamming.

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Feasibility of Meteor Burst Buoy Relay as a Command and Control Asset

by

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ABSTRACT

Meteor burst communication is currently being researched as a survivable, backup means to long-range communications due to a perceived vulnerability to HF and satellite communications. A specific hypothetical link that is analyzed in this thesis is that of a meteor burst relay buoy network. The network consists of fixed land facilities, permanently moored ocean buoys, and air-deployable buoys, all in support of deployed submarines. The advantage of such a system for the submarine fleet is that it would allow the ability of establishing communications while maintaining a covert posture on-station. This is due to the meteor burst phenomenon of scattering, where a meteor trail projects a small ground illumination footprint, as compared to HF communications. As a result, a meteor burst channel has inherent characteristics that are resistant to ground-based interception and jamming.

TABLE OF CONTENTS

LIST OF FIGURES

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I. INTRODUCTION

A. RENEWED INTEREST IN METEOR BURST

Interest was renewed in meteor burst (MB) technology as an alternative to long-range communications in the mid-1970s, after a void period of approximately 12 years. Originally, the development of satellite communications had caused interest in MB to dwindle.

MB was rejuvenated for two reasons: first, the development of the micro-processor had simplified and enhanced the use of MB; and second, the need to explore backup alternatives to satellite communications (SATCOM). Military interest was spurred due to the nuclear survivability issue of the MB medium being superior to other beyond line-of-sight (LOS) media.

Indicative of the renewed interest, the U.S. Department of Agriculture (USDA), in the mid-1970s, implemented MB for its snow-pack telemetry (SNOTEL) system in the western U.S., for monitoring snow depths (Schanker, 1990, p.23). In 1981, the Defense Communication Agency (DCA) pursued a feasibility study of MB utilization for the Minimum Essential Emergency Communications Network (MEECN) (DCA CCTC TR 197-81, 1981, p. 1-1). The civilian sector is also involved; the Northern

Natural Gas Company network utilizes MB for pipeline monitoring (SAIC, 1991, p. 1).

B. BUOY RELAY NETWORK

This thesis considers a hypothetical system in which the phenomenon of MB is used as a backup means for existing long-range communication systems, via an oceanic buoy relay network. The main buoy network would consist of land based facilities, permanently moored oceanic buoys, air deployable buoys, and suitably equipped submarines. Messages would be transmitted from the land facilities to transceivers installed on the permanently moored buoys. The moored buoys would be positioned along the continental shelf, so that the Navy and Coast Guard would be able to conduct security patrols and periodic maintenance inspections. The moored buoys would then relay the messages to the air-deployed buoys, which would store the messages until queried by a submarine. Although primarily envisioned for the submarine community, all naval assets equipped with MB equipment could utilize the network for backup communications. (See Figure 1)

C. SCENARIO

The scenario takes place in an open ocean environment, approximately 1000 nautical miles (nm) from the coast of a NATO country. Navy P-3 patrol aircraft tasking will include deploying patterns of MB relay buoys in specific areas of

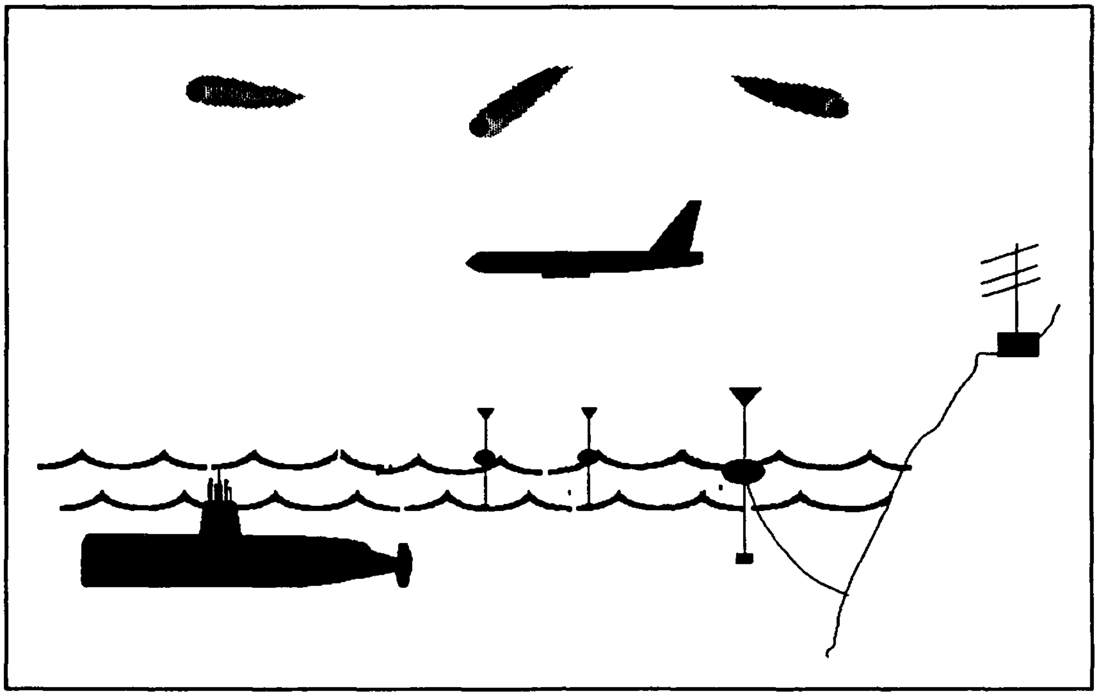

Figure 1: Components of MB Buoy Relay Network

ocean. The buoy spacing ranges between 220 and 330 nm apart, approximately 400 and 600 kilometers (km), respectively. The buoys have a life expectancy of three to four months based on battery discharge rates, at which time they would be replaced.

The scenario involves a submarine operating covertly on patrol, requiring communication with the Submarine Operational Authority (SUBOPAUTH). The Commanding Officer (CO) determines that there is no immediate threat to the submarine, but does not wish to extend the very low frequency (VLF) trailing antenna wire. Instead, he decides to utilize the MB relay equipment recently installed on the submarine. The order is given to ascend to periscope depth and raise the MB antenna mounted on top of the periscope. At that point, the submarine is integrated into the MB network. (See Figure 2)

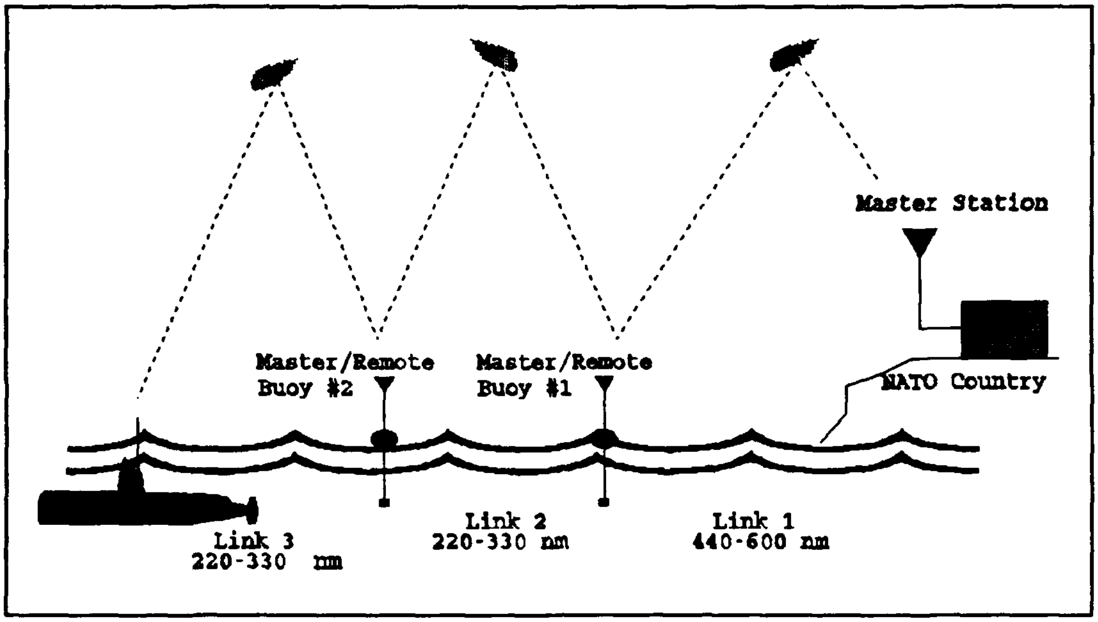

Figure 2: Link Signal Path

The submarine initiates the relay process by periodically transmitting a 20 msec probe signal, and awaits a response. When an air-deployed buoy receives the probe signal, it will burst any messages currently stored in its memory to the submarine. After each successive relay transmission, the buoys will revert to the monitoring mode, awaiting the next broadcast or message.

D. OPERATIONAL REQUIREMENTS

Submarines have certain operational requirements to copy message broadcasts, which are periodically transmitted throughout the day. Currently, the broadcasts are carried over VLF and satellite communication channels. The primary method involves utilizing VLF transmissions, which have extremely long ground wave propagation and the ability to penetrate shallow depths of water. To receive VLF signals, a submarine must deploy a long trailing antenna wire, while maintaining its current depth. The antenna is positively buoyant and floats at or just below the surface, based on the length of cable deployed and the speed of the submarine. The VLF data rate is very low, approximately 50 to 150 bits-per-second (bps), requiring from 20 to 60 minutes to copy an entire administrative broadcast.

The backup system for broadcast monitoring is SATCOM. To receive SATCOM transmissions, the submarine must surface or rise to periscope depth, to query the satellite. A disadvantage of SATCOM is the perceived vulnerability of satellites to jamming and the possible threat of anti-satellite weaponry.

E. SCOPE OF THESIS STUDY

This thesis addresses the buoy relay network, current military and civilian applications for MB systems, and research currently being conducted in the field.

This thesis will not address shore-based station topologies, or the threat to shore-based stations. Cost/benefit issues, such as the optimum number of permanently moored or air-deployed buoys, also will not be addressed.

F. ORGANIZATION OF THESIS

Chapter II reviews C^2 concepts as they relate to MB.

Chapter III consists of an overview of MB.

Chapter IV is the link analysis that pertains to the scenario.

Chapter V reviews current applications and research in the MB field.

Chapter VI lists the advantages, disadvantages and future recommendations for MB.

The Appendix contains spreadsheet calculations for the link analysis from Chapter IV.

II. MBC AS A COMMAND AND CONTROL ASSET

A close relationship exists between command and control (C^2) and communications. Due to this relationship, many authors will combine the terms into C^3. It has been argued that C^2 is only as effective as its communication system is reliable. This may be true; still, communication systems serve only as the necessary means to convey information and orders; they are not part of the decision or implementation process.

A. C^2 ISSUES

Effective C^2 results in successful interaction of a complex architecture composed of people, procedures, and equipment. The architecture may be transparent to the user, who might not be aware of its complexity, as long as the conveying of information and orders are unimpeded.[1] (Bethmann and Malloy, 1989, p. 1)

As with any C^2 asset, the ability to provide a commander with timely and accurate information will directly influence how well a situation is resolved. Commanders require a flow of information from sensors and subordinates, in addition to

[1] C^2 systems are normally transparent to the user, only coming to light when a problem arises. It is this very transparency, which is an asset in the field, that becomes a hinderance when budget constraints have to be implemented.

guidance and direction from superiors to make optimum decisions.

MB communication (MBC) has been advertised as a survivable and reliable mode of communication with inherent capabilities that thwart the jamming and interception of signals. The system would permit command decisions to be made, disseminated and implemented, with little or no increase in threat to the on-station platform than current systems. MB is useful for applications that involve low volume communications or data exchange requirements between fixed or mobile land sites, submarines, ships, or aircraft (NOSC TR 1150, 1986, p.9).

MBC has several unique features that are desirable to the Department of Defense (DOD). There is an inherent covertness characteristic, resulting from the restricted footprint of reflections off the ionized trails. This characteristic has prompted much research into low probability intercept (LPI) of MB systems for DOD. Interception by beyond-the-horizon receivers is extremely unlikely; however, if a receiver is within line-of-sight (LOS), the MB system would be vulnerable to interception if spread spectrum techniques were not employed. (Oetting, 1980, p. 1594)

The vulnerability of a MB signal to jamming is similar to that of interception. Jamming a MB signal is improbable unless the jammer is within LOS of a terminal. If a jammer were beyond-the-horizon, it would have to rely on meteor trails or ionoscatter to propagate the jamming signal. Such a situation could easily be detected and countered simply by increasing the link frequency. (Oetting, 1980, p. 1594)

B. FUNDAMENTAL DEFINITIONS

1. Command and Control

The term command and control can be interpreted differently by different people, therefore, its meaning will be clearly stated here. DOD standards are incorporated into the Joint Chiefs of Staff Publication 1-02 (Joint Pub 1-02), which defines command and control as "The exercise of authority and direction by a properly designated commander over assigned forces in the accomplishment of the mission." (JCS, 1989, p. 77) The exercise of authority referred to in the definition is the legal authority given to a commander by virtue of rank or assignment. The definition goes on to say "Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission." (JCS, 1989, p. 77)

2. Command and Control System

A second important term defined in Joint Pub 1-02 is the command and control system: "The facilities, equipment, communications, procedures, and personnel essential to a commander for planning, directing, and controlling operations of assigned forces pursuant to the missions assigned." (JCS, 1989, p. 77) A C^2 system refers to the entire network of interconnected components that makes up a commander's support organization, thereby ensuring effective C^2. MBC and other communication systems are only subsystems of the overall C^2 system. Generally, communication systems are the most dominant of subsystems, but not necessarily the most important. (Bethmann and Malloy, 1989, p. 9)

3. Protocols

Communication protocols are sets of rules required for all communication systems to: initiate message exchange, verify correctness of transmission, number the "blocks" composing a message, apply correctness-checking redundancies to each block, and retransmit blocks for erroneous transmissions. (Beam, 1989, p. 74)

MB protocols, in the past, have been designed and developed in a proprietary format for specific contractor applications. Many of the protocols have been based on the International Consultive Committee for Telephone and Telegraph (CCITT) X.25, the protocol for packet switching systems (Schanker, 1990, pp. 101-103). Interoperability problems however, are still encountered.

