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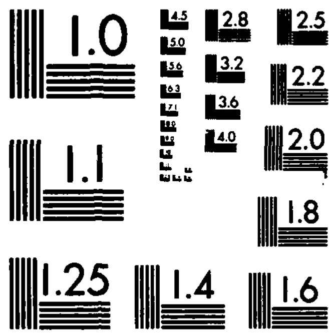

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METEOR-BURST COMMUNICATIONS:
IS THIS WHAT THE NAVY NEEDS?

by

Gretchen Ann Helweg

JUNE 1987

Thesis Advisor: Leon B. Garden

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Meteor-Burst Communications: Is This What the Navy Needs?

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This thesis evaluates the limitations of meteor-burst communications for Navy requirements. The author examines the basic physics of the meteor-burst concept and the history of meteor-burst systems to determine inherent or persistent shortcomings. These findings are then compared to ongoing research and Navy applications for this communications medium. Limitations of meteor-burst communications are discussed with respect to potential Navy applications. Recommendations of possible applications of this technology are provided.

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I. INTRODUCTION

In 1929 an article was published in Proceedings of the Imperial Academy of Tokyo suggesting that radio wave reflections from meteor trails might be responsible for sharp variations in shortwave reception [Ref. 1]. This observation marked the discovery of the communications phenomenon that would become meteor-burst communications. Twenty years would pass, however, before the reflection would be considered anything more than an interesting anomaly.

With the end of World War II the military began to invest research funds trying to develop an alternative to traditional HF for secure long-haul communications. Two possibilities emerged from this effort: satellite and meteor-burst communications. Although satellite communication was ultimately selected, the preliminary research in meteor-burst communications and system configuration came out of this period, providing the foundation for later research.

Today, the Navy finds itself faced with the vulnerability of both its HF and satellite long-haul communications systems and is again expressing an interest in the meteor-burst communications concept. The question remains as to whether meteor-burst can fulfill the Navy's needs, and if so, to what extent.

The purpose of this thesis is to determine the limitations critical to the Navy if it is to utilize a meteor-burst system and to suggest applications appropriate to the strengths and weaknesses of this system. The method used was primarily a library search, with limited input from persons active in ongoing MBC research. Discussions with fellow students in the Electronic Warfare curriculum provided an updated corroboration of potential system vulnerabilities. The structure of this research was to establish an understanding of the basic physics involved in meteor-burst communications, and investigate the historical thrust of research in this field. From this investigation, a set of inherent limitations was established and examined in light of ongoing research and the Navy's perceived requirements. The author then compared the expectations for MBC systems to the actual limitations and vulnerabilities in order to draw preliminary conclusions as to the applications of meteor-burst communications.

II. THE METEOR-BURST COMMUNICATION CONCEPT

Meteor-burst communication (MBC) is a simple concept that involves three complex elements: meteors, the ionosphere, and radio signals. Each element must be analyzed as an individual entity for its importance in the overall MBC scheme to be fully understood.

As the earth moves in its orbit around the sun, it is constantly bombarded by meteoroids, which form meteors upon entering the earth's atmosphere. It is estimated that between one million and ten billion meteors are created every twenty-four hours. Most of these are the size of dust particles with small individual mass, but together they deposit approximately one ton of matter in the ionosphere daily. The larger meteors may be visible as transient fiery streaks and, on rare occasion, will strike the earth. Any meteoroid that falls to earth is classified as a meteorite. All meteoric debris collected to date has been composed of substances common on earth, including iron and calcium [Ref. 2].

Meteoroids are defined as "any of the small bodies, often remnants of comets, traveling through space." [Ref. 3] The origin of meteoroids was unclear for many years, as to whether they are an interstellar phenomenon or indigenous to our solar system. In order for them to be members of our solar system, they have to be in elliptical orbit around the sun and have a speed not exceeding 42 kilometers per second, or 72 kilometers per second relative to the speed of the earth. Anything greater would result in a hyperbolic orbit, indicative of interstellar travel. [Refs. 4,5] Recent research tends to support the idea that meteoroids are from this solar system. If correct, the meteoroids' elliptical orbit will cause them to pass by the earth at regular intervals, instead of a solitary occurrence.

The distribution pattern of meteoroids is not completely understood. Larger meteoroids, which result in visible meteors, seem to be concentrated in the ecliptic plane, while the smaller meteoric particles, commonly called sporadic meteors, seem to originate from the apex of the earth's direction of travel [Ref. 6]. (See Figure 1)

Although meteoroid sizes vary from the microscopic to the tremendous, the ones discussed here are those for which a probability of daily occurrence can be calculated. Of these, the mass of an individual meteoroid may range from 10^{-12} grams up to 10 kilograms, having a diameter from a fraction of a micrometer to about eight centimeters respectively. The number of incident meteoroids of various sizes is estimated to be inversely proportional to their mass. This would mean formation of approximately ten very

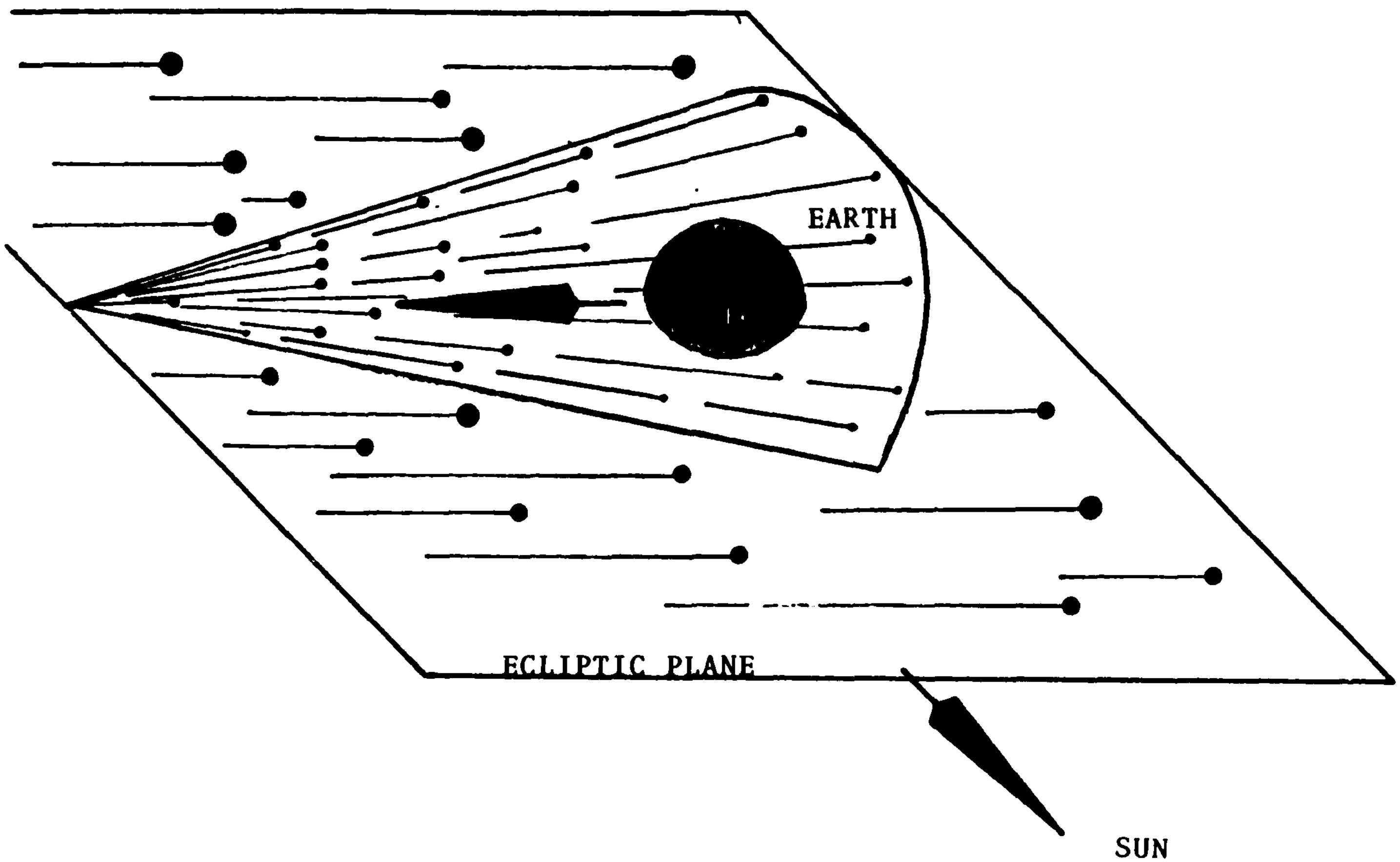

Figure 1 - Distribution Pattern of Meteors

large (10 kilogram) meteors each day as compared to the 10^{12} daily meteors with a mass of 10^{-7} [Ref. 7]. The speeds at which meteoroids enter the earth's atmosphere are widely varied also, with an assumed maximum of 72 kilometers per second relative to the earth. Much of the variation is caused by the relative motion of the earth, both in solar orbit and daily rotation. Calculated average speeds range from twenty to forty kilometers per second relative.

Whether an incident meteoroid is considered useful for meteor-burst applications is primarily dependent on its size and the quantity of meteoroids of similar size that can be expected in a given time period. The minimum mass for a useful meteoroid is approximately 10^{-3} grams [Ref. 8]. While size tends to dictate the amount of ionization that occurs, it is heavily influenced by other factors and cannot be calculated directly. Because the occurrence of meteors is random in time, sporadic meteors are of greatest interest from a communications viewpoint as they occur in the atmosphere almost continuously. Considering just these two parameters, it is estimated that 100 million useful meteors are generated every day [Ref. 9]. Relative speed and direction of approach or incidence are also considered when determining the utility of a meteor, but these tend to be amplifying considerations vice a true determining factor.

Because of the earth's motion, both rotational and orbital, and the angle of the earth with respect to the sun, varying meteor patterns are created. These patterns vary with the time of day (diurnally) and with the seasons. Additional patterns are created by periodic meteor showers which may occur annually or on a multi-year cycle.

Diurnal variation is caused by the earth's forward motion combined with its rotation. At any given time, the hemisphere of the earth facing the direction of orbital travel will observe a greater incidence of meteors. This increase is due to running down slower meteoroids in the earth's path and is associated with a significant increase between 0400 and 0600 local each day. Conversely, the majority of meteors observed by the trailing hemisphere are overtaking the earth at the time of incidence. [Ref. 10] Since comparatively fewer meteoroids travel at speeds greater than the earth's forward motion, there is a marked reduction in meteor activity between 1700 and 1800 local. (See Figure 2) These diurnal variations are most pronounced at the equator and least at the poles, reinforcing the concept that meteoroids are concentrated in the ecliptic. The ratio between the maximum and minimum rates of incidence can be as great as 20:1, but are usually between 3:1 and 5:1. The exact time of the minimum and maximum meteor activity for a given day is also affected by the ecliptic

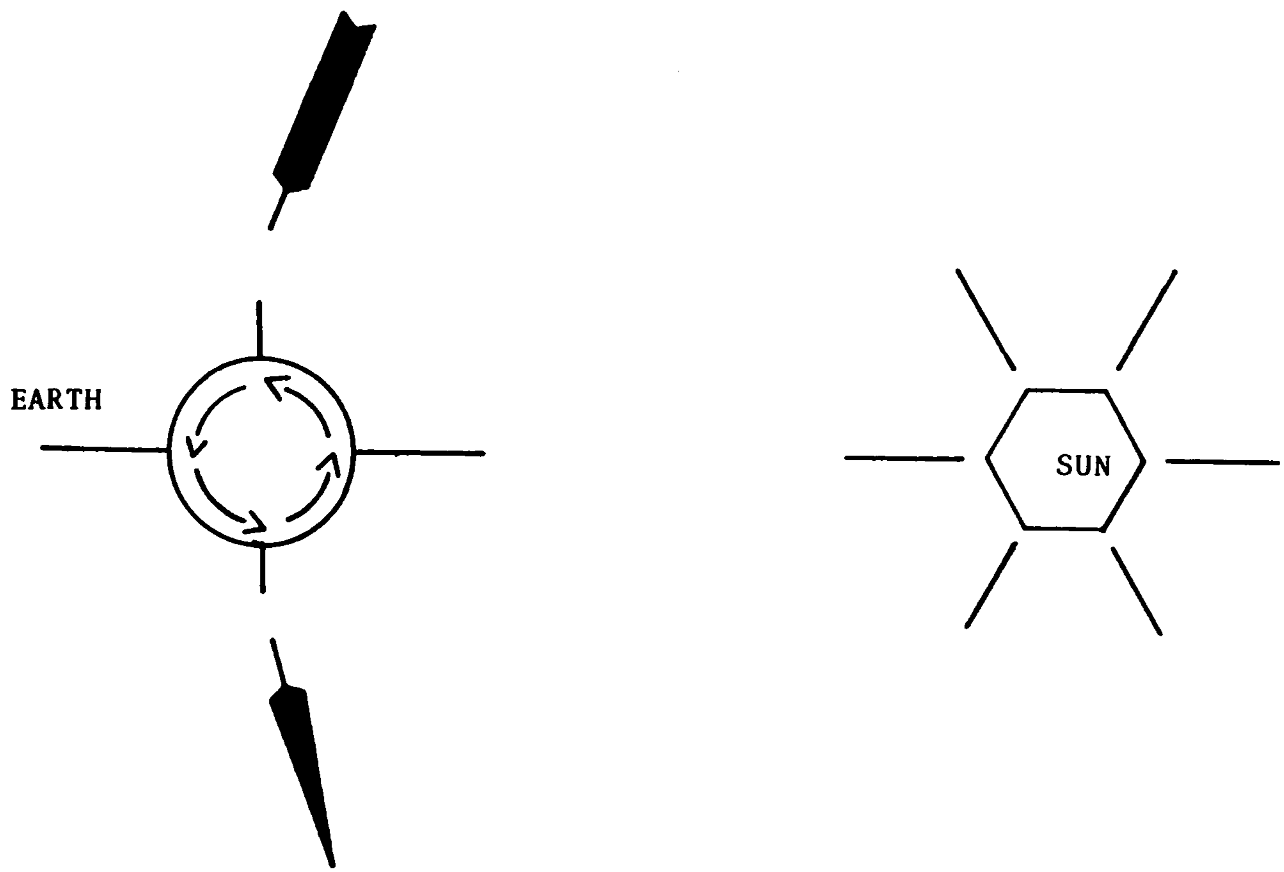

Figure 2 - Diurnal Variation Created by the Earth's Motion

plane concept. Assuming meteoroids are captured in the ecliptic explains why the morning maximum occurs after 0600 at summer solstice and before 0600 at winter solstice. As might be expected, the maximum occurs at 0600 during the autumnal equinox. Inexplicably, the vernal equinox often exhibits dual maxima, occurring before and after 0600. (See Figure 3) One other unexplained diurnal phenomenon is a slight enhancement in the quantity of meteors at noon, which is observed six months out of a year [Ref. 11].

Another meteor pattern variation is seasonal. Because the equatorial plane is not within the ecliptic, the northern hemisphere is tilted away from the apex of earth's travel in the spring and toward the apex in the fall. As a consequence, increased meteoric activity is observed in the northern hemisphere in the fall, while the southern hemisphere experiences increased activity in the spring. These seasonal variations are most pronounced at the poles and almost imperceptible at the equator. This is due to the proximity of the equator to the apex regardless of the earth's tilt and the curvature of the earth as it nears the poles exaggerating the same tilt. In the northern hemisphere, the lowest seasonal activity occurs in spring, while the highest occurs during July and August. With the exclusion of these summer months, twice as many meteors fall in the second half of the calendar year as in the first.

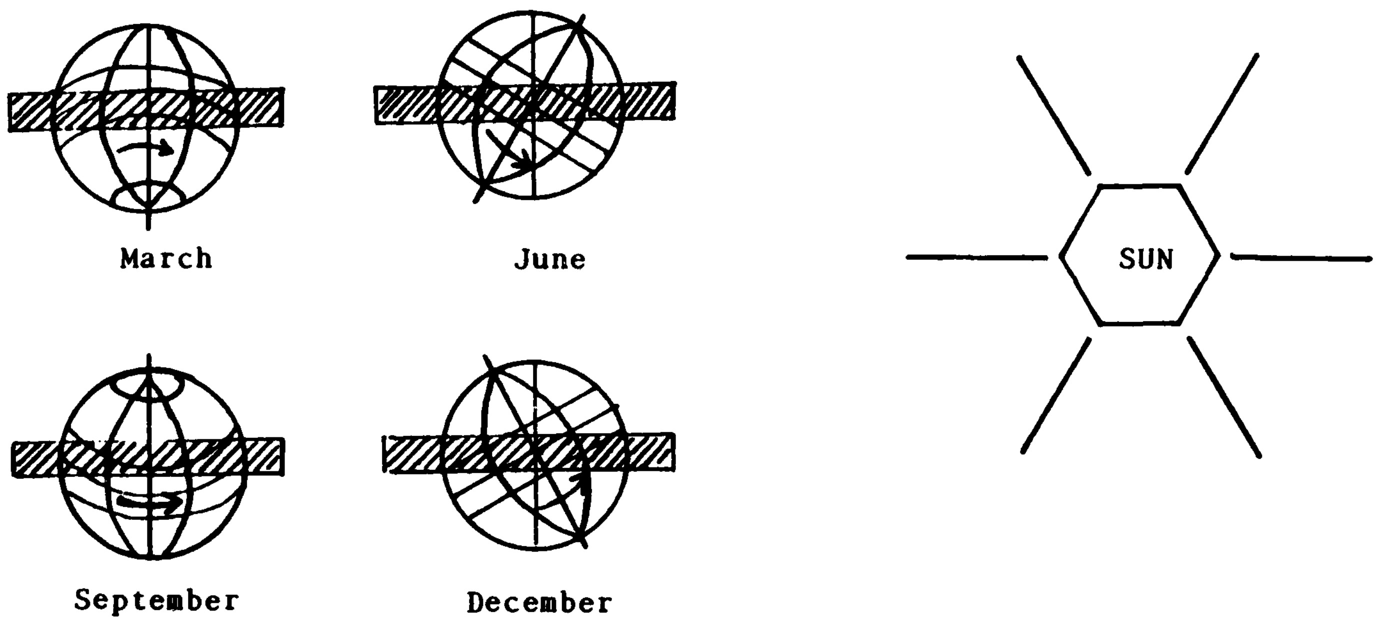

Figure 3 - Seasonal Fluctuations in the Diurnal Pattern

The ratio of maximum to minimum variation caused by seasonal factors is 3:1. Unlike diurnal variation, seasonal variations are not as likely to show wide disparities (i.e. 20:1 on a given day) unless meteor showers are included.

