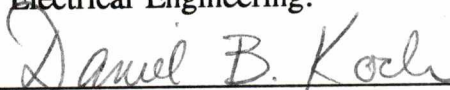
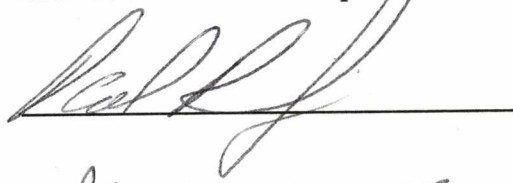
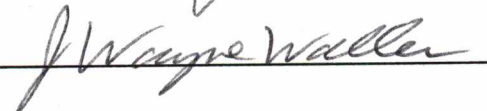


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**RADIO TRUNKING  
FOR THE  
OAK RIDGE RESERVATION**

**A Thesis  
Presented for the  
Master of Science  
Degree  
The University of Tennessee, Knoxville**

**BRIAN JOSEPH KALDENBACH  
May, 1993**

## **DEDICATION PAGE**

**To Barry and Justin, you are both capable of dwarfing my accomplishments.**

## ACKNOWLEDGEMENTS

Special thanks to Randy Gillis for showing me how to program using the time functions in C. To Mike Jones for helping determine how to interface the ICOM receiver. To Motorola's Roger Conrad and George Brinton and Softwright's Larry Ellis and Michael Wiebe for being so open with your products and answering all my questions. To Bill, without your vision I would have had to find another topic. To Mike, Becky, and Karen for the considerable reviews, cleaning up my work so it can be published.

## ABSTRACT

This thesis is intended to convince the reader that a single repeater site can be used to cover the multiple facilities in the Oak Ridge Reservation. The reader is provided with a step by step process from which that conclusion was drawn. This conclusion is based on radio signal propagation analysis which uses the specific performance parameters of an existing radio trunking system into account. In addition a detailed analysis of system loading is provided. Software tools for propagation analysis and queuing theory are reviewed as are their specific applicability to the system and area being considered. Additional software tools are provided to allow specific loading projections at a later date, including a program to analyze the use of conventional radio networks. This work was accomplished while the author was gainfully employed by Martin Marietta Energy Systems and is a direct result of local concern on this subject. The vast majority of this work was accomplished by the author over a two year period. The overall philosophy of this work is - be conservative. Whenever there was a choice between an optimistic or conservative parameter or approach, the conservative was chosen.

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## LIST OF SYMBOLS, KEYWORDS, AND ABBREVIATIONS

AG 88  
Airtime 3, 61, 63, 64, 67, 68, 70, 71, 72, 73, 74, 79, 84, 85, 92, 93, 94, 95, 96  
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Announcement group 4  
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UHF 3, 14, 43, 82, 86, 88  
USGS 18, 19, 55  
VHF 43, 46, 88  
Voting receiver 6, 8, 10

## **CHAPTER 1**

### **PURPOSE / STATEMENT OF NEED**

The radio frequency spectrum is a precious natural resource. Some frequency bands are very congested and since there is no way to manufacture more, ways are needed to efficiently use existing spectrum. The government Land Mobile Radio (LMR) band is one of the most congested government bands. This is the case in the Oak Ridge area.

While all, or most, of the available LMR channels may be allocated to specific users, some of the channels may be used less frequently than others. It is also possible that some channels are used at different times. These tendencies make sharing of the channels an attractive way to improve efficiency of spectrum usage.

Simply loading several user groups' radios with each others channels is not a practical way to implement a solution. It would be very difficult to find particular users with whom you wish to communicate. The additional traffic caused by users looking for their other party could wipe out the effectiveness of this approach. It is, however, possible to design a switching system that tracks channel usage and assigns available channels as they are needed. This approach requires microprocessor controlled radios that communicate with a switch controller. This essentially describes the operation of a radio trunking system.

Martin Marietta Energy Systems Inc. (Energy Systems) operates three facilities in the Oak Ridge reservation, as well as various office buildings located in town, for the Department of Energy (DOE). These facilities are physically separated by several ridges. The placement of these facilities was intentional and provides desired isolation from observers as well as protection from accidental blasts. However, these site locations make it very difficult to cover more than one facility with a single radio system.

Years ago this was not a large problem since the facilities were managed and operated as separate entities. Today however, it is important to share resources whenever possible,

especially where emergency response is concerned. Also, environmental restoration efforts are not limited to the fenced-in perimeters of these facilities. For these reasons radio users of one facility need to be able to communicate with the radio users of other facilities. As they move between facilities these users must stay in touch with their home dispatch centers. Any new radio system implemented in Oak Ridge must make it possible to communicate between facilities.

The Energy Systems Emergency Management organization has defined two-mile emergency notification zones and five-mile emergency planning sectors around each facility. In addition this organization has stated the need for coverage between portable radios in any two-mile zone and coverage between any mobile radio in any five-mile sector. Coverage between any portable radio in a two-mile zone and a mobile in a five-mile sector is also required [1]. A map showing these areas is provided in Figure 1 [2].

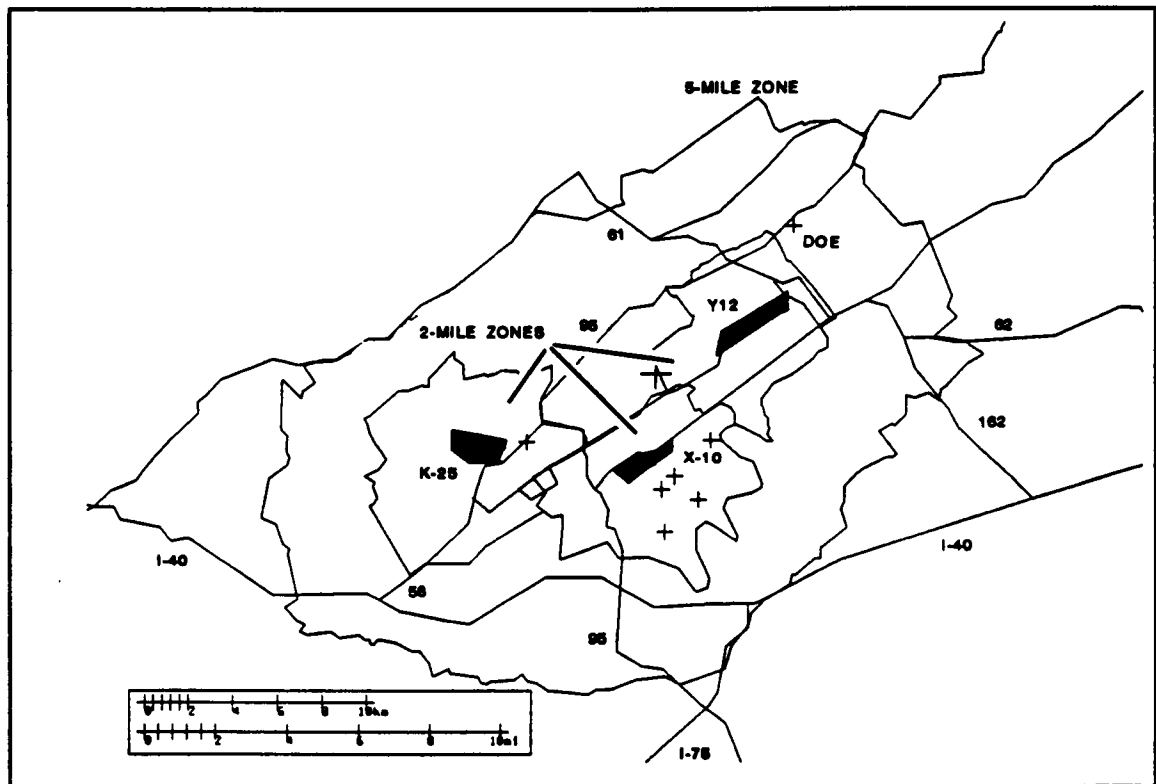


Figure 1 - Emergency Planning Zones

## **RADIO TRUNKING BASICS**

Radio trunking systems take a group of radio channels and use them much like trunked telephone lines between telephone switches. When a radio channel is needed, a user activates his radio which sends a request to the switch controller which in turn assigns an available channel. The controller automatically notifies all user radios associated with the requester to tune to the assigned channel. Once the users are tuned in to the correct channel a normal radio conversation can take place. The technical issues with this approach are: 1) How does one communicate with the radios? 2) How does one know when a channel is available for reassignment? 3) How does one determine who gets the next channel if requests outnumber channels? 4) Should a user's airtime be limited in times of heavy system usage? 5) Does one grant the users the channel for the duration of a conversation, which may contain pauses, or just while they are actively using it? 6) How does one decide if users are actively using the channel? 7) Is it possible to assign channels for fixed blocks of time or is an adaptive time slot needed? 8) How does one determine how long a user needs a channel? 9) How does one determine who needs to talk to whom? How these and other questions are answered determines the architecture of the system being implemented. As expected there are several ways to combine the possible answers and there are several manufacturers of radio trunking equipment.

## **MOTOROLA'S RADIO TRUNKING ARCHITECTURE**

Energy Systems has recently implemented a radio trunking system at the Y-12 Plant. This system is just a start in providing radio trunking for the entire Oak Ridge Reservation. The current system utilizes five UHF channels but is capable of being expanded to 28 channels. The system was procured from Motorola Inc. and uses their proprietary trunking architecture.

Details of Motorola's radio trunking architecture are available in many writings by Motorola engineers as well as in Proposed Federal Standard 1044 [3]. This paper is not intended to

cover these details - only overview their approach as necessary to determine the best way to provide coverage of the entire service area.

Motorola's architecture dedicates a radio channel as a control channel. On a five-channel system, four are available for voice communications. The control channel is Frequency Shift Keying (FSK) modulated and time division multiplexed between users. A central controller is used to assign channels, track channel usage, verify user access rights, and perform various other system functions. The central controller transmits a timing synchronization pulse about once every 23 milliseconds in order to provide individual radios a reference for their transmissions. The system can use one of four channels as the control channel and rotates the one used on a daily basis. Each radio is programmed to know the frequencies of the possible control channels, and when powered on, scans those channels for the central controller timing pulses [4].

As a user desires a channel, he presses the Push to Talk (PTT) button, and the radio places a request on the control channel. The central controller determines if access is authorized, determines if a channel is available, and sends a notification to all radios in the user's talkgroup to move to the assigned channel. A talkgroup is a group of users that require communications with each other; it is the basic building block in a Motorola trunking system.

The repeater for that channel transmits a sub-audible connect tone onto which the individual radios lock and listen for a carrier transmitted by the radio. Users then use this channel as they would a conventional channel, as long as they respond to each other within the preset "hang time" of the repeater. The hang time is adjustable and is currently set for two seconds.

This sequence of events is used for normal talkgroup calls as well as announcement group calls. An announcement group is simply a grouping of several talkgroups where a user can place a call to all users in all associated talkgroups at once. Additional types of calls supported by the system include call alert pages, private calls, and telephone interconnect calls. A call alert page will target a specific radio and make it beep. Once the user presses

the PTT a normal talkgroup call takes place. On a private call the system will dedicate a channel to two users. As long as they respond to each other within the hang time of the repeater the channel is theirs. If the repeater times out they will need to wait on the next available channel before resuming the conversation. A telephone interconnect call allows a call to be placed on the local telephone system. This type of call dedicates a channel to the radio user for the duration of the call, up to an adjustable preset limit. There is no hangtime setting for this type of call. The current system does not support telephone interconnect calls.

If all channels are in use when a user requests one, the user is placed in a busy queue. The user's place in the queue is based on his user priority and talkgroup priority. Higher priority users, or users of higher priority talkgroups, go to the top of the busy queue.

## **WAYS TO GET AREA COVERAGE**

There are basically four ways to provide wide area coverage with the Motorola trunking architecture: 1) Use multiple systems, each covering part of the required area. 2) Simulcast from various transmitter points on the same set of frequencies. 3) Use one central transmit site with remotely located receiver stations used as required to fill holes in coverage. 4) Use a single transmitter station which utilizes a tall tower and high gain antennas as needed. Each of these options is reviewed as they relate to the coverage area required by Energy Systems. Cost is not addressed in this work. A feel for relative cost can be obtained by comparing the complexity of the various approaches.

### **Multiple Systems**

The Motorola architecture allows several separate systems to be tied together so that large systems can be created. This approach is referred to by Motorola as Automatic Multiple Site Select (AMSS). There are AMSS systems in operation today that cover entire states and countries. A system is considered that uses three sites, one at each of the major DOE facilities in Oak Ridge. This approach requires three transmitter sites and associated

hardware. Three separate sets of trunking frequencies are required since the sites are too close geographically to allow frequency reuse. This requires fifteen channels or 30 frequencies.

One site is designated as the "master" site. Each site uses a trunked central controller to control the users at that site. In addition a second central controller is required at the master site that communicates to the "remote" sites via dedicated land lines or microwave links. The master site also utilizes voting receiver equipment that is used to determine which site receives the best signal from the user since more than one site may be within range. Each site has a complete set of repeaters for the number of channels that site requires. Repeaters are designated as "local" or "wide area." The wide area repeaters at the various sites are linked together and all transmit the same traffic.

All radios are programmed with the information necessary to operate on all systems. As the user moves from the range of their home system, their radio looks for available systems in the new area. The central controller at the site picked up determines authorization of the user and assigns its traffic to the repeaters assigned to wide area coverage. Using a wide area coverage repeater network, the users are able to communicate between facilities.

A block diagram for an AMSS system is provided in Figure 2. This approach requires a significant amount of effort for system management. Three separate sites must have central controllers programmed with up-to-date user access information. This information must include all access privileges. (For example; private call, call alert, telephone interconnect, etc). The natural tendency to operate and maintain the sites as separate systems would complicate matters.

This approach is not practical simply because it uses a significant amount of spectrum (remember - one of the goals is efficient use of the spectrum). In fact this approach would require more frequencies for the total system than are currently in use. The multiple site system requires 30 frequencies (three sets of five channels each, two frequencies per channel). Currently there are 15 frequencies in use in non-trunked radio systems (six repeater networks and three simplex networks).

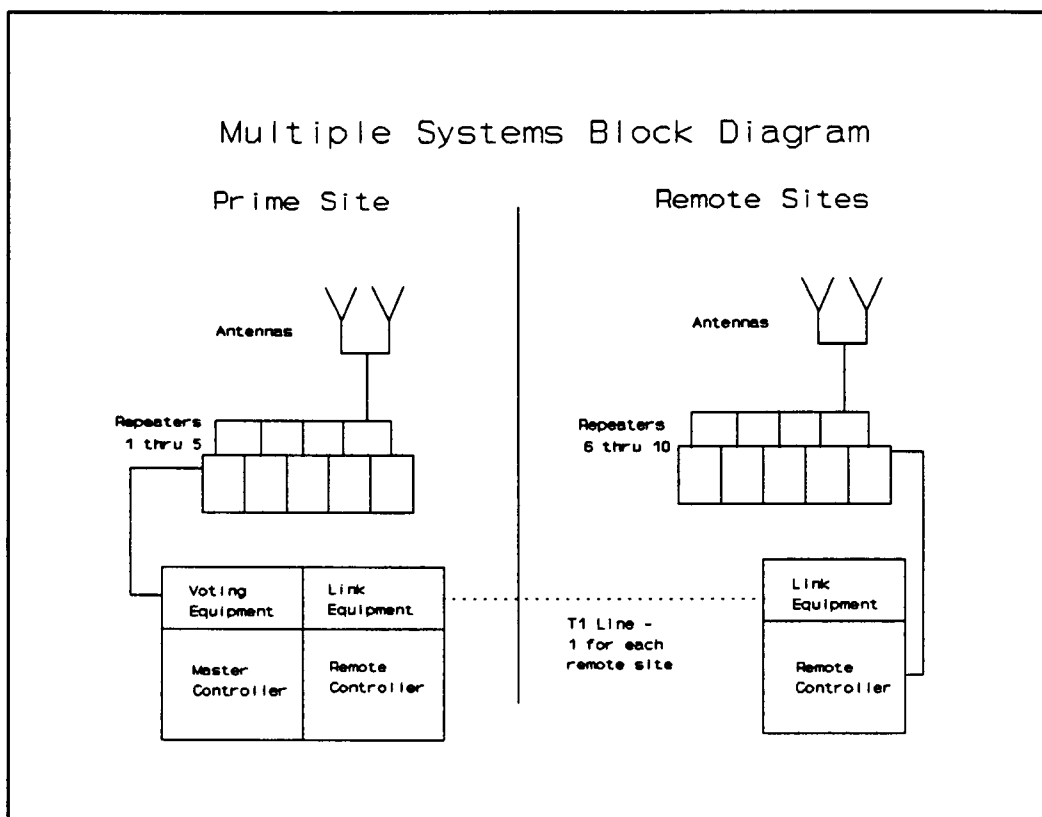


**Figure 2 - Multiple Systems Block Diagram**

It is possible to configure a multiple site system such that redundant central controllers are used. This approach makes it possible to reuse the repeater input frequencies at all sites since voting receivers are used. With this configuration only 20 frequencies are required.

### **Simulcast System**

A simulcast system utilizes several transmitter sites all using the same set of frequencies. This approach is complex because the timing of transmitting the signals is critical. If two stations transmit the same signal out of phase the signal could be canceled at the receive unit. In coverage overlap areas, system performance is highly dependent on the tuning of the stations and how well they adhere to the system timing standards. Expensive timing standards are required in this approach.

Generally the same number of sites would be used for this approach as for the AMSS approach. In fact the sites would be the same and utilize the same equipment with the exception of the timing electronics. This approach also utilizes voting receiver equipment as shown in Figure 3.

System management is simplified over the AMSS approach since only one system database is needed. However, it is still more complex than a single site because several sites are involved. For example, channel assignment in the conventional non-trunked mode used if the central controller becomes disabled (failsoft channel assignment) is more complex.

In spite of the complex timing equipment, this approach is preferred over the AMSS because it uses spectrum more efficiently. Only one set of frequencies is required for the entire system.

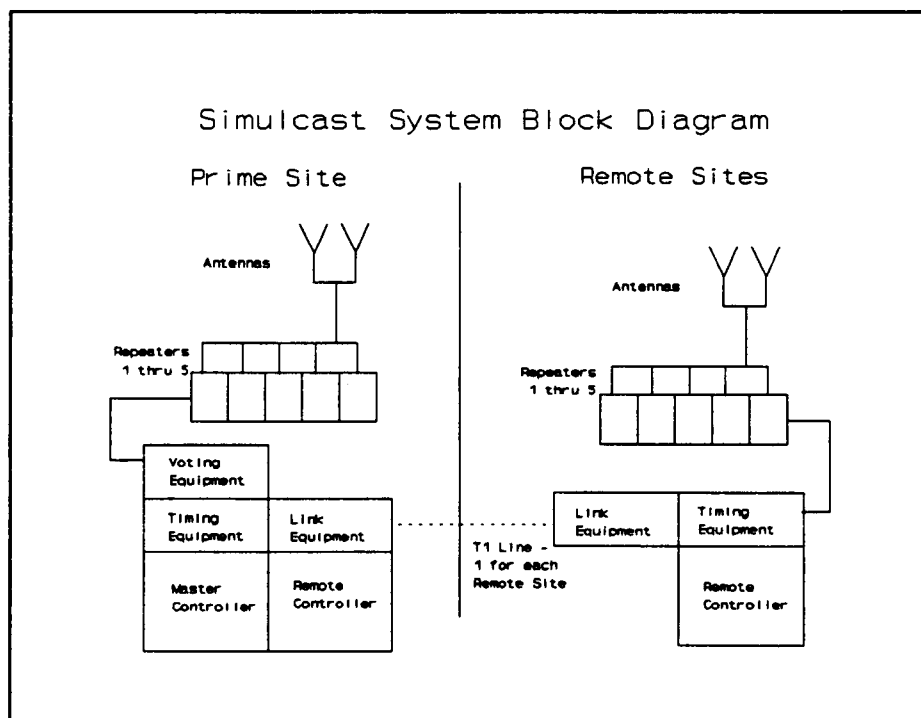


Figure 3 - Simulcast System Block Diagram

## **Single Transmitter Site With Voting Receivers**

It has been widely recognized in industry that the weak link in a radio system is the ability of the portable radio to "talkback" to the repeater. The repeater, using approximately 100 Watts and a 9 decibel (dB) gain antenna, can usually reach a portable radio long after the portable has moved out of talkback range. With this in mind, it is possible to set up receivers in areas known to have poor talkback coverage. This in effect enlarges the coverage area of the system. With radio trunking, the remotely located receivers typically used are more complex than conventional systems; however, they are still greatly simplified over the two approaches previously mentioned.

In the trunking system the control channel cannot be ignored and needs special consideration. Because of it, clocking equipment is needed at the remote receiver site as shown in Figure 4. In addition, a remote central controller is needed. It may appear that this is no simpler than the simulcast or AMSS systems. It is important to remember that this equipment is used to complement a strategically placed central site. That is to say the location of the sites in the AMSS and simulcast systems is not as critical. They are located to provide coverage of one portion of the entire coverage area. With the remote receiver approach it is assumed that the central site has been located at the best location to cover the entire area and that there may be a minimum number of areas where talkback coverage is less than optimal. It is also important to remember that remote sites are receiving only as opposed to transmitting and receiving. The frequency set used for this approach is the same as simulcast; only one set of frequencies is required.

System management of this approach is probably simpler than the simulcast approach, depending on the number of remote receiver sites needed. For Energy Systems it appears that only one remote receiver site would be necessary, if in fact it is necessary at all.

This approach, although discussed prior to the "super-site" approach, is viewed as an alternative if the super-site is not adequate. Use of this approach is only advocated if there are areas that have inadequate coverage under the super-site.

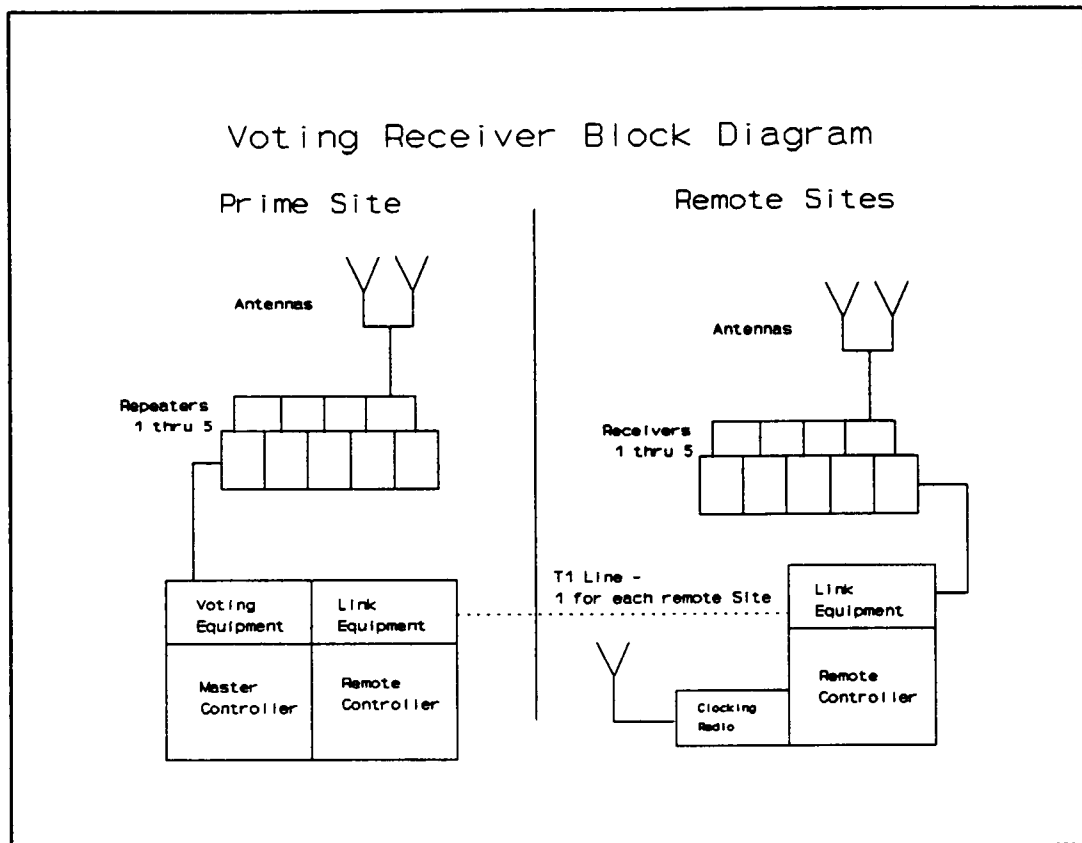


**Figure 4 - Voting Receiver System Block Diagram**

### **Super-site**

As its name implies this approach utilizes a single transmitter site that is centrally located and has a tall tower. In this approach only one set of trunking control equipment is required as shown in Figure 5. The transmit and receive antennas are elevated to a height adequate to provide the required coverage.

Since only one set of equipment is required, this approach is the least complex. As long as the tall tower is less expensive than the complex timing and link equipment of previous approaches, it is also the least costly. This approach is also the easiest to manage and maintain and will likely have a lower operating cost than a more complex system. Alternate or backup systems should be provided when using a single site system since a catastrophic event such as an earthquake or tornado could destroy a repeater site or tower. Backup

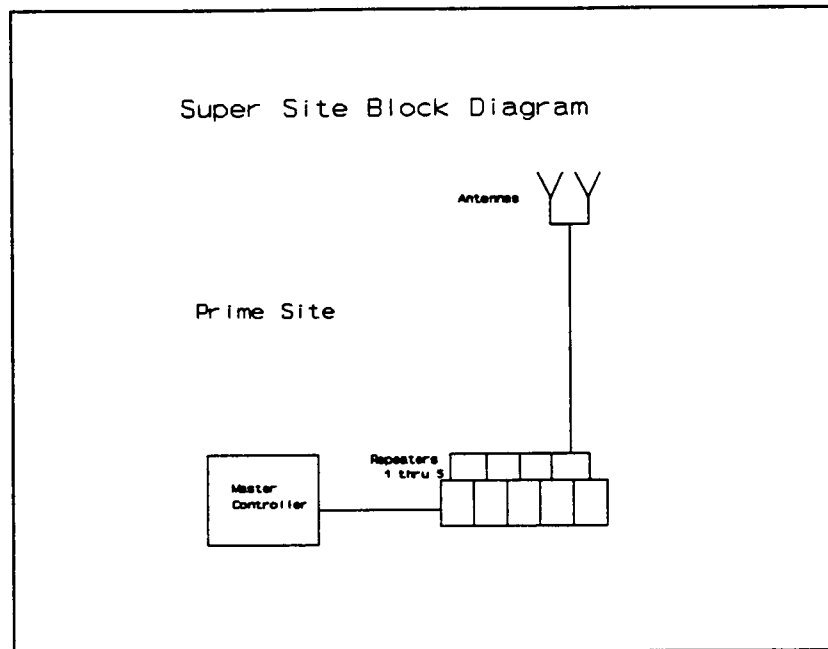


**Figure 5 - Super-Site Block Diagram**

systems and hot standby redundancy are among the many system design issues that should be addressed in a complete system design.

At Energy Systems this is the approach of choice. If it is possible to cover the required area with a super-site, then this approach is the most attractive. The problem, however, is locating a site that provides this coverage. An exhaustive study must be performed to look at all the possibilities and evaluate their suitability. Describing the steps necessary to find that site is the major intent of this paper.

These four wide area coverage options are summarized in Table I. As might be expected the super-site approach rates very favorably relative to the others. This assumes of course that it is possible to cover all facilities with a single repeater site. Costs, both recurring and non-recurring, can be assumed to track with complexity. Configuration control and ease-of-use issues will also track with complexity.

