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The Use of Burst Transmission to Increase Communication Range — A Feasibility Study

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Preface

The study presented in this report represents a major portion of a project supported by the U.S. Army Communications Systems Agency, Fort Monmouth, New Jersey, on project order No. 107 RD. The action officer at the Communications Systems Agency was Mr. Peter S. Jaworski. The project technical monitor was Mr. George Lane of the U.S. Army Communications - Electronics Engineering Installation Agency, Fort Huachuca, Arizona.

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THE USE OF BURST TRANSMISSION TO INCREASE COMMUNICATION RANGE--A FEASIBILITY STUDY

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Although the use of transmissions that are composed of bursts of information is not new, its application in a terrestrial environment at VHF and UHF is. The usual way of expressing the variabilities in received signal level due to propagation effects for the design of conventional telecommunication systems is inadequate for burst transmission. Instead of using time and location variabilities, the concept of "waiting distance" is introduced and its magnitude is estimated. The waiting distance represents how far one terminal probably must move to have reached a favorable location where a transmitted burst will be successfully received. Acceptance of the waiting distance is a trade-off to achieve an extended range or a power advantage.

This report first examines the concepts of a burst transmission system in the context of using the location variability to estimate the waiting distance, and the associated range extension, in terms of the correlation distance of the received signal level. Using this theory and both previous and current measurements the correlation distance is estimated and, hence, so is the waiting distance. The estimates of the correlation distance range from 200 to 800 m. Recommendations for future efforts are proposed.

Key words: burst transmission; radio propagation; terrain; UHF; VHF; variability

1. INTRODUCTION

A new kind of radio communication system has been suggested for use in such areas as Army tactical communications and, more generally, land mobile communications. The word "new" is perhaps an exaggeration; for although the use proposed is certainly new, the basic concepts have been known before. Calling the concept "burst transmission," the idea is that a message to be sent is first stored in a local memory device and the system waits until a link to the intended

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receiver can be established; when radio propagation conditions are sufficiently good, the message is quickly transmitted in a single burst.

One can imagine several protocols for establishing the required link. One that comes immediately to mind is presently used in "meteor-burst" communication systems that make use of the intermittent appearance of ionized meteor trails in the lower ionosphere. In a typical meteor-burst system when a "master" station wishes to receive a message, it probes one or more "remote" stations by repeatedly transmitting a command signal. When a remote station receives one of these command signals and identifies its address in the signal, it can assume that a suitably positioned meteor trail has formed; it therefore immediately transmits its message (on an adjacent frequency) before the meteor trail has had time to disperse.

In the system we are studying here we do not mean to rely on meteor trails but wish to use the usual mechanisms of radio propagation in the VHF and UHF ranges. We therefore rely on the fact that at these frequencies the received signal levels exhibit large, erratic variations in both time and space, and our system waits until the signal levels are sufficiently high. Instead of dreading those moments when the signal has faded below the system threshold, we look forward to those times or places when it is exceptionally high. We have a reliable communication system with an unreliable propagation path.

2. RADIO WAVE PROPAGATION AND BURST TRANSMISSION

In the following sections we shall make some preliminary calculations related to a burst communications system.

As we have said, such a system will depend for success on the variability of received signal levels. To understand how the system will perform, we should study this variability, trying to understand what its sources are, how large the variations are and over what ranges they take place.

Let us first point out that in the usual way of looking at the subject there are two quite different scales of variability--i.e., two different ranges of fluctuation rates--that must be considered. There is a small scale, usually related to multipath, and a considerably larger scale that has to do with gross changes in the terrain or in the atmosphere. One principal reason for making this distinction is that multipath fading is often amenable to hardware solutions. Most diversity schemes, for example, will provide fairly successful solutions to multipath problems, and some of the spread spectrum systems, particularly those that involve frequency hopping, will similarly smooth multipath fading. On the other hand, these same solutions will not be effective in combatting the large scale ("power fading") variations.

2.1 Temporal Variability

Variations in time are due mostly to changes in the atmosphere. The refractivity of air is a function of temperature, pressure, and humidity, and these quantities can vary quite considerably from instant to instant and from point to point. On paths where the dominant mode of propagation is tropospheric scatter, the radio waves scatter from numerous "blobs" of changing refractivity high in the turbulent atmosphere. The received signal is therefore the vector sum of many waves of varying strengths and relative phases. The received power is then a rapidly varying random function of time whose first order statistics within, say, an hour of time, follow the Rayleigh distribution. This is the small scale, multipath variability. The observed median power (the "hourly median") will depend on the number of scattering "blobs" and their scattering efficiencies, both of which depend in turn on the general condition of the atmosphere. Since this general condition is continually varying, there will be an hour-to-hour change in the median power, and this will represent the large-scale variability. Since we are talking here about weather, we would expect diurnal and seasonal effects.

On shorter paths, where the direct line-of-sight wave and diffracted waves overwhelm waves that may be scattered from atmospheric inhomogeneities, there is usually very little small-scale variability--only a slight scintillation. Large-scale changes come about because of overall changes in the refractivity structure of the atmosphere. These changes cause the rays to be bent by differing amounts, thus changing points of reflection and diffraction angles. The consequent changes to received signal level, however, are usually minor.

Occasionally there will be a short, fixed path that exhibits strong, rapid fluctuations. Such a path is probably obtaining a signal by way of a large multiplicity of waves scattered from trees, buildings, and hillsides. The relative phases of the various waves change, and these changes are, in turn, caused by local changes in atmospheric refractivity or by motion of the scattering objects such as when the wind blows in the trees or when vehicular traffic is present.

Other causes of occasional short-term enhanced fields are mostly concerned with objects in the sky: ionized meteor trails, airplanes, birds, insects, and the radar "angels." The latter three, of course, are effective only at microwave frequencies.

This summary of the causes and effects of time variability shows, it seems to us, that such variations cannot be counted upon for a burst communication system. There are, of course, meteor burst systems. And for tropospheric scatter paths "adaptive receivers" have been designed which have many of the properties of a burst communications system and in that way help to combat the short-term fading. But for frequencies between 100 MHz and 1000 MHz and for intermediate distances, time variability seems neither adequate in size nor sufficiently rapid to render any particular advantage to a burst system. Long-term variability, for example, occurs diurnally or even seasonally. Having to wait days for a message to be sent does not seem worthwhile.

2.2 Spatial Variability

Spatial variability, however, may very well provide a different result. In this case we should imagine a mobile system in which one or both of the terminals is continually in motion. In that way, spatial variability is translated to variations in time that are the bane of the usual mobile communications, but could prove beneficial to a burst system.

Small-scale spatial variability is due to multipath caused by scattering from various objects--particularly from those near the moving terminal. It is usually present when the moving antenna is at the normal heights for a mobile unit. Very often the multiplicity of paths is sufficient to produce statistics observed over short runs that follow the Rayleigh distribution.

Large-scale spatial variability is usually referred to as "location" or "path-to-path" variability. It is mostly due to the simple fact that when a terminal changes position the terrain between terminals changes. Off-path terrain might also enter as when a hill or mountain is in clear sight of both terminals. Both small-scale and large-scale variability are nearly always present. Small-scale variability has a standard deviation of perhaps 5 dB and large-scale a standard deviation approaching 10 dB. These numbers make a burst transmission system seem attractive.

To understand just how attractive, we must compare it with a normal system. Let us call such a normal system a "demand" system to emphasize that it should be available on demand whenever one wants to send a message. Now, in designing a demand system, one must remember that the received signal level will vary and that therefore one must allow for a "fade margin"--an extra amount that the system's power budget must have to combat particularly low signal levels. On the other hand, a burst system might possibly use a negative fade margin--an amount that the power budget does not need because the system can wait for a high signal level. The advantage could be 20 dB or greater.

To utilize this advantage, one might employ more compact equipment with lower output power and smaller antennas; or one might, as we shall do below, use the same power output and the same antennas and expect that the system will be viable over an extended range.

2.3 Relevant Previous Measurements

Data from previous radio propagation measurement programs and from terrain studies may provide some understanding of the effects of using a modulation format composed of bursts. Based on the previous discussion we shall consider a burst communication system to depend principally on location, or path-to-path, variability. In other words, at some receiver terminals within a given area of interest the received signal levels could vary greatly, yet all of the terminals could be considered to be essentially equidistant from the transmitter. Present estimates of the location variability are empirical and have been found to be dependent on the large-scale terrain irregularity, characterized by the parameter Δh, the wavelength λ, and to a lesser extent on the antenna elevations. Longley (1976) shows that the standard deviation σ of the location variability is a function of the ratio $\Delta h/\lambda$.

In addition to the variability in signal level from one location to another we may also observe rapid fluctuations as one antenna is moved several wavelengths. This fading, caused by the phase interference between multiple components in the received signal, is usually called multipath fading. The two types of variation can be considered separately if we consider medians of short runs or stationary measurements in estimating the location variability, and then to consider the additional effects of multipath. In general, the measurements have shown that the location varability follows a log-normal distribution, while the multipath distribution is usually Rayleigh or modified Rayleigh.

In the following we shall describe past measurements that appear to be relevant to this study. In most cases the information we are seeking cannot be obtained from the published data; instead, one must acquire the raw or complete data, which are probably in the form of analog strip charts and difficult to use. Some of these measurements, however, are the basis of a propagation model that can be used to compute the location variability and, in turn, the range extension. This model is described in Section 3.

Those few of the previous measurements that contain sufficient information have been examined and are used to compute a correlation distance. These measurements are described in Sections 4.3.1 and 4.3.2.

1. The TASO Measurements. These measurements at VHF and UHF were made on television transmissions from about 15 cities in the United States. The transmitters, therefore, were fixed and the receivers were mobile. Using frequencies that ranged from 55 to nearly 800 MHz, measurements were made along radials from the transmitters to distances of 145 to 160 km, in some cases. A wide range of terrain types was involved--from very smooth to highly mountainous. This large body of data provides much information on location variability and its dependence on terrain irregularity and radio frequency. A summary of this measurement program is given by Head and Prestholdt (1960).

2. Measurements by the FCC. These measurements were made by the Federal Communications Commission using three frequencies in New York City and its environs. The three transmitters were located on the same tower; their frequencies were 55, 175, and 578 MHz. The measurements were made along radials and circular arcs, and are described by Hutton (1963). These measurements are similar to the TASO measurements.

3. Measurements made by ITS and its Predecessors. This large series of measurements were made from mobile transmitters to stationary receivers at frequencies that ranged from 20 MHz to 10 GHz. The terrain included all types from very smooth to highly mountainous. In nearly all of the measurements, the transmitting antennas were less than 10 m above the ground. The measurements were made under the direction of A. P. Barsis (see Barsis et al., 1964, 1965, and 1969). Further measurements or results and analyses have also been published (Hufford and Montgomery, 1966; Johnson et al., 1967; Kirby and Capps, 1956; Kirby et al., 1956; and McQuate et al., 1968, and 1971). These measurements represent a major portion of the basis of the ITS Irregular Terrain Model--the ITM. This model has been called the Longley-Rice model (Longley and Rice, 1968; Hufford et al. 1982). It will be used in Section 3 to make computations of range extensions.

4. The Ohio-Mobile Measurements. These measured data were collected by a mobile receiver on circles centered on the transmitter. The frequencies measured were near 100 MHz. These data were collected and reported by the United Broadcasting Company (UBC) under subcontract to the Central Radio

Propagation Laboratory (CRPL) of the National Bureau of Standards (a predecessor of ITS). This work was documented in a series of informal UBC reports between March 1950 and June 1953. Reference to these reports and the measurements can be found in Herbstreit and Rice (1959). These data are the kind needed to make estimates of the correlation distance.

5. Measurements with Low Antennas. These propagation measurements used very low antenna heights and were made at 230 and 410 MHz. They are reported by Hause et al., (1969).

6. Sensor Communication Measurements. These measurements involved very low antennas and frequencies in both the VHF and UHF ranges. They are described by Longley and Hufford (1975).

7. Bell Aerosystems Data. During 1963 and 1964, Bell Aerosystems Company performed propagation measurements for the U.S. Army Electronic Proving Ground, Fort Huachuca, Arizona. The objective was to obtain data that would be suitable for conversion to values of propagation path loss. Frequencies in both the VHF and UHF ranges were measured. These were spot measurements on a number of paths with a common terminal in both the smooth desert and the mountains of Arizona (Williams, 1965).

2.4 Recent Measurements in Colorado

Because of a set of favorable circumstances, it was possible to perform some measurements as part of the work done on this study. It was possible for the Institute for Telecommunication Sciences to borrow equipment that used a burst type transmission format. This equipment was of a prototype nature; therefore it had been designed to provide certain performance measures such as block and message counts. The received signal level data were also provided at a test port on the receiver.

A short measurement program was carried out during August and September of 1981 in the vicinity of Boulder, Colorado. It was the intent of these measurements to collect propagation data relevant to a burst system over several kinds of terrain. Measurements were made on the rolling high plains of eastern Colorado, through the "eastern slope" mountains and foothills, and on paths that parallel the mountains. Measurements were made while one terminal was in motion and when both were stationary. The propagation data referred to above include records of successful block (10 characters) and message (130 characters) transfers with a simultaneous record of the received signal level. We reasoned that this information could provide an estimate of the waiting distance or waiting time. The appendix to this report describes the equipment, procedures, and the data collected.

There were several disadvantages in using this equipment which was designed for meteor-burst applications. One of the basic shortcomings was that the burst length was fixed. Another major shortcoming was that the block and message counters would only tally to 999 and then simply begin with 000 again. Although satisfactory for the study of meteor-burst transmission, the rapid accumulation of blocks or messages recorded at infrequent intervals rendered these data unreliable for our purposes. The receiver dynamic range was only 30 dB which was insufficient for the signal level ranges expected and observed in the terrestrial environment.

Some of the problems were overcome. A wide dynamic range receiver was used to augment the received signal level data from the borrowed equiment. Some episodes of measurement were slow enough to allow valid counts of blocks or messages. Examples of the measurements are given in the appendix and some of the data are used in Section 4 to examine the waiting distance.

3. RANGE EXTENSION

To compute what an extended range might be, we shall appeal to the ITS Irregular Terrain Model--the ITM (see Longley and Rice, 1968, and Hufford et al., 1982). This is a general purpose model of radio propagation for the VHF and higher bands. It emphasizes the signal variability and therefore seems ideally suited for the kind of analysis we want to make.

Our first task is to design the demand system. We shall suppose that the threshold signal level must be exceeded for a rather conservative 90% of the locations. This value is the <u>required location availability</u>. Its value is a compromise between demanding a suitable signal at all locations and not requiring an unreasonably large fade margin. We shall also have to choose frequency and antenna heights, but for the remaining system parameters of power output and antenna gains, we merely assume that the system has been designed for a given range in average terrain and that the power budget is properly adjusted for that range. The 90% quantile of basic transmission loss at the given range thus becomes the <u>tolerable loss</u> for the demand system. For a burst system we then relax the required location availability and compute the new, larger range at which the tolerable loss is reached.

In Table 1 we present the results of such calculations for two different basic systems. The first is a small mobile-to-mobile system using 2 m antenna

Table 1. Range Extension Using Burst Communications

System[1]	f (MHz)	Δh (m)	Tolerable Loss (dB)	Range as a function of Location Availability 90%[2] (km)	50% (km)	20% (km)	10% (km)
A	50	90	151	10	20	31	38
		200	151	9	21	34	41
A	150	90	160	10	22	33	40
		200	160	9	22	33	39
A	400	90	164	10	22	32	37
		200	164	7	16	25	30
B	150	90	170	50	75	91	100
		200	170	46	73	91	101
A'	150	90	165	10	35	48	55
		200	165	9	34	47	54
B'	150	90	175	50	93	112	130
		200	175	46	93	113	124

Note 1: Systems A and A' have 2 m high antennas and are designed so that in average terrain the demand system has a range of 10 km. Systems B and B' have 15 m antennas and a demand system range of 50 km. Systems A and B use special techniques to control multipath fading. Systems A' and B' do not, and the values here assume Rayleigh fading.

Note 2: The 90% column represents a demand system. The remaining columns show how a burst system might behave. In any case, values given are design figures; with 90% confidence there will be at least 90% of the time during which system performance is better than that shown.

heights and having the demand system designed for a 10 km range. Results for three different frequencies are given. The second system is larger with 15 m antenna heights and a 50 km range. All demand systems are designed to operate properly in average terrain--i.e., in terrain with an irregularity parameter Δh=90 m. Also shown are the resulting ranges when the same systems operate in mountainous terrain with Δh=200 m. For the burst systems we have used three successively smaller design specifications for the required location availability. Clearly, the smaller the value one is willing to use here, the larger will be the resulting extended range.