The final type of meteor pattern variation is the meteor shower. It is hypothesized that meteor showers are created cause sizable fluctuations in the quantity of meteoric debris encountered. All meteoroids in a given shower travel at the same velocity and appear to diverge from a single fixed point on the celestial sphere for which they are named [Ref. 12]. They travel in streams, staying in well-defined solar orbits. A shower only occurs when the earth sweeps through the meteoroid stream, causing the individual particles to collide with the atmosphere. This type of meteoric activity is most common in June, July and August, with each shower lasting several hours. As the exact increase in meteoric debris attributable to meteor showers is difficult to separate from that of seasonal variation, most reports lump them together. However, it is estimated that shower activity alone accounts for a 3:1 increase during the affected period.

The second major element in any meteor-burst system concerns the ionosphere. When a particle enters the earth's ionosphere, it becomes heated as a result of numerous collisions with air molecules. As more heat is produced, the particle becomes subject to excitation and then ionization of the particle's atoms. This ionization forms a trail of free electrons in the wake of the meteor. [Ref. 13] It is this column of ionized particles that is used in meteor-burst communications.

At a height of 40-300 kilometers above the earth's surface, the molecular density of the atmosphere is sufficiently low to allow free electrons and ions to move about for an extended period without recombining into neutral atoms. Called the ionosphere, it is actually several layers of ionization, most of which are caused by ultraviolet radiation from the sun. [Ref. 14] The layer between 80-120 km above the surface is where formation of the meteoric trails useful for communications occurs. (See Figure 4) A particle may ionize at a greater altitude, but its trail diffuses faster in the lower molecular density and is of no practical use. For example, a trail formed at 115 km will diffuse at the rate of 140 meters^2 per second, while an identical trail at 85 km will diffuse at the rate of 1 meter^2 per second [Ref. 15]. Ionization could also occur below 80 km, but the ionizing particle is usually consumed before it reaches this lower altitude. In addition to ultraviolet radiation and meteor ionization, the ionosphere is also affected by electric-field gradients, magnetic fields, proton emanation, and gamma radiation associated

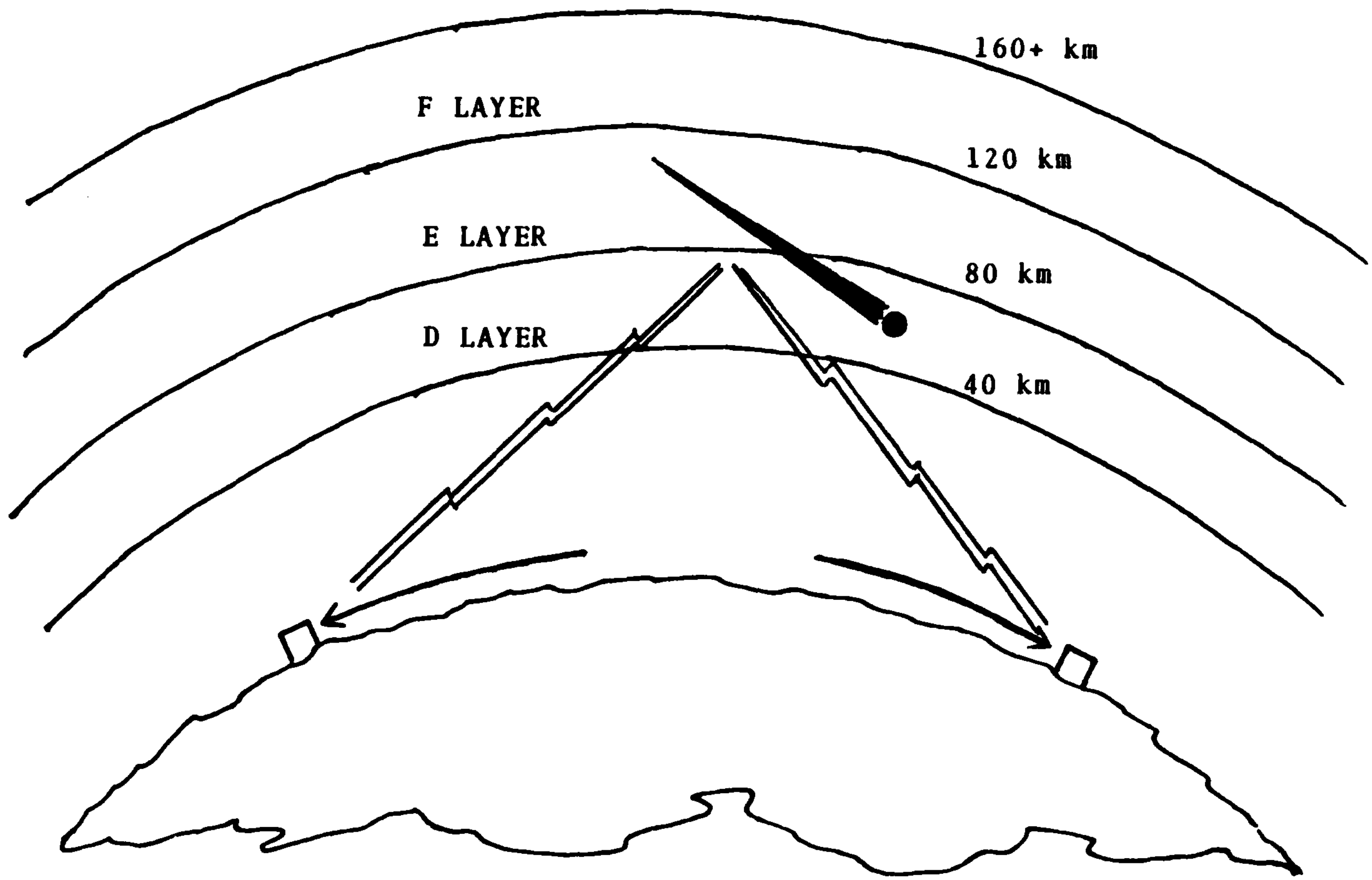

Figure 4 - Ionospheric Layers

with solar flares. Cosmic rays and high energy particles from deep space also contribute to the ionospheric character. [Ref. 16]

In addition to the meteor trails, there are three significant ionospheric phenomena which affect meteor-burst communications: ionospheric scatter, sporadic E, and auroral activity. Each can enhance MBC as well as degrade it, depending on the circumstances.

Ionospheric scatter is the reflection of radio signals entering the ionized layer by each free electron the signal encounters. Since the electrons are widely diffused and moving about freely, the signal is randomly reflected by each electron. The result is a collection of extremely weak signals with little directivity. This scattering can be used for radio transmission, but it requires large antennas, high-power transmitters, and wide bandwidth [Ref. 17]. It is also subject to interference and can only operate at very low data rates. The importance of ionospheric scatter is two-fold: it raises the signal-to-noise ratio in the ionosphere by constantly reflecting small background signals over hundreds of miles and it can directly distort the MBC signal through the scattering process. The positive aspects of ionospheric scatter are that it does occasionally contribute to the propagation of an MBC signal and, unlike MBC, it is continuous.

Another ionospheric phenomenon is sporadic E. Sporadic E is a thin layer of intense ionization in the E region of the ionosphere. It is believed to be the consequence of interaction between high velocity winds in the neutral atmosphere with the earth's magnetic fields. This neutral state is usually maintained in the ionosphere by a natural balance between the number of positive ions and free electrons. When two wind streams of differing direction and/or velocity come in contact, called shearing, both types of charged particles (positive ions and free electrons) collide with particles in the opposing stream. The free electrons are torn from the less mobile positive ions and are then affected by the earth's magnetic fields. The magnetic field forms the electrons into thin layers of intense ionization which are highly reflective. This sporadic E layer will vary in thickness from 1-4 km and in electron density from $2x10^{11}$ to $3x10^{12}$ per cubic meter. For comparison, the E region density is usually 10^7 electrons per $meter^3$. The result of this concentrated ionization is signal reflection that is a hundred to a thousand times greater than that produced by ionospheric scatter. Sporadic E has been used to enhance signal propagation from distant VHF transmitters, particularly during sunspot activity. Because of its enhanced propagation characteristics, sporadic E can be a major cause of multipath propagation or interfering signals from other VHF stations within a range of 1200 to 2000 km. The frequencies most likely to be reflected are the lower VHF bands, as has been demonstrated with TV channels two through six. The reflection will continue up to 88 MHz in some cases, but rarely higher. Sporadic E layers are disbursed by the precipitation of charged particles at high altitudes and unstable plasma in charged-particle streams at the magnetic equator. The wind-shear that causes sporadic E is most common in the temperate zones. [Ref. 18]

The last major natural ionospheric phenomenon is auroral activity. Like sporadic E, it is not uncommon for radio waves to be reflected by auroral phenomena. During periods of solar activity, the sun ejects charged particles which travel to the earth and enter the atmosphere twenty-four to thirty-six hours later [Ref. 19]. Here they react with the earth's magnetic fields to form the aurora, a curtain of fluorescence in the E region that can reflect radio waves with frequencies greater than 20 MHz. The aurora distorts VHF signals by scattering them much like ionospheric scatter, but returning a much stronger signal. The higher the VHF frequency, the more distortion occurs. Since auroral activity primarily causes frequency dispersion, its effects are less severe on the narrow bandwidth of single sideband. Unfortunately, MBC requires a wide bandwidth and has been blacked out by auroral propagation for hours [Ref. 20]. Other research indicates that this loss of MBC propagation may be avoidable as MBC has, on other occasions, operated without any significant distortion during major auroral flares. On the positive side, auroral ionization has accounted for a significant fraction of the total usable time on MBC systems in northern latitudes [Ref. 21].

The phenomenon that we are most interested in is the ion trail formed by ionizing meteoric particles. The trails first became of interest when it was determined that meteors frequently caused significant signal enhancement at the E-region height (100 km). Although a single observer can see only two or three visible meteors per hour, hundreds of trails can now be detected in the same period using sensitive radio equipment. Trails are measured in line densities (electrons/meter) and range from 10^{10} to 10^{18} electrons per meter, with each trail extending for several kilometers [Ref. 22]. Average trail length is fifteen to thirty kilometers.

One of the most important characteristics of an ion trail is its duration. The duration of a detected meteor trail can fluctuate from a few milliseconds to whole minutes. The average duration of a useful trail is 0.2 seconds, while the minimum is usually 3 milliseconds. The minimum usable duration is determined by the propagation delay to the trail from the transmitter and from the trail to the receiver as compared to the duration of the meteor trail itself. For most MBC systems and applications, the ion trail duration cannot be less than the total propagation delay.

The diameter of the meteor trail increases with time due to diffusion. A newly formed trail has a highly directive reflection which becomes less directive as a result of diffusion and distortion.

There are two major categories of meteor trails: overdense and underdense. The qualitative difference between the two trail types is the degree to which an incident wave can penetrate the meteor trail without undergoing serious modification.

If the line density of a specific trail is sufficiently high, a column of negative dielectric constant will surround the axis of the meteor trail, and prevent significant signal penetration. Instead, the electron shield will reflect the wave as though the column were a metallic cylinder. The negative dielectric constant is formed by a coupling between the individual electrons on the surface of the column [Ref. 23].

A meteor trail which suffers distortion and no longer forms a single, well-defined reflection is termed non-specular. Non-specular trails are a special case of the overdense trail, as underdense trails do not last long enough to exhibit this level of distortion.

Both specular and non-specular overdense trails are roughly defined as having line densities greater than 10^{14} electrons per meter. Viewed graphically, the overdense trail rises to full amplitude gradually and remains near its peak amplitude for some limited period before falling off sharply. (See Figure 5) This reflects the expanding surface of the column as the electrons begin to diffuse outward, followed by a slowing expansion as the core of the column becomes relatively empty. The final drop in amplitude indicates the point at which diffusion results in the de-coupling of the electron shield, and the signal is able to penetrate the meteor column instead of being reflected. The point at which the dielectric shield de-couples and begins to collapse is its critical value. In the very last stages of collapse, the trail could be classified as underdense, but the remaining trail is so brief its existence is usually ignored.

The actual duration of the overdense meteor column is difficult to calculate, as one area may appear to fade and then return or produce several other alternate paths from the same trail. Duration is also dependent on the size of the meteor, the speed at which it enters the upper atmosphere, its orientation with respect to the transmitter

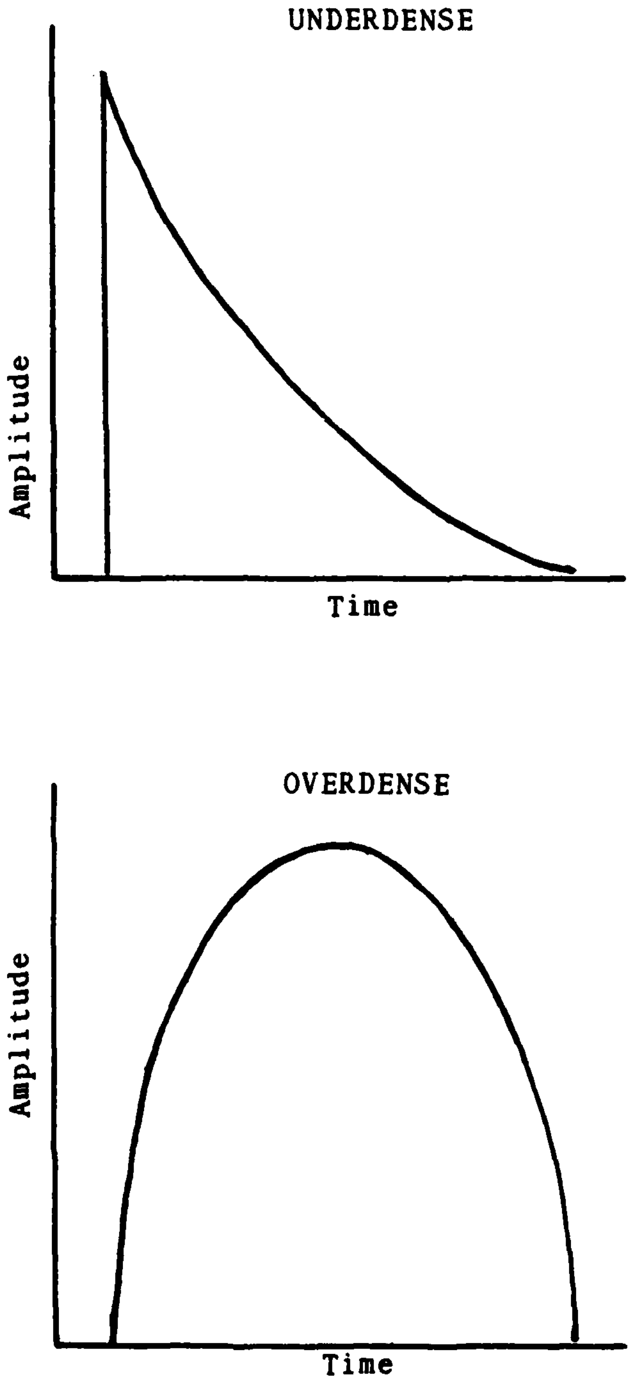

Figure 5 - Underdense and Overdense Ion Trails

and receiver, and the action of the high altitude winds. The net effect of overdense meteoric activity is formation of trails having greater-than-average duration, but occurring with less frequency.

Distortion of the specular overdense ion trail by wind or small scale turbulence results in the non-specular overdense type of trail. Strong fading is a common non-specular condition, caused by bending or distortion of a trail segment such that more than one reflecting surface is present. Trails whose initial specular orientation did not permit an MBC signal to reach the intended receiver, may be distorted by wind shear until an appropriate path is established. When a overdense trail is blown into the correct orientation, signal fading recurs until the trail is dissipated. This defines the classic non-specular overdense signal. Non-specular overdense signals account for 19% of all the columns presently used for MBC systems. By comparison, 37% of the utilized trails are the specular overdense type. The remaining 44% are underdense trails. [Ref. 24]

Underdense trails are physically different in their effect on the radio waves. If the line density of a particular trail is sufficiently small, the incident wave can penetrate the column without serious modification. There is a small core region of negative dielectric constant, but it only exists momentarily. The signal is reflected by uncoupled electrons; a scattered signal resulting from the motion of the individual electrons [Ref. 25]. Unlike ionospheric scatter, underdense scattering is highly directional. The ion column that is formed is narrower than the overdense type, being only a few centimeters in diameter, but it does start to immediately expand through diffusion. Graphically, an underdense trail rises dramatically and then falls in an exponential manner. (See Figure 5) This depicts the faster outward diffusion due to the lower density and lack of electron coupling. The exponential drop is the result of the rapid, uncoupled expansion of a very small trail, followed by an equally precipitous collapse.