**Table I - Radio Trunking Area Coverage Options**

|                        | COMPLEXITY | CONFIGURATION<br>CONTROL | EASE OF<br>USE | NUMBER OF<br>FREQUENCIES |
|------------------------|------------|--------------------------|----------------|--------------------------|
| APPROACH               |            |                          |                |                          |
| MULTIPLE<br>SYSTEMS    | 4          | 4                        | 4              | 4                        |
| SIMULCAST              | 3          | 3                        | 2              | 1                        |
| SATELLITE<br>RECEIVERS | 2          | 2                        | 1              | 1                        |
| SUPER-SITE             | 1          | 1                        | 1              | 1                        |
| 1 = BEST<br>4 = WORST  |            |                          |                |                          |

## **DOCUMENT STRUCTURE**

Now that it has been determined that the super-site is the preferred approach to providing wide area trunking coverage to the Oak Ridge Reservation, the rest of this report is dedicated to determining how to make that happen. Chapter 2 concentrates on determining the best super-site location from a coverage point of view. The tools used to determine this are introduced and demonstrated. Detailed analyses and results are also covered. Chapter 3 concentrates on how to determine the final system size required to provide adequate service to all facilities. The tools used to make this determination are discussed. A suggested strategy for determining system size at a later date is provided. Chapter 4 provides results and conclusions of the overall work.

## **CHAPTER 2**

### **SITE SELECTION**

In this chapter factors that must be considered in selecting a repeater site and performing an analysis on potential repeater sites are discussed. A general discussion is provided on the different types of propagation analysis models. More specific information is provided for the model chosen for this work as well as particular settings used. Potential super-sites are compared and a particular super-site is selected.

The preferred way to provide radio trunking coverage to all DOE facilities in the reservation is to establish a single transmitter site that can cover the entire area. This is quite a challenge due to the hilly terrain and distance separating the facilities. It has been debated for years by radio users in the community whether or not it was even possible to locate such a site.

Recent developments in computer technology and specialized software have made accurate radio signal propagation predictions feasible. Using these predictions, it is possible to determine if a super-site can cover the desired area and through extensive analysis determine the best site.

### **FACTORS INVOLVED IN ANALYSIS**

No matter how powerful the computer or software, the analysis performed is only as good as the data and assumptions put into it. A complete analysis will take into account all factors that affect system performance. However, as is the case with most engineering studies it is impractical to take ALL factors into account. Factors that affect radio system performance include:

Antenna Gain/Directional Antenna  
Antenna Orientation  
Antenna Location  
Line Losses  
Shadowing Caused by Terrain  
Building Shadowing

Antenna Height  
Distance Between Antennas  
Transmitter Power  
Receiver Sensitivity  
Reflections  
Foliage

Directional antennas can be used to reduce loss due to radiating power in unnecessary directions. Height of transmitting and receiving antennas directly affect how much attenuation obstructions cause. Horizontally or vertically polarized antennas that are not oriented on the same plane will experience polarization loss. Antennas located near a body or other surface that interferes with the ground plane will experience shielding loss. Higher transmitted power levels can improve the amount of signal reaching the receiver. Losses in the transmission line and connectors reduce the amount of radiated or received power. The sensitivity of the receiver determines just how much signal is necessary for proper operation.

Foliage can have a significant impact on some RF systems. Generally the higher the frequency the more attenuation this causes. For UHF, only certain types of foliage are a big factor - specifically long leaf pines whose needles are almost exactly a quarter wavelength. However, that is only a factor for signals passing through the trees. How much loss this causes is highly dependent upon the distance the signal must pass through the trees.

These factors can be taken into account one-by-one in the analysis or grouped together into a link margin figure. The best analysis is not necessarily the one that does the most exhaustive computation on all known factors but the one that gives proper attention to the factors with the largest contribution to performance. It is safe to group together the factors that have little or constant effect into a single element.

Terrain shadowing is a major concern and is given serious attention in this analysis. Power levels, sensitivities, transmission line losses, antenna gain, antenna height, antenna patterns, and receiver sensitivity are all considered individually. Building shadowing, foliage loss, body shielding loss, etc. are grouped into a link margin factor. Reflections are not considered since taking additive and destructive reflections into account for all possible surfaces would

require a super computer and a three dimensional approach. A single two-dimensional analysis that ignores reflections can require a data point every 0.04 miles for each of 360 radials at 25 miles per radial. This requires

$$\frac{1 \text{ point}}{.04 \text{ miles}} \times \frac{25 \text{ miles}}{\text{radial}} \times 360 \text{ radials} = 225,000 \text{ points} \quad (1)$$

which results in data files that are several megabytes in size. Additive reflections are assumed to compensate for destructive reflections.

A radio signal propagating from a transmitter loses much of its strength before it reaches the receive antenna. If the transmitter and receiver are within clear line-of-sight of each other a significant amount of free space loss still occurs due to the distance between them. Since the signal propagates (as light does) from a point outward in all directions, the signal strength is inversely proportional to distance. The formula for free space loss in dB (assuming true omni-directional antennas) is provided in Equation 2 [5].

$$Loss_{\text{freespace}} = 20 \log \left( \frac{4 \times \pi \times d}{\lambda} \right) \quad (2)$$

where

$d$  = Distance from the source

$\lambda$  = Wavelength

There is an imaginary area around the direct line-of-sight of a transmitted signal known as the Fresnel zone. For free space loss to be the only loss, the Fresnel zone must be free of obstructions for the full distance between transmitter and receiver. This zone can be used to determine loss due to obstructions in the path of the signal. The distance between the line-of-sight and the first Fresnel zone (or the first Fresnel zone radius) can be calculated from Equation 3 as shown in Figure 6 [6].

$$r_1 = \sqrt{\frac{\lambda \times D_1 \times D_2}{D_1 + D_2}} \quad (3)$$

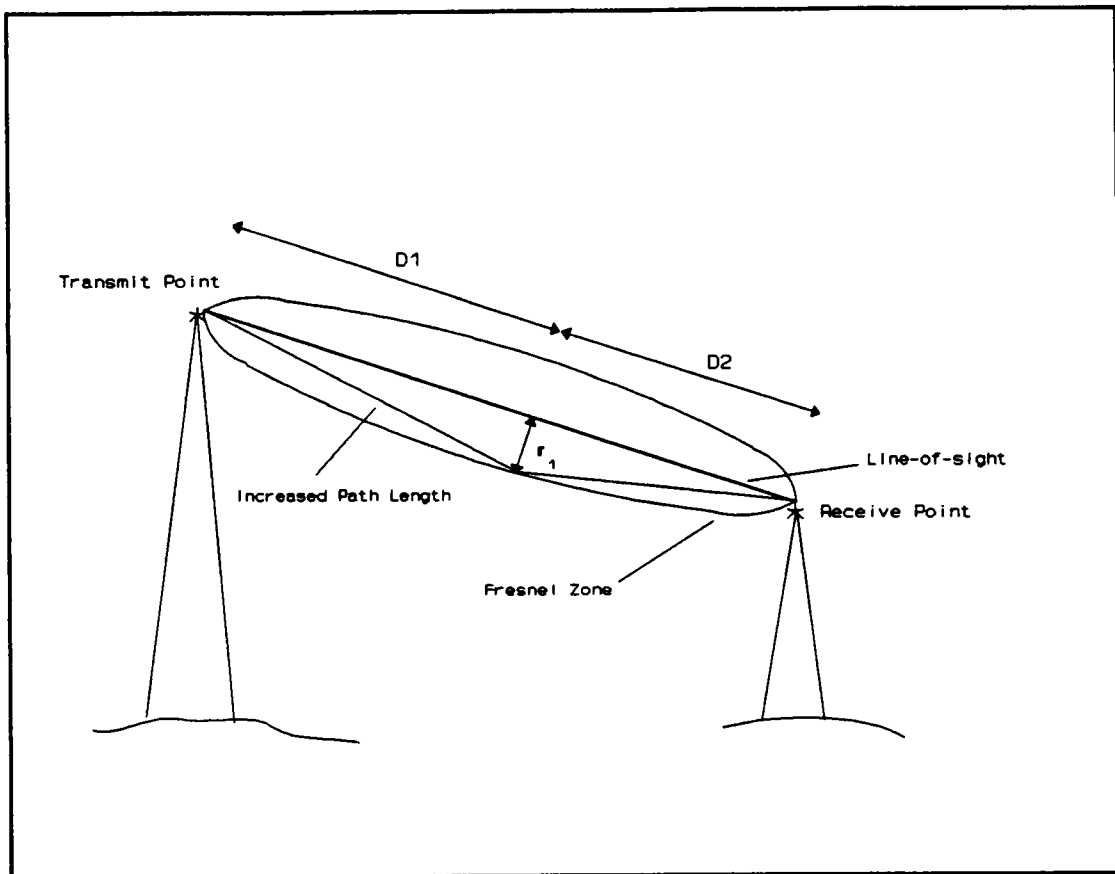


**Figure 6 - Computation of the Fresnel Radius**

where

$r_1$  = radius of first Fresnel zone

$D_1$  = Distance from the transmitter to the point under study

$D_2$  = Distance from the point under study to the receiver

$\lambda$  = Wavelength

For other Fresnel zones Equation 4 can be used to calculate the radius based on the radius of the first Fresnel zone.

$$r_n = r_1 \sqrt{n} \quad (4)$$

where

$n$  = number of Fresnel zone of interest

**Fresnel Zone** - A set of points, determined in such a manner that the sum of the distances from the two fixed points, namely, the transmitting and receiving points, has a constant path-length difference from the shortest path length between these two points, forms a prolonged ellipsoid with an axis passing through the two points. The region within the ellipsoid surface which gives the path-length difference ( $\lambda/2$ ) is called the Fresnel zone [6].

If an obstruction between the transmitter and receiver penetrates 50 percent of the first Fresnel zone, attenuation results. If an obstruction has a surface that coincides with the even-numbered Fresnel zones (predominantly the second) a reflected signal is produced that arrives at the receiver  $180^\circ$  out of phase, thereby causing cancellation of the desired signal. Surfaces coinciding with odd numbered Fresnel zones cause reflections where the reflected signal arrives at the receiver in phase with the desired signal [7]. For Frequency Modulated (FM) signals the reflections from odd numbered Fresnel zones add to the desired signal. A profile of a sample propagation path showing obstructions to the line-of-sight and 50 percent of the first Fresnel zone is provided in Figure 7.

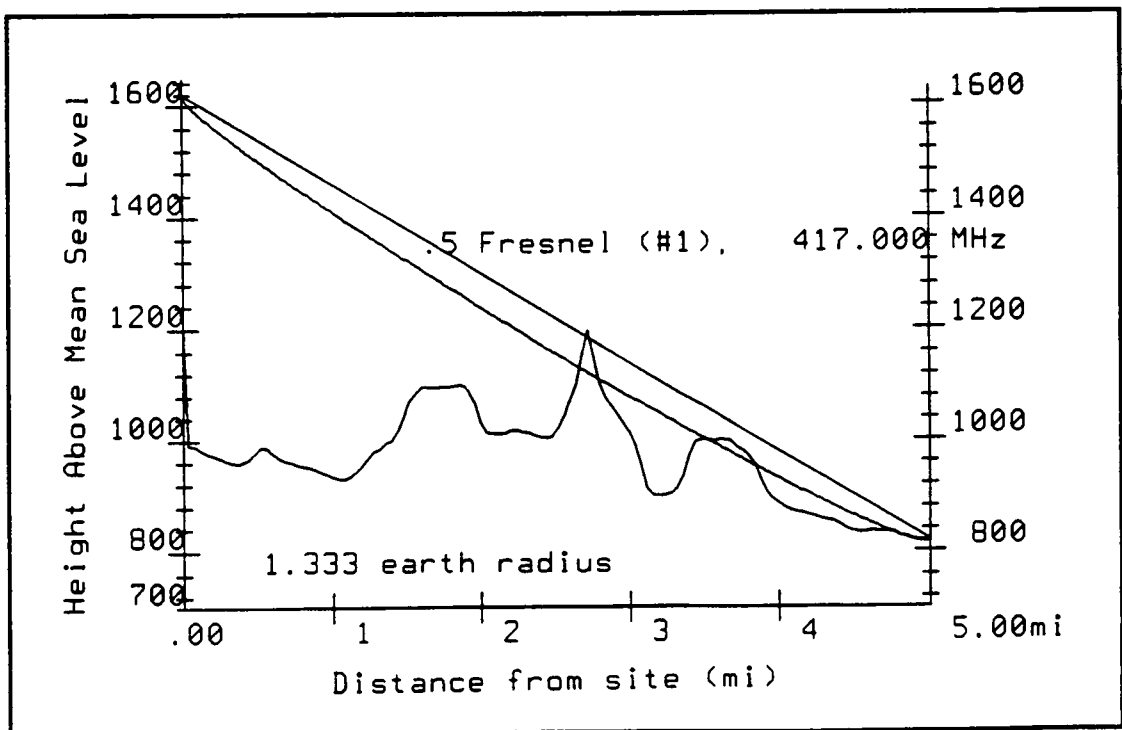


**Figure 7 - Sample Terrain Profile**

The inversion principle is used for signal strength predictions. This principle allows one to calculate the signal strength at various points in the field produced by a portable radio located at the top of a tower. This is equivalent to the radio being located out in the field talking back to the top of the tower.

## **THE MODEL**

A signal strength simulation and analysis software package is used to predict signal strength in the desired coverage area based on the characteristics listed above. This software, called the Terrain Analysis Package (TAP) from Softwright [8] is used to retrieve 3 second terrain data from the U. S. Geological Survey (USGS) database. This data is used as a basis for determining the shadowing the terrain causes radio signals. The model also incorporates specific performance parameters for the radio equipment to be used.

In a sparsely populated area with rough terrain, such as East Tennessee, perhaps the largest single performance degrading factor is terrain shadowing. In flat metropolitan areas, building obstructions generally cause the most degradation. TAP can be configured to emphasize those factors most important to a given analysis.

## **TERRAIN DATA AND RETRIEVAL**

TAP comes complete with 3 and 30 second terrain data provided by the USGS. The three second data is based on the World Geodetic System (WGS) 72 DATUM which uses a point in Kansas (the center of the lower 48 states) as the reference point. This data is the most accurate and is of the best resolution currently available for use with TAP. A completely new 30 meter database is being prepared by the USGS which allows better resolution. Although this data is available for East Tennessee, it is of a completely different format and does not function with current versions of TAP.

TAP comes complete with a module to retrieve elevation data from the USGS database. A radio system utilizes a signal source which can be viewed as radiating along radials from the point of origin. Unfortunately the USGS database consists of rectangular data that is arranged in neat rows and columns. Since the rectangular data points rarely fall directly on the points on the radials where data is needed, TAP interpolates between the data points that surround the required point.

Three different approaches are available for converting the rectangular data to radial data: *four point interpolation*, *twelve point weighted interpolation*, and *worst case*. As the name implies, the *four point* method interpolates between the four points nearest to the required point. This approach has a tendency to flatten peaks and raise valleys. A more accurate method is the *twelve point weighted interpolation* which uses the twelve nearest points to analyze trends. If the trend is upwards to the point, the slopes are considered and the result is a more realistic peak. The *worst case* method simply picks the highest value of the four closest points. The *worst case* method is intended for use in microwave path planning and is too conservative for Land Mobile Radio use.

## Resolution

When terrain is a degrading factor, it is important to use the proper resolution in the analysis. The best resolution available should be used in East Tennessee. With the many hills and bluffs it is possible to lose a few hundred feet in altitude by moving a few hundred feet in one direction or the other. These changes in altitude can have a significant impact on radio system performance. Using fewer elevation points than are available has a tendency to flatten the digital representation of the terrain which results in a higher predicted signal strength. Using more points than are available in the database just duplicates points and therefore increase processing time and file sizes.

Specific calculations are necessary to determine the resolution, in feet, of the three second terrain data for the latitudes and longitudes in the Oak Ridge area. The span of two minutes of latitude covers 2.3 miles. This results in 0.0576 miles per three seconds.

Likewise, two minutes of longitude spans 1.88 miles which results in 0.0469 miles per three seconds [9]. Therefore the best the three second data can do is one data point per 0.04 miles. This is the resolution that is used in most of the analysis.

Normally in land mobile radio system design a service provider is concerned with providing good coverage for mobile radio units over many square miles. These units are high powered and usually moving several feet per second. Therefore small pockets of low signal are not important and the resolution necessary for the analysis can be lower. It is difficult to analyze a large area to a high resolution due to the large number of data points involved. However, a typical local radio user is a maintenance person who is on foot and operating in a building within one of the facilities. It is not realistic to assume that his position will change by several hundred feet in a few seconds if an area of poor coverage is encountered. Any wide area radio system installed must provide good coverage for this type of user. To determine potential system performance it is necessary to look at the highest resolution signal strength contours available relative to the facility maps to determine in which buildings a user may have coverage problems.

#### **Chosen Terrain Data Retrieval Settings**

Since the best possible resolution is more important than computation time, the terrain data is retrieved at .04 mile increments using the *twelve point weighted interpolation* method.

#### **FIELD STRENGTH CALCULATIONS**

There are several algorithms available to calculate field strength at a specific point. These methods can be categorized as either statistical or analytical. This work is not intended to be an exhaustive survey of the various algorithms available in industry. It is provided to identify those readily available at the time of this work, why the particular one used was chosen, and how it applies to the specific problem at hand.

## Statistical Methods

Statistical methods include: FCC Part 72 Carey Curve and FCC Part 73 FM/TV Broadcast methods. These methods use Height Above Average Terrain (HAAT) to predict  $f(50,50)$  or  $f(50,10)$  curves for a given signal strength contour. These curves are useful in determining spacing of broadcast stations only. They are not effective in determining how well the area around a transmitter site is covered. These methods do not show any holes in coverage, just a rough outline of the desired signal strength contour. The notation  $f(50,50)$  indicates that in 50 percent of the sectors designated the specified signal level will be exceeded 50 percent of the time. A sector is a region (typically 4 to 20 wavelengths) over which a transmission loss distribution is constructed [10].

A statistical model falls short of detailed coverage predictions for two reasons: 1) Any terrain within the first two miles nearest the site is ignored. (It is assumed that a broadcast antenna is located high enough that this terrain is not a factor) and 2) Only the HAAT (not the individual undulations in terrain) is used in calculating the distance a signal will travel.

## Analytical Models

An analytical model, on the other hand, uses detailed information on the terrain to make a signal strength prediction at each desired point along radials from the transmitter sight. With an analytical model, it is possible to predict how signal strength increases and decreases as a result of the terrain. This type of analysis shows holes in the coverage as well as areas of strong signals. Two analytical methods used are Okumura and Bullington.

The Okumura method is based on extensive measurements taken by Yoshihisa Okumura [11]. These measurements were taken in Japan and are categorized into terrain type: urban, suburban, open, etc. This method makes it possible to account for specific area terrain type, terrain slope, and street orientation among others. The use of this method in East Tennessee is probably not accurate since the categories used in Japan are not indicative of this area. Tokyo is used as the baseline for urban data.

The Bullington method uses a more general approach and actually calculates a signal strength for a desired point based on local terrain obstructions of the Fresnel zone and line-of-sight. Any obstruction penetrating 50 percent of the first Fresnel zone will cause an attenuation which can be calculated based on how far into the Fresnel zone the penetration occurs. The Bullington model also considers diffraction of the signal as it passes obstructions, as well as diffraction loss and reflection caused by the curvature of the earth [12]. This method is numerically intensive because it must track all attenuations in a path, not just the one at a given point of interest.

### ***Bullington - The Model of Choice***

For East Tennessee, the most accurate method for determining signal strength is the Bullington analytical method. TAP applies the Bullington method in such a way that field calculations for individual points can be combined to produce signal strength contours. Using these contours it is possible to determine where holes in coverage are and where coverage for a given system is acceptable. TAP also allows this data to be viewed in many different ways, thereby completely demonstrating how well the area of concern is covered by a given system. Field threshold plots, reliability contours, and signal strength at specific points are all based on the output of the Bullington model and can be used together in a complete analysis.

### ***Summary of the Bullington Model***

In order to better understand the results of the TAP, it is useful to review how the Bullington model works. To perform the Bullington method for a given point, complete the following steps:

- \* Compute the elevation of the line-of-sight from the receiver to the center of the transmit antenna.
- \* Compute the elevation of half the first Fresnel zone for the line-of-sight path.

- \* Determine if terrain points penetrate the Fresnel zone calculated above. If so determine the ratio between the line-of-sight clearance of the obstruction and distance between the line-of-sight and Fresnel zone.
- \* Use the ratio acquired in the previous step to determine a loss value from Figure 10 of the Bullington paper [12] (provided in Figure 8).

The TAP implementation of the Bullington method steps down each radial at a specified height above ground level. A line-of-sight radial is drawn to the transmitter site and the elevation of the Fresnel zone is calculated for each point. The terrain elevation points between the point under study and transmitter are checked for Fresnel zone penetration. If no penetration occurs, free space loss is calculated and the next point is determined. If obstructions occur, an attenuation value is calculated for each obstruction. The signal strength for a point is the strength of the previous point minus free space loss plus a loss for each obstruction. Figure 9 compares a sample radial terrain profile to the signal strength calculated via the Bullington method for points along that radial. This figure clearly shows how the signal strength fluctuates with the terrain.

As the point of study traverses along the radial, the location of the terrain obstruction points change. Study points farther from the transmitter site may not see the same terrain features as obstructions as points closer to the site do. Figure 10 illustrates this with a single radial profile with line-of-sight drawn from two different points of interest. Terrain features that are obstructions for points at the end of a radial are not even taken into consideration for closer points since they are beyond the point of study. Also, since the spacing between data points is fixed and the spacing between obstructions is not, it is possible to have several data points affected by the same obstruction.

An algorithm is used to determine when an attenuation is caused by a new obstruction as opposed to a single large obstruction. TAP allows the user to specify if this determination is made based on an *inflection* method or *minimum distance between obstructions* method. The *inflection* method tracks the attenuation caused by obstructions. As an obstruction penetrates further into the Fresnel zone, the resulting attenuation increases. As the

obstruction leaves the Fresnel zone, the attenuation decreases. The point of inflection is defined as the point where the attenuation is higher than at the previous and next points. [8]. The peak attenuation is used as the attenuation caused by the obstruction, not the sum total attenuation from the entire obstruction. This is important since an analysis could be based on data points spaced hundreds of feet apart and the obstructions could be thousands of feet thick.

In reality the terrain and signal path are continuous. However, TAP and the Bullington model treat these as discrete points. The sample profile provided in Figure 10 is seen as a series of thin bars as in Figure 11. The model then treats each terrain elevation point that penetrates the Fresnel zone as a "knife edge" diffraction.

