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SOUTH AUSTRALIA

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METEOR BURST COMMUNICATIONS SYSTEMS

by

M. Irving and G. Silver

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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
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COMMUNICATIONS DIVISION

TECHNICAL REPORT

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METEOR BURST
COMMUNICATION SYSTEMS

by

M. Irving and G. Silver

SUMMARY

This document presents a summary of Meteor Burst Communication Systems, based on the results of twenty-nine papers published between 1953 and 1988. It also includes information on the various modelling techniques employed.



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LIST OF ABBREVIATIONS

AJ/LPI	Anti Jamming/Low Probability of Intercept
ARQ	Automatic Repeat Request
MBC	Meteor Burst Communications
MBCS	Meteor Burst Communications System

1 INTRODUCTION

The Earth's atmosphere is constantly bombarded by vast numbers of meteors, travelling at thousands of kilometres per hour. Upon entering the atmosphere, the friction of the air produces enough heat to completely vaporise these meteors. In the denser atmosphere at around 115 km altitude, the vaporised atoms collide with air molecules, producing a trail of free electrons⁽ⁱ⁾. Complete vaporisation generally occurs by 80 km altitude.

The possibility of reflection of radio waves from these ionisation trails has been entertained since 1931, when Pickard suggested it as a plausible explanation for abrupt increases in shortwave broadcast reception. [11, 28]. After some study of the phenomenon, various experimental communications links were developed during the nineteen fifties and sixties. [9, 10, 11, 14, 23, 24, 29] Like modern systems, they relied on compressing information into small packets, and transmitting these packets in short bursts. The transmission was made by reflecting a radio wave of 40-50 MHz from a suitable meteor trail to a receiving station, where the information was then reassembled [4, 17, 19] Hence the title 'Meteor Burst Communication System' (MBCS).

The rate of information transfer, and its efficiency, are dependent on the following factors, [3, 6, 14, 24, 25, 28]. These factors are discussed in later sections of this report.

- Geographic location of transmitter and receiver.
- Time of day.
- Time of year.
- Orientation and position of meteor trail.
- Presence of ionospheric layers of tropospheric duct conditions.
- Radiated power of transmitting antenna.
- Gain patterns of transmitting and receiving antennas.
- Background noise level at receiving sites.
- Frequency of transmission.
- Polarisation.
- Instantaneous data rate.
- Packet size.
- Error control techniques.

The comparatively low cost and power requirements, high inherent security, good immunity to upper atmospheric disturbances, and adaptability have resulted in a resurgence of interest in MBCS for a variety of applications.

⁽ⁱ⁾ The trail also contains positive ions, but in the communications theory, these are ignored as being too massive to vibrate under an applied electromagnetic wave.

2 OCCURRENCE OF METEOR TRAILS

Experimental evidence indicates that the number of meteors entering the atmosphere is inversely proportional to their mass, and that around 10^{10} meteors of various sizes arrive each day [3, 10, 12, 14, 17, 19, 23, 25]. Meteor velocities have been found to lie entirely within the range 11.3 to 72 km/s, where 11.3 km/s is the escape velocity for particles leaving the Earth and 72 km/s is the sum of the Earth's linear velocity (30 km/s) and the escape velocity for a particle leaving the solar system (42 km/s). This result implies that meteors are members of the solar system.

It has been found that meteors tend to reside in fixed orbits about the Sun. As the Earth's path intersects these orbits, meteors enter the atmosphere, giving rise to a seasonal variation in the number of meteor trails detected. The tilt of the Earth's axis causes the planet to intersect a majority of meteor orbits in summer, and a minimal number in winter, leading to seasonal peaks and troughs in number of trail observation [2, 3, 5, 8, 10, 14, 17, 19, 21, 23, 27]. These seasonal variations are greatest at the poles [2, 16].

Similarly, there are a number of predictable meteor showers, but as these occur relatively infrequently, they cannot be relied upon for regular communications [3, 6, 10, 12, 14, 17, 19, 25, 27].