Underdense ion trails exhibit comparatively small electron line densities that vary from 10 to 10^{14} electrons per meter. They do not have sufficient ionization density to reflect a radio wave as the column in the overdense case. Instead, the individual electrons are excited by radio waves and begin to act as miniature dipoles which re-radiate the signal toward the intended receiver [Ref. 26]. Most of the received signal is being re-radiated from the electrons that form a length of the trail called the Fresnel zone. Although each electron-dipole scatters the wave in the receiver's direction, the propagation distance from transmitter to electron-dipole to receiver is slightly different. Using the shortest propagation distance as the base, any propagation distance which does not vary from the base by more than one-half the wavelength is in the first Fresnel zone, and forms the primary contribution toward propagation by an underdense trail. So great is this contribution that for purposes of calculation, only the principal (first) Fresnel zone need be considered. The scattering done by these independent dipoles is specular in nature.

The underdense trail has a duration ranging from less than 0.1 seconds to a little over one minute, with an average of 0.34 seconds per meteor. The duration of the signal amplitude is considerably less on the order of a few tenths of a second for frequencies in the 30 to 50 MHz region. This is because of increasingly destructive interference from scattering by individual electrons. As the column diameter increases, so does the interference, until the trail is completely diffused.

Unlike the overdense columns, underdense trails are not very susceptible to distortion. Since distortion in any trail is negligible for the first half-second, the ensuing distortion has little effect on the exponentially decaying underdense signal.

The third and final major element in any meteor-burst communication system is the radio signal used. Most of the limitations placed on the choice of the radio signal are in response to the characteristics of meteors and their ion trails. For example, the expansion rate due to diffusion of a meteor trail dictates the strength of its reflection, which in turn limits the time during which the radio signal is strong enough to be detected. Most signals are detected for less than one second, while a minute fraction are detected for periods greater than ten seconds. Some restrictions are a function of more typical considerations, like the requirement for a signal to exceed a minimum detectable signal-to-noise ratio. These and other radio signal considerations must be understood in order for a MBC system design to be effective.

Perhaps the most important aspect of the radio signal is its frequency. One of the strongest incentives for trying to use VHF band signals for long-haul communications is the hope that these frequencies might be more immune to the ionospheric disturbances which plague HF communications. In comparison to HF, the VHF signal appears to bounce off meteor paths or any high ion density area, whereas HF refracts or bends away from ionization in much lower concentrations. This characteristic VHF bounce or reflection occurs between 30 and 100 MHz. However, most MBC systems use frequencies of 30 to 50 MHz, with a few operating between 50 and 80 MHz.

In choosing a frequency for a MBC system, the lower limit is determined primarily by rising ionospheric interference. The meteor signals experience increased fading at the lower frequencies, with attendant competing modes of propagation. As the frequency is decreased, the amount of signal reflected by ionospheric scatter increases, which raises the noise level and increases the likelihood of undesirable multipath propagation when the meteor path is established. Below 40 MHz, sporadic E may become a serious problem and near 30 MHz the possibility of ionospheric refraction (HF-type propagation) increases dramatically. Also observed at the lower VHF frequencies is interference from sunspot activity, lightning and atmospheric noise. Although this interference is less pronounced than with HF, it can still result in errors or even blackouts lasting several hours depending on the frequency of the signal and the strength of the interference. These effects are greatest at frequencies below 50 MHz.

The upper limit on the radio frequency band used for MBC is determined by the level of attenuation. As the frequency increases, the reflection from the ion trail becomes weaker and more difficult to detect. This weakness appears as both a decrease in signal strength and a shorter signal duration.

These limitations can be countered somewhat by either increasing the sensitivity of the MBC receiver or using only the more dense meteor trails. When the system is limited to a type of meteor trail which occurs less frequently, the delay between transmissions increases. To avoid unacceptable delays, those whose probability of occurrence cannot be calculated, most MBC systems do not exceed 80 MHz.

Also inherent in using the larger meteor columns to accommodate higher frequencies are distortion considerations, and their effect upon the radio signal. When points on the same column reflect at angles different than that of the specular trail, irregular reflections, referred to as glints are formed [Ref. 27]. Glints cause the total reflected energy to be less directive, and frequently interfere with the primary reflected signal and each other, further reducing the received signal strength. It is these complicated trade-offs that make frequencies near 50 MHz so attractive.

Another major consideration when discussing the MBC signal is interference. Some types of signal interference are man-made. Interference from a second MBC transmitter is possible only if both transmitters are on the same frequency and within the same footprint, assuming no multipath. To date, this particular type of interference has been rare. More common is interference from the numerous VHF adjacent-channel radio-telephone transmitters and TV stations, whose signals are unwittingly propagated over long distances by meteoric and ionospheric phenomena.

The man-made interference that causes the most concern is that generated by power lines and automobile ignitions. This type of interference is described as "impulsive" [Ref. 28] and is frequently misinterpreted as an indicator for a viable transmission path. This, in turn, leads to unintentional dumping of information to a non-existent meteor trail. For this reason, MBC systems cannot be exposed to the noise of an internal-combustion engine ignition system or power line. [Refs. 29,30]

A prominent type of natural signal interference is multipath. Multipath occurs when two or more transmission paths exist simultaneously. If the propagation delay of the paths is significantly different, distortion, signal fading or transmission errors can result.

Two suitably oriented meteors occurring in the same time frame is one cause of multipath. In order for interference to occur, the amplitude of the signal from one trail must exceed the operating threshold, causing the system to attempt transmission. The second signal must be comparable in amplitude to that of the first trail and, if sufficiently delayed, will cause errors rather than just fading. [Ref. 31] Most multipath transmissions by two meteor trails are harmless, either because one reflected signal is much stronger or because the path differences are such that the signals arrive in phase at the receiver. It is also a relatively rare phenomenon for two equally strong signals to occur in the same vicinity at the same time. Mathematically speaking, if communication is possible on a meteor trail for a fraction F of the time, there will be multipath propagation for approximately a fraction F^2 of the time [Ref. 32].

Another more serious type of multipath interference is caused by ionospheric scatter. Also known as the background continuum, ionospheric scatter can be predicted using the Rayleigh-fading equations, limiting some of its undesirable effects [Ref. 33]. This continuum interference is responsible for a significant fraction of the transmission errors observed, particularly in wideband applications.

Whenever a non-specular overdense meteor trail occurs, there is a possibility that distortion will cause two principal Fresnel zones to form along the trail resulting in multipath interference. With this type of multipath, the signal then develops two transmission paths, causing some difference in propagation delay. Few errors are created at low data rates as the path lengths are so similar that the delay difference is small. In fact, this type of multipath frequently goes undetected in these low data rate transmissions. The delay caused by two zones can become significant, however, at very high instantaneous rates.

Very sensitive equipment has been able to detect multipath caused by meteor head reflection, F layer return, and ground scatter. To date, ground scatter and F layer return have been so weak and infrequent as to be considered inconsequential. No F layer return has ever been detected above 40 MHz. Since the MBC concept does not depend upon the meteor head for communications but rather the ion trail left by it, the system may initiate transmission due to a detected reflection from the head, but by the time the data reaches the reflection point, only the ion trail is left. Thus, meteor head reflections are not considered a source of multipath interference.

Other types of natural interference fall in the category of phenomena whose effects include noise or path disruption, as opposed to multipath propagation. While ionospheric scatter occasionally generates multipath interference, it is always present as a source of unwanted noise. Scatter noise is the primary input used to determine the minimum threshold signal-to-noise ratio for an MBC system, particularly at low VHF frequencies. The orientation of the scattered signals is essentially along a great circle path connecting the two communicating terminals.

Sporadic E and auroral activity, as previously discussed, can also interfere with the MBC signal. However, these types of interference are usually detected as complete signal loss or disruption. When transmission has been possible during auroral activity, the rapidly fluctuating auroral signals resulted in an extremely high error rate and the intelligence in several instances was completely garbled [Ref. 34]. Unlike most sources of interference, however, auroral interference decreases at lower frequencies.

In contrast to sporadic E and auroral activity, the following sources of interference do not characteristically obscure the signal. Tropospheric scatter, which occurs in the inner layer of the atmosphere, may interfere over fairly short paths where the amplitude of the MBC signal has been reduced due to the angle of reflection. This type of scatter is also a great circle phenomenon, oriented similarly to the ionospheric scatter signals. It can, in the rare instances of tropospheric ducting, have signal levels sufficient to obscure a meteor-burst signal.

F layer propagation is only of concern in years of high solar activity, when backscatter may interfere with MBC signals at or near the maximum usable frequency (MUF) and at distances exceeding 1200 miles. Backscatter is the scattering of a signal in the direction of the transmitter, a concept similar to radar.

Electrical storms and precipitation static occasionally produce low level noise interference or momentary loss of an ongoing MBC signal. The primary concern with these particular phenomena is that they are considered a major source of impulse interference, which can erroneously trigger data transmission.

Because the formation of meteor trails is a random occurrence of limited duration, MBC systems use a burst-mode concept. The flow of data in a burst-mode system is intermittent, transmitting only when a correctly oriented propagation path is present and the reflected signal meets a minimum signal-to-noise threshold. This method is used to combat the effects of signal fading or loss inherent in a continuous-mode system at similar frequencies. Where in continuous systems the signal must be used throughout a signal fade, a burst system needs to tolerate signal fading only until the information transmission can be halted. Furthermore, by restricting transmission to intervals when the reflected signal amplitude is relatively large, the probability of error or non-receipt is decreased.

Delay is inherent in any intermittent system, especially one whose operation is determined by the occurrence of a random event. While undesirable, the significance of the delay can be minimized by signaling at high data rates when a transmission path is available. By comparison, continuous systems are limited to significantly lower data rates because of weak signal reflection and fading. The marked difference in instantaneous data rates allows a burst-mode system to achieve an average transmission rate equal to or higher than that of a continuous transmission system.

The delay and subsequent high speed transmission of data encountered in a burst-mode system makes some method of queuing imperative. Calculation of the required storage capacity is a complex process, developed from projected data rates, availability of transmission paths, and average message length. Due to the short duration of a meteor trail and the high data rates used, the storage system must be capable of high speed input at the receiving site as well as high speed output at the transmitting end.

Higher data rates are typically achieved by increasing the bandwidth of the transmitted signals. As bandwidth is increased, the threshold level is also increased to maintain a constant signal-to-noise ratio. This increase in threshold effectively selects only the trails with strong signal reflection characteristics and results in longer delays between usable transmission paths. Ultimately, the advantage to be derived from increasing the bandwidth in a MBC system will be offset by delay considerations.

The basics of meteor-burst communications have been described from the standpoint of its three primary elements:

meteors, the ionosphere, and radio signals. The interaction of these entities is a simple concept wrapped in the intricacies that make the system work. The next section will describe these interactions and their importance in a meteor-burst communications system.

An important aspect of any MBC transmission path is its geometry. Whether or not a given meteor trail can scatter a signal in the desired direction depends on its orientation and position in space and on the number of free electrons initially formed per unit of trail length. Since one objective of MBC is to use VHF for long-haul communications, it is assumed that the transmitter and receiver are beyond line-of-sight. Since VHF signals will not bend with the curvature of the earth, the meteor trail is used as the top of a triangle, reflecting or scattering the signal from the transmitter toward the receiver. In order to maximize the distance between sites, the meteor trail reflection should occur approximately 100 km above the ground. At this height, a maximum range between 2000 and 2400 km can be achieved with the differences being a function of the equipment selected and antenna orientation. The ion trails can actually occur as low as 80 km or as high as 120 km and still be useful for signal reflection, but at lower altitudes the range of the signal will suffer and at higher altitudes the rapid diffusion will attenuate the signal.

The ionospheric layer at this altitude is called the E region, and is the optimum layer for a useful meteor to occur in. (See Figure 6)

When the scattering or reflection is specular, the angles of incidence and reflection relative to the trail are equal. Even when a trail is non-specular, most of the reflected radio energy is confined near those directions corresponding to specular reflection of the trail. These angular conditions for successful reflection are satisfied when the transmitter and receiver are located at the foci of a three-dimensional ellipse and the trail is tangent to the ellipse [Ref. 35]. Actually, the trail is tangent to one of a family of concentric ellipses, each having the same foci defined by the station positions. (See Figure 7) Portions of the trail that are not tangent will not be capable of reflecting the signal between the sites. When a meteor trail does appear, it is important that at least half of the principal Fresnel zone be formed within the tangent segment if the trail is to scatter a signal of any appreciable strength to the receiver [Ref. 36].

Directly above the midpoint between transmitter and receiver on a great-circle path, meteor trails must be horizontal to satisfy the geometrical requirement for tangency. A meteor's direction of travel is rarely parallel to the surface of the earth, thus horizontal trails are

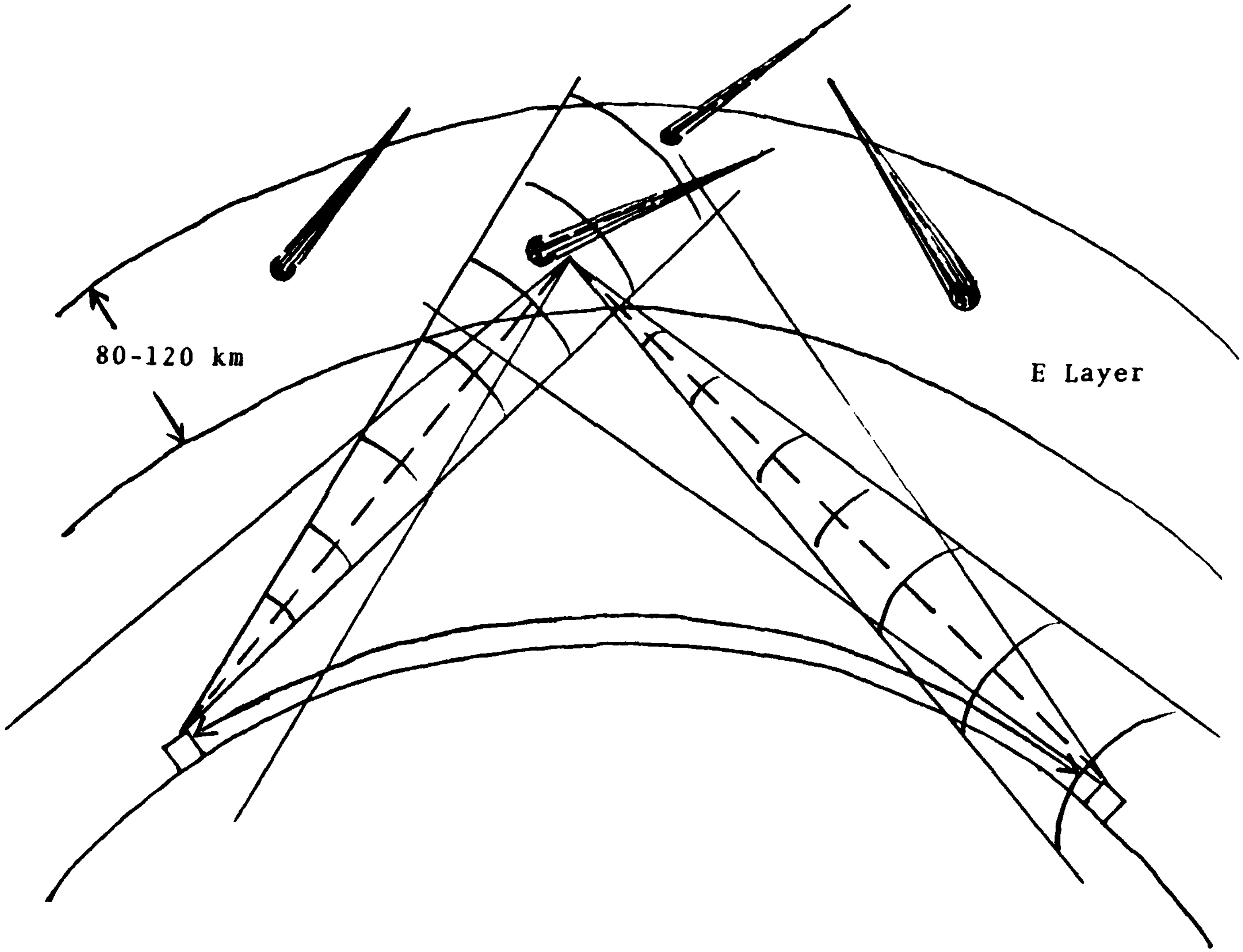

Figure 6 - Signal Reflection in the E Layer

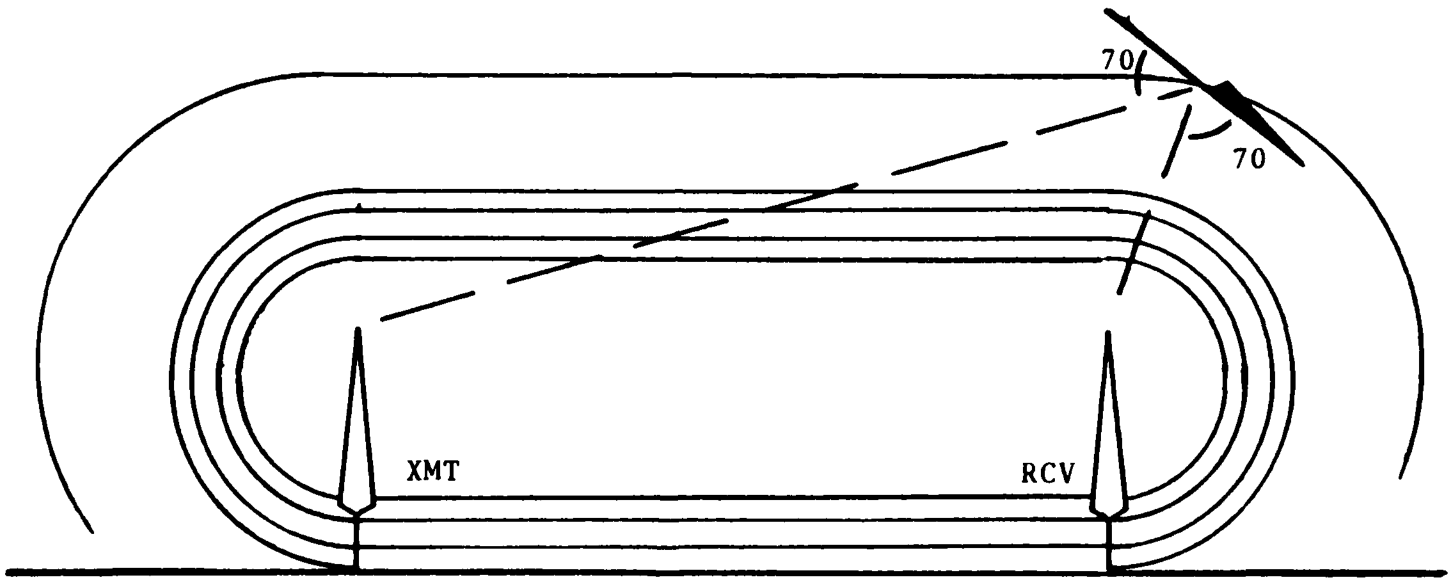

Figure 7 - Tangent Ion Trail Produces Successful Reflection

extremely rare. If the antennas are directed along the great circle path, the number of meteors detected will be reduced. The number of observable bursts increases when the antennas illuminate the area on either side of the the great circle path instead of the midpoint of the path itself. Empirical data has confirmed that the regions of the sky most likely to contain a useful trail lie to the sides of the great circle segment between the transmitter and the receiver. Although it varies, this off-path phenomena can be as great as 30 degrees [Ref. 37].