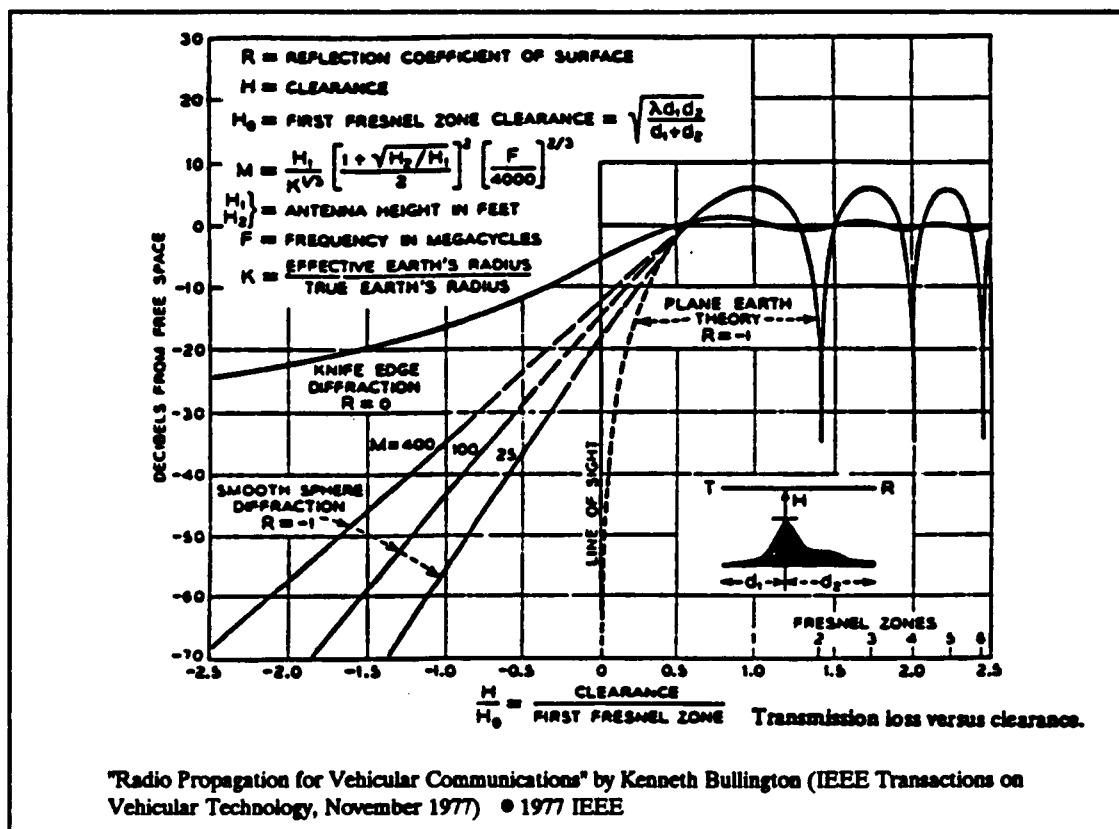


Figure 8 - Bullington: Radio Propagation

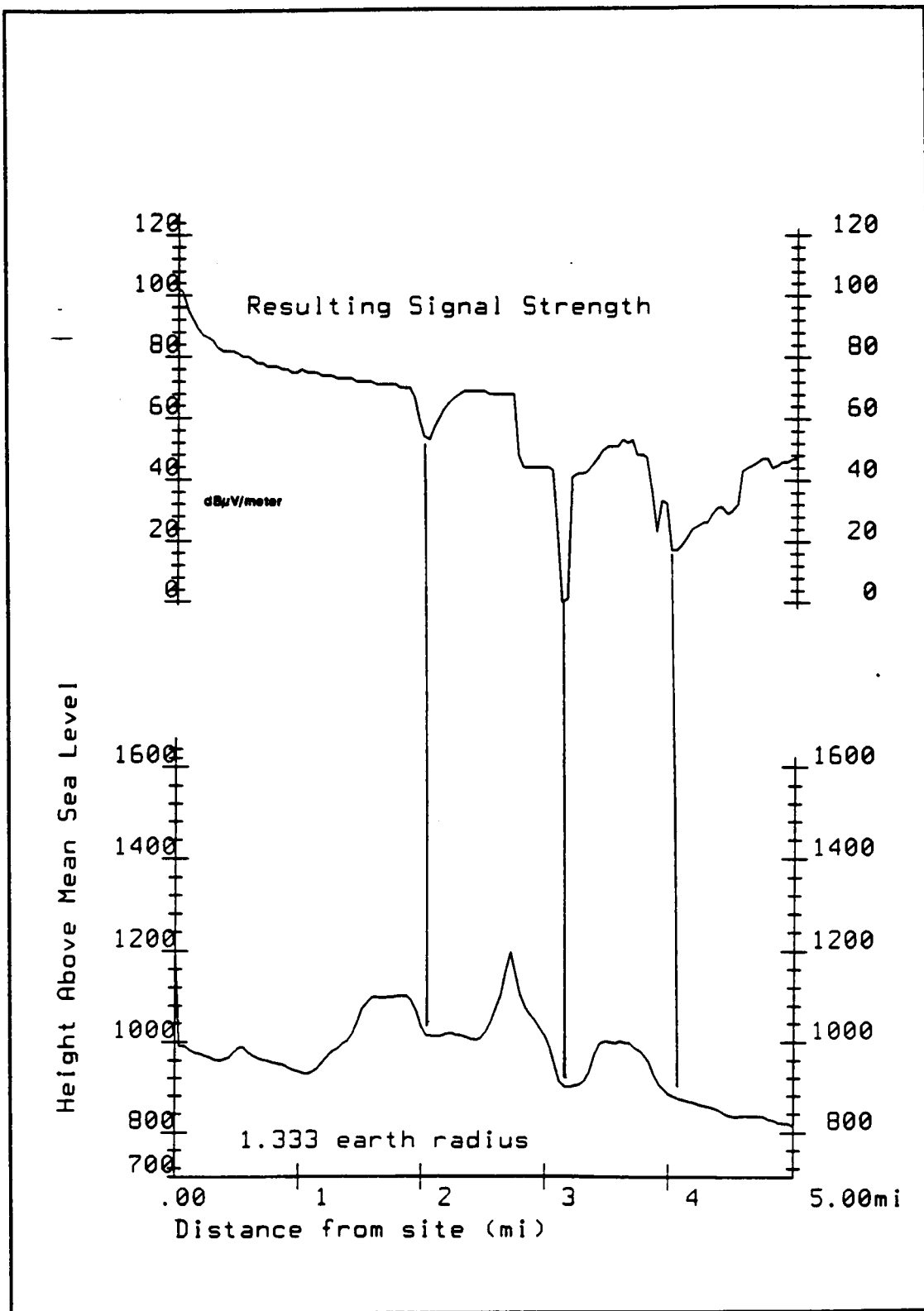


Figure 9 - Terrain to Signal Level Comparison

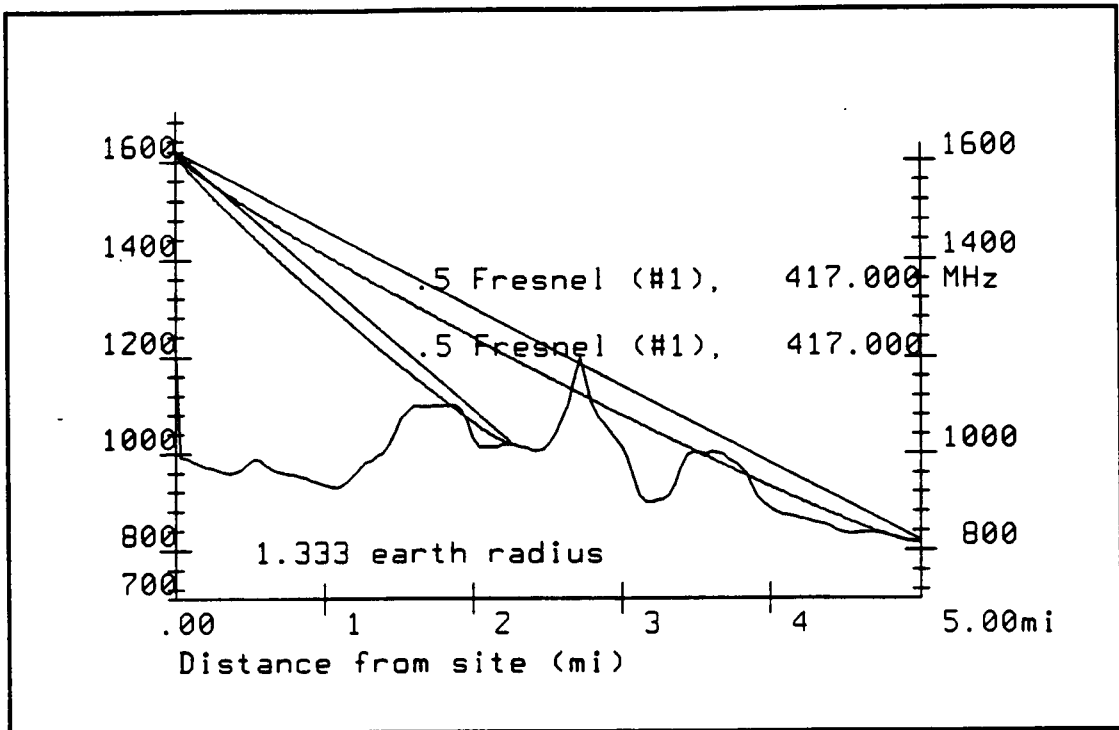


**Figure 10 - Sample Radial Profile from Multiple Study Points**

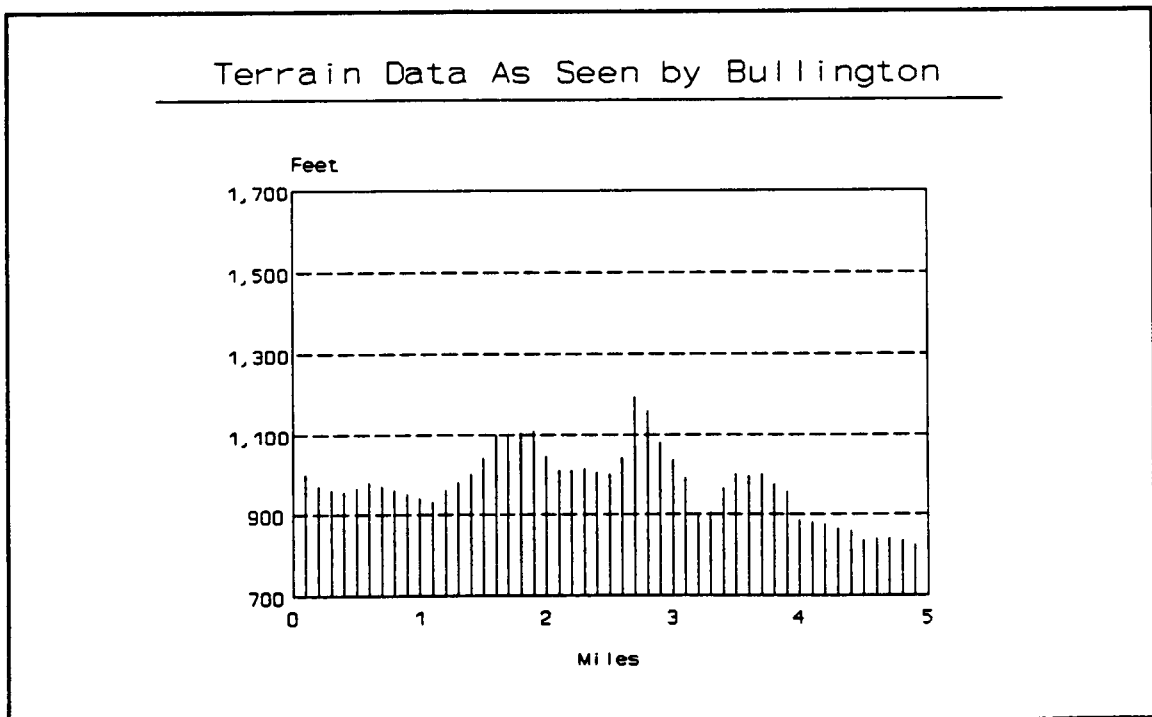


**Figure 11 - Discrete Terrain Profile**

The *inflection* method falls short for rolling hills to flat terrain in areas like Kansas where a single obstruction is easily taken for several obstructions. This results in too much attenuation being computed and therefore resulting in an unrealistically conservative analysis. The *minimum distance* method allows a limit to be set on how close obstructions can be. This prevents the same obstruction from being responsible for multiple losses. The engineer must know enough about the area in question to predict the minimum distance between obstructions. The TAP *minimum distance* method is not used in this analysis; the *inflection* method is used exclusively.

## BOUNDARY LINES

TAP provides a module that makes it possible to define and draw reference points and boundaries such as roads and political boundaries. This module is used to define the various facilities of interest relative to local streets. The two mile zones and five-mile sectors are also digitized using this module. It is then possible to plot out the different TAP results relative to these boundaries at various scales. Figure 12 shows the labeled boundary lines that are plotted with the various analysis plots. For clarity the labels are not shown on each of the signal plots that follow Figure 12.

## TAP OUTPUTS - A COMPLETE SYSTEM ANALYSIS

TAP software provides a number of possible ways to view system performance. No single output tells the complete story; therefore, it is necessary to look at system performance from a variety of angles and piece together the complete picture. TAP allows the system to be viewed in terms of; single point signal strength, shadow plots, reliability contours, field threshold plots, and signal strength contours. Each of these are used at various points in this report.

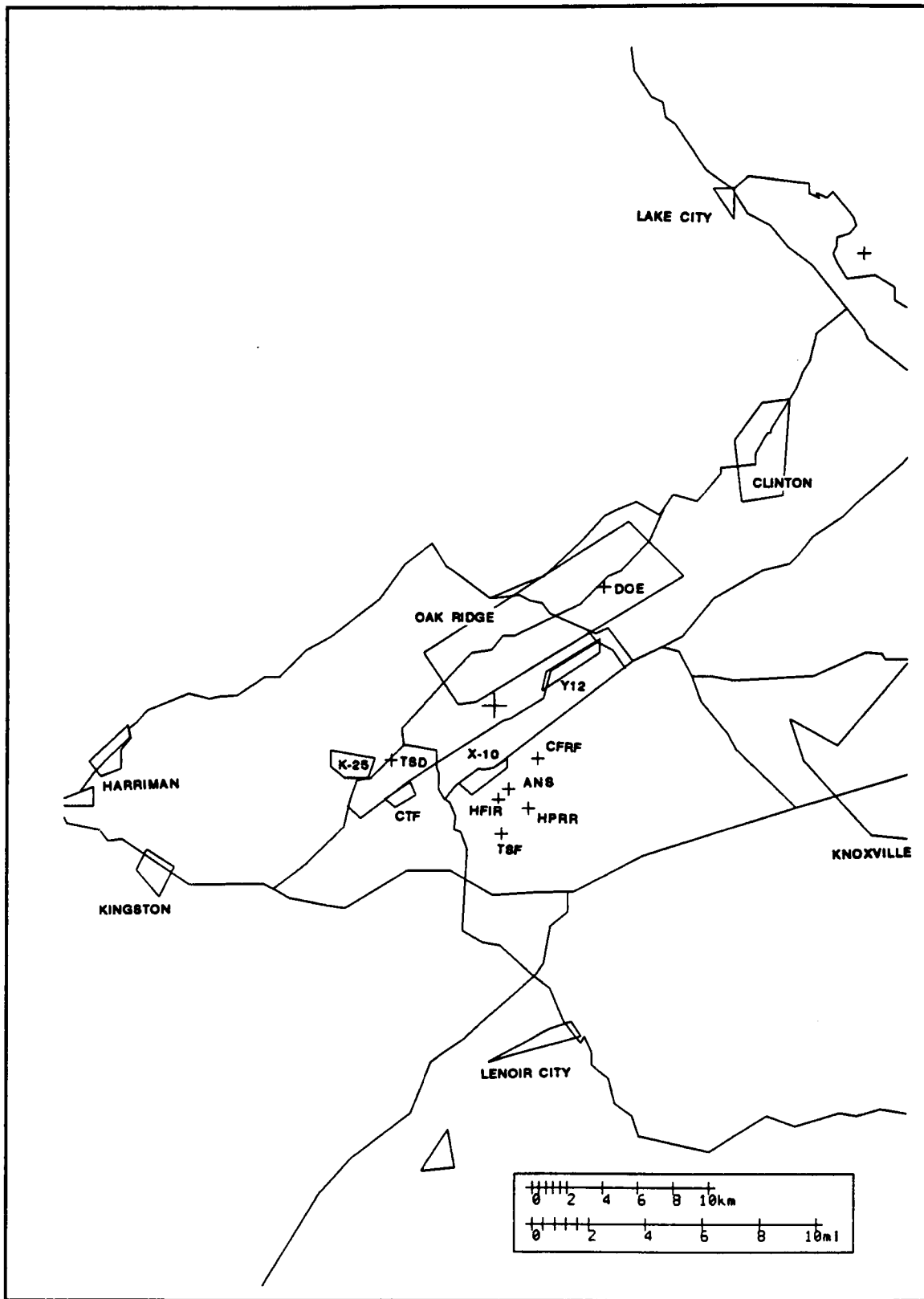


Figure 12 - Boundary Lines

## **Single Point Signal Strength**

The most basic result of the Bullington model is a single data point. All other possible outputs are groupings of these single points into other representations. It is occasionally useful to look at the signal strength prediction at a single point. This is the preferred method when working with a system limited to fixed locations. It may also be desirable to compare predictions with measured data at specific points.

## **Shadow Plot**

The shadow plot is a quick way to determine generally how well a potential site will cover the desired coverage area. The shadow plot is based on penetration of the Fresnel zone and blockage of the line-of-site. It is not a result of signal strength predictions. This plot allows a quick look at a site without a lot of computations. It is the first step in narrowing down several potential sites. Shadow plots are provided for each of the sites analyzed later in this report.

The drawback of a shadow plot is that it does not show any calculated signal strength - only blockage of the line-of-sight and Fresnel zone. Even though a signal has blockage, this does not mean adequate signals are not present for system operation. The converse argument holds for points far away from the site; just because there is no blockage, it does not mean adequate signal strength is present at that point.

This plot is good for getting a basic idea of system coverage and for quickly comparing several potential sites.

## **Reliability Contour**

Another useful analysis tool is the signal strength reliability contour. With this tool, it is possible to develop an understanding of the limits (or radius) of coverage of the potential system. The contour plotted is selected based on the intended receiver threshold and

output power of the desired transmitter. It is possible to include several contours on the same plot to show the repeater talk-out coverage alongside portable talk-back coverage from a given repeater site. A sample reliability contour is provided in Figure 13.

This type of plot is limited because it does not show areas of coverage outside the specified reliability contour. The reliability contour is determined by checking signal strengths along the radial from the transmitter site for points above the desired threshold. When the number of points above or equal to the desired level reaches the specified percentage of all points encountered to that point, the contour is drawn. It is possible for large pockets of coverage area to be ignored if they are separated from the site by an area of low signal strength. Holes in coverage within the contour are also not shown with this type of plot. This plot is useful for determining the overall radius of coverage from a given site.

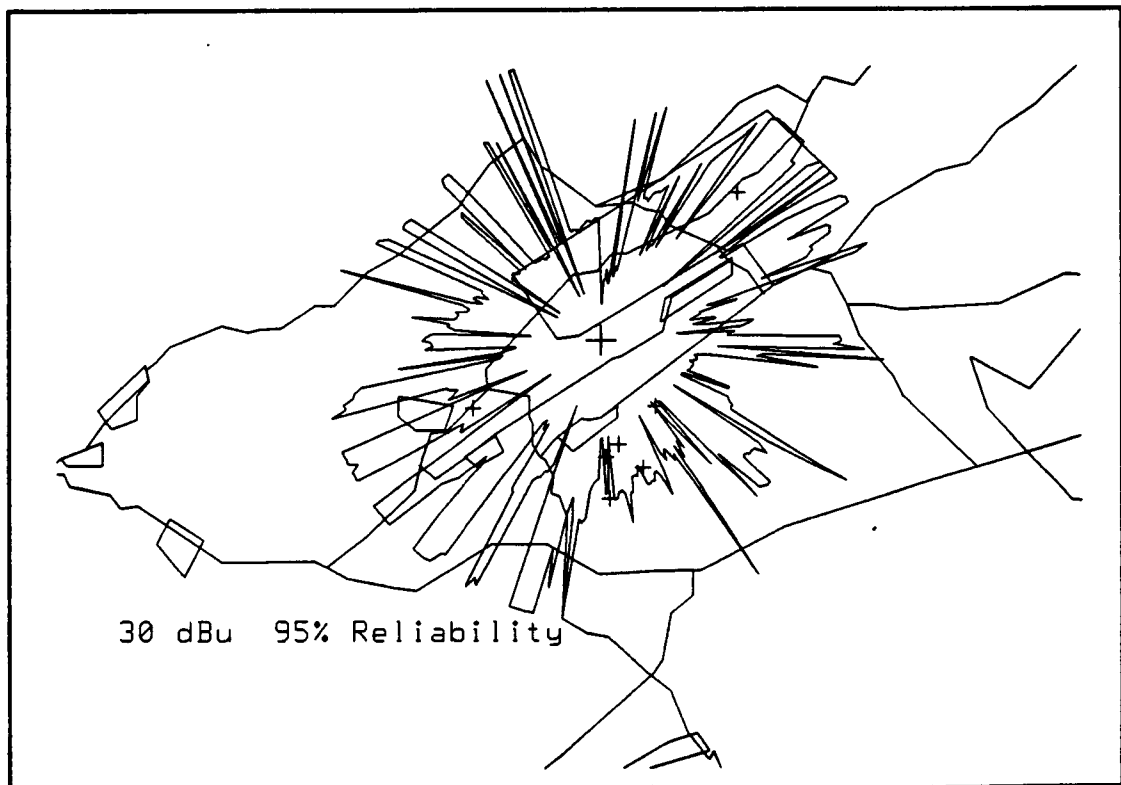


**Figure 13 - Sample Reliability Contour**

## Field Threshold Plot

A field threshold plot is another plot based on signal levels and complements the reliability contour. This plot shows areas of signal strength between levels  $x$  and  $y$ . It is possible to show several thresholds on a single plot. The threshold plot helps to identify those pockets of coverage beyond the reliability contour. Figure 14 is a sample field threshold plot.

The drawback of this plot is its resolution. The entire system coverage area can be viewed but only in terms of a few different signal levels. This results in potentially large differences between levels. Exactly what the level is at a given point can not be determined. It is only known that it is somewhere between two values, which may be 20 dB apart.

This plot is useful in developing an understanding of pockets of coverage beyond the radius of coverage defined in the reliability contour as well as areas of low signal within the reliability contour.

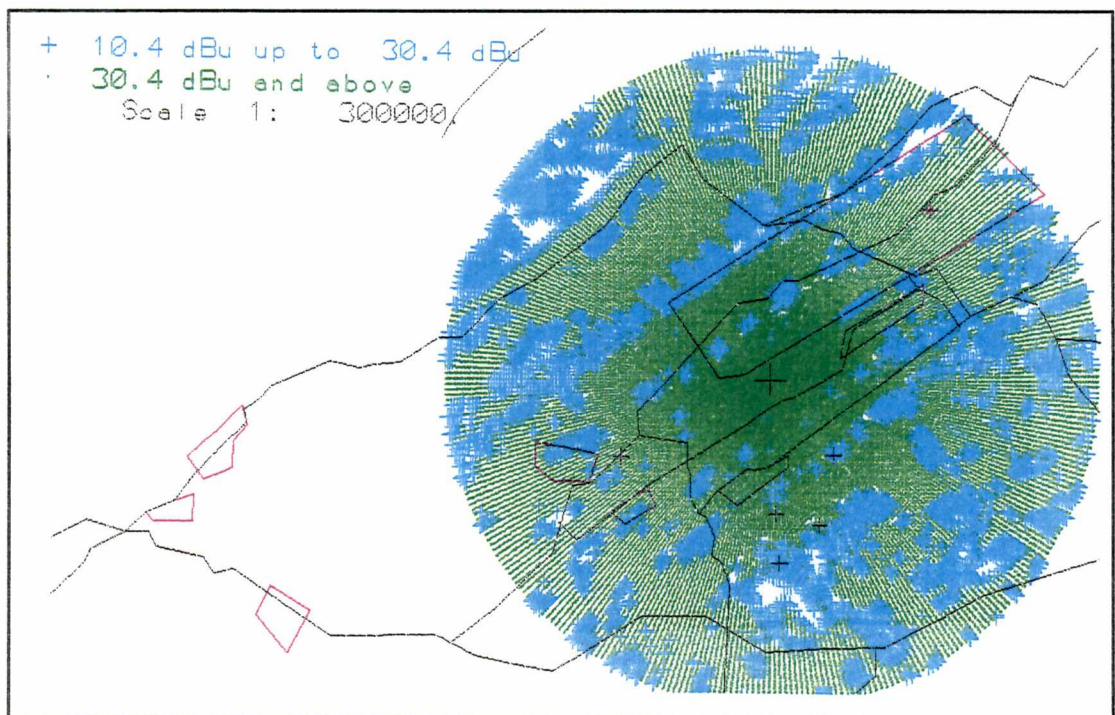


Figure 14 - Sample Field Threshold Plot

## **Signal Strength Contour Plot**

Perhaps the ultimate coverage plot is a signal strength contour plot showing all (or most) signal strength contours. Using TAP and the plotting software bundled with it (SURFER, by Golden Software [13]), it is possible to calculate closed contours of signal strength. The result is much like a topographic map. In fact, placing the resulting contours over a topo map of the same scale, it is possible to see which topographic features cause signal shadows. For this output, the highest resolution is desired to show the best detail. This is especially important for this analysis since specific building coverage is desired. High resolution in the contour plot can show which buildings are covered and which are not.

This plot is limited by its ability to obtain enough data for good resolution over the entire area of interest. SURFER is limited in the number of points it can use. As a result either the coverage area or the number of points under study in the analysis must be reduced. This issue is not a major concern for this effort. Since the DOE facilities in the Oak Ridge Reservation are localized to certain areas, it is possible to define specific areas of interest that are small enough to study with good resolution. Each major facility is bounded by a square and is shown in Figure 15. It is possible then to obtain high resolution terrain data for these areas and concentrate the Bullington analysis on these. A sample of a signal strength contour plot is provided in Figure 16 which is the specific area of interest around the Y-12 plant based on a portable talking back to the super-site. The procedure for producing this plot deserves some attention.

## **PIES AND SQUARES**

Since a signal radiates from its transmitter in all directions it is natural to work from the transmitter site outward along radials. The result is either a circular area (assuming radials are taken for the full 360 degrees) or a pie shape (assuming a limited number of radials are used). The shadow, reliability contour, and field threshold plots are well suited to the circular coverage area. In fact the reliability contour really needs a complete circle for

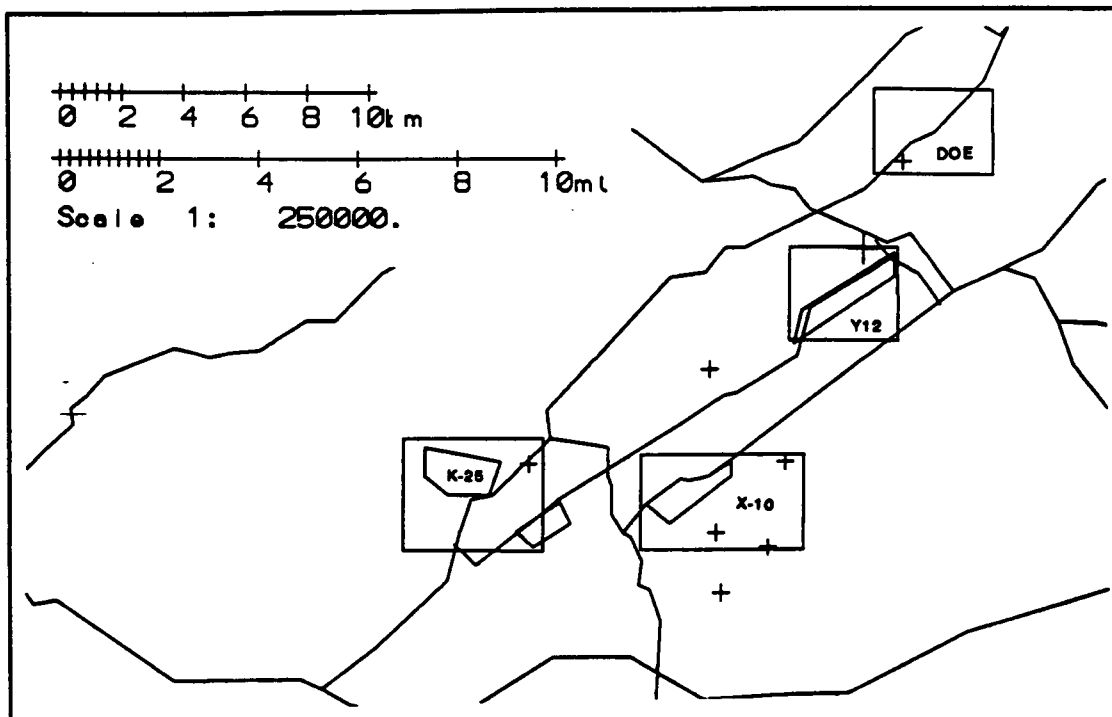


Figure 15 - Areas of Particular Interest

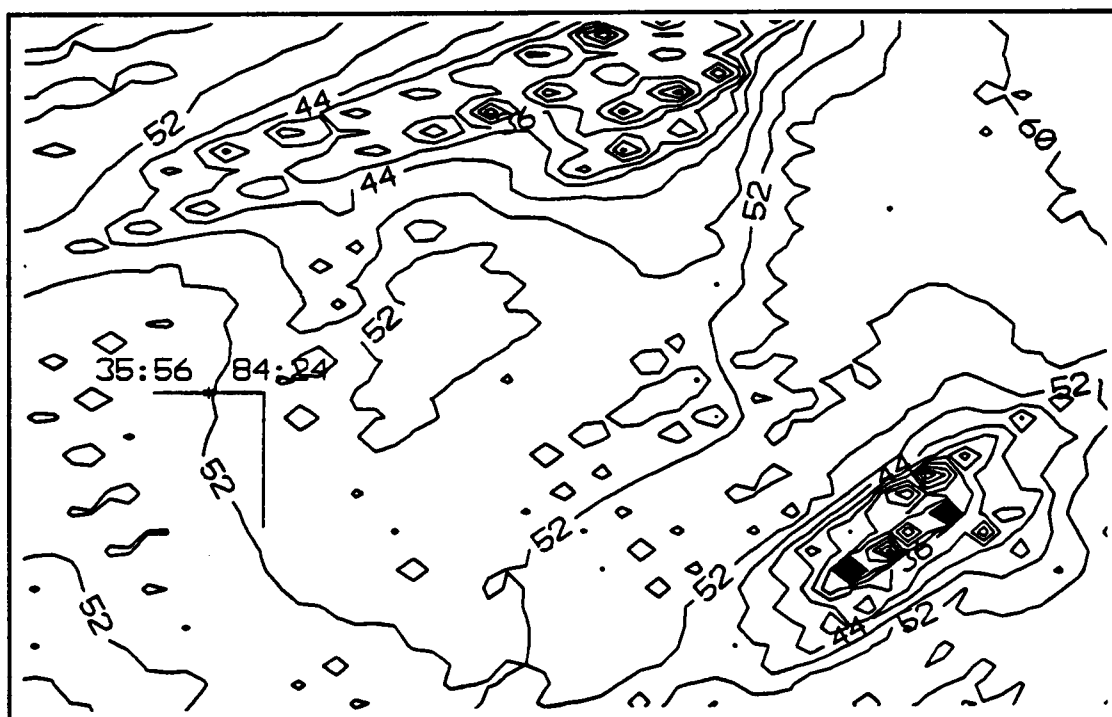


Figure 16 - Signal Strength Topographic Plot

accurate representation of the contour. However, the signal strength contours do not need a circular coverage area for good results.

TAP allows the user to define the coverage area in terms of a start, stop, and radial interval. These radials are then used by the TAP terrain and Bullington models to determine a signal strength value for each point along the radial. SURFER is then used to turn these pie-shaped areas into rectangular plots of the specific area under study.

The data points on the radials fan out from the transmitter site and are not equally spaced in a rectangular grid. To solve that problem SURFER provides a program (named GRID) to transform the pie-shaped data into a rectangular grid. Figure 17 shows a sample area of interest relative to the pie shaped area used by TAP.

