# NAVAL POSTGRADUATE SCHOOL
# Monterey, California

# THESIS

METEOR BURST COMMUNICATION
WITH
ARTIFICIAL TRAILS

by

Tommy H. Smith

June, 1994

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|---|---|
| Principal Advisor: | R. C. Olsen |
| Associate Advisor: | Dan C. Boger |

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# REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704

| | | |
|---|---|---|
| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE<br>15 June 1994 | 3. REPORT TYPE AND DATES COVERED<br>Master's Thesis |

| | |
|---|---|
| 4. TITLE AND SUBTITLE METEOR BURST COMMUNICATION WITH ARTIFICIAL TRAILS UNCLASSIFIED | 5. FUNDING NUMBERS |
| 6. AUTHOR(S) Tommy H. Smith | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>Naval Postgraduate School<br>Monterey CA 93943-5000 | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER |

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

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|---|---|
| 12a. DISTRIBUTION/AVAILABILITY STATEMENT<br>Further distribution only as directed by Code PH/OS, Naval Postgraduate School, Monterey, CA 93943-5000 and/or Superintendent, Code 043, Naval Postgraduate School, Monterey, CA 93943-5000, or higher DoD Authority. | 12b. DISTRIBUTION CODE<br>*F |

13. ABSTRACT *(maximum 200 words)*

There exists a substantial requirement for secure, beyond line-of-sight communications, as clearly shown by Desert Storm. There are limited channels for this type of communications, particularly in areas where there is no established communications architecture. Meteor Burst Communications (MBC) offers a low probability of intercept (LPI) and anti-jam (AJ) capability to meet these tactical requirements. Existing MBC technology has limited average data rates. This thesis explores the concept of creating artificial meteors trails to substantially increase data throughput. A 1/3 gram copper sphere (beebee) will produce an electron line density of $3x10^{16}$ electrons/m. The velocity required to ionize the test sample is 6 km/s. A shaped charge warhead launched from a missile should produce the velocity required for ionization to occur. A link analysis shows a 27 dBm link margin. Nominal 20 to 200 kilobyte packets could be sent over the link. Studies of ionization and recombination characteristics for small projectiles are needed, followed by technology tests.

| | | | |
|---|---|---|---|
| 14. SUBJECT TERMS Meteor Burst Communication, Artificial Meteor Trails | | | 15. NUMBER OF PAGES 62 |
| | | | 16. PRICE CODE |
| 17. SECURITY CLASSIFICATION OF REPORT<br>Unclassified | 18. SECURITY CLASSIFICATION OF THIS PAGE<br>Unclassified | 19. SECURITY CLASSIFICATION OF ABSTRACT<br>Unclassified | 20. LIMITATION OF ABSTRACT<br>UL |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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# Meteor Burst Comunication
# with Artificial Trails

by

Tommy H. Smith
Captain, United States Air Force
B.S., United States Air Force Academy, 1986

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS TECHNOLOGY
(COMMAND, CONTROL, AND COMMUNICATIONS)
from the

NAVAL POSTGRADUATE SCHOOL
June 1994

Author: ______________________
Tommy H. Smith

Approved by: Richard Christopher Olsen
R. C. Olsen, Principal Advisor

Dan C Boger
Dan C. Boger, Associate Advisor

______________________
Paul H. Moose, Chairman
Command, Control, and Communications Academic Group

# ABSTRACT

There exists a substantial requirement for secure, beyond line-of-sight communications, as clearly shown by Desert Storm. There are limited channels for this type of communications, particularly in areas where there is no established communications architecture. Meteor Burst Communications (MBC) offers a low probability of intercept (LPI) and anti-jam (AJ) capability to meet these tactical requirements. Existing MBC technology has limited average data rates. This thesis explores the concept of creating artificial meteors trails to substantially increase data throughput. A 1/3 gram copper sphere (beebee) will produce an electron line density of $3 \times 10^{16}$ electrons/m. The velocity required to ionize the test sample is 6 km/s. A shaped charge warhead launched from a missile should produce the velocity required for ionization to occur. A link analysis shows a 27 dBm link margin. Nominal 20 to 200 kilobyte packets could be sent over the link. Studies of ionization and recombination characteristics for small projectiles are needed, followed by technology tests.

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# ACKNOWLEDGEMENTS

The author would like to thank Professor R. C. Olsen and Professor Dan Boger for their insight and assistance with turning this blue sky concept into a viable thesis on a new capability.

The author would also like to acknowledge that the idea for artificially creating meteor trails is due to Dr. Jerry Jost from Systems Planning Corp, Houston, TX.

# I. INTRODUCTION

In recent years, the need for secure, over-the-horizon communications has increased dramatically. For communications in areas where there is no established architecture of land lines or terrestrial microwaves, there are few channels of communication capable of reaching over the horizon. The most common are high frequency (HF) ionospheric scatter, satellite communications (SATCOM), and Meteor Burst Communication (MBC). Each of these channels has differing strengths and weaknesses, but they can be woven together to form a flexible web of communication for anywhere on earth. Figure 1 compares the altitudes, distances, and some effects involved with SATCOM, HF and Meteor Burst (MB) [Yavuz, 1990].

Ionospheric scatter operates in the high frequency (HF) band and takes advantage of the ionosphere's capability to refract signals back to the earth a substantial distance away. Both the angle of the transmitted signal and the frequency are important in determining whether the link will be established. Improper values will skip the signal over the intended receiver or send it through the ionosphere. Other factors which affect the propagation are: time of day, presence of various layers in the ionosphere, solar activity, and auroral activity near the poles. Any of these factors could cause a given receiver to be unreachable.

Satellite communication uses much higher frequencies, ultra high frequency (UHF) or super high frequency (SHF), that penetrate through the ionosphere to reach orbiting satellites. The higher operating frequencies provide high bandwidth for communication. Most communications satellites are in geosynchronous orbit (one rotation every 24 hours) near the equator. Geosynchronous satellites provide coverage up to about 60 degrees latitude, but not in the polar regions. To reach this orbit, approximately 23,400 miles above the earth, the signal loses much of its strength as it spreads out. Therefore, expensive, high power amplifiers and directional antennas are required. Since the signal covers so much area, it could be easily intercepted by unintended receivers, and since it is diffuse, it could be jammed by a localized jammer. There is a limited number of satellites and frequency bands, and demand for access to them can far exceed their capabilities, as was seen in Desert Storm. Many low priority users found that they could not gain access to a satellite channel or were delayed several hours or even days. This trend will continue as more systems rely on satellite communications.

Meteor Burst Communication (MBC) takes advantage of the fact that there are billions of meteors that enter the Earth's atmosphere every day. Most of these meteors are vaporized as they pass through, leaving a trail of ionized gases in their wake. This trail of ions and electrons, in particular the free electrons, provides a path for the propagation of radio waves. These trails occur randomly and are very short-lived, most lasting under a second. Communications via this channel is limited to brief digital message packets. The messages are usually reassembled by computer on the receiving end. Although this characteristic limits the ability for voice communications, it does provide a viable path for data communications. The geometry of the meteor burst channel inherently provides for communications that are resistant to ground-based intercept and jamming. Meteor burst systems operate in the lower portion of the very high frequency (VHF) band. While the current technology is adequate for monitoring remote sites, in order for meteor burst to realize its potential for secure, over-the-horizon communication, the throughput of this channel would have to be increased. This thesis will investigate the possibility of creating such a larger capacity, longer lasting channel by artificially generating a plasma to reflect radio waves.

The following chapter will describe meteors and Meteor Burst Communication. Chapter III will look at the feasibility of creating an artificial meteor trail. The primary research questions deal with the physics of the artificial meteor trail (plasma). How much can we make? How long will it last? How much signal can we bounce off from it? Chapter IV will perform a link analysis to determine if such a system is feasible. Chapter V will be the conclusion and will highlight areas for follow-on research.

# II. DESCRIPTION OF METEOR BURST COMMUNICATIONS

## A. METEORS AND METEOR TRAILS

### 1. Meteor Characteristics

Meteors are extraterrestrial objects that enter the Earth's atmosphere. Meteoroids, meteors before they enter the atmosphere, range in size from specks of dust to asteroids weighing thousands of tons [American Heritage Dictionary, 1980]. Meteoroids are usually associated with debris from the origin of the solar system or remnants from passing comets. These fragments orbit around the sun in the same direction as the planets, some occasionally being swept up by the Earth. Meteors that survive passage through the atmosphere and reach the Earth's surface are called meteorites [American Heritage Dictionary, 1980]. The average meteor is about 1 millimeter in diameter, or about the size of a grain of sand. The velocities of meteors approaching the Earth range from 11.3 to 72 km/sec [Sugar, 1964].

#### *a. Shower Meteors*

There are two classifications of meteors, shower meteors and sporadic meteors. Shower meteors follow predictable orbits around the sun and are responsible for many displays of increased meteor activity at certain times of the year. Table 1 shows a listing of the major meteor showers [Schanker, 1991]. Shower meteors provide an increase in communication capabilities while they occur. However, since they only occur at infrequent intervals throughout the year, MBC systems rely on sporadic meteors. Figure 2 shows an artist's rendition of a meteor shower [Foley, 1994].