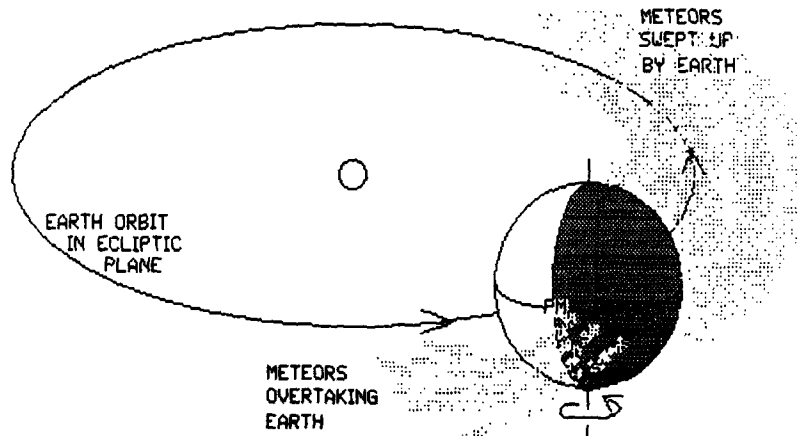


Figure 1 Motion of earth with respect to sun and sporadic meteors

The frequency of occurrence of meteors varies with the time of day. As the Earth rotates towards the Sun, it intercepts the meteors, overtaking them. Then, towards evening, their frequency of occurrence decreases, since a meteor would be required to overtake the Earth in order to enter the atmosphere. This diurnal variation has been plotted and tends to be roughly sinusoidal

throughout the day, with a four-to-one order of magnitude [2, 3, 10, 12, 14, 17, 19, 21, 23, 25, 27]. The meteor velocity patterns take the same form, with a 10 to 15 km/s variation about a daily mean of 35 to 40 km/s. This velocity variation affects the meteor trail height similarly, and hence influences the diffusion time constant, leading to diurnal variations in burst duration [8, 9], with the greatest variation occurring at the equator [2, 17].

The complex variations described above have been quantified by Meeks and James, 1957, but the assumption of random (Gaussian) arrival of useful meteors is generally considered to be sufficient [8]. This has the advantage of allowing the use of statistical methods to develop models of MBC link parameters [11, 22].

3 REFLECTION PROPERTIES OF METEOR IONISATION TRAILS

Meteors ranging in mass from 10^{-5} to 10^{-1} grams (with diameters of 0.2 up to 2 mm) produce trails suitable for communications [9, 24]. These trails occur at an average altitude of 100 km, and are typically 15 km long, although some trails as long as 50 km have been recorded. The initial radius of an MBC trail is typically of the order 0.5 to 4 m, and expands by diffusion, usually dissipating within seconds, or tenths of seconds [4, 15, 22, 25].

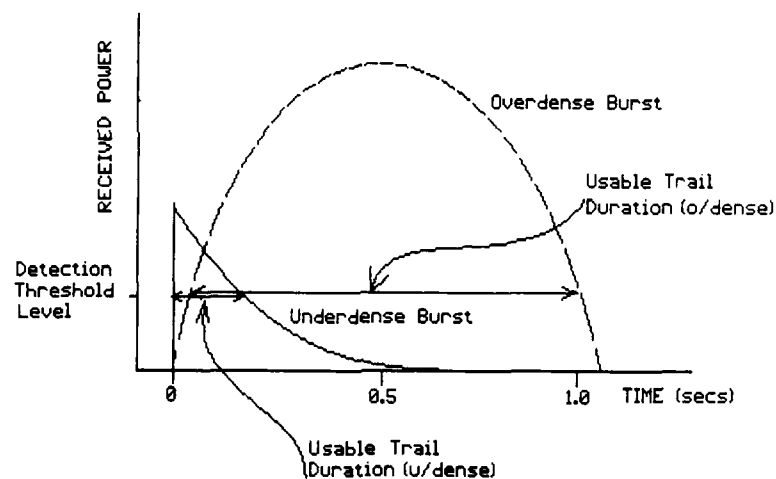


Figure 2 Assumed amplitude envelopes for meteor ionisation trails

These meteor trails are generally classified into two types [25], underdense trails and overdense trails.

- (i) Underdense trails are defined as those with an electron line density such that when a radio wave is incident on the trail, each electron reflects independently of the

others. (ie. $q_0 < 2 \times 10^{14}$ electrons/m). Underdense trails are formed by meteors with masses between 10^{-5} and 10^{-3} grams, and can be used to communicate for 0.5 to 1.0 s, with waiting times of several minutes.