The ITM uses three different kinds of statistics to describe signal level variability. In addition to location variability, there are (long-term) time variability and "situation" variability (prediction error). The latter may be interpreted as the variability observed when the entire system is transported from one area to other similar areas. It can be used to define confidence levels, especially when one contemplates using a system in only one area. For the values in Table 1 we have used the 90% quantiles for both the situation and time variabilities. Thus one should read the results as saying that with 90% confidence there will be at least 90% of the time when both the demand systems and the burst systems perform better than indicated. The numbers given are fairly conservative design figures.

At the demand system range, the effect of decreasing the specified location availability from 90% to 50% is about 13 dB. This results from the fact that the location variability is normally distributed with a standard deviation of 10 dB. This 13 dB would offset the increased transmission loss at an extended range. This can also be viewed as a power advantage which is quantified in Table 2.

Table 2. Power Advantage versus Location Availability

Location Availability, %	90	70	50	30	10
Power Advantage, dB	0	7.6	12.9	18.2	25.7

Thus far we have not mentioned the small-scale multipath fading; nor has it entered into our calculations. These calculations, therefore, refer to systems that combat multipath fading by, for example, using diversity reception or some suitable form of spread spectrum modulation. On the other hand, if we want to consider a simple narrowband system that does not employ diversity, we must make a further analysis.

For the demand system, a common design procedure here is to assume Rayleigh fading and to require an additional fade margin so that under the worst of the design conditions the signal level will still be high enough to allow reception at 80% of the points of a short mobile run. From the Rayleigh law it follows that the additional fade margin needed is 4.9 dB. The Rayleigh law is assumed because, when conditions are otherwise bad and the local median signal level is low, then multipath fading is very likely to be Rayleigh distributed.

For a burst system it would seem unnecessary to require this additional fade margin. Indeed, believing that under worst conditions Rayleigh fading is the rule, it should even be possible to plan on a negative margin. If we use a not too optimistic 20% quantile here, we can plan on a margin of -3.7 dB, giving us an 8.6 dB advantage over the demand system. Providing messages are short enough to be sent during an up-loop of the fading process, there should be almost no penalty attached to this advantage since the high signal levels should be available within a very few wavelengths.

The last two rows of Table 1 show the effects of including Rayleigh fading in the calculations. The systems treated are the same as above except that their power budgets have been increased to allow the demand systems to directly combat small-scale fading.

3.1 Contributions of Anomalous Propagation

Table 1 is based primarily upon standard modes of radio wave propagation, those that are sufficiently prevalent, predictable, and reliable to achieve the demand system. Of course, there are other modes of propagation associated with other than the usual, prevalent atmospheric structures and/or off-path conditions. However, because their occurrence or other characteristics have been considered insufficient for reliable telecommunications, they are known as the anomalous (or non-standard) modes of propagation. Some examples are:

- propagation via surface ducts and/or elevated ducting layers in the presence of strong atmospheric refractivity layering

- off-path scattering from heavy rainfall, or dominant terrain features (LOS from both terminals).

Each of these anomalous modes in the proper geometry is characterized by propagation losses that can be significantly less than those of the standard modes and is therefore capable of providing range extensions that can appreciably exceed those of Table 1.

Of course, ducting has long been recognized as a source of significant range extensions, but it is also a somewhat localized phenomenon over land. Although elevated ducts are quite common in some localities (for up to 50% of some seasons near the Great Lakes and in the vicinity of the Gulf of Mexico and Southern California coasts), for only a fraction (tenths) of those occasions will the ducting accommodate transmissions in the VHF bands (Dougherty and Dutton, 1981). Despite the significance of locale and operating frequency, this ducting mode is capable of tremendous range extensions (several hundreds of kilometers over land, thousands of kilometers over, or in the vicinity of water) and may be of interest for future work. However, the use of short bursts of information (tenths of seconds or less) is not required for exploiting the range extensions achievable by elevated ducts.

The range extensions by scattering from rainfall or dominant terrain features (visible from both terminals) are less impressive, but they exhibit a similar dependency upon locale. Both the occurrence of heavy rainfall and of dominant terrain features are very much (probably uncorrelated) functions of geography. In a sense, the contributions of these off-path scatterers may already be included in Table 1 in the estimates of time variability and/or locational variability and the Δh. Their contributions in a systematic manner are worthy of further future study.

4. WAITING DISTANCES

As we have pointed out, it is location variability that is most promising for making a burst communication system worthwhile. There is, however, a penalty to be paid for the advantageous extended ranges given in Table 1 -- one must wait for some interval of time before an intended message will be transmitted. In this section we will discuss how we might compute such waiting times. Or rather, since it makes more sense here to ask how far we must move before a message is sent, we shall try to compute what we might call a waiting distance. Note that it is a random variable subject to laws of probability; it is thus more correct to say it is the distance we will probably need to go before the message is sent.

This may be illustrated by an allied question, but one simpler to answer. Consider the case where we make a discrete sequence of independent trials at each of which we determine whether or not the message was sent successfully. We then ask how many trials are probably required until success is finally achieved.

Let q be the probability of success at each trial. Then p=1-q is the probability of failure. After the first trial there will be probability p that the message has not yet been sent. After n trials there will be probability p^n that none of the trials were successful and that the message has not yet been sent. Thus

$$r = 1 - (1 - q)^n \tag{1}$$

is the probability that the message has been sent on or before the nth trial. Solving for n, we find

$$n = \ln(1 - r)/\ln(1 - q) \quad , \tag{2}$$

which is the number of trials needed in order to achieve success with probability r. Note that this formula is in terms of the "availability" q of the signal and the "reliability" r for which the system is successful. For example, if we have 10% availability of the signal and if we require a 90% reliability, then we should plan on making about 22 trials.

4.1 Probability of Success

For the problem in which we are directly concerned, we must suppose that the received signal level w(s) is a random function of the displacement s along the route the moving terminal takes. We must suppose a threshold value W and must ask for the distance x that the terminal should move until the probability that w(s)>W will exceed a reliability r. This differs from the above problem of discrete trials in that (1) there is now a continuum of trials to be made and (2) successive trials are not independent.

The inverse problem is to compute the probability that w(s)>W over an interval of length x. Allied problems are to find the cumulative distribution of the maximum value of w(s) over the same interval or to compute statistics for the number of "upcrossings" over that interval of the level W. These are important problems that arise in several branches of applied mathematics. Unfortunately, there seems to be no convenient solution to any of them.

To make the problem more definite, we shall assume that w(s) is a stationary Gaussian process so that all statistics are well defined once we know the mean w, the standard deviation σ, and the autocorrelation function $\rho(s)$. The latter represents the correlation between signal levels measured at two points separated by an interval of length s. To justify this assumption we note first that empirical measures of the first order statistics of location variability have consistently suggested a normal distribution. It does not seem far-fetched to suppose that higher order statistics will also be normal. Justifying stationarity is a little more difficult. Propagation models such as the ITM will particularly predict that there is a nontrivial dependence on the path length (between the two terminals) and on the terrain irregularity of the mean, the standard deviation, and probably of the autocorrelation function. We must assume that the moving terminal always moves transversely to the propagation path and that the terrain is homogeneously irregular. Alternatively, we can try to extract such trends from the data and speak only of the residuals. While somewhat abstract, one would expect the consequences to be extendable to the realistic situation.

But even when such simplifying assumptions are made, there seems to be no simple solution to our problem. While it is easy enough to formulate the solution, the resulting limit of repeated integrals cannot be reduced to a manageable form. A summary of what is known about the solution may be found in Cramér and Leadbetter (1967). Heuristic developments of some of these results are given by Rice (1945).

Using the standard notation of Abramowitz and Stegun (1964), we set

$$Z(v) = \frac{1}{\sqrt{2\pi}} e^{-v^2/2} \tag{3}$$

$$Q(v) = \int_v^\infty Z(v)\, dv \tag{4}$$

so that Z(v) is the density function of the standard normal distribution and Q(v) its complementary cumulative distribution function.

Let $p_1(W,x)$ be the probability that $w(s) \leq W$ for all s in an interval of length x. (Because the process is stationary, we need not specify the location of this interval, only its length.) Then p_1 is the probability that the system fails to send its message within the interval. We have $p_1 = 1 - r$, where r, the reliability, is the probability of success. Note that $p_1(W,x)$ is also the cumulative distribution function of the maximum value of $w(s)$ within an interval of length x. Note also that

$$p_1(W,0) = p = 1 - q \tag{5}$$
$$= 1 - Q((W - \bar{w})/\sigma)$$

where q is the location availability--the probability that a sufficient signal level is immediately available.

To continue, we must assume that the autocorrelation function $\rho(s)$ satisfies certain regularity conditions. Of course, we automatically know that $\rho(s)$ is an even function with $\rho(s) \leq 1$ and $\rho(0)=1$. In addition, we assume $\rho(s)$ tends smoothly to zero as s becomes large, and that for small s we have

$$\rho(s) = 1 - \frac{s^2}{2D^2} + O(s^4). \tag{6}$$

The notation $O(f(s))$ means, as in its customary use, a residual function of s having the same order of magnitude as $f(s)$. Most natural processes will satisfy these conditions. For example, if the second derivative $\rho''(0)$ does not exist (as in the simple Markov process where $\rho(s)=e^{-\alpha|s|}$), then the function $w(s)$ is nowhere differentiable and is unbounded in any interval--certainly not the kind of behavior one expects for the received signal level.

4.2 The Waiting Distance Function

Note that in (6) we have introduced a new parameter D. We shall call it the correlation distance for it provides a measure of the distance within which the process remains strongly correlated. If the residual function is small enough, we may say that D is approximately the distance at which the correlation decreases to 1/2. It will turn out to be an important parameter for us.

We define the quantity

$$\mu = (2\pi)^{-1/2} Z(v), \tag{7}$$

where

$$v = (W-\bar{w})/\sigma. \tag{8}$$

Then Cramér and Leadbetter (1967) provide us with two limiting results that are useful.

First, if x is small, we have

$$P_1(W,x) = p - \mu x/D + O(x^2). \tag{9}$$

The quantity $\mu x/D$ is also the expected number of upcrossings in an interval of length x. Thus (9) tells us that the probability of failure is equal to the probability that the signal level is initially below threshold less the probability that there be at least one upcrossing in the interval.

The next result concerns the other end. When x is large, we have the asymptotic result

$$P_1(W,x) \sim e^{-\mu x/D} \text{ for } x \sim +\infty. \tag{10}$$

Actually, this result is valid only when both x and W simultaneously increase in such a way that μx remains constant. But this satisfies our own purposes since we shall want to suppose that $p_1=1-r$ is previously given.

Looking at (9) and (10), we would propose here the formula

$$p_1(W,x) \approx pe^{-\mu x/Dp}. \tag{11}$$

It clearly satisfies (9) and, because p rapidly approaches unity when W becomes large, it also satisfies (10). However, the formula is meant as only an approximation: it is a kind of interpolation between 0 and ∞. Actually, it is known that intermediate values do definitely depend on the entire function $\rho(s)$ and not merely on its behavior near the origin.

Solving (11) and rephrasing (5), (7), and (8), we find

$$x = D\,\frac{1-q}{\mu}\ln\frac{1-q}{1-r} \text{ for } r > q, \tag{12}$$

where

$$\mu = \frac{1}{2\pi}e^{-v^2/2},$$

$$v = Q^{-1}(q). \tag{13}$$

Thus we have expressed the waiting distance x in terms of the location availability q, the desired reliability r, and the correlation distance D. For $r \leq q$, the waiting distance is zero since sufficient signal will be immediately available with that degree of reliability.

In Figure 1 we have used (12) to plot waiting distance as a function of location availability using values r=0.5 and 0.9. For r=0.5, we have the "median waiting distance": for half of the messages we would need to wait a longer distance. The second curve, for r=0.9, probably represents a suitable design criterion: 90% of the attempted communications should have been successful before the indicated distance. If one imposes a required maximum 90% distance, one can find the allowed fraction q and then the resulting extended range.

Note that the curves of Figure 1 are given in units of the correlation distance D. Until we know the magnitude of this distance, we cannot say that we have determined the necessary design criteria; nor can we even say that we have determined whether a burst communications system is viable. It would seem that this important parameter can be determined only from empirical evidence, and the next section will consider what can be done.

4.3 The Correlation Distance

As we have seen, whether it is worthwhile to construct a burst communication system that depends on large-scale location variability will be decided by the size of the correlation distance D, defined in (6). If it is too large, one would have to wait an unacceptably long distance before most messages would have been sent successfully.

Unfortunately, very little is known about the "second-order statistics" that go to make up such quantities as correlations. There are too many questions one might ask, and suitable measurements are difficult to arrange.

However, let us note that it is possible to come up with some general orders of magnitude. First, we recall that it is the large-scale location variability we must study, and to do that we must remove from any set of data the small-scale multipath fading. Normally, we would consider only smoothed data in which local means or medians are measured and small-scale deviations are discarded. There will then be necessarily a high correlation between such smoothed data whenever the two points under consideration are separated by distances that do not exceed the intervals defining the local means. Since we would want to include many

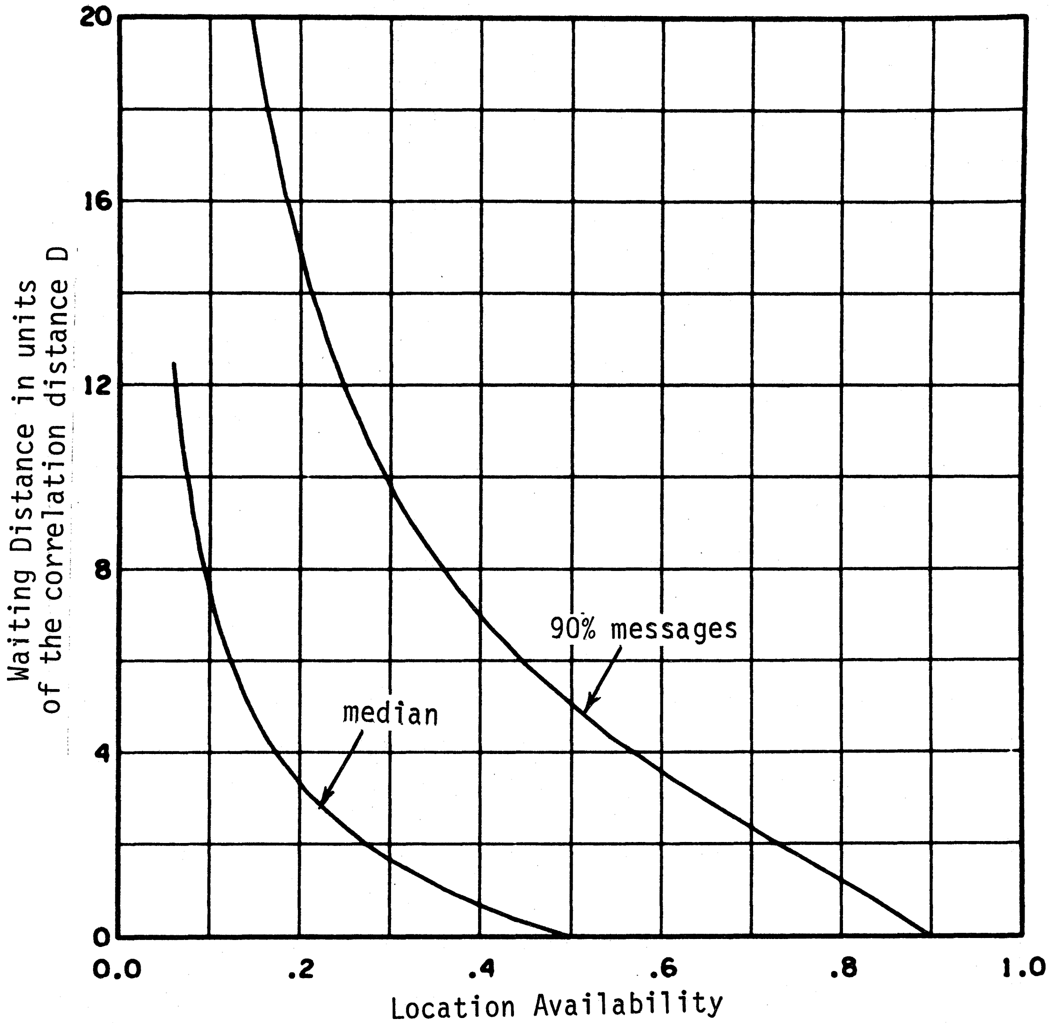


Figure 1. Quantiles of the waiting distance as a function of the location availability.

wavelengths in these local measurements, we can conclude that correlation distances must exceed some tens of meters.