To date, no Federal Standard has been adopted for MBC. The Meteor Communications Corporation (MCC) however, has recently relinquished its proprietary restraints on the Proposed Federal Standards 1055, 1056, and 1057, which had been delaying the acceptance process. All of the proposals are under consideration, with approvals expected by the third quarter of 1992. The proposals address backward compatibility between equipment under development and existing fielded MBC equipment. (Tanaka, DISA, 1992)

4. Networks

A network is simply a collection of transmitter-receiver terminals, or point-to-point links, that are interconnected. The network is governed by a protocol to avoid mutual interference with simultaneous transmissions and to set precedence or priority for message handling. The protocol also specifies how communications will be conducted between the components of the buoy relay network. (Schanker, 1990, p. 103)

C. MB OPERATIONAL MODES

Three modes of operation exist for MB transmissions: point-to-point, netted, and broadcast. The modes have certain characteristics and advantages to consider depending on the intended purpose of the MB link and the environment in which the link will operate.

1. Point-to-Point

The point-to-point mode involves a two-way communication link between terminals, establishing a "handshaking" procedure to determine accurate reception of individual message bursts. A feedback path, via the same ionized trail that the message bursts were sent, can utilize either full- or half-duplex methods depending on the protocol.

2. Netted

The netted mode consists of a group of remote MB stations that are routinely queried or probed by a master MB station. Upon receipt of the probe signal, each remote station in-turn will transmit its data to the master station. The DOA's SNOTEL system is an operational example of the netted mode.

3. Broadcast

The broadcast mode utilizes master stations, stationed around the world, to retransmit messages continually to the receiver stations. The reason for the retransmission is to ensure a high probability of reception at the receiver stations.

D. C^2 PROCESS

Throughout the years, the C^2 concept has remained relatively unchanged. The commander of a force is responsible for making the necessary decisions to lead effectively that force in the accomplishment of its objectives. The C^2 process however, is continually changing as technology progresses. Through technological advancements, complex systems have become simplified allowing for effective and efficient control over vast forces without geographical limitations, a physical impossibility 50 years ago. Communications are clearly the link between the commander and the other C^2 systems. (Bethmann and Malloy, 1989, p. 21)

Advancements in the computer field, in particular microprocessors, have greatly simplified the usage of MB and increased the reliability of the system and the data throughput. Computers, in addition, have virtually made MBC transparent to the user.

The C^2 process has three major functional areas: information management, decision management, and execution management. Each functional area is made up of four basic functions that interact with the environment. The basic functions are: observe, orient, decide, and act, originally presented by Colonel John Boyd. Commonly known as the O-O-D-A Loop, it is driven by the state of the environment, which the C^2 process is attempting to manipulate. (Bethmann and Malloy, 1989, pp. 13-14)

MBC is primarily involved with the information management portion of the C^2 process. Information management inputs are received from local and remote sensors within the environment for situational assessment and also from higher levels of authority providing guidance and direction. The ability for a C^2 system to provide timely and accurate information will significantly impact how well a commander can accomplish the mission. (Bethmann and Malloy, 1989, p. 17)

E. C² SYSTEM CHARACTERISTICS

All C^2 systems have six characteristics in common, they are: reliability, survivability, flexibility, responsiveness, interoperability, and user-orientation. (Bethmann and Malloy, 1989, pp. 26-27)

1. Reliability

The reliability of a C^2 system is measured by the mean time between failures (MTBFs), which is estimated while the system is in the design phase of its life cycle. The MTBFs of the system have to meet or exceed peace/war time specifications for acceptance.

2. Survivability

A C^2 system must have a high probability of survival in both hostile and natural environments. The loss of a single component cannot cause catastrophic failure of the entire system. Redundancy has to be developed into the system to prevent such occurrences.

3. Flexibility

The system must be capable of adapting to changes in the employment roles, and it must be compatible with future technological upgrades. Changes or "improvements" cannot cause negative or detrimental effects to the system.

4. Responsiveness

The C^2 system must respond quickly and accurately to multiple situations in order to provide time critical information to the commander. "Time-late information is useless information." (Bethmann and Malloy, 1989, p. 27)

5. Interoperability

Interoperability is essential in a joint or combined operations environment. New C^2 systems of the uniform services must be compatible with other new or preexisting systems, to provide combined force effectiveness. Joint Pub 1-02 defines interoperability as "The ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use them to operate effectively together." (JCS, 1989, p. 190)

6. User-orientation

C^2 systems should not be difficult for the user to incorporate into existing systems. Information must be provided in a concise and unambiguous format. Personnel should be able to enter messages into the system just as efficiently as the messages are extracted.

F. STRATEGIC NUCLEAR C^2

Strategic nuclear C^2 is essential to the detection of incoming attacks and the ability to provide direction to the Armed Forces. A nation with an established strategic nuclear C^2 system that is responsive, accurate, survivable, and reconstitutable will possess a formidable deterrent against any would-be adversary. (Bethmann and Malloy, 1989, p. 71)

1. Strategic Forces

The strategic defense of the United States consists of three different forces with the same mission of deterrence. The Strategic Air Command controls two of the forces, the intercontinental ballistic missiles (ICBMs) and the long-range manned bomber. The U.S. Navy controls the other, the sea launched ballistic missile (SLBMs), aboard the ballistic missile nuclear submarines (SSBNs). Control of the Strategic Triad is combined under the Single Integrated Operational Plan (SIOP), specifying principal targets and employment options.

2. North American Aerospace Defense (NORAD)

NORAD is responsible for the detection, assessment, and warning of incoming attacks against the U.S. and Canada. NORAD's detection capability has multiple fixed and mobile early warning radar sensors surrounding the North American continent. After detection, NORAD assesses the incoming attacks and relays the information to the National Command Authority (NCA).

Currently, NORAD is employing a MBC link established in May 1990. The link connects MacDill AFB, FL to Wasilla, AK, via multiple relay stations (Hewish, 1990, pp. 143-144). The link provides an operational backup for satellite communications and an intelligence communication system. The

Wasilla terminal is connected to the Alaska Air Command's North Warning System, in Anchorage. The North Warning System operates a separate MB network as a backup to satellites. The network relays information from remote early warning radar sites, strategically placed along the Alaskan border, to the Air Command's headquarters, and then onto NORAD's MB link. (Schanker, 1990, pp. 24-25)

3. Minimum Essential Emergency Communications Network (MEECN)

The MEECN is an assortment of strategic nuclear C^2 systems/assets designed to ensure the connectivity between the NCA and the U.S. Armed Forces. New assets are continually being added to MEECN due to advancements in technology.

In 1981, DCA was tasked to investigate airborne MB as a potential asset for MEECN. Through tests conducted at Wright-Patterson AFB, OH, airborne MB was proven to be feasible and compatible with ground MB terminals. The tests simulated sending an 80 character test message between a master station aboard a specially equipped KC-135 aircraft and a remote station in a ground mobile platform. The test results showed a high message receipt rate with low waiting times between bursts. MBC in an airborne environment was concluded to be practical and worth further consideration as a MEECN asset. (CCTC TR 197-81, 1981, pp. 7-1/2)

a. National Emergency Airborne Command Post (NEACP)

The U.S. has three alternative command posts, two of which are fixed site locations and the third, an aircraft. The two installations are not expected to be survivable, unlike the aircraft. The airborne command center has the communication equipment necessary to establish links between the NCA and forward-deployed commanders and other strategic forces. This capability allows the NCA to direct the retaliatory forces during a trans- and post-nuclear environment.

b. Strategic Submarine Communication System (TACAMO)

The TACAMO aircraft relays radio messages between the NCA and the SSBNs. Two aircraft are continuously airborne over the Atlantic and Pacific Oceans. The aircraft trail VLF long-wire antennas for broadcasting Emergency Action Messages (EAMs) to the deployed SSBNs, if the need should arise.

G. CURRENT STRATEGIC COMMUNICATIONS

The survivability of strategic communications is critical to effective strategic nuclear C^2. Intrusion or interference, whether due to enemy intervention, high-altitude nuclear bursts, or natural disturbances, can result in warning, alert, EAM, and termination messages not being transmitted or received.

The primary DOD strategic communication system in use today is the Defense Satellite Communication System (DSCS), utilizing super-high frequency (SHF) SATCOM. DSCS is considered a national asset, but with limited resources, it will be unable to meet the increasing demand. As dependence on SATCOM continues to grow, the vulnerabilities of the system need to be considered. SATCOM is susceptible to jamming and evolving anti-satellite weapons. Another point of contention against satellites is the existence of only two satellite launch facilities within the U.S., Cape Kennedy, FL and Vandenburg AFB, CA, both of which are on the coasts and vulnerable to air, land, and sea attack.

An alternative means of long range communication, planned to be operational in the early 1990s, is the Ground Wave Emergency Network (GWEN). The system utilizes VLF remote relay stations across the U.S. to link the NCA to strategic command centers and SIOP forces. The system has built-in redundancy, using packet switching techniques for reconstruction of connectivity if system damage occurs.

H. SUMMARY

As a potential C^2 asset, MBC is a flexible system with various operational modes available to meet a commander's needs and objectives. Inherent characteristics, such as its survivability and covertness, make MBC desirable to the DOD as an alternative long-range communication system. A number of MBC systems have been successfully tested in the air, on land and at sea, and have been proven feasible and reliable. The establishment of a MBC buoy relay network would ensure open lines of communication to the deployed submarine fleet and other suitably equipped platforms. At times when the "fog of war" seems thickest, unobstructed communication links are essential for effective C^2, thereby allowing the dissemination of orders and reduction of uncertainty.

III. METEOR BURST: AN OVERVIEW

A. METEORS AND METEOR TRAILS

Billions of meteor particles enter the earth's atmosphere daily. The vast majority of meteors are believed to have originated within the solar system and orbit the sun in the same direction as the planets.

Meteor showers are thought to be remnants of comets within our solar system, and are grouped together in streams. The streams are in elliptical orbits around the sun, periodically passing by earth and causing a hail of visible electrons. These showers are grouped as follows: Quadrantids (January), Arietids (May, June), Perseids (July, August), and Geminids (December) (Freeman, 1991, p. 661). Meteor showers are not continuous, therefore they will not be considered for our purposes; however, data throughput is increased during the showers. Instead, sporadic meteors are used as the source of meteor trails for our calculations.

Sporadic meteors, although random in nature, occur approximately 10^{12} times per day, throughout the year. The number of meteors of any given size that enter the earth's atmosphere each day varies inversely to size, with smaller meteors being more plentiful than the larger meteors. Table 1 shows this relationship (Sugar, 1964, p. 119).

Table I: ESTIMATES OF THE PROPERTIES OF SPORADIC METEORS

	Mass (grams)	Radius (cm)	Number swept up by earth per day	Electron line density (electrons /meter)	
Meteors that strike earth	10^4	8	10		
Meteors burned up in atmos.	10^3	4	10^2		
	10^2	2	10^3		
	10	0.8	10^4	10^{18}	
	1	0.4	10^5	10^{17}	
Meteors utilized by MBC	10^{-1}	0.2	10^6	10^{16}	
	10^{-2}	0.08	10^7	10^{15}	
	10^{-3}	0.04	10^8	10^{14}	Overdense Underdense
	10^{-4}	0.02	10^9	10^{13}	
	10^{-5}	0.008	10^{10}	10^{12}	

As meteors enter the atmosphere, trails form when they collide with the relatively dense air molecules of the lower atmosphere. The collisions with the air molecules cause the particles to evaporate or burn-up, leaving trails of positive ions and free electrons. The trails are approximately 20 km in length and initially less than a meter in diameter, but due to ambipolar diffusion, will dissipate in a matter of seconds (Griffiths, 1987, p. 234). This occurs in what is known as the Meteor Region, which is between 120 and 85 km above the earth's surface. (Rasmussen, 1991)

In the late 1920s, an accidental discovery was made that meteor trails could actually reflect or reradiate VHF radio signals. However, it was not until the late 1940s that research dealing with meteor scatter was actively pursued. (Weitzen, 1991)

B. MBC CHARACTERISTICS

Intermittent burst transmissions are inherent to MB communication systems, thus generating very low data rates. Data throughput typically range from tens to hundreds bps (Freeman, 1991, p. 658). Inherent also to MB is the interval between suitable meteor trails, known as the waiting time. This time parameter suggests approximately how long a message may be idle before initial or subsequent transmission. Waiting times can range from a few seconds to several minutes (Schanker, 1990, pp. 13-14). As a result, MBC systems cannot support voice communications, although it has been successfully tested using synthesized voice. (Rasmussen, 1991)

C. RANGE OF MBC

The range of a MB link is dependent on the altitude of the meteor trail and curvature of the earth. A MB system can expect ranges between 0 and 2000 km; however, the shorter ranges will more likely experience propagation by direct LOS, not an ionized trail. (Schanker, 1990, p. 20)

Specifically, the range is directly related to the amount of "common volume" within the meteor region that is illuminated by the two terminals' antenna patterns. Paths greater than 2000 km between terminals have virtually no common volume illuminated. Longer ranges have been attained, but required utilizing MB relay stations. (NOSC TR 1171, 1987, p. ES-1)