Each off-path region then provides the greater number of useful trails for a part of the day. For an east-west path, the antenna should be directed to the north of the path during morning hours and to the south of the path during the afternoon. For a north-south path, the antenna should be directed to the east of the path in daylight and to the west of the path at night. [Ref. 38]

The angle of the transmitting and receiving antennas also affects the transmission distance. The more perpendicular the antenna aspect to the surface of the earth, the shorter the transmission distance. This is because of the equal angles of incidence and reflection.

The inherent directivity of MBC ensures that the signal reflected from a particular trail may be received within only a limited area on the earth's surface. This area, referred to as a footprint, varies in size, shape, and position depending on the meteor trail, the angles involved, and other conditions of reflection. The footprint is generally elliptical in shape with its major axis in the direction of transmission. (See Figure 8) A typical long-haul footprint using an underdense trail would be an ellipse with axes of 30 and 15 miles. By comparison, the major and minor axes of the overdense, non-specular footprint may be as large as 3000 and 40 kilometers, respectively. The smaller footprint of the underdense trail provides a certain amount of protection from interference generated at limited distances from the transmitter or receiver. This allows MBC stations to use high instantaneous signaling rates of similar or identical frequency without interference, even when located relatively close together. This ability is called natural or spacial multiplexing [Ref. 39].

Because of the randomness of meteor trail formation and the resultant intermittent nature of burst-mode communications, MBC presents a unique challenge when discussing capacity, throughput, and other common data considerations. For example, capacity is commonly expressed as the rate of information transfer in bits per second. In contrast, the capacity of a meteor-burst system must be frequently re-calculated from the probability of available trails, their estimated duration, and the instantaneous data

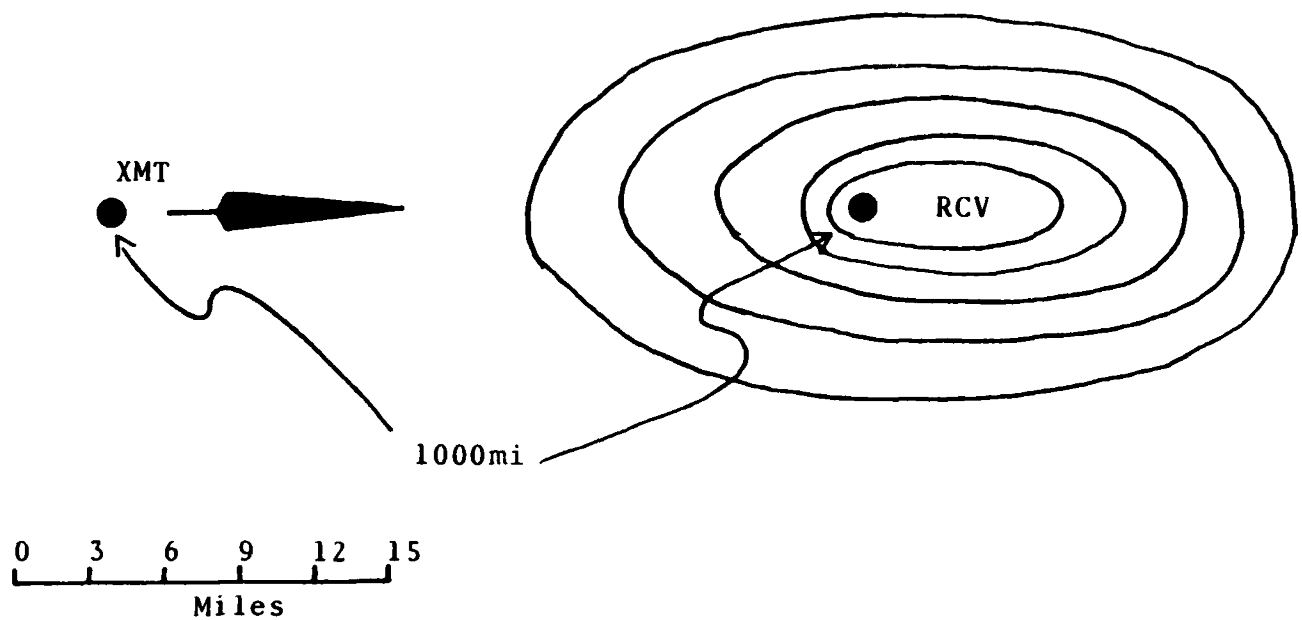

Figure 8 - Footprint from a Reflected Signal

rate to be used. This instantaneous rate is the actual rate of data transmission at any precise moment during the burst and is proportional to the signal bandwidth in a fixed bandwidth system. Since little can be done to affect the availability or duration of the trails, increased throughput is typically achieved by raising the instantaneous data rate. The upper limit on total message duration commonly used for capacity calculations is one second. Assuming a 50 millisecond preamble, 950 milliseconds are available for data transmission. At an instantaneous rate of 2000 bits per second, which is typical for a meteor-burst system, the individual message would be limited to 1900 bits. Empirical data indicates that average burst length is approximately 1120 bits or 140 characters, and lasts for 0.5 seconds [Ref. 40]. Although increases in the instantaneous data rate and/or transmitted power would allow a greater number of characters to be transmitted, the corresponding increase in delay between meteor trails of sufficient strength might offset any perceived advantages.

Availability in meteor-burst communications is used to describe the frequency of useful meteors as a number per given time period. It is availability that is most directly affected by meteor pattern variations. Also, as previously noted, when bandwidth requirements increase, there is an apparent decrease in the availability of useful meteors.

Duration is simply the length of time a trail is present. Trail duration typically increases in the afternoon, possibly because meteor speeds are relatively slower due to earth's rotation. The average morning duration is four seconds, while in the late afternoon, the duration averaged twenty seconds and occasionally reached two to three minutes in length.

Central to all meteor-burst calculations is the concept of duty cycle. The link duty cycle is the fraction of time that the received signal exceeds the prescribed threshold level. This threshold ensures that although the receiver may detect the transmitter's carrier, the system will not permit data transmission unless a trail is strong enough to support the high instantaneous data rate. A high duty cycle may be caused by meteor trails occurring more frequently, even overlapping in time, or by meteor trails of greater duration. Variations in duty cycle are also a product of path latitude, season, and meteor shower activity. An increase in duty cycle causes a corresponding increase in the mean rate of information transfer without an increase in bandwidth and a decrease in the mean delay time through the system.

The mean data rate is the measure of data transmitted over time. It is similar to the continuous system's data rate. The disadvantage of this method of measurement is that it varies with equipment, time of day, orientation, and all the other variables inherent in a meteor-burst communications system.

Mean Data Rate = Instantaneous Rate x Duty Cycle [Ref. 41]

III. PREVIOUS AND/OR EXISTING SYSTEMS

In the early 1950's, several experimental systems were developed to investigate the possibility of using meteor-reflected signals for communications. The military establishments in Canada and the United States were seeking an alternative to HF, capable of long-haul teletype operations. This interest provided the scientific community with funding for research into meteor phenomena and experimental systems. [Ref. 42] Some of the communications systems developed have had a major impact on the MBC community. Five of these were experimental and contributed heavily to the basic knowledge of MBC. Three existing operational systems will be discussed in light of their use and the advantages or disadvantages of MBC they demonstrate.

A. NATIONAL BUREAU OF STANDARDS SYSTEMS

One of the earliest MBC systems belonged to the National Bureau of Standards (NBS). A link between Cedar Rapids, Iowa and Sterling, Virginia had been established for forward-scatter and sporadic E research under a contract between NBS and Collins Radio Company. As the effects of meteor trails upon the circuit became obvious, the thrust of the research was shifted to assess the possibility of communicating by signal reflection from the trails. In

1951, four months after first observing the phenomenon, Collins demonstrated the increased propagation characteristics of meteor reflection to the Air Force. The USAF contracted for a Forward Propagation Ionospheric Scatter system (FPIS), classified and code-named "BITTERSWEET". It was to operate continuously between Thule, Greenland and Limestone, Maine, using ionospheric scatter augmented by meteor reflections when available. Designed to carry four teletype channels, it was a marginal system at best, built on the limited technology of the 1950 NBS system. BITTERSWEET was declassified in 1957. [Ref. 43]

Meanwhile, Collins and the NBS had used the Iowa-Virginia link to collect more data concerning meteor activity and the orientation required for useful signal reflection. In May of 1953, they began communicating via meteor reflection, ionospheric scatter and sporadic E, transmitting continuously. The link used rhombic antennas whose main lobes intersected at the midpoint of the great circle path between the two sites. In September, one line of test symbols was repeatedly transmitted from the Iowa site. It was observed that data rates up to 3200 per second could be transmitted via meteor reflection for the duration of a trail. Even with significant increases in transmitted power, ionospheric scatter was unable to compete with these higher data rates.

Several other experiments were conducted under the auspices of the NBS. A test between Erie, Colorado and Long Branch, Illinois, established the empirical propagation distance of meteor reflections as 1295 km at a nominal frequency of 50 MHz. Another link between Walpole, Massachusetts and Sterling, Virginia, was used to collect propagation data on north-south oriented paths.

In 1958, the NBS introduced their first burst-mode system, using equipment specifically designed for meteor-burst communications. Installed in trailers for mobility, it was used to study the effects of geography and alignment on the duty cycle. The equipment operated around 50 MHz with a one-half MHz spacing to allow for full-duplex operation.

The terminal equipment for the link was teletypes, which operated at 60 words per minute. By comparison, the transmitters and receivers operated at an instantaneous rate of 2400 bits per second, or eighty times the speed of the teletypes. Magnetic tape recorders were used at both ends as buffers for the incoming and outgoing traffic. These tapes were in continuous loops, each capable of holding one hour's teletype traffic. If the transmitter's magnetic tape storage was emptied during a burst, the system would automatically shift and read the incoming teletype paper tape.

Full duplex operation of the system was achieved by having the transmitter at each end of the link sending constantly, trying to establish a path with the distant end. This process is known as probing and can be done by one or both of the transmitters. Whenever a probe was received by the distant end and its signal strength exceeded a preset threshold, the collocated transmitter was allowed to begin data transmission. This was done on the assumption that if a signal could be detected, a usable trail must exist, and therefore, a reciprocal path was available. The transmission was stopped under two conditions: when the signal strength dropped below the preset threshold, or when a receiving terminal ran out of storage space. Since the terminals were identical, either one could stop transmission. An advantage of this system was that the absence of data to transmit at one end of the link did not cause a system stop. Instead, the transmitter without data returned to its probing pattern.

In this particular system, separate antenna arrays were used for the transmitter and receiver at each end. This was done in an effort to reduce the effects of strong local transmitter signals upon the local receiver sensitivity. Each array was deployed so that the major lobes were offset approximately ten degrees from the great circle path. This was done to minimize scatter interference and to take advantage of increased meteor activity in these areas called hotspots. (See Figure 9)

The results of these NBS experiments led to conclusions which affected the early direction of meteor-burst research. One such conclusion, based on the continuous transmission data and the successful intermittent system prototype, was the belief that increased overall system capacity could be achieved in MBC using wider bandwidths and higher power transmitters. No experiments were performed by the NBS to verify this theory or ascertain its limits. [Ref. 44]

Even while the experiment was ongoing, it was apparent that the theoretical capacity of the meteor-burst path was not being realized. The researchers concluded that multipath interference was the primary cause of capacity loss, with scatter interference being secondary. Equipment limitations also lead to some capacity loss.

The NBS provided the world with some of the earliest and most complete information about meteoric activity and ionospheric effects. Theirs was the first system to demonstrate the possibility of using meteor trails for signal reflection. The discovery of hotspots, the areas of increased meteor activity on either side of the great circle path, was also made on the NBS system. Had the first NBS system used offset antennas, the number of meteor-burst signal paths would have quadrupled.

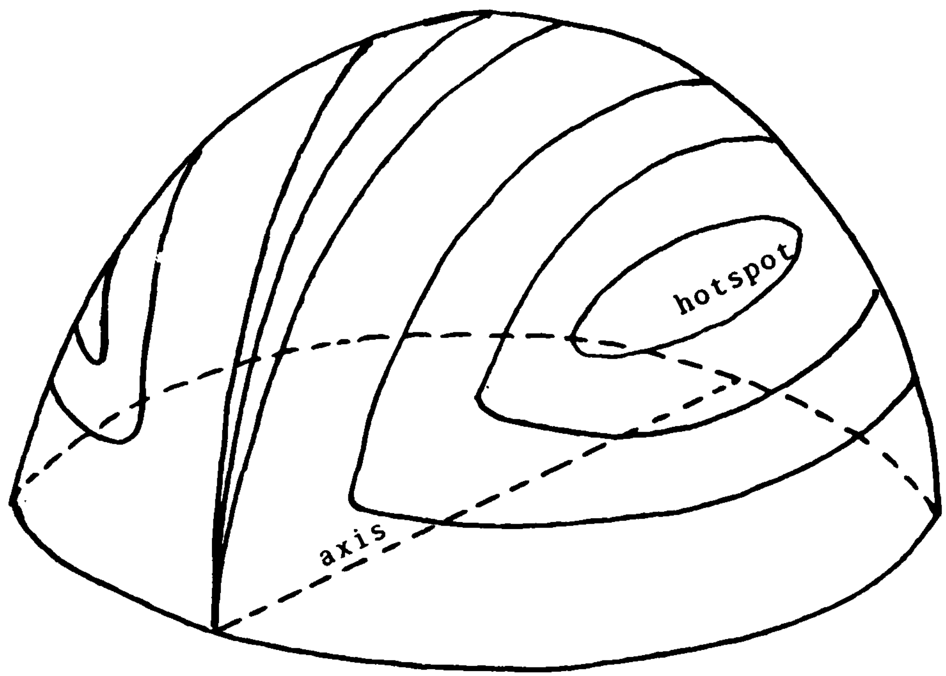

Figure 9 - Hotspots in Relation to a Great Circle Path

As previously noted, the NBS meteor-burst system suffered from multipath interference. The NBS researchers pioneered methods of automatically identifying and rejecting those meteors which produce overdense, non-specular trails. These trails tend to be of long duration, making them subject to multipath-producing distortion and deep fades. The easiest method, used in the later NBS systems, was to stop transmission after the first detection of multipath or the first deep fade. A limited amount of channel capacity was lost by not allowing the system to transmit until the questionable trails had expired.

To reduce end of signal errors, an error-sensing technique was used. Special equipment at the receiver site compared the timing of the incoming signal to known transmitter timing values. If the received signal's timing varied more than a preset amount, the receiver would signal the transmitter to stop. The system was very effective against multipath and noise and had a negligible impact on the link capacity.

Much of the difficulty with the NBS system was caused by a preference for the stronger, overdense trails which are the most susceptible to multipath distortion and fading. Even in their most developed system, the longest delays were not caused by lack of available meteors, but from competing interference. The discovery of the split-beam antenna configuration was helpful in offsetting this problem in later systems. The offset hotspots are not only more active, but have a lower scatter noise level. This results in more underdense trails being detected and utilized, resulting in fewer multipath and fading errors.

B. STANFORD RESEARCH INSTITUTE SYSTEMS

In the same timeframe as the NBS, Stanford Research Institute (SRI) also became interested in the meteoric phenomena. The original concept was to use a continuous system, vice a burst-mode, utilizing scatter and other propagation techniques when a meteor trail was not present. The low data rate, high error rate and increased power requirements for this type of system ultimately led to its replacement with the intermittent burst concept.

SRI was under contract to the USAF when they created their first meteor-burst communications link between Palo Alto, California and Bozeman, Montana. The system was designed as a one-way link with the transmitter at Montana State College and the receiver at Stanford University in Palo Alto. The great circle distance was 820 miles. A secondary link was set up from Phoenix, Arizona to Palo Alto so that comparisons could be made between north-south propagation and east-west propagation.