At the other extreme, we might recall the statistical observations that result from those measurement programs involving many different terminal locations. Almost all such programs report fairly large standard deviations--usually from 8 to 10 dB--and this happens irrespective of the size of the area covered by the program. If correlation distances were large, one would expect correlations between measurement points and a consequent diminishing of the observed standard deviations, particularly as the size of the area decreases. We can conclude, therefore, that correlation distances must lie between a few tens of meters and a few kilometers.

In general, we would suspect that correlation distances might depend on all the system parameters and environmental parameters--on the path length, frequency, antenna heights; on the degree of terrain irregularity; and also on whether motion is along the propagation path or transverse to it. Without a large measurement program, we can hope only to find estimates of the general order of magnitude of this quantity.

Finally, let us devote some thought to how one might measure a correlation distance. It is, of course, a statistical parameter which can only be measured through a statistical estimator and will always be subject to sampling error.

The most obvious way to determine the value of D is to construct the autocorrelation function and then, in accordance with (6), to fit a parabola through the first few values. Unfortunately, unless we define what sort of fit to use and just how many of the first few values should be involved, there is an undesirable subjectivity in this approach. In addition, we suspect that results are very sensitive to the observed correlation values and therefore will have a large sampling error.

It is probably better to use the fact, mentioned in connection with (9), that $\mu x/D$ is the expected number of upcrossings in an interval of length x. Since μ attains its maximum value of $1/2\pi$ when the level of concern is the mean level, we get the smallest sampling error when we consider crossings of the mean. In the literature one refers to "zeroes" or "zero crossings" since normally one subtracts the mean from the observed data to obtain a zero mean process. If n_c is the total number of observed crossings (both upcrossings and downcrossings), then we may write

$$D = \frac{d}{\pi n_c}, \tag{14}$$

where d is the total length of the route along which the data were observed. This is a simple to use, well-formulated estimator that is asymptotically unbiased.

4.3.1 Previous Measurements

We have managed to find one set of suitable measurements reported in the literature. Kirby and Capps (1956) have analyzed some mobile runs in which signals from broadcast stations in the Washington-Baltimore area were measured, the principal aim being to find what correlations would be present.

Of most interest to us is a run of about 56 km made along a road that was almost exactly the perpendicular bisector of the line joining two FM broadcast stations--one in Washington, the other in Baltimore. Frequencies, of course, were about 100 MHz. Distances from the mobile receiver to the two transmitters were about 28 km, and the receiving antenna was 4.5 m above ground.

The data, recorded on paper roll charts, were treated in two important ways prior to analysis. First, they were smoothed: The route was divided up into successive intervals ("sectors") of length 400 m (1/4 mi); then in each interval the median signal level was scaled off, and it is the sequence of local medians that is used in further analyses. This process should have removed the small-scale multipath fading, leaving only the large-scale variability, which exactly suits our own purpose. Second, the authors have subtracted from the local medians a value predicted by a propagation model (one that was subsequently to evolve into what the Federal Communications Commission now uses). The purpose here is not to compare data with model (although that falls out automatically) but to remove any systematic effects due to the slight changes in path lengths and, hopefully, to convert the underlying random function into a stationary one. Although for our own purposes we would think that the 400-m intervals used are rather large, the two pre-analysis processes employed seem correct and necessary for a study of location variabilities.

The subsequent analysis of these residual deviations of local medians included the first order statistics for the two stations, their autocorrelation functions, and the correlation between them. The report includes graphs of the smoothed signal levels and of the autocorrelation functions, from which can be derived values for the correlation distance D. For the Washington station the standard deviation was 5.3 dB. In 48.3 km of actual measurements there were 28 crossings of the mean level, and hence from (14) we obtain D=550 m. For the Baltimore station there were a standard deviation of 7.0 dB and 23 crossings of the mean level. Thus the measured correlation distance becomes 670 m. Both values of D seem to fit the corresponding autocorrelation curves fairly well.

From the autocorrelation functions the authors conclude that at a 3200 m (2 mi) separation the data are completely uncorrelated and that, therefore, samples taken that far apart can be assumed independent. They also show that the correlation between signals from the two stations does not differ significantly from zero.

The same report describes a second measurement run which traversed a circle 59 km in radius around Washington. Again, two signals were measured: the same Washington FM broadcast signal and a television signal that emanated from the same location at a frequency of 72 MHz (TV channel 4). It is well-known that such a difference in frequency will produce small-scale multipath fading signals that are completely independent. Nevertheless, the report shows that the local medians that describe the large-scale location variability are highly correlated with correlation coefficients between 0.8 and 0.9. This would seem to imply that the correlation distance does not depend very critically on the frequency.

4.3.2 WTOP-TV, Washington D.C.

In our possession we have the results of a measurement program conducted in 1960 but never reported in the literature. The data consist of field strength measurements using the transmitter of television station WTOP-TV. This station is located in Washington, D.C., and operates at a frequency of about 190 MHz (TV channel 9). What makes these data attractive to us now is that they were taken at a large number of points distributed fairly uniformly along circles that surrounded the transmitter. They seem ready-made for a study of autocorrelation.

There were seven circles with increasing radii; of these, the middle three contained over a hundred measurement points, and it is these three that we shall analyze. Figure 2 is a map of the area showing the location of the transmitter and the three circles. In Table 3 we list the parameters for the three circles: the radii, the numbers of measurement points, and the separation distances. The error specifications represent one standard deviation for the actual data. The remaining columns of Table 3 present the results of our analyses and will be described below. Note that at each receiver location there were two measurements, one with the receiving antenna 3 m above ground and one 9 m above ground.

There are two aspects of this measurement program that make the data not entirely well suited to our present purposes. They are "spot" data--the receiver

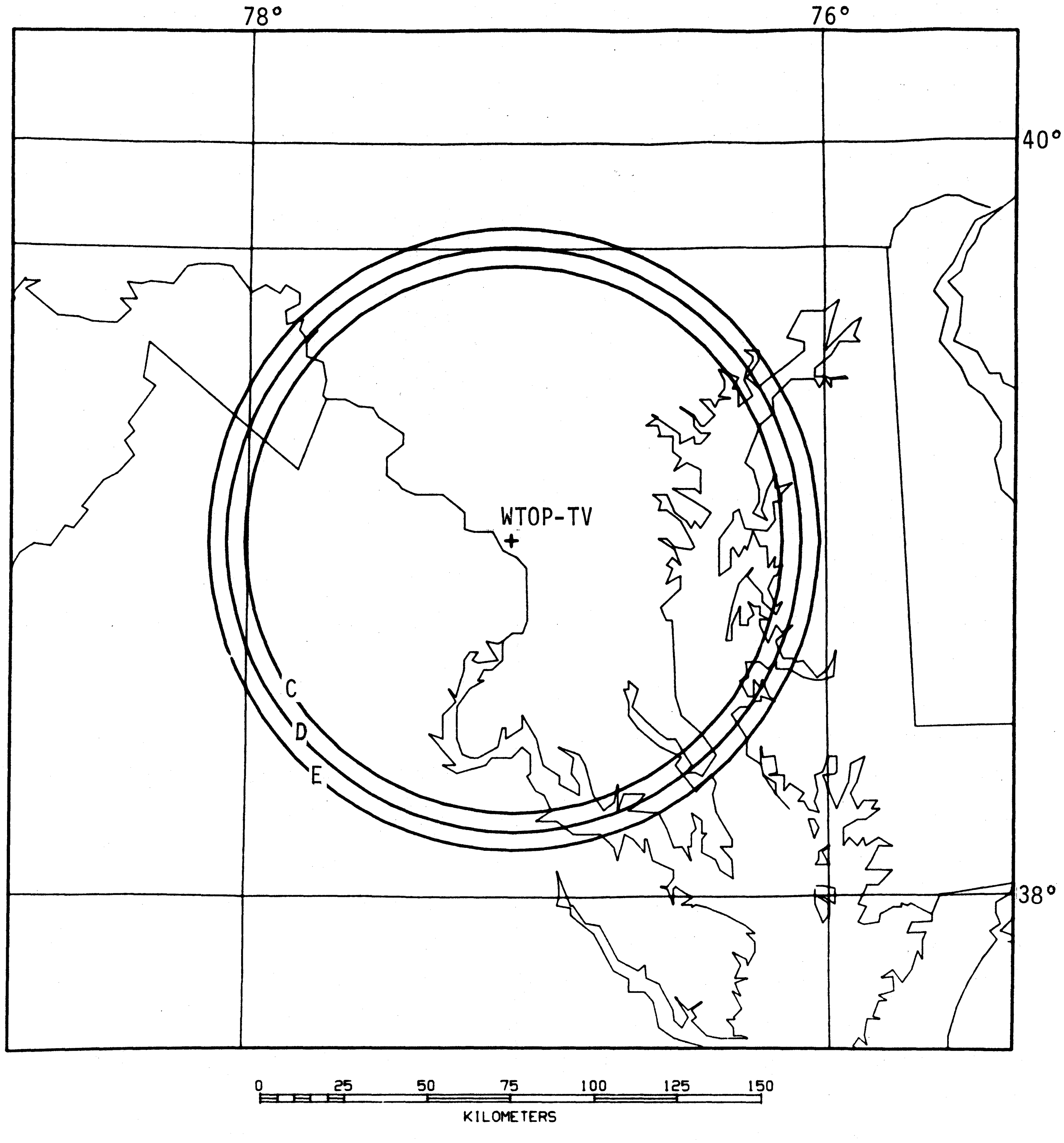


Figure 2. Map showing the service area of WTOP-TV and the three circles used in the present analysis.

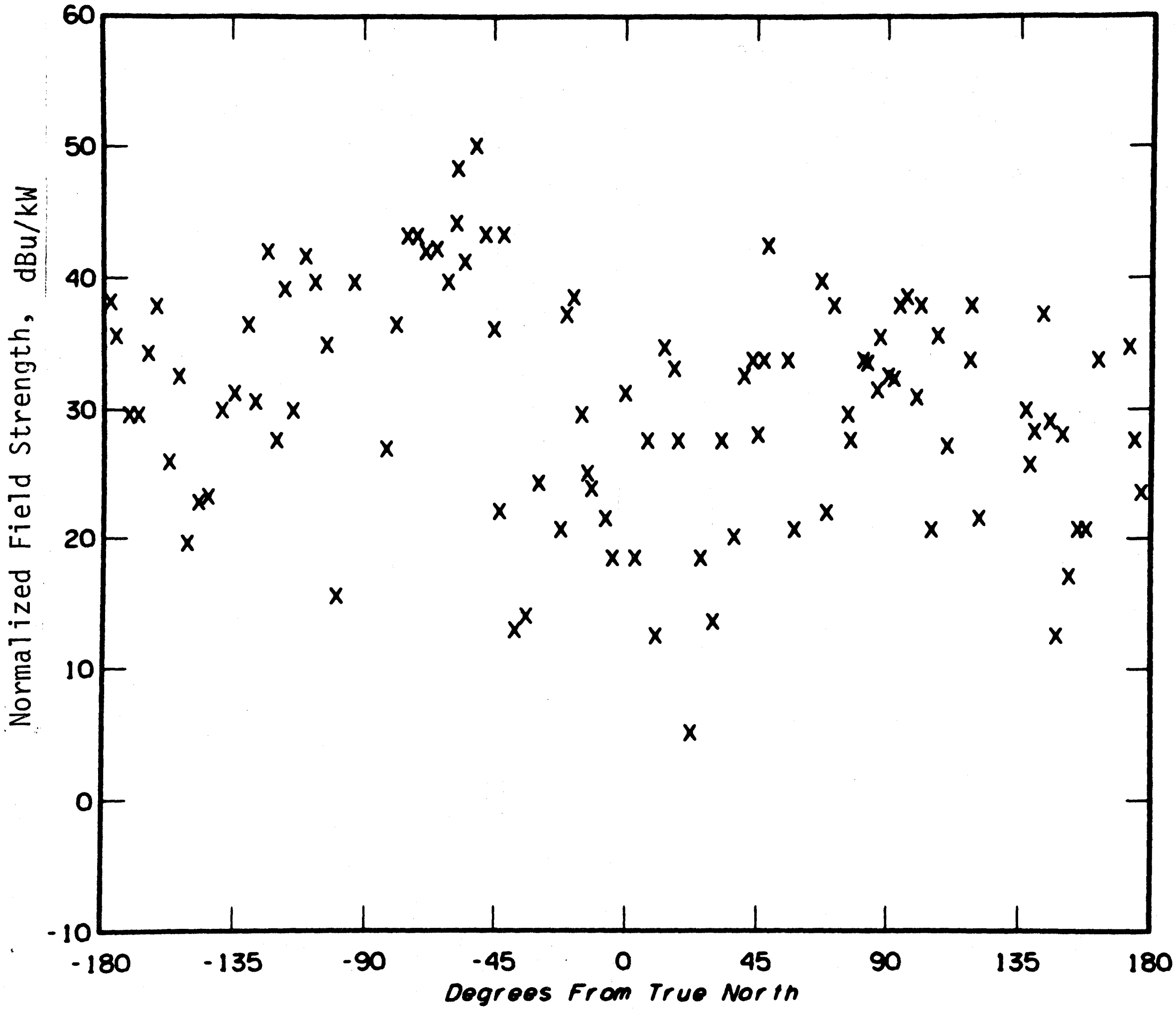
was driven to each spot and the measurements were immediately taken. This means that there has been no attempt to remove whatever multipath fading might have existed. Second, although there are a large number of data, the separation distances listed in Table 3 lead one to suspect it is still not large enough. According to the criterion of Kirby and Capps (1956), described in Section 3.2.1 the data will be entirely independent data. All we should expect here is either to deny or not to deny this prior experience.

Table 3. Parameters and Statistics for the Three Circles of Data Around WTOP-TV

Circle	Radius	Number Points (km)	Separation (km)	Receive Height	Standard Deviation (dB)	Zero Crossings	Correlation Distance D (km)
C	80.6±0.6	104	4.9±3.0	3	8.4	46	3.5
				9	8.0	48	3.4
D	86.2±0.6	122	4.4±2.2	3	8.5	62	2.8
				9	7.3	48	3.6
E	91.6±0.5	104	5.5±2.7	3	8.2	52	3.5
				9	7.2	50	3.7

There are six sets of data corresponding to the three radii and the two antenna heights. To illustrate their appearance we have plotted one of these sets in Figure 3. The abscissa is the azimuthal bearing of the receiver from the transmitter. Note how dense the data appear and how they are uniformly distributed over the entire range of bearings. The remaining five sets look very similar.

Our major task is to compute the autocorrelation functions corresponding to each set of data. The standard formulas for this assume the data are given at exactly equal intervals of the independent variable, but, unfortunately, that is not quite the case here: The data are only approximately uniformly distributed around the various circles. Now, fundamentally, to make such calculations, we should imagine that the signal level is actually a continuous function of bearing and that the data we have are simply point samples of that function. Then the autocorrelation function becomes a simple integral involving that continuous function. The standard formulas are simply



WTOP-TV, Circle C, 9 m height

Figure 3. Measured signal levels versus azimuth for one of the six sets of data.

convenient and efficient numerical quadratures of that integral. For irregularly spaced points we must find other quadrature methods.

In general, most numerical quadratures will develop an interpolating formula that passes through the given data and then will provide the result of integrating that formula. It therefore seems appropriate in computing autocorrelation functions to first find an interpolation function that passes through all the given data, then to pick off interpolated values which are spaced at equal intervals, and finally to use the standard formulas applied to these interpolated values. This approach is easy to implement and does no injury to the underlying concepts.