The power received due to underdense reflection is;

$$P_{\text{rec}}[t] = \frac{P_T G_T G_R \lambda^3 q^2 \sigma_e \sin^2 \alpha}{(4\pi)^2 R_{CT} R_{CR} (R_{CT} + R_{CR})} \frac{\exp - \left[\frac{32\pi^2 D t + 8\pi^2 r_0^2}{\lambda^2 \sec^2 \vartheta} \right]}{(1 - \sin^2 \vartheta \cos^2 \beta)}$$

where σ_e = effective echoing area of electron
 β = angle of trail to great circle path
 α = angle between the electric vector of the incident radio wave and the meteor trail, and is a measure of the change of polarization upon scattering.

and other symbols are as defined in paragraph 7.4.

A first order approximation of such a trail is a right circularly cylindrical electron cloud.

- (ii) Overdense trails are those in which the electron line density is great enough ($q_0 < 2 \times 10^{14}$ electrons/m) that an incident wave is incapable of penetrating the electron cloud to a significant extent, and hence is completely reflected. These occur much less frequently than underdense trails, having typical waiting times of twenty minutes. However, the overdense trails can prove useful in MBC systems, since they possess properties of high reflectivity and longer lifetimes. The relatively long lifetimes may make these trails susceptible to distortion by high altitude winds, inducing multipath fading and consequent intersymbol interference.

A useful model of overdense trails was proposed by Hines and Forsythe in 1957, as being a metallic cylinder with received power from forward-scatter reflection determined by :

$$P_{\text{rec}}[t] = \frac{P_T G_T G_R \lambda^2 \sin^2 \alpha^2 \left[\frac{4Dt + \pi r_0^2}{\sec^2 \vartheta} - \ln \left[\frac{r_e q \lambda^2 \sec^2 \vartheta}{\pi^2 (4Dt + r_0^2)} \right] \right]^{\frac{1}{2}}}{32\pi^2 R_{CR} R_{CT} (R_{CR} + R_{CT}) (1 - \sin^2 \vartheta \cos^2 \beta)}$$

NOTE: This model may be inaccurate over short ranges, where the contribution due to back-scatter becomes significant.[1]

4 THE GEOMETRY OF A SIMPLE POINT-TO-POINT MBC SYSTEM

MBC systems are commonly used to propagate radio waves in the lower VHF range. The lower frequency limit (20 to 30 MHz) is determined by the desire to avoid reflections via ionospheric scatter, while the upper limit is determined by receiver sensitivity, since the attenuation increases with the cube of frequency. Frequencies between 20 and 120 MHz can be supported, with the optimum frequency range being 40 to 50 MHz⁽²⁾ [3, 10, 19, 23].

Such frequencies travel in line-of-sight paths, thus the maximum range of an MBCS is around 2000 km. In order to establish communication between a transmitter and receiver via meteor trails, those trails must connect the points through (approximately) specular angles of reflection. That is, favourable meteor trails are those whose central axis lies at a tangent to any of a family of ellipsoids of revolution, having the transmitter and receiver as foci. Point P on Figure 3 below is such as to satisfy these requirements.

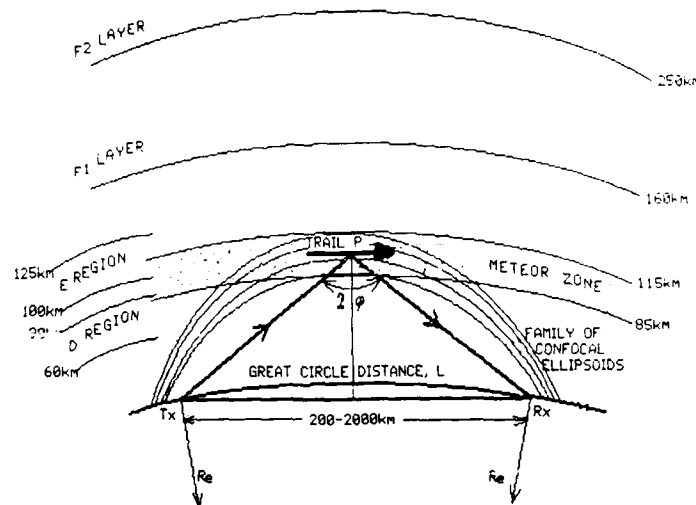


Figure 3 Geometry of a point-to-point MBC system

⁽²⁾ For systems requiring rapid post-upper-atmospheric-nuclear-explosion recovery, higher frequencies must be utilised.