#### *b. Sporadic Meteors*

Sporadic meteors follow much more random orbits around the sun. They occur in larger numbers, enter the Earth's atmosphere much more frequently, and so provide a steady supply of meteors for communications purposes. The number of sporadic meteors of a given size entering the atmosphere is inversely proportional to the size. Table 2 represents estimates of the properties of sporadic meteors entering the Earth's atmosphere [Schanker, 1991]. Meteors with a mass greater than a kilogram pass all the way through the atmosphere. Meteors with a mass of less than $10^{-8}$ grams float through the atmosphere causing no ionization. The electron line density (i.e. the number of electrons per meter) in the trail is proportional to the mass of the particle [Sugar, 1964]. The amount of signal returned from a meteor trail is dependent on the electron line density.

### 2. Trail Classification

Meteor trails are classified by the amount of ionization they produce. The meteors that are a milligram or lighter produce trails that are called underdense, and trails from heavier meteors are referred to as overdense. The division in terms of electron line density, is $2\text{x}10^{14}$ electrons/m [Yavuz, 1990].

Table 1: MAJOR METEOR SHOWERS

| Shower | Date Range | Peak Date |
|---|---|---|
| Quadrantids | Jan 1 - 6 | Jan 3 |
| Eta Aquarids | Apr 21 - May 12 | May 4,5 |
| Arietids | May 29 - Jun 19 | Jun 7 |
| Perseids | Jul 23 - Aug 20 | Aug 12 |
| Orionids | Oct 2 - Nov 7 | Oct 20 |
| Geminids | Dec 4 - 16 | Dec 13 |

Table 2: ESTIMATES OF SPORADIC METEOR PROPERTIES

| Mass (grams) | Radius (cm) | Number per Day | Electron Line Density (electrons/m) |
|---|---|---|---|
| $10^4$ | 8 | 10 | - |
| $10^3$ | 4 | $10^2$ | - |
| $10^2$ | 2 | $10^3$ | - |
| $10^1$ | 0.8 | $10^4$ | $10^{18}$ |
| $10^0$ | 0.4 | $10^5$ | $10^{17}$ |
| $10^{-1}$ | 0.2 | $10^6$ | $10^{16}$ |
| $10^{-2}$ | 0.08 | $10^7$ | $10^{15}$ |
| $10^{-3}$ | 0.04 | $10^8$ | $10^{14}$ |
| $10^{-4}$ | 0.02 | $10^9$ | $10^{13}$ |
| $10^{-5}$ | 0.008 | $10^{10}$ | $10^{12}$ |
| $10^{-6}$ | 0.004 | $10^{11}$ | $10^{11}$ |
| $10^{-7}$ | 0.002 | $10^{12}$ | $10^{10}$ |

### *a. Underdense Trails*

Underdense trails are those where the electron density is low enough that the incident wave passes through the trail, and the trail can be modeled as an array of independent scatterers [Sugar, 1964]. Signals received from an underdense trail rise to a peak value in a few hundred milliseconds, and then tend to decay exponentially. Decay times from a few milliseconds to a few seconds are typical [Freeman, 1991]. Since they occur with higher relative frequencies (see Table 2), MBC systems rely on trails produced by underdense meteors [Schanker, 1991]. Figure 3 shows the Received Signal Level (RSL) from an underdense trail [Desourdis, 1991]. For underdense meteor trails, received power is proportional to $1/f^3$, where $f$ is the operational frequency. This limits the maximum useful frequency to below 80 MHz [Freeman, 1991].

### *b. Overdense Trails*

Overdense trails are those where the electron density is high enough to prevent complete penetration of the incident wave to cause reflection similar to ionospheric reflection [Sugar, 1964]. These trails are usually modeled as metallic cylinders that completely reflect the incident signal [Desourdis, 1991]. They are characterized by an initial rapid rise as the trail forms, continued slow rise as the trail expands, followed by a slow decay as the trail diffuses, eventually transitioning to an underdense trail [Weitzen, 1988]. Overdense trails can be expected to last substantially longer than underdense trails. Figure 4 shows the RSL from an overdense trail [Desourdis, 1991]. The returned signal power is more complicated as it varies as $q^{0.5}$ for overdense trails, in contrast to $q^2$ for the underdense case, where $q$ is the electron line density. As with underdense trails, the return signal power varies as $1/f^3$. [Sugar, 1964]

### 3. Temporal Variations

The arrival rate of meteors varies with the position and orientation of the link site on the Earth's surface, resulting in diurnal and seasonal variations. The amount of temporal variation is dependent on the latitude of the link, with equatorial links having significantly greater variation than transpolar links [Desourdis, 1991].

#### *a. Diurnal Variation*

The Earth's rotation causes the meteor arrival rate to have a roughly sinusoidal variation throughout the day with a maximum around 6 a.m. and a minimum around 6 p.m. The ratio of maximum to minimum averages around 4, depending on latitude. [Hawkins, 1956] The peak on the morning side is due to the meteors being swept up by the forward motion of the Earth in its orbit [Sugar, 1964]. Conversely, the meteors on the evening side must overtake the Earth. Figure 5 shows this sweeping up of meteors by the Earth [Desourdis, 1991].

#### *b. Seasonal Variation*

There is also a seasonal variation of similar magnitude in the arrival rate of meteors, due to the tilt of the Earth. In the Northern Hemisphere, there is a maximum in July when the north pole tilts in the direction the Earth is traveling around the Sun, and a minimum in February when the south pole is tilted forward [Desourdis, 1991]. There is also seasonal variation caused by the non-uniform distribution of meteors along the Earth's orbit [Sugar, 1964]. Figure 6 shows the seasonal variation of meteor arrival rate [Sugar, 1964].

## B. CHARACTERISTICS OF METEOR BURST COMMUNICATIONS

The earliest indication that meteors could cause ionization in the upper atmosphere came in 1931 from the observed correlation of trans-Atlantic HF signals with meteor showers [Pickard, 1931]. It was not until the late 1940's, when technology had pushed the radio spectrum into the VHF band, that research into this phenomenon was pursued [Weitzen and Ralston, 1988]. Recent advances in microprocessor technology and communication techniques have helped make this a viable communications channel.

### 1. Formation of Meteor Trails

The meteors primarily used in Meteor Burst Communication systems are small and have high velocities when they enter the Earth's atmosphere. As they penetrate deeper into the atmosphere, between 80 and 120 km, friction between the meteors and the increasingly dense atmosphere causes the meteors to vaporize quite quickly. These particles collide with air molecules and ionize, forming a trail of positive ions and free electrons. Radio wave scattering is primarily due to the effects of the electrons, since the positive ions are too massive to vibrate under the influence of an electric field [Weitzen, 1993]. The free electrons absorb the incoming radio wave and then reradiate the electromagnetic energy 180 degrees out of phase. The trail, usually under one meter wide initially, lasts for only a brief time before it recombines or is dispersed by the wind. Typical lengths, where the ionization returns a signal above the detection threshold, range up to 50 km with a most probable length of about 15 km [Sugar, 1964]. The lifetime of the average trail may range from a few hundred milliseconds to a few seconds [Schanker, 1991].

### 2. Link Geometry

Geometry plays an important role in Meteor Burst Communications, as only those meteors that enter the atmosphere with the correct orientation of angles and distances will support communications between two points. The path of the ionized meteor trail must be tangent to an ellipse with the transmitter and receiver at the foci. Figure 7 shows the appropriate geometry for a Meteor Burst link [Desourdis, 1991]. The point of tangency defines the center of a region of constructive interference known as the first Fresnel zone [Weitzen and Ralson, 1988]. The range of a meteor burst link is dependent on the altitude of the meteor trail and the curvature of the Earth. Normal ranges are up to 2000 km [Schanker, 1991].

There are "hot spots", or regions of enhanced probability of scattering or reflection, on either side of the great circle path between the transmitter and receiver. This is because only infrequent trails parallel to the earth would reflect along the great circle path. Trails with usable orientations occur much more frequently in these areas about 50 to 100 km offset on either side of the midpoint of the path [Yavuz, 1990]. Figure 8 shows the estimated percentages of useful trails by displacement for terminal separation of 1000 km. [Freeman, 1991] Most MBC systems sacrifice some of the sensitivity, or gain, of their antennas for wider beams in order to have these hot spots within the common volume of sky covered by both transmitting and receiving antennas.

### 3. Low Probability of Intercept (LPI) and Antijam (AJ)

One of the primary advantages of Meteor Burst Communications is that there is an inherent covertness or security to the channel. As mentioned above, only meteor trails with the proper geometric orientation will allow propagation of signals to the receiver. Because of the random arrival, duration, and orientation of meteor trails, an unintended receiver or jammer would have to use the same short-lived meteor trail. There is only a small area on the ground, called a ground illumination footprint, where signals reflected back to Earth from one meteor trail can be received [Weitzen, 1993]. Unintended receivers would have to be inside of this small footprint, as well as the primary receiver, to be able to receive the signals. This means that there is a very low probability of the signal being detected or intercepted by an unwanted receiver.