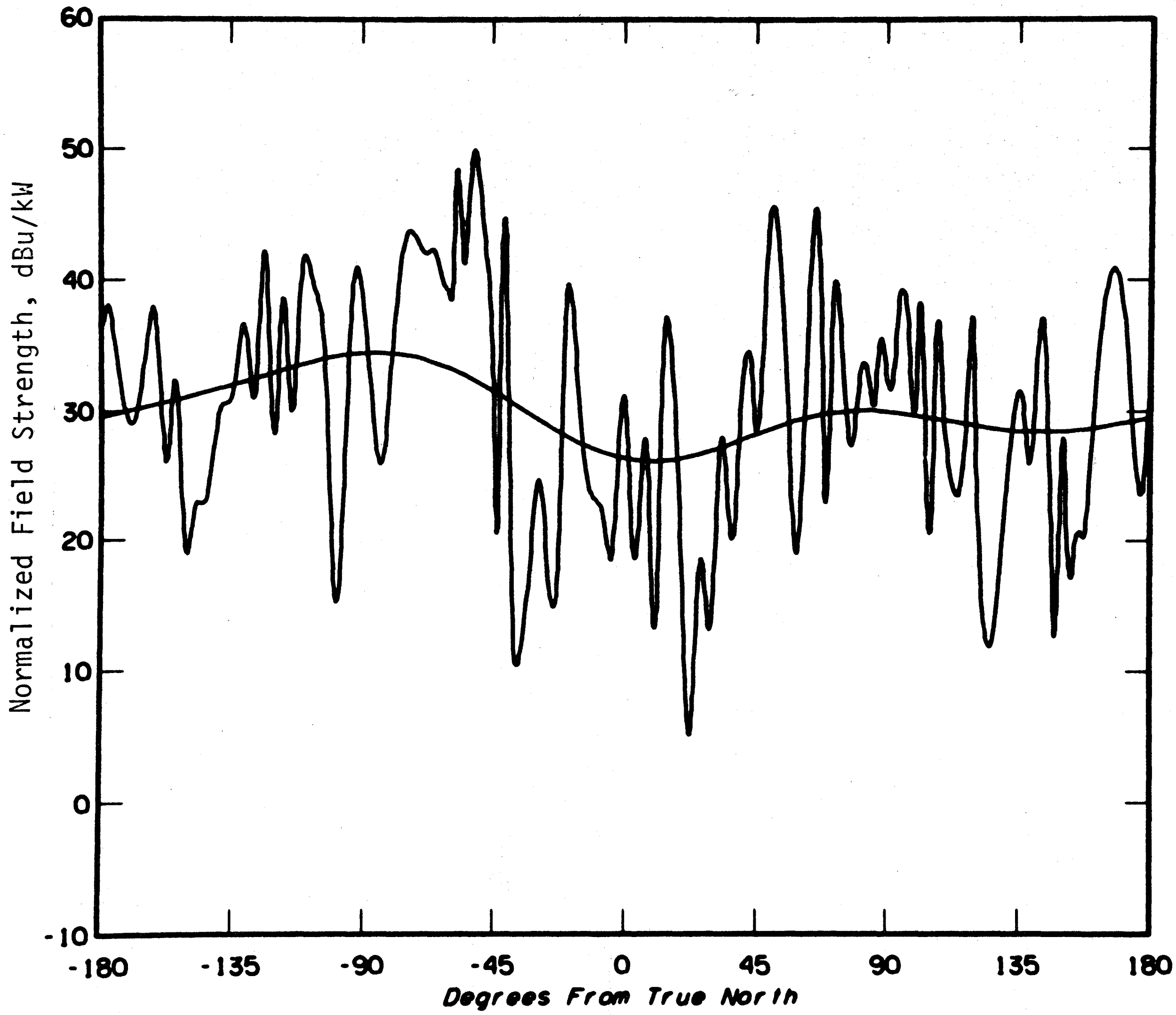
For the interpolation, we have used a simple cubic spline curve with a continuous first derivative. An example of the resulting interpolating function is graphed in Figure 4. It should be emphasized that this function is produced only for arithmetical convenience. It is not meant to represent what would actually have been observed if further measurements had been made, and any results we obtain must be carefully interpreted.

From curves such as that in Figure 4, we have selected 256 equally spaced values. This number nicely overdefines the function so that we may reproduce it fairly accurately. Being a power of 2, it also provides easy access to the Fast Fourier Transform (FFT), a further arithmetical convenience.

There is, of course, no distance dependence for a set of these data. However, with the Blue Ridge Mountains to the northwest and the flat coastal areas to the southeast, one suspects that there might well be a terrain dependence that will still make the data nonstationary and that should be extracted. In Figure 4 we have also plotted the curve that results when the first curve is passed through a very restrictive low pass filter using only the first few Fourier components. Rather than use the predictions of a propagation model to show the effects of terrain, we have simply subtracted off this "moving mean" to arrive at what we hope is a stationary process.

After these preliminary steps, it is a straightforward matter to compute the autocorrelation functions. An example is shown in Figure 5 where we have plotted correlation versus the separation of azimuthal bearings. The other five curves look very similar. They all decrease nicely towards zero after a separation of 5° or less.

We have also counted the zero crossings (whose number now become the number of crossings of the moving mean curve) and computed the resulting estimates of the correlation distance. These results, together with standard



WTOP-TV, Circle C, 9 m height

Figure 4. The interpolating function for the data of Figure 3. Also shown is the moving media curve.

deviations of the data are listed in Table 3. Note that the correlation distances given correspond fairly well to what one might estimate from the autocorrelation functions such as that in Figure 5 (where 3.4 km corresponds to 2.4°). Note, too, that these distances are all considerably less than the average separation distances of the original data. This indicates to us that indeed the separations were too large for our present purpose and that all we can really say is that the computed values give outside maxima for correlation distances.

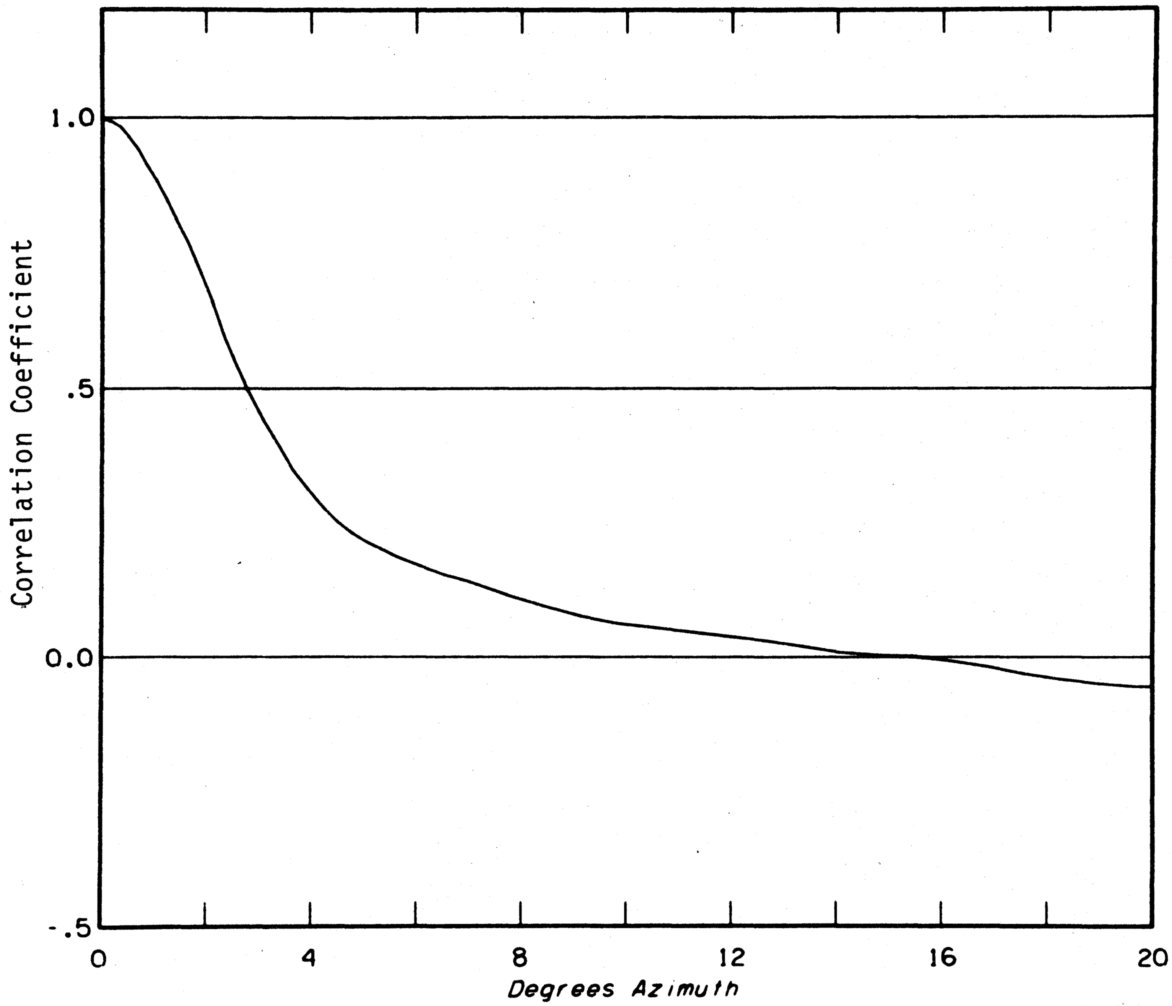
Let us examine this question a bit further. A "random sample" is a set of data taken from a common statistical population so that each element is entirely independent of all the others. It is quite reasonable to suppose that our six data sets (especially after the moving mean has been subtracted out) are such random samples.

If we have a random sample it is still possible to imagine the data arranged in a sequential fashion and to count the number of zero crossings--i.e., the number of times two successive data are on opposite sides of the mean. Suppose there are N data in the sample, and suppose we allow also a crossing between the last element and the first (as in a circular arrangement of the data). If, concerning the population distribution, we merely assume that the median equals the mean, it is easy to show that the expected number of zero crossings is N/2 and that the standard deviation is $\sqrt{N/2}$. Looking at the zero crossings listed in Table 3, we see that with one exception (the D circle with 9 m height) all the counts are good approximations to this estimate. We therefore see no reason to suppose that the data sets are not random samples.

4.3.3 A Mountain Road, Colorado

As indicated in Section 2.2, and described in the appendix, part of the present work to study how burst communications systems might lead to extended ranges involved a companion measurement program. Of the several measurement runs made, we have chosen first to analyze the one into the mountains. This has seemed to us the most interesting of the runs, and path distances are relatively constant.

Measurements used a mobile transmitter operating at a frequency of about 50 MHz. The antenna was a vertical monopole mounted 2 m above ground on the flat roof of a small truck. The receiving antenna was at a fixed location 10.2 m above ground.



WTOP-TV, Circle C, 9 m height

Figure 5. The autocorrelation function corresponding to the interpolated data from Figure 4.

The area of the measurements is in Colorado where the Great Plains give way abruptly to the foothills of the Front Range, a part of the Rocky Mountains that contains some of the highest peaks in the United States. The receiving terminal was actually in the plains some 2 km east of the first foothills. As sketched in Figure 6, the mobile transmitter began at Boulder and climbed up Boulder Canyon to the town of Nederland, gaining some 900 m in altitude. At the top of the canyon, and of the other canyons that cut through the foothills, there is an interlude of relatively level terrain before the true peaks of the Front Range rise about 5 km further west. At Nederland the transmitter turned north on a highway that crosses on this relatively level terrain to the town of Estes Park. Then it turned east and descended the Big Thompson Canyon back to the plains and the city of Loveland. The two canyons are narrow with steep walls; the road connecting them sometimes passes behind local hills and sometimes in front.

The data were originally recorded as AGC voltages on an analog tape. Using calibration curves, they were subsequently digitized in absolute form. The digitizing rate was 20 Hz which means, since the average speed of the vehicle was about 15 m/s (35 mph) and the wavelength was 6 m, that there were about eight points per wavelength. This should be entirely satisfactory.

Further reduction of the data is difficult and, unfortunately, subject to several dubious assumptions. At the receiver terminal there were actually two receiving sets attached to a common antenna. They had quite different characteristics. One was a narrowband receiver (about 2-kHz bandwidth) with excellent sensitivity but very small dynamic range--it would saturate at about -100 dBm. The other, to which we refer as the wideband receiver, had a bandwidth of about 20 kHz. It had an excellent dynamic range, but in addition to the extra 10 dB thermal noise, it was subject to a considerable amount of adjacent channel interference. (The band employed is the low VHF mobile band which is well-used by local communicators.) This was usually manifest as an intermittent squelching effect, presumably caused by the transmission of some nearby base station.

Thermal noise power in the narrowband set should have been -141 dBm, and indications are that the receiver could actually distinguish signals down to -130 or -135 dBm. It should be noted that the site on which the receiver terminal was located is officially designated a Quiet Zone at which man-made noise and interfering radio fields are kept to a minimum by both Federal and

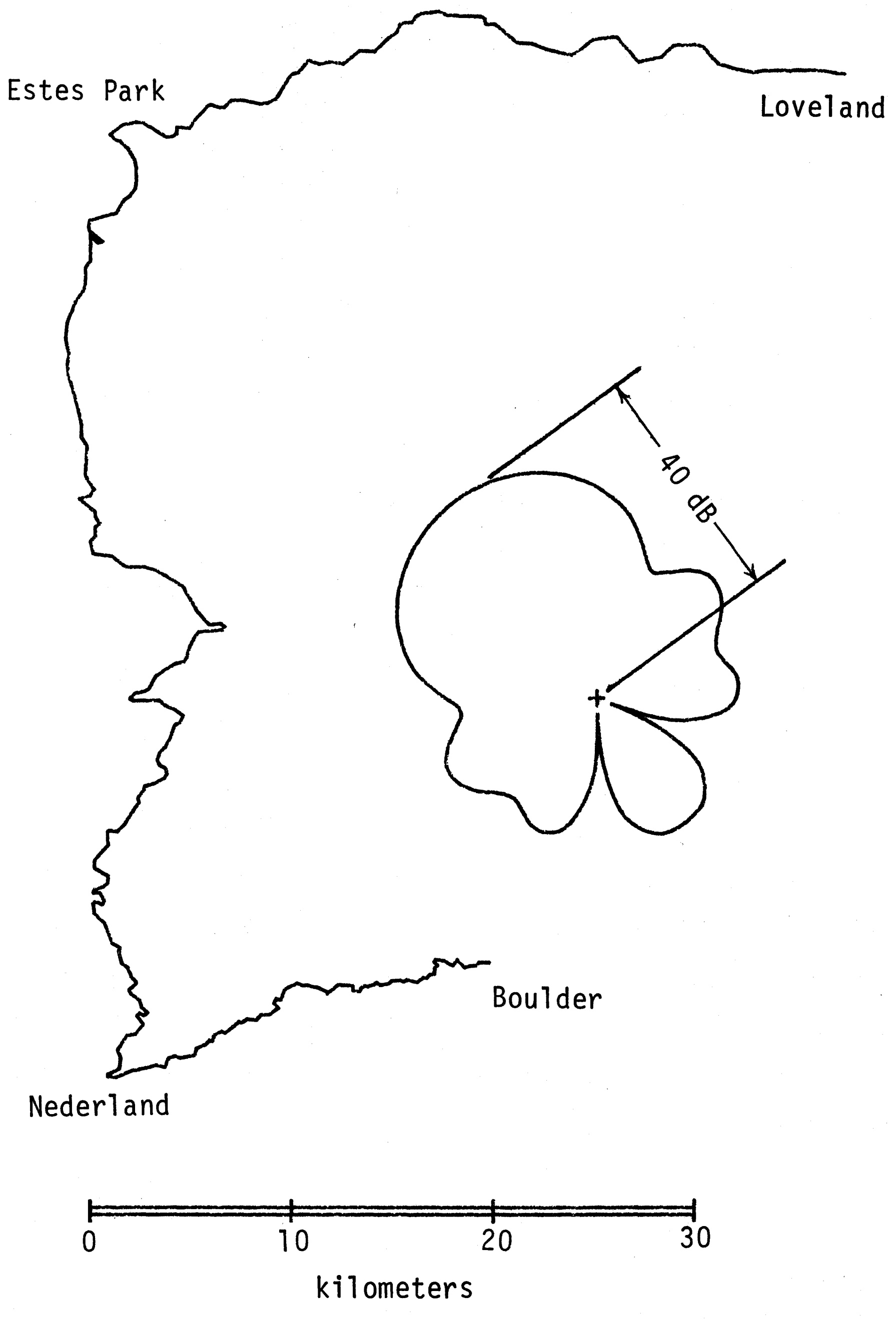


Figure 6. Map showing the route of the mountain road measurements. Also shown is the assumed antenna pattern at the receiving terminal.

State regulations. As it happened, the measurements we are reporting here would have been impossible without the protection thus provided.

The final result is that we have two measurements of signal level; one is valid in the range from perhaps -135 to -100 dBm, the other from -120 to -35 dBm. In the overlapping range the two measurements were very nearly equal. It therefore seems quite reasonable to combine the two measurements into one that should be valid from -135 to -35 dBm. In the overlapping region we have used a weighted average in which the narrowband weight increases steadily below -100 dBm and the wideband weight increases above -120 dBm.