Equipment included transmitters and receivers at both sites, but while the transmitter at Montana sent both operational control characters and informational data, SRI's transmitter was used only to send the operational control data. They used a nominal frequency of 40.38 MHz for data transmission, while control characters were sent at 32.8 MHz. They hoped that these frequencies were close enough to allow good path correlation, but separated enough not to experience cross-coupling. In operation, a continuous wave (CW) signal was transmitted from both the transmitter and the receiver. When the receiver detected a signal that exceeded a preset signal-to-noise ratio, its local transmitter began sending. This signal-to-noise ratio was referred to as the decision level and was a marked improvement over the standard strength preset, in that the signal-to-noise ratio takes varying noise levels into account. The system transmitted the data at 600 words per minute, or ten times the teletype rate. Transmission was discontinued when the signal to noise ratio fell below the decision level, when the receiving buffer was full, or when the receiving end detected a system malfunction. The duty cycle was a function of the receiver's decision level, the antenna gain, and the transmitter's power level.

As in the NBS system, storage and buffering were major issues. Again, data was stored at the rate of 60 wpm, the speed of the incoming teletype circuit, and transmitted at the instantaneous rate of the meteor-burst link. It was stored on magnetic tape at the receiving end and fed to magnetic core memory used as a buffer for the teletype printer.

If the teletype was unable to print out all the information on the core memory before the magnetic tape became full, a warning signal was sent to the transmitter rather than allowing the tape recorder to write over the data. The core memory only held 240 complete characters, which took the printer approximately forty seconds to type. Magnetic core was considered a very advanced concept because it employed no moving parts and could operate at speeds exceeding one million words per minute. However, its small capacity was a limitation, as was its inability to read and write at the same time.

The SRI system was noted for pioneering the meteor-burst voice concept. Although it has not become very popular, the ability to transmit voice does exist over a MBC system. The system developed by SRI used a 20 KHz bandwidth and simply transmitted the signal at five times the speed of a normal voice. Signal detection and circuit control were accomplished in this system configuration the same way as in the data circuit. The voice was recorded on a magnetic tape loop at the transmitter site that was the same length as the loop as the receiver. When transmitted, the receiver recorded the voice on its magnetic tape loop and slowed it to one-fifth of the transmission speed before playing it back on a speaker. With a Nyquist sampling period of 125 microseconds, up to 50 microseconds of voice could be lost with no effect on intelligibility, eliminating the need to compensate for signal fading or tape start up times.

A second SRI circuit was located between Phoenix and Palo Alto, and was used to determine the differences between east-west propagation as compared to north-south. The researchers observed classical diurnal and seasonal variation on the east-west link, but not on the north-south for the same time period. The north-south circuit experienced a scatter of data points and many erratic changes for unknown reasons. This phenomenon is still under investigation, as is the 3:1 variation from day to day observed on north-south paths without comparable variations on the east-west path.

SRI researchers contributed to a basic understanding of the physics of meteor trails, including the identification of the curves associated with the underdense and overdense trails. Their experimental system was designed and tested as a low power system only, and thus it used primarily the intermittent propagation paths from ionized meteor trails. Certain irreducible delays in starting and stopping the data flow caused a slight reduction in the duty cycle of the system. This represented a loss of seventeen microseconds per burst and possibly an additional sixteen microseconds before the information stopped being transmitted due to the fact that the transmitter would not stop mid-character. These delays resulted in errors referred to as end-of-burst errors. These errors were most common when multipath or signal fading occurred. Since signals have been observed fading as rapidly as 500 decibels per second, the system compensated by using a signal-to-noise decision level higher than the minimum ratio needed for detection. This was effective for any fade less than 200 decibels per second, but was done at the expense of the system's duty cycle. The researchers concluded that higher transmitter power and more elaborate antenna arrays might alleviate some of the fading problem, along with diversity reception techniques, but none of the concepts were tested. They also felt that using a transmission rate greater than 600 wpm was inefficient, in that the duty cycle was lowered to accommodate the higher data rate requirements, balancing out any gains they may have obtained from the increased rate. The underlying assumption was that MBC systems are designed to work with 60 wpm teletypes, and thus had storage and buffer requirements which precluded higher instantaneous rates.

One conclusion reached after operating with both magnetic tape and core memory storage systems was that the ability to read and write simultaneously was important, making the core memory a poor choice for any future system. The 240 character storage was usually sufficient, as was the ten-to-one speed up capability used in this particular system. Although occasionally the core storage was exceeded resulting in termination of the circuit, the efficiency loss was not appreciable. Core could have been added, but then the time between reads and writes would have increased.

The tape loop concept was the first of its kind and was used by several later systems, including the NBS system. The tape held 900 characters and had a speed ratio of approximately ten-to-one. The likelihood of exceeding the magnetic tape storage was remote. Ultimately, it was decided that the magnetic tape itself could be reasonably used as a buffer, eliminating the need for the core memory altogether. [Ref. 45]

The long term contributions of this system includes much of the theoretical information available in the 1950's. SRI collected detailed data on the occurrences and patterns associated with trails, signal fading, and propagation patterns. They verified the existence of hotspots, discovered signal fading in excess of 400 decibels per second, and were the first researchers to try to unravel the north-south and east-west propagation differences.

While collecting signal data, they discovered that the largest number of signals received are only one character in length, transmitted on a underdense trail of less than 0.2 seconds.

The performance of the SRI antennas when offset from the great circle resulted in the use of offsets in the final NBS system and all subsequent systems. The researchers used rotatable antenna arrays and found the hotspots to be offset as much as 30 degrees from the great circle path. They were the first to determine that on an east-west path, the antenna lobes should be focused south of the path in the evening and north of the path in the morning to maximize available meteor trails. Similarly, north-south paths should have antenna lobes directed to the east in daylight and to the west at night. [Ref. 46]

They were the first to successfully transmit voice with a maximum propagation distance of 2200 km. This is still considered the maximum usable range for any ground-to-ground transmission where the antennas are at or near sea level.

C. JANET

JANET was the first system designed from its inception to be meteor-reflection only, with burst type transmission. It was the brainchild of the Radio Physics Laboratory (RPL) of the Defense Board of Canada, and was the longest running, most studied MBC research system. The preliminary research work for JANET began in 1952, when the results of the early NBS system and the beginning efforts at SRI were discussed at a communications symposium. The RPL decided on a three phase preliminary investigation. The three phases were:

1. assess the utility fo reflected signals for communications
2. establish the existence of reciprocal path propagation with different frequencies
3. demonstrate ability to transfer data by meteor-burst.

In Phase 1, the utility of the signals was determined by taking crude measurements of their strength and duration. Made in late 1952, the measurements were taken at distances of 900 and 1200 km. These measurements indicated that a sufficient number of communications paths would exist for modest transmitter power levels.

Phase 2 was to establish that reciprocal propagation paths existed for two different frequencies, and that the bandwidth was sufficient to support two different signals on the same meteor trail without mutual interference. In June of 1953, modulated signals were transmitted simultaneously but in opposite directions over a distance of 1050 km from Ottawa to Port Arthur. Due to the short life of meteor trails, it was decided that detection and selection of a suitable trail would have to be done simultaneously. This was accomplished by having an identical transmitter and receiver at each end, constantly radiating a CW carrier. When the receiver at the distant end detected the carrier, it compared the existing carrier-to-noise ratio to a preset carrier-to-noise ratio. Whenever the existing ratio exceeded the preset ratio, the transmitter initiated the high speed modulation for transmission. This marked the first successful automatic operation of a two-way circuit in which the modulation of the transmissions was initiated by the occurrence of a suitable meteor trail.

Phase 3 demonstrated that the meteor-burst system was capable of information transfer. The issue here was that the duration of the reflected signal would be so short or distorted that the amount of data actually transferred would be minimal. The same rudimentary system used in Phase 2 sent a message from Ottawa to Halifax and back via the MBC link, and was then compared with the original message. The system concept was declared feasible in March of 1954 after teletype data was successfully transmitted. The error rate on this preliminary system was on the order of 1.5 percent.

After successful completion of the preliminary program, RPL placed a contract for the development of meteor-burst equipment for full duplex transmission. It included a transmitter, receiver, control unit, gated transmission storage, receiver storage, and an antenna. The system was designed to transmit 1300 bits per second from one magnetic tape storage to another, with the receive-end tape storage acting as a buffer for the teletype as well. It was delivered and fielded in late 1954.

From 1955 through 1957, RPL continued to collect more empirical data on the reflected signals, particularly the variation in numbers, strength, and orientation. Links were maintained between Halifax and Ottawa, Ottawa and Port Arthur, and Port Arthur and Toronto. (See Figure 10) The Canadians had hoped the system would be an inexpensive method of long-haul communications for remote areas in Canada.

A second major system, called Canadian JANET B, was introduced in 1958. Also known as the Edmonton-Yellowknife JANET Circuit, it was located in the auroral zone between Edmonton, Alberta and Yellowknife, North West Territory. Initially operated at 40 MHz, it suffered severe polar blackouts and excessive error rates during the auroral activity. From December 1958 until April of 1959, the frequency was varied between 40 and 50 MHz, and long-term statistical data was accumulated. [Ref. 47]

The JANET system is considered to have been the first system to demonstrate the feasibility and reliability of the MBC concept. It was debatable then, as now, whether the system could compete with the more established techniques. The technology in JANET still did not approach the theoretical capabilities of the system, and program development was slow due to its statistical nature. For their purposes, the utility of the JANET system had to be

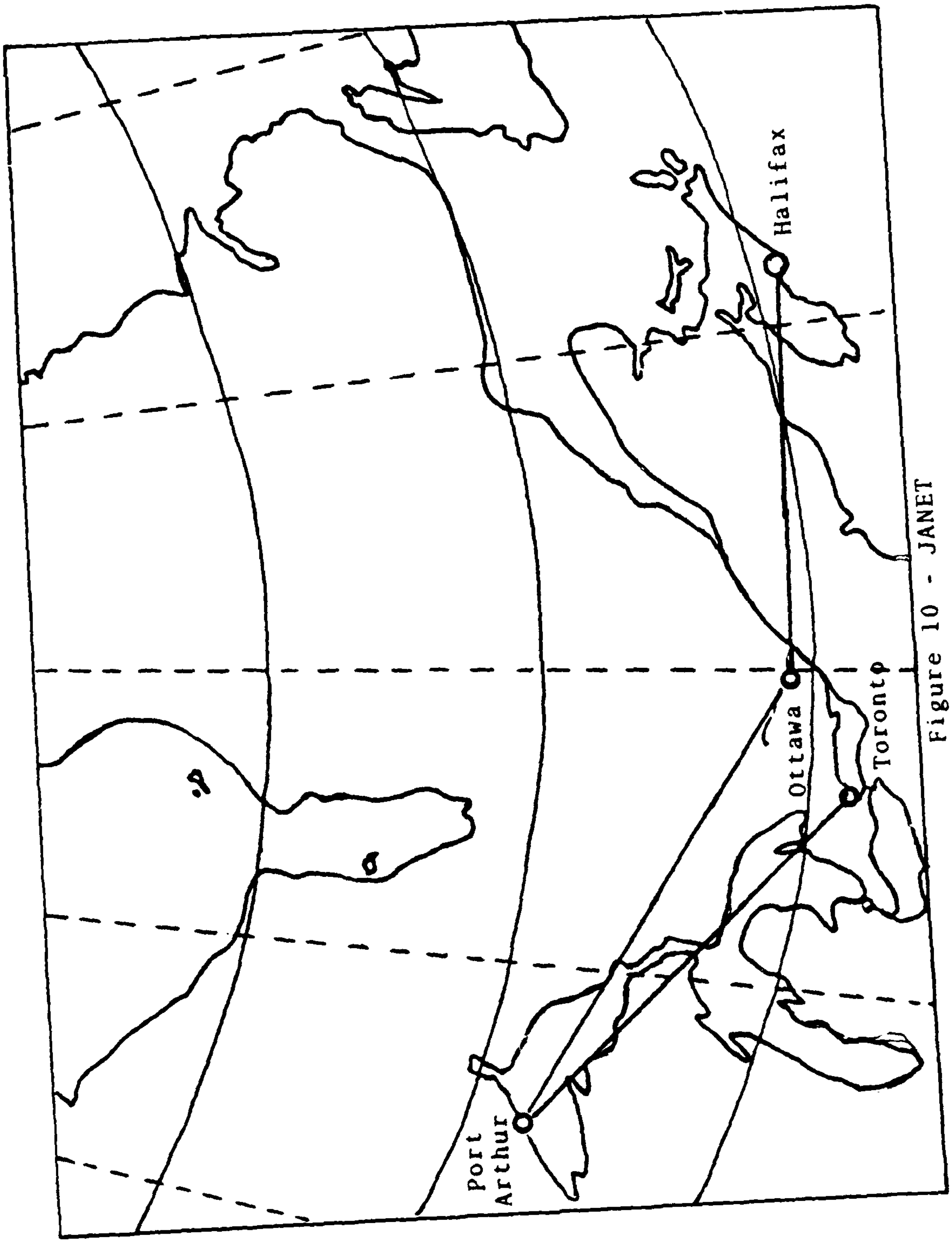

Figure 10 - JANET

considered in light of the intended operating environment. They needed a low power, reliable, point-to-point communications system with a range of 500 to 1500 km. The major disadvantages assessed were the complexity of storage and buffering and the inherent delay in the system. In some areas, the range limitations would require an automatic relay system.

The contribution of JANET cannot be understated. In addition to empirically validating the concept, it was the first system to exhibit the theoretical characteristics of a MBC system, allowing the first empirical comparisons between MBC and more conventional communications methods. It demonstrated that although there are fewer trails formed in the afternoon, they are of longer duration, compensating for the decrease in numbers. By varying the signal-to-noise ratio thresholds, it was discovered that the time spent above the threshold (duration) has a greater impact on the capacity of the system than the number of meteors available. Since the various links used different antenna systems, the system was able to demonstrate that there is no advantage to using high gain antennas and may even be a disadvantage if they are oriented on a great circle path. The long term statistical data showed that the number of signals seen depends on the latitude, path length, and circuit orientation.

D. RADIO CORPORATION OF AMERICA (RCA) FACSIMILE

In late 1957, the Air Force Cambridge Research Center sponsored a program to develop a meteor-burst facsimile transmission system. RCA won the contract for both system design and equipment fabrication. The system was designed as a one-way transmission of data, with no feedback from the receiver to the transmitter.

The actual experiment was conducted on a 1465 km link between an NBS Field Station in Long Branch, Illinois and the RCA Laboratories in Riverhead, New York. The antennas were oriented on a common volume approximately six degrees north of the great circle path, which favored signal reflections during normal working hours.

Several facsimile methods were considered. One idea was to send the complete image in one burst. This would have required a wide bandwidth to accommodate the detail in a reasonably sized picture and a greater than average transmitter power.

A second concept was to send the facsimile in several sections on different bursts. While this reduced the power and bandwidth requirements, the complexity of the reassembly problem outweighed the advantages. For simplicity, the decision was to send one frame per burst.

This MBC facsimile system used a scanner which completed two scans of the desired image every second. It recorded the image in black and white only, as opposed to half-tones. Both the scanner and the transmitter ran continuously, sending the facsimile frame over and over. The receiver also ran continuously, triggering the recorder when an incoming signal was detected. The recorder then ran for one-half second, the duration of one complete frame, stopped automatically, and sent the received data to the processing equipment. The bandwidth required for this system was 106 KHz. [Refs. 48,49]

While the system itself was an experimental oddity, it did contribute some valuable MBC experience. It was the first facsimile system to use meteor-burst as a method of transmission and demonstrated the feasibility of the concept. More importantly, it explored the impact of very wide bandwidth transmissions on duty cycle, multipath delay, and power requirements. The duty cycle for facsimile transmission is much greater, since the wider bandwidths require stronger meteor trail reflections. Only two percent of the detected meteors produced a usable trail for facsimile. However, a moderate increase in the transmitter power offset the reduced trail availability, resulting in a more acceptable duty cycle.

An important contribution of this system was the development of synchronizing pulses for recorder activation. This prevented the inadvertent recorder activation caused by static crashes and interfering VHF stations. Other MBC systems quickly developed similar techniques to prevent the accidental discharge of data. Although multipath was detected during these tests, it did not prove to be a problem. The delay was on the order of a few microseconds and produced little distortion. Signal loss accounted for the majority of the facsimile distortion.

E. HUGES AIRCRAFT METEOR-BURST SYSTEM

In the late 1950's, Hughes Aircraft won a USAF contract to develop an air-to-ground MBC system. The parameters for the system and the design criteria for development were the responsibility of the Communication and Navigation Laboratory at Wright Air Development Center in Dayton, Ohio. The interest in MBC for aircraft was an outgrowth of the desire to find alternatives to the cumbersome operation of HF and the range limitations of line-of-sight UHF [Ref. 50]. The USAF stated their concerns in the requirements submitted. The first requirement was for the successful transmission of one message every three minutes or less, ninety-five percent of the time. The error rate was to be less than 0.5 percent even in the presence of sporadic E or auroral activity. The system's coverage must provide for a moving aircraft anywhere from 500 to 2200 km from the transmitting station. Finally, the system must be capable of single frequency (simplex) operation at both ends of the link.

The accepted system concept designated the ground station to probe for a path to the aircraft by repeatedly transmitting a 100 bit interrogation signal. Between transmissions, the ground site was to monitor its receive circuit for a response from the aircraft. When the aircraft received the interrogation signal, it was either to transmit an outgoing message to the ground site or a preamble indicating that it was ready to receive traffic. This method allowed the ground station and the aircraft to share a single frequency, using propagation paths that were exactly reciprocal. To reduce the inherent burst delay problem, any message exceeding 100 bits was automatically segmented into sections, each less than 100 bits. Each would be individually handled, transmitted, error checked and acknowledged.