Intentional jamming is likewise an improbable occurrence since the jammer would have to be within the footprint in order to interfere with the signal. The size of the footprint is dependent on the location and orientation of the trail, as shown in Figure 9 [Weitzen, 1993].

### 4. Survivability

Meteor Burst Communications can be described as survivable. In the event of a nuclear detonation, electromagnetic pulses (EMP) may cause scintillation which may disrupt communications via the ionosphere or satellites. Intense solar flare activity may cause increased absorption of HF signals or may disable satellites. Despite either of these occurrences, meteors are expected to continue to enter the atmosphere and produce trails usable for communications.

### 5. System Performance

Since MBC systems rely on underdense trails from randomly occurring meteors for propagation, there are some important system performance parameters to consider in designing a MBC system.

#### *a. Waiting Time*

The waiting time between suitable meteor trails is an important characteristic of MBC. This time represents the time until the next meteor trail suitable for communication. A meteor trail is suitable if it scatters sufficient incident signal to exceed a specified receive signal level (RSL) threshold. Typically, this threshold is set to meet a minimum average bit error rate (BER) that is required by the system [Desourdis, 1991]. Since the occurrence of underdense meteors is random, the time until arrival of the next meteor can be approximated by a Poisson distribution. In order to use the Poisson distribution, it must be assumed that the times between meteor arrivals are exponentially distributed and independent from arrival to arrival. The Poisson equation is:

$$P = 1 - e^{-Mt},$$

where $P$ is the probability of a meteor occurrence in time $t$. $M$ is the meteor density, in number of meteors per hour, and $t$ is the time in hours [Freeman, 1991]. Typical waiting times range from a few seconds to a few minutes or more, depending on link parameters. Waiting time can be decreased by increasing transmitted power [Freeman, 1991].

#### *b. Average Burst Length*

The average burst length, or duration, is a measure of how long signals reflected from meteor trails are above the RSL threshold. The average burst length is proportional to $1/f^2$, where $f$ is the operating frequency. This means that lower frequencies result in longer average bursts, which allow the required data to be transferred more quickly. The length of a burst also depends on the power and sensitivity of the system using the meteor trail. More powerful transmitters and more sensitive receivers can use a trail for longer periods of time [Schanker, 1991].

### *c. Duty Cycle*

Duty cycle is a measure of the average percentage of time that the meteor link is actually active and sending data. Similar to the average burst length, the duty cycle is proportional to $1/f^2$, where $f$ is the operating frequency. Duty cycle is defined as the average burst length divided by the average waiting time [Schanker, 1991]. Typically, duty cycles are of the order of a few percent and are a function of transmitter power, antenna gains and link distance [Yavuz, 1990]. In practice, the presence of overdense trails increases the duty cycle [Sugar, 1964].

### *d. Throughput*

Throughput is a measure of the rate at which data flows through the system. Throughput is defined as the average number of correct data bits received per unit time. Throughput of meteor burst systems depends on several factors, including transmitted power, operating frequency, range, encoding scheme, and instantaneous, or burst, data rate. Experimental results with constant output power indicate that throughput varies as $R^{0.4}$, where $R$ is the instantaneous data rate [Oetting, 1980]. Most MBC systems transmit data at high data rates while a suitable meteor trail is present. Burst rates for most systems range from 2 to 16 kbps [Schanker, 1991]. On commercial links, average throughputs range from 10 bps to 100 bps [Desourdis, 1991].

## C. METEOR BURST SYSTEMS

### 1. Military Standard

In an attempt to standardize operation of future MBC systems, the Defense Information System Agency (DISA), formerly Defense Communications Agency, published the "Interoperability and Performance Standard for Meteor Burst Communications," (MIL-STD-188-135). The standard specifies that all new MBC systems will have the following operating characteristics: a frequency range of 30.000 to 88.000 MHz; an occupied bandwidth restricted to 20 kHz or less; the Differential Binary Phase Shift Keying (DBPSK) modulation method 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 for error detection (MIL-STD-188-135, 1988, cited in Williams, 1992).

The standard specifies that MBC systems will support long-term average throughput under benign conditions from 10 to 100 bps with a bit error rate (BER) of $3x10^{-4}$ or better (MIL-STD-188-135, 1988, cited in Williams, 1992). According to the standard, MBC is used for communications and remote sensing. Included under communications are such missions as order wire; damage assessment; recovery, reconstitution, and retargeting; logistics; force direction and reporting; and continuity of operations. The remote monitoring missions include fallout monitoring and collection of meteorological data (MIL-STD-188-135, 1988, cited in Williams, 1992).

## 2. Modes of Operation

### *a. Broadcast*

Systems using this protocol employ a master station broadcasting data to silent remotes. Short messages are continuously transmitted over a comparatively long period of time to ensure a high probability of reception by all remote stations. Complete messages longer than the burst duration are subdivided at the transmitter and then pieced back together at the receiver. Such systems can be useful, for example, for covert message broadcast applications [Freeman, 1991].

### *b. Channel Probing*

This protocol uses a master station continuously sending a short probe toward the remote. When the remote receives the probe, a meteor trail exists between the two stations and the remote transmits a return signal for handshaking, followed by a burst of data. In half-duplex operation, both the forward and return links are on the same frequency. In full-duplex, both links are on separate frequencies, reducing the time spent on overhead. The channel probing, or point-to-point, systems are more common and are commercially available in several versions [Yavus, 1990].

### *c. Network*

This mode of operation is an extension of channel probing where one master station services many remote stations. Each remote station is polled, or probed, one at a time. Once the remote receives its probe, it transmits its data to the master station, in a fashion similar to channel probing. The Department of Agriculture's SNOTEL is an example of network operation, with up to 600 remotes serviced by each master station [Freeman, 1991].

### 3. Recent Applications

#### *a. Snowpack Telemetry (SNOTEL)*

As was mentioned above, the Department of Agriculture's SNOTEL is an example of a networked MBC system. It operates with up to 600 remotes serviced by each master station. The SNOTEL system consists of small, self-contained, solar/battery powered tranceivers, placed by helicopter in remote and difficult-to-access locations. One system covers eleven western states with master stations located in Boise, Idaho, and Ogden, Utah [Allen, 1989]. Another system monitors Alaska with the master station located in Anchorage. It is based on commercially available hardware to obtain remote environmental data such as snow conditions, temperature, humidity, and wind velocity. It has been operational since 1977, is a very reliable system, and provides a necessary service at low cost [Dennis, 1993].

#### *b. Alaskan Air Command*

In 1985 the USAF Alaskan Air Command installed a Meteor Burst Communications system to provide a backup connection between the Regional Operations Control Center (ROCC) at Elmendorf AFB, near Anchorage, and the Long Range Radar (LRR) sites located throughout the state. The system sends radar track data from the LRRs to the ROCC and has demonstrated the ability to maintain a real time radar display. The system also includes limited voice capability where a small number of preprogrammed commands can be relayed to the pilot via a voice synthesizer [Dennis, 1993].

### c. *Vehicle Tracking*

A MBC system has been developed for tracking commercial trucks while on the road. The system is capable of two way data communications, to include position information from an on-board LORAN-C or GPS receiver [Williams, 1992]. In the tactical arena, small portable tranceivers could be used by the military in a variety of applications, such as tracking battle field troop movements, resupply, status of force situation reports, and intelligence nets [Dennis, 1993].

### d. *Advanced Meteor Burst Test Bed*

As part of the Advanced Meteor Burst Test Bed, tests have recently been carried out by the Advanced Research Projects Agency (ARPA) transmitting voice and high speed data, with a continuous average throughput of 2400 bps and above, between Rome, NY and Charleston, SC. The cost of the system is about $80k per ground station, not including MBC modems [Bauman, 1994].

### 4. Ongoing Research

Since one of the chief drawbacks to MBC systems is the relatively slow average data rates, most research is into ways to improve throughput. Research showed that, by using techniques that match information transfer rate to the dynamic capacity of the channel, large increases in throughput could be achieved. This led to the development of adaptive, variable data rate modems which transmit at very high burst rates when the channel can carry it, and then drop down to lower rates as the performance diminishes [Larsen, et al., 1990].

Protocols are studied to determine how to efficiently transmit the data, without increasing the probability of errors. Several protocols, including Feedback Adaptive Variable Rate (FAVR), Forward Error Correction (FEC), and *M*-ary Frequency and Phase Shift Keying (MFSK and MPSK), are explored in chapters 4 through 8 of *Meteor Burst Communications, Theory and Practice*, edited by Donald Schilling [Shilling, 1993].