Having settled on the signal level measurements, we must turn our attention to the independent variable. In the tape recording this is represented as time, but for our purposes we must use distance along the route. There are several points (principally where the driver stopped to telephone) that are identifiable both on the record of measurements and on the map. After digitizing the route we can equate corresponding times and distances. For points in between the identifiable points we can only assume that the vehicle traveled at a constant speed.

In Figure 7 we show the results of these manipulations. There we have plotted the combined received signal level against our computed distances. The first three strips show successive 45 km intervals along the route; the total length was a little short of 125 km. The fourth strip is an expanded view of an arbitrarily chosen 1 km interval; it shows the multipath fading that was almost continuously present during the run. The gaps that appear in the data show where measurements were unavailable for one reason or another. One particular reason was that the signal level was greater than -100 dBm, and that the wideband receiver was squelched. The large gap at about 80 km, however, was due to a momentary failure of the transmitter.

The next step in reducing the data is to construct a smoothed version so as to eliminate the multipath fading. To do this we have used averages over a "moving window" whose shape is a raised cosine with a total length of 120 m. Its "effective length" is thus 60 m or 10 wavelengths. In the literature it is often suggested that means or medians of 30-m mobile runs should be used to represent locally smoothed signal level data. Here, we have doubled this interval length to accommodate the low frequency.

Computations were made every 60 m along the route so that consecutive windows were overlapping. Quantities evaluated included not only the weighted average but also the average slope (the trend) and the standard deviation of

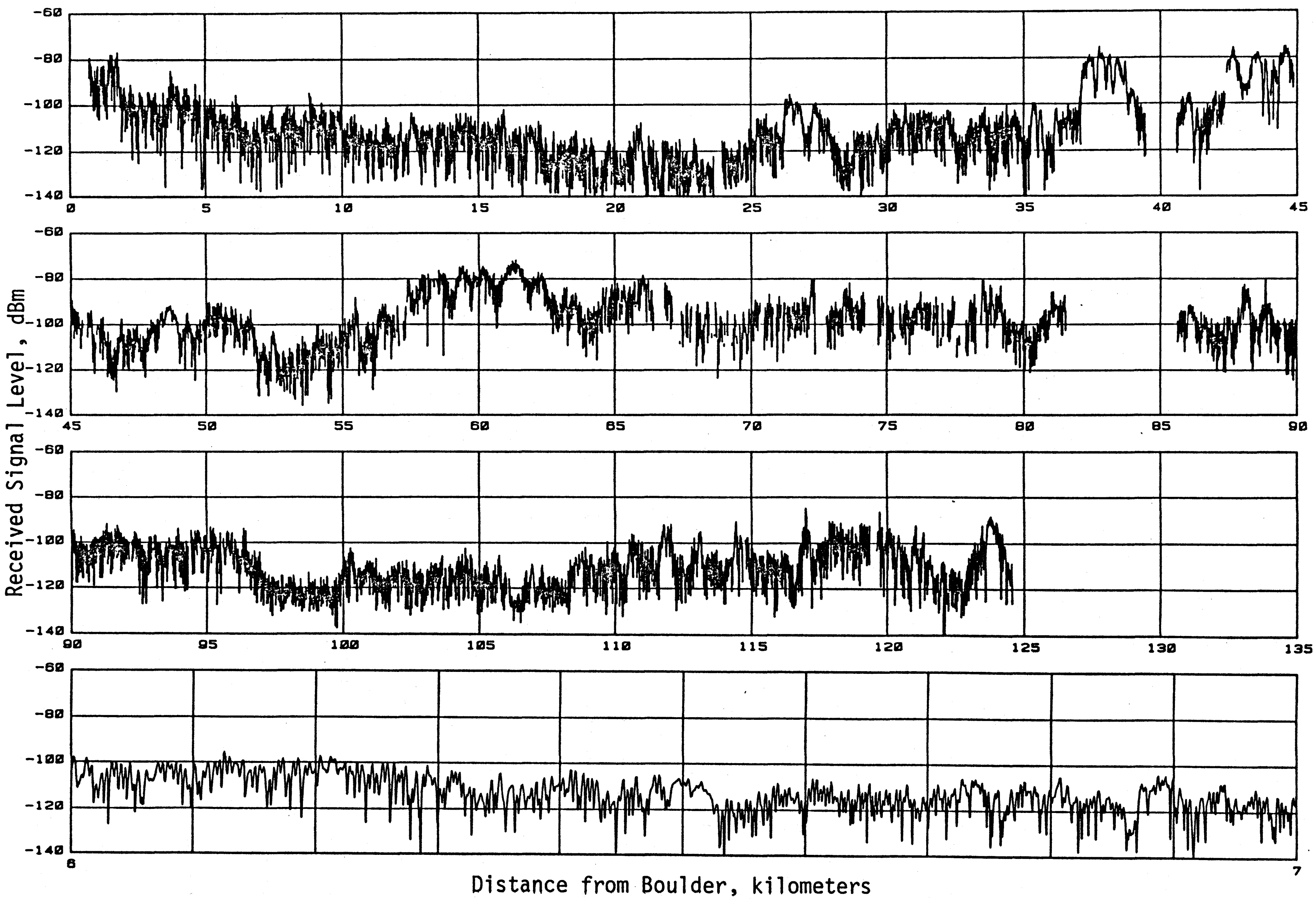


Figure 7. Combined signal level versus distance along the route.

the residuals. Note that the resulting record gives our smoothed data at equally spaced intervals despite any changes in vehicle speed.

The last bit of data reduction must be to remove expected trends and so to produce what is hopefully a stationary process. To remove the dependence on path length, we have subtracted the corresponding signal levels predicted by the ITM in the area prediction mode. We have assumed the terrain is homogeneous with Δh equal to 423 m. (This value is the median of a large set of measured values taken over paths where the transmitter terminals are evenly distributed along the route.) We used what the ITM calls the "reference attenuation" without alteration for the statistics involved because it is these very statistics that we are interested in measuring.

A second trend which is probably even more important than that caused by path length changes is that caused by the antenna patterns. The transmitting antenna we can assume was omnidirectional, so there is no trouble there. But the receiving antenna was a five-element Yagi oriented vertically; although such an antenna has a broad beamwidth of about 60°, the azimuthal changes along the route greatly exceed this. Unfortunately, circumstances made it impossible to measure the pattern, and we are left in the uncomfortable position of having to depend on measurements made on a similar antenna. For this we have used the five-element Yagi array measured by Viezbicke (1976) and designed according to his criteria. The resulting pattern has been plotted in Figure 6. We have pointed it in the general direction of Estes Park but have adjusted it slightly so that the notch roughly fits a similar notch in the observed data.

In Figure 8 we present the results of these last reductions. The top strip shows the smoothed deviations of measured data from predictions; the lower strip shows the local standard deviations of the small-scale variability. It should be remembered that we have introduced predicted values only in an attempt to remove trends in the recorded data. It is not our purpose here to compare measurements with predictions. As an aside, however, we might note that the average deviation in Figure 8 is -5.2 dB. (On the other hand, this value is obtained using the second system calibration described in the appendix, Section A.3; it is only as reliable as that calibration.)

We might also pause to discuss the curve of local standard deviations. If a signal suffers Rayleigh fading and if one measures it in a decibel fashion, then the standard deviation will equal the fixed value of 5.57 dB.

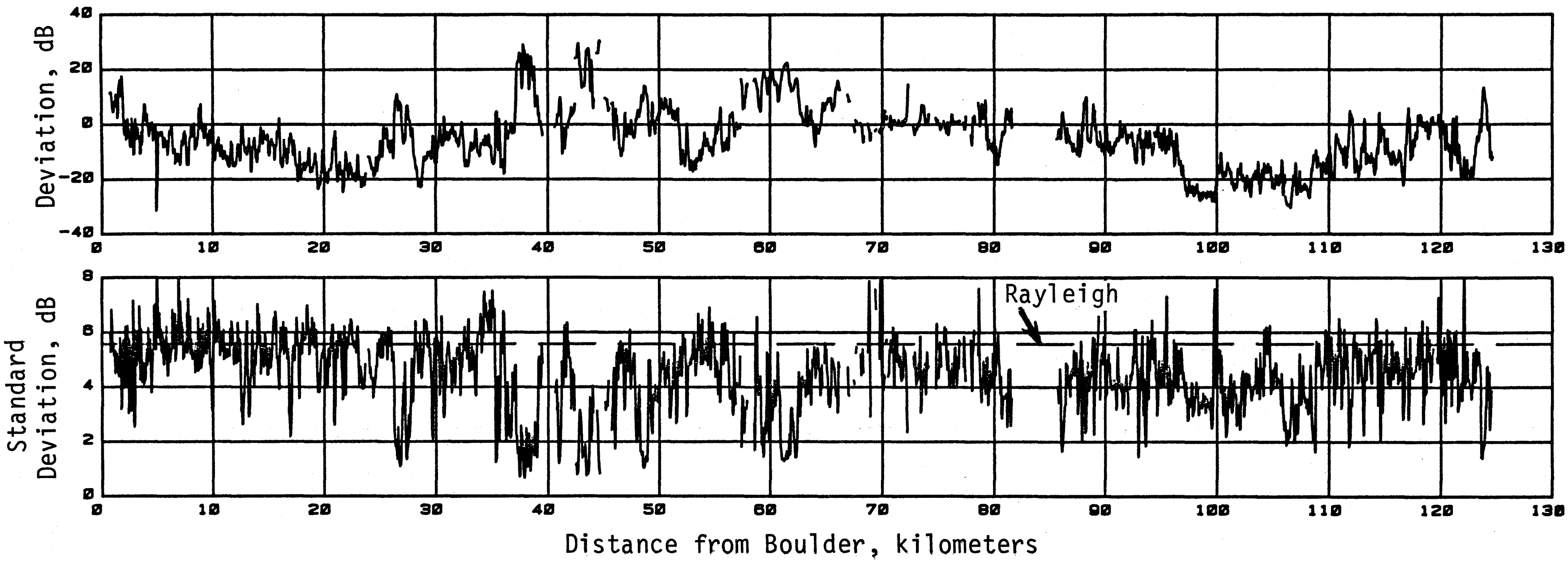


Figure 8. Local mean and local standard deviation of the deviations of measured data from predictions.

This value is indicated on the graph in Figure 8. Note how the observed standard deviations appoximate the Rayleigh value for a large proportion of the route; the rather wide and rapid oscillations about this value we would attribute to sampling error. In consequence, we can probably conclude that over most of the route the small-scale variability was Rayleigh distributed. Note that for those portions of the route where the local standard deviation is small, there seems to be a tendency for the smoothed deviations to be positive and fairly large.

Returning to our major concern, it is now straightforward to compute the autocorrelation function of the smoothed deviations of Figure 8. A plot of the results is shown in Figure 9. We view this plot with some dismay; whereas previously determined autocorrelation functions, such as that in Figure 5 or those reported by Kirby and Capps (1956), have decreased fairly steadily to zero, this one has a well-defined plateau at 0.5 km and a long tail beginning at about 2 km. Even at 10 km it is still significantly different from zero. This anomalous behavior may be simply atypical; or perhaps it is to be expected in mountainous terrain. Evidently the subject deserves more study than we shall be able to provide here.

The standard deviation of the smoothed deviations in Figure 8 is 10.8 dB. There are 179 crossings of the mean level, and this implies a correlation distance of 220 m--a value that fairly well fits the very first part of the curve in Figure 9.

Our purpose in obtaining the correlation distance is to enable us to scale the ordinate in Figure 1 and so allow us to find absolute waiting distances. But with our present data we now have an opportunity to make direct measurements of the waiting distance. We simply imagine that we initiate a message at a random point, uniformly distributed, along the route, and we ask for the resulting statistics of the distance we must go until the data exceed a given threshold. By following such an approach we shall provide a check on the theory given in Section 3.1 and also provide some insight as to how the anomalous behavior of our autocorrelation function affects this theory.

At the outset we should note that our results are more accurately called "empirical waiting distances" since another set of data, even one with the same characteristics, will be expected to give somewhat different values. We should also note that we will be using the smoothed deviations of Figure 8. Removing the expected trends gives us results that are more universally

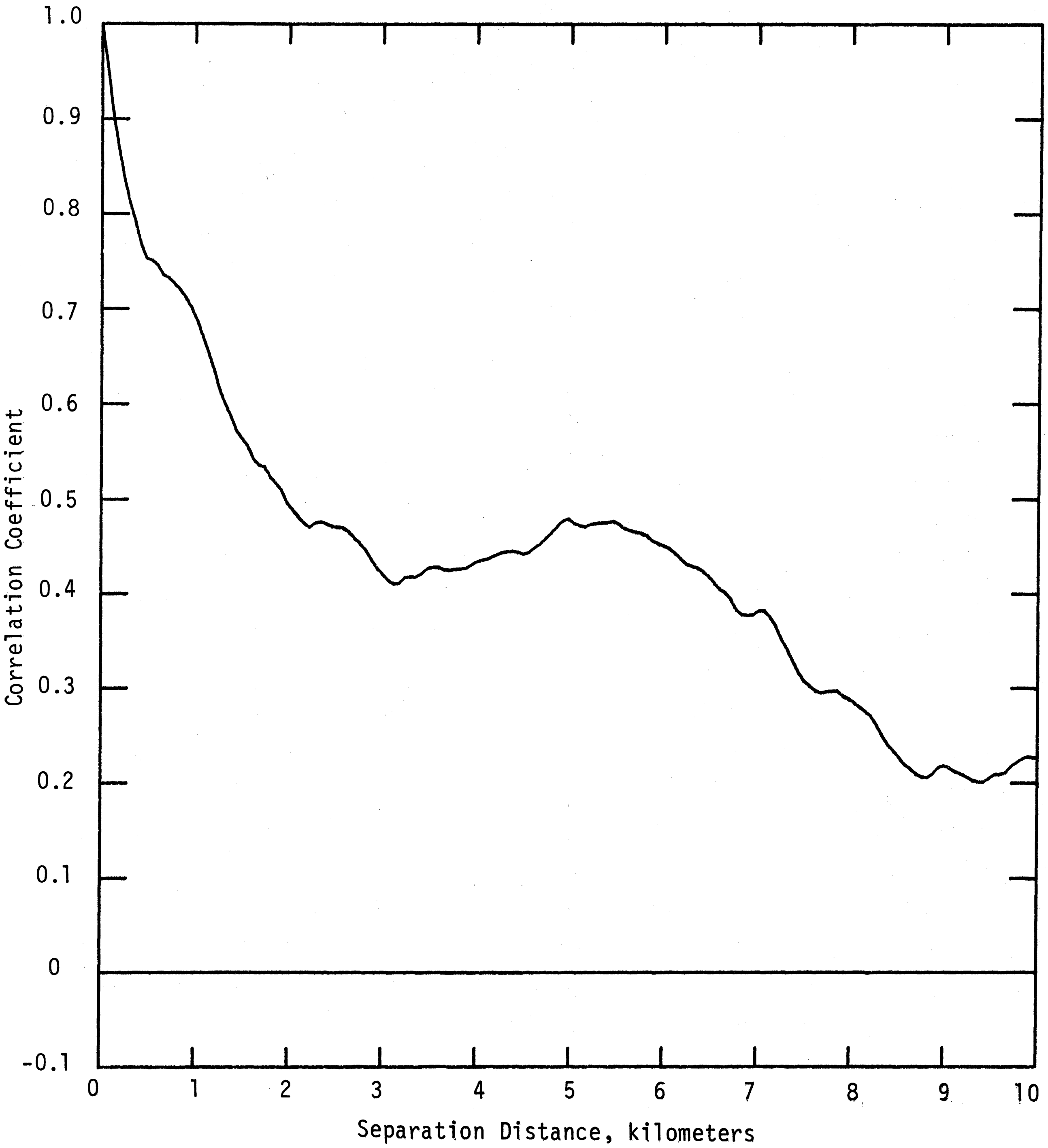


Figure 9. Autocorrelation function for the mountain road measurements.

meaningful, but at the same time it removes us somewhat from reality since an actual burst communications system will also have to contend with these same trends.

The computation of empirical statistics of waiting distances is fairly simple. We suppose as before that our data are described by the function $w(s)$ and that the threshold has the value W. We then find all points at which $w(s)$ crosses the threshold, and we consider the collection of maximal intervals where $w(s) < W$. These intervals represent the points where a message cannot be immediately transmitted. Let q_i be the length of the <u>ith</u> such interval divided by the total length d of the route. Then q_i is just the probability that the point at which the message is initiated falls within the <u>ith</u> interval. The remaining intervals represent the points where the message can be immediately sent, and their total length divided by d is the location availability q.