D. SPATIAL AND TEMPORAL VARIATIONS

1. Spatial

Spatial refers to the meteor distribution varying with latitude. Meteor intensity is lowest at the higher latitudes, but more uniformally distributed diurnally. The middle latitudes experience a sinusoidal variation with higher meteor intensity, depicted in Figure 3. The meteor intensity at lower latitudes is currently under study with the use of a MB test bed in Brazil, established in 1991 (Rasmussen, 1991). (Freeman, 1991, p. 661)

2. Temporal

a. Diurnal Variation

The middle latitudes have most of the meteor trail activity occurring approximately at 6 am local time. The reason is that, as the earth travels through space, the leading edge of the planet "sweeps-up" slower meteors in its

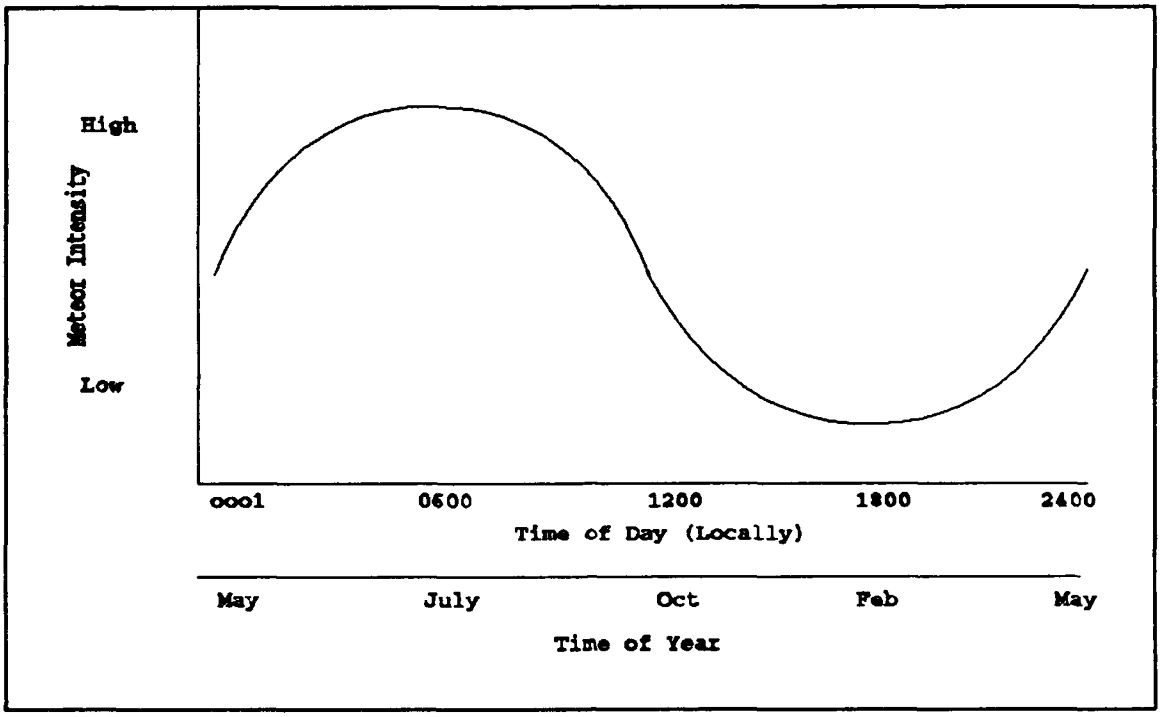

Figure 3: Middle Latitude Temporal Variations

path, in addition to those meteors traveling on a collision course with the planet, as shown is Figure 4. The minimum amount of meteor trail activity occurs during the early evening hours, approximately at 6 pm local time. The only meteors entering the earth's atmosphere at this time are those that overtake the earth. (Weitzen, 1991)

The time interval between usable trails is measured by the average waiting time. In the mornings, 50% of the trails have an average waiting time of five seconds. During the evenings, 50% of the trails have average waiting times of 20 seconds. The time intervals for morning and evening trails are based on empirical meteor activity data from the middle

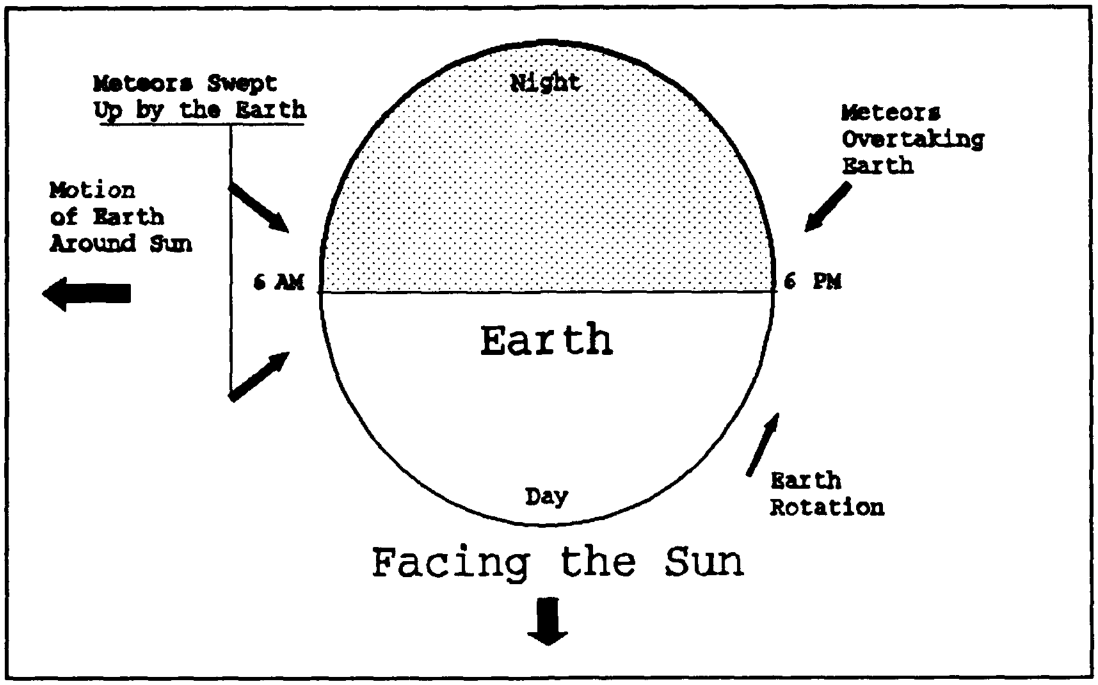

Figure 4: Cause of Diurnal Variation

latitude research sites using a 40 MHz signal. (Rasmussen, 1991)

b. Seasonal Variation

Seasonal variation also affects the number of meteor trails observed. The variation is latitude and hemisphere dependent, caused by the seasonal tilt of the earth's axis and recurring meteor showers. In the northern hemisphere, seasonal variation peaks in July and decreases to the minimum by February, also depicted in Figure 3. Combining the diurnal and seasonal variations, the number of trails between a February evening and a July morning differs by a factor of ten. The opposite holds true for seasonal variation in the southern hemisphere. (Weitzen, 1991)

E. METEOR TRAIL GEOMETRY

A meteor trail must have the proper geometry with respect to the transmitter and receiver sites to ensure the necessary connectivity required for a MB link. This geometry, depicted in Figure 5, can be thought of as a three dimensional series of ellipses sketched between the two sites. Signal propagation requires a meteor trail to enter tangentially to an ellipse, allowing the angle of incidence to equal the angle of reflection. (Schanker, 1990, p. 90)

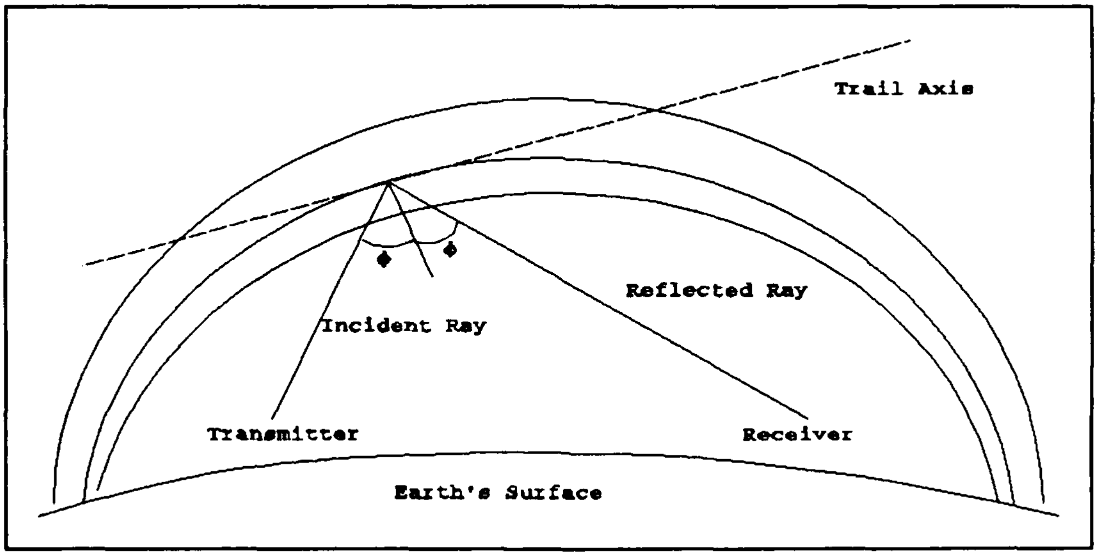

Figure 5: Trail Geometry

1. Hot Spot Regions

The point of reflection for a meteor trail is not usually over the center of the great circle path or along the axis between the two sites. To enter that region, a meteor would have to travel horizontally, thus penetrating more atmosphere and burning-up before getting over the path. The majority of usable reflections occur off to either side of the path, in regions known as hot spots.

Figure 6 depicts the hot spot regions for a path length of 1000 km. The majority of usable ionized trails will occur 100 km to either side. The inner regions show the relative signal contributions from the sky area. (Schanker, 1990, p. 20)

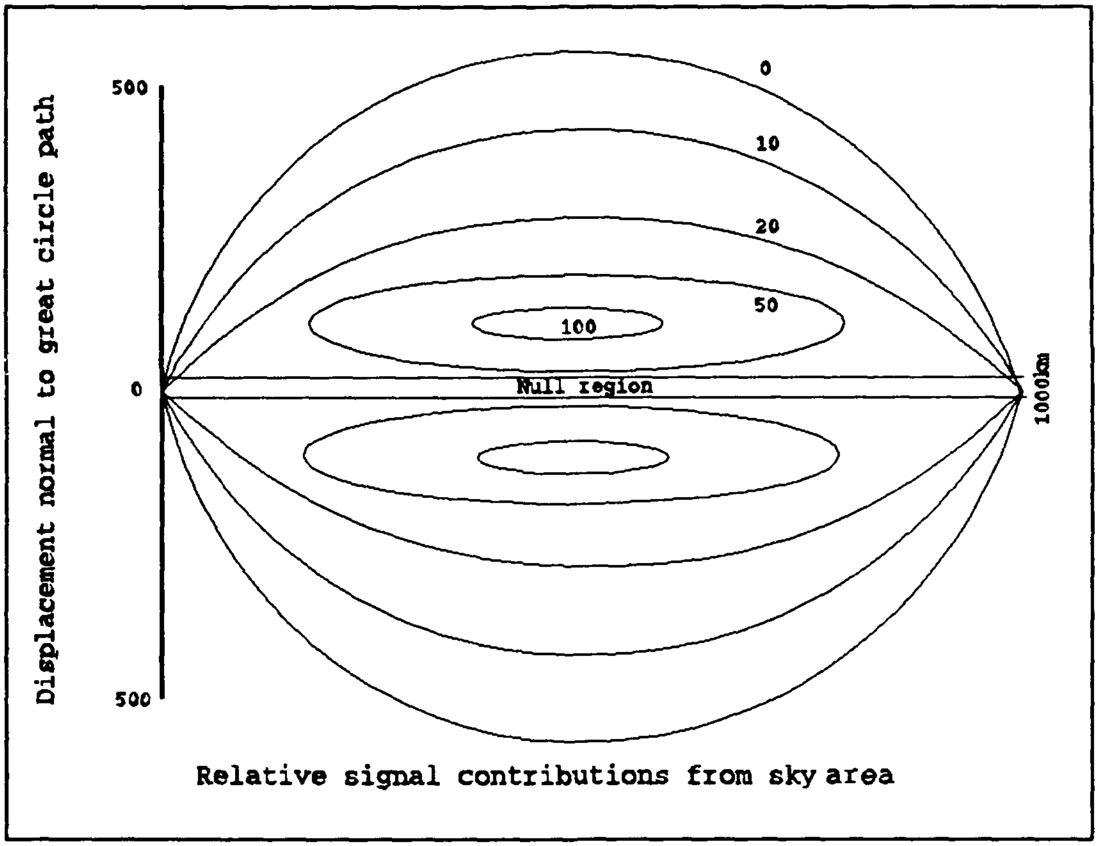

Figure 6: Hot Spot Regions

Hot spots are dependent on time of day and geometry of the link path. Knowing these two factors, the hot spot phenomenon can then be used to the communicator's advantage by positioning directional antennas toward the particular areas of the sky with the highest probability of usable meteor trails.