Computer models, such as METEORLINK, have been developed to predict various aspects of MBC. Results from these models can be used to predict MB link sensitivity to temporal parameters, antenna patterns, power margins, and range. These models can also be used to predict the ground illumination footprint of signals transmitted over meteor trails [Desourdis, 1991].

At the Advanced Meteor Burst Test Bed, ARPA has been working on the development of smart antennas, with beam and null steering. The test link also uses variable rate modems, such as the MCC 6560 from Meteor Communications Corporation, which is capable of trasmitting data between 2 and 128 kbps. These antennas have the ability to increase the received Signal to Noise Ratio (SNR) by increasing the gain once a link is established and decreasing noise from localized sources. The way these smart antennas work is that the antenna uses a low gain, wide beam to search and acquire the signal. Once a link is established, a high gain, narrow beam is steered to lock onto the trail. Similarly, nulls can be steered to block out noise from localized sources such as motors or jammers. These capabilities mean that more meteor trails will be usable longer, allowing more data to be sent [Bauman, 1994].

The next chapter of this thesis will investigate the possibility of artificially generating meteor trails. If possible, this will create the capability to augment meteor burst communications using naturally occurring meteors by placing an artificial meteor trail of specified size, duration, and signal carrying capacity at a desired location and time. This will allow increased throughput on a MBC link at desired time, when it may be critical to ensure the message gets through immediately, while maintaining the covert aspects of MBC.

## III. PREDICTIONS FOR ARTIFICIAL PLASMAS

As meteors enter the atmosphere, friction with the atmosphere heats the meteor up to the point where it forms a cloud of ionized particles called a plasma. This chapter will look into this plasma, examining the following questions. How much plasma could be made by an artificial meteor? How long it will last? How much signal could be bounced off from it?

First, we will look at how much plasma could be created by a sample test object, a 0.33 gram copper 'beebee'. Using the following equation, we can determine how many atoms in the sample.

$$Number_{atoms} = mass_{sample} / mass_{atom}$$

Since the atomic mass of one copper atom is $1.06 \times 10^{-22}$g [Halliday and Resnick, 1988], there are $3.11 \times 10^{21}$ atoms in the sample. If all of the atoms were singly ionized (that is, where one electron from each atom has enough energy that it breaks free from the atom) then there would be $3.11 \times 10^{21}$ free electrons generated and available for propagation of radio signals.

How does this number compare with expected values? Table 2 shows that the electron line density for a one gram meteor is $1 \times 10^{17}$ electrons/m. Since the sample's mass is 0.33 g, it should produce an electron line density of about

$3 \times 10^{16}$ electrons/m. This value is above $2 \times 10^{14}$ electrons/m, and the trail would be considered overdense. Overdense trails, as discussed in an earlier section, last longer than underdense trails, and tend to have a higher received signal level. As was previously noted, meteor trails are typically up to 50 km long [Sugar, 1964]. If we assume that the trail generated by the sample is 50 km long, this accounts for $1.667 \times 10^{21}$ electrons. The remainder would be those generated when the received signal level is below the threshold for detection.

How much energy is required to singly ionize the sample? First, the sample must be heated from solid phase through liquid phase to gaseous phase. The heat of vaporization plus the heat of fusion for copper is 4937 J/g [Halliday and Resnick, 1988]. Then the atoms in the gaseous sample must be ionized. The ionization energy of a copper atom is approximately 8 eV per electron [Halliday and Resnick, 1988]. Therefore, to singly ionize all the atoms in the sample would require $2.49 \times 10^{22}$ eV or 3979 J. Thus, the total heat ($Q$) required to take the sample from solid to singly ionized plasma is 4937 J/g * 0.33 g + 3979 J = 5608 J, or 17,000 J/g (or kJ/kg). Another way of describing this amount of energy is about 15 eV/atom.

How fast would the sample have to be going to ionize? Since this heat is to be generated by friction caused by the kinetic energy of the sample, we will use the following equation to determine what velocity is required to produce the required amount of heat.

$$1/2 * m * v^2 = Q * m$$

Solving for velocity, using the proper units:

$$v = (2000 * Q)^{0.5}$$

Using the value of Q calculated above (17 MJ/kg), the velocity required to singly ionize all of the atoms in the sample would be 5.83 km/s. As a means of comparison, it should be noted that the velocities of naturally occurring meteors range between 11.3 and 72 km/s.

How could the sample be accelerated to such a high velocity? The velocity required to ionize the sample could be achieved by a projectile that fires a shaped charge explosive. A shaped charge is typically a cylinder of explosive with a hollow cavity in one end and a detonator at the opposite end. The hollow cavity causes the energy from the detonation to be focused, producing an intense localized force. If the hollow cavity is lined with a thin layer of metal, such as copper, or some other substance, the liner forms a jet when the explosive charge is detonated. The collapse of the liner material on the centerline forces a portion of the liner to flow in the form of a jet where jet tip velocity can travel in excess of 10 km/sec. The presence of a velocity gradient causes the jet to stretch until it fractures into a column of jagged pieces [Walters, 1990]. Figure 10 shows the collapse of a shaped charge with a conical liner [Walters, 1990].

In 1966, the U.S. Army Ballistic Research Laboratory, in conjunction with the former Defense Division of the Firestone Tire and Rubber Company, developed shaped charge meteor simulators for NASA [Woodall and Clark, 1966, cited in Walters, 1990]. The objective of these studies was to obtain the luminous efficiency (percent of kinetic energy converted into visible light) of a meteor-like body of known mass, composition, and speed during re-entry into the Earth's atmosphere. The study tested combinations of pellet characteristics generated by a specific shaped charge design flown on a solid state propellant vehicle, which was used to achieve the necessary velocities. The rocket was designed to carry the shaped charge above the atmosphere, turn, and allow the detonated shaped charge to accelerate at hypervelocity through the Earth's atmosphere [Woodall and Clark, 1966, cited in Walters, 1990].

How much signal could be bounced off from it? The most common model for received power due to reflection from an overdense trail is given as [Weitzen, 1993]:

$$\mathrm{RSL}(t) = \frac{P_{\mathrm{T}} G_{\mathrm{T}} G_{\mathrm{R}} \lambda^2 S}{32\pi^2 R_{\mathrm{R}} R_{\mathrm{T}} (R_{\mathrm{T}} + R_{\mathrm{R}})(1 - \cos^2\beta \sin^2\phi)} \quad \mathrm{x}$$

$$[((4Dt + r_0) / \sec^2\phi) \ln(r_e q \lambda^2 \sec^2\phi / \pi^2 (4Dt + r_0^2))]^{1/2},$$

where $P_{\mathrm{T}}$ is transmitter power,
$G_{\mathrm{T}}$ is transmitter antenna gain,
$G_{\mathrm{R}}$ is receiver antenna gain,
$R_{\mathrm{T}}$ is distance from the transmitter to the trail in meters,
$R_{\mathrm{R}}$ is distance from the receiver to the trail in meters,
$\lambda$ is the signal wavelength in meters,

$q$ is the electron line density in electrons/meter,
$r_e$ is the classical radius of an electron, $2.8178\text{x}10^{-15}$ m,
$S$ is the polarization coupling factor,
$\phi$ is 1/2 the angle included between $R_T$ and $R_R$,
and $\beta$ is the angle of the trail relative to the propagation plane.

How long it will last? Once the trail is formed, it expands by ambipolar diffusion at a relatively low rate. The approximate radius of the trail after time $t$ can be defined by the quantity $(4Dt+r_0^2)^{1/2}$ where $D$ is the diffusion coefficient in square meters/second and $r_0$ is the initial radius of the trail in meters. $D$ varies from 1 $m^2/s$ at 85 km height to 140 $m^2/s$ at 115 km. The initial trail radii are in the range of 0 to 1.2 m [Sugar, 1964].

The duration, $\tau$, of a signal returned from an overdense trail is given by [Desourdis, 1991]

$$\tau = [(\lambda r_e/\pi^2)q - (r_0^2\cos^2(\phi))]/(4D\cos^2(\phi)),$$

where $\lambda$ is the wavelength of the signal in meters, $r_e$ is the classical radius of an electron, $2.8178\text{x}10^{-15}$ m, $q$ is the electron line density in electrons/meter, and $\phi$ is 1/2 the angle included between the path of the transmitted and received signal. Figure 11 shows plots of RSL versus time for exact and approximate overdense trail models [Desourdis, 1991]. The sample, with an electron line density of approximately $3\text{x}10^{16}$, is very close to the q3 sample in Figure 11, and should therefore also last just over 10 seconds.

This information about duration and received signal level is modeled and displayed in Figure 11. Using q3 to represent our sample, we find that the peak RSL, or peak received power, is approximately -87 dBm. We will look into this question more in the next chapter when we investigate the link budget for a MBC system.