If we assume the condition that the point is indeed within the <u>ith</u> interval, then the waiting distance is uniformly distributed over that interval. Thus the conditional probability that the waiting distance is less than or equal to x is given by $\min(x/dq_i,1)$. It then follows from the rules of conditional probabilities that the total probability the waiting distance is less than or equal to x is given by

$$r = q + \Sigma_i \min(x/d,q_i). \tag{15}$$

Before continuing this approach, we have performed one final manipulation of the data in which we closed the several gaps by a smooth interpolation. This seemed to be the only way we could find explicit estimates of all the required intervals. Then we chose a sequence of suitable thresholds W, found the corresponding location availabilities q and the collection of normalized interval lengths q_i, and solved (15) for x when r took on the values 0.5 and 0.9. In Figure 10 we have plotted the resulting quantiles of waiting distances against the observed location availability. As one can see, the plotted points exhibit the general predicted behavior but quantitatively there seems to be a discrepancy larger than could be accounted for by sampling error. We would attribute the larger than expected mid-range waiting distances to the anomalous behavior of the autocorrelation function.

In Figure 10 we have also redrawn the curves of Figure 1 assuming, however, that D=800 m. We chose this value not because it fits any of our

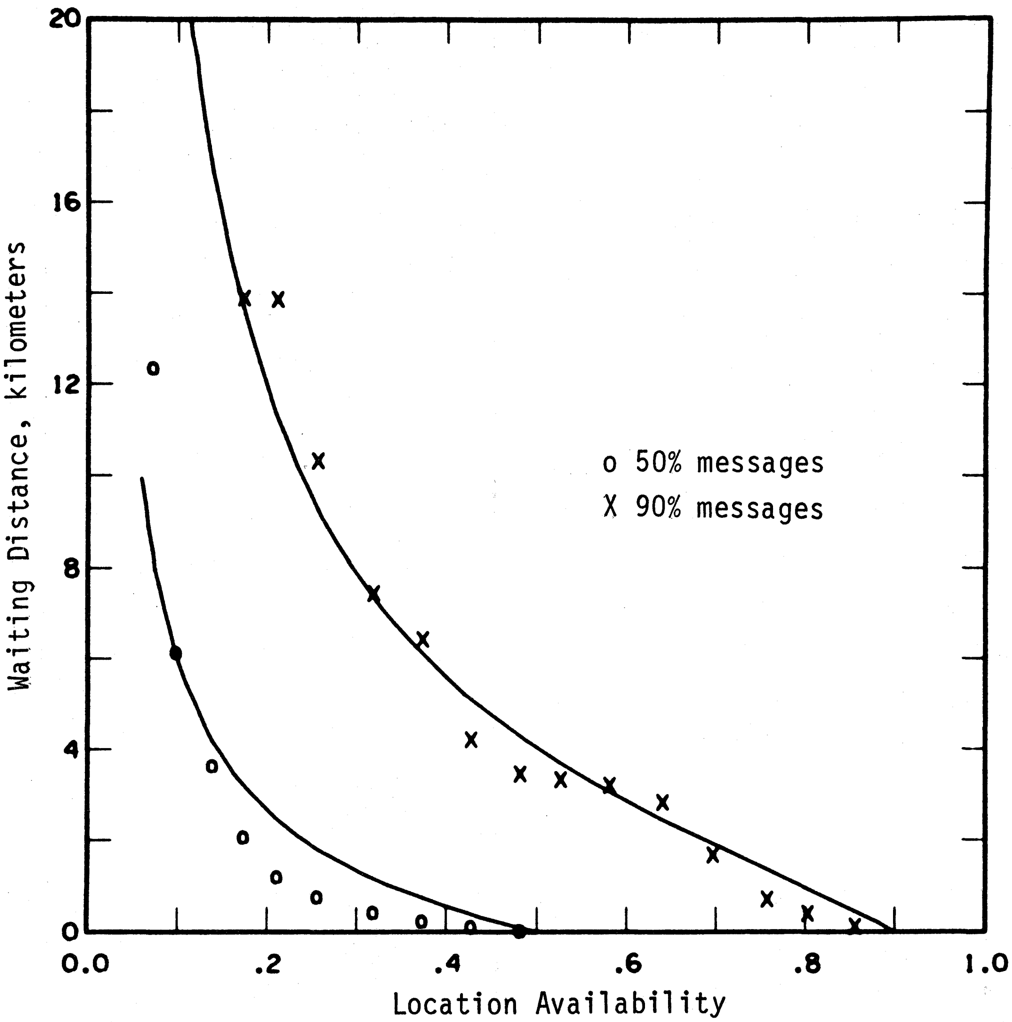


Figure 10. Empirical waiting distances for the mountain road measurements. The curves show the proposed approximation using D = 800 m.

theory, but simply because the curve of 90% quantiles seemed then to pass through the mid-range observations. This 800-m value, incidentally, provides a parabola for Figure 9 that seems to lie midway between one that fits the very first part of the curve and one that might fit the plateau that extends from 0.5 to 1.0 km. Note that if instead we had used D=220 m, we would have had a very good fit for the smaller of the waiting distances.

4.3.4 A Plains Road, Colorado

The second of these runs that we have been able to analyze took place directly east of the receiver in the plains of Colorado. The route began about 6 km southeast of the receiving terminal and went almost straight east for 98.2 km. It then turned around and came back along the same road.

This route differs from the mountain route of the previous subsection in three important respects: It runs radially out from the receiver terminal rather than transversally, it is over considerably flatter terrain, and nearby trees and buildings are almost non existent. (The area is one of farm lands and grazing lands with only sparse population.)

In Figure 11 we show a chart of the received signal levels where, as before, we have combined the two receiver measurements and have changed the abscissa from the recorded time to an assumed distance along the route. There are several features to note here. As one would expect, the signal level shows a very definite trend, decreasing fairly steadily on the out-bound trip and increasing on the return. Many of the notable features of the trace on the out-bound trip are duplicated quite accurately on the return trip--although we could sometimes wish that the duplication was even better. The most prominent feature, however, is the fact that the signal level trace here is much smoother than that of the mountain road--there seems to have been an almost complete absence of multipath components. Only after about the 80 km mark does the signal trace break into a fairly severe case of small-scale fading. This point is where the road descends into a shallow creek bed so that perhaps the direct wave is greatly attenuated and extra, off-path components become important. We do not know why there are, at the longer distances, so many measurements below the noise level of about -135 dBm.

In the previous analyses of this report we have insisted that trends in the data must be removed, and we shall do so here, too. But it might be wise to first review the reasons for removing a trend, particularly on routes such as this one where the trend is clearly more important than the variability.

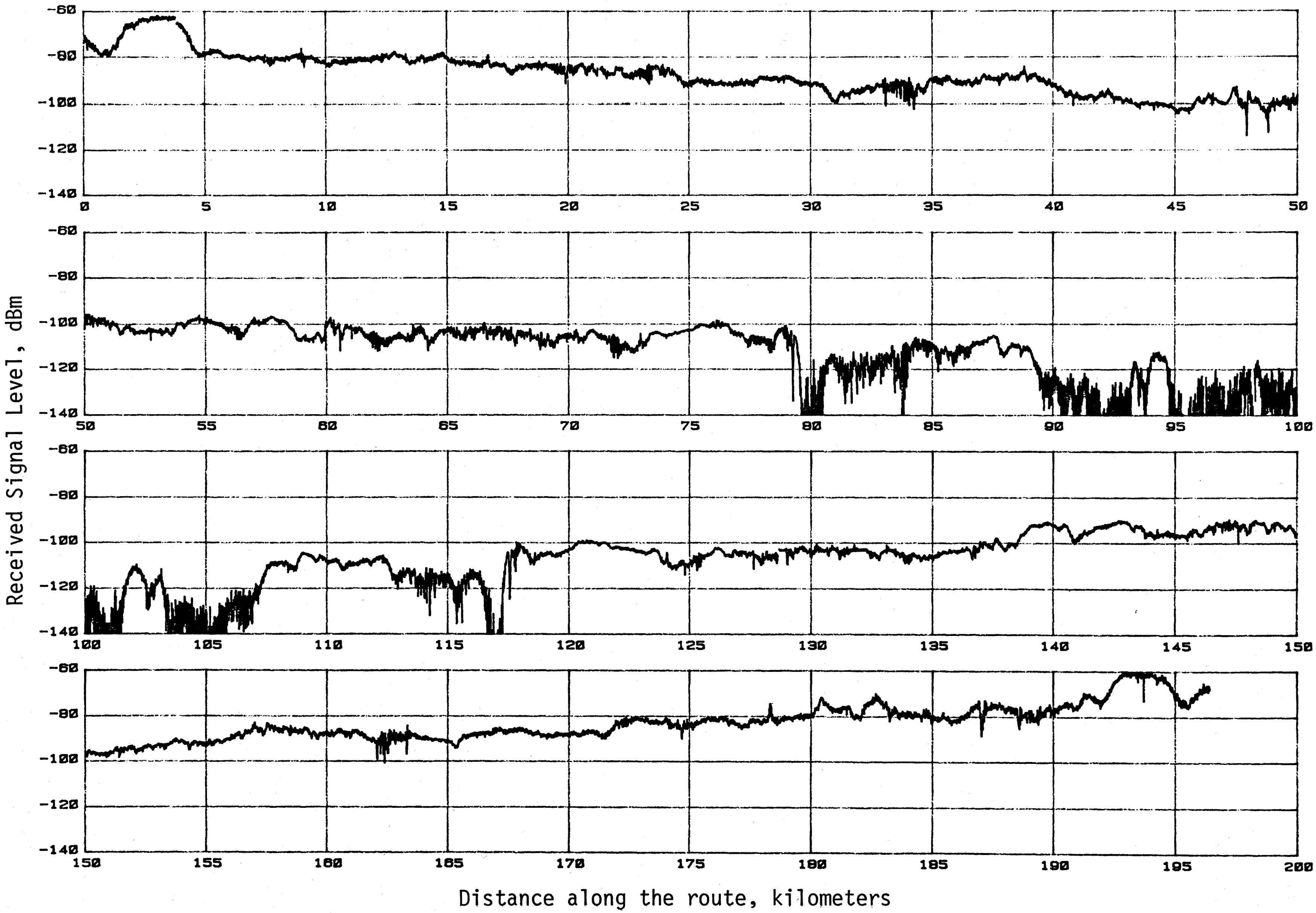


Figure 11. Combined signal level versus distance along the plains route.

In general we must think of waiting distances as functions of the path length. Partly this is because the correlation distance might change, but mostly it is because the location availability is a function of path length. And the princial reason that location availability changes is simply that the median signal level drops with increasing distance. If one proceeds along a route in which the path length is steadily increasing, then one must admit that if a message has not yet been sent, the prospects that it will soon be sent becomes ever more remote. Clearly there is even the possibility that the message is never sent--one has passed out of range of the system, even if that range is an extended one. But these effects can all be computed once we know the median signal level, the standard deviation, and the correlation distance, all of which might be functions of position along the route. What our measurement analyses are designed to do is simply to measure these separate quantities from which further calculations and design approaches may be made. Removing the trend in the data then amounts to a resolution of the median signal level after which the other two statistics can be treated.

As in the case of the mountain road, we have smoothed the signal level trace using 120-m moving windows spaced 60 m apart. Then to remove the trend we have subtracted the "reference" signal level as predicted by the ITM in the area prediction mode. Parameters used in the prediction include a Δh of 60 m and a receiving antenna height of 106 m--this latter because the receiving terminal is actually on a low mountain that overlooks the plains and whose height above the plains we have to add to the actual height of antenna above ground. The results of these reductions are presented in Figure 12. The two pairs of strips show first the smoothed deviations of measured data from predictions and second the local standard deviations of the small-scale variability. Note that the latter clearly shows that for most of the route there is essentially no small-scale variability. Only at the far distances does this variability become noticeably different from zero, approaching Rayleigh or near-Rayleigh values.

The autocorrelation function of the smoothed deviations is plotted as the solid curve in Figure 13. As in the case of the mountain road in Figure 9 there is initially a rapid decrease from unity and then a definitely slower decrease. The mean deviation is -6.9 dB and the standard deviation is 6.3 dB. For the 196 km of the route there are 131 crossings of the mean which implies a correlation distance of 480 m.

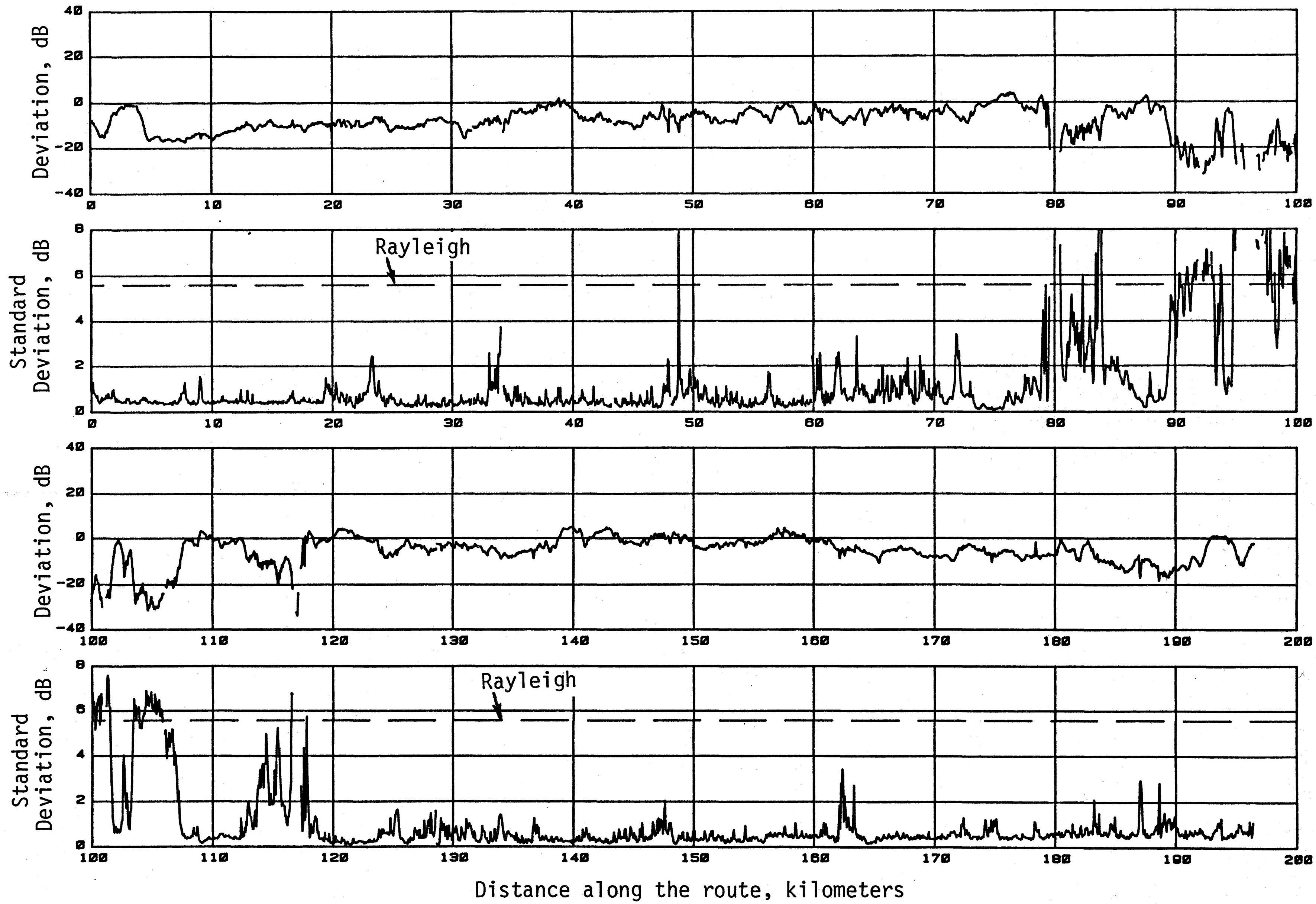


Figure 12. Local mean and local standard deviation of the deviations of measured data from predictions on the plains route.