As reflections from meteor trails are not perfectly specular, an ellipse is formed about the target receive area, within which the transmitted message may be received [3, 4, 9, 14, 17, 21, 23]. This area is referred to as the receive footprint. The dimensions of the footprint are commonly quoted as being 10 x 35 km but, in reality, the size is related to the communication range, operating frequency and percent likelihood of message receipt. This is illustrated in figure 4. Also, it has been found that at large separations, fading signals (such as those from an overdense trail distorted by wind shear) contribute significantly to the size of the footprint. Hence, footprint size can be reduced by transmitting only during the non-fading part of each burst [23].

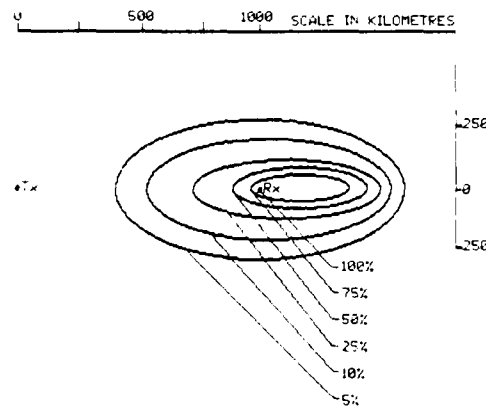


Figure 4 Typical MBC footprint

The zone around the mid-point of the ellipse has a low probability of finding suitable trails, as these would have to be almost parallel to the ground [27]. Such trails, when they do occur, either fail to reach the reflection point before burning up completely, are so high as to produce a relatively short duration trail, or produce trails with line density so low as to render them almost undetectable and useless for communication purposes. Instead, there exists two 'hot spots' located 50 to 100 km on either side of the great circle path joining the two terminals, where the highest probability of detecting suitable trails occurs [5, 10, 12, 17, 24, 27, 28]. The hot spots arise because of the specular reflection condition described above, and the fact that trail duration is directly dependent on $\sec^2 \phi$ [17], where ϕ is as defined in Figure 3. These two conditions are maximised in the hot spot regions illustrated in Figure 4 [17]. The relative magnitudes of these hot spots varies with the time of day and the orientation of the path. Therefore the beamwidths of the antennae are set wide enough to include both hot spots at all times [10 21].

The burst duration is found to be dependent on operating frequency and link geometry, but independent of threshold level and duty cycle. Threshold level is that level for which the signal-to-noise ratio at the receiver is just sufficient for bit detection. This level is dependent on

receiver noise level and signalling speed. The duty cycle of a link is defined as the fraction of time that the received signal power exceeds the detection threshold level [22].

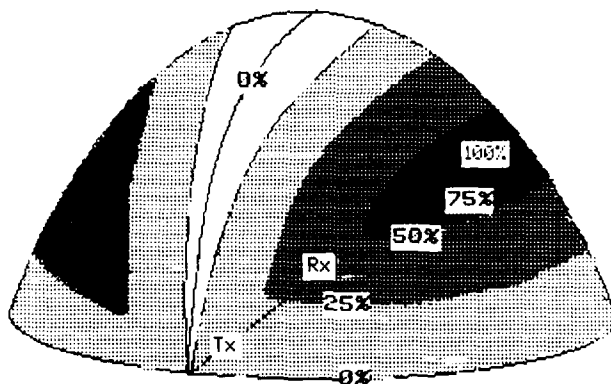


Figure 5 Hot spots on the hemisphere above the horizon circle showing percentage occurrence of useful meteor trails

5. METEOR BURST TRANSMISSION

The bursty nature of MBC systems requires long messages to be split into packets, so that it is not necessary to wait for a meteor trail of sufficient length to transmit the entire message [3]. Instead, the packets can be sent quickly, in any order, along many short trails and then reassembled at the final destination. A typical average bit rate, using 1987 technology, is 200 to 300 bits/s [21]. Such a format requires that both transmitter and receiver have a memory capacity [17, 23, 24]. The transmitter will store information while waiting for a suitable trail, and the receiver will require storage space for packets of data, while waiting to receive the complete message.