Assuming the model shown in Figure 11 can be extrapolated for larger samples with higher electron line densities, it should be easy to scale up or down to meet required RSL and duration. For example, assume a requirement existed for a RSL of -75 dBm over a trail length of 50 km. To achieve that signal level, an electron line density of $10^{19}$ electrons/m would be required. That electron line density over that distance translates into 50 x $10^3$ x $10^{19}$ or $5\text{x}10^{23}$ electrons, which is about 5/6 mole. The number of particles in one mole is $6.02\text{x}10^{23}$ (Avogadro's constant). The atomic mass of copper is 63.5 grams/mole [Halliday and Resnick, 1988]. Therefore, to meet this requirement, we would need to ionize about 53 grams, or 1.9 oz, of copper.

How would this system be employed? Ideally, this system could be launched using an existing military weapon system with minimal alteration, for example, a Sparrow (AIM-7) missile from an aircraft or a Standard (RIM-66C) missile from a ship. All that would be required would be to exchange the standard warhead for the shaped charge warhead, update the guidance to specify where, and at what attitude, to detonate the warhead, and then have the ship or aircraft launch the missile. Integrating with an existing system would keep the development and operational cost for the system very low. In addition, shaped charge warheads are already fitted to several systems such as the Maverick (AGM-65D) and the Hellfire (AGM-114A) missiles, so fitting a properly sized shaped charge should be relatively easy [Nicholas and Rossi, 1993].

Which missile system can do the job? The biggest drawback to using an existing military system is that they all have a relatively low operational ceiling. Since aircraft rarely fly much above 50,000 feet (15,244 meters) and almost never above 80,000 feet (24,390 meters), the missiles designed to shoot them down are not designed to fly above those altitudes. The following are the operational ceilings of some of the higher flying missiles [Nicholas and Rossi, 1993]:

| | | |
|---|---|---|
| AMRAAM (AIM-120A): | 40,000 ft | 12.2 km |
| HAWK (MIM-23B): | 60,000 ft | 18.3 km |
| PATRIOT (MIM-104A): | 79,000 ft | 24.1 km |
| PHOENIX (AIM-54C): | 81,000 ft | 24.7 km |
| SPARROW (AIM-7M): | 70,000 ft | 21.4 km |
| STANDARD II MR (RIM-66C): | 80,000 ft | 24.4 km |

Looking at the ceilings in kilometers, none of these missiles reach the altitude where meteor trails are produced, 80 to 100 km. Therefore, if one of these missiles is used to launch the shaped charge, the trails will be formed at a much lower altitude than theory predicts. Assuming the trail formation is similar at these lower altitudes, the trails will be significantly shorter in both duration and distance due to the substantially increased atmospheric density. The approximate atmospheric particle number density at 100 km is $10^{19}$ $m^{-3}$, while at 25 km is $10^{24}$ $m^{-3}$ [Olsen, 1993]. This means that the mean free path, the average distance traveled by a particle between collisions, is $10^{-5}$ less at 25 km than at 100 km [Halliday and Resnick, 1988]. Also, geometry will dictate a lesser range between transmitter and receiver. For example, if a trail with a particular orientation at 100 km allowed propagation between two sites 2000 km apart, the same trail with the same orientation at 25 km would only allow propagation between sites 500 km apart.

As an alternative, there are other launch vehicles that could be used instead of an existing military weapon system, such as the now-terminated anti-satellite missile (ASAT), sounding rockets, the booster used for NASA's barium or lithium plasma release experiments, the booster used for the Army Ballistic Research Laboratory's 1966 meteor simulation, or a small space launch system such as the Pegasus. All of these systems are easily capable of carrying small payloads, such as our shaped charge, to the desired altitudes.

# IV. LINK ANALYSIS OF METEOR BURST PATH

## A. REPRESENTATIVE PARAMETERS

The purpose of the link analysis is to test whether a link can be established from the transmitter across the propagation media and to the receiver. There are many factors and parameters that have to be properly accounted for in order to successfully establish the link. This chapter will begin by reviewing some of the considerations, and then see if a positive link margin can be reached for a system with a representative set of values.

As was noted earlier, according to MIL-STD-188-135, all new MBC equipment for the Department of Defense shall have an operating frequency range of 30 - 88 MHz, have an occupied bandwidth (BW) restricted to 20 kHz or less, will utilize the Differential Binary Phase Shift Keying (DBPSK) modulation method 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. MBC systems will support long-term average throughput under benign conditions from 10 to 100 bps with a bit error rate (BER) of $3 \times 10^{-4}$ or better .

Reflected signal amplitude, as noted previously, is proportional to $1/f^3$ and the time duration to $1/f^2$. This means that a given trail will appear smaller and shorter as frequency is increased. Frequencies in the 20 - 50 MHz range are the most practical [Freeman, 1991].

High transmit power can decrease the message waiting time. Average MBC systems operate with transmitter power in the range of 150 to 200 W [Freeman, 1991].

There is a tradeoff between antenna gain and the amount of sky encompassed by an antenna beam looking for suitable meteor trails. The optimal point on the tradeoff curve is +16 dBi for short links (400-600 mi) and +21 to +24 dBi for longer range links (600-1200 mi) [Freeman, 1991].

## B. LINK ANALYSIS

Based on the above considerations, this thesis will analyze a system which has the following operating characteristics:

Operating Frequency ($f$): 50 MHz
Bandwidth ($BW$): 20 kHz => 43 dB
Transmitter Power ($P_t$): 200 W => 23 dBW
Antenna Gain ($G_t$ and $G_r$): +16 dBi
Distance between terminals: 1000 km

and will otherwise be in compliance with MIL-STD-188-135.

### 1. Receiver Threshold

Man-made noise is the predominant source of noise in frequencies used by Meteor Burst Communication systems. The median noise ($F_{am}$) value for the environment can be calculated by [Freeman, 1991]:

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

where $f$ is the operating frequency in MHz, and $c$ and $d$ are environmental noise values. Assuming the system will be operating in a rural environment with a relatively low level of man-made noise, the values for $c$ and $d$ are $c = 62.7$ dB and $d = 27.7$ dB [Freeman, 1991]. Substituting in the values listed for the sample system gives: $F_{am} = 62.7 - 27.7(\log 50) = 15.6$ dB.

Noise power ($P_n$) present at the receiver is given by [Freeman, 1991]:

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

where $D_u$ and $\sigma$ are deviation values, $BW$ is the system's bandwidth, $k$ is Boltzman's constant ($1.38 \times 10^{-23}$ J/K), and $T_o$ is the system's effective temperature (290 K). For a system operating at 48 MHz in a relatively low noise rural environment, $D_u = 5.3$ dB and $\sigma = 3.2$ dB [Freeman, 1991]. Substituting in the values gives: $P_n = 15.6 + (5.3 + 3.2) + 16.3 + (-204) = -164.6$ dBW.

Receiver Threshold ($T_r$) is the amount of power presented to the input of the receiver that is required to achieve a specified bit error rate. Receiver threshold is calculated by [Freeman, 1991]:

$$T_r = P_n + E_b/N_o$$

where $E_b/N_o$ is the receiver signal bit energy per thermal noise. Coherent DBPSK modulation with a BER of $3 \times 10^{-4}$ leads to an $E_b/N_o$ of 8.7 dB [Freeman, 1991]. These values give a receiver threshold of: $T_r = -164.6 + 8.7 = -155.9$ dBW = -125.9 dBm.

### 2. Transmission Losses

Free-space loss ($L_s$) represents the amount of signal power loss due to propagation through the atmosphere. Free-space loss can be calculated by [Freeman, 1991]:

$$L_S = 32.45 + 20(\log f) + 20(\log D)$$

where $f$ is the operating frequency in MHz and $D$ is the distance between terminals in km. Calculating for the given parameters gives: $L_S = 32.45 + 34.0 + 60.0 = 126.45$ dB.

Meteor scatter loss ($L_{sl}$) represents the signal loss due to reflection by an ionized trail. Table 3 contains values for meteor scatter loss [Freeman, 1991].

Included in these values are the orientation of the trail relative to the transmitter and the receiver as well as the electron line density of the meteor trail, assumed to be $10^{14}$. For our system the meteor scatter loss is: $L_{sl} = 57$ dB.

Total transmission losses ($L_{tl}$) is given by:

$$L_{tl} = L_s + L_{sl}$$

substituting in the above values gives: $L_{tl} = 126.45 + 57 = 183.45$ dB.

TABLE 3: MBC TRANSMISSION LOSSES AT 40 MHz

| Distance (km) | MBC Scatter Loss (dB) | Free-Space Loss(dB) | Total Loss(dB) |
|---|---|---|---|
| 300 | 52 | 114.03 | 166 |
| 500 | 53 | 118.46 | 171.5 |
| 1000 | 57 | 124.49 | 181.5 |
| 1500 | 58.5 | 128.01 | 186.5 |
| 2000 | 61.5 | 130.5 | 192 |

### 3. Link Summary

Equivalent Isotropic Radiated Power (*EIRP*) is indicative of the amount of signal power radiated towards the receiver. *EIRP* is defined by [Freeman, 1991]:

$$EIRP = P_t + G_t - L_l$$

where $P_t$ is transmitter power output in dBW, $G_t$ is transmitter antenna gain in dB, $L_l$ is transmitter line loss in dB. Assuming the line loss is negligible (0 dB), then the *EIRP* for this system is: $EIRP = 23 + 16 - 0 = 39$ dB.