It is necessary to define for GRID the rectangular area of interest. This must be done in terms of maximum and minimum values of  $x$  and  $y$  (GRID does not operate with latitude and longitudes). Since the radials are preset when defining the pie shaped region the angles necessary for calculating the  $x$ 's and  $y$ 's are readily available. First, the corners of the box must be measured where they touch the outer most radials, as shown in Figure 17. Next, use Equations 5 thru 8 to determine the maximum and minimum values of  $x$  and  $y$  for use in GRID. The resulting values for  $x$  and  $y$  are measured in miles.

$$x_{\min} = \text{upper}_{\text{corner}} \sin \beta_1 \quad (5)$$

$$x_{\max} = \text{lower}_{\text{corner}} \sin \beta_2 \quad (6)$$

$$y_{\min} = \text{lower}_{\text{corner}} \cos \beta_2 \quad (7)$$

$$y_{\max} = \text{upper}_{\text{corner}} \cos \beta_1 \quad (8)$$

where

*upper\_corner* and *lower\_corner* are radial distances from the site

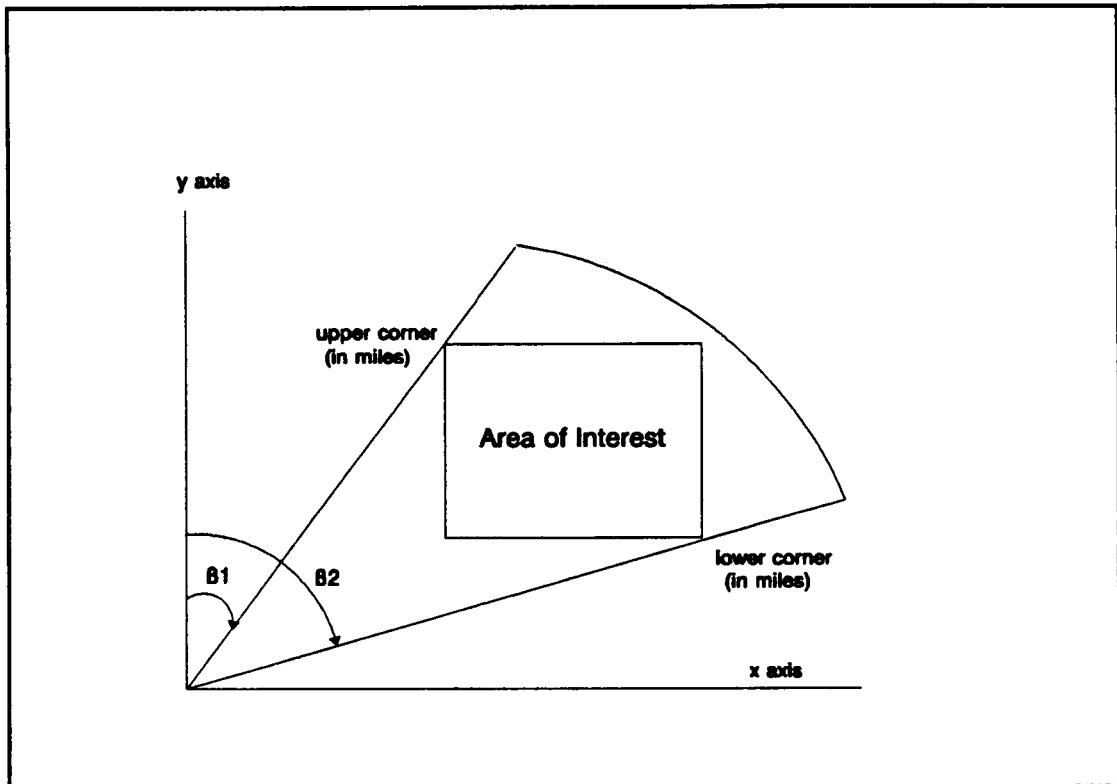


**Figure 17 - Rectangular Area of Interest**

The GRID program must interpolate between the data points in the area of interest to create the rectangular grid. GRID provides good flexibility in defining how the surrounding points affect the point of interest. Several interpolation techniques are provided: *inverse distance*, *Kriging*, and *minimum curvature*. *Kriging* is a regional variable theory technique that assumes an underlying linear variogram [13]. The *inverse distance* method is the preferred approach and is used with a weighting factor of two (the default). With this method all data points are considered when determining the value of a particular grid point; however, the effect of each point is weighted by the inverse of the square of its distance to the grid point [13].

Once a rectangular grid is available the SURFER program connects the signal strength values into closed contours. These contours are very useful in determining how well a given system covers the area of interest.

## **CHOSEN PROPAGATION ANALYSIS SETTINGS**

Each propagation analysis is highly dependent on antenna height, transmit power, and receiver sensitivity. Levels used for Effective Radiated Power (ERP) and receiver sensitivity used in the super-site analysis include all relevant factors. These factors are covered in the following paragraphs.

Typically the weakest part of communications is talkback from a portable radio to the repeater site. (In all cases where a portable radio will operate, a mobile radio, with its higher gain antenna and higher power output, will also operate.) For these reasons the mobile radio performance is not considered in this analysis.

### **Effective Radiated Power**

ERP is not simply the power produced by the transmitter. It is the product of the power into the antenna and antenna gain. Cable losses, transmit combiner losses, filter losses etc. all impact the amount of power presented to the antenna input and therefore affect the ERP.

### ***Repeater ERP***

On the existing radio trunking system the output power from each repeater was measured, both at the repeater and at the output of the transmit combiner. (A transmit combiner is used to allow all 5 transmitters to use the same transmit antenna.) The output from the transmitter with the lowest measured power out of the transmit combiner was 36 Watts.

This is the value that was used in the coverage analysis from the repeater out to the surrounding area. In addition to combiner output power the following factors are used in this analysis:

|                                            |         |
|--------------------------------------------|---------|
| Transmit Notch Filter Insertion Loss       | 1.0 dB  |
| Transmit Lightning Arrester Insertion Loss | 1.5 dB  |
| Transmit Jumper Cable Insertion Loss       | 0.3 dB  |
| Transmit Antenna Gain                      | 9.2 dBd |
| Transmit Antenna Cable Insertion Loss      |         |
| 450' cable length                          | 1.7 dB  |
| 530' cable length                          | 2.0 dB  |
| 630' cable length                          | 2.4 dB  |

The antenna gain can be expressed relative to an isotropic (dBi) or dipole (dBd) antenna. A notch filter is used in the trunking system transmit output to eliminate interference with another system. For the transmit cable length an extra 50 feet is assumed which is required to run between the building and tower base. Therefore a 400 foot antenna height requires a 450-foot cable length. The jumper cable is a smaller, more flexible grade cable used to connect to the equipment on the inside of the building. All cable insertion loss values are obtained from Andrew's HELIAX Coaxial Cable Loss Calculator software [14].

Using these values the calculated ERP for the repeater site out to the surrounding area is shown in Equations 9 thru 11 [8].

$$ERP_{rpt} = PWR_{out} + Gain - Losses \quad (9)$$

where

$ERP_{rpt}$  in dBW

$PWR_{out} = 36 \text{ W (measured)} = 15.6 \text{ dBW}$

$Gain = \text{antenna gain} = 9.2 \text{ dBd}$

$Losses = \text{includes the following line losses in dB}$

|                           |            |
|---------------------------|------------|
| Filter                    | 1.0        |
| Lightning Arrester        | 1.5        |
| Jumper Cable              | 0.3        |
| Feed Cable @ 450'         | <u>1.7</u> |
| 450 Cable Feet      Total | 4.5        |

Substituting into Equation 9:

$$ERP_{rpt} = 15.6 + 9.2 - 4.5 = 20.3 \text{ dBW} \quad (10)$$

then the *ERP* in watts for a 450 foot cable becomes

$$OUTPUT_{power} = 10^{\left(\frac{ERP_{ant}}{10}\right)} = 10^{\left(\frac{20.5}{10}\right)} = 106.5 \text{ Watts} \quad (11)$$

For this report a 400 foot antenna height (450 foot cable length) is used.

The maximum gain of the existing antenna is 9.2 dBd. This antenna has a uniform azimuth pattern, that is it has the same gain in all azimuth directions. The peak elevation gain occurs at an angle of zero degrees. It has been proven [15] that mounting an antenna on the side of a tower results in a distorted pattern. TAP provides a module developed by the Antenna Specialists Company to calculate the distorted pattern based on tower face dimensions, frequency, mounting configuration, and mounting distance away from the tower. This module also calculates the optimum distance from the tower to minimize distortion. This optimization routine is used to select the mounting distance and the resulting pattern can be reviewed. The pattern is then studied for optimum rotation to provide the most gain in the directions of the facilities where it is most needed. The resulting pattern is shown in Figure 18.

TAP allows the user to specify the maximum gain when determining ERP and then uses the gain pattern to reduce the ERP in each direction relative to this maximum gain. The result is signal strength predictions that take antenna pattern into account.

### ***Portable Radio ERP***

A portable radio does not have a significant amount of equipment between its amplifier and antenna like a repeater. For a Motorola System Saber III portable trunking radio (the only model currently in service on the trunking system) the power output is rated at 5 Watts. The radio's standard flexible antenna is measured at -4.8 dBd (-2.65 dBi) gain [16]. Therefore the ERP from a portable radio is shown in Equations 12 and 13 with

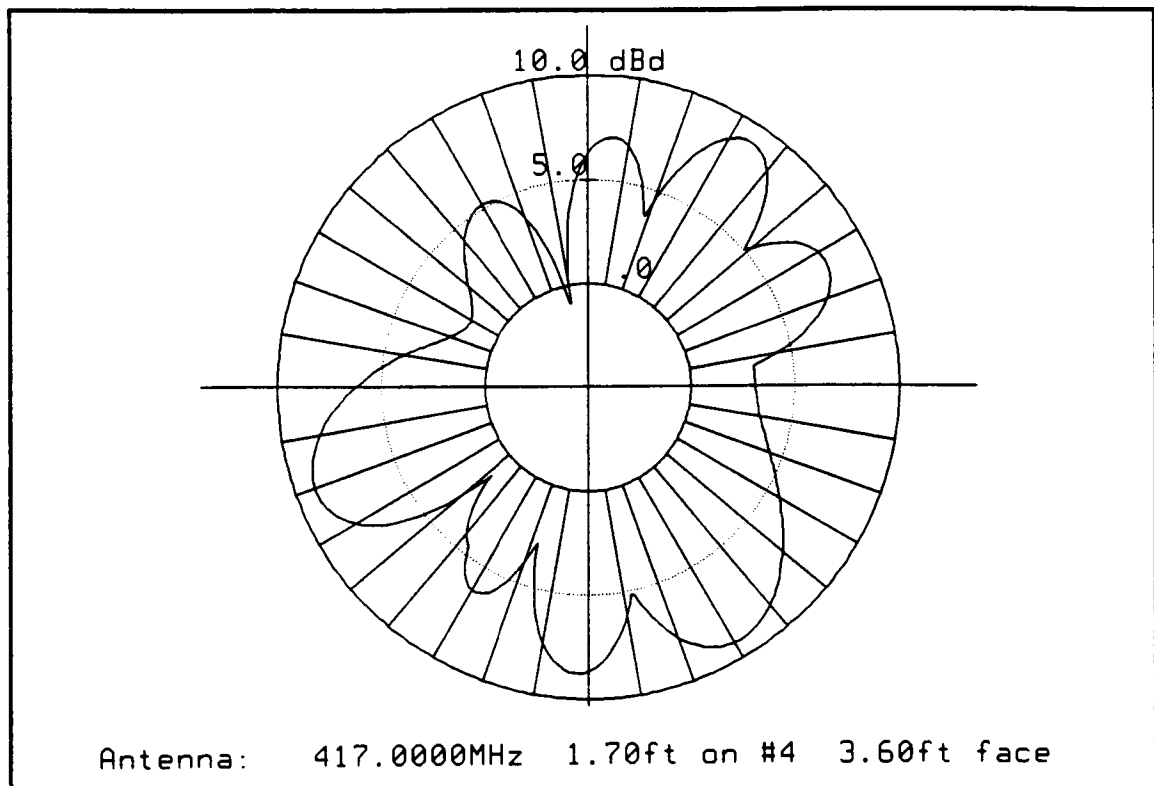


**Figure 18 - Antenna Pattern Distorted from Tower Mounting**

$ERP_{port}$  in dBW

$PWR_{out} = 5 \text{ W} = 7 \text{ dBW}$

$Gain = \text{antenna gain} = -4.8 \text{ dBd}$

$Losses$  are negligible

Substituting into Equation 9:

$$ERP_{port} = 7 - 4.8 - 0 = 2.2 \text{ dBW} \quad (12)$$

then the  $ERP$  in watts becomes;

$$OUTPUT_{power} = 10^{\left(\frac{ERP_{port}}{10}\right)} = 10^{\left(\frac{2.2}{10}\right)} = 1.7 \text{ Watts} \quad (13)$$

## **Receiver sensitivity**

One could spend days contemplating the receive signal strength necessary to activate a certain receiver. A radio wave propagating in the atmosphere is an electromagnetic field (or E-field) and is not normally handled in the same units of measure as it is when it is considered within the receiver circuitry. The E-field is usually thought of in terms of microvolts per meter, however, once inside the receiver circuitry volts or power is used [8]. A receiver's sensitivity is specified in terms of microvolts across a 50 $\Omega$  load. In addition to the required conversion of units, cable losses, antenna gains, etc. must be considered.

## ***Repeater Sensitivity***

The following factors were used in determining the receiver sensitivity used in this analysis:

|                                           |                    |
|-------------------------------------------|--------------------|
| Bandpass Filter Insertion Loss            | 1.5 dB             |
| Receive Lightning Arrester Insertion Loss | 1.5 dB             |
| Receive Jumper Cable Insertion Loss       | 0.3 dB             |
| Receive Antenna Gain                      | 9.2 dBd (11.4 dBi) |
| Receive Multicoupler Gain                 | 3.0 dB             |
| Optional Tower Top Preamplifier Gain      | 20.0 dB            |
| Receive Antenna Cable Insertion Loss      |                    |
| 450'                                      | 1.7 dB             |
| 530'                                      | 2.0 dB             |
| 630'                                      | 2.4 dB             |

For the existing trunking system a power splitter/amplifier combination (referred to as a receive multicoupler) is used to allow all channels to use the same receive antenna. A bandpass filter is required to keep the transmit frequencies from causing interference to the receivers. A preamplifier can be used at the top of the tower to provide extra sensitivity for weak signals, although one is not in use in the current system.

The rated sensitivity of the Motorola MSF 5000 repeaters is .25 microvolts. However the existing repeater's squelch levels are programmed above that. (Using a higher squelch setting ensures a clean signal is used and noisy borderline signals are ignored.) Therefore, the squelch level should be used as the required sensitivity. The highest squelch level of the

existing repeaters is .324 $\mu$ V or -9.8 dB $\mu$ V. This is the value used for repeater sensitivity in this analysis.

Using these values the calculated sensitivity for the existing repeaters is shown in Equations 14 thru 17 [8]. This is the signal strength a portable (or mobile) radio must produce at the receive antenna for proper repeater activation. For this report a 400 foot receive antenna height is assumed although heights of 480 and 580 feet are also investigated.

$$dB\mu V = dB\frac{\mu V}{meter} + gain(dBi) - losses - 20\log(f) + 29.8 \quad (14)$$

then

$$dB\frac{\mu V}{meter} = dB\mu V - gain(dBi) + losses + 20\log(f) - 29.8 \quad (15)$$

where

$dB\mu V$  = receiver sensitivity (-9.8 for 0.324  $\mu$ V squelch setting)

$dBi$  = dBd + 2.2

$f$  = 417 MHz, the center of the radio transmit band

$gain$  = 11.4 dBi

$losses$  include multicoupler gain, filter, cable, and arrester losses  
(2.0 dB total without preamp -18.0 with preamp)

$$dB\frac{\mu V}{meter} = -9.8 - 11.4 + 2.0 + 20\log(417) - 29.8 = 3.5 dB\frac{\mu V}{meter} \quad (16)$$

without a tower top preamplifier or:

$$dB\frac{\mu V}{meter} = -9.8 - 11.4 - 18.0 + 20\log(417) - 29.8 = -16.5 dB\frac{\mu V}{meter} \quad (17)$$

with a tower top preamplifier. These are the signal strengths required at the receive antenna to activate the repeater.

### *Portable Sensitivity*

The Saber III has a programmable squelch. The service manual for these radios specifies that this should be set for .35 microvolts or better for 12 dB Standard Signal-to-Noise Ratio (SINAD) [17]. Therefore this is the required signal threshold that is used. As with the ERP calculations for the portable, there is not much that needs to be considered with the portable required receive signal. The same -4.8 dBd (-2.7 dBi) antenna gain is used.

Using these values the calculated sensitivity for the portable radios is shown in Equations 18 and 19. This is the signal strength a repeater must produce at a portable's receive antenna for proper radio operation.

$$dB\frac{\mu V}{meter} = dB\mu V - gain(dBi) + loss + 20\log(f) - 29.8 \quad (18)$$

where

$$dB\mu V = -9.1 \text{ for } .35 \mu V \text{ receiver}$$

$$gain = -4.8 \text{ dBd} = -2.7 \text{ dBi}$$

$$loss = 0$$

$$f = 407 \text{ MHz, the center of the repeater transmit band}$$

then

$$dB\frac{\mu V}{meter} = -9.1 + 2.7 - 0 + 20\log(407) - 29.8 = 15.9 \text{ dB}\frac{\mu V}{meter} \quad (19)$$

### **Receiver Thresholds and Building Penetration**

The above calculations show the minimum signal required to activate the system. The Bullington analysis calculates the signal strength from transmitter to receiver assuming both are outside. A building penetration loss must be added to these levels to predict where in-

"Standard Signal-to-Noise Ratio (SINAD) - The Ratio of: the power of signal-plus-noise-plus-distortion to the power of the noise-plus-distortion at the test load." [18]

building coverage is provided. The factor used for building penetration is greatly debated among experts in the industry. The exact attenuation that a building will cause is highly dependent on the construction of the building. As Table II shows, the floor the radio user is on also greatly affects this attenuation [19]. For this analysis, a 27 dB building loss is assumed.

Adding this 27 dB factor to the receiver sensitivities calculated above yields the indoor equivalent values provided in Table III. This building loss factor is added directly to the receiver sensitivity values to provide the signal strength necessary assuming the transmitter is indoors. Table III summarizes the signal strength values required at the repeater antenna for outdoor and indoor equivalent, with and without preamps, for the various antenna cable lengths.

TAP provides an opportunity to define buildings to be used as obstructions in the Bullington analysis. TAP treats these building obstructions like knife edge obstructions made of rock. It is not necessary to create a building obstruction database and include them as obstructions since a healthy building loss margin is used. Using both the building obstructions and a 27 dB building loss factor would be "double taxing" the signal strength and would be too conservative.

**Table II - Building Losses**

---

| <i>Measured losses inside building (in dB)</i> |              |              |
|------------------------------------------------|--------------|--------------|
| <i>Floor</i>                                   | <i>VHF</i>   | <i>UHF</i>   |
| <i>Basement</i>                                | <i>-34</i>   | <i>-27</i>   |
| <i>1st</i>                                     | <i>-29.5</i> | <i>-23.5</i> |
| <i>3rd</i>                                     | <i>-26</i>   | <i>-20</i>   |
| <i>5th</i>                                     | <i>-23</i>   | <i>-15</i>   |
| <i>10th</i>                                    | <i>-12</i>   | <i>-3.5</i>  |
| <i>14th</i>                                    | <i>-7.8</i>  | <i>+2</i>    |

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From "Two-way Personal Radio System Design", General Electric Company

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**Table III - Receiver Sensitivity Summary**

| Required Signal Strength (in dBμV/meter) |                   |       |       |       |
|------------------------------------------|-------------------|-------|-------|-------|
| REPEATER                                 |                   |       |       |       |
| Antenna Cable Length                     |                   | 450'  | 530'  | 630'  |
| No Preamp                                | OUTDOORS          | 3.5   | 3.7   | 4.1   |
|                                          | INDOOR EQUIVALENT | 30.5  | 30.7  | 31.1  |
| Preamp                                   | OUTDOORS          | -16.6 | -16.3 | -15.9 |
|                                          | INDOOR EQUIVALENT | 10.5  | 10.7  | 11.1  |
| PORTABLE                                 |                   |       |       |       |
| OUTDOORS                                 |                   | 15.9  |       |       |
| INDOOR EQUIVALENT                        |                   | 42.9  |       |       |

### The Weak Link Verified

As previously stated the weak link in an LMR system is the portable radio talking back to the repeater. Now that the ERP and sensitivities have been calculated one can summarize this mathematically. As summarized in Table III, the repeaters are most sensitive at 450 cable feet (3.5 dBμV/meter) and the portable is much less sensitive at 15.9 dBμV/meter, a difference of 12.4 dB (using the outdoor sensitivities calculated in Equations 16 and 19). This difference is more than compensated for by the additional ERP available in the repeater (106.5 Watts versus 1.7 Watts). The difference in ERP in dB is shown in Equation 20.

$$ERP_{diff} = 10 \log \left( \frac{1.7 \text{ Watts}}{106.5 \text{ Watts}} \right) = 18.1 \text{ dB} \quad (20)$$

Therefore, the repeater has a 18.1 dB - 12.4 dB = 5.7 dB advantage over the portable in reaching its intended receiver. The portable is the weak link after all.

## **SELECTING A SUPER-SITE**

All of the tools and assumptions have now been reviewed. It is time to apply them to determine if it is possible to cover the entire area from a single site and, if so, where it should be located. Is it possible just to pick a convenient place and build a tower? Site selection is a fundamental element in ensuring the proper operation of this type of system; it is not possible to just randomly pick a site and expect it to work.

### **SITES ANALYZED**

Each existing DOE repeater site in the reservation (except Buffalo Mountain) is analyzed for possible wide area coverage. None of them provides coverage adequate to be designated as the super-site. Buffalo Mountain is not studied due to its distance from the area of interest which would result in equipment maintenance and protection concerns.

The elevation provided for each site is the elevation at the base of the tower. In each case, a 400 foot tower is assumed. For moderately high towers the driving cost factor is painting and lighting required to avoid air traffic accidents. Towers below 200 feet are not required to meet any special Federal Aviation Administration (FAA) requirements unless they are located near an airstrip. Towers above 200 feet are required to be properly painted and/or lighted. Requirements for marking and lighting become more stringent at 150 foot increments [20]. A tower height of 400 feet was arbitrarily selected as a good starting point, but not so high as to be prohibitively expensive.

It is not realistic to do a complete analysis on each potential site. One tower height was used to screen out potential sites. That is not to say that a potential site could not work with a tall enough tower. Using the same tower height for all screening helps to determine the best overall site. It may not be the only possible site but should be the best of those tested.

A shadow plot was produced for each potential site as discussed below. A receive antenna height of 5 feet and a frequency of 417 MHz were used for screening for each site. Remember, a shadow plot simply tells where the signal line-of-sight and Fresnel zones are blocked by obstructions. In these figures clear line-of-sight is represented by a green period (.), blocked Fresnel zone is shown as a blue asterisk (\*) and blocked line-of-sight is shown as white space ( ).

After a site is selected the tower height is adjusted to determine what was optimal. Details are provided in the discussion of the selected site.

### **Existing Repeater Sites**

The following repeater sites are developed radio repeater sites on the Oak Ridge Reservation. Each is analyzed for suitability as a super-site.

#### ***Chestnut Ridge***

The repeater site at Chestnut Ridge is located just west of Y-12 at 35:57:38N latitude and 84:17:15W longitude with an elevation of 1110 ft. It is a nice modern facility. The coverage of K-25 is very poor. Large areas of "no" coverage are shown in the shadow plot of Figure 19, one of which passes right through the middle of the plant.

#### ***Melton Hill***

The Melton Hill repeater site is a favorite of many radio users in the area. The repeater site is located at 35:54:34N latitude and 84:18:19W longitude with an elevation of 1307 feet, which is the highest point in a several mile radius. This site has given area wide coverage to several VHF networks for many years. The facility has always been well maintained and is particularly attractive as a super-site for these reasons. However, it does not provide adequate coverage to Y-12, which is shadowed by Fanny Knob. Figure 20 is a shadow plot from Melton Hill.

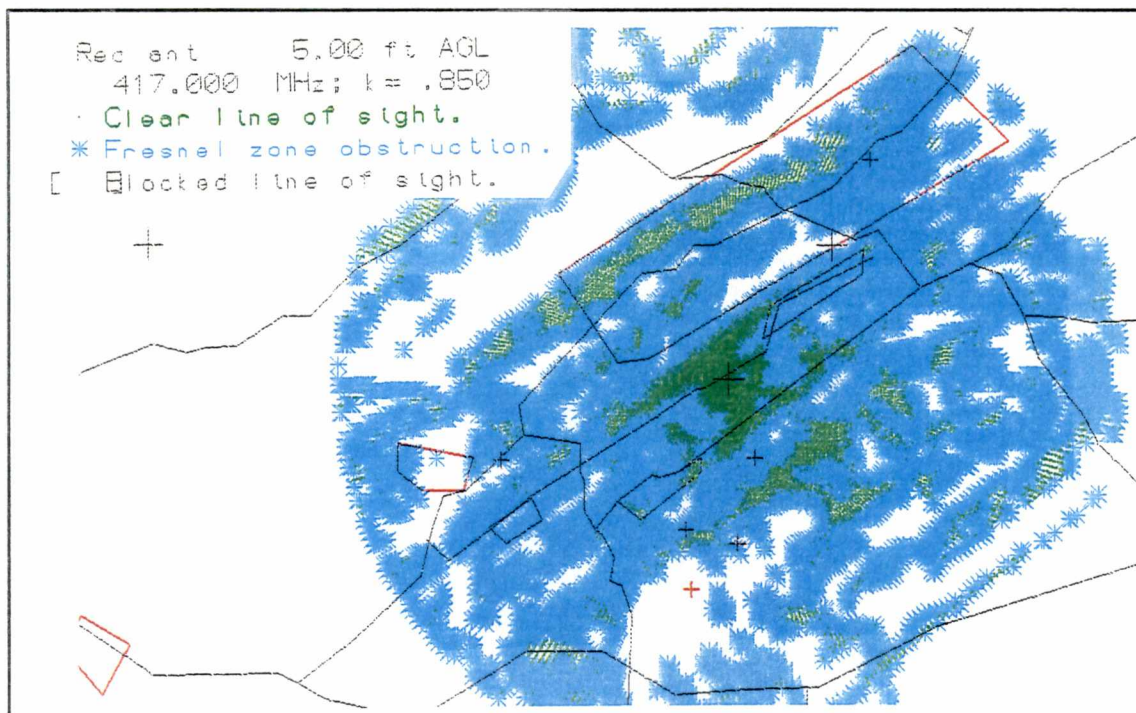


Figure 19 - Shadow Plot from Chestnut Ridge

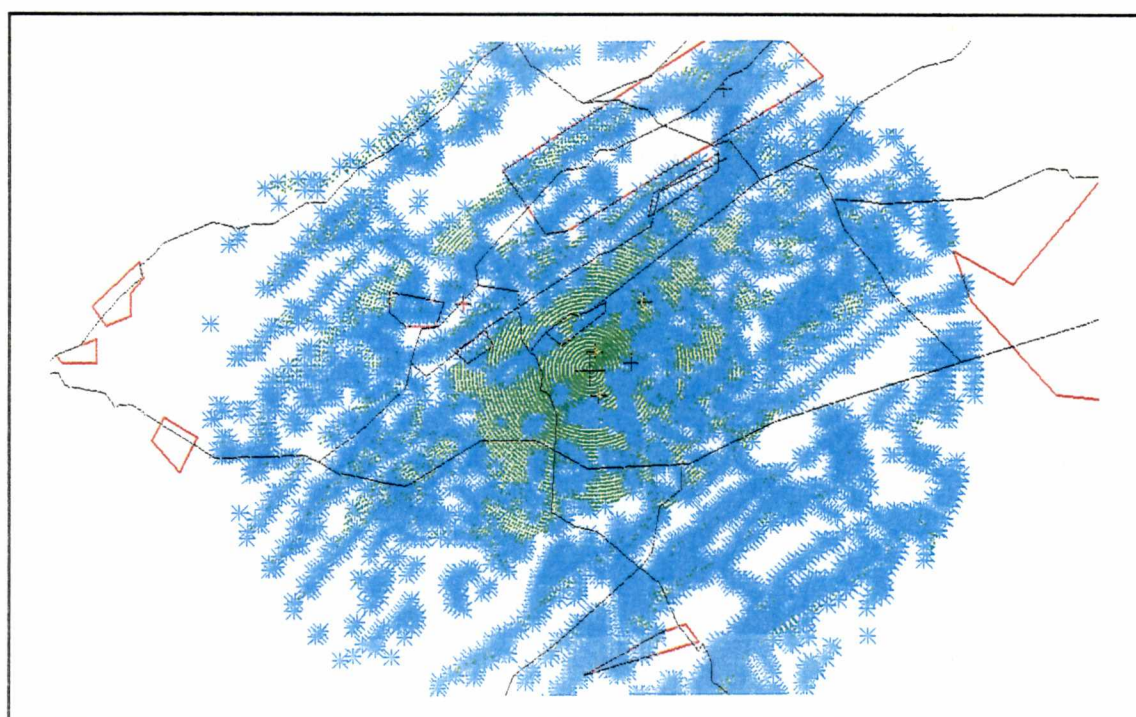


Figure 20 - Shadow Plot from Melton Hill

### *McKinney Ridge*

McKinney Ridge is the main repeater facility at K-25. The Repeater site is located at 35:56:32N latitude and 84:22:55W longitude with an elevation of 1010 feet. This is an excellent site for K-25 but does not provide good coverage to the other facilities as shown in the shadow plot of Figure 21. Y-12 and X-10 are completely shadowed by Pine and Chestnut Ridges.