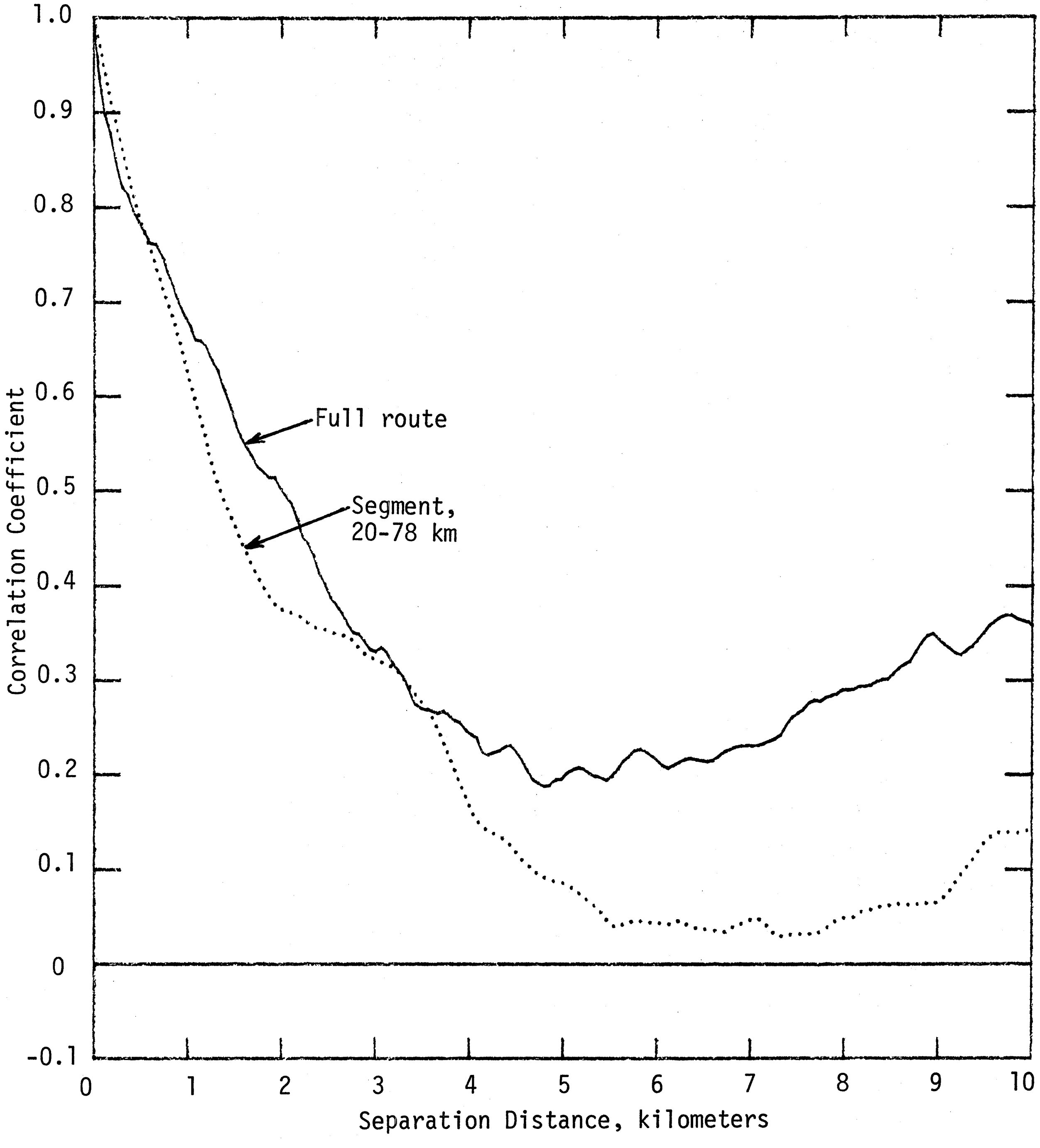


Figure 13. Autocorrelation functions for the plains road measurements.

There is, of course, an obvious change in the characteristics of the process after the 80-km mark. To explore this change we have examined the segment that extends from the 20-km to the 78-km marks. The dotted curve in Figure 13 shows the resulting autocorrelation function--it is remarkably similar to that for the full route. The mean deviation is now -6.0 dB and the standard deviation is only 3.5 dB. In these 58 kilometers there are 53 crossings of the mean and so an estimated correlation distance of 350 m.

With such small standard deviations there will be little advantage gained by a burst transmission system. On the other hand, it will usually be true that we do not need an advantage at the shorter distances, while at the longer distances we may note that the standard deviation seems to have markedly increased. It is unfortunate that we do not have enough reliable data at these longer distances to explore the possibilities.

We have also computed waiting distances for these data just as we did for those of the mountain road, the computations of which are plotted in Figure 10. From the new computations we would have been inclined to estimate a correlation distance of about 1040 m for the full route and of 640 m for the shorter segment. Again we see that for intermediate distances our approximation seems a little optimistic.

4.4 Signal Persistence Distance

In addition to the waiting distance, there is another terrain-related measure relevant for the burst system. After a waiting distance of x kilometers, when the long-term variation can be expected to produce a signal above the threshold and the message is received, the signal then must also have persisted in the presence of the short-term variation at or above the threshold level long enough to exceed the message duration, t in seconds. That means the threshold level or higher must have persisted for a distance

$$\ell \geq v\ t, \tag{16}$$

when the terminal is moving at an average velocity of v.

This signal-persistence interval ℓ is a function of the short-term, approximately Rayleigh-distributed signal variation; specifically, ℓ is the duration of the "upfades" from the median level. Bodtmann and Arnold (1982) give a theoretical value of the mean duration as

$$\overline{\ell} = 0.48\lambda,$$

where λ is the transmission wavelength. Although this estimate may be terrain related, the measurements described in Section 4.3.3 for travel along the mountain road (see the bottom trace of Figure 7) exhibit upfade durations that generally exceed about 2.4 m or 0.4λ. The value in (17) seems fairly accurate.

Using (17) with a wavelength of 6 m and assuming an average speed of 16 m/s (35 mph) we find from (16) that we should be able to transmit any message whose duration does not exceed 0.18 s. On the other hand, if, as suggested in Section 3, we try to utilize these upfades to help out with the power budget, then this maximum average duration must be somewhat reduced.

4.5 Summary

Equation (15) has been applied to the measurements described in Section 4.3.3 to determine correlation distances ranging from 200 to 800 m. Using the latter, the conservative value, one can convert the vertical scale of Figure 1 to meters and obtain Figure 10. Figure 10 expresses the location availability for a mobile burst system as a waiting distance of travel. Assuming one is willing to wait 5 km of travel along a road before 90% of the message is received, Figure 10 shows that this corresponds to a location availability of 43%. A 10-km wait corresponds to a location availability of 24%.

The numbers presented here, of course, are only tentative. The measurements on which they are based are inadequate in some degree. There appears to be no available set of measurements to fully satisfy the need.

5. TRADE-OFFS

The purpose of telecommunications is the transfer of information to or from a remote point. Hence, any telecommunications system has an available information transfer capacity that may exceed, equal, or fall short of the capacity required for a particular application. In the specification of a burst system to replace the demand system, this required/available ratio of information transfer capacities provides the opportunity for trade-offs that improve upon the demand system's performance.

In general, the burst system introduces a trade-off of acceptable waiting distance for an extended range, or power advantage, or both. In addition, determination of an acceptable waiting distance would involve trade-offs between the elements of information transfer capacity. To the extent that these trade-offs can be effected while still meeting the required system performance, the burst-system design would be successful.

5.1 Extended Range

The demand system and burst system required performance has been described in Section 3 as a 90% confidence that there will be at least 90% of the time that 90% of the messages will be received. For the conditions f = 50 MHz, Δh = 90 m, and a tolerable loss of 151 dB, Table 1 lists a demand system range of 10 km and extended ranges for reduced values of location availability. Combining this information with that of Figure 10, one obtains Figure 14. Figure 14 constitutes the trade-off relationship between waiting distance and range extension. For example, if the demand system users felt they could accept a waiting distance of 5 km (or q = 43%), that would extend the system's useful range by 120% to 22 km.

5.2 Power Advantage

In a similar manner, one can combine Figure 10 and Table 2 to obtain Figure 15, the trade-off between waiting distance and power advantage. If the demand system users considered a waiting distance of 5 km acceptable, then the demand system range could still be achieved but with about 11 dB less system power (i.e., reduced transmitter power, antenna gains, etc.).

Of course, an acceptable waiting distance could also provide trade-offs of both an extended range and a power reduction. Figure 16 shows a plot of the combinations of extended range and power reduction that could be achieved by trade-offs for an acceptable waiting distance of either 5 km or 10 km (q = 43% or 24%). For example, if a waiting distance of 5 km were acceptable, the system transmitter power and/or antenna gains (perhaps a smaller and lighter unit) could be reduced by 5 dB while still achieving a range extension of 50% to 15 km.

5.3 Other Trade-Offs

In each of the trade-offs described above, the acceptability of a particular waiting distance value was postulated. However, this acceptability depends upon a number of other trade-offs. For example, when the demand system has an information transfer capability that exceeds the required (mission-determined) capability, then one might raise a question such as

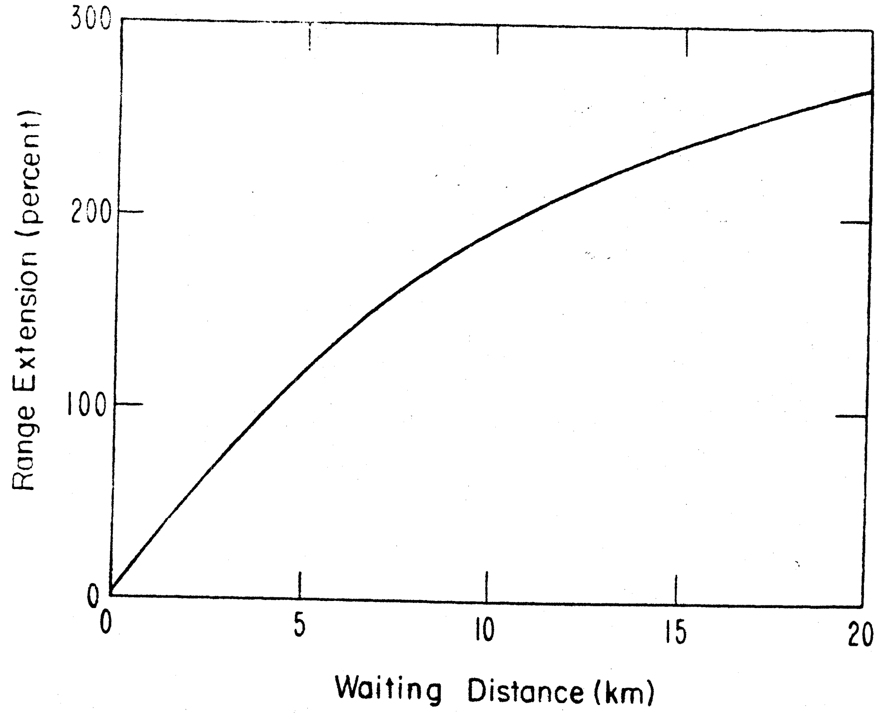


Figure 14. The empirical trade-off of waiting distance for range extension.

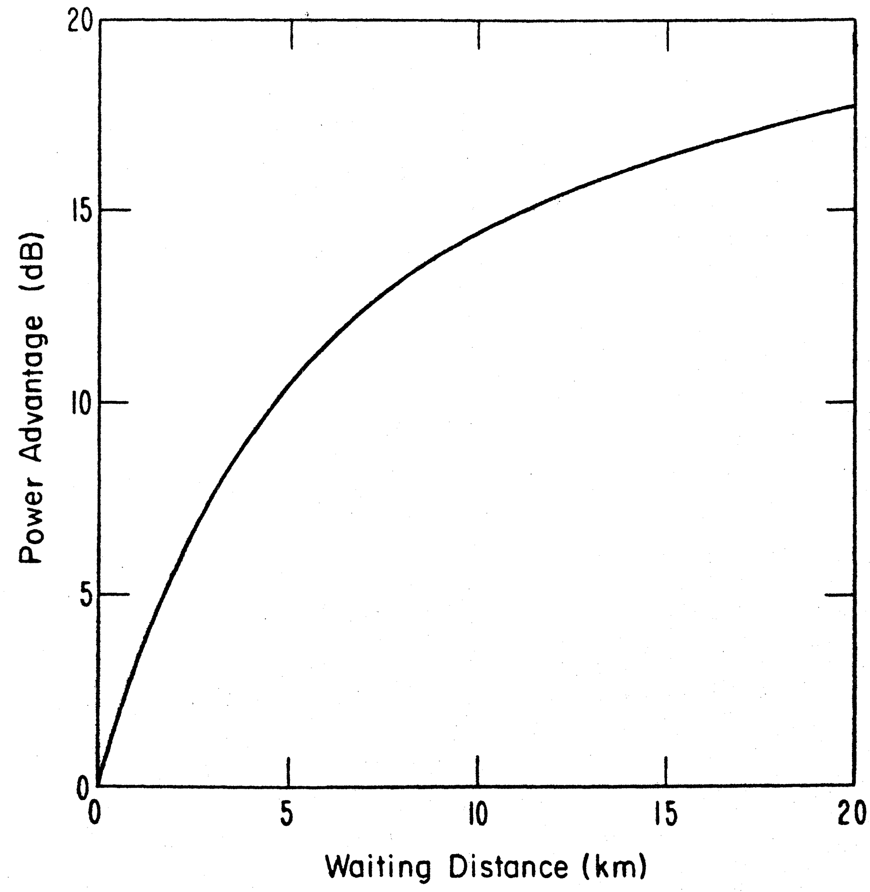


Figure 15. The empirical trade-off of waiting distance for power advantage.

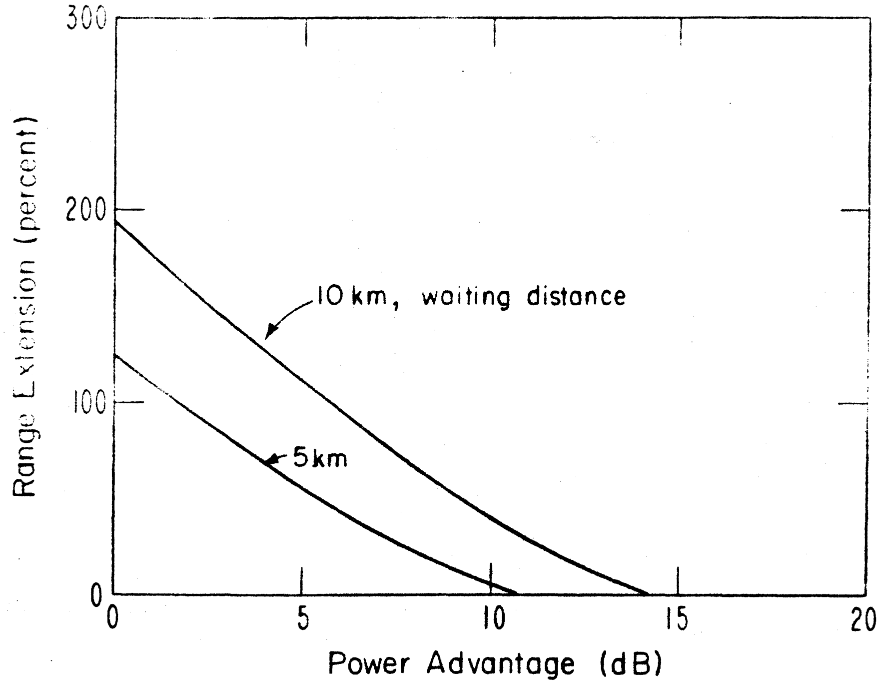


Figure 16. The empirical trade-off between range extension and power advantage available for an acceptable waiting distance x in kilometers.

follows. Can the demand system be replaced by a burst system to achieve an extended range or a power reduction (or both) by reducing the information transfer capacity to what is required? From Sections 5.1 and 5.2, the answer is clearly yes, and also it is clear that the allowed reduction in information transfer capacity is what determines the acceptable waiting distance.

To summarize, we can make the following statements:

- The system's information transfer charactistics and their associated trade-offs, in a proposed conversion from demand to burst system, will determine the maximum acceptable waiting distance.

- For the propagation and terrain characteristics, the burst system's desired extended range and power reduction combination will determine the minimum required waiting distance.

This separation is fortunate in that, for any proposed conversion from demand system to burst system, joint information transfer and terrain/propagation studies are not mandatory. Such studies can advance independently until the operational system design stage.