Ideally, a MBC link should have at least one directional antenna, either at the transmitter or receiver site. Two omnidirectional antennas may not have enough gain required to establish the link. (Schanker, 1990, p. 19)

F. TRAIL CLASSIFICATION

Meteors are classified as either overdense or underdense. The classification refers to the electron line density of the ionized trail being above (overdense) and below (underdense) $1X10^{14}$ electrons per meter. (See Table 1)

1. Underdense Trails

Underdense trails do not actually reflect the RF energy due to the electron line density, rather the energy is reradiated by exciting the individual electrons in the trail. Underdense trails are characterized by a rapidly rising signal to a peak followed by exponential decay, lasting from a few hundred milliseconds to a few seconds, as shown in Figure 7. The electron density of the trail weakens as the trail's radius increases due to ambipolar diffusion. (Schanker, 1990, p. 9)

2. Overdense Trails

Conversely, overdense trails actually reflect RF energy off the trails due to the electron line density being

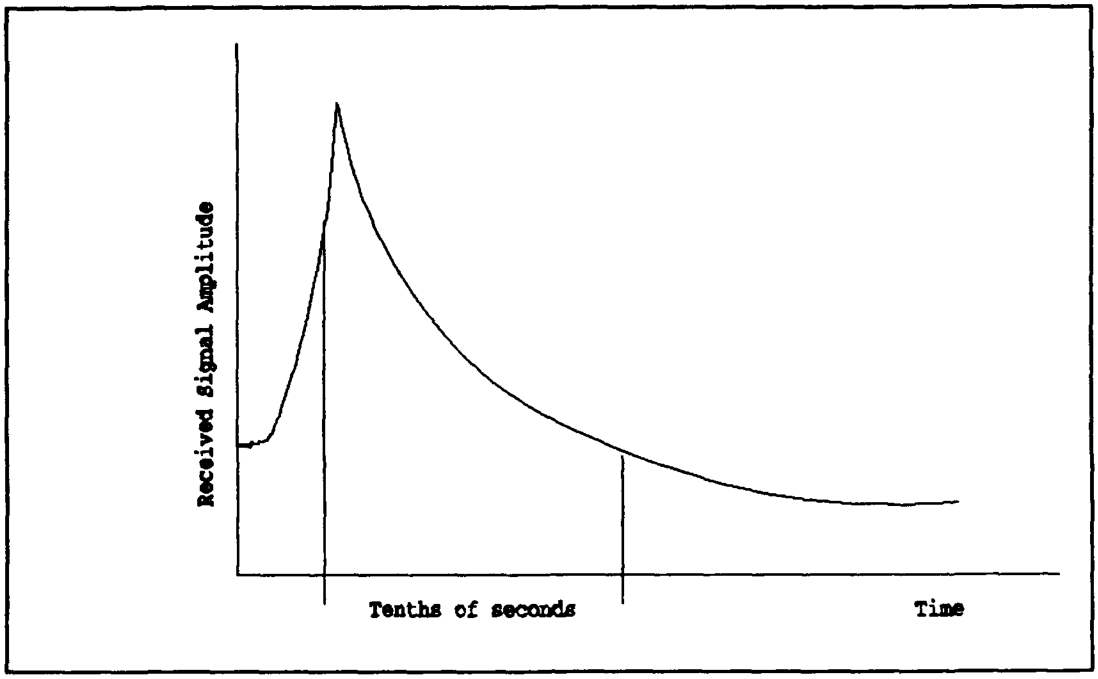

Figure 7: Underdense Trails

so great. They are characterized by a slow rising signal that stabilizes and then begins to dissipate, transitioning to an underdense trail, as shown in Figure 8. Overdense trails are preferred because they last longer, however they account for less than five percent of the number of trails suitable for MBC. Even so, overdense trails carry approximately thirty percent of the throughput of a MBC system. (Schanker, 1990, p. 9)

G. IONOSPHERIC DISTURBANCES AND SURVIVABILITY

An ionospheric-disturbed environment can be caused by either a solar flare or a nuclear detonation. High latitudes experience conditions that naturally simulate such an

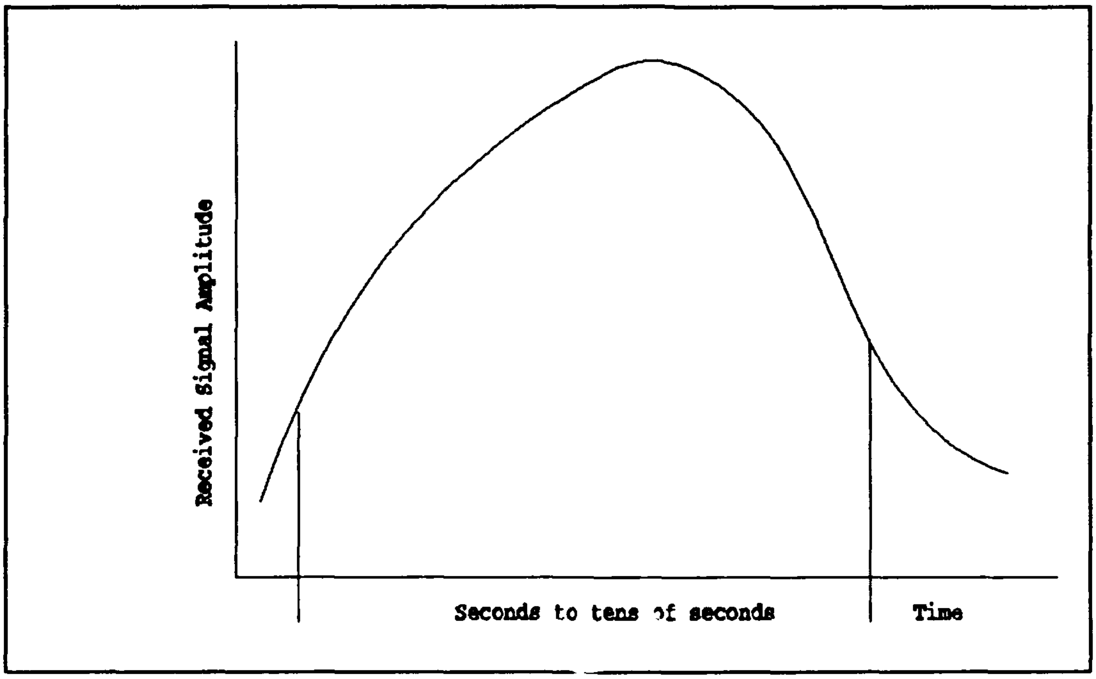

Figure 8: Overdense Trails

environment. A common phenomenon caused by solar disturbances is the aurora. Auroral regions are located in the northern and southern hemispheres, centered on the magnetic poles.

In the interest of studying the effects of such an environment, a high latitude test bed was established in Greenland. The test site, a 1250 km link from Thule Air Base to Sondrestrom Air Base, was created by Phillips Laboratory (formerly the Air Force Geophysics Lab) to study auroral effects on a MB system. The occurrence of a large solar flare will produce a burst of charged protons radiating into space. When the protons reach the earth's magnetic fields they are deflected and "funneled" into the magnetic polar regions. The charged particles effectively make the D layer of the ionosphere thicker by creating additional electrons. The thicker D layer becomes more absorptive than usual, allowing only the highest of frequencies to penetrate.

A tradeoff exists for MB between frequencies and data rates. Meteor trails vary depending on the frequencies that can be reflected or reradiated by the trails. Based on data collected at the high latitude test bed, Phillips Lab recorded the average number of trails for six frequencies. Four trails per minute, with a capacity of 150 bps, were observed at 45 MHz, as compared to one trail every two minutes, with a capacity of less than 50 bps at 104 MHz. As a result, a higher percentage of data was passed with the lower frequency, under normal conditions. In August 1989, a polar cap absorption phenomena was recorded by the Lab revealing that the lower frequencies were unavailable for a day and a half, while the higher frequencies with very low data throughput were unaffected by the disturbance. (Rasmussen, 1991)

This is the reasoning on which the MB survivability issue is based. MB and HF sky wave transmissions both have to penetrate the D layer, as shown in Figure 9, to communicate with the receiver; but MB systems will be operational sooner since it utilizes frequencies in the VHF range. Regardless of the type of disturbance, meteors will continue to enter the earth's atmosphere forming meteor trails, and maintaining the ability to support communications. (Rasmussen, 1991), (Weitzen, 1991)

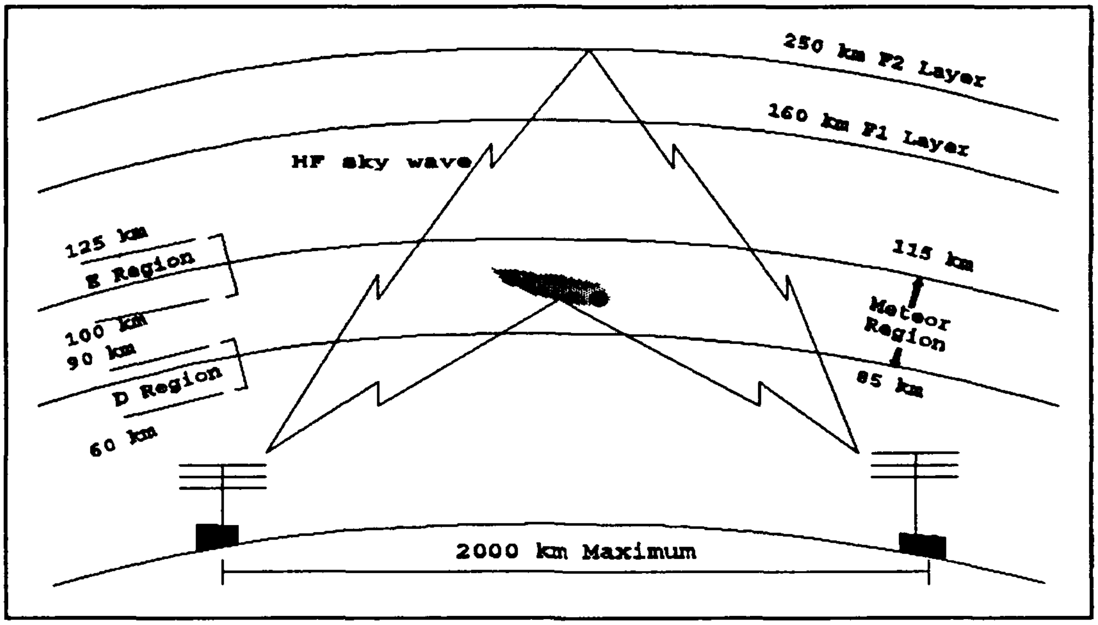

Figure 9: Ionosphere Propagation Path

H. MBC EQUIPMENT

MBC links consists of two types of terminals, masters and remotes. Masters operate as the active components, while remotes operate passively, until activated by a master. Both terminals are transceivers, typically configured for half-duplex operation, where alternating transmit and receive transmissions occur on separate frequencies (Freeman, 1991, pp. 664-665). Other configurations include full-duplex operation, where simultaneous transmit and receive transmissions occur on separate frequencies; simplex operation, where alternating transmit and receive transmissions occur on the same frequencies; and broadcast operation, where a master continually transmits on a single frequency, and remotes monitor that frequency. Link connections can be established between: masters, a master and remotes, and remotes via a master.

I. COVERTNESS

MBC has inherent low-probability-of-intercept (LPI) and anti-jam (AJ) features, successful against ground based interception.

1. Low Probability of Intercept

When a radio signal is propagated by a meteor trail, only a small swath or footprint is illuminated on the earth's surface. An intended receiver must be within that footprint to receive the radio signal. The footprint size is based on the location of the trail in relation to the transmitter and receiver sites, as depicted in Figure 10. As a result, each trail will illuminate a different footprint on the surface. Depending on the length of the message, it can be relayed over multiple trails with only the intended receiver common to all footprints. (Weitzen, 1990, p. 428)

The possibility does exist however, that an unintended receiver may be within the footprint of the receiver, on occasion. To combat this possibility, an encryption device, such as the KG-84A, can be integrated into a MBC system.

Direction finding is also made difficult for distant interceptors because MB propagation does not occur along great circle paths. The direction of arrival of the signal

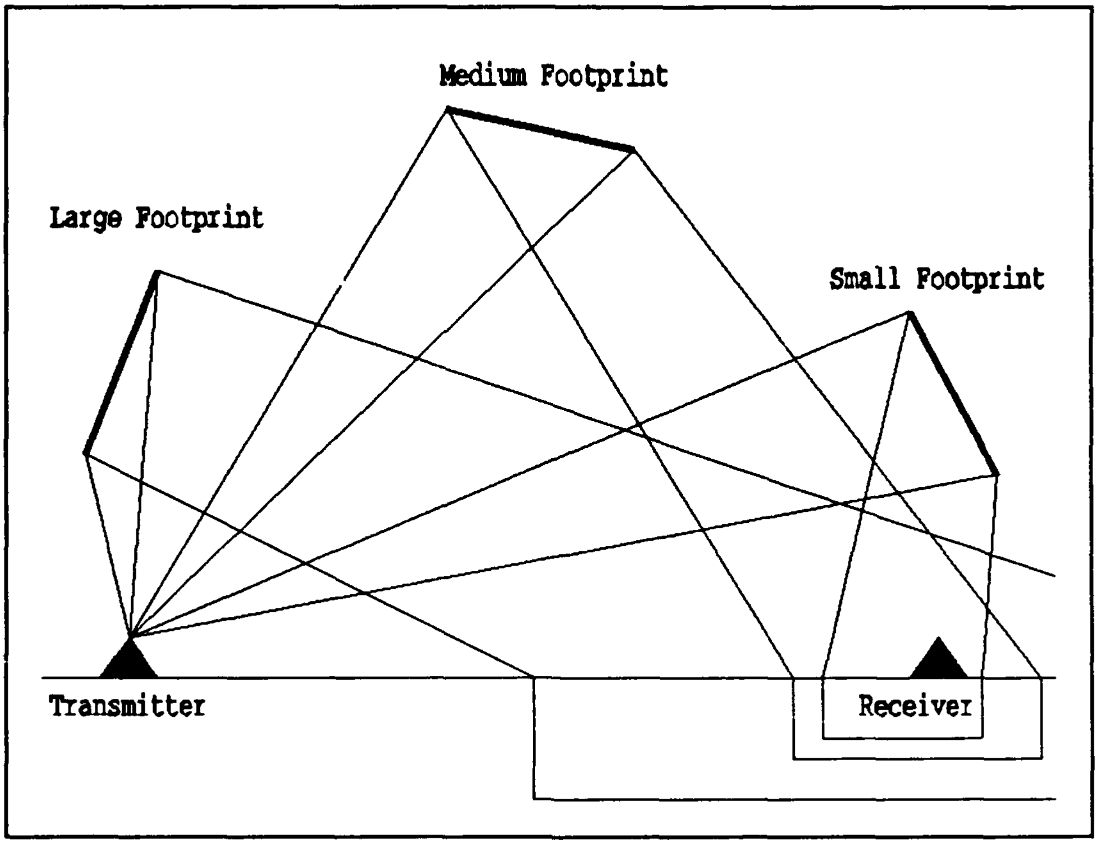

Figure 10: Relative Footprint Sizes

continually changes as each new meteor trail becomes available. This is not true for interceptors that are close by, within groundwave range of a terminal. (NOSC TR 1150, 1986, pp. 3-5)