### *Polecat Ridge*

Polecat Ridge is a local name for Chestnut Ridge on the south side of Y-12. The repeater site is located at 35:58:55N latitude and 84:15:20W longitude with an elevation of 1077 feet. This site is excellent for Y-12 systems that must be protected as it is inside the fenced area. It does not provide coverage to K-25 as the shadow plot of Figure 22 clearly shows.

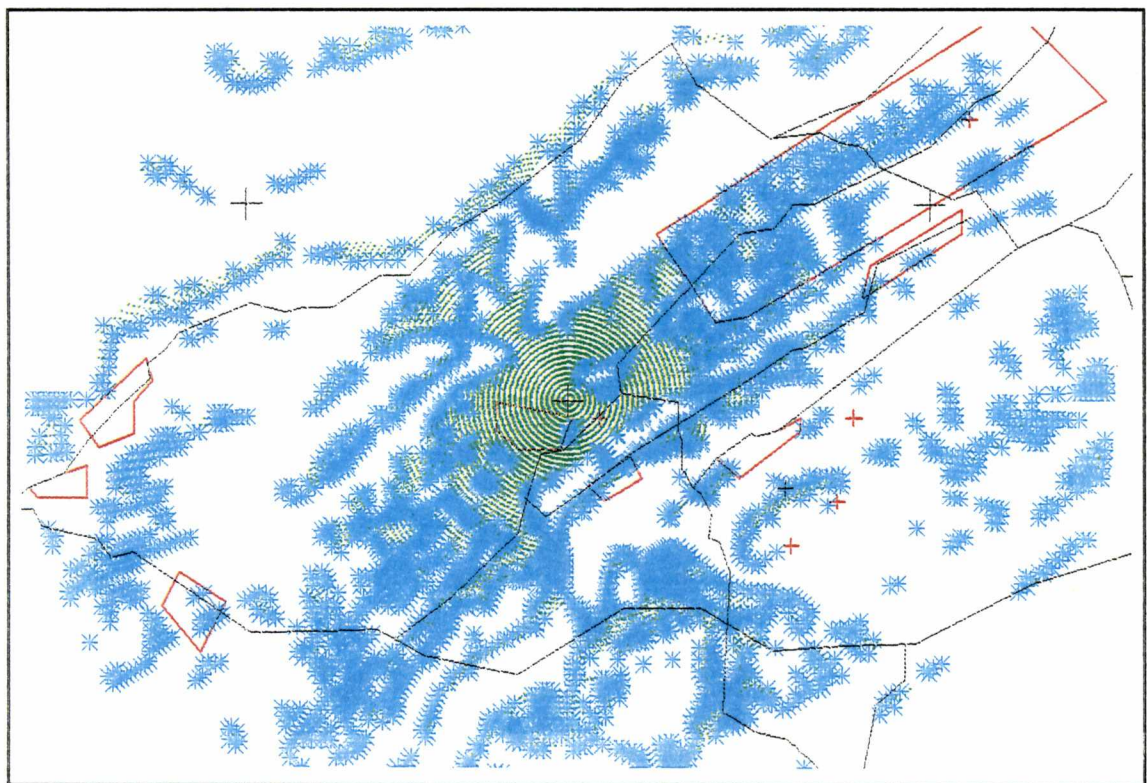


Figure 21 - Shadow Plot from McKinney Ridge

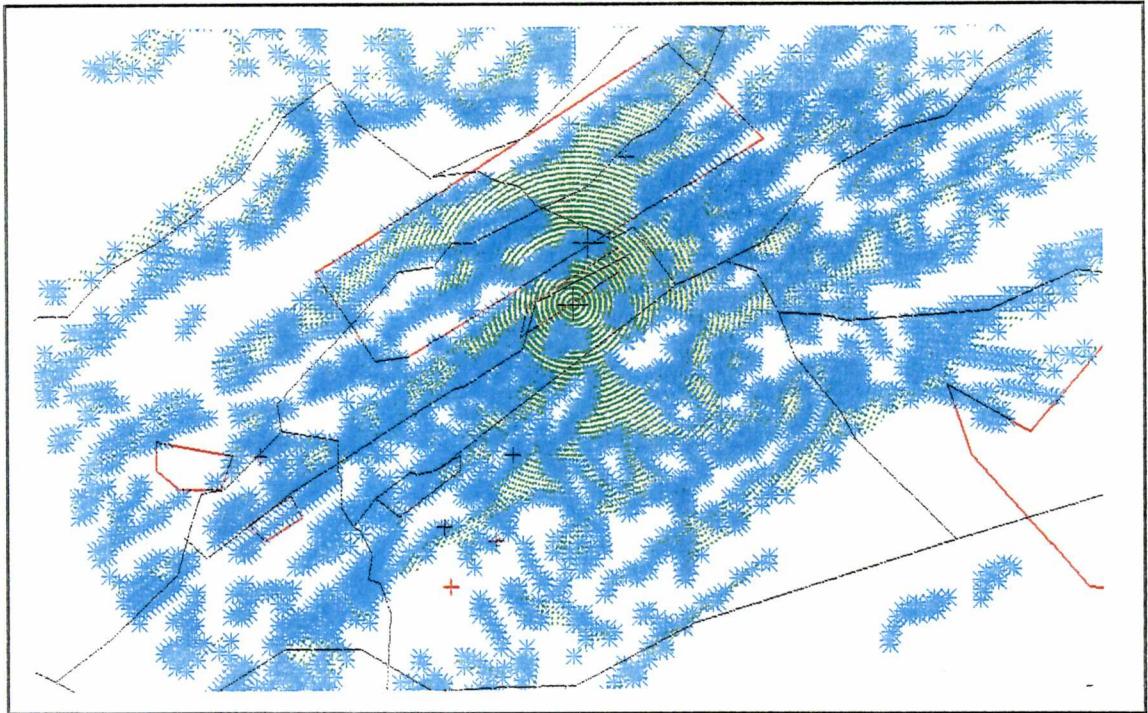


Figure 22 - Shadow Plot from Pole Cat Ridge

### *Pine Ridge West*

The Pine Ridge West repeater site is located along Pine Ridge just north of Y-12 at 35:59:41N latitude and 84:14:57W longitude with an elevation of 1180. This is the site where the trunking system currently resides. The current tower is 180 feet. As with all sites located at Y-12, K-25 coverage is not provided. Figure 23 demonstrates this site's limitations.

### *Pine Ridge East*

A separate analysis is not performed for Pine Ridge East, also known as the 'water tower,' since it is located so close to Pine Ridge West. The coordinates of this site are 35:59:50N latitude and 84:14:41W longitude.

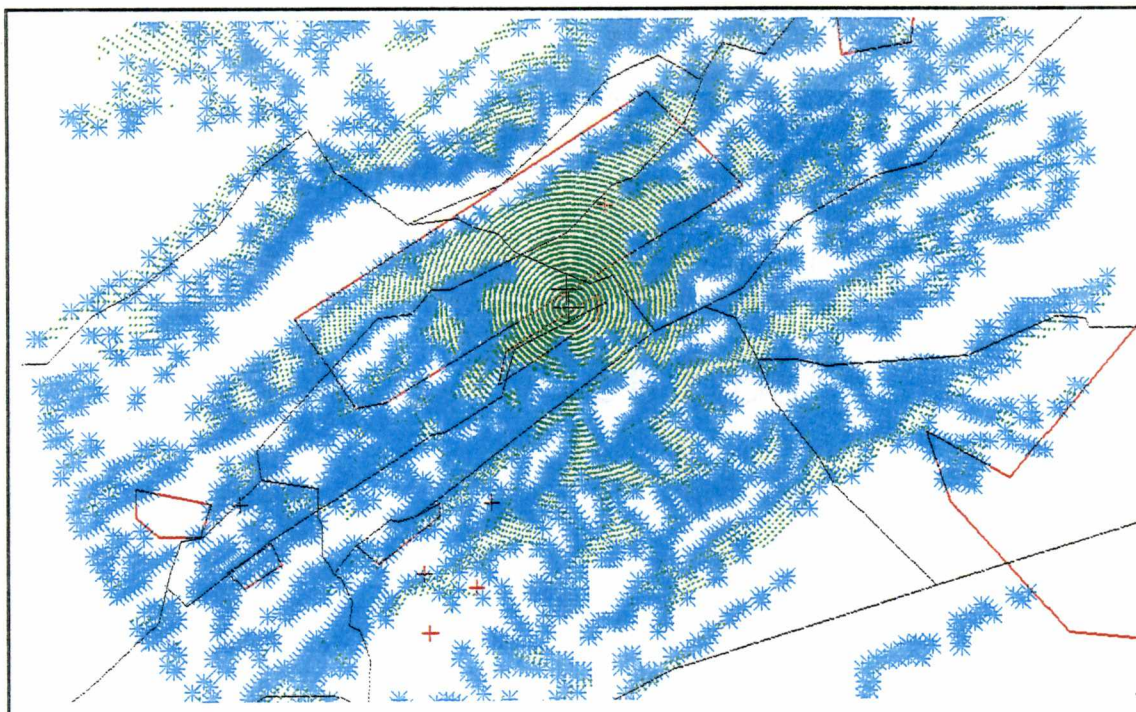


**Figure 23 - Shadow Plot from Pine Ridge West**

### ***Pine Ridge at K-25***

There is an unused repeater site on Pine Ridge just south of K-25. The Repeater site is located at 35:55:08N latitude and 84:23:13W longitude with an elevation of 1090 feet. As the shadow plot of Figure 24 shows there is a region of blocked line-of-sight in each of the Y-12 and X-10 facilities as well as much of Oak Ridge.

### **Potential New Sites**

The following sites are potential sites and are undeveloped.

### ***Fanny Knob***

This was the first in a series of non-existing repeater sites explored. It is a relatively high peak just south of Y-12. It is located at 35:58:24N latitude and 84:15:39W longitude with

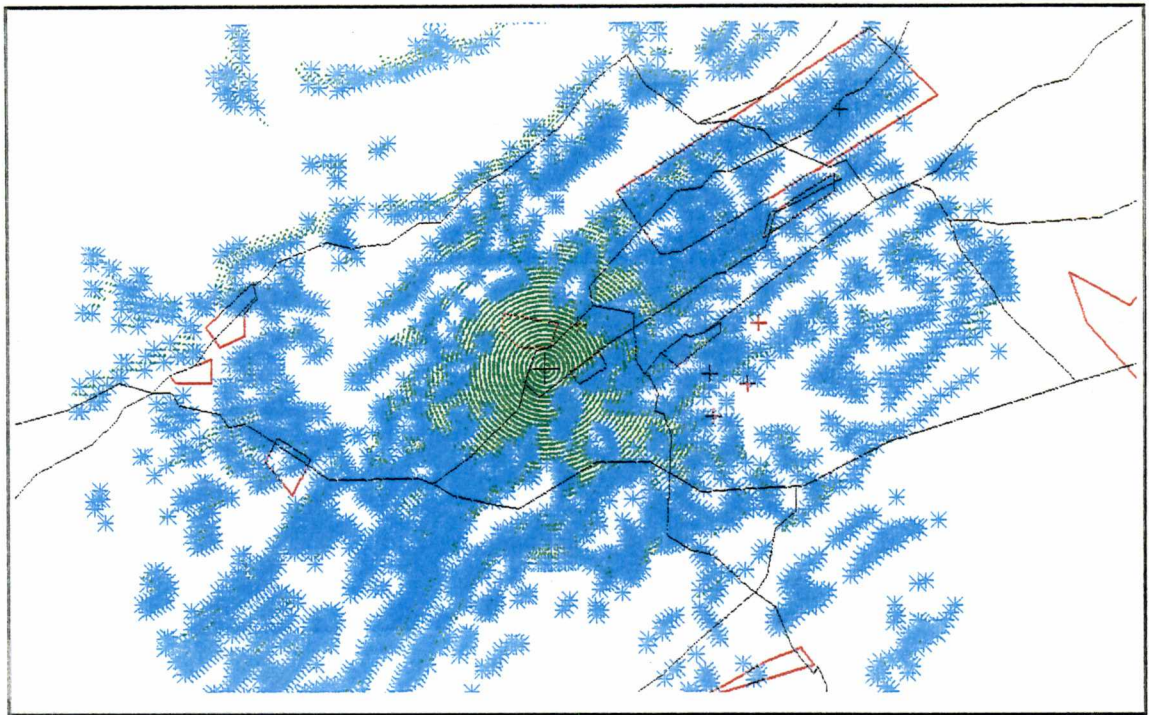


**Figure 24 - Shadow Plot from Pine Ridge at K-25**

an elevation of 1260 feet. This site provides poor coverage to K-25 as the shadow plot of Figure 25 demonstrates.

### ***Dumbo***

This site obtained its nickname due to the fact that the Disney character Dumbo had a trunk. It is actually located on a peak on Pine Ridge that is shaped like a duck. It is located at 35:57:03N latitude and 84:19:46W longitude with an elevation of 1120 feet. This site provides truly great coverage to K-25 as shown in the shadow plot, Figure 26. A more detailed analysis is performed for this site for signal strength at Y-12. A signal strength topographic plot, Figure 27, shows portable coverage has a shadow at Y-12. Figure 27 is color coded to show areas of indoor coverage (no contours), areas of indoor coverage if a tower top preamp is used and outdoor coverage without a preamp (light blue), outdoor coverage with or without a preamp (purple), outdoor coverage with a preamp but no coverage without (dark blue), and no coverage (red).

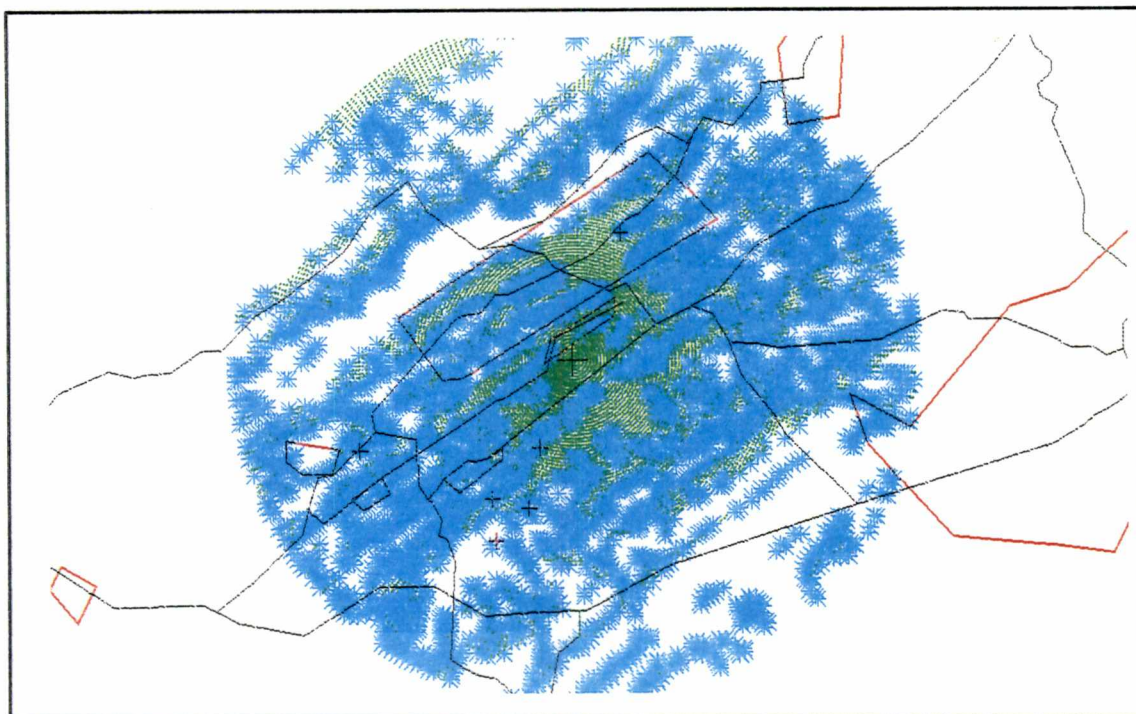


Figure 25 - Shadow Plot from Fanny Knob

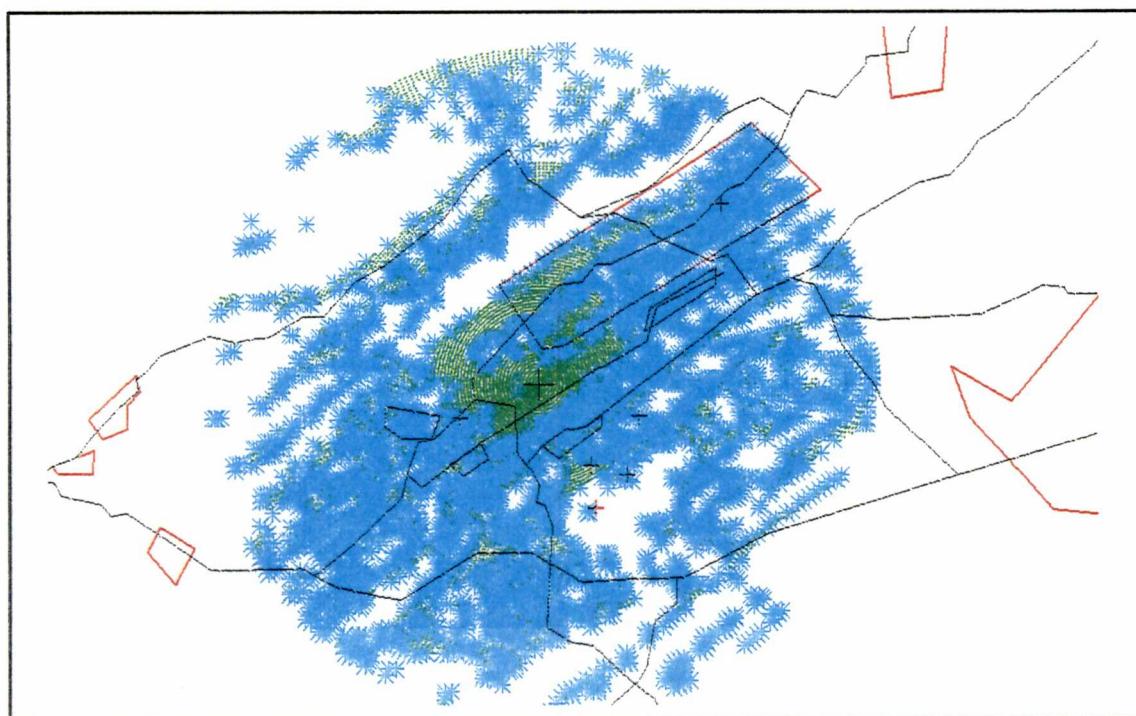


Figure 26 - Shadow Plot from Dumbo

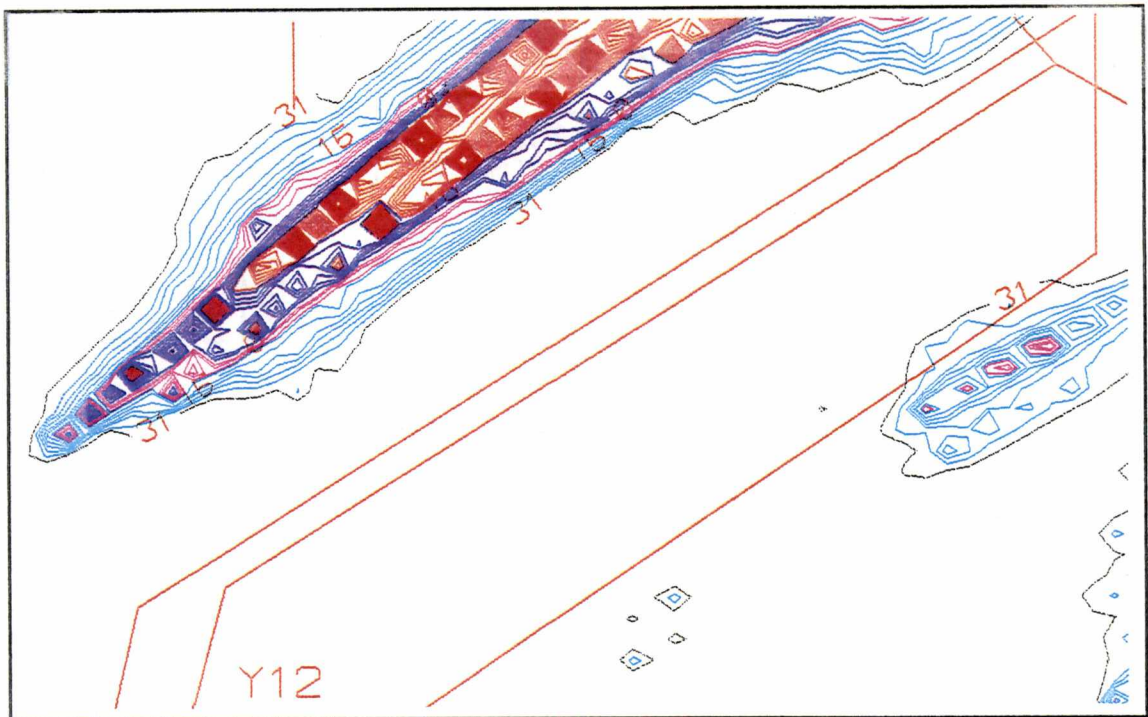


**Figure 27 - Signal Strength Topographic Plot of Y-12 from Dumbo**

### ***Bear Creek***

Moving east on Pine Ridge from Dumbo towards Y-12 the next peak is selected. There is no special reason for the nickname 'Bear Creek' other than that the Bear Creek valley and road are nearby. This site is located at 35:57:20N latitude and 84:19:15W longitude with an elevation of 1140 feet. Figure 28, the shadow plot, suggests the coverage from this site is at least as good as from Dumbo. A more detailed analysis of this site (shown in the signal strength topo plot of Figure 29) shows the shadow at Y-12 is reduced, although not gone. Figure 29 uses the same color scheme as Figure 27.

### ***The Dump***

Moving further east on Pine Ridge to just west of the Roane/Anderson county line another high peak is found. This site is located at 35:57:53N latitude and 84:18:19W longitude near

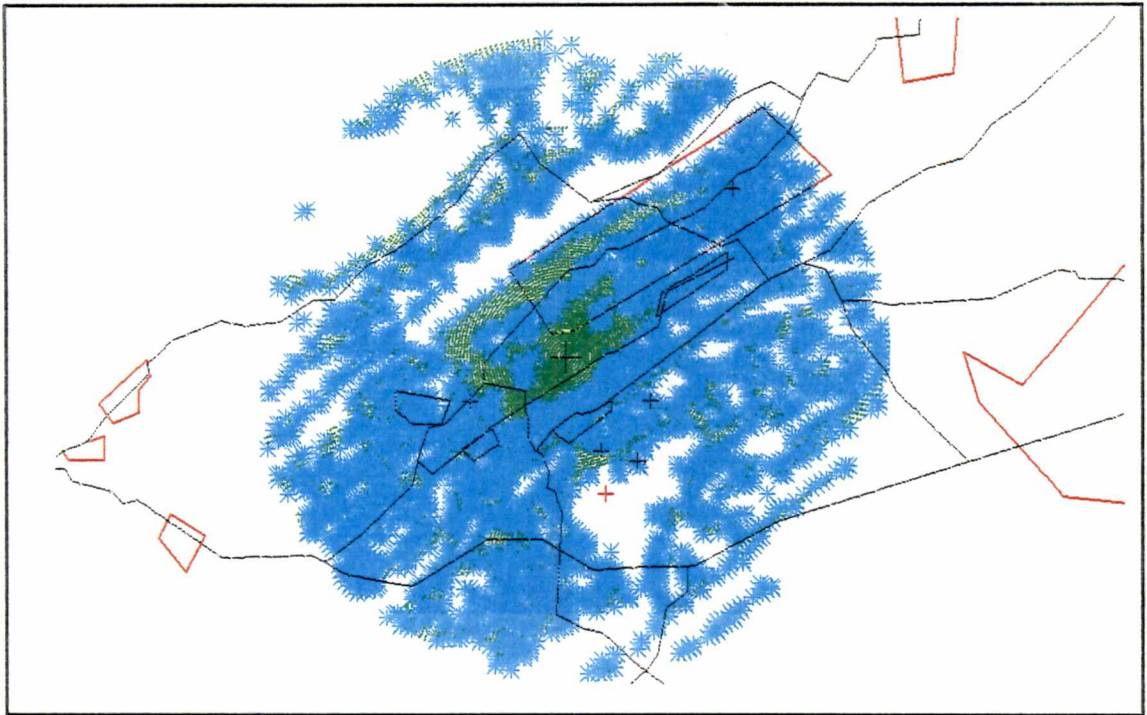


Figure 28 - Shadow Plot from Bear Creek

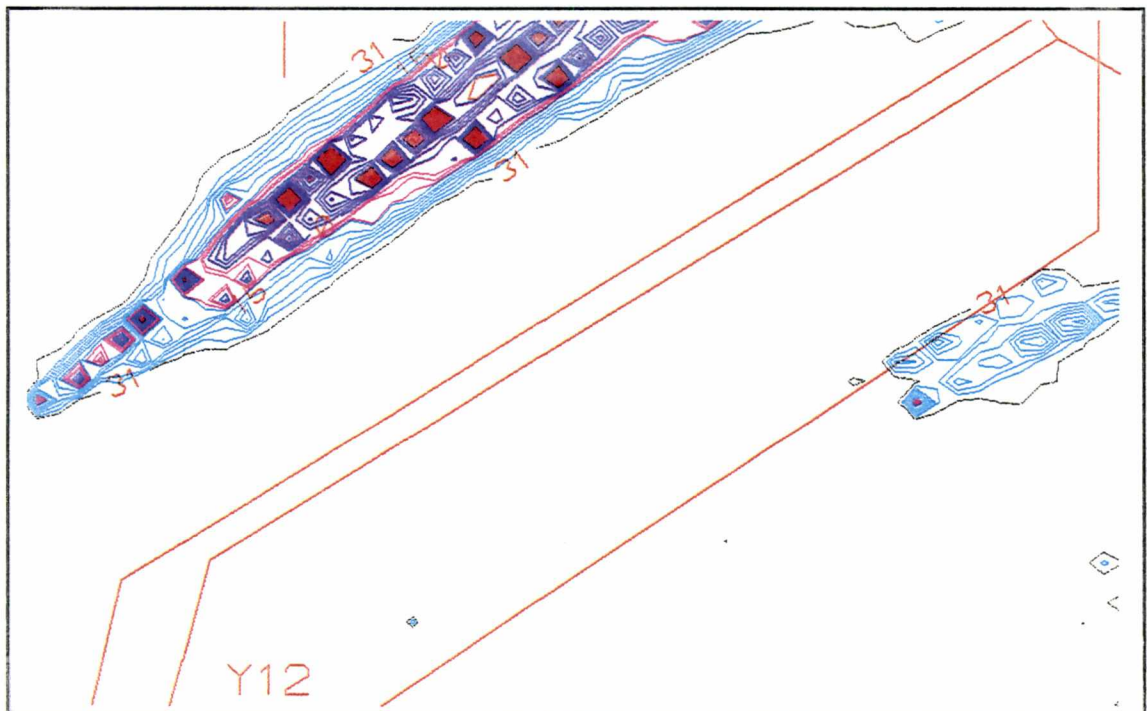


Figure 29 - Signal Strength Topographic Plot of Y-12 from Bear Creek

a landfill and has an elevation of 1220 feet. This site is as far east as practical as McKinney Ridge starts to cast a shadow over the back side of K-25, as shown in Figure 30. One truly great benefit of this site is that it appears unobstructed down the valley to Y-12. This site is clearly in Y-12's favor by not significantly changing the coverage provided by the existing location. Another great benefit of this site is there is a notch in Chestnut Ridge that provides a clear path to much of X-10. The detailed analysis of this site is summarized in the following sections. This site is referred to as the super-site in the remainder of this report.