The advent of microprocessor technology has made this a viable proposition [12, 14, 19, 21, 23, 24]. A transmitting station can be programmed to receive analog or digital data at a convenient rate from an external source, such as a keyboard or temperature sensor, and assemble this information into packets, each with a label to facilitate message re-assembly. Each packet incorporates a checksum to provide some error detection capacity. These packets can then be transmitted over the meteor trails at the necessarily high rates of instantaneous data flow, as and when suitable trails are detected. The receiving station is programmed to check the incoming data for errors, before reassembling the message and either storing the information in memory, or displaying it appropriately, eg. on a printer or a monitor. Automatic Repeat Request (ARQ) protocols are used to request retransmission of erroneous packets, or packets interrupted by

the termination of a burst. At the start of each burst, transmission commences with a header which contains a synchronization field (synchronizing the receiver clock with the incoming data rate), an address field (if the system contains more than one remote), a control field (which controls such parameters as frequency, operating characteristics of the remote station etc). The header may also include a text field or a packet identification field [19].

MBC systems can be set up in ground-to-ground, ground-to-air, or ground-to-sea configurations [11, 25], in either point-to-point, network, or broadcast configuration [3, 4, 10, 19, 21, 23].

5.1 Point-to-point

This is the simplest of all possible implementations. For correct operation, at least one terminal must be capable of detecting the presence of a suitable meteor trail and some form of feedback must be available. In this configuration, the master station probes continually for suitable trails. When such a trail occurs, the remote station detects the master's probe and transmits one or more packets of information along the same meteor trail. Some systems then wait to receive an acknowledgement of correct receipt of the packet from the master before transmitting again. Should the master station detect an error in any incoming data packet, it will send a request for retransmission of that packet, instead of an acknowledgement of correct receipt. When the meteor trail is no longer viable for communication, either the master will not receive the next packet of data, and so will not transmit an acknowledgement, or else the probe will not receive the acknowledgement, and hence will not transmit. In each case, the master station will revert to a probing mode and the remote station to the 'listening', (non-transmitting) mode. When a link is re-established the remote station will transmit its first unacknowledged data packet.

In an Automatic Repeat Request (ARQ) system data is sent down the link continuously for as long as the link exists. It is interrupted by the receiver only when an error has been detected, in which case the character in error is retransmitted. The receiver keeps a record of the correctly received information and whenever a link is established sends the remote transmitter an identifier to indicate the point at which the remote station should commence its data transmission.

Operation of point-to-point MBC systems may be in half-duplex, where forward and return transmissions use the same frequency, or in full-duplex, where each uses a different frequency spaced widely enough apart that interference cannot occur.

5.2 Network

Where a master station is required to receive data from a number of different remote stations, each remote location is assigned a unique address. The master probes for responses from the remote stations either by addressing one particular remote, or (more efficiently) by using a partial address, to which several remote stations may respond. If the addresses have been assigned such that remote stations lying within a common footprint have

sufficiently different addresses, then it is unlikely that more than one station at a time will respond to the probing signal, due to the random occurrence of meteor trails. Once a remote station has successfully transmitted its data to the master, it may be inhibited against further transmission for a short time to allow other remote stations to respond to the probing signal.

5.3 Broadcast

In this case the information is broken down into packets of such a size that each may be transmitted by a single burst of average duration. Each packet is then transmitted repeatedly, enough times to ensure that there is a high probability of it being correctly received by all remote stations. No acknowledgement is required by the transmitter.

6 ADVANTAGES AND DISADVANTAGES OF MBCS

Flexibility: The same transmitter-trail-receiver format can be applied to a wide variety of configurations, including both line-of-sight and beyond-line-of-sight ranges. [14, 19, 23]

Mobility: Equipment could be installed in an aircraft or a small van using easily deployed antenna systems. As no cabling is required between the transmitter and the receiver, portability is greatly improved. [10, 14, 22]

Ease of automation: Since the critical transmitting and receiving functions are microprocessor controlled, a minimum of operator supervision is required. This enables remote automated stations to be set up which are capable of reporting system status details plus other data, eg. telemetry, to a conveniently located master station. Such automation also decreases the amount of operator training required to master the system by simplifying the control functions. [10, 14, 21, 22]