Receive signal level (*RSL*) is the signal strength at the input to the receiver. The receive signal level described by [Freeman, 1991]:

$$RSL = EIRP - L_{tl} + G_r$$

where $G_r$ is receiver antenna gain in dB. Using values previously calculated, the receive signal level is: $RSL = 39 - 183.45 + 16 = -128.45$ dBW = -98.45 dBm.

Link margin (*LM*) is a measure of whether the system in focus will meet the constraints imposed upon it. Also called net signal margin, it is a cumulative measure of all the gains and losses in the link, or a signal to noise ratio. A positive value for the link margin means that the system is capable of meeting the design constraints. The link margin is calculated by [Freeman, 1991]:

$$LM = RSL - T_r$$

For this system, the link margin is: $LM = (-98.45) - (-125.9) = 27.45$ dBm. Since the link margin is positive, the system described above can make the link between transmitter and receiver along the meteor burst channel. In fact, there is enough extra margin that it would be possible to loosen some of the design criteria, perhaps by substituting an antenna with lesser gains or covering a greater distance between transmitter and receiver. However, having a high link margin may allow longer communications using individual meteor trails and may help messages get through using meteor trails that produce lower ionization levels.

As was determined in the previous chapter, the RSL predicted from the sample is -87 dBm. Assuming the parameters such as gains of the antennas used in the prediction and in the link budget calculations were the same, the sample will allow a link to be established with an even greater margin: $LM = (-87) - (-125.9) = 38.9$ dBm. This high link margin means that data can be sent across the link as long as the margin remains positive, which is until the RSL drops to -125.9 dBm, which is the receiver threshold.

How many bits can be sent over this trail? The theoretical bandwith occupancy of a radio system using binary modulation is 1 bit per Hz. The Nyquist bandwidth for coherent DBPSK is $B$, where $B$ is the gross bit rate transmitted along the system [Freeman, 1991]. This implies that, if the maximum occupied bandwidth is 20 kHz, and the modem is capable of transmitting at that speed, then 20,000 bits can be sent across the trail each second that the link margin remains positive. This number of bits will include overhead such as synchronization, error control, as well as the data being sent. For the sample, the RSL from the trail was above threshold for 10 seconds. Therefor, assuming that the system analyzed above was used, a total of 200,000 bits could be sent over this trail during its useful lifetime. Providing the model in Figure 11 can be extrapolated for larger samples, then if a sample ten times as large were used, forming a trail with an electron line density of $10^{17}$, the useful lifetime would be 100 seconds. The total bits sent over that trail would be two million. If the bandwidth restriction were lifted, then even more data could be sent at even higher rates. However, the VHF band is very crowded. Frequency or bandwidth allocation would have to be arranged to allow for the increased bandwidth requirement. As mentioned earlier, increasing the operating frequency would increase both meteor scatter and free space losses in the link, decreasing the received signal level and the useful lifetime of the trail.

# V. CONCLUSION

In conclusion, Meteor Burst Communications is a viable means of communications for beyond line-of-site ranges. The advantageous characteristics of low probability of intercept and low probability of jamming are especially useful in today's New World Order. With research continuing into areas such as adaptable data rate modems and smart antennas, in the future we will see a significant increase in the data throughput capacity of the meteor burst channel.

Meteor Burst Communications with artificial meteor trails is an excellent way to augment the traditional approach to this medium. This technology allows the JTF commander to send important information to units located beyond line-of-site with little fear of interception or jamming. It allows significantly more data, possibly including imagery, to be sent than practical using the natural meteor channel. It allows communication with areas where there is no established, or accessible, communications architecture. Also important is the fact that it uses existing commercially available off-the-shelf equipment, and does not increase the burden on satellite communication.

This capability should be integrated into the military's communication architecture, working together with SATCOM and HF, and augmenting MBC using naturally occurring meteors. This is a technology that future Joint Task Force commanders should have available to ensure successful mission completion.

## A. FOLLOW-ON RESEARCH

Further research needs to be carried out into the ionization and recombination characteristics of small projectiles. This will give a more detailed understanding into the process, allowing a more detailed model of overdense trail formation.

Testing the basic technology needs to be performed. This implies designing and conducting an experiment where a shaped charge warhead is built, placed on a missile, and launched to verify the concept.

Using a missile to send a shaped charge warhead to the proper altitude is very expensive. Studies need to explore ways to achieve the desired altitudes at a lower cost. Possible methods include rocket assisted shells and electric guns. For possible places to start, contact:

Professor Joe Sternberg
Physics Department
Naval Postgraduate School
Monterey, CA. 93943

Charlie Murphy
Army Research Lab
Aberdeen Proving Ground, MD 21005

or

Dr Randy Rohr
Defense Nuclear Agency
Alexandria, VA 22304.

# APPENDIX: FIGURES

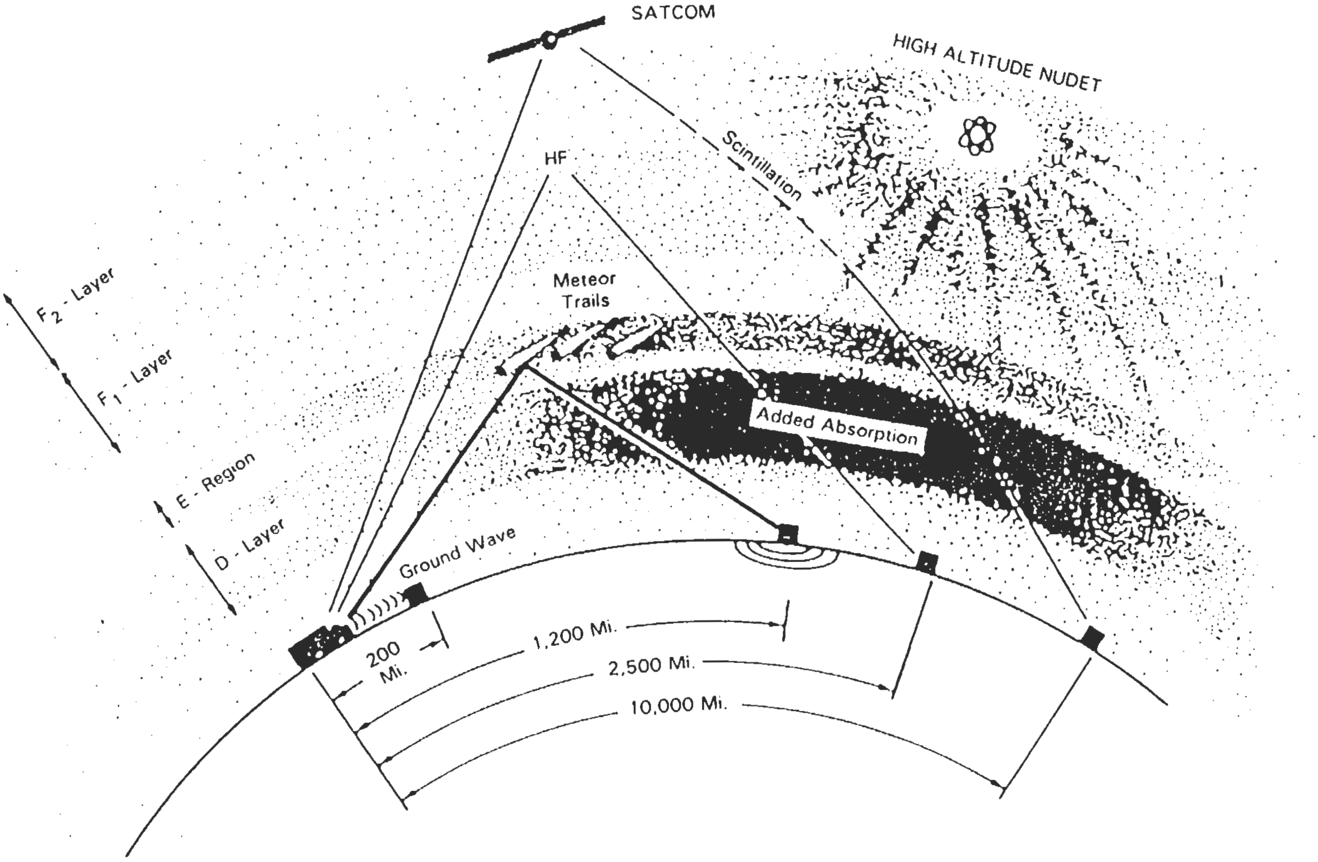

Figure 1: SATCOM, HF and MB Propagation and Relevant Ionospheric Effects and Regions.