2. Anti-Jam Characteristic

The same footprint phenomenon, which is true for LPI, also holds when considering the vulnerability of a MB link to jamming. An interfering signal, whether intentional or not, from an unintended transmitter must be within the footprint of the intended transmitter to propagate to a MB receiver. (Oetting, 1980, p. 1591)

3. Ionospheric Anomalies

There are certain anomalous propagation conditions that might limit the covertness of MBc. Under Sporadic E (E_s) conditions[2] for instance, links could be established for extended lengths of time. MB links would have continuous instead of burst connectivity, allowing high throughput rates to be experienced; however, the signal would be scattered in all directions, propagated over vast distances and easily detected. Similar effects may also be experienced under spread F and auroral scatter[3] propagaton conditions. (Oetting, 1980, p. 1592)

J. DATA RATES

1. Techniques

Two data rate techniques exist for MB when transmitting a signal. A fixed rate technique transmits data at a specified rate from the time the trail is observed until

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[2]The E_s layer is a thin ionized cloud with highly dense electrons, that forms within the meteor region. The cloud may either be stationary or drift along at the same altitude, thus its sporadic nature. E_s is normally a daytime phenomenon, but can be present at night.

[3]Spread F is when the F layer becomes more diffuse, resulting in greater multipath effects. Auroral scatter results from signals propagating off the intensely charged auroral regions, centered at the earth's magnetic poles. (Freeman, 1991, p. 555)

it dissipates. The adaptive rate technique continuously deter ~es the data capacity of a trail, and adjusts the data rate accordingly. As a trail strengthens or weakens, the data rate can be increased or decreased, respectively. In order for an adaptive system to function, the system requires an adaptive rate modem which is configured for full-duplex operation. The terminals will continually pass control signals to determine current trail strength, and vary the data rate accordingly. (Morgan, 1988, p. 59)

2. Data Throughput

Data throughput can be measured by instantaneous burst data rate and average data rate. A MBC terminal will transmit data in high-rate bursts throughout the duration of a meteor trail, approximately 0.2 to 2 seconds. Burst data rates for most systems range from 2 to 8 kbps, but have been demonstrated up to 38.4 kbps (NOSC 1150, 1986, p. 3). Average data rates combine the instantaneous burst data rates with the waiting times between suitable meteor trails and average those values over time. Common average data rates range from less than 100 to 200 bps. (Freeman, 1991, p. 667)

IV. LINK ANALYSIS

The link analysis has calculations and tabulations useful in determining the signal power and interfering noise power available at the receiver. The link summary can then be determined and used as an estimate for the evaluation of a communication system's performance. The summary also can be useful in the consideration of system trade-offs and configuration changes, and help in the understanding of the subsystems' interdependencies. (Sklar, 1988, pp. 188-189)

A. EXPERIMENTAL BUOY RELAY SYSTEM

Research completed by the Naval Ocean Systems Center (NOSC) in the mid-1980s considered the feasibility issue of a meteor burst communication (MBC) buoy relay system. NOSC reviewed the hardware and software requirements for transoceanic, ship-to-shore and ship-to-ship MBC. Multiple types of buoys, antennas, batteries, transmitters and receivers were evaluated for survivability and reliability in an ocean environment. (NOSC TR 1150, 1986, pp. vi-xii)

Actual MBC experiments were conducted by NOSC utilizing a specially designed moored relay buoy and a relay ship to establish a 2000 nm MBC link between San Diego and Hawaii.

The experiment proved that such a relay system was possible and worth further investigation.[4] (NOSC TR 1171, 1987, pp. ES 7-13)

B. LINK ANALYSIS

The link analysis will review four operating frequencies in the MB frequency spectrum. Various link distances also will be considered to reflect the continually changing network geometry caused by ocean currents and the uncertainty of exact buoy placement.

A typical MBC system will average about 100 words per minute throughout the day at a frequency range between 40 and 50 MHz, though the frequency possibilities range from 30 to over 100 MHz (Griffiths, 1987, p. 234). MBC consists of multiple transmission bursts, occurring at random intervals of a few seconds to minutes, therefore the average data rate will be substantially slower than the burst data rate.

1. Military Standard (Mil-Std)

The Defense Information System Agency (DISA), formerly DCA, published the Mil-Std "Interoperability and Performance

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[4]Unfortunately, the moored MBC buoy's tethered line was cut by a passing ship and set adrift prior to the completion of all tests. The buoy was never recovered, although the master terminal in San Diego was able to establish and maintain a MB link for seven months before losing contact. It is believed that the loss of contact was due to the buoy drifting over 1000 nm south of San Diego and not caused by battery discharge.

Standard for Meteor Burst Communications," (Mil-Std-188-135).[5] The document establishes the DOD standards that manufacturers have to follow if their MBC equipment is to be accepted, and be compatible with existing systems. According to the Mil-Std-188-135, all new equipment shall have: a frequency range of 30.000 to 88.000 MHz; an occupied bandwidth (BW) restricted to 20 kHz or less; the modulation method Differential Binary Phase Shift Keying (DBPSK) with coherent detection; burst data rates capable of two, four, and eight kbps; automatic repeat request (ARQ) retransmission technique for error control; and ANSI-16 Cyclic Redundancy Check (CRC) for error detection. (Mil-Std-188-135, 1988, pp. 8-9)

The Mil-Std also states MBC systems " . . . will support long-term average throughput[6] under benign conditions from 10 to 100 bps with a bit error rate (BER) of 3×10^{-4} or better." A "benign condition" is that which is restricted to galactic and manmade noise, collocated radiators, and mildly disturbed media, such as auroral propagation and limited D-layer absorption. (Mil-Std-188-135, 1988, p. 2)

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[5]Proposed Federal Standards 1055-1057, dealing with MBC, are scheduled to supersede the Mil-Std upon approval in the third quarter of 1992. Minor changes should be anticipated.

[6]Long-term average throughput is the mean data rate of a MB system, derived by combining the burst data rate with the waiting time between transmissions averaged over a period of time.

2. Buoy Relay Specifications

The air-deployed buoys will utilize two different types of batteries, namely a 35 lb. nickel-cadmium battery for its high discharge rate and a 50 lb. lithium battery for recharging the first battery. The lithium battery also would double as ballast by being suspended from the buoy. The purpose of the ballast is to keep the buoy in an upright orientation in high sea states. (NOSC TR 1150, 1986, p. 58)

Because the buoy has a finite power supply, the power output of the transmitter is limited to 300 watts (W). An additional buoy design limitation is the omnidirectional, vertical J-antenna, required due to its higher probability of surviving in an ocean environment. The J-antenna is telescopic, which allows for ease in erecting upon water entry. Vertically polarized antennas, as compared to horizontally polarized antennas, have the optimum gain when mounted at lower heights, i.e., ten feet above the surface. The buoy relay antenna will experience a five dB gain due to its vertical polarity and the ocean surface acting as a ground plane, enhancing signal reflection. (NOSC TR 1150, 1986, pp. 17 & 58)

3. Link Performance

The following equations predict the performance of a MBC link summary (Freeman, 1991, pp. 596-598, 668-686).

a. Receiver Threshold

The calculations for the MBC receiver noise threshold are similar to the HF method standardized in the International Consultive Committee for Radio (CCIR) Report 258-4. A commonality exists for all receivers in communication links, that is they are externally noise limited. The MBC buoy relay system operates in a "quiet" open-ocean environment, absent of manmade noise and unaffected by atmospheric noise that influences frequencies below 20 MHz. The dominant noise in such an environment is galactic, which originates outside the earth's atmosphere, from the sun and other cosmic sources. The median noise (F_{am}) value for the environment can be calculated from the following expression:

$$F_{am} = c - d(\log f)$$

where f = the operating frequency in MHz, and
c and d = the constant values that represent the noise found in the environment.

The values for galactic noise are found in CCIR Report 258-4. A caveat to the report advises that the equation above may give erroneous values for a low noise environment, where galactic or rural noise is predominant.

The equation for noise power (P_n) present at the receiver is:

$$P_n = F_{am} + (D_u + \sigma) + 10(\log BW) + 204\ dBW$$

where D_u and σ = deviation values for F_{am}, and
BW = the system's bandwidth.

An assumption will be made that the values for D_u and σ are both zero for simplicity, based on available information from CCIR Report 258-4. The value 204 dBW is the log of Boltzmann's Constant, 1.38×10^{-23}, combined with the log of the system's effective temperature, 290°K. The receiver threshold (T_r) can be derived by:

$$T_r = P_n + \frac{E_b}{N_o}$$

where E_b/N_o = the receiver signal energy per bit per hertz of thermal noise.

The requirement for DBPSK modulation with a BER of 3×10^{-4} dictates an E_b/N_o of 8.7 dB, which must be available at the receiver. (Freeman, 1991, p. 431)

b. MBC Transmission Loss

The MBC transmission loss (MBC_{TL}) is a combination of free-space loss (L_s) and MBC scatter loss (MBC_{sl}). L_s is common to all VHF communication links and based on two variables, the operating frequency of the link and the distance between the terminals. The L_s equation is:

$$L_s = 20(\log f_{MHz}) + 20(\log D_{km}) + 32.45$$

where f = the operating frequency in MHz, and
D = distance between terminals in km.

$$P_n = F_{am} + (D_u + \sigma) + 10(\log BW) + 204\ dBW$$

where D_u and σ = deviation values for F_{am}, and
BW = the system's bandwidth.

An assumption will be made that the values for D_u and σ are both zero for simplicity, based on available information from CCIR Report 258-4. The value 204 dBW is the log of Boltzmann's Constant, 1.38×10^{-23}, combined with the log of the system's effective temperature, 290°K. The receiver threshold (T_r) can be derived by:

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$$L_s = 20(\log f_{MHz}) + 20(\log D_{km}) + 32.45$$

where f = the operating frequency in MHz, and
D = distance between terminals in km.

expressed in decibel notation referenced to one milliwatt (dBm), is:

$$EIRP_{dBm} = P_t + G_t + L_l$$

where P_t = the transmitter's power output in dB,
G_t = the transmitter antenna's gain in dB, and
L_l = the transmission line loss in dB.

A value of zero will be assumed for the transmission line loss for the buoy relay system.

The system's receive signal level (RSL) is the signal strength at the input to the receiver. The RSL has three elements: the EIRP, the MBC_{TL}, and the gain (or loss) of the receive antenna, given by:

$$RSL = EIRP + MBC_{TL} + G_r$$

where G_r = the receiver antenna's gain in dB.

The link margin (LM) shows whether a system will meet its requirements comfortably, marginally, or not at all. The LM equation is:

$$LM = RSL - T_r$$

If the link margin is positive, then the system is viable.

Figures 12-15 reflect the link summaries for a worst case scenario, where a link is established between two air-deployed buoys with vertical J-antennas. The summaries compare four different bandwidths with four frequencies representative of the MBC frequency spectrum, ranges that represent possible buoy spacing, and the system's link margins. The figures show that the best system performance occurs at the lower frequencies, with the lower bandwidths, and shorter ranges between buoys.

A Lotus 1-2-3® spreadsheet was written to compute the necessary calculations to produce the figures. The Appendix contains a copy of the spreadsheet.