The preliminary test of the system was run on two ground stations, one belonging to Hughes in the Los Angeles area and the other at Bozeman, Montana. This test was plagued by intolerable high-level power leakage from nearby power lines. Although California Edison Company was able to reduce the power line interference, car ignitions and other urban sources continued to interfere with the Los Angeles circuit.

The actual air-to-ground test used four basic commands to organize the time-sharing of the circuit.

1) RTT - Ready to Transmit
This code is used by the ground station in its interrogation signal when it has traffic for the aircraft.

2) RTR - Ready to Receive
This code is used by the ground station in its interrogation signal when it does not have any traffic for the aircraft. Also used by the aircraft in response to a RTT from the ground station. It is used to notify the ground station to transmit, that the link is operative. It is also used by either party to get a message retransmitted.

3) MF - Message Follows
This code is used by either the ground station or the aircraft when a message immediately follows the preamble. It notifies the recipient that the 150 characters following the preamble are to be interpreted as a message.

4) MR - Message Received
This code is used by either the ground station or the aircraft whenever a message has been received as part of the preamble, and there were no uncorrectable errors. Failure to transmit an MR will result in retransmission of the message until acknowledged.

If more than one aircraft is being used, selective calling codes (SELCAL) are added to the preamble to distinguish between the aircraft. [Ref. 51]

The disadvantages of this system are significant under certain conditions. First, if more than one aircraft is operating, the SELCAL codes must be added to both incoming and outgoing messages. Besides complicating operations, the added overhead on the messages lowers the overall system capacity.

A more serious system problem is created by the short bursts which end while the message or message segment is still being transmitted. This causes incomplete messages or uncorrectable errors, which require retransmission of the entire message. While increased data rates reduce the likelihood of this occurring, the longer preambles and SELCAL codes aggravate the problem.

The most noticeable disadvantage is a combination of the delay inherent in MBC and the single frequency concept. To maximize the number of usable trails detected, a transmitter should be constantly probing. But in order for the distant end to acknowledge establishment of a path on this simplex circuit, the transmitter must stop transmitting. The Hughes system operates the ground station transmitter in probe mode approximately half the time, listening the other half. This results in roughly a fifty percent reduction in the number of suitable meteor trails available. With more than one aircraft per ground station, the situation worsens dramatically. Largely because of this drawback, this system was never operated with more than one aircraft per ground station.

The primary contribution of this system was the incorporation of error-correction codes to reduce the number of retransmissions required [Ref. 52]. Using the error-correction techniques, Hughes achieved a instantaneous data rate of 2400 bits per second.

Also important was the experience with smaller, mobile platforms like aircraft. The aircraft didn't require directional high-gain antennas. Instead, it was able to use antennas already mounted on the aircraft. The aircraft also found it could maintain radio silence until it desired to transmit, and then the reflection geometry provided low probability of intercept (LPI). This LPI characteristic is a by-product of the small, focused footprint typically produced by MBC systems. Another advantage is that unlike HF, frequency changes are not required in a MBC system.

Conversely, the USAF found the range of this and other MBC systems to be a limitation. During increased tempo operations, the Hughes MBC system became rapidly backlogged, and the users disliked the delay between message generation and message transmission. It was also discovered that the ground station had to increase their power level to overcome high AC electrical noise aboard the aircraft.

F. COMET

COMET, which is an acronym for COmmunications by MEteor Trails, was the first operational system fielded for military use. Developed and operated by the SHAPE Technical Center, it was intended to provide telegraph communications in the VHF band over distances up to 2000 km. Whenever a transmission path was available, the system could transmit up to 2400 bits per second. Following Hughes' lead, they incorporated an error detection and correction system known as ARQ (Automatic ReQuest). This system minimizes the start delay and allows operations to continue until the circuit expires with few errors. It has even minimized the problem with rapidly fading signal paths. This system also uses frequency, space, and height diversity.

The system configuration is also different than the previously discussed systems. COMET has a transmitter site in La Crau, France near Toulon, and a receiver in Staalduinen, Netherlands near The Hague. There are five additional sites monitoring all the transmissions. They are located in Forest Moor (Harrogate), Noordwijk, Saclay (Paris), Breisach (Freiburg), and Santa Marinella (Rome).

The ARQ error detection scheme is what makes this system so important in the development of MBC. ARQ is an intermittent system in which the flow of information is interrupted every time an error is detected at one or the other terminal and a repetition of the mutilated character is requested. It uses a synchronization procedure to cope with path variations up to one character in length. Out of 128 possible combinations of seven binary elements, ARQ uses thirty-five. Only if the error is identical to one of the thirty-five ARQ codes will the error go undetected. This type of error correction scheme has resulted in an average error rate of less than 1 per 3000 characters. The worst case yet encountered was errors of 1 in 1000. The system can stay in synchronization even when it is not in contact with the distant end, which is 98 to 99 percent of the time. This is achieved by allowing ARQ to treat no contact as a received error. The ARQ continues to request retransmission until contact is restored. A large advantage of the ARQ scheme is that it can have as few as two missed characters retransmitted, instead of the entire message.

One of the less positive findings of the SHAPE Technical Center was in relation to the LPI inherent in the system. Theoretically, the signals should be fairly focused with small footprints, making interception difficult. Using their monitoring stations, SHAPE Technical Center has found that the various types of multipath are resulting in widespread transmission. For example, the Santa Marinella site was able to detect more than five percent of the transmissions between other sites twenty percent of the time. Backscatter also contributed to a scattered reflection of the signal onto the transmitting station or behind it, in the opposite direction intended.

The system also incorporated many significant improvements. In addition to ARQ, the use of space, height, and frequency diversity increased signal duration and helped to minimize multipath interference. Together, these improvements resulted in a marked improvement in capacity. This system averaged between four and eight 60 wpm teletype circuits during the morning, and typically maintained two circuits in the evening. Hourly data rates of 150 bits per second were achieved [Ref. 53]

Variation is still a major consideration, however. Besides the diurnal variation in the number of circuits, the seasonal variation causes the average daily capacity in December to be only 2.3 channels, while in June the average is 6.2 channels. The maximum capacity yet achieved was forty circuits!

Although COMET was the only major meteor-burst program fielded in the 1960's, it certainly was a vast improvement over its predecessors. With the average burst carrying 140 characters and duty cycles varying diurnally between ten and twenty seconds, COMET certainly demonstrated the best of MBC technologically to date.

G. SNOTEL

SNOpack TELemetry (SNOTEL) was the "only non-military, non-experimental system currently in operation."[Ref. 54] Designed and operated by Western Union under contract with the Department of Agriculture, the system is considered "the showcase meteor-burst system." [Ref. 55] Actually, it also is distinctive as the first large network and the first MBC system with unmanned stations.

SNOTEL began operation in 1977 under the Management of the Soil Conservation Service (SCS). It is used to collect water resource data in eleven western states, including Washington, Oregon, California, Nevada, Colorado, Utah, Wyoming, Montana, Idaho, Arizona, and New Mexico. Microprocessors measure the amount of snow cover, additional snowfall, rain, and the temperature in the Rocky Mountains. As the western states depend on snow for seventy percent of their water supply, the available and future water supplies can determine irrigation practices or even crop selection. The hydrometeorological data collected is also used for flood and runoff control.

The system consists of two master stations and 511 solar-powered remote stations. Every morning the master stations, located in Boise, Idaho and Ogden, Utah, poll their respective remote units by transmitting a probing waveform containing the desired remote's address. When a path is opened, the remote site recognizes its address on the probe and transmits the data that has accumulated in storage in the last twenty-four hours in 100 millisecond bursts. If the master detects an error, it will request a retransmission. SNOTEL remote sites are grouped into eight geographical areas per master station. These polling groups allow the master to reuse the same set of probing addresses in each area. If two-trail multipath occurs allowing two remote units with the same address to receive the probe, the master station may receive two interfering signals. In this case, the master will wait until the trails have collapsed and then reinitiate its request. The procedure is similar to that used when a single-site error is received.

The masters can also do a supplemental interrogation of a remote unit to update or request additional data. The units' solar batteries are designed to transmit three 100 millisecond bursts per day. Western Union claims that this system can poll 200 sites and receive 200 error-free bits from each of 180 of the sites in less than twenty minutes [Ref. 56]

The cost of this system was concentrated in the master stations, which cost between $75,000 and $100,000 each, including installation. By comparison, the remotes cost $5,000 without a microprocessor for data collection and $8,000 with one.

Although LPI is not a detection or security issue for SNOTEL, the system has been designed to use even the smaller meteors, creating small footprints. The decrease in average footprint size permits more spatial multiplexing, reducing the likelihood of mutual interference. Within the eight polling groups per master station organization, no two sites in one group are located within fifteen miles of each other, further reducing the chances of interference.

H. ALASKA METEOR-BURST COMMUNICATIONS SYSTEM

In 1978, a year after SNOTEL, Alaska Meteor-Burst Communications System (AMBCS) became operational as a jointly owned MBC asset, used by several government agencies. One master station, located in Anchorage, covers the entire state of Alaska. Among its users is the Bureau of Land Management which uses AMBCS to send messages to and from remote survey camps. The Soil Conservation Service uses this system as they do SNOTEL, for water resource data, flood prediction, and soil condition. Stream and river gauging is accomplished via AMBCS for the U.S. Geological Survey and the Army Corps of Engineers. The FAA had AMBCS licensed as the first FCC-licensed Meteor-Burst Common Carrier. They use it for flight weather service and emergency communications during search and rescue operations. At one time the USAF also used the circuit and still can preempt certain users during emergencies. The National Weather Service is also passing meteorological data on AMBCS. Even FEMA (Federal Emergency Management Agency) operates two portable stations and five remote terminals to ensure prompt dissemination of information in a national emergency.

Based on experience gained from the SNOTEL system, the AMBCS has similar operating procedures for such things as error detection and retransmission. It does not, however, use polling groups with redundant addresses, reducing the chance of mutual interference between two remote stations. Also, the ability for AMBCS to identify small meteor trails and utilize them for communication paths appears to be greater than previous systems, including SNOTEL. Even with remote sites that are less than two miles apart there has been little interference.

The most obvious question concerns the system's performance during auroral activity. The JANET system experienced great difficulty with auroral effects, indicating that either AMBCS is better able to cope with the auroral interference or the system's low usage makes this a non-problem at this time.

IV. NEW TECHNOLOGY AND ONGOING RESEARCH

With the advent of satellite communications, meteor-burst communications became more of an oddity than a seriously considered communication alternative. Even so, scientific interest in MBC has continued, leading to a better understanding of meteoric phenomena and improved methods for exploitation.

The most noticeable improvements to MBC systems are the equipment size and complexity reductions. In the past twenty years, the equipment for an individual site has been reduced from seventy-seven cubic feet to less than three [Ref. 57]. Much of the improvement is the result of basic technological growth, eliminating the slower electro-mechanical switches, the smaller and less reliable buffers, and close to three hundred vacuum tubes. The replacement of the tubes with transistors alone reduced power consumption by more than 350 watts. [Ref. 58]

Less obvious but equally important is the ongoing improvements in propagation and detection avoidance through antenna design. Because of the nature of meteor-burst communications, there has been little advantage to using high gain antennas. In fact, this type of antenna can reduce the number of available trails since they look at a smaller portion of the ionosphere. But experience indicates that there is a solid trade-off between antenna gain and unfriendly detection of the transmitter, leading to additional studies in MBC antenna design. The emphasis in research today is to maximize antenna coverage of the hot spots while suppressing side lobes and the great circle path. Some systems have two lobes, one for each hot spot, which can be used separately depending on the time of day. Other efforts utilize steerable beams which not only allow focusing on the hot spot but also can turn to reduce the likelihood of unfriendly detection. [Ref. 59]

One of the most important areas of equipment research is the development of adaptive MBC systems. These systems provide an alternative to halting transmission when multipath propagation or fading occurs. Since both multipath and fading are sensitive to changes in frequency, frequency-adaptive systems are being investigated. Whenever the undesirable propagation states are detected, the system automatically notifies the distant end and shifts to a higher frequency. A major drawback to this concept is that it requires either redundant equipment or equipment components, making it an expensive alternative.

The other adaptive system relies on a change in bit rate to reduce the negative effects of multipath or fading. The concept is to match the bit rate to whatever data rate the trail can support without increasing the number of errors. This system has the advantages of comparative simplicity and less expense, and is beginning to predominate the adaptive efforts. [Ref. 60]

Behind any improvements in MBC is the understanding of the meteoric phenomena and its random nature. In developing probability models, researchers have made five critical assumptions [Ref. 61]:

1) all trails have the same length of 25 km
2) ionization occurs at 93 km above the earth
3) only correctly oriented trails produce return
4) meteors are uniformly distributed over the earth
5) angles of incidence are random and uniform in distribution.

While these assumptions allow for simplification of the statistical problem, they also can lead to erroneous calculations. Continuing collection of statistical data is used to refine these assumptions, yielding better predictive equations. The equations are then used to derive the probabilities for meteor size and occurrence, location and angle of fall, and type of trail produced. The type of trail, whether underdense or overdense, specular or non-specular, affects the duration and strength of each, which can then be calculated. The benefits of this statistical research include better understanding and exploiting meteoric propagation.

A third area of MBC that is subject to ongoing research is propagation characteristics and system design. Transmission systems are now being tailored to utilize only specific types of meteor trails, depending on the equipment design and the overall system objectives. For example, if the system objective is to maintain a covert posture while communicating, the system would be designed to use higher gain antennas and underdense meteor trails. By comparison, a shore-based weather facsimile broadcast system would want to use overdense trails to reduce the amount of facsimile piecing required at the receiving end.

An extension of the above efforts to tailor propagation characteristics used by a system is to control the size and shape of the resulting footprint. The signal's footprint varies with the angle of reflection, the type of trail, and other parameters. This effort is still in the data collection stage while the exact parameters of the various footprints are determined. The successful control of footprint dimensions is critical in controlling both interception and interference.

As a matter of curiosity but also of importance to mobile platforms is the yet unexplained north-south propagation anomalies [Ref. 62]. Data is being collected by mobile platforms under varying conditions in an effort to resolve this issue. While north-south links exhibit more irregularity than east-west links, their overall capacity is comparable. Thus, the problem is more an issue of delay and inconvenience than true loss of performance.

Improvements that should be forthcoming in the meteor-burst arena make the system concept even more competitive with alternate communications methods. One such improvement will be the continued reductions in equipment size and complexity. For example, the Navy Research Laboratory (NRL) is developing small unattended weather buoys equipped with miniaturized MBC systems. The equipment will provide reliable transmission of 2000 bits per hour to a master site ashore. The average distance is expected to be 1500 km. [Ref. 63]

Increased statistical knowledge and improved propagation and transmission techniques can be expected to increase system capacity and reduce undesirable detections. The isolation and exclusive utilization of underdense meteors will reduce the footprint size as well as avoid the propagation mechanisms most likely to result multipath detection.

Some increase in capacity will be achieved by reducing the time required to initialize a circuit. This can be accomplished using improved synchronization and framing methods. A reduced error rate also contributes to increased capacity, and this is achievable through low overhead coding techniques. Another error reduction scheme is to reduce the effects from man-made interference by isolating the equipment whenever possible. This can be done using an RF link for remote operation of a MBC master station located in a low noise area.

The most promising near-term improvement is the adaptive rate systems. The difference between calculated and empirical throughput of MBC systems would be significantly reduced if the equipment could vary the data rate to match the instantaneous capacity of the transmission path. Using state-of-the-art equipment, it is estimated that these systems could achieve instantaneous data rates exceeding one megabit per second.

V. MBC AND THE NAVY: WHAT DOES THE NAVY HOPE TO GAIN?

Twenty years ago the Navy and Air Force were both funding research into the meteor phenomena and its communications potential. No operational MBC system was purchased; however, the Navy opted to invest in satellite communications. Now the Navy is showing renewed interest in meteor-burst communications. What is the Navy hoping to achieve with MBC?

One of the great attractions of MBC is its apparent Low Probability of Intercept (LPI). The small footprint created by the meteor-burst signal would be difficult to detect unless two trail multipath occurred or the unfriendly detector were within the same footprint as the intended receiver. The likelihood of two trails occurring at the same time with sufficient strength and the right geometry to reach two geographically separated receivers is extremely rare. More common would be a detector within the same footprint or on the edge of the footprint, trying to intercept the signal. Again because of the small size of the footprint, a detector on the edge would receive at best an incomplete transmission. In the Navy's at sea scenario, if a detector were close enough to intercept the intended receiver's communications, he would be within surveillance and weapon sensor range of the receiving platform [Ref. 64]. The only fallacy in this premise is that if a platform is using MBC to remain undetected, he may also be minimizing the activation of organic sensors. Of course, critical in this entire premise is the ability to limit footprint size by using only underdense meteor trails [Ref. 65].

The LPI issue also applies when the platform is transmitting. In today's full-duplex MBC systems, the platform must at least transmit some type of "go ahead" signal to inform the distant site that a transmission path is present and he may begin transmission. The short duration of the transmission and its random occurrence increases the platform's chances of not being detected [Ref. 66]. This is because the more prevalent traditional direction finding techniques require a signal of longer duration. Even if the signal is detected due to some propagation anomaly, the detector only knows where the meteor trail was, not the angle of incidence, without which it is almost impossible to locate the ship. [Ref. 67]

A second favorable characteristic of MBC for Navy applications is an inherent resistance to jamming. Again using the classic scenario of a platform at sea communicating with a shore station, the jammer would have to be in one of the footprints in order to jam. With the advertised footprint size on the order of 100 km by 25 km, the jammer could be detected and neutralized. [Ref. 68]

Another characteristic of MBC which contributes to its jam resistance is the short duration of its transmissions. Many jammers take a set period of time to lock onto the signal they des'ze to jam. In MBC, the transmission may be over before the jammer can begin.