Figure 2: Meteor Shower

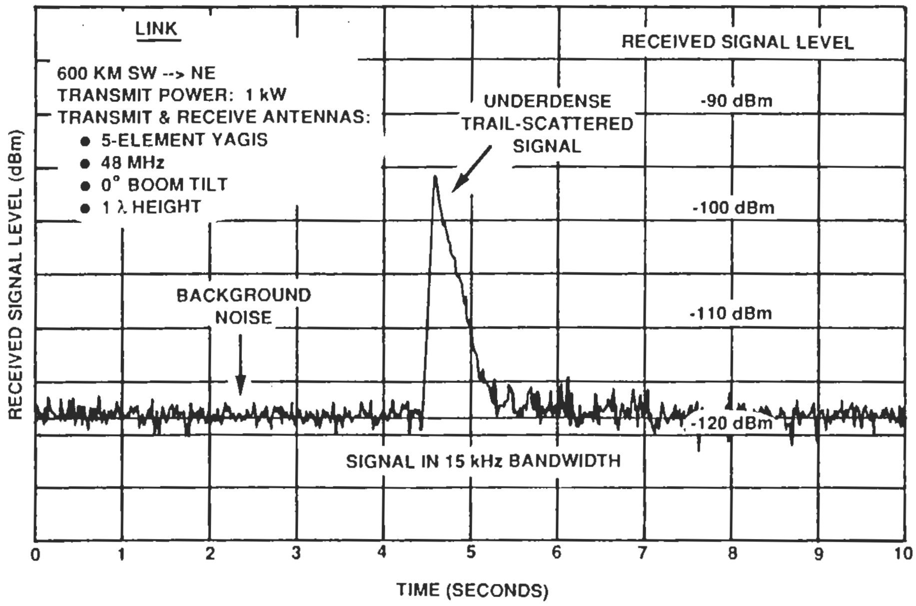

Figure 3: RSL From an Underdense Trail

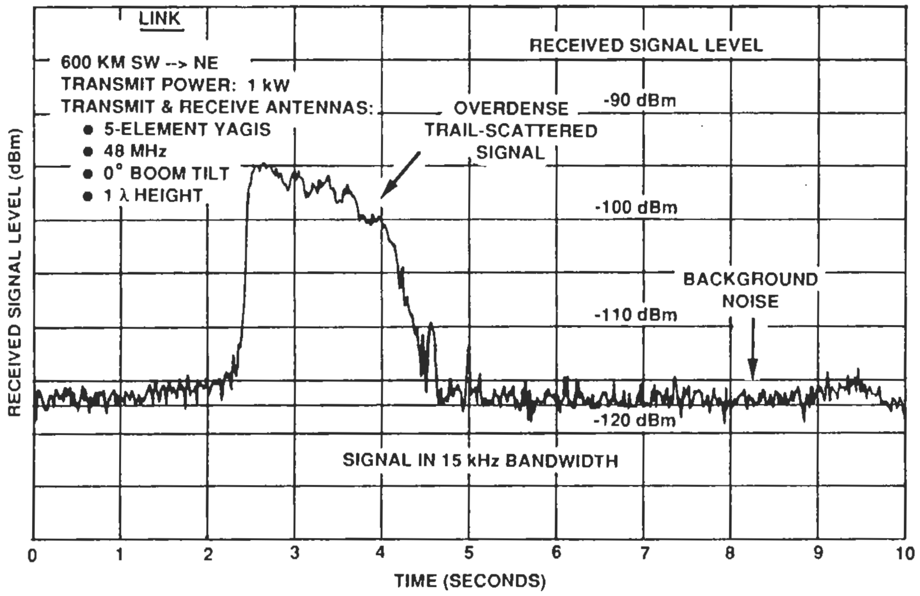

Figure 4: RSL From an Overdense Trail

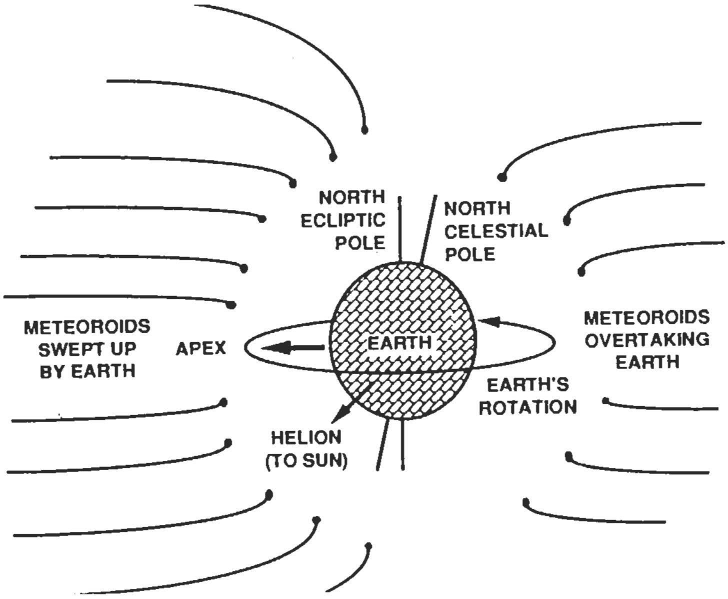

Figure 5: Diurnal Variation of Meteor Arrival Rate

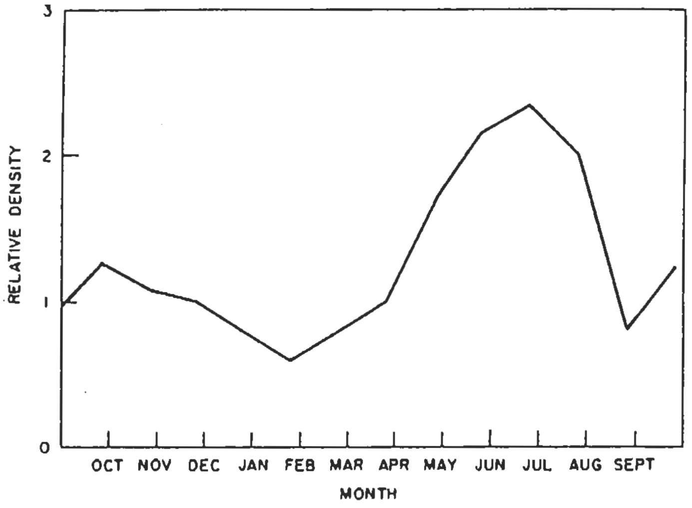

Figure 6: Seasonal Variation in Meteor Arrival Rate in Northern Hemisphere

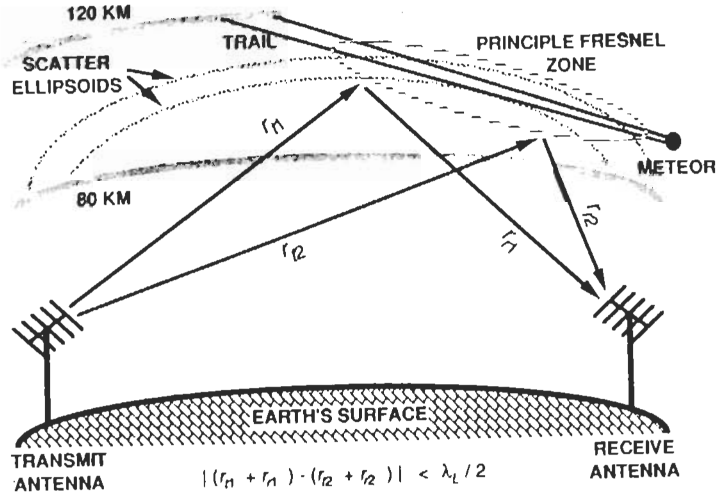

Figure 7: Link Geometry

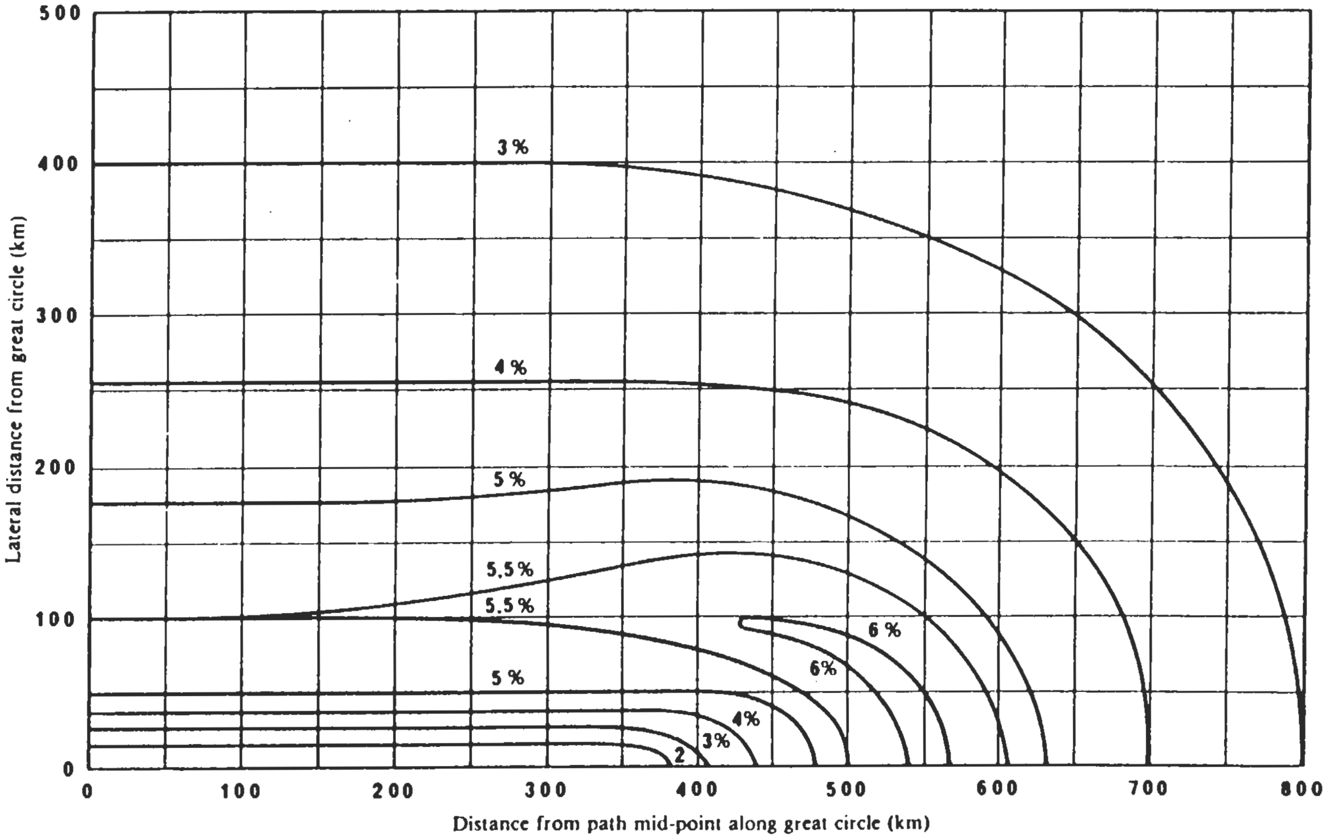