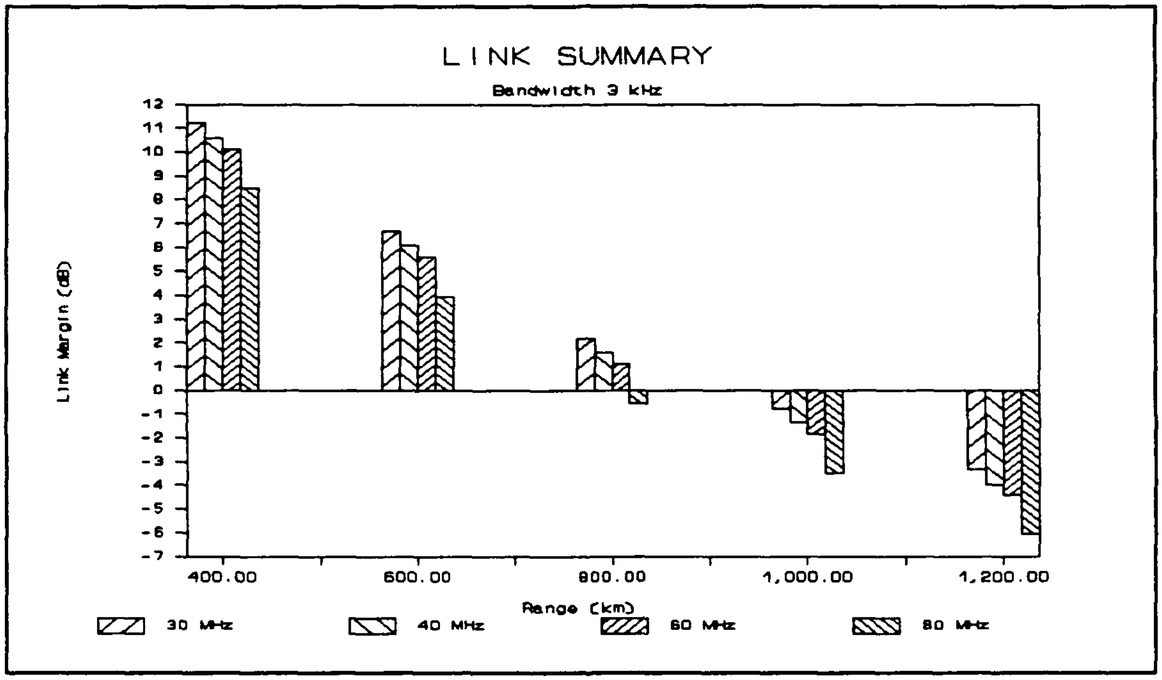

Figure 12: Link Summary - 3 kHz Bandwidth

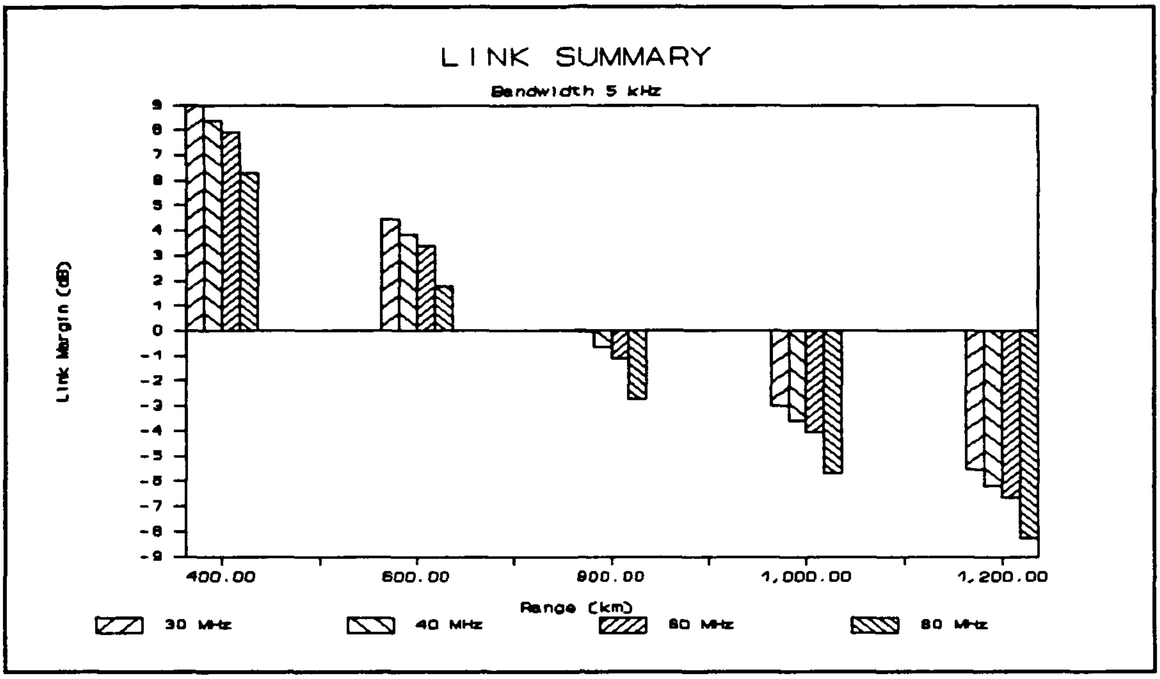

Figure 13: Link Summary - 5 kHz Bandwidth

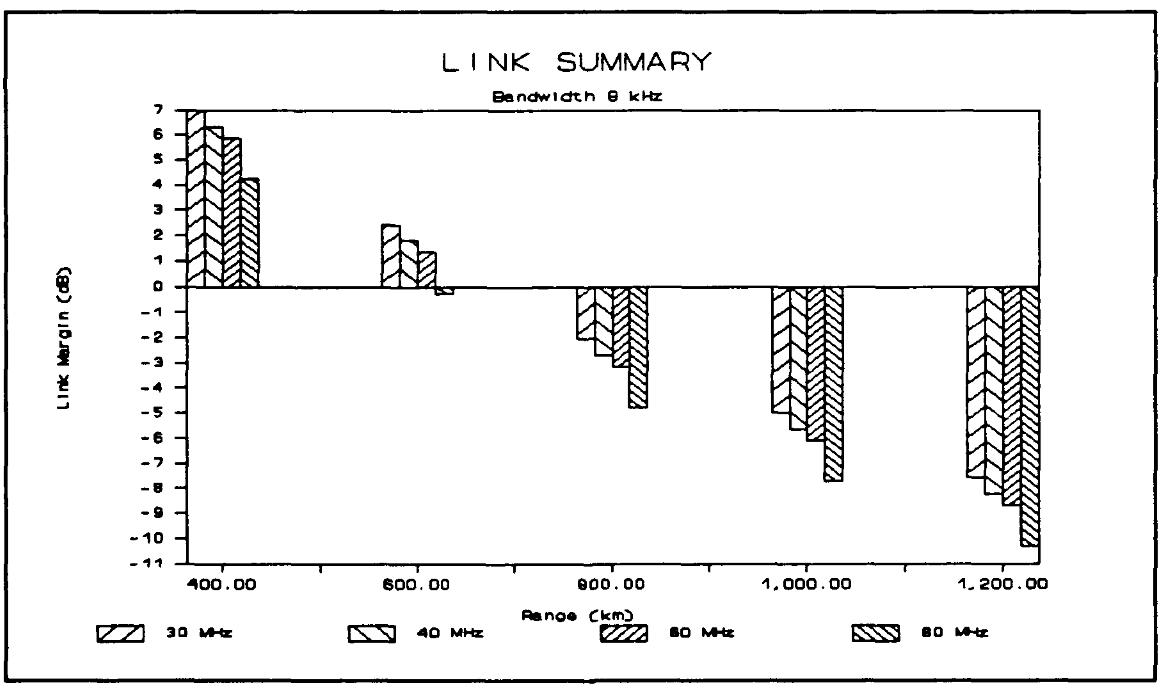

Figure 14: Link Summary - 8 kHz Bandwidth

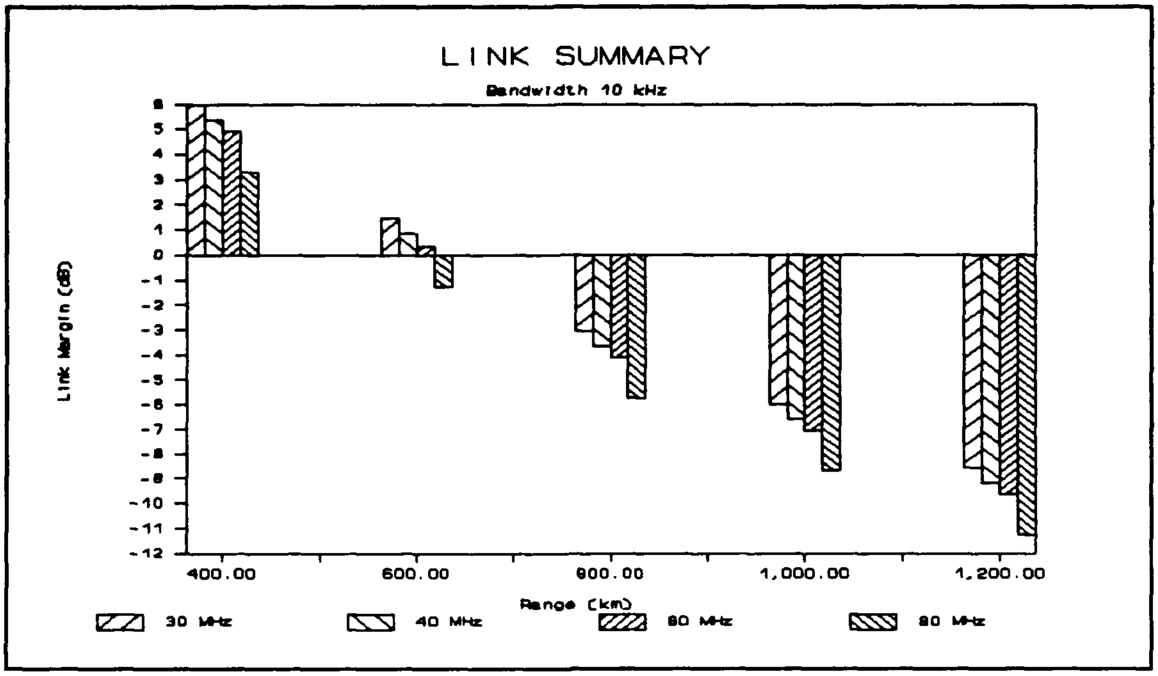

Figure 15: Link Summary - 10 kHz Bandwidth

C. ADDITIONAL LINK CHARACTERISTICS

There are additional MB prediction parameters that go beyond the scope of this thesis. These parameters include: meteor rate, burst time duration, burst rate correction factor, and waiting time probability. All these parameters vary as a function of geographic location. Explanations for these topics can be found in either Freeman or Schanker.

V. METEOR BURST IN THE 1990s

In light of recent events in the Soviet Union, the chance of a nuclear confrontation appears to be diminishing every day. In the past, the primary reason behind DOD's interest in meteor burst communication (MBC) was its inherent nuclear survivability characteristic. Now with the breakup of the Soviet Union, the nuclear survivability issue is no longer at the forefront of DOD's concerns.

A. RECENT APPLICATIONS FOR MBC

According to the Mil-Std, there are two basic types of MB applications: communications and remote sensing. The communication missions accommodate order wire; damage assessment; recovery, reconstitution and retargeting; logistics; force direction and reporting; and continuity of operations. The remote missions accommodate fallout monitoring and meteorological collection. (Mil-Std-188-135, 1988, p. 1)

As previously mentioned, MB is best suited for programs involving low volume communications or data exchange. The following applications have been or are recent proposals for operational systems.

1. Small Intercontinental Ballistic Missile (ICBM)

The USAF had planned to using MB technology with their Small ICBM program until its cancellation by President Bush, in the fall of 1991. The plan entailed transmitting launch orders from a mobile launch control site to the mobile missile platforms within a specified amount of time. Experimentation was done using frequency diversity to counter MB fading, whereby the same message was transmitted over two frequencies using the same meteor trail. Fading occurred between the frequencies, but not simultaneously, allowing for the complete message to be spliced together. Test results showed that lower frequencies did better under normal conditions, whereas higher frequencies did better under disturbed natural conditions. (Rasmussen, 1991)

2. Vehicle Tracking

In the civilian sector, a MB contractor and a commercial trucking company have successfully completed testing on a vehicle tracking system using MB technology. The tests involved monitoring a vehicle's position and status and conducting two-way data communications while on the road. The vehicle's position was automatically determined via an on-board LORAN-C receiver. The testing laid the ground work for a nationwide mobile data communications network scheduled to be operational by the fall of 1992. The system expectation is to upgrade to a Global Positioning System (GPS) receiver when available. (Propst, MCC, 1992)

The system works similar to other MB systems. It operates by a master station transmitting a probe signal every 15 ms. When a meteor occurs within the proper geometry, a remote station will detect the probe signal and then transmit its response message. Upon receipt of the message, the master station will send an acknowledgement (ACK) signal plus any stored messages. The total time to transmit both a data message and an ACK is typically less than 100 milliseconds.

A military application for such a system might be the monitoring of battle-field troop movements in a fast-paced and dynamic environment. In such circumstances, it may not be possible or practical to provide routine situation reports (sitreps) to the commander. The tracking system would automatically provide sitreps while the unit maintains a covert posture.

An additional application might be tracking merchant vessels in high traffic areas for the Coast Guard. Such a system has been considered in the past as part of the Prince William Sound Vessel Tracking Service (VTS). A proposal for an automatic MB vessel tracking system recognized that as the Valdez, AK port expanded, an increase in vessel traffic would result. This promoted an unsatisfactory condition, given the present vessel tracking method of utilizing voice position reports at specific check points. Unfortunately, nothing ever materialized from the 1981 proposal, eight years before the worst oil spill in U.S. history, the Exxon Valdez incident. (MCC TR CG-D-68-81, 1981, pp. 1-5)

3. Remote Data Collection

Many remote MB systems are currently in use worldwide. Such systems are used in remote locations that are otherwise inaccessible or impractical to routine human surveys.

a. Snowpack Telemetry (SNOTEL)

The largest and most well known MB system is the USDA's SNOTEL network, operating since the late 1970s. The network covers the eleven western states of the US, and consists of two master stations and approximately 540 remote stations. The remote sites monitor the depth and water content of the snowpack, in addition to precipitation, soil moisture, temperature, and wind direction and velocity. The information is collected daily, and then translated into water supply forecasts, published by the USDA's Soil Conservation Service. (USDA 536, 1988, pp. 4-11)

The Alaska Meteor Burst Communication System (AMBCS) is a similar network, monitoring snowpack conditions, lake levels, and tidal movement. The AMBCS interrogates its remote stations hourly due to the rapidly changing meteorological conditions in that part of the world. (USDA 536, 1988, p. 11)

b. Water Management

Many countries have set up MB systems for water management. Egypt set up the Nile River Irrigation Data Collection System (NRIDCS), which is the largest water monitoring project in the world. Argentina uses MB technology to monitor precipitation in their upper plains for flood forecasting. China also uses such a system for monitoring the water capacities of their reservoirs. (MCC, 1987, p. 2)

c. Pipeline Monitoring

The Northern Natural Gas Company uses a remote MB system to monitor the following conditions of its pipelines: pressure, temperature, flow control, and external environmental conditions. The country of Indonesia also uses a similar system to monitor their oil pipelines. (SAIC, 1991, p. 1-1)

B. ONGOING MB RESEARCH

The Defense Advanced Research Project Agency (DARPA) is conducting state-of-the-art research in the MB field. They are looking at a wide spectrum of MB technology, with the extremes being a significant increase in data throughput through extending the life of remote battery powered sensors by reducing peak power demands. (Bauman, DARPA, 1992)

1. Increasing MB Throughput

Current MB antennas experience a tradeoff between data throughput and beamwidth. Maximizing data throughput involves being able to focus an antenna toward the "hot spot" regions of the sky to increase the probability of encountering meteor trails. However, focusing an antenna requires reducing the beamwidth, thus limiting the number of trails the antenna is capable of "seeing."