## **DETAILS OF THE SUPER-SITE ANALYSIS**

Power levels and receiver sensitivities used in this analysis have already been covered and are summarized in Table IV.

### **Elevation Data Adjustments**

The USGS digital data is based on photo and topographic maps. This data can contain errors simply because the photos and maps are hard to read. These errors are most likely near steep slopes and are compounded by errors in the TAP interpolation process. TAP provides the opportunity to correct the data through an edit feature in the *retrieve elevation data* routine.

The radial elevation data retrieved from the database for the super-site is compared with the standard Oak Ridge Area S-16 topographic map prepared by the Tennessee Valley Authority for DOE [9]. The S-16 map is based on the 1927 North American DATUM. Only major discrepancies in peak elevations are corrected and typically only one point for each major obstruction. When several hundred data points are taken on each radial, correcting each entire radial would be labor intensive. Since only the peak of an obstruction is required in the Bullington model, correcting the entire radial is not necessary.

Staying with the general philosophy of the analysis, the corrections to the digital radial terrain data are on the conservative side. If the digital data is lower than the topographic

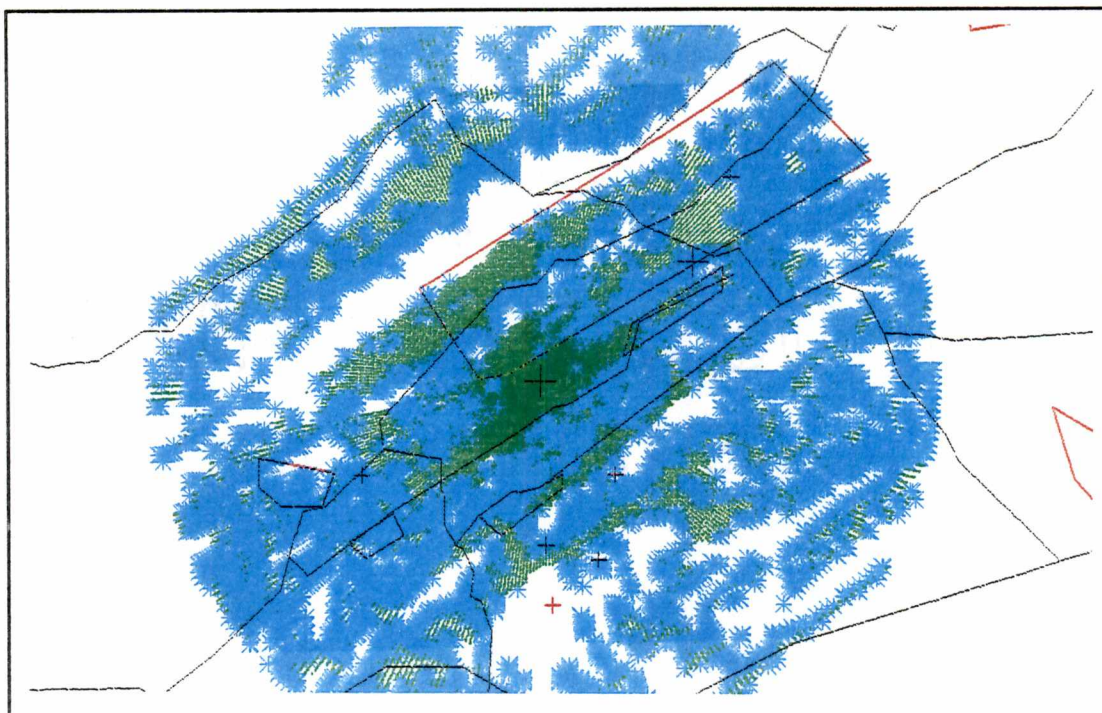


Figure 30 - Shadow Plot from the Dump

Table IV - ERP and Receiver Sensitivity Summary

|                                                              |       | OUTDOORS | INDOOR EQUIVALENT |
|--------------------------------------------------------------|-------|----------|-------------------|
| <b>PORTABLE</b>                                              |       |          |                   |
| ERP (Watts)                                                  | 1.66  |          |                   |
| Sensitivity (dB $\mu$ V/m)                                   |       | 15.9     | 42.9              |
| <b>REPEATER</b>                                              |       |          |                   |
| ERP (Watts)                                                  | 106.5 |          |                   |
| Sensitivity Without<br>Tower Top Preamp<br>(dB $\mu$ V/m) at |       |          |                   |
| 450 Cable Feet                                               |       | 3.5      | 30.5              |
| 530 Cable Feet                                               |       | 3.7      | 30.7              |
| 630 Cable Feet                                               |       | 4.1      | 31.1              |
| Sensitivity With<br>Tower Top Preamp<br>(dB $\mu$ V/m) at    |       |          |                   |
| 450 Cable Feet                                               |       | -16.5    | 10.5              |
| 530 Cable Feet                                               |       | -16.3    | 10.7              |
| 630 Cable Feet                                               |       | -15.9    | 11.1              |

map then a correction is made. If the digital data is higher then it is not modified. All 360 radials are corrected for the area on the S-16 map. Although the radial data is taken for 25 miles, only the area immediately surrounding the DOE facilities is of high resolution interest. The areas outside the S-16 map are only of mobile coverage interest and the enormous amount of time necessary to correct all 360 radials for 25 miles is not invested. Also, correcting the elevation data for all potential sites is not necessary. Correcting the data in this manner has a tendency to decrease the signal strength, rather than increase it. Therefore, since the other potential sites have been eliminated, correcting the data for each potential site is not necessary.

### **Bullington Analysis of the Super-site**

Reliability field strength contours are reviewed from various antenna heights from the super-site. The most effort is concentrated on talkback coverage from a portable radio. Antenna heights of 400, 480, and 580 feet are used. Required signal levels at the repeater receive antenna are adjusted to allow for the longer antenna cable. These values are summarized in Table IV.

Adding 180 feet to the tower does not provide a significant improvement in the K-25 coverage. Adding 80 feet went practically unnoticed as seen by studying Figure 31. The shadow caused by McKinney Ridge is reduced somewhat but is still present. Detailed signal strength contours are prepared for the K-25 site to determine specifically where this shadow falls. When these plots are overlaid on the S-16 topographic map it is seen that the shadow is over the back portion of the plant, specifically over the back part of the K-25 building (also known as the U). This shadow is between 1 and 12 dB, that is, a portable radio operating indoors in this region would be 1 to 12 dB short of being able to activate the repeater (assuming the building has a 27 dB penetration loss). There is not a problem activating the repeater from outdoors. This shadow (as seen in Figure 32) is the only coverage limitation for the chosen super-site.

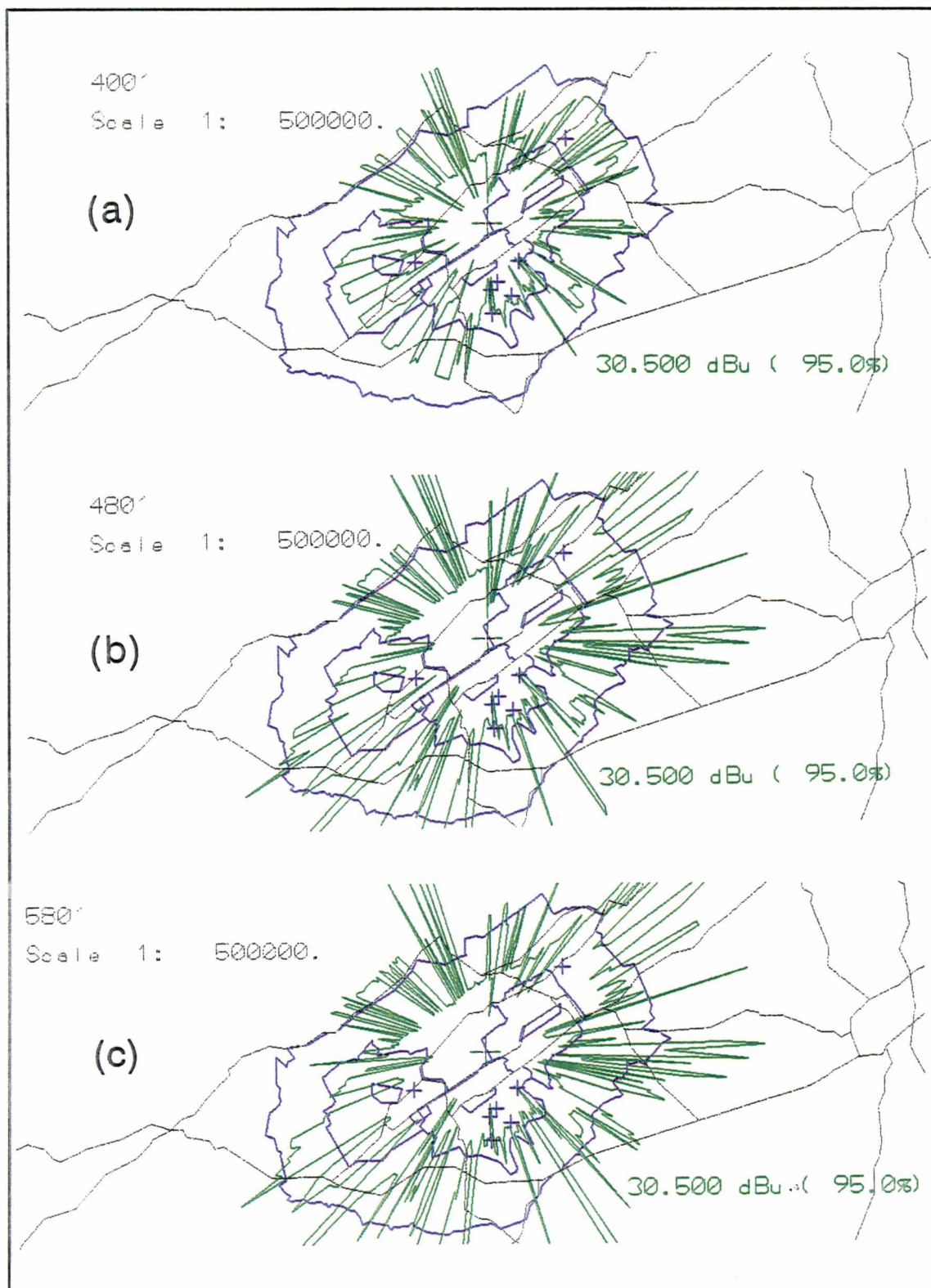


Figure 31 - Effect of Increasing Tower Height

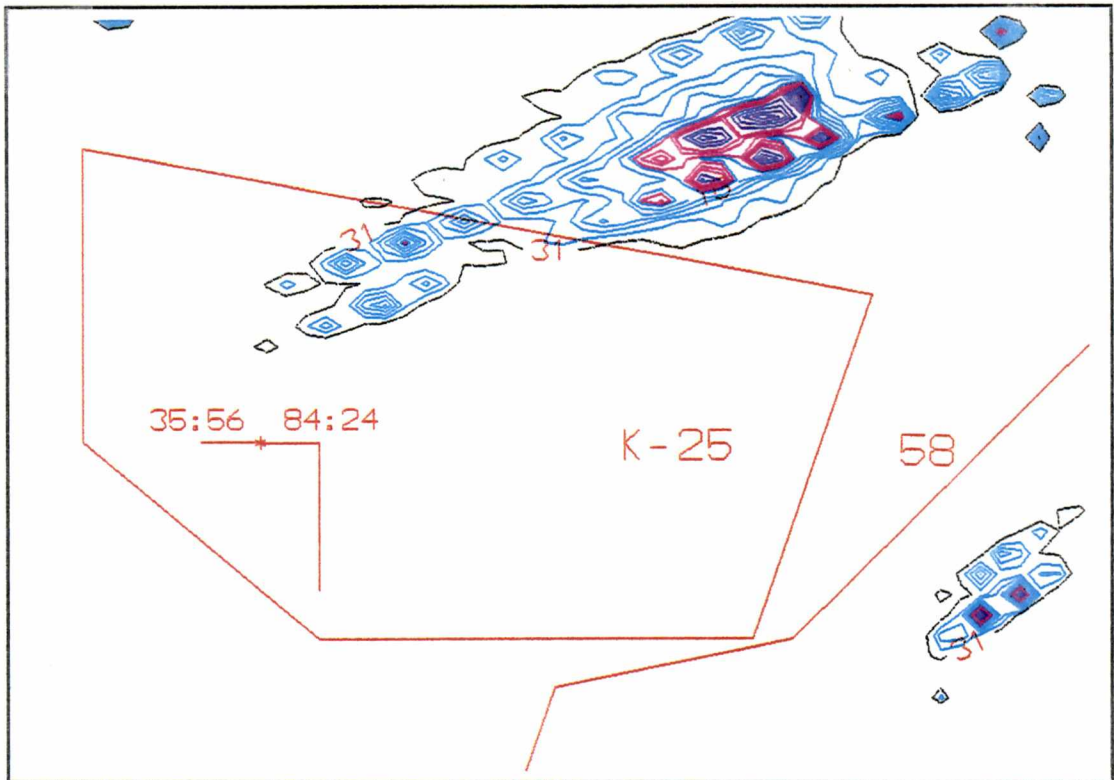


Figure 32 - Signal Strength Topographic Plot of K25 from the Dump

### Tower Top Preamplifier

It is possible to install a tower top pre-amplifier that provides 20 dB gain to signals received at the antenna. This amplifier is placed at the top of the tower so the gain comes before the loss (and therefore added noise) of the cable, filters, and other equipment. With a tower top preamplifier, there are no holes in the indoor coverage from the proposed super-site.

The coverage predictions provided in this report are conservative. Also, a portable trunking radio can currently activate the trunking repeaters (located at 150 feet at Pine Ridge West) from outdoors behind the K-25 building. This suggests that a tower top preamplifier may not be needed at all. Reflections are generally known to provide added coverage to a radio system that was not predicted. The local terrain provides many opportunities for signal

reflections, as do the various buildings nearby. It has been pointed out previously that the TAP model makes no attempt to predict reflections.

Since reflections are a fact of life but cannot be predicted and this analysis is conservative, perhaps the tower should be constructed and coverage tested without the preamplifier. If necessary the preamplifier could be added at a later date.

## **CHAPTER 3**

### **SYSTEM SIZING AND DESIGN**

In this chapter factors affecting radio trunking system sizing and design are discussed. An acceptable grade of service is defined. Traditional queuing theory is compared to the radio trunking system and data obtained from the system management terminals are used to select an approach. A family of curves is provided for the selected approach. These curves will allow the required number of channels to be determined when users are added to the system in the future. An example is provided which compares airtime data from an existing conventional network to the trunking system to show the effect of moving these users to the trunking system.

Now that a super-site has been identified, it is time to concentrate on determining the capacity required by this system. When this work was begun it was hoped that the number of channels necessary for the final system could be determined. However, as the work progressed it became apparent that there is simply not enough information to make that determination at this time. Instead, this report describes the tools and techniques that can be used to make that determination in the future.

### **FACTORS IN SYSTEM SIZING AND DESIGN**

Perhaps the biggest concern the user community has about a super-site radio trunking system is that it will not have enough channels to handle their needs. This is especially true of the Emergency Response community. It is a well known fact that radio traffic increases when there is an emergency situation. Not only is there additional traffic from the emergency responders themselves, there is additional facility maintenance and other support radio traffic as they attempt to help out any way possible. Final determination of system

size should allow for two simultaneous emergencies that occur during the busiest time period.

The single most important factor in determining if a radio trunking system has enough channels is the number of busy signals. The radio trunking busy signal is equivalent to a blocked telephone call caused by busy telephone trunks. Busy signal statistics are readily available on the Motorola system through various system management terminals.

Factors that affect, directly or indirectly, the probability of a user receiving a busy signal are: the number of radio users, the number of available channels, the number of calls per unit time, and the length of time per call. A radio trunking system is like a telephone network in that the users are voice users who share a trunk group of several channels. However, they are like data system users in that their traffic is passed in short segments which are time division multiplexed.

Radio users do some internal processing of their own. For example, if they hear others using their talkgroup they will wait their turn before keying up. It is impossible, however, for a user to know when other talkgroups are using the channels and occasionally the system will be busy when a channel is requested. The user receives a busy signal as a result. Radio trunking is like a data network in that there is a queue for the users receiving a busy signal. The network will call a user back when a channel is available.

A combination of voice and data network analysis techniques is required. In telephone system sizing, the main point of interest is the probability of a blocked call. In the data network, the average delay a packet experiences is most important.

The National Telecommunications & Information Administration (NTIA), which governs Government users in spectrum matters, does not have specific channel loading requirements for trunked systems. However, the FCC, which governs private and public safety systems, requires that a radio trunking system be loaded with 100 users per channel [21]. This soft criteria clearly is meaningless for the type of radio users in the Oak Ridge Reservation.

There are already over 900 radios assigned to the five channel trunking system and busy signals are virtually non-existent.

The key to determining the final system size for the proposed radio trunking system is determining how existing conventional radio users will impact the airtime on the trunking system when they start using it. Knowing exactly how many users there are is not as important as knowing the amount of traffic they generate and how this additional traffic will impact the probability of receiving a busy signal. This effort concentrates on obtaining traffic data and basing performance projections on this information.

#### **DEFINITION OF ACCEPTABLE GRADE OF SERVICE**

For this report an acceptable grade of service for the radio trunking system is defined as the probability of a busy signal equal to 0.2 or less. A secondary criterion is an average delay of two seconds or less. An optimum system meets both of these criteria. This definition is consistent with [10] where the acceptable grade of service is defined as the probability of a successful call equal to 0.8.

#### **UNITS OF MEASURE**

The following terms are used further in determining system performance relative to the probability of a busy signal just defined.

##### **Erlang**

The Erlang is a unit of measure to categorize the amount of traffic a group of users imposes on a system. It is a dimensionless unit and is independent of the system they are using. The Erlang for a voice network is the call arrival rate times the average length of a call. A user's load can be defined in terms of an Erlang averaged over any period of time. In the telephone world the busiest hour of the day is used. The most conservative approach is one

**ERLANG** - A measure of communications traffic intensity representing the full-time use of a communications facility [22].

that uses the smallest time increment. For this work a 15-minute period is used. For this effort the traffic load in Erlangs is the airtime (in seconds) in a single 15-minute period divided by 900 (the number of seconds in 15 minutes).

### **Average Delay**

The average delay is the amount of time a user has to wait for a clear channel. It is the sum of the processing delay and the delay of waiting for a clear channel in the event that all channels are busy. Average delay can be determined for all calls (the most common approach) or only for calls that are delayed. Which is used depends on the queuing approach that is applied. Various queuing approaches are discussed in the following section.

## **QUEUING THEORY**

As previously mentioned radio trunking combines typical voice and data techniques. There are several standard approaches to performing these calculations assuming that the number of traffic sources is infinite (or at least very large relative to the number of channels): Erlang B, Poisson, Erlang C, and Crommelin-Pollaczek. Queuing theory for finite sources is not applied since over 900 users qualifies as very large relative to four voice channels.

The Erlang B approach assumes an equal traffic density per source and blocked calls are cleared. The Poisson approach assumes an equal traffic density per source and blocked calls are held. The Erlang C approach assumes that blocked calls are delayed, served in the order of their arrival, and that the holding time is exponential. The Crommelin-Pollaczek approach assumes that blocked calls are delayed, served in the order of their arrival, and

that the holding time is constant. The probability of blocking for each is calculated from Equations 21 thru 24 [5, 23].

$$P_{\text{busy}}(\text{Erlang B}) = \frac{\frac{E^s}{s!}}{\sum_{x=0}^s \frac{E^x}{x!}} \quad (21)$$

$$P_{\text{busy}}(\text{Poisson}) = \sum_{x=s}^{\infty} \frac{E^x e^{-E}}{x!} \quad (22)$$

$$P_{\text{busy}}(\text{Erlang C}) = \frac{\frac{E^s}{s!} \frac{s}{s-E}}{\sum_{x=0}^{s-1} \frac{E^x}{x!} + \frac{E^s}{s!} \frac{s}{s-E}} \quad (23)$$

$$P_{\text{busy}}(\text{C-P}) = 1 - e^{-E} \left( \sum_{n=1}^{\infty} \frac{e^{-wE}}{w} \sum_{n=0}^{\infty} \frac{(wE)^n}{n!} \right) \quad (24)$$

where

$P$  = probability of blocking

$E$  = offered traffic in Erlangs

$s$  = number of channels

Each of these approaches provides a way to calculate the average delay. For Erlang B and Poisson the average delay is taken over all calls and is shown in Equation 25. For Erlang C and Crommelin-Pollaczek the delay is averaged over all calls or averaged over only those calls delayed. These equations are provided in Equations 26 thru 29 [5, 23].

$$Delay_{avg}(Erlang B, Poisson) = \frac{\text{process delay}}{1 - \frac{E}{s}} \quad (25)$$

$$Delay_{all calls}(Erlang C) = P_{busy}(Erlang C) \frac{h}{s - E} \quad (26)$$

$$Delay_{delayed calls}(Erlang C) = \frac{h}{s - E} \quad (27)$$

$$Delay_{all calls}(C-P) = \sum_{w=1}^{\infty} e^{-wE} \left( \sum_{u=ws}^{\infty} \frac{(wE)^u}{u!} - \frac{s}{E} \sum_{u=ws+1}^{\infty} \frac{(wE)^u}{u!} \right) \quad (28)$$

and

$$Delay_{delayed calls}(C-P) = \frac{Delay_{all calls}}{P_{busy}(C-P)} \quad (29)$$

where

$P$  = probability of blocking

$E$  = offered traffic in Erlangs

$s$  = number of channels

$h$  = average holding time

Next, actual radio trunking data is analyzed and compared to each of these approaches.

## ANALYSIS OF EXISTING TRAFFIC

In order to determine how additional users will impact the performance of the system it is necessary to characterize how the existing system performs. It is also necessary to determine which of the approaches just discussed best models the radio trunking system. Data available for the trunking and conventional networks are analyzed and compared to the queuing theory approaches.

## Radio Trunking System Usage Reports

The radio trunking system has several system management tools available that provide usage statistics. These statistics can be specified on a daily, hourly, or 15 minute basis. They can be obtained for the entire system, each channel, talkgroups, announcement groups, groups of radios, or individual radios.

Figure 33 shows the average call length per week and is the total airtime for a week divided by the number of calls in the week. An average exchange consists of four of these calls: an initial call, a response, a message, and a confirmation. For example "Alpha1 to Alpha4", "Go ahead Alpha1", "I'm finished here, can you pick me up at building 6", "Be there in a few minutes." Four of these calls is an average of just under 17 seconds.

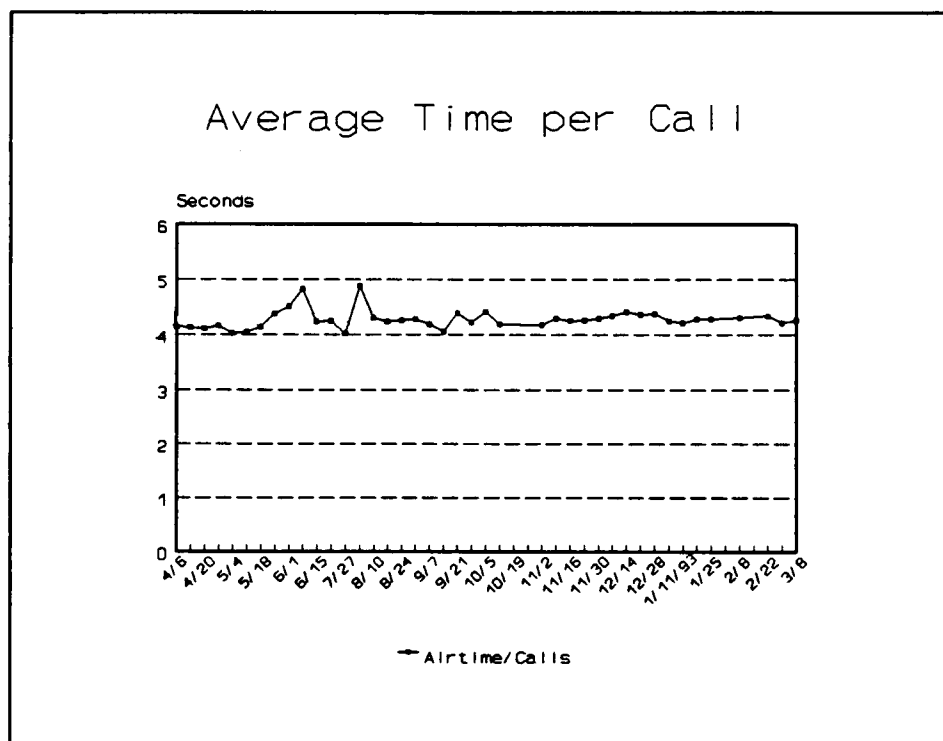


Figure 33 - Average Call Length

Over an average month it is possible to see where the busy days are and where the weekends are. The work force in the reservation is predominately single shift. Very few people work nights and weekends. Figure 34a clearly shows this trend. This figure shows the number of calls in a typical month on a daily basis. The same format is used in Figure 34b which shows the airtime per day for the same month. The number of busy signals and the amount of busy time encountered in the same month are shown in Figures 35a and 35b.