Survivability: As MBC is less affected by ionospheric disturbances than other communications systems it may be operated effectively at high latitudes. It is also anticipated that upper atmospheric nuclear explosions would have a less significant effect on MBCS than on other long-range communications media. The equipment itself is also less subject to physical degradation than satellites and cables as it can be sited in a more benign environment. [10, 14, 19, 21, 23, 24]

AJ/LPI: As indicated previously, when a meteor burst communication system is operated at beyond-line-of-sight ranges, it possesses inherent anti-jamming and low probability of intercept capabilities. [10, 14, 19, 21, 23, 24]

Power consumption: This is considerably less than that required by a comparable ionoscat system. [10, 17]

Cost: An MBC system is many times less costly than a satellite system. Nor does it incur the expense associated with installing terrestrial lines between points, eg. a telephone system. [10, 19, 23]

Frequency considerations: Unlike HF systems, MBC systems require no frequency management during operation. In fact, due to the intermittent nature of the medium, there is a possibility that two relatively close MBCS link could operate on the same frequency without either suffering significantly from interference. The bandwidths available to MBCS are, however, significantly curtailed by the desire to avoid interfering with other systems operating in the HF and VHF ranges. [10, 21]

Noise: MBC systems are highly susceptible to cosmic, man-made and internal noise. Where an MBC receiver is sited in a relatively noisy environment, the transmitter may be required to use higher power to ensure receipt of data. [3, 11, 22, 24]

Intermittency: This implies a need for buffering of data and precludes the possibility of utilising an MBCS for real-time speech. Instead, MBC systems are used in applications where transmission of data with a high information content is required and waiting times of several seconds or minutes are acceptable. [10, 12, 14, 19, 21, 22, 23, 24]

MBC systems have inherently good survival capabilities. It is anticipated that MBCS would recover more rapidly from the effects of atmospheric nuclear explosions than HF and satellite technology. However, since such explosions would tend to increase the density of free electrons in the atmosphere, higher frequencies than the optimum 40-50 MHz range would need to be employed in order to penetrate the D-region of the ionosphere. This implies the need to increase the power of the transmitter in such a situation, to overcome the attenuation experienced by higher frequencies. [4]

7 MODELLING OF MBCS

7.1 History

The most common, and simplest, method of modelling meteor bursts uses a comparison technique. This is based on the theory of Sugar, [25] wherein the properties of the link of interest are determined by appropriately scaling those of a reference link. This has proved to be an adequate means of modelling changes in operating parameters, and has relatively low associated computing costs. However, reference models do not take into account the effects of latitude, which influences diurnal and seasonal rates of arrival, nor hot spot migration. Additionally, due to the many simplifications and approximations, they are not capable of predicting the absolute number of meteor bursts to be expected at a given time, on a given link. If such results are required, a meteor arrival rate or

astronomical model must be utilised. These are relatively more costly than the reference models as they make fewer approximating assumptions and include astronomical data concerning the link of interest. They hence involve a greater number of more complex calculations. Such models have been developed independently by David W. Brown [5, 6] and by Jay A. Weitzen. [28]

The performance of a model depends on the technique it uses to predict the arrival rate of meteor trails. Sugar [25] states that:

$$M \sim \left(\frac{P_T G_T G_R}{P^2 T_R R^3} \right)^b$$

where M = arrival rate of meteor trails exceeding an arbitrary threshold.
 T_R = minimum receive power satisfying the signal-to-noise ratio.
 b = constant, such that $0.5 < b < 1$

and other symbols are as defined in paragraph 7.4.

So, M/M_{ref} can be used to predict the long-term average arrival rate, M , of the link under consideration, based on the known properties of a reference link with arrival rate M_{ref} . This value, M , can then be scaled appropriately to take into account the effects of diurnal and seasonal variations, giving the required arrival rate.

The above technique does not incorporate the antenna patterns of the transmitter and receiver. In order to achieve this refinement to the model, Eshleman and Manning [14] introduced the following requirement.