Experiments are underway concerning a new MB antenna, known as a "smart antenna." The antenna involves acquiring a meteor trail and then forming a high-gain beam directed at the trail. An adaptive rate modem would then be used to adjust the instantaneous burst rate, based on the electron density of the ionized trail. Together, the beam forming and the adaptive rate modem would maximize the number of bits over each trail. (Bauman, DARPA, 1992)

DARPA also is researching ways to combat the high noise environment which is detrimental to a MB link. MB systems historically have had slim link margins, whose data throughput can be disrupted with the onset of noise, especially that which is manmade. The research involves the ability to steer an antenna null toward the noise source, effectively reducing or eliminating the noise. (Bauman, DARPA, 1992)

2. Conserving Battery Power

For remote sensors, battery life is a critical factor. The loss of a battery charge might mean the loss of a sensor for an extended period or until a replacement can be set up.

With the anticipated development of the smart antenna, a system tradeoff can be considered. Given that the new antenna has a high gain, the peak power demand at the remote sensor can be reduced, thereby extending the life of the battery. Typically, a remote data sensor does not require as much throughput as a communication system, thus the remote sensor can afford a reduction of data throughput. (Bauman, DARPA, 1992)

A field test is scheduled to take place in July 1992, to demonstrate DARPA's progress made to date in the forenamed areas. A MB link will be established between Griffis AFB, NY and Camp LeJeune, NC, for the demonstration.

3. Future Trends

The Alaska Air Command has specified a need for a real or near-real time voice capability over its North Warning System. As a result, NORAD is sponsoring DARPA to look into the feasibility of utilizing voice over a MB link. As previously mentioned, only synthesized voice has been successfully applied in the past. (Bauman, DARPA, 1992)

The scientists at DARPA hypothesize that four kbps average throughput is possible with MB. Such a throughput is an order of magnitude increase in today's ability. This hypothesis is based on the belief of the existence of a near-continuous MB channel in the ionosphere, first theorized in the 1950s. The channel would allow linear encoded voice signals, ranging from 600-1200 bps, to be continually transmitted over a MB link. DARPA will conduct a field test in Alaska testing the voice capability of MB later next year. (Bauman, DARPA, 1992)

4. Computer Simulation

The above research is possible by advancements with computer simulation. In the past, such experiments would have been to costly to conduct in the field. Now, numerous repetitions of experiments can be run in the laboratory and later verified in the field. Simulations allow the simplification of the "what-if" process, and also allow system optimization.

VI. CONCLUSION

The perceived need for an alternative, long range communication system has resulted in a renewed interest in Meteor Burst (MB) as a medium. Currently, the DOD and USDA are both actively using MB in operational systems, and are pursuing ongoing research in the field.

A. ADVANTAGES AND DISADVANTAGES

As in almost any form of communication, there are several tradeoffs to consider when evaluating MBC systems. Several pros and cons must be understood.

1. Advantages

One of the primary reasons that DOD is interested in MB is the nuclear survivability issue. MB has the ability to recover more rapidly in a nuclear environment than does the HF communication medium. This is due to MB's higher operating frequencies being less susceptible to ionospheric absorption as compared to HF frequencies. In addition, MB is especially useful for long-range communications at higher latitudes where ionospheric disturbances are more common.

The DOD also is interested in the fact that MB is naturally secure. Inherent to MB are the low probability of intercept (LPI) and anti-jamming (AJ) characteristics, which enable the remote terminals to remain somewhat covert to ground-based interception and jamming. This results from the small ground-illumination footprints continually changing each time a new meteor trail occurs. In addition, KG-84A encryption devices and/or spread spectrum techniques can be utilized with MBC systems to minimize any information that might be intercepted.

Frequency management is not a problem for MB systems. A single frequency can be used for a MBC network, despite diurnal cycles, because the medium does not rely on the continually changing ionosphere to reflect signals. This greatly simplifies the process of ensuring that all stations are operating on the proper frequency.

MB systems are typically cheaper than most other communication media. In addition, MB systems have a single hop range up to 2000 km which can be extended further by communication relays. With its low cost and long range, it is a viable alternative for applications with low data rates requiring beyond line-of-sight transmissions.

2. Disadvantages

The disadvantages for MB systems are few, but they are significant. MB is limited because there is a waiting time associated with each transmission. Short data packets, typically separated by null periods of a few seconds to several minutes, are later regrouped to form the message. To date, near-real time communication is the best that can be expected from such a system. However, preliminary research, taking place today in government laboratories, indicate that this may soon change.

The data rates for MB systems are low by today's standards. MB systems have a high burst data rate, but when averaged over time, have a low data throughput. This fact has a significant impact on the type and size of transmissions that can be sent via MB. The average data throughput can range from 100 to 300 words per minute, depending on the time of day, location of the link, and the protocol in use.

MB systems require high power requirements due to its signal scatter characteristics. High power at the transmitter is necessary to produce ranges comparable to HF systems.

B. RECOMMENDATIONS

Continued research is essential in the MB field if this medium is to be completely exploited. Ongoing research in the field allows for an increase in exploration and experimentation, thereby maximizing the usefulness of MB. New applications, previously not thought possible, will result as the medium becomes better understood.

Applications that require substantial investments in research and development (R&D) might be better off avoided, given present circumstances with a shrinking defense budget. The DOD should consider adapting proven civilian applications, such as vehicle tracking, thereby minimizing cost and R&D risk to the government.

Budgetary concerns stated, the MB Buoy Relay System requires a lot of R&D yet to be accomplished. NOSC completed some preliminary work, as far as system designs and concepts, but only one large, prototype buoy was built. The next challenge is to consider making a prototype of the air-deployed buoy. Battery conservation and a survivable, high-gain antenna will be the challenges that need to be met to make this system a feasible and reliable C^2 asset for DOD and the Navy.

APPENDIX

Frequency 30.0 MHz Bandwidth 3.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.48	1.48	1.48	1.48	1.48
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	18.03	18.03	18.03	18.03	18.03
Bandwidth (dB)	34.77	34.77	34.77	34.77	34.77
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(151.18)	(151.18)	(151.18)	(151.18)	(151.18)
Pn: (dBm)	(121.18)	(121.18)	(121.18)	(121.18)	(121.18)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(112.48)	(112.48)	(112.48)	(112.48)	(112.48)
MBC TRANSMISSION LOSS					
Frequency (dB)	29.54	29.54	29.54	29.54	29.54
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	114.03	117.56	120.05	121.99	123.58
MBC Scat Loss (dB)					
from Figure 10	52.00	53.00	55.00	56.00	57.00
MBC Trans Loss (dB)	166.03	170.56	175.05	177.99	180.58
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(166.03)	(170.56)	(175.05)	(177.99)	(180.58)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(101.26)	(105.78)	(110.28)	(113.22)	(115.80)
Rcvr Threshold (dBm)	(112.48)	(112.48)	(112.48)	(112.48)	(112.48)
LINK MARGIN	11.22	6.70	2.20	(0.74)	(3.33)

Frequency 40.0 MHz   Bandwidth 3.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.60	1.60	1.60	1.60	1.60
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	15.15	15.15	15.15	15.15	15.15
Bandwidth (dB)	34.77	34.77	34.77	34.77	34.77
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(154.05)	(154.05)	(154.05)	(154.05)	(154.05)
Pn: (dBm)	(124.05)	(124.05)	(124.05)	(124.05)	(124.05)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(115.35)	(115.35)	(115.35)	(115.35)	(115.35)
MBC TRANSMISSION LOSS					
Frequency (dB)	32.04	32.04	32.04	32.04	32.04
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	116.53	120.05	122.55	124.49	126.07
MBC Scat Loss (dB)					
from Figure 10	53.00	54.00	56.00	57.00	58.00
MBC Trans Loss (dB)	169.53	174.05	178.55	181.49	184.07
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(169.53)	(174.05)	(178.55)	(181.49)	(184.07)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(104.76)	(109.28)	(113.78)	(116.72)	(119.30)
Rcvr Threshold (dBm)	(115.35)	(115.35)	(115.35)	(115.35)	(115.35)
LINK MARGIN	10.59	6.07	1.57	(1.37)	(3.95)

Frequency 60.0 MHz Bandwidth 3.0 kHz

RANGE (km)

	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.78	1.78	1.78	1.78	1.78
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	11.10	11.10	11.10	11.10	11.10
Bandwidth (dB)	34.77	34.77	34.77	34.77	34.77
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(158.10)	(158.10)	(158.10)	(158.10)	(158.10)
Pn: (dBm)	(128.10)	(128.10)	(128.10)	(128.10)	(128.10)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(119.40)	(119.40)	(119.40)	(119.40)	(119.40)
MBC TRANSMISSION LOSS					
Frequency (dB)	35.56	35.56	35.56	35.56	35.56
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	120.05	123.58	126.07	128.01	129.60
MBC Scat Loss (dB)					
from Figure 10	54.00	55.00	57.00	58.00	59.00
MBC Trans Loss (dB)	174.05	178.58	183.07	186.01	188.60
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(174.05)	(178.58)	(183.07)	(186.01)	(188.60)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(109.28)	(113.80)	(118.30)	(121.24)	(123.83)
Rcvr Threshold (dBm)	(119.40)	(119.40)	(119.40)	(119.40)	(119.40)
LINK MARGIN	10.12	5.60	1.10	(1.84)	(4.42)

	Frequency 80.0 MHz				Bandwidth 3.0 kHz
	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.90	1.90	1.90	1.90	1.90
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	8.23	8.23	8.23	8.23	8.23
Bandwidth (dB)	34.77	34.77	34.77	34.77	34.77
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(160.98)	(160.98)	(160.98)	(160.98)	(160.98)
Pn: (dBm)	(130.98)	(130.98)	(130.98)	(130.98)	(130.98)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(122.28)	(122.28)	(122.28)	(122.28)	(122.28)
MBC TRANSMISSION LOSS					
Frequency (dB)	38.06	38.06	38.06	38.06	38.06
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	122.55	126.07	128.57	130.51	132.10
MBC Scat Loss (dB) from Figure 10	56.00	57.00	59.00	60.00	61.00
MBC Trans Loss (dB)	178.55	183.07	187.57	190.51	193.10
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(178.55)	(183.07)	(187.57)	(190.51)	(193.10)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(113.78)	(118.30)	(122.80)	(125.74)	(128.32)
Rcvr Threshold (dBm)	(122.28)	(122.28)	(122.28)	(122.28)	(122.28)
LINK MARGIN	8.50	3.97	(0.53)	(3.46)	(6.05)

Frequency 30.0 MHz   Bandwidth 5.0 kHz

RANGE (km)

	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.48	1.48	1.48	1.48	1.48
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	18.03	18.03	18.03	18.03	18.03
Bandwidth (dB)	36.99	36.99	36.99	36.99	36.99
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(148.96)	(148.96)	(148.96)	(148.96)	(148.96)
Pn: (dBm)	(118.96)	(118.96)	(118.96)	(118.96)	(118.96)
DBPSK, BER 3.0E-4 Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(110.26)	(110.26)	(110.26)	(110.26)	(110.26)
MBC TRANSMISSION LOSS					
Frequency (dB)	29.54	29.54	29.54	29.54	29.54
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	114.03	117.56	120.05	121.99	123.58
MBC Scat Loss (dB) from Figure 10	52.00	53.00	55.00	56.00	57.00
MBC Trans Loss (dB)	166.03	170.56	175.05	177.99	180.58
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(166.03)	(170.56)	(175.05)	(177.99)	(180.58)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(101.26)	(105.78)	(110.28)	(113.22)	(115.80)
Rcvr Threshold (dBm)	(110.26)	(110.26)	(110.26)	(110.26)	(110.26)
LINK MARGIN	9.00	4.48	(0.02)	(2.96)	(5.54)

	Frequency 40.0 MHz			Bandwidth 5.0 kHz	
			RANGE (km)		
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.60	1.60	1.60	1.60	1.60
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	15.15	15.15	15.15	15.15	15.15
Bandwidth (dB)	36.99	36.99	36.99	36.99	36.99
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(151.83)	(151.83)	(151.83)	(151.83)	(151.83)
Pn: (dBm)	(121.83)	(121.83)	(121.83)	(121.83)	(121.83)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(113.13)	(113.13)	(113.13)	(113.13)	(113.13)
MBC TRANSMISSION LOSS					
Frequency (dB)	32.04	32.04	32.04	32.04	32.04
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	116.53	120.05	122.55	124.49	126.07
MBC Scat Loss (dB)					
from Figure 10	53.00	54.00	56.00	57.00	58.00
MBC Trans Loss (dB)	169.53	174.05	178.55	181.49	184.07
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(169.53)	(174.05)	(178.55)	(181.49)	(184.07)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(104.76)	(109.28)	(113.78)	(116.72)	(119.30)
Rcvr Threshold (dBm)	(113.13)	(113.13)	(113.13)	(113.13)	(113.13)
LINK MARGIN	8.37	3.85	(0.65)	(3.59)	(6.17)