Using these charts alone to predict traffic patterns is a bit dangerous. One cannot assume that the number of calls is evenly distributed over the normal day or week. Figure 36 shows the number of calls for a typical work day in 15-minute increments. This chart clearly shows that the traffic is not uniformly distributed. In fact there is not a standard probability distribution curve to fit this traffic pattern. As an interesting exercise, one can study Figure 36 and determine what time the work force starts working, takes breaks, eats lunch,

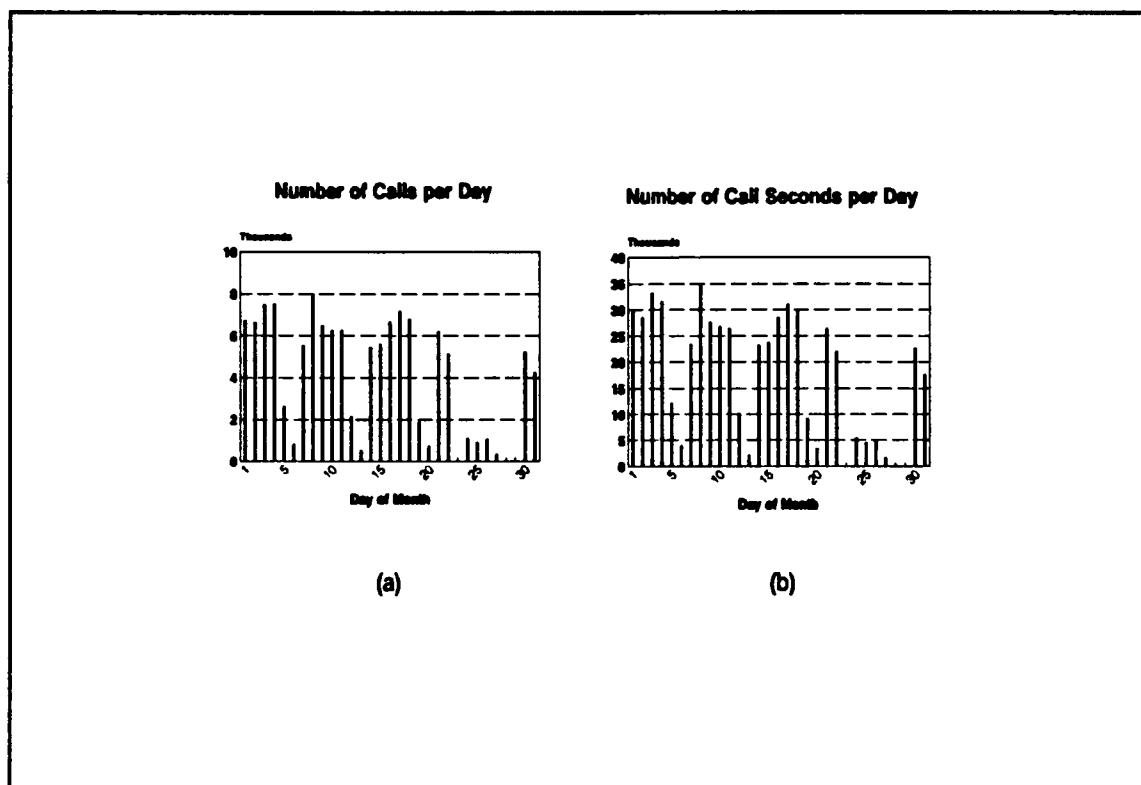


Figure 34 - Daily Number of Calls and Airtime

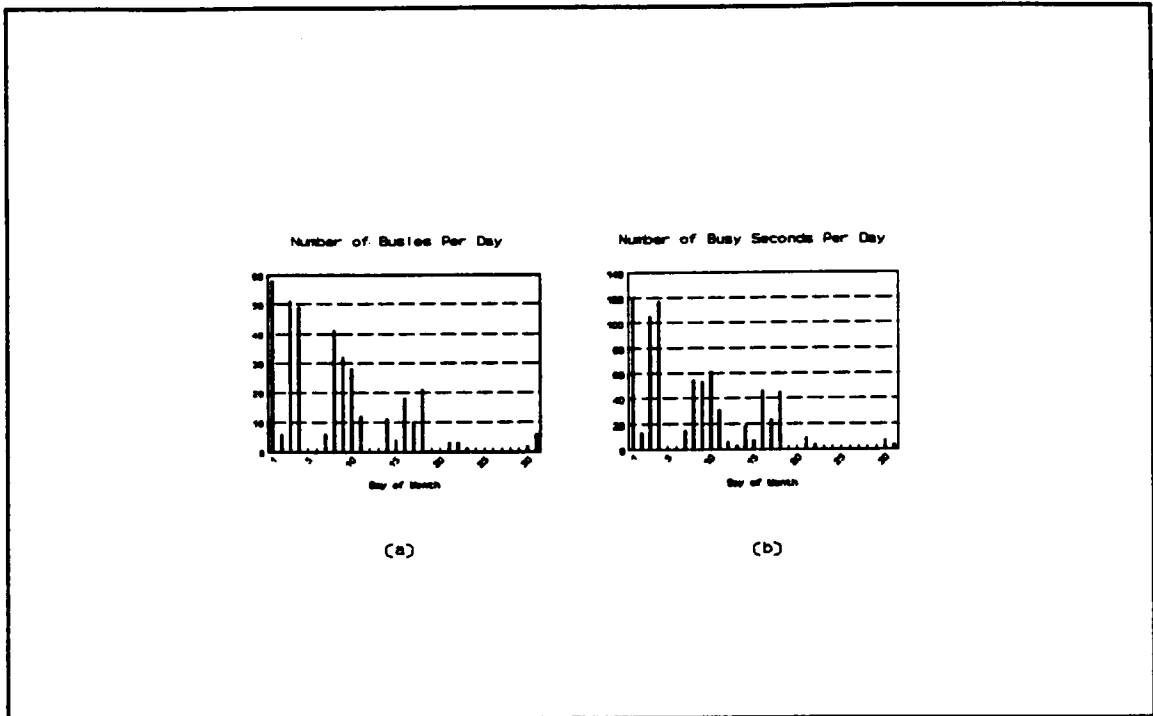


Figure 35 - Daily Number of Buses and Busytme

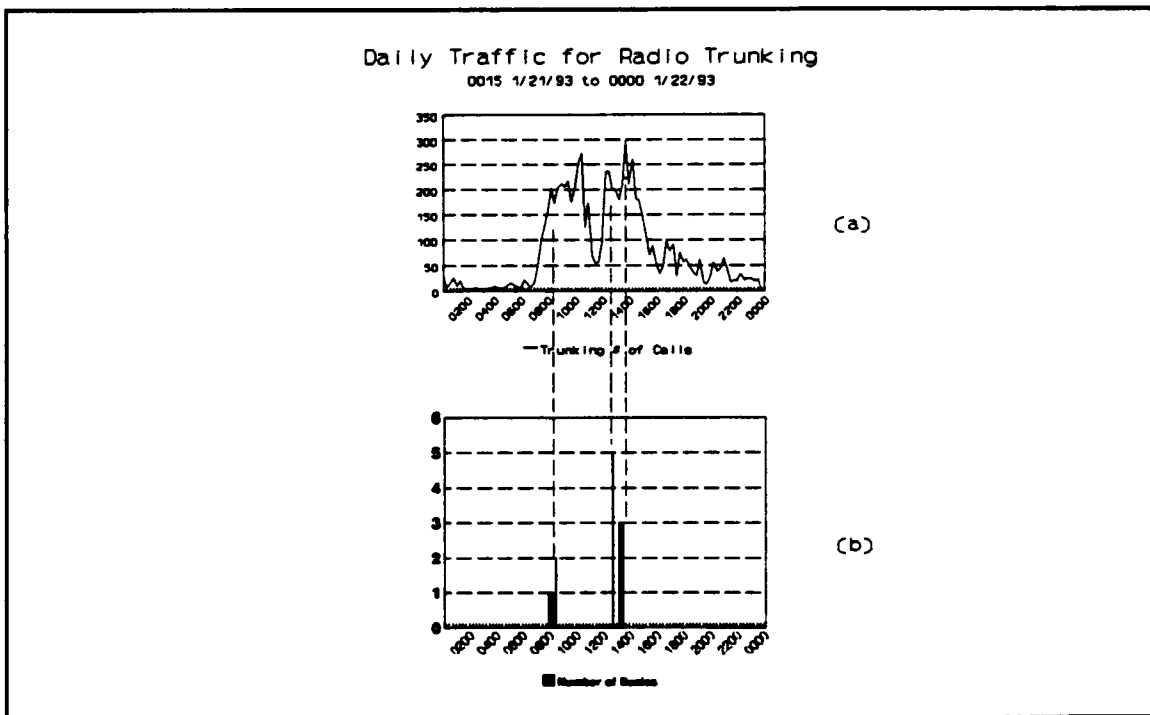


Figure 36 - Radio Trunking Traffic over 24 Hours

works overtime, and goes home. This figure shows there are typically two busy hours which are around 10 a.m. and 2 p.m. System sizing needs to take into account these busy hours (or 15-minute periods within these hours) not averaging traffic over a larger period of time. Studying these figures suggests that using a 15-minute period has its merits.

### **Conventional Airtime Logger**

Now that the type of usage data that is available for the trunking system has been viewed, it is beneficial to obtain the same sort of information for conventional networks. The current traffic can then be projected onto the trunking system.

Until this work was begun, there was no known convenient tool. An ICOM IC-R9000 receiver was available to monitor various networks to get a feel for the amount of traffic, but there was nothing available that tabulated statistics. There was also available an interface box for the ICOM that provided an RS-232 connection to a personal computer. This interface box was designed to allow the computer to send commands to the receiver to set parameters such as frequency, bandwidth, modulation type, etc. With a close review of the schematic diagrams for the ICOM and its interface box [24, 25], it was determined that this interface could be used to provide squelch opening and closing information. The computer was then programmed to record this data.

The interface box is connected to the ICOM jack intended to provide control of a remote tape recorder. The ICOM receiver intentionally leaves this contact closed for a period of time after the squelch is closed to prevent the tape recordings from running together. Repeaters typically have a hang time where the carrier remains active, giving users time to respond to a call. In addition there is a necessary delay for the software to cycle through various loops. For these reasons, a calibration factor is subtracted from each call logged.

The software source code provided in Appendix B was written to log airtime and number of calls on a conventional network for each 15-minute period of the day. The totals are summed at the end of each 15-minute and 24-hour period and written to a file. A new file is opened at midnight. The file names are taken from the date.

This system is used to log airtime of a single channel of the radio trunking system. The results are compared to the data provided by the trunking systems System Watch II terminal. These two independent loggings of the same data are provided in Figure 37. When the airtime is accumulated over the entire day the ICOM approach shows a three percent error compared to the trunking report. The calibration factor is selected to allow the ICOM to record more time than the System Watch II report. This three percent accuracy is found very acceptable.

Using this ICOM approach all responses to a call are logged as one call if they fall within the hangtime of the repeater and ICOM remote record signal delay. As the network becomes more busy the likelihood of recording multiple calls as a single call is greatly increased. This is easily seen in the fluxuation of the average airtime calculation provided by the software. A sample of the output is provided in Appendix C. The trunking system does not have this limitation since it knows which specific radios are keyed at any time by

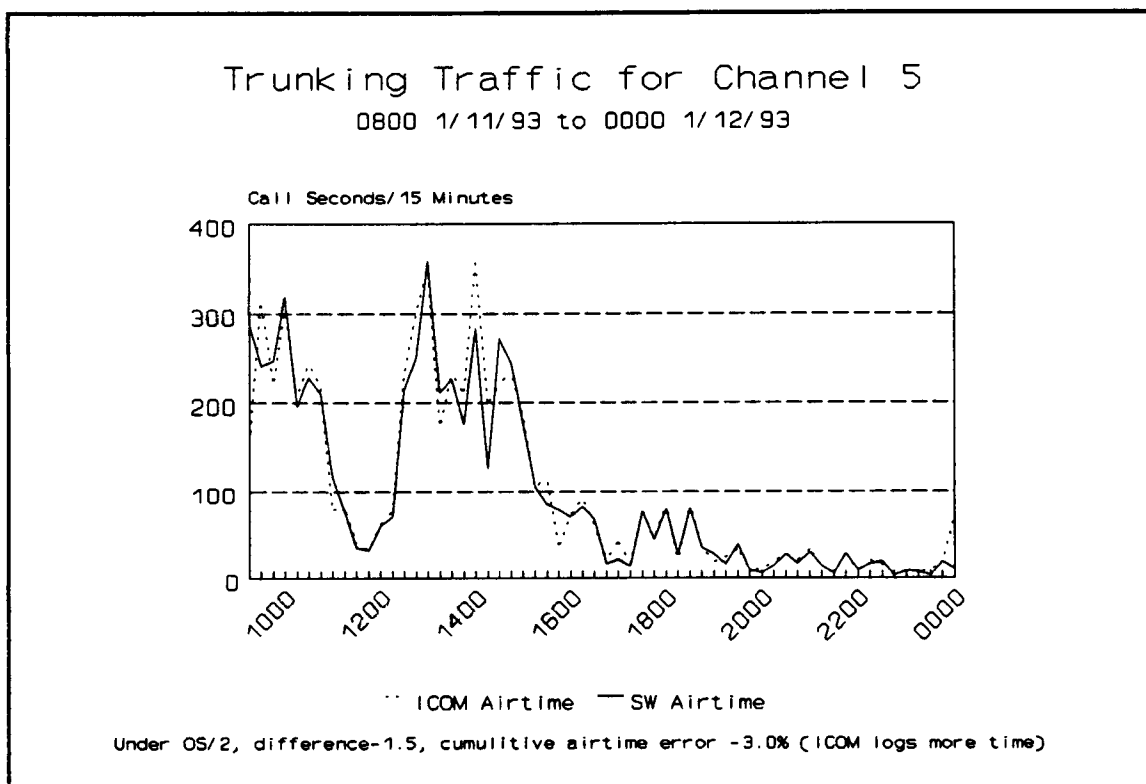


**Figure 37 - Accuracy of the Conventional Airtime Logger**

use of the control channel. The usage statistics provided by the System Watch II terminal are taken directly off the control channel. For these reasons the number of calls as recorded by the ICOM approach vary from the number of calls recorded by the System Watch II terminal. Care must be taken when making projections based on the number of calls recorded by the ICOM approach.

## **PROBABILITY OF BUSY SIGNALS**

It would be nice if the busy signals correlated with the airtime and number of calls. However, there is such a low amount of traffic that the probability of receiving a busy signal is near zero. This is seen when comparing Figures 36a and 36b where maximum number of busy signals does not occur at the peak traffic periods. There are more busy signals at 0815 than at the peak traffic AM period which occurs at 1030. Likewise the afternoon traffic peak occurs at 1330; however, the peak in busy signals occurs at 1245. One would expect the most busies at the same time as the most calls or the most airtime.

The result of reviewing the existing busy curves is that one cannot predict how additional users will impact the probability of busy signals because there simply is not enough data: no trend is evident. As with most networks the probability of a busy increases proportionally with the amount of traffic as the system becomes more utilized.

### **Busy Data Generation**

In an attempt to generate some busy statistics, the current four-channel system is reduced to a two channel system for a short period of time. The resulting usage numbers for 15-minute periods sorted by the number of calls is provided in Table V. These numbers can be used to calculate directly the probability of receiving a busy, the average length of delay each call received, and the average length of each busy. The results of these calculations are also provided in Table V.

**Table V - Busy Data Summary**

| <i>Airtime<br/>(sec)</i> | <i>Number<br/>of Calls</i> | <i>Busy<br/>Time<br/>(sec)</i> | <i>Number<br/>of Buses</i> | <i>Prob<br/>of Busy</i> | <i>Average<br/>Delay<br/>(sec)</i> | <i>Average<br/>Busy Length<br/>(sec)</i> |
|--------------------------|----------------------------|--------------------------------|----------------------------|-------------------------|------------------------------------|------------------------------------------|
| 7                        | 2                          | 0                              | 0                          | 0                       | 0                                  | 0                                        |
| 29                       | 9                          | 0                              | 0                          | 0                       | 0                                  | 0                                        |
| 57                       | 14                         | 0                              | 0                          | 0                       | 0                                  | 0                                        |
| 202                      | 53                         | 0                              | 0                          | 0                       | 0                                  | 0                                        |
| 342                      | 84                         | 20                             | 6                          | 0.071                   | 0.238                              | 3.333                                    |
| 732                      | 164                        | 115                            | 19                         | 0.116                   | 0.701                              | 6.053                                    |
| 923                      | 191                        | 299                            | 42                         | 0.22                    | 1.565                              | 7.119                                    |
| 1156                     | 254                        | 389                            | 64                         | 0.252                   | 1.531                              | 6.078                                    |
| 1375                     | 272                        | 815                            | 94                         | 0.346                   | 2.996                              | 8.67                                     |
| 1559                     | 333                        | 1599                           | 144                        | 0.432                   | 4.802                              | 11.104                                   |

One of the trunking system logging reports is used to track exactly how the users react to the busy signals they encounter. Do they use the channel when the system calls them back or do they give up and try again later? The System Watch II logging data is reviewed for user reaction. It appears from this logging report that the vast majority of the users take advantage of the channel they are granted after a busy signal. For example in a 2 minute period sixteen users utilize the channel they are granted after a busy signal, where only two users do not in the same time period.

An attempt is made to determine if there as a magic length of busy signal after which the users give up. There does not appear to be such a number. One user had to wait fourteen seconds before accessing a channel. Both of the quitters viewed in this period had moderate busy lengths - four and five seconds. This review also shows that there was no correlation between the length of the call placed after a busy and the length of the busy or even the fact that a busy is received.

The results of this exercise are probability of busy and delay versus usage curves for a two channel system. A system with more channels will have similar curves, although the break points will be in a different place. A family of curves for a system with various numbers of channels are presented once a particular queuing approach is selected.

## **Queuing Theory -vs- Busy Data / Selecting an Approach**

The airtime values in Table V can easily be converted to Erlangs and substituted directly into the various probability of busy and delay equations, Equations 21 thru 29. This is done in an effort to determine which of these approaches most realistically represents the current system. The resulting calculations are presented in the curves of Figure 38 which also includes a plot of the probability of busy column of Table V. By studying this figure, it can be concluded that the Erlang B equations provide the best mathematical representation for the system as presented. Erlang B theory is based on; infinite sources, an equal traffic density per source, and lost calls cleared. In our trunking system the number of sources is very large relative to the number of channels and can be assumed infinite (900 users verses four voice channels), the average time per call is constant between users, and lost calls are delayed.

### **A Family of Curves for Later Use**

As mentioned before the probability of busy and average delay curves have the same basic shape regardless of the number of channels the system has. They do, however, differ in where the break point is. That is, at some usage rate the probability of busy (or delay) starts to become a real problem. This breakpoint is at a higher usage rate for systems with more channels. This trend is clearly shown in Figures 39a and 39b where probability of busy and average delay are plotted against offered traffic in Erlangs. These curves are based on the Erlang B equations.

### **SIZE VERSUS EFFICIENCY**

For communications systems bigger is almost always better. In the case of a shared trunked system it can be easily shown that all users receive a better level of service when they pool their resources. This has already been seen at Y-12 where the users of conventional networks pooled together on the trunking system. The same argument holds true for adding the users at the other facilities. It is much more efficient to satisfy these users'

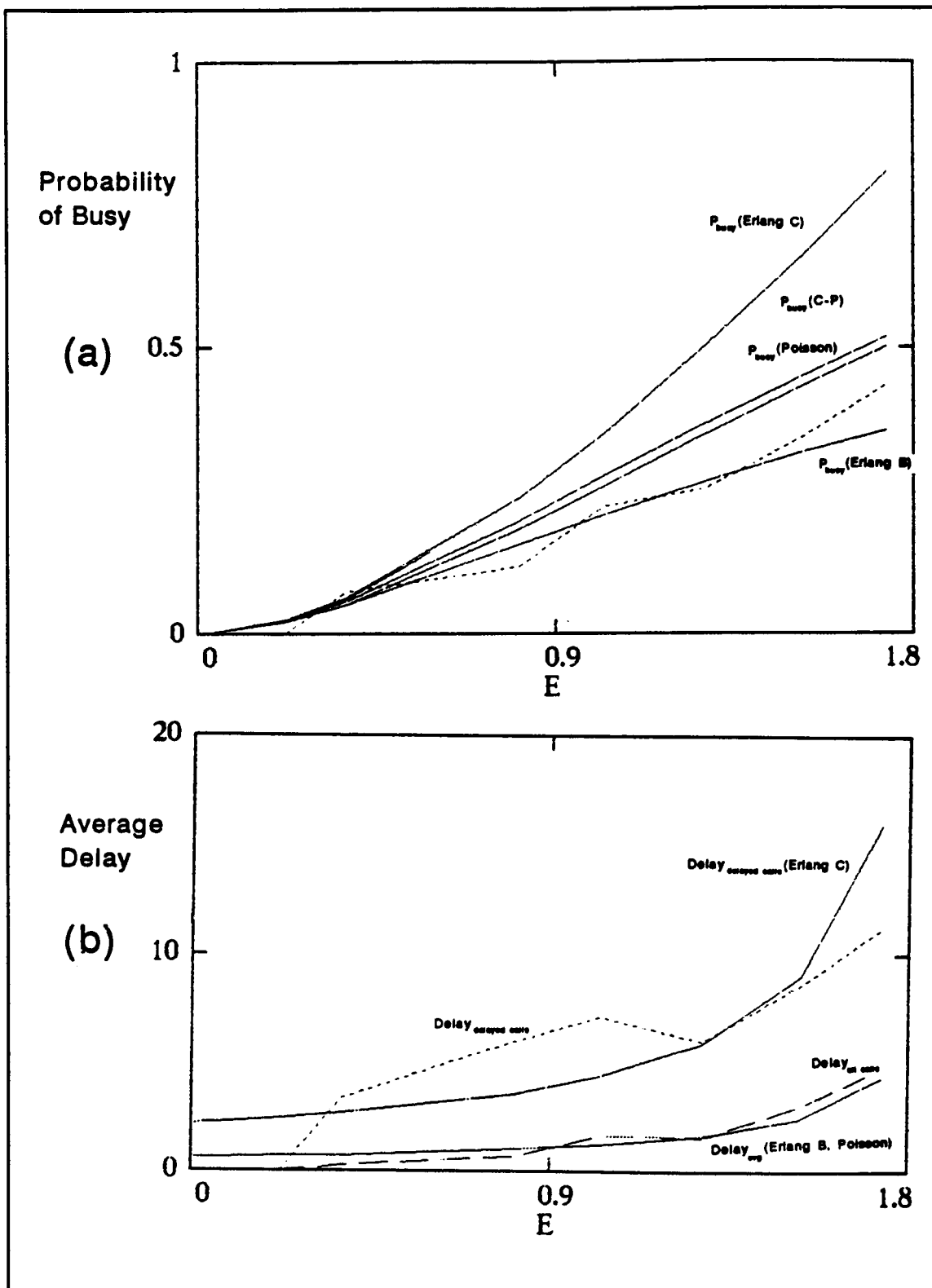


Figure 38 - Probability of Busy and Delay Curves - Various Approaches

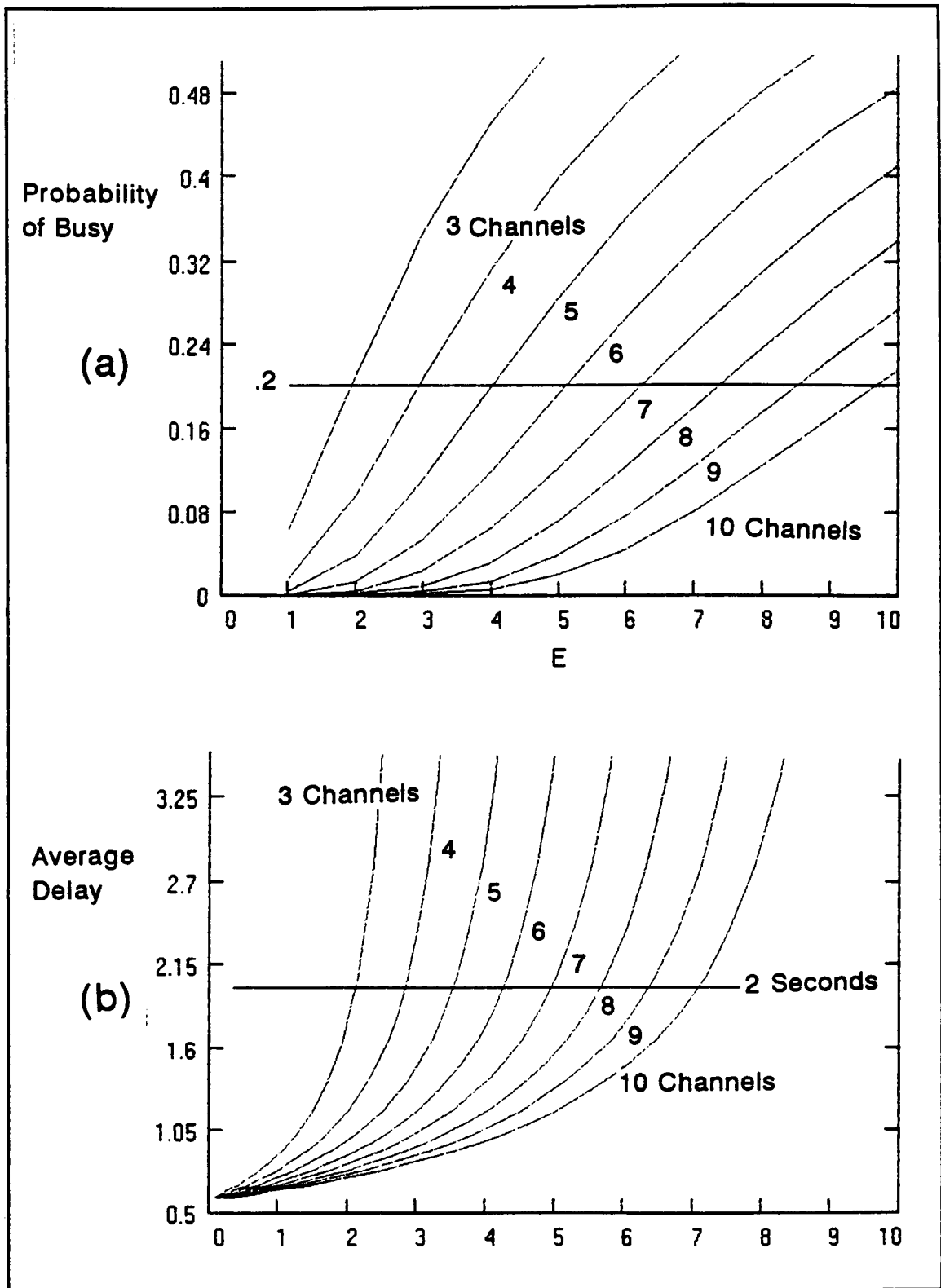


Figure 39 - Family of Curves for P(busy) and Average Delay

requirements from a single system than if separate systems are installed. For a given level of service (probability of busy = 0.2) assuming seven Erlangs of offered traffic (three Erlangs at Y-12 and two Erlangs at each K-25 and X-10), Figure 39 can be used to project number of channels for one system and for three separate systems. As this figure shows it would take ten channels for a single system with seven Erlangs of traffic but would take three separate smaller systems of five and four channels each (thirteen channels total) to carry the same load. The results of using Equation 21 to determine the actual probability of blocking are provided in Table VI. As this table shows four channels for the three Erlang system and three channels for the two Erlang system provides a probability of blocking slightly greater than the 0.2 requirement. This table also shows that the probability is met with eight channels with a single system but ten channels are required to meet both the probability of busy and average delay goals.

#### EFFECT OF MOVING A CONVENTIONAL NETWORK TO TRUNKING

The ultimate goal is to project the system capacity required when ALL radio users in the Oak Ridge reservation are using the trunking system. In order to do that, it is necessary to measure the usage on all conventional networks, a process that will take a significant

Table VI - Size -vs- Efficiency Calculations Summary

| <i>Number of<br/>Erlangs</i> | <i>Number of<br/>Channels</i> | <i>Probability<br/>of Busy</i> | <i>Average<br/>Delay (sec.)</i> |
|------------------------------|-------------------------------|--------------------------------|---------------------------------|
| 7                            | 8                             | 0.179                          | 4.64                            |
| 7                            | 9                             | 0.122                          | 2.61                            |
| 3                            | 4                             | 0.206                          | 2.32                            |
| 3                            | 5                             | 0.110                          | 1.45                            |
| 2                            | 3                             | 0.211                          | 1.74                            |
| 2                            | 4                             | 0.095                          | 1.16                            |

amount of time. The time is not available to make these measurements as part of this study. However, it is possible to do this for one of the networks to demonstrate the steps required.

Figure 40a is a 24 hour recording of conventional network KRF 260, shown here in Erlangs. Using Erlangs as the y-axis in this figure facilitates the use of the probability equations. This is the very next network of users scheduled to transition to the trunking system. Adding this traffic load to the trunking system's traffic load on the same day yields Figure 40b. From this figure it can be seen that the peak for KRF 260 is 0.5 Erlangs at two p.m. while the trunking system has a peak of 1.3 Erlangs at this same time. The combined peak traffic load for these two networks is 1.8 Erlangs. Applying Equations 21 and 25 the probability of busy and average delay for the combined traffic are shown in Table VII.

The result of adding the KRF 260 users to the trunking system is an insignificant increase in the probability of busy signals or average delay.