To further frustrate jamming, the directional antennas can use an elevated azimuth, resulting in reduced transmission ranges, but also frustrating all but overhead jammers [Ref. 69]. Multiple transmitters on the same frequency but different locations can transmit the same data, requiring the jammer to try to jam each individually. And, if desired, MBC can be modified to use spread spectrum techniques [Ref. 70].

The Navy has long been interested in replacing or supplementing HF communications. This is because of the vagaries of the medium, including changes in the ionosphere requiring frequency changes and areas where reception is impossible because of the bounce geometry. Also undesirable is the high probability of intercept caused by widespread signal propagation, resulting in direction finding and localization.

By contrast, MBC seldom requires a frequency change, as it is not using the ionosphere as its reflective surface.

Meteor-burst systems are considered to not have skip zones, because when the reflection geometry is not correct for reception, the system doesn't transmit.

Finally, ionospheric conditions in general have a greater impact on signals in the HF band than those in the VHF band. For these reasons, the Navy hopes to supplement HF communications with MBC. MBC could not replace HF as it has considerably lower data rates, and cannot transmit over the same distances without relay.

Perhaps the most commonly cited reason for Navy interest in meteor-burst communications is the need for a non-satellite-dependent communications system that can operate in the trans-nuclear and post-nuclear environment [Ref. 71]. MBC has a distinct advantage in that meteors trails are constantly being formed, and the supply cannot be disrupted [Ref. 72]. Since the system is relatively inexpensive and can operate remotely, it is a logical choice for a decentralized system network, making it more survivable [Ref. 73].

The main concern is that satellites and their ground stations are highly vulnerable and once destroyed, are largely irreplaceable. There is no graceful degradation if multiple satellites or ground stations are disabled. At this juncture, HF would become the primary means of communicating with the fleet. But the ionosphere is sensitive tc high-altitude nuclear bursts and their resultant electro-magnetic effects. It is theorized that a nuclear blast will leave holes in the ionosphere, making HF communications impossible. MBC, by contrast, should be able to use the newly forming ionization from incoming meteors to continue communicating. [Ref. 74] Another possibility is that the ionosphere will be largely ionized, forming a gigantic turbulent mirror. Because of the turbulence and the increased reflection, the HF signals would propagate haphazardly and over extended distances, interfering with each other and making communicating virtually impossible. While MBC would also suffer in a mirror-like environment, it is more likely to suffer distortion from high noise levels than be blanked out completely. [Ref. 75]

In the post-nuclear environment, MBC is also expected to play an important role. As the ionosphere returns to normal, the MBC systems will be able to function before any HF systems will, since again, MBC doesn't use the ionosphere as its reflecting surface. It is therefore considered a readily reconstitutable resource. [Ref. 76] It may in fact, work better in the post-nuclear environment as the particles in the upper atmosphere left by the blast begin to fall back to earth [Ref. 77].

VI. CONCLUSIONS AND RECOMMENDED APPLICATIONS

Despite the forthcoming improvements, some major limitations in meteor-burst communications will remain. Whether or not these limitations are critical will depend on a careful analysis of the system to be supported by MBC. In a Navy context, there are some obvious drawbacks to MBC that make it unsuitable for many of the communications functions.

The inherent delay in burst-type systems combined with the probabilistic nature of meteor trails result in unpredictable availability and capacity [Ref. 78]. These parameters are inversely related in an MBC system, requiring the system design to reflect the preeminence of one characteristic or the other. Regardless of the priority chosen, the system will still exhibit a level of unknown delay with each transmission, making MBC an inappropriate transmission method for time sensitive information.

The appropriateness of MBC systems is not limited to the time sensitivity issue. MBC cannot achieve the levels of throughput available with satellite or continuous HF transmission. The efforts to increase the duty cycle and thereby the timeliness of the system simply result in further reduction of capacity. The operational systems today still have an average throughput of 100 words per minute over a twenty-four hour period [Ref. 79]. Even with the advent of adaptive data rate transmission, MBC will not be able to replace either of the primary means of fleet communications today. [Ref. 80]

Still another issue is voice transmission. The use of voice both in the fleet and ship-to-shore environments has continued to increase. Yet voice is not yet a viable part of the MBC concept. Although a voice transmission of sorts was achieved in the early experimental system at Stanford Research Institute, it contained the typical MBC delay and could only be played back directly to a speaker or a tape recorder. If a meteor trail could not support an entire statement, the statement would simply be transmitted in whatever fragmented form the propagation medium allowed. In the operational environment, this type of transmission would be unacceptable.

Tied to the randomness of meteor activity is the problem of probing. For full-duplex meteor-burst communications to take place, at least one station must be transmitting a probe. For the most efficient use of the available paths, both ends of a desired link should be probing, so that transmission may begin at both sites simultaneously upon detection of a trail.

The obvious drawback in any type of probing is the likelihood of detection. While one particular probe signal may not reach the intended receiver, it may have been reflected to a detection site or unfriendly platform. And although it is presently considered impossible to calculate the origin of that probe, it certainly alerts the unintended receiver to the existence of a transmitter in his vicinity. It is also debatable for how long MBC would be resistant to localization from probe detection were MBC to become a common communications medium. Also, while it is not detectable by most traditional DF methods, it may not be immune to other more sensitive systems were they to attempt it.

If a platform wanted to remain covert by having only the shore station probing, the problem arises of how the shore station knows the probe has been received and transmission may begin. The ship is still forced to send some type of return signal to initiate transmission. At the power levels typically used in MBC transmissions, any detector within 400 km will observe the momentary VHF burst.

Once detected, the MBC system's ability to resist jamming becomes paramount. If the jammer is located in the receiving platform's footprint, the introduction of noise will lower the receiver signal-to-noise ratio, closing the circuit. While the assumption has been made by the Navy that the jammer would have to be so close as to make itself vulnerable, there is mounting evidence that given its target's location and operating frequency, the jammer could disrupt communications from a distance beyond line-of-sight.

Were the jammer to be located in the footprint of the probing end, it could introduce noise at the transmission frequency which would be transmitted along with the probe, making circuit initiation impossible. Perhaps more dangerously, it could imitate the probe, possibly causing inadvertent data initiation, or at least a "go ahead" response from the receiving platform.

Any of these techniques would effectively disrupt MBC communications. Use of high gain antennas with steerable beams help to reduce the effectiveness of a noise introducing jammer, but at the cost of system availability. As the antenna lobe area is decreased or steered to avoid the jammer, the amount of the propagation hotspot that is illuminated will also be reduced. This results in an overall decrease in available meteor trails, and therefore, throughput. [Ref. 81]

Of particular concern are those methods which expose the system to exploitation. This type of interference is defeated by complex coding and signaling routines. These security measures in turn add to the MBC system overhead, reducing the amount of information transmitted.

Also questionable is the time it takes a jammer to lock onto a signal in order to jam it. Jammers now in existence can capture a signal which is less than .001 seconds, well within the time required to disrupt an MBC signal.

Another jam avoidance technique of any MBC system is to adjust the azimuth of the antenna to vertical. By using this technique, only an overhead system could disrupt the signal. The disadvantage of this technique is the range reduction of the communications path. While the idea of an airborne system hovering over a platform, waiting to jam any MBC signals is not very practical, the possibility of satellite systems detecting the VHF signals that are not reflected or that are scattered is a very real concern. It is beyond the scope of this paper to determine whether any systems in existence today could detect and utilize these signals, either for jamming or localization of the emanating platform.

The final area in which MBC systems may be seriously affected is the nuclear environment. While there is little doubt that MBC will be able to survive and operate better than either satellite or HF systems in the trans- and post-nuclear environment, it is still not an optimal solution. The previously discussed limitations of timeliness and capacity would be overwhelming were MBC to suddenly be the only available means of communications. Also, were the ionosphere to become mirror-like, the spatial multiplexing of MBC, which allows several sites to use the same

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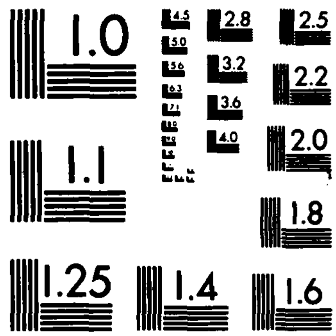

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

frequencies in relatively close proximity, would be lost. With the wide bandwidths and limited frequency spectrum used in MBC transmission, this could be an insurmountable interference problem.

Of equal concern in this mirror-like environment is the loss of any LPI characteristics. If meteor-burst is the only available method of communicating with remaining forces, any response to the probe would result in widespread detection [Ref. 82].

Up to now, the focus has been on point-to-point applications of meteor burst. Even the one master-multiple slave configuration of SNOTEL, COMET and AMBCS is a variation on point-to-point, since each system establishes one link at a time and the slaves cannot intercommunicate. However, both a non-hierarchical netted configuration and a broadcast mode have been proposed for MBC application.

In a broadcast mode, one site transmits without receiving any acknowledgment from the receiving platform or platforms. In MBC, the transmitter continuously sends data without regard to existing paths, eliminating the typical probing sequence. Instead, it retransmits the message a preset number of times. This number is calculated from empirical data and represents the number of retransmissions required to achieve a given probability of reception. The concept of message retransmission to achieve a high probability of reception is no guarantee that reception actually occurred. [Ref. 83] This alone makes MBC broadcast unacceptable for most military applications. In addition to the concern over non-reception, the requirement for repeated transmission makes broadcast the least efficient of the MBC configurations.

While a considerable improvement over the broadcast mode, non-hierarchical netted relays also have serious drawbacks. One difficulty is frequency allocation, which is illustrated in the following example. In point-to-point MBC communications, two frequencies are used: F1 for transmitting from site A to site B, and F2 for transmitting from B to A. With the introduction of a site C, when site A communicates with C, it will transmit on F1 and receive from site C on F2. When site B tries to communicate with site C, it will attempt to transmit on F2 and receive on F1, completely unsuccessfully. In order for all three sites to be able to communicate, at least one site, site C for example, would have to be able to exchange its transmitting and receiving frequencies. Once the exchange has occurred, site C can no longer receive on F1, which is now its transmitting frequency. Thus, the system would be unaware when site A was trying to communicate and would have no impetus to reverse its frequencies again. (See Figure 11) In a large network, this would result in serious network

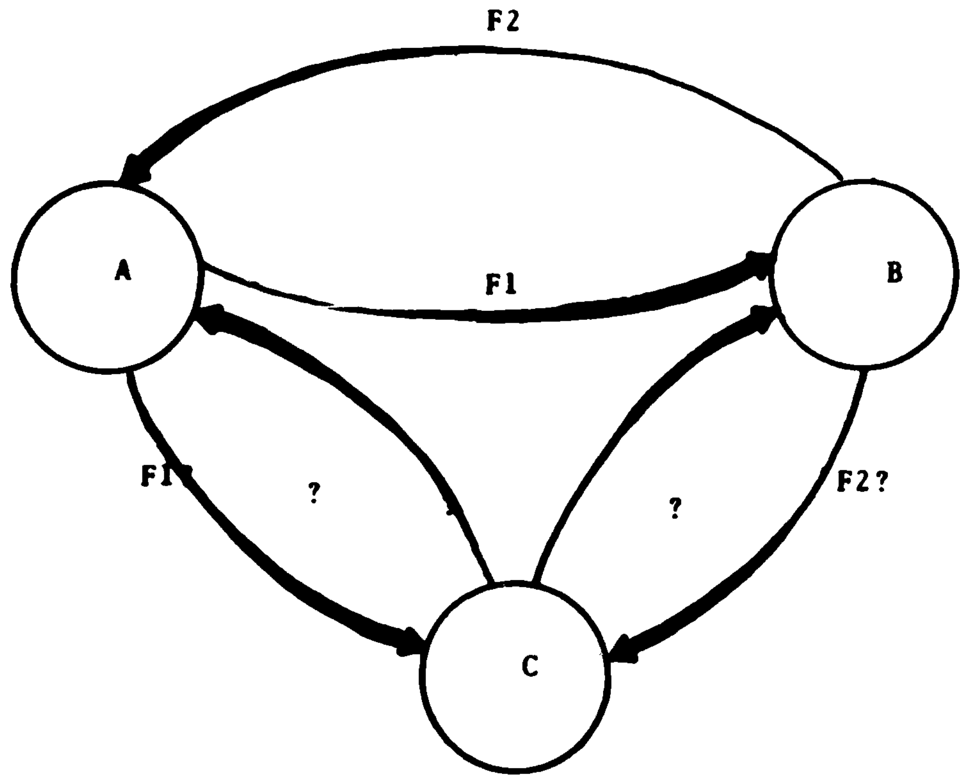

Figure 11 - Frequency Allocation Problem in a Netted Relay

design complications, leading to complex and/or redundant equipment configurations and greatly increased frequency requirements. [Ref. 84]

One solution is to use a single frequency for the entire network. In this configuration, each station would probe for a short period at random intervals, using an address for the desired receive site. The remaining time would be spent listening for a response or incoming probe from another station. This approach markedly decreases the number of available meteors that can be used and limits communications to one direction at a time once a link is established. The equipment would also have to be modified to not initiate its own probe when an ongoing transmission is detected or interference may result. [Ref. 85] Regardless of the approach chosen, the limitations in a non-hierarchical network appear to override any possible advantages.

The closest MBC configuration to the traditional network is the master-slave arrangement, where the master station probes each of its slave sites, establishes contact, and then exchanges data on a full-duplex circuit. A variation of this configuration allows the slave stations to respond to the master station probe only when they have data to send. The drawback to this scheme is the inability of the master station to deliver traffic to slaves which have no outgoing traffic. When the slaves have nothing to transmit, they will not answer the probe, unaware of the backlog building at the master site. A blend of the two master-slave configurations would be ideal, but is yet to be developed.

A common shortcoming of both master-slave configurations is one-way probing. The probing site must first transmit the probe and then listen for a response, limiting the number of available meteors that can be utilized by the system. It also does not allow for simultaneous acquisition of probing signals, limiting the time available for full-duplex transmission. [Ref. 86]

Despite the many limitations discussed, there are several applications of meteor-burst communications which may be of interest to the Navy. One is facsimile transmission for data that is not sensitive to delays up to one hour. An example might be large weather plots or intelligence photographs. By utilizing very high bandwidths, this facsimile method can be designed to transmit entire pictures or more detailed images in pieces. The advantage of using meteor-burst for a facsimile application is that it can free the real-time systems from transmission of bulky, time-insensitive data.

A second application of MBC is as an alternative and backup to HF for some of the administrative requirements. It appears to provide a less exploitable signal than HF for covert operations and requires few if any frequency changes. It is also less sensitive to atmospheric anomalies, which will provide a level of communications not otherwise available when HF is adversely affected. It cannot, however, replace HF, since it has neither the range nor the throughput.

A third application, and the one MBC is best adapted to, is remote stations for unmanned sensor sites. MBC has been proven operationally to be ideal for automating the transmission of data to a central site for processing. SNOTEL is the classic example of this MBC application. It is inexpensive, reliable, and cost-effective, while consuming little of the frequency spectrum with its spatial multiplexing. The "advantages of long range, low peak transmitter power, and equipment simplicity make this technology a candidate for numerous remote manned and automated sensing stations." [Ref. 87]

The final application for MBC is in the trans- and post-nuclear environment. While the possibility of the mirror-like ionization disabling the MBC system in the trans-attack period is of concern, the system exhibits some distinct advantages over the other available communications mediums. Because MBC is inexpensive and easy to operate in comparison to either HF or satellite, it is a logical choice for pre-positioning and widespread availability. This combined with its cost and size will allow some reconstitution of communications before either HF or satellite repairs can be affected. Also, MBC will operate well in ionospheric holes where HF will not. And in the event of ionospheric mirroring or other severe ionospheric disturbance, MBC will recover its ability to transmit through it long before the ionosphere will settle enough to predictably refract HF transmissions. It has also been suggested that MBC be used in its unmanned sensor capacity for measuring the amount and movement of heavy fallout concentrations in the post-nuclear environment [Ref. 88].

The idea of meteor-burst communications triggers the imagination with its use of an inexhaustible resource: meteors. Yet, its inherent problems and the limitations of near-term technology make this communications system less than ideal for most Navy requirements. The system does have limited applicability in some specific scenarios and provides yet another backup system for HF communications, though it replaces no Navy communications system in existence today. The value to the Navy of pursuing further development should be carefully evaluated against the limited applications of meteor-burst communications, the costs involved in fielding yet another system, and the inherent and emergent vulnerabilities of MBC.

LIST OF REFERENCES

1. Nagaoka, H., "Possibility of Disturbance of Radio Transmissions by Meteor Showers," Proceedings, Imperial Academy of Tokyo, v. 5, p. 632, 1929.

2. Forsyth, P.A., Hansen, D.R., Hines, C.O., and Vogan, E.A., "The Principles of JANET--A Meteor-Burst Communication System," Proceedings of the IRE, v. 45, p. 1644, December 1957.

3. The Random House College Dictionary, p. 841, Random House, Inc., 1973.

4. Forsyth, P. A., Hansen, D. R., Hines, C. O. and Vogan, E. A., "The Principles of JANET--A Meteor-Burst Communication System,"Proceedings of the IRE, v. 45, p. 1645, December 1957.

5. University of Wisconsin Department of Electrical and Computer Engineering, Contract Number N00039-81-C-03-39, Feasibility High Speed Digital Communications of the Meteor Scatter Channel by W. P. Birkemeier and M. D. Grossi, p. 1, 1 May 1983.

6. Eshleman, V. R. and Mlodnosky, R. F., "Directional Characteristics of Meteor Propagation Derived from Radar Measurements," Proceedings of the IRE, v. 45, p. 1716, December 1957.

7. Naval Research Laboratory Report 8286, Meteor-Burst Communication Systems: Analysis and Synthesis, by A. E. Spezio, p. 1, 28 December 1978.