Frequency 60.0 MHz Bandwidth 5.0 kHz

RANGE (km)

	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.78	1.78	1.78	1.78	1.78
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	11.10	11.10	11.10	11.10	11.10
Bandwidth (dB)	36.99	36.99	36.99	36.99	36.99
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(155.89)	(155.89)	(155.89)	(155.89)	(155.89)
Pn: (dBm)	(125.89)	(125.89)	(125.89)	(125.89)	(125.89)
DBPSK, BER 3.0E-4 Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(117.19)	(117.19)	(117.19)	(117.19)	(117.19)
MBC TRANSMISSION LOSS					
Frequency (dB)	35.56	35.56	35.56	35.56	35.56
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	120.05	123.58	126.07	128.01	129.60
MBC Scat Loss (dB) from Figure 10	54.00	55.00	57.00	58.00	59.00
MBC Trans Loss (dB)	174.05	178.58	183.07	186.01	188.60
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(174.05)	(178.58)	(183.07)	(186.01)	(188.60)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(109.28)	(113.80)	(118.30)	(121.24)	(123.83)
Rcvr Threshold (dBm)	(117.19)	(117.19)	(117.19)	(117.19)	(117.19)
LINK MARGIN	7.90	3.38	(1.12)	(4.06)	(6.64)

Frequency 80.0 MHz   Bandwidth 5.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.90	1.90	1.90	1.90	1.90
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	8.23	8.23	8.23	8.23	8.23
Bandwidth (dB)	36.99	36.99	36.99	36.99	36.99
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(158.76)	(158.76)	(158.76)	(158.76)	(158.76)
Pn: (dBm)	(128.76)	(128.76)	(128.76)	(128.76)	(128.76)
DBPSK, BER 3.0E-4 Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(120.06)	(120.06)	(120.06)	(120.06)	(120.06)
MBC TRANSMISSION LOSS					
Frequency (dB)	38.06	38.06	38.06	38.06	38.06
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	122.55	126.07	128.57	130.51	132.10
MBC Scat Loss (dB) from Figure 10	56.00	57.00	59.00	60.00	61.00
MBC Trans Loss (dB)	178.55	183.07	187.57	190.51	193.10
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(178.55)	(183.07)	(187.57)	(190.51)	(193.10)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(113.78)	(118.30)	(122.80)	(125.74)	(128.32)
Rcvr Threshold (dBm)	(120.06)	(120.06)	(120.06)	(120.06)	(120.06)
LINK MARGIN	6.28	1.75	(2.74)	(5.68)	(8.27)

Frequency 30.0 MHz   Bandwidth 8.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.48	1.48	1.48	1.48	1.48
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	18.03	18.03	18.03	18.03	18.03
Bandwidth (dB)	39.03	39.03	39.03	39.03	39.03
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(146.92)	(146.92)	(146.92)	(146.92)	(146.92)
Pn: (dBm)	(116.92)	(116.92)	(116.92)	(116.92)	(116.92)
DBPSK, BER 3.0E-4 Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(108.22)	(108.22)	(108.22)	(108.22)	(108.22)
MBC TRANSMISSION LOSS					
Frequency (dB)	29.54	29.54	29.54	29.54	29.54
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	114.03	117.56	120.05	121.99	123.58
MBC Scat Loss (dB) from Figure 10	52.00	53.00	55.00	56.00	57.00
MBC Trans Loss (dB)	166.03	170.56	175.05	177.99	180.58
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(166.03)	(170.56)	(175.05)	(177.99)	(180.58)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(101.26)	(105.78)	(110.28)	(113.22)	(115.80)
Rcvr Threshold (dBm)	(108.22)	(108.22)	(108.22)	(108.22)	(108.22)
LINK MARGIN	6.96	2.44	(2.06)	(5.00)	(7.58)

Frequency 40.0 MHz Bandwidth 8.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.60	1.60	1.60	1.60	1.60
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	15.15	15.15	15.15	15.15	15.15
Bandwidth (dB)	39.03	39.03	39.03	39.03	39.03
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(149.79)	(149.79)	(149.79)	(149.79)	(149.79)
Pn: (dBm)	(119.79)	(119.79)	(119.79)	(119.79)	(119.79)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(111.09)	(111.09)	(111.09)	(111.09)	(111.09)
MBC TRANSMISSION LOSS					
Frequency (dB)	32.04	32.04	32.04	32.04	32.04
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	116.53	120.05	122.55	124.49	126.07
MBC Scat Loss (dB)					
from Figure 10	53.00	54.00	56.00	57.00	58.00
MBC Trans Loss (dB)	169.53	174.05	178.55	181.49	184.07
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(169.53)	(174.05)	(178.55)	(181.49)	(184.07)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(104.76)	(109.28)	(113.78)	(116.72)	(119.30)
Rcvr Threshold (dBm)	(111.09)	(111.09)	(111.09)	(111.09)	(111.09)
LINK MARGIN	6.33	1.81	(2.69)	(5.63)	(8.21)

Frequency 60.0 MHz   Bandwidth 8.0 kHz

RANGE (km)

	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.78	1.78	1.78	1.78	1.78
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	11.10	11.10	11.10	11.10	11.10
Bandwidth (dB)	39.03	39.03	39.03	39.03	39.03
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(153.84)	(153.84)	(153.84)	(153.84)	(153.84)
Pn: (dBm)	(123.84)	(123.84)	(123.84)	(123.84)	(123.84)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(115.14)	(115.14)	(115.14)	(115.14)	(115.14)
MBC TRANSMISSION LOSS					
Frequency (dB)	35.56	35.56	35.56	35.56	35.56
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	120.05	123.58	126.07	128.01	129.60
MBC Scat Loss (dB) from Figure 10	54.00	55.00	57.00	58.00	59.00
MBC Trans Loss (dB)	174.05	178.58	183.07	186.01	188.60
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(174.05)	(178.58)	(183.07)	(186.01)	(188.60)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(109.28)	(113.80)	(118.30)	(121.24)	(123.83)
Rcvr Threshold (dBm)	(115.14)	(115.14)	(115.14)	(115.14)	(115.14)
LINK MARGIN	5.86	1.34	(3.16)	(6.10)	(8.68)

Frequency 80.0 MHz Bandwidth 8.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.90	1.90	1.90	1.90	1.90
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	8.23	8.23	8.23	8.23	8.23
Bandwidth (dB)	39.03	39.03	39.03	39.03	39.03
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(156.72)	(156.72)	(156.72)	(156.72)	(156.72)
Pn: (dBm)	(126.72)	(126.72)	(126.72)	(126.72)	(126.72)
DBPSK, BER 3.0E-4 Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(118.02)	(118.02)	(118.02)	(118.02)	(118.02)
MBC TRANSMISSION LOSS					
Frequency (dB)	38.06	38.06	38.06	38.06	38.06
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	122.55	126.07	128.57	130.51	132.10
MBC Scat Loss (dB) from Figure 10	56.00	57.00	59.00	60.00	61.00
MBC Trans Loss (dB)	178.55	183.07	187.57	190.51	193.10
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(178.55)	(183.07)	(187.57)	(190.51)	(193.10)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(113.78)	(118.30)	(122.80)	(125.74)	(128.32)
Rcvr Threshold (dBm)	(118.02)	(118.02)	(118.02)	(118.02)	(118.02)
LINK MARGIN	4.24	(0.29)	(4.78)	(7.72)	(10.31)

Frequency 30.0 MHz Bandwidth 10.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.48	1.48	1.48	1.48	1.48
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	18.03	18.03	18.03	18.03	18.03
Bandwidth (dB)	40.00	40.00	40.00	40.00	40.00
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(145.95)	(145.95)	(145.95)	(145.95)	(145.95)
Pn: (dBm)	(115.95)	(115.95)	(115.95)	(115.95)	(115.95)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(107.25)	(107.25)	(107.25)	(107.25)	(107.25)
MBC TRANSMISSION LOSS					
Frequency (dB)	29.54	29.54	29.54	29.54	29.54
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	114.03	117.56	120.05	121.99	123.58
MBC Scat Loss (dB)					
from Figure 10	52.00	53.00	55.00	56.00	57.00
MBC Trans Loss (dB)	166.03	170.56	175.05	177.99	180.58
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(166.03)	(170.56)	(175.05)	(177.99)	(180.58)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(101.26)	(105.78)	(110.28)	(113.22)	(115.80)
Rcvr Threshold (dBm)	(107.25)	(107.25)	(107.25)	(107.25)	(107.25)
LINK MARGIN	5.99	1.47	(3.03)	(5.97)	(8.55)

Frequency 40.0 MHz Bandwidth 10.0 kHz

RANGE (km)

	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.60	1.60	1.60	1.60	1.60
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	15.15	15.15	15.15	15.15	15.15
Bandwidth (dB)	40.00	40.00	40.00	40.00	40.00
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(148.82)	(148.82)	(148.82)	(148.82)	(148.82)
Pn: (dBm)	(118.82)	(118.82)	(118.82)	(118.82)	(118.82)
DBPSK, BER 3.0E-4 Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(110.12)	(110.12)	(110.12)	(110.12)	(110.12)
MBC TRANSMISSION LOSS					
Frequency (dB)	32.04	32.04	32.04	32.04	32.04
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	116.53	120.05	122.55	124.49	126.07
MBC Scat Loss (dB) from Figure 10	53.00	54.00	56.00	57.00	58.00
MBC Trans Loss (dB)	169.53	174.05	178.55	181.49	184.07
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(169.53)	(174.05)	(178.55)	(181.49)	(184.07)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(104.76)	(109.28)	(113.78)	(116.72)	(119.30)
Rcvr Threshold (dBm)	(110.12)	(110.12)	(110.12)	(110.12)	(110.12)
LINK MARGIN	5.36	0.84	(3.66)	(6.60)	(9.18)

Frequency 60.0 MHz Bandwidth 10.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.78	1.78	1.78	1.78	1.78
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	11.10	11.10	11.10	11.10	11.10
Bandwidth (dB)	40.00	40.00	40.00	40.00	40.00
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(152.87)	(152.87)	(152.87)	(152.87)	(152.87)
Pn: (dBm)	(122.87)	(122.87)	(122.87)	(122.87)	(122.87)
DBPSK, BER 3.0E-4 Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(114.17)	(114.17)	(114.17)	(114.17)	(114.17)
MBC TRANSMISSION LOSS					
Frequency (dB)	35.56	35.56	35.56	35.56	35.56
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	120.05	123.58	126.07	128.01	129.60
MBC Scat Loss (dB) from Figure 10	54.00	55.00	57.00	58.00	59.00
MBC Trans Loss (dB)	174.05	178.58	183.07	186.01	188.60
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(174.05)	(178.58)	(183.07)	(186.01)	(188.60)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(109.28)	(113.80)	(118.30)	(121.24)	(123.83)
Rcvr Threshold (dBm)	(114.17)	(114.17)	(114.17)	(114.17)	(114.17)
LINK MARGIN	4.89	0.37	(4.13)	(7.07)	(9.65)

Frequency 80.0 MHz Bandwidth 10.0 kHz

	RANGE (km)				
	400	600	800	1000	1200
RECEIVER THRESHOLD					
Frequency (dB)	1.90	1.90	1.90	1.90	1.90
c: Constant	52.00	52.00	52.00	52.00	52.00
d: Constant	23.00	23.00	23.00	23.00	23.00
Fam: Med Noise (dB)	8.23	8.23	8.23	8.23	8.23
Bandwidth (dB)	40.00	40.00	40.00	40.00	40.00
Boltzmann's k (dB)	(228.60)	(228.60)	(228.60)	(228.60)	(228.60)
Effective Temp (dB)	24.62	24.62	24.62	24.62	24.62
Pn: Noise Pow (dBW)	(155.75)	(155.75)	(155.75)	(155.75)	(155.75)
Pn: (dBm)	(125.75)	(125.75)	(125.75)	(125.75)	(125.75)
DBPSK, BER 3.0E-4					
Eb/No (dB)	8.70	8.70	8.70	8.70	8.70
Rcvr Threshold (dBm)	(117.05)	(117.05)	(117.05)	(117.05)	(117.05)
MBC TRANSMISSION LOSS					
Frequency (dB)	38.06	38.06	38.06	38.06	38.06
Range (dB)	52.04	55.56	58.06	60.00	61.58
Constant (dB)	32.45	32.45	32.45	32.45	32.45
Ls: Free Space (dB)	122.55	126.07	128.57	130.51	132.10
MBC Scat Loss (dB)					
from Figure 10	56.00	57.00	59.00	60.00	61.00
MBC Trans Loss (dB)	178.55	183.07	187.57	190.51	193.10
LINK SUMMARY					
Tx Output (dB)	24.77	24.77	24.77	24.77	24.77
Conversion (dBm)	30.00	30.00	30.00	30.00	30.00
Tx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
EIRP (dBm)	59.77	59.77	59.77	59.77	59.77
MBC Tx Loss (dB)	(178.55)	(183.07)	(187.57)	(190.51)	(193.10)
Rx Ant Gain (dBi)	5.00	5.00	5.00	5.00	5.00
RSL: Rx Sig Lvl (dBm)	(113.78)	(118.30)	(122.80)	(125.74)	(128.32)
Rcvr Threshold (dBm)	(117.05)	(117.05)	(117.05)	(117.05)	(117.05)
LINK MARGIN	3.27	(1.26)	(5.75)	(8.69)	(11.28)

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