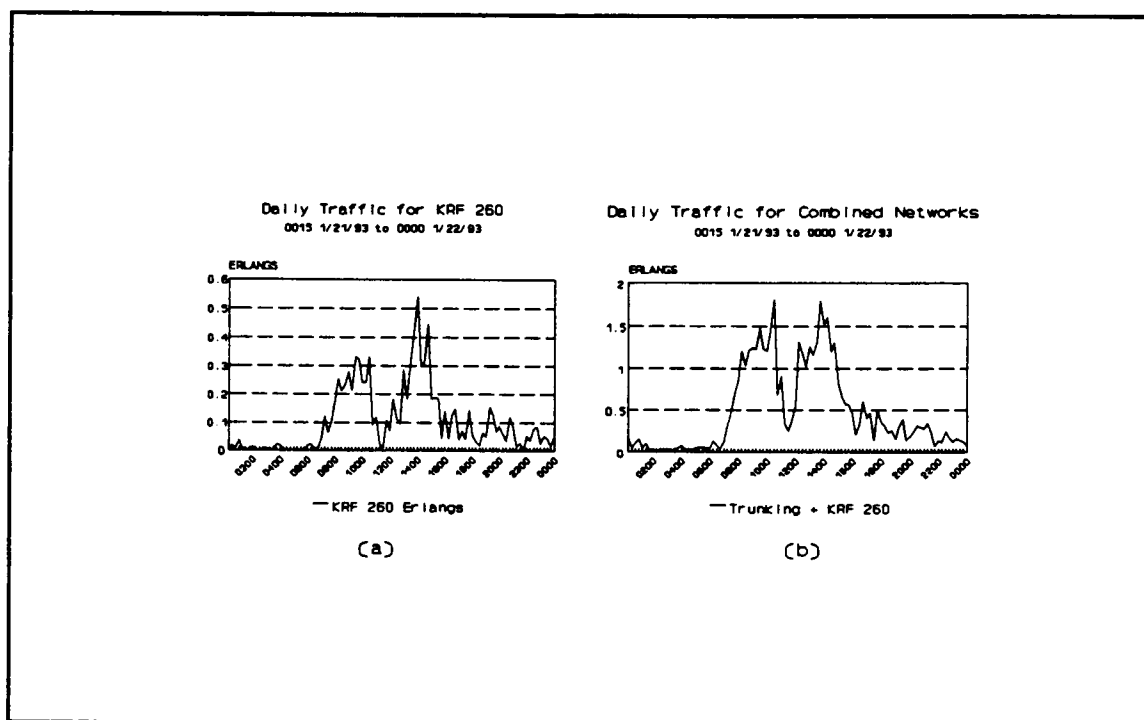


Figure 40 - Conventional Network Impact on the Trunking System

**Table VII - Combined Traffic Calculation Summary**

|                                 | <i>Erlangs</i> | <i>Probability<br/>of Busy</i> | <i>Average<br/>Delay</i> |
|---------------------------------|----------------|--------------------------------|--------------------------|
| <i>KRF 260</i>                  | <i>0.5</i>     | <i>0.002</i>                   | <i>0.671</i>             |
| <i>Trunking</i>                 | <i>1.3</i>     | <i>0.029</i>                   | <i>0.844</i>             |
| <i>Combined</i>                 | <i>1.8</i>     | <i>0.075</i>                   | <i>1.055</i>             |
| <i>Using Erlang B Equations</i> |                |                                |                          |

### **EFFECT OF EMERGENCY TRAFFIC**

As previously discussed the radio trunking system is used for emergency response and therefore must be sized to handle the additional traffic load an emergency situation brings. The best way to project what additional load emergencies provide is to measure radio traffic with and without an emergency in progress. Using the conventional airtime logger developed for this report it is possible to do just that. During the time that conventional radio network KRF 260 was being monitored an emergency situation occurred. Figure 41a shows usage of KRF 260 for a 24 hour period which includes a three hour period when an emergency response was in progress.

During this emergency regular KRF 260 users were prohibited from using the network. Therefore, it can be assumed that all traffic during the emergency response was emergency traffic. This three hour period is enclosed in bars in Figure 41.

For greatest accuracy it is necessary to include the traffic of the users that were prohibited from using the network. We can assume that these users would have used the network just as they did on the previous day when there was no emergency. Figure 41a shows the previous day's traffic for this time period. Adding the emergency traffic to the projected typical traffic yields the third curve in Figure 41a. If this projected emergency plus typical traffic is added to the trunking system's traffic for the same 24 hour period, the resulting projected total traffic load is shown in Figure 41b. The peak of two Erlangs occurs at 10 a.m. which is a typical busy hour.

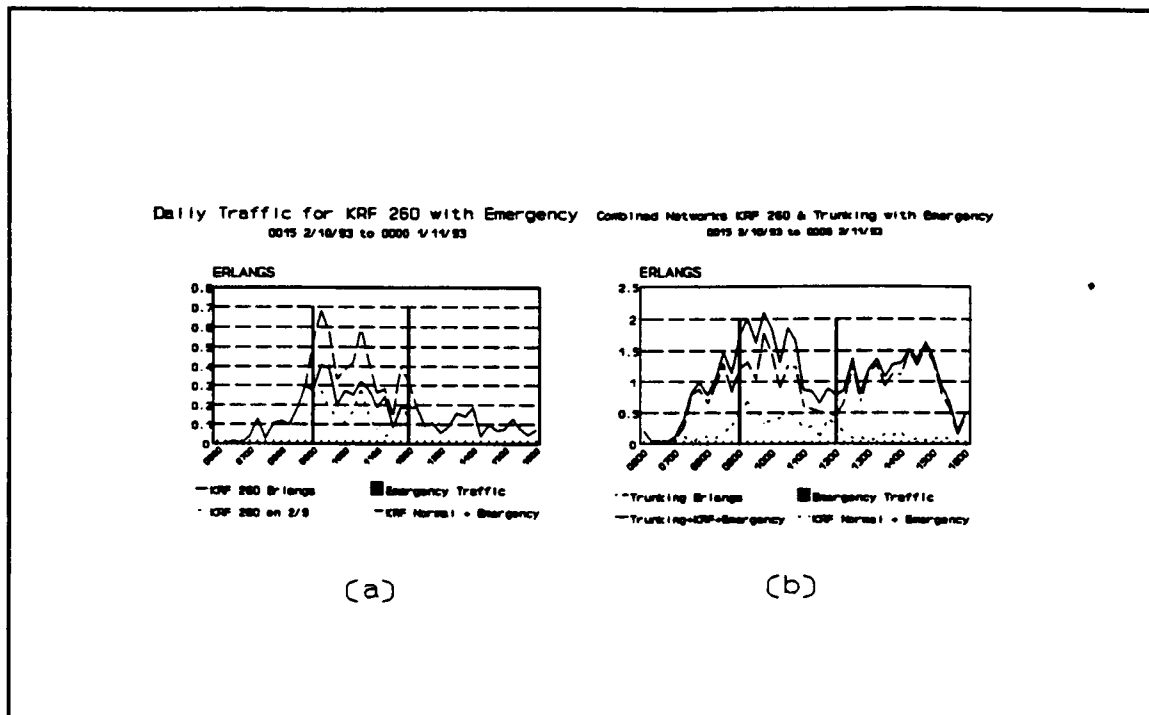


**Figure 41 - KRF 260 with Emergency**

This exercise is conservative for the following reasons: the emergency responders are a group that includes some of the normal KRF 260 users. Therefore, their normal traffic should have been subtracted. The traffic over the three hour emergency period contains non-emergency traffic of users unaware of the emergency situation, breaking in, and being told to clear the network. Emergency situations handled on the trunking system will not be subject to this additional burden since emergency only talkgroups would be used. Figure 41 makes no attempt to correct for this additional traffic.

## CHAPTER 4

### RESULTS AND CONCLUSIONS

In this chapter a summary of the results provided in this report is furnished. Suggestions are made for additional tasks that should be performed in the future. These tasks should verify the results provided here as well as complete the effort begun, namely, to provide a complete system design for a radio trunking super-site.

The results of this work highly suggest that a super-site radio trunking system is able to meet the wide area radio communications needs for the Oak Ridge reservation. This work identifies a location along Pine Ridge just west of the Anderson/Roane county line (35:57:53N latitude, 84:18:19W longitude) as the best location for such a site. It is possible for a portable radio located anywhere in one of the DOE facilities in the reservation to produce a signal 27 dB over the repeater receive threshold. The back side of K-25 is a possible exception; however, this can be compensated by using a 20 dB tower-top preamplifier.

In addition to identifying a promising super-site, this work has provided the tools necessary to determine the number of channels a super-site will need. These tools can be used to project the radio trunking probability of busy signals resulting from adding each current network of conventional users. These projections can be based on the amount of traffic the conventional users have on their existing networks. A 0.2 or less probability of busy is defined as the limit of acceptable system performance.

Since only limited time and resources were available for this effort there are a few items that should be pursued as a continuation of this work. These can be divided into verification and projection tasks.

## **VERIFICATION TASKS**

These are tasks that should be accomplished to verify the various items covered in this report. The propagation model and queuing theory selected should be verified. Specific suggestions follow.

### **PROPAGATION**

All factors that affect radio signals for this specific geographic area are not completely known. Each transmission site will combine the factors discussed in this report in a unique way. For example, the amount of foliage signals travel through will vary as will the type of foliage. As discussed before, the long leaf pine trees cause the biggest problem; however, this is not the only type of foliage in this area. These trees do have a tendency to concentrate in specific locations which may or may not impact the users within the facilities. The only way to determine the exact impact of foliage is to make field measurements.

Building penetration is also a big concern. It is a known fact that penetration to the deepest parts of all buildings is not possible with a cost-effective system. It is possible to estimate where the holes in coverage are; however, this is just a projection and specific coverage depends on building construction, reflections etc. Again, field measurements are the only mechanism to ensure that a potential system will perform adequately.

Radio wave reflections are a fact of life. In many cases these reflections allow a system to provide coverage in areas that are thought questionable after computer analysis. This is the case with the existing location of the trunking equipment. How these reflections benefit the system coverage cannot be predicted. Again field tests are necessary to show just how well the area is covered. However, a word of caution is appropriate for this phenomenon: at UHF the reflector does not have to be extremely large. It is possible for a reflecting surface to be present during a field test but be moved before the system is installed. Tractor trailers make fine reflectors but are quite mobile.

Field tests are one way to build confidence before a system is built and are recommended for this system. There are however some precautions that should be taken in performing these field tests. These precautions are provided along with a suggested testing strategy in the following section.

## **FIELD TESTING SUGGESTED STRATEGY**

This test strategy is intended to be a launching pad for testing that can be performed to verify the predictions in this report and to determine a few unknowns that were present in the development of this report. These are suggestions only and are not intended to be viewed as a conclusive test plan.

It is necessary to either transmit or receive the test signal from the very location of the final repeater antenna, or as close as possible. This will require the use of a portable tower, helicopter, or hot air balloon type platform. It is probably best to receive from the repeater site and transmit with the same type portable radio as will be used in the final system from various points in the field. This approach would allow the users to roam in the very same spots that they expect the system to operate in that may be difficult to reach with the necessary receive test equipment. This approach also allows the tests to duplicate the body shielding loss characteristics that will be present in the final system. The most complete test strategy would also test by transmitting from the tower location and receive from hip mounted portable radios wandering around in the field. Although this is not really necessary, the weak link is almost always receiving the signal from the portable radios.

When receiving the signal and determining whether it is adequate to activate a repeater (or other target receiver), it is necessary to either use identical antennas, cables, feed lines, filters, etc. as those that will be used in the final system. Properly calibrated equipment must be used so the received signal strength can be accurately determined. Care must be taken which units of measure are being recorded, dB $\mu$ V or dB $\mu$ V/meter. This report uses the latter; therefore, field tests intended to be compared with the results herein must take

the calibration factor of the test antenna into account. Overall pattern of the test antenna must also be considered and factored into the results.

With a 400-foot tower, it is possible that antenna downtilt may be required. It is also possible to peak the antenna gain in the direction it is needed most. An effort should be made to ensure that antenna pattern nulls do not occur in the direction of required coverage.

Perhaps the only way to give the user community the comfortable feeling that the final system will work is to allow them to test their radios from the areas that they normally operate. Coordinating this and providing a test configuration that allows this may be difficult to impossible but should be considered. There are over 200 of the portable radios in service in a conventional mode at K-25 and over 40 at X-10 that could be called upon for these tests, so test sources should not be a problem.

## **QUEUING THEORY CURVE VERIFICATION**

As more users move to the current system the airtime and busy data should be studied. When there is enough busy data a busy versus usage curve should be plotted for increasing number of channels. This actual data curve should then be compared to the family of curves provided in Figure 39 to verify that the selected queuing theory approach remains the best. It is possible that the trunking system will perform differently as more channels and more traffic are added. Since no queuing theory approach is tailor made for the trunking system, it may be better approximated by one approach for a large number of channels and another for a small number of channels. Remember, the busy data used as a basis for comparison was for a two-channel system.

## **PROJECTION TASKS**

These are tasks that should be accomplished to make projections concerning the additional use of the trunking system. Accurate predictions of how additional users will impact the system performance are necessary to allow additional channels to be sought well before they are actually required. The suggestions provided here will assist in this process.

### **ADDITIONAL USAGE PROJECTIONS**

It has been suspected, although not proven, that people use the trunking radios more than they used a conventional radio simply because there is less congestion. If a user has to contend with 150 other users for airtime, he may not bother unless absolutely necessary. With trunking it is possible to divide up the users into talkgroups where a user only shares with 50 or so others, all who have similar job functions. If this theory of additional use is accurate, then a straight projection of airtime from one system to another may not be realistic.

To validate this additional use claim, airtime data should be compared for the conventional users before and after they move to trunking. The KRF 260 conventional network would be an excellent first attempt at this since their network is to be divided into four talkgroups. These talkgroups should be monitored for a period of time and their usage statistics compared to those recorded for KRF 260 before the move. This comparison could result in a factor that could be applied against conventional traffic data for users scheduled to migrate in the future. The factor could be updated as each conventional network is migrated to the trunking system and more data is available.

## **MEASUREMENT OF CONVENTIONAL NETWORKS**

Each of the existing conventional networks should be monitored for a minimum of one month. Usage statistics resulting from this monitoring should be added to determine the total traffic load to which a wide area trunking system would be subject. To eliminate fluctuations in activity the preferred approach is to measure all networks over the same time period. However, this is not realistic or possible so the measurement period used for each network should be long enough to identify peak periods of usage.

## **COMPLETE SYSTEM DESIGN**

A super-site should not be built without first giving considerations to all elements of system design. A super-site is a potential single point of failure from the aspect of the tower blowing down or other catastrophic events. Radio trunking is inherently failsafe; however, a tornado could wipe out an entire repeater facility. (The tornado that hit Oak Ridge in February 1993 started within a few hundred feet of the Pine Ridge West tower.)

Conventional networks and hot standby of radio trunking equipment should be thoroughly studied before a system is implemented. If there are holes in coverage that do not satisfy the user community, perhaps judicious use of a conventional UHF network is the best way to provide supplemental coverage. Each site already has one conventional UHF repeater network at their disposal. These networks should be used to complement the super-site trunking system.

## **CONCLUSION**

All indications are that a super-site will provide the required coverage and make everyday life for radio users and administrators more pleasant. The super-site should be built.

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## APPENDICES

## APPENDIX A

### INSERTION LOSS CALCULATIONS

I - L - C A L C <sup>tm</sup> (Insertion Loss Calculator)

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FREQUENCY: 417 MHz  
CONNECTOR #1: TYPE N  
CONNECTOR #2: TYPE N  
CABLE LENGTH: 450 Ft

| ANDREW<br>CABLE TYPE | ATTENUATION<br>dB PER 100 Ft | ATTENUATION<br>dB TOTAL | INSERTION<br>LOSS TOTAL dB | EFFICIENCY<br>IN PERCENT |
|----------------------|------------------------------|-------------------------|----------------------------|--------------------------|
| FSJ1P-50A            | 3.78                         | 17.00                   | 17.07                      | 1.96                     |
| FSJ4P-50B            | 2.23                         | 10.02                   | 10.07                      | 9.84                     |
| LDF2P-50             | 2.21                         | 9.93                    | 10.00                      | 10.00                    |
| LDF4P-50A            | 1.45                         | 6.53                    | 6.60                       | 21.88                    |
| LDF5P-50A            | 0.80                         | 3.59                    | 3.72                       | 42.46                    |
| LDF6P-50             | 0.59                         | 2.66                    | 2.79                       | 52.60                    |
| LDF7P-50A            | 0.49                         | 2.22                    | 2.33                       | 58.48                    |
| HJ4P-50              | 1.70                         | 7.67                    | 7.76                       | 16.75                    |
| HJ4.5P-50            | 1.02                         | 4.60                    | 4.73                       | 33.65                    |
| HJ5P-50              | 0.79                         | 3.55                    | 3.64                       | 43.25                    |
| HJ7P-50A             | 0.43                         | 1.94                    | 2.01                       | 62.95                    |
| HJ12P-50             | 0.36                         | 1.63                    | 1.70                       | 67.61                    |

Attenuation calculations are based on nominal specifications. Insertion loss calculations include the nominal attenuation, the cable reflective losses, and the connector losses. Because insertion loss calculations include reflective losses, premium low VSWR cable is assumed because it provides a maximum guaranteed VSWR.

You should note that your actual measurements may differ from these calculations due to the accuracy of the measuring equipment. On shorter lengths where the insertion loss is less than 1.0 dB, the equipment accuracy can contribute significantly to the total measurement.

If you should have any questions, please contact Andrew Corporation for more information.

ANDREW CORPORATION  
10500 West 153rd Street  
Orland Park, IL 60462 U.S.A.  
Phone: 708-349-3300 or 800-255-1479 (in USA only)

## APPENDIX B

### CONVENTIONAL AIRTIME LOGGER SOURCE CODE

```
/* Conventional radio traffic counter
   Tracks number of calls and airtime for each 15 minute period in
   a 24 hour period produces one file per day
   Counts the number of squelch openings - January 12, 1993*/

#include <stdio.h>
#include <math.h>
#include <time.h>
#include <dos.h>
#include <stdlib.h>

#define IQUIT 0

double difference = 0, inc_airtime=0, airtime=0;
time_t *start_time, *stop_time, *inc_time, *now_time;
struct tm *time_data, *time_hold, *inc_data;
char *file_name, netid[20];
int total_calls=0, inc_calls=0, this_min, inc_mark=0,
    day_mark=0, inc_min, hold_min=0, hold_yday;
FILE *fp;

/* Function to determine how long the network was busy this squelch opening */

double squelch()
{
time_t *call_start, *call_stop;

*call_start = time(NULL);
while(inportb(1022) == 16)
{
}
*call_stop = time(NULL);
difference = difftime(*call_stop, *call_start)-1.5; /*subtract out ICOM delay */
return difference;
}

/* Function to wrap up and quit gracefully so data is not lost */

int wrapup (void)
{
printf("I Quit!\n");
airtime = airtime + inc_airtime;
```

```

total_calls = total_calls + inc_calls;
fprintf(fp,"%02d%02d\t%.2f\t%.2f\n",inc_data->tm_hour,inc_data->tm_min,
        inc_airtime,inc_calls,inc_airtime/(inc_calls+.001));
printf("%02d%02d\t%.2f\t%.2f\n",inc_data->tm_hour,inc_data->tm_min,
        inc_airtime,inc_calls,inc_airtime/(inc_calls+.001));
fprintf(fp,"\n---TOTALS---\n\n");
fprintf(fp,"%02d%02d\t%.2f\t%.2f\n",inc_data->tm_hour,inc_data->tm_min,
        airtime,total_calls,airtime/(total_calls+.001));
fclose (fp);
exit(IQUIT);
}

main()
{
    ctrlbrk(wrapup);          /* quit if ^C encountered */

/* initialize the program with the date
create and open a file using the date as the filename */

    *inc_time = time(NULL);          /* inc_time is marker for */
    inc_data = localtime(inc_time);  /* each 15 min interval */
    inc_min = inc_data->tm_min;        /* hold_time is day marker */
    hold_min = time_hold->tm_min;
    *start_time = time(NULL);
    time_hold = localtime(start_time);

/* create the file_name and open the file */
    sprintf(file_name,"%d_%d.DTA",(time_hold->tm_mon+1),time_hold->tm_mday);
    fp = fopen(file_name,"w");

    printf("\n ^ C TO QUIT\n");
    printf("Enter the Net ID of the Network being monitored:\t");
    gets(netid);

    fprintf(fp,"The Network Being Monitored is: %s\n",netid);
    fprintf(fp,"Filename -> %d_%d.DTA\n",(time_hold->tm_mon+1),
            time_hold->tm_mday);
    p r i n t f ( " F i l e n a m e - >
%d_%d.DTA\n",(time_hold->tm_mon+1),time_hold->tm_mday);

    fprintf(fp,"\nPeriod\tAirtime\t\tCalls\tAvg Time per Call\n");
    printf("\nPeriod\tAirtime\t\tCalls\tAvg Time per Call\n");

/* start collecting data */

    for (;;)
    {
        *now_time = time(NULL);

```

```

time_data = localtime(now_time);
this_min = time_data->tm_min;

/* use day_mark and inc_mark to keep from writing the
   data for a full minute */

if(this_min >= hold_min+1 && time_data->tm_hour==00)
    day_mark=0;
if(this_min >= inc_min+1)
    inc_mark=0;

/* Check for a new day wrap up the old day and start a new file */

if (time_data->tm_hour == 00 && time_data->tm_min==00 &&
    time_data->tm_yday > hold_yday && day_mark==0)
{
    day_mark=1;
    airtime = airtime + inc_airtime;
    total_calls = total_calls + inc_calls;
    fprintf(fp,"%02d%02d\t%.2f\t\t%.2f\n",inc_data->tm_hour,
        inc_data->tm_min,inc_airtime,inc_calls,
        inc_airtime/(inc_calls+.001));
    printf("%02d%02d\t%.2f\t\t%.2f\n",inc_data->tm_hour,
        inc_data->tm_min,inc_airtime,inc_calls,
        inc_airtime/(inc_calls+.001));
    fprintf(fp,"n---TOTALS---\n\n");
    fprintf(fp,"%02d%02d\t%.2f\t\t%.2f\n",inc_data->tm_hour,
        inc_data->tm_min,airtime,total_calls,
        airtime/(total_calls+.001));
    fclose(fp);
    airtime = 0;
    total_calls = 0;
    inc_airtime = 0;
    inc_calls = 0;
    *start_time = time(NULL);
    time_hold = localtime(start_time);
    hold_min = time_hold->tm_min;
    hold_yday = time_hold->tm_yday;
    sprintf(file_name,"%d_%d.DTA",(time_hold->tm_mon+1),
        (time_hold->tm_mday));
    fp = fopen(file_name,"w");
    fprintf(fp,"The Network Being Monitored is: %s\n",netid);
    fprintf(fp,"Filename -> %d_%d.DTA\n",(time_hold->tm_mon+1),
        time_hold->tm_mday);
    printf("Filename -> %d_%d.DTA\n",(time_hold->tm_mon+1),
        time_hold->tm_mday);
    fprintf(fp,"nPeriod\tAirtime\t\tCalls\tAvg Time per Call\n");
}

```

```

        if((this_min==0 || this_min==15 || this_min==30 || this_min==45)
            && inc_mark==0)
        {
            inc_mark=1;
            fprintf(fp,"%02d%02d\t%.2f\t\t%.2f\n",inc_data->tm_hour,
inc_data->tm_min,inc_airtime,inc_calls,
                inc_airtime/(inc_calls+.001));
            printf("%02d%02d\t%.2f\t\t%.2f\n",inc_data->tm_hour,
                inc_data->tm_min,inc_airtime,inc_calls,
                inc_airtime/(inc_calls+.001));
            airtime = airtime + inc_airtime;
            total_calls = total_calls + inc_calls;
            inc_airtime = 0.;
            inc_calls = 0;
            *inc_time = time(NULL);
            inc_data = localtime(inc_time);
            inc_min = inc_data->tm_min;
        }
        if(inportb(1022) == 16)
        {
            inc_calls = inc_calls + 1;
            inc_airtime = inc_airtime + squelch();
        }
    }
}

```

## APPENDIX C

### CONVENTIONAL AIRTIME LOGGER SAMPLE OUTPUT

The Network Being Monitored is: trunking channel 5

Filename -> 1\_11.DTA

| Period | Airtime |    | Calls | Avg Time per Call |
|--------|---------|----|-------|-------------------|
| 0915   | 153.00  | 18 | 8.50  |                   |
| 0930   | 315.00  | 22 | 14.32 |                   |
| 0945   | 220.00  | 22 | 10.00 |                   |
| 1000   | 306.50  | 31 | 9.89  |                   |
| 1015   | 206.50  | 23 | 8.98  |                   |
| 1030   | 244.50  | 25 | 9.78  |                   |
| 1045   | 217.50  | 21 | 10.36 |                   |
| 1100   | 79.50   | 13 | 6.11  |                   |
| 1115   | 79.00   | 6  | 13.16 |                   |
| 1130   | 40.00   | 10 | 4.00  |                   |
| 1145   | 31.00   | 4  | 7.75  |                   |
| 1200   | 61.00   | 10 | 6.10  |                   |
| 1215   | 76.50   | 13 | 5.88  |                   |
| 1230   | 232.00  | 30 | 7.73  |                   |
| 1245   | 301.00  | 34 | 8.85  |                   |
| 1300   | 350.00  | 38 | 9.21  |                   |
| 1315   | 174.00  | 24 | 7.25  |                   |
| 1330   | 234.50  | 27 | 8.68  |                   |
| 1345   | 210.00  | 20 | 10.50 |                   |
| 1400   | 257.00  | 28 | 9.18  |                   |
| 1415   | 199.50  | 21 | 9.50  |                   |
| 1430   | 219.50  | 29 | 7.57  |                   |
| 1445   | 235.50  | 25 | 9.42  |                   |
| 1500   | 186.50  | 31 | 6.02  |                   |
| 1515   | 104.00  | 18 | 5.78  |                   |
| 1530   | 118.00  | 12 | 9.83  |                   |
| 1545   | 35.00   | 6  | 5.83  |                   |
| 1600   | 70.50   | 7  | 10.07 |                   |
| 1615   | 92.00   | 6  | 15.33 |                   |
| 1630   | 60.50   | 5  | 12.10 |                   |
| 1645   | 21.00   | 4  | 5.25  |                   |
| 1700   | 41.50   | 5  | 8.30  |                   |
| 1715   | 16.50   | 3  | 5.50  |                   |
| 1730   | 77.00   | 10 | 7.70  |                   |
| 1745   | 45.50   | 5  | 9.10  |                   |
| 1800   | 82.50   | 9  | 9.17  |                   |
| 1815   | 18.00   | 4  | 4.50  |                   |
| 1830   | 85.50   | 9  | 9.50  |                   |

|      |       |   |      |
|------|-------|---|------|
| 1845 | 35.00 | 6 | 5.83 |
| 1900 | 18.00 | 4 | 4.50 |
| 1915 | 23.00 | 4 | 5.75 |
| 1930 | 32.50 | 5 | 6.50 |
| 1945 | 9.50  | 3 | 3.17 |
| 2000 | 10.00 | 2 | 5.00 |
| 2015 | 18.00 | 4 | 4.50 |
| 2030 | 27.00 | 4 | 6.75 |
| 2045 | 19.50 | 3 | 6.50 |
| 2100 | 32.00 | 4 | 8.00 |
| 2115 | 13.50 | 3 | 4.50 |
| 2130 | 5.50  | 1 | 5.49 |
| 2145 | 27.50 | 3 | 9.16 |
| 2200 | 8.00  | 2 | 4.00 |
| 2215 | 20.00 | 4 | 5.00 |
| 2230 | 15.00 | 2 | 7.50 |
| 2245 | 3.50  | 1 | 3.50 |
| 2300 | 7.50  | 1 | 7.49 |
| 2315 | 6.50  | 1 | 6.49 |
| 2330 | 9.00  | 2 | 4.50 |
| 2345 | 18.00 | 4 | 4.50 |
| 0000 | 7.00  | 2 | 3.50 |

---TOTALS---

|      |         |     |      |
|------|---------|-----|------|
| 0000 | 5862.50 | 693 | 8.46 |
|------|---------|-----|------|

## VITA

Brian Joseph Kaldenbach was born in LaPlata Maryland on May 29, 1958. After graduating from LaPlata High School with honors in June 1976, he worked as an electronics technician while pursuing higher education working on phased array antennas, target trackers and Monolithic Microwave Integrated Circuits. He received a Bachelor of Science in Engineering with an emphasis in Electronics from the University of Central Florida in July 1983. After graduation, attended Officer Candidate School for the U.S. Air Force and was commissioned in November 1983. He was assigned to the Rome Air Development Center as a development engineer in satellite communications research and development and was involved in several interesting programs developing processing satellites. This included adaptive antennas and a packet satellite communications network involving hundreds of small low earth orbiting satellites. After separation from the Air Force he worked as a systems engineer in various communications systems including land mobile radio systems. He entered the University of Tennessee in August of 1988 and received a Master of Science degree in Electronics Engineering in May 1993.