For a trail to be a useful part of a communication link, the following criteria must be satisfied,

- point P on Figure 6 below must lie within the common transmit and receive volume,
- the cylinder which approximates the trail must ionize at least one half of the Principal Fresnel Zone, where the Principal Fresnel Zone satisfies,

$$|(L_{TP} + L_{PR}) - (L_{TP'} + L_{PR})| < \frac{\lambda}{2}$$

where;

P = the point of tangency,
 P' = any point on trail

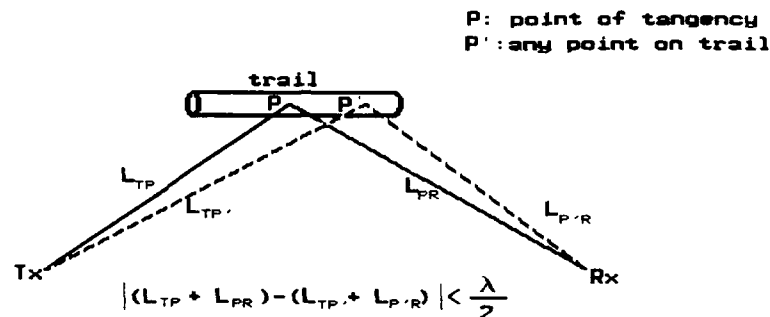


Figure 6 The Principal Fresnel Zone

In order to simplify calculations, constant trail height, h and trail length L are assumed. If L and h are chosen to be the mean of observed meteor trail lengths and heights, then statistically, this simplification is not expected to significantly effect the results attained.

Then p , the probability density of detecting a usable trail, may be calculated by finding the ratio of correctly oriented trails to the total number of trails entering a differential area, and then integrating over all such areas, for any given meteor radiant distribution.

Eshleman and Manning (and later Hines and Pugh[18]) assumed a spatially uniform distribution. It has since been found that meteor trails are more prevalent near the ecliptic [17], so Meeks and James' assumption that meteors radiate entirely from the ecliptic proved to be significantly more accurate. A further refinement was introduced by Brown, who incorporated Lovell's experimental observations of meteor radiants into his astronomical arrival model. Similarly, Rudie used Davies' experimental data to improve on the work of Hines and Pugh.

7.2 The Brown model

The Brown Model [5] predicts the number of trails per unit time; the fraction of time that a trail exists between transmitter and receiver; and the average burst duration. It saves the intermediate result of contribution versus position in the potential volume.

It finds these values by dividing the layer of atmosphere between 75 and 115 km, extending to the 115 km horizon, into $20 \times 20 \times 6$ km cells. Then the contribution of each cell to the total is determined. Lovell's meteor radiant distribution is utilized in this process - for any potential trail location the equation of the ellipsoid passing through it is calculated and the tangent plane derived. To ensure that trails are not counted more than once, only the contribution (from each cell) that lies in the first Fresnel zone is considered.

Data concerning the link is input by the user and used to determine the number of trails that will produce a signal above the receiver threshold. The time above threshold is calculated as $T = N \times T_{\text{um}}$ [24]

7.3 The Weitzen model

The Weitzen model [26] uses Rudie's radiant distribution transformed to a more convenient coordinate system. It transforms the link parameters into the same system, allowing model predictions to be displayed relative to the link itself. Meteor radiants which are geometrically suited to communication are then selected. Each radiant is first multiplied by the intensity of activity in that orbit and then summed over all orbits. This gives the location and migration of hot spots by giving a scale factor at each point of interest which takes seasonal, diurnal and geometric considerations into account.

The minimum meteor mass required to produce a trail which exceeds minimum signal threshold is then calculated, taking into account variation of ionisation with height and zenith angle. Separate calculations determine the antenna's gain at each point, including the effects of ground reflections, polarisation coupling and Faraday rotation loss.

Integration from minimum to infinite mass then determines the number of particles arriving per minute for a uniform distribution. The decay constant at each point is multiplied by the arrival rate and summed over the common volume to obtain the duty cycle. The value at each point is multiplied by the geometric scale factor. To obtain total rates, integrate over the total volume.

This model predicts the number of meteors per minute exceeding a given signal level and gives two dimensional contour maps showing relative intensity of arrival pattern versus location in common volume.

7.4 A model to calculate the probability of message receipt.

The user is required to enter the following information.

- Transmitter power and gain.
- Receiver power and gain.
- Common illumination area.
- Latitude and longitude of transmitter and receiver.
- Operating frequency.
- Modem rate.
- Clock synchronisation time.
- Number of bits per character.
- Length of message.
- Required delivery time.

From the entered antenna coordinates the Great Circle path length may be calculated. If possible an external function should be incorporated allowing determination of the illumination area from a description of antenna properties.