Figure 8: Estimated Percentages of Useful Trails as a Function of Scattering Position for a Terminal Separation of 1000 km.

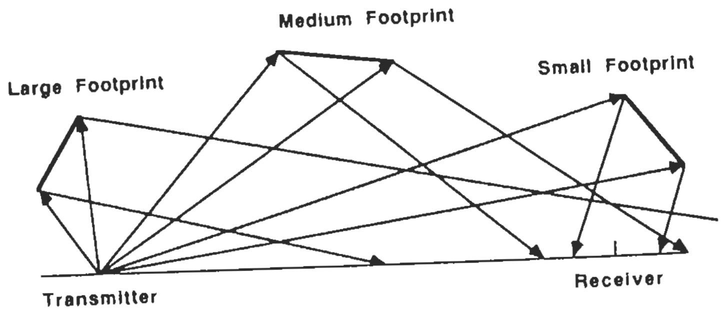

Figure 9: Effect of Trail Location on Size of Footprint

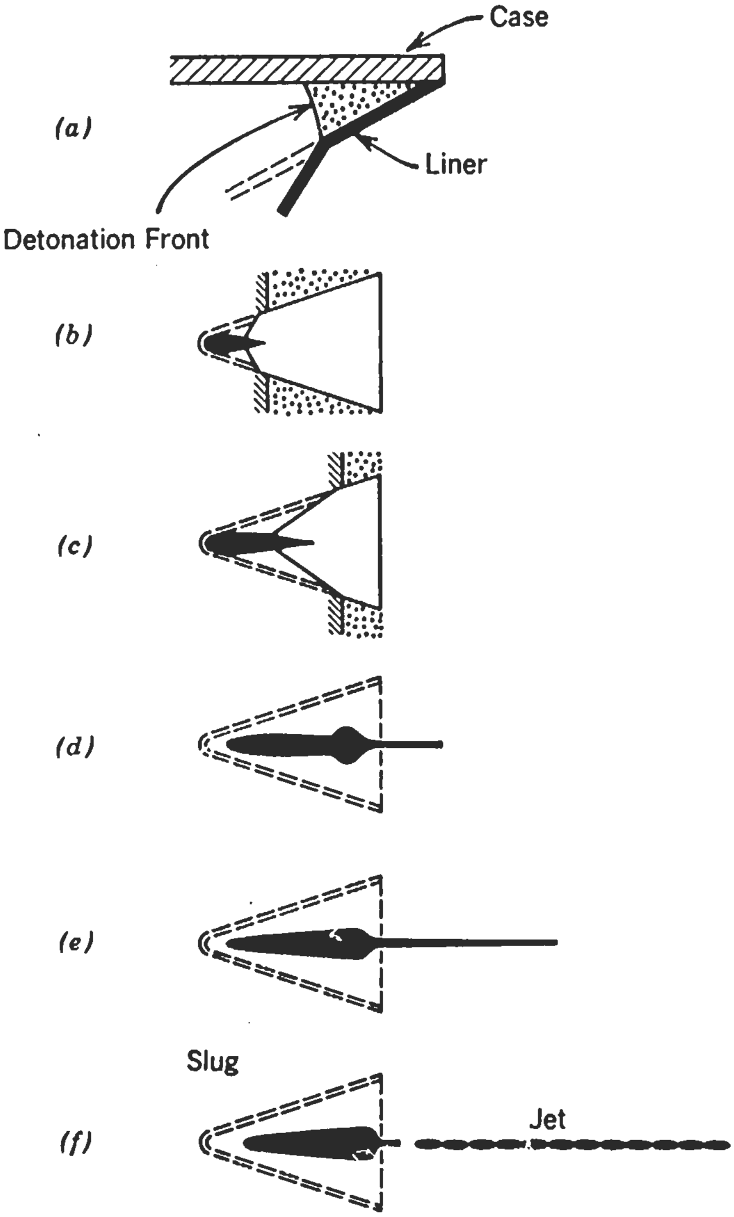

Figure 10: The Collapse of a Shaped Charge with a Conical Liner

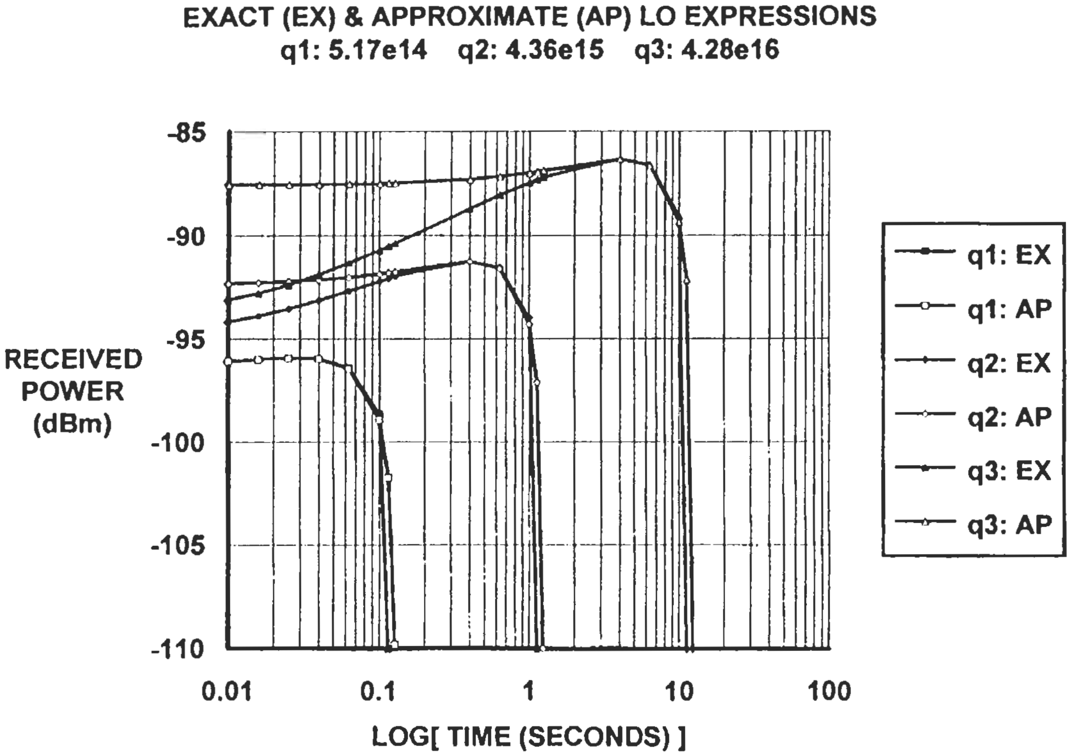

Figure 11: Exact and Approximate RSL Versus Time

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10. Capt Tommy H. Smith 1
RD #3 Box 111
Oxford, NY 13830