8. Gray, K. G., "Meteor Burst Communications," Signal, p. 125, May/June 1982.

9. Gray, "Meteor Burst Communications," p. 125.

10. McGrath, P. A., Meisner, T. L. and Winters, B. H., Meteor Burst Report, p. 3, 31 July 1983.

11. Forsyth, P. A., Hansen, D. R., Hines, C. O. and Vogan, E. A., "The Principles of JANET--A Meteor-Burst Communication System," Proceedings of the IRE, v. 45, p. 1652, December 1957.

12. University of Wisconsin Department of Electrical and Computer Engineering, Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel, by W. P. Birkemeier and M. D. Grossi, p. 8, 1 May 1983.

13. Ibid., p. 10.

14. The ARRL Antenna Book, 14th ed., pp. 1-6, American Radio Relay League, 1983.

15. McGrath, P. A., Meisner, T. L. and Winters, B. H., Meteor Burst Report, p. 4, 31 July 1983.

16. Gottlieb, I., "Meteoric Bursts Could Deep Post-Attack Communications Open," Defense Electronics, p. 61, November 1981.

17. Eshleman, V. R., "On the Wavelength Dependence of the Information Capacity of Meteor-Burst Propagation," Proceedings of the IRE, v. 45, p. 1711, December 1957.

18. Davis, E. W. and Smith, E. K., "Wind-Induced Ions Thwart TV Reception," IEEE Spectrum, v. 18, p.52-55, February 1981.

19. The ARRL Antenna Book, 14th ed., p 1-16, American Radio Relay League, 1983.

20. Crysdale, J. H., "Analysis of the Performance of the Edmonton-Yellowknife JANET Circuit," IRE Transactions on Communications Systems, pp. 33-39, March 1960.

21. Forsyth, P. A., Hansen, D. R., Hines, C. O. and Vogan, E. A., "The Principles of JANET--A Meteor-Burst Communication System," Proceedings of the IRE, v. 45, p. 1657, December 1957.

22. Naval Research Laboratory Report 8286, Meteor-Burst Communication Systems: Analysis and Synthesis, by A. E. Spezio, p. 2, 28 December 1978.

23. University of Wisconsin Department of Electrical and Computer Engineering, Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel by W. P. Birkemeier and M. D. Grossi, p. 40, 1 May 1983.

24. Jaye, W. E., Peterson, A. M., Sifford, B. M., Vincent, W. R. and Wolfram, R. T., "Analysis of Oblique Path

Meteor-Propagation Data from the Communications Viewpoint," Proceedings of the IRE v. 45, p. 1701, December 1957.

25. Richmond, R. L., "Meteor Burst Communications, Part I: MBC Advance Assist C^3 Objectives," Military Electronics/Countermeasures, p. 69, August 1982.

26. McGrath, P. A., Meisner, T. L. and Winters, B. H., Meteor Burst Report, p. 1, 31 July 1983.

27. Montgomery, G. F. and Sugar, G. R., "The Utility of Meteor Bursts for Intermittent Radio Communication," Proceedings of the IRE, v. 45, p. 1689, December 1957.

28. Carpenter, R. J. and Ochs, G. R., "The NBS Meteor Burst Communication System," IRE Transactions on Communications Systems p. 271, December 1959.

29. Carpenter, R. J., Ochs, G. R. and Sugar, G. R., Elementary Considerations of the Effects of Multipath Propagation in Meteor-Burst Communication," Journal of Research of the National Bureau of Standards--Radio Propagation, v. 64D, p. 496, September-October 1960.

30. Campbell, L. L. and Hines, C. O., "Bandwidth Considerations in a JANET System, Proceedings of the IRE, v. 45, p. 1659, December 1957.

31. Crysdale, J. H., "Analysis of the Performance of the Edmonton-Yellowknife JANET Circuit," IRE Transactions on Communications Systems, p. 34, March 1960.

32. Oetting, J. D., "An Analysis of Meteor Burst Communications for Military Applications," IRE Transactions on Communications, v. COM-28, pp. 1599-1600, September 1980.

33. Forsyth, P. A., Hansen, D. R., Hines, C. O. and Vogan, E. A., "The Principles of JANET--A Meteor-Burst Communication System," Proceedings of the IRE, v. 45, p. 1646, December 1957.

34. Oetting, J. D., "An Analysis of Meteor Burst Communications for Military Applications," IEEE Transactions on Communications v. COM-28, p. 1592, September 1960.

35. Naval Research Laboratory Report 8286, Meteor-Burst Communication Systems: Analysis and Synthesis by A. E. Spezio, pp. 6-11, 28 December 1978.

36. Eshleman, V. R. and Mlodnosky, R. F., "Directional Characteristics of Meteor Propagation Derived from Radar Measurements," Proceedings of the IRE, v. 45, p. 1715, December 1957.

37. Eshleman and Mlodnosky,"Directional Characteristics of Meteor Propagation Derived from Radar Measurements," p. 1717.

38. Eshleman and Mlodnosky, "Directional Characteristics of Meteor Propagation Derived from Radar Measurements," p. 1712-23.

39. Meteor Communications Consultants, Inc. Report 797, Analysis of Meteor Burst Communications for Navy for Navy Strategic Applications by T. G. Donich, R. E. Leader and D. K. Smith, pp. 7-12, February 1980.

40. Morgan, E. J., "The Resurgence of Meteor Burst," Signal, pp. 69-73, January 1983.

41. Davis, G. W. L., Gladys, S. J., Lang, G. R., Luke, L. M. and Taylor, M. K., "The Canadian JANET System," Proceedings of the IRE v. 45, pp. 1666-1678, December 1957.

42. University of Wisconsin Department of Electrical and Computer Engineering, Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel by W. P. Birkemeier and M. D. Grossi, p. 2, 1 May 1983.

43. Carpenter, R. J. and Ochs, G. R., "The NBS Meteor Burst Communication System," IRE Transactions on Communications Systems pp. 263-271, December 1959.

44. University of Wisconsin Department of Electrical and Computer Engineering, Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel, by W. P. Birkemeier and M. D. Grossi, p. 5, 1 May 1983.

45. Campbell, L. L., "Storage Capacity in Burst-Type Communication Systems," Proceedings of the IRE, v. 45, pp. 1661-1666, December 1957.

46. Jaye, W. E., Peterson, A. M., Sifford, B. M., Vincent, W. R. and Wolfram, R. T., "Analysis of Oblique Path Meteor-Propagation Data from the Communications Viewpoint," Proceedings of the IRE V. 45, pp. 1701-1707, December 1957.

47. Crysdale, J. H., "Analysis of the Performance of the Edmonton-Yellowknife JANET Circuit," IRE Transactions on Communications Systems, pp. 33-39, March 1960.

48. Bliss, W. H., Wagner, Jr., R. J. and Wickizer, G. S., "Experimental Facsimile Communication Utilizing Intermittent Meteor Ionization," Proceedings of the IRE, v. 45, pp. 1734-1735, December 1957.

49. Bliss, W. H., Wagner, Jr., R. J. and Wickizer, G. S., "Wide-Band Facsimile Transmission Over a 900-Mile Path Utilizing Meteor Ionization," IRE Transactions on Communications Systems, pp. 252-256, December 1959.

50. University of Wisconsin Department of Electrical and Computer Engineering, Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel, by W. P. Birkemeier and M. D. Grossi, p. 5, 1 May 1983.

51. Chambers, J. T., Evans, G. L., Hannum, A. J. and Otten, K., "Air-to-Ground Meteoric Scatter Communication System," IRE Transactions on Communications Systems, pp. 113-132, June 1960.

52. University of Wisconsin Department of Electrical and Computer Engineering, Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel, by W. P. Birkemeier and M. D. Grossi, p. 6, 1 May 1983.

53. Ibid., pp. 6-7.

54. "Implementation of SNOTEL," Signal, January 1979.

55. Richmond, R. L., "Meteor Burst Communications, Part I: MBC Advances Assist C^3 Objectives," Military Electronics/Countermeasures, pp. 68-72, August 1982.

56. Richmond, "Meteor Burst Communications, Part I: MBC Advances Assist C^3 Objectives," pp. 68-72.

57. Davis, G. W. L., Gladys, S. J., Lang, G. R., Luke, L. M. and Taylor, M. K., "The Canadian JANET System," Proceedings of the IRE, v. 45, pp. 1666-1678, December 1957.

58. Bartholome, P. J. and Vogt, I. M., "COMET--A New Meteor-Burst System Incorporating ARQ and Diversity Reception,"

IEEE Transactions on Communication Technology v. COM-16, pp. 268-278, April 1968.

59. Meteor Communications Consultants, Inc. Report 797, Analysis of Meteor Burst Communications for Navy for Navy Strategic Applications, by T. G. Donich, R. E. Leader and D. K. Smith, p.47, February 1980.

60. University of Wisconsin Department of Electrical and Computer Engineering, Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel, by W. P. Birkemeier and M. D. Grossi, pp. 19-44, 1 May 1983.

61. Naval Research Laboratory Report 8286, Meteor-Burst Communications Systems: Analysis and Synthesis, by A. E. Spezio, pp. 10-14, 28 December 1978.

62. Eshleman, V. R. and Mlodnosky, R. F., "Directional Characteristics of Meteor Propagation Derived from Radar Measurements," Proceedings of the IRE v. 45, pp. 1715-1723, December 1957.

63. Naval Research Laboratory Report 8286, Meteor-Burst Communications Systems: Analysis and Synthesis by A. E. Spezio, pp.68-83, 28 December 1978.

64. Oetting, J. D., "An Analysis of Meteor Burst Communications for Military Applications," IEEE Transactions on Communications, v. COM-28, pp. 1591-1601, September 1980.

65. University of Wisconsin Department of Electrical and Computer Engineering Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel, by W. P. Birkemeier and M. D. Grossi, p. 13, 1 May 1983.

66. Gray, K. G., "Meteor Burst Communication," Signal, pp. 125-134, May/June 1982.

67. Oetting, J. D., "An Analysis of Meteor Burst Communications for Military Applications," IEEE Transactions on Communications, v. COM-28, pp. 1591-1601, September 1980.

68. Richmond, R. L., "Meteor Burst Communications, Part I: MBC Advances Assist C^3 Objectives," Military Electronics/Countermeasures, pp. 68-72, August 1982.

69. Meteor Communications Consultants, Inc. Report 797, Analysis of Meteor Burst Communications for Navy for Navy Strategic Applications, by T. G. Donich, R. E. Leader and D. K. Smith, pp. 43-45, 4 February 1980.

70. Rockwell International Corporation, The Role of Meteor Scatter in Post-Nuclear Attack Communications, p. 69, 20 December 1980.

71. Gottlieb, I., "Meteoric Bursts Could Keep Post-Attack Communications Open," Defense Electronics, pp. 61-69, November 1981.

72. Blackwell, A. T., Griffin, A. A. and Halliday, I., "The Frequency of Meteorite Falls on the Earth," Science, v. 223, pp.53-67, 30 March 1984.

73. Rockwell International Corporation, The Role of Meteor Scatter in Post-Nuclear Attack Communications, p. 56, 20 December 1980.

74. Gottlieb, I., "Meteoric Bursts Could Keep Post-Attack Communications Open," Defense Electronics pp. 61-69, November 1981.

75. Rockwell International Corporation, The Role of Meteor Scatter in Post-Nuclear Attack Communications, p. 39, 20 December 1980.

76. Morgan, E. J., "The Resurgence of Meteor Burst," Signal pp. 69-73, January 1983.

77. Rockwell International Corporation, The Role of Meteor Scatter in Post-Nuclear Attack Communications, p. 45, 20 December 1980.

78. McGrath, P. A., Meisner, T. L. and Winters, B. H., Meteor Burst Report, pp.7-9, 31 July 1983.

79. Richmond, R. L., "Meteor Burst Communications, Part II: Upgrading Performance Doesn't Cost," Military Electronics/Countermeasures, pp. 56-61, September 1982.

80. University of Wisconsin Department of Electrical and Computer Engineering Contract Number N00039-81-C-03-39, Feasibility of High Speed Digital Communications on the Meteor Scatter Channel, by W. P. Birkemeier and M. D. Grossi, p. 11, 1 May 1983.

81. Carpenter, R. J., Ochs, G. R. and Sugar, G. R., "Elementary Considerations of the Effects of Multipath Propagation in Meteor-Burst Communication," Journal of Research of the National Bureau of Standards--Radio Propagation, v. 64D, pp. 495-500, September/October 1960.

82. Bartholome, P. J. and Vogt, I. M., "COMET--A New Meteor-Burst System Incorporating ARQ and Diversity Reception," IEEE Transactions on Communication Technology, v. COM-16, pp. 268-278, April 1968.

83. Meteor Communications Consultants, Inc. Report 797, Analysis of Meteor Burst Communications for Navy for Navy Strategic Applications by T. G. Donich, R. E. Leader and D. K. Smith, p. 7, 4 February 1980.

84. McGrath, P. A., Meisner, T. L. and Winters, B. H., Meteor Burst Report, pp. 26-34, 31 July 1983.

85. Rockwell International Corporation, The Role of Meteor Scatter in Post-Nuclear Attack Communications, p. 29, 20 December 1980.

86. Chambers, J. T., Evans, G. L., Hannum, A. J. and Otten, K., "Air-to-Ground Meteoric Scatter Communication System," IRE Transactions on Communications Systems, pp. 113-132, June 1960.

87. Morgan, E. J., "The Resurgence of Meteor Burst," Signal, pp. 69-73, January 1983.

88. Rockwell International Corporation, The Role of Meteor Scatter in Post-Nuclear Attack Communications p. 43, 20 December 1980.

BIBLIOGRAPHY

Akram, F., Grossi, M. D., Javed, A. and Sheikh, N. M., "Impulse Response of a Meteor Burst Communication Channel Determined by Ray-Tracing Techniques," IEEE Transactions on Communications v. 25, April 1977.

Bokhari, S. H., Grossi, M. D. and Javed, A., "Data Storage for Adaptive Meteor Scatter Communication," EEE Transactions on Communications, v. 23, March 1975.

Casey, J. P. and Holladay, J. A., "Some Airborne Measurements of VHF Reflections from Meteor Trails," Proceedings of the IRE, v. 45, December 1957.

Cavers, J. K., "Variable-Rate Transmission for Rayleigh Fading Channels," IEEE Transactions on Communications, v. COM-20, February 1972.

Day, W. E., "Meteor Burst Communications Offer a Vital Alternative," Defense Systems Review, January 1984.

Ehrman, L. and Monsen, P., "Troposcatter Test Results for a High-Speed Decision-Feedback Equalizer Modem," IEEE Transactions on Communications, v. COM-25, December 1977.

Feher, K. and Takhar, G. S., "A New Symbol Timing Recovery Technique for Burst Modem Applications," IEEE Transactions on Communications, v. COM-26, January 1978

Forsyth, P. A. and Hines, C. O., "The Forward-Scattering of Radio Waves from Overdense Meteor Trails," Canadian Journal of Physics, v. 35, 1957.

Gedaminski, B. F. and Griffin, Jr., W. G., "Transmitting Facsimile Messages Over Meteor-Burst Paths," Electronics, v. 34, 19 May 1961.

Hayes, J. F., "Adaptive Feedback Communications," IEEE Transactions on Communications Technology, v. COM-16 February 1968.

Hines, C. O. and O'Grady, M., "Height-Gain in the Forward-Scattering of Radio Waves by Meteor Trails," Canadian Journal of Physics, v. 35, 1957.

James, J. C. and Meeks, M. L., "On the Influence of Meteor-Radiant Distributions in Meteor-Scatter Communication," Proceedings of the IRE, v. 45, December 1957.

Jaye, W. E., Peterson, A. M., Sifford, B. M., Vincent, W. R. and Wolfram, R. T., "A Meteor-Burst System for Extended Range VHF Communications," Proceedings of the IRE, v. 45, December 1957.

Jones, J. J., "Multichannel FSK and DPSK Reception with Three-Component Multipath," IEEE Transactions on Communications Technology, v. COM-16, December 1968.

Kennedy, R. S. and Lebow, I. L., "Signal Design for Dispersive Channels," IEEE Spectrum, v. 1, March 1964.

Knight, T. G., "Applicability of Multipath Protection to Meteor Burst Communications," IRE Transactions on Communications Systems, September 1959.

Lindsey, W. C., "Error Probabilities for Rician Fading Multichannel Reception of Binary and N-ary Signals," IEEE Transactions on Information Theory, October 1964

McKinley, D. W. R. and Millman, P. M., "Determination of the Elements of Meteor Paths from Radar Observations," Canadian Journal of Research, v. 27, 1949.

Monsen, P., "Feedback Equalization for Fading Dispersive Channels," IEEE Transactions on Information Theory January 1971.

Montgomery, G. F., "Intermittent Communication with a Fluctuating Signal," Proceedings of the IRE, v. 45, December 1957.

Morgan, D. R., "Error Rate of Phase-Shift Keying in the Presence of Discrete Multipath Interference," IEEE Transactions on Information Theory, July 1972.

Rach, R. A., "An Investigation of Storage Capacity Required for a Meteor-Burst Communications System," Proceedings of the IRE, v. 45, December 1957.

Runge, W. A. and Willson, F. E., "Data Transmission Tests on Tropospheric Beyond-the-Horizon Radio System," IRE Transactions of Communications Systems, March 1960.

Sugar, G. R., "Loss in Channel Capacity Resulting from Starting Delay in Meteor-Burst Communication," Journal of

Research of the National Bureau of Standards--Radio Propagation, v. 64D, September/October 1960.

Yao, K., "On Minimum Average Probability of Error Expression for a Binary Pulse-Communication System with Intersymbol Interference," IEEE Transactions on Information Theory, July 1972.

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