The user inputs are substituted into Abel's simplified model [1] for an underdense burst:

$$\frac{P_R}{P_T} = \frac{r^2}{32\pi^2} - \frac{q_0^2 G_T G_R \lambda^3}{R_T^3} - \exp\left(\frac{-2t}{\tau}\right) - \exp\left(\frac{r_0^2}{2D\tau}\right)$$

where;

$$\begin{aligned} r_e &= \text{radius of an electron } (2.817939 \times 10^{-18} \text{ km}) \\ e &= \text{charge on an electron } (1.602192 \times 10^{-19} \text{ C}) \\ q_0 &= \text{threshold electron line density for detection} \\ G_T, G_R &= \text{gain of transmitter and receiver respectively} \\ \lambda &= \text{operating wavelength} \\ t &= \text{time from formation of trail} = \tau \times \sec^2 \phi \\ \tau &= \text{decay time constant} = \frac{\lambda^2 \sec^2 \phi}{16\pi^2 D} \quad [7] \end{aligned}$$

$$\begin{aligned} r_0 &= \text{initial trail radius} = \log_{10} r_0 = 0.035h - 3.45 \\ R_T &= \text{nominal range to trail} \\ &\sim \text{distance from transmitter to trail, } R_{CT} \\ &\sim \text{distance from trail to receiver, } R_{CR} \end{aligned}$$

$$R_T^2 = \frac{L^2}{4} + \left(h + \frac{L^2}{8R_e}\right)^2$$

$$\begin{aligned} D &= \text{diffusion constant} = \log_{10} D = 0.067h - 5.6 \quad [7] \\ \alpha &= \text{angle between the electric field vector } E \text{ at the trail and } R_{CR} \\ \beta &= \text{angle between the principal axis to the trail and the plane formed by } R_{CT} \text{ and } R_{CR} \\ \phi &= \text{angle of incidence of transmitted plane wave.} \end{aligned}$$

$$\sec^2 \phi = 1 + \frac{L^2}{\left(2h + \frac{L^2}{4R_e}\right)^2}$$

$$\begin{aligned} R_e &= \text{radius of Earth } (6371 \text{ km}) \\ h &= \text{trail height} = 17 \log_{10} f + 124 \text{ (km)} \quad [7] \\ f &= \text{operating frequency (MHz)} \\ L &= \text{Great Circle path length (km)} \end{aligned}$$

From this the electron line density q_0 can be found.

The minimum mass required to produce this line density is then [26]:

$$\log_{10} m = \log_{10} q_0 - 16.58$$

And since meteor flux is related to mass, N_0 can then be calculated as [13]:

$$\log_{10} N_0 = -14.37 - 1.213 \log_{10} m$$

The time of year and time of day is used to scale N_0 to take annual and diurnal variations into account.

The model may be modified later to use an appropriate radiant distribution at this point and also to include the effects of shower meteors.

The interval between bursts which are long enough to sustain communication for at least the synchronisation time, t_w , is [10]:

$$t_w = \frac{1}{HN_0} \exp\left(\frac{t_0}{\tau}\right) \ln\left(\frac{1}{1-P}\right)$$

where;

H is common area of antenna illumination at relevant altitude, and

P is probability that interval between trails $< t_w$ (set to 90% or 50% level)

The value determined for the time interval between bursts is then used in Oetting's model for the probability of message receipt within time t_D [22]:

$$P_d(t_D) = \exp\left[-\left(\frac{t_D}{t_{BA}} + \frac{t_M}{t_{BA}}\right)\right] \cdot \sum_{n=1}^{\infty} \frac{(t_D/t_{BA})^n}{n!} \cdot e_{n-1}(t_M/t_{BA})$$

where;

$$e_n(x) = \sum_{j=0}^n \frac{x^j}{j!}$$

t_M = message length (seconds) without overhead

t_{BA} = average interval between bursts

t_{BA} = average burst duration

and the summation is terminated at $n = 20$ in order to minimise computation time, since the sum converges rapidly.

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Oetting's correction for overhead time is not used, since waiting time is calculated taking it into account.

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17 SUMMARY OF ABSTRACT

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A discussion of meteor burst communications systems based on the results of twenty nine separate papers on the subject published between 1953 and 1988. Also described are the various computer modelling techniques employed.

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