6. FUTURE STUDIES AND MEASUREMENTS

The behavior of a burst transmission system has been analyzed using available data and propagation models. It is now clear that the location variability of the signal is the particular aspect of propagation at VHF/UHF in a terrestrial environment that will certainly be beneficial to a burst transmission system. That variability may be expressed in two quantities; the long-term quantity is the correlation distance, the short-term quantity is the duration of "upfades." The correlation distance is directly related to the waiting distance, of which the minimum value is that required to barely achieve the desired burst-system performance. The duration of "upfades" defines a minimum signal-persistence distance which, together with the system's information-transfer parameters, defines the system's maximum tolerable waiting distance.

There are very few data available that could yield information on the correlation distance, especially as a function of the terrain irregularity. There may be more sensitivity to the radio frequency than this preliminary study has indicated. A more solid basis of measurements is needed. We can envision a fairly extensive measurement program involving a fixed terminal and a mobile terminal, and a variety of sites in all kinds of terrain. (Another question arises when we ask for the system behavior with both terminals in motion.) Such a measurement program could be augmented with a computer-based study of terrain effects in which a file of digitized topography would be used. In addition, if the autocorrelation function of Figure 9 turns out to be fairly typical, then it would be desirable to construct a more robust theory of waiting distance.

6.1 Terrain Parameter Studies

This report has identified the appropriate burst-system performance measure as a waiting distance that is determined by two terrain-related parameters, the long-term correlation distance and the short-term upfade interval. In order to obtain improved estimates of these two parameters and their dependency upon terrain, a data-gathering study is recommended.

Measurements under various terrain conditions are proposed, to achieve:

- empirical descriptions of correlation distance, the short-term distribution, and its distribution of "upfade" intervals;
- an empirical description of the waiting distance and its dependency upon the correlation distance; and
- a comparison of the predicted and observed range extension.

To achieve these will require certain measurement system characteristics.

6.1.1 General Requirements

To obtain the appropriate data, the following characteristics are required:

- Transmission frequency of 200 to 300 MHz so as to minimize the atmospheric and man-made noise and to reduce the likelihood of anomalous propagation;

- Dynamic Range of 80 dB or more to maximize the data acquisition for statistical analysis;

- Information Capacity sufficient for transmission, from mobile terminal to fixed terminal, of measurement-related information (time, position, speed, etc.);

- Measurement Records, on magnetic tape for later processing, of the instantaneous received signal level, the message content, the received message percent accuracy, time, and location data;

- Signal Polarization transmitted vertical, but adaptable to horizontal for spot measurements;

- Mobile Antenna preferably 2 m above ground with an antenna pattern that is omnidirectional in the horizontal plane and broadbeam in the vertical plane.

The transmitter power, its antenna height and gain pattern, and the receiver sensitivity and noise figure are selected to define the reference demand system performance.

6.1.2 Plan Requirements

The route of measurement, such as Figure 6, should be layed out with the aid of both terrain maps and road maps so that milestones (road intersections or forks, bridges, railroad crossings, and other identifiable terrain features) may be identified and located on the route map.

6.1.3 Mobile Unit Requirements

The mobile unit must be equipped for continual recording of time, velocity, transmission events, and passing landmarks on tape while moving. The transmission events are the start and end of transmission. The message content should contain the time and velocity of the start of transmission and at least three conveniently grouped standard numerical sequences (1,2,3,--n) to mark the duration of the message and to provide a basis for estimating the received signal's error rate.

6.1.4 Fixed Terminal Requirements

The fixed terminal must be equipped for continual tape recording of the time, transmission/reception events, the instantaneous received-signal level, and the message summaries. These received message summaries would include the start time and velocity for each message, the number and accuracy of each message and message block as well as their durations for 90% accuracy or greater.

6.1.5 Required Signal Processing

The received signal must be normalized to remove the systematic effects such as propagation path length and fixed-station antenna gain with the expectation of thereby converting the underlying random process into a stationary one. This normalized signal (the residual recording) must be identified in terms of placement (of the mobile unit) along the recording route.

This residual signal must be processed to determine its short-term distribution (with and without adjustment to a zero median), its mean and standard deviation, the number of upfades above the median, and the distribution of the durations of these upfades. If necessary, these short-distributions can be defined as persisting for 10 or more transmission wavelengths of travel or for at least 20 median level crossings. The long-term distribution, its mean, standard deviation, auto correlation function, number of mean crossings, and associated range are also required. If there is more than one test channel (i.e., more than one fixed station, operating frequency, polarization, or antenna height), then in addition to the above short-term and long-term statistical averages, the cross-correlation functions would be valuable.

6.2 Burst Transmission Propagation Data from the SNOTEL System

An opportunity is present for collecting useful and otherwise
by a modest instrumentation of the SNOTEL (SNOpack

TELemetry) system. This data aquisition system is the largest scale application of burst transmission that we know of in the world today. Its purpose is to provide hydrological and meteorological data from about 500 remote sites two or more times a day. The SNOTEL system is operated by the Water Supply Forecasting Unit, West Technical Service Center, Soil Conservation Service, U.S. Department of Agriculture, in Portland, Oregon. The entire system is controlled from there with dedicated lines connecting the control center with the master stations. The two master stations are located at Boise, Idaho, and at Ogden, Utah. The remote stations are distributed throughout the western mountain ranges: the Rockies, Sierras, and Cascades.

Although this system is based on the well-known principles of using ionized-meteor trails (Oetting, 1980; Gottlieb, 1981) known as a meteor-burst system, we suspect that not all of the radio signals are propagated via meteor trails (or reflections off aircraft). These particular cases may be very interesting to the study of extended range communications.

The protocol is typical for a meteor-burst system. The master station repeatedly sends a polling message that contains groups of addresses (each remote station has a unique address). When a suitably positioned meteor trail forms and a particular remote station identifies its address, it immediately sends the data stored in a buffer using an adjacent frequency. This transaction takes about 100 ms. When the master station verifies that it has received all of the data from that particular remote, it sends an acknowledgment. When the remote receives this acknowledgment it turns off its receiver for a fixed period of time (typically, 1 hr). Figure 17 is a diagram that shows the sequence of events beginning with a polling sequence from a master station through a remote station and back to the master station receiver. Note that in the example shown the first acknowledgment (ACK) sent by the master was not received by the remote.

Certain remote stations are observed to respond very early in a polling sequence and to do this with some regularity (Vancil, 1981, Soil Conservation Service, Portland OR, private communication). The signals in these cases could be propagating via line of sight, diffraction, and/or tropospheric scatter modes. If this is true, monitoring the system performance for these remote/master combinations would provide useful propagation data for a burst transmission system.

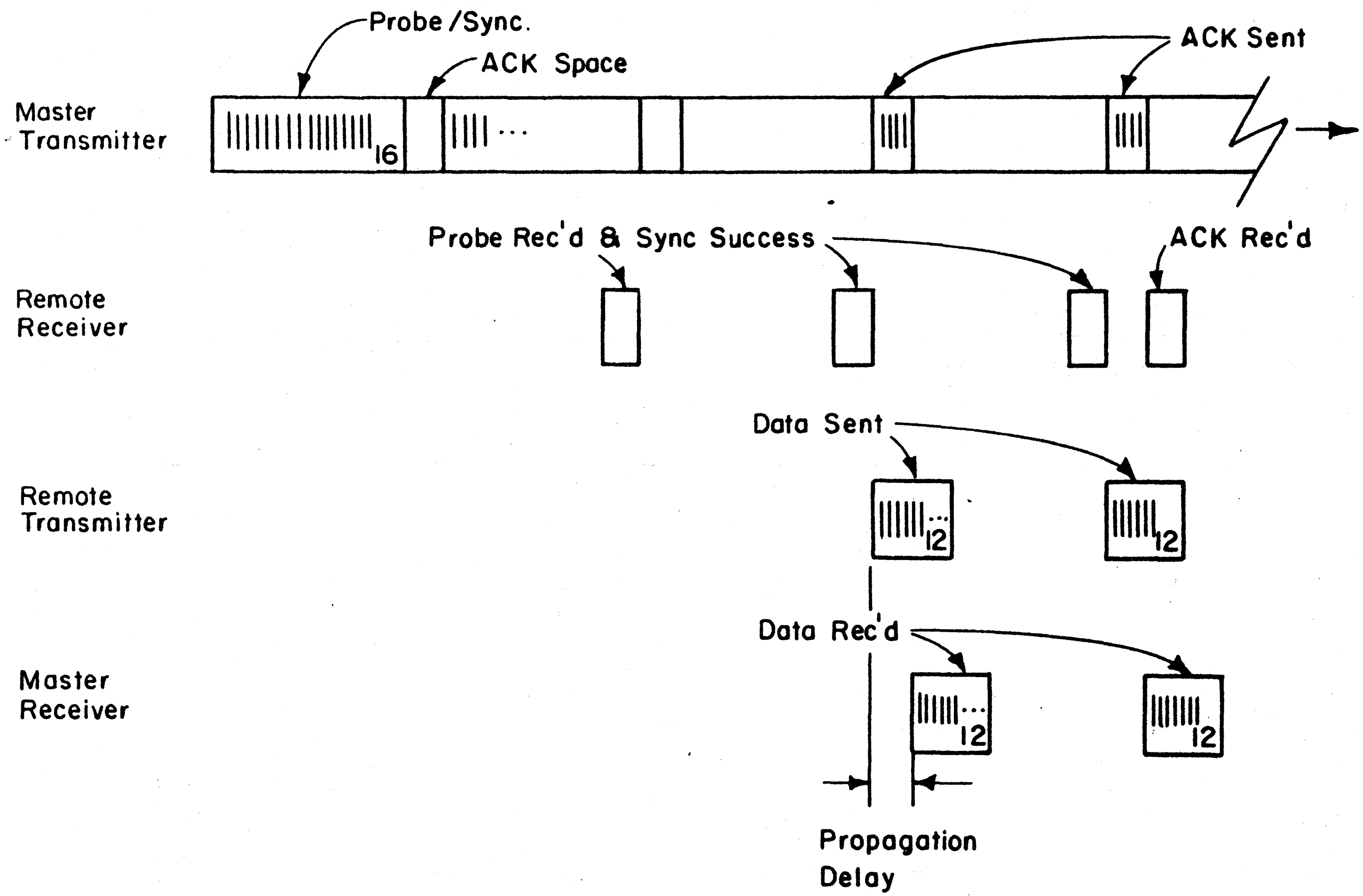


Figure 17. An example of a master-remote interchange in the SNOTEL system showing the system protocol. Time advances from left to right.

The success rates for polling messages from the master received at the remote, data messages sent by the remote, and acknowledgments sent by the master represent information that can be related to waiting times. There are possibly three different burst lengths here. The collection of these data require simultaneous records of the messages sent and received at each station. Computer software at both the master and remote could be provided to do this. A remote would transmit its message counts, both transmitted and received, as part of its data message. The message counts would be accumulated at the master station.

In addition to the message success rate data, the level of each received message could be recorded. This, of course, would require additional instrumentation at each station. The received signal levels at the remote would become part of the data message; these would be stored with the other data in the master station computer.

It is also desirable to have a way of checking the propagation path. One way of accomplishing this is to use a sufficiently accurate and precise clock at both stations. Keeping a record of event times would permit the determination of the propagation delay. This, in turn would be used to categorize each message sent as being propagated via a "meteor" or a "nonmeteor" path. The propagation delay for a meteor path would be on the order of a millisecond or more; for the non meteor path it would be on the order of a microsecond or less.

7. ACKNOWLEDGMENTS

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The field measurements were performed by Richard E. Skerjanec, Joseph E. Farrow, and Dean Smith of this Institute. They also provided the appendix to this report.

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APPENDIX: FIELD MEASUREMENTS

As part of the work done for this study of burst transmission systems, there was a limited field measurement program designed to explore some of the pertintent aspects of radio propagation and some of the possibilities of anomalous propagation. A portion of the data collected has been analyzed in Sections 4.3.3 and 4.3.4. In this appendix we shall describe the equipment used, the procedure followed, and some of the additional data that were obtained.

A.1. EQUIPMENT DESCRIPTION

The equipment used for these measurements was designed for meteor-burst operation but was adaptable to the shorter paths discussed here since the meteor-burst mode would contribute very little to the total amount of data gathered for the transmission distances involved. Figure A-1 is a block diagram of the transmitter used in the program and Figure A-2 is a block diagram of the receiver and data recording system. Tables A-1 and A-2 give the salient parameters of the system.

In operation, the transmitter sent a predetermined message of 130 characters divided into 10-character blocks. The microprocessor-controlled receiver would search the incoming data for these patterns and log the number of blocks and the number of complete messages received during each approximate 5-minute interval. Both were counted because individual blocks were more likely to be correctly decoded by the receiver than an entire message and this fact is reflected in the results.

Table A-1. Equipment Parameters

Transmitter:

- Output power: Variable to 1000 Watts
- Modulation Rate: 2 kBPS PSK
- Frequency: 49.85 MHz
- Antenna Type: Vertical Whip
- Antenna Height: 3 Meters -- Van Mounted

Receiver:

- Sensitivity: 131 dBm (Receiver noise only)
- Noise Figure: 4 dB
- Antenna Type: 5 Element Yagi
- Antenna Height: 10.5 Meters--Tower Mounted

Table A-2. Receiving - Recording System

* Recivers Calibrated with Signal Generator
* Wideband Receiver: 100 dB Dynamic Range
* MCC Receiver: 30 dB Dynamic Range
* MCC Receiver Block and Message Count
* Strip Chart Recording of Analog Parameters
* Magnetic Tape Recording of Analog Parameters
* Time Code Recorded on Magnetic Tape

For convenience of operation, the transmitter was mounted in a mobile van and moved throughout the measurement area while the receivers and recording instruments were located in an available building. One of the problems encountered in setting up the measurement scheme was in finding a location where the ambient radio noise level was low enough to permit full exploitation of the receiver sensitivity. It was found necessary to locate the receiving system in a "radio quiet zone" on Table Mountain near Boulder, Colorado. This location provided clear reception free from foreground obstructions.

Although the meteor burst equipment was usable for these measurements, it had several serious shortcomings as far as data collection was concerned which should be corrected in any future measurement program. First, the frequency of operation, 50 MHz, placed it in a very difficult part of the spectrum. The use of frequencies near 50 MHz is heavy and man-made and atmospheric noise is difficult to avoid. This reduces the possible number of locations where such a test system can be used. Test systems operating at frequencies above 200 MHz would not be subject to these limitations.

Another serious drawback to the meteor-burst equipment was the narrow dynamic range of the received-signal-level indication. The useful range of this parameter was only from noise level to about 30 dB above; the received signals were expected to vary over a range of 80 dB or more. This necessitated obtaining a tunable receiver that had a sufficient dynamic range but considerably less sensitivity to permit observation of high signal levels. Careful attention to test receiver characteristics would solve these problems of data acquisition.

A.2. TEST LOCATIONS

In order to obtain the maximum number of data points possible in the limited time available, most of the measurements were taken with the transmitter van moving along a preselected route. The idea was to examine many locations for very brief intervals and then to return to any location which showed interesting or unusual effects. Figure A-3 is a map of the general measurement area with salient features identified.

A.2.1 Terrain Types

Three general terrain types were easily accessible for measurements. The first type of terrain is the high plains east of Table Mountain which are characterized as gently rolling hills generally without trees or other perennial vegetation except in the valleys along water courses. (Figure A-4 is a map showing the location of some of the plains paths). The terrain profiles in Figures A-5 and A-6 are typical profiles for this area. The second type is the foothills terrain along the Front Range of the Rocky Mountains which is similar to the plains but with more broken terrain and higher mountains near enough to affect propagation. (Figure A-7 is a map showing the locations involved and) Figures A-8 and A-9 are terrain profiles for this area. The third type of terrain is the actual foothills of the Rocky Mountains with very broken terrain and measurement locations generally restricted to roads that tend to follow canyons and other such natural features. And (Figure A-10 is a map showing the path locations). Figures A-11 through A-15 are terrain profiles of these mountain paths. Each of the terrain types had different effects on the radio signal which led to three distinct patterns of received signal level.

The three types of received signal patterns will be referred to in the following discussion as plains, foothills, and mountains, respectively.

A.2.1.1 Plains Data

The plains data showed the least rapid variation in received signal level of the three types and generally showed a tendency to follow the contour of the terrain at short and medium distances, that is, when the transmitter was on a hill, the signal was high and when the transmitter van moved into a valley, the signals became much lower. There were very few extremely large changes in the received signal level that occurred over short distances as happened, for instance, in the mountain data. The most rapid changes observed appeared to be due to aircraft reflections which gave rise to a time-varying two-component multipath propagation mode. At these shorter distances the signal showed little variation with time and the data collected with the transmitter van at fixed locations showed stable signal levels. At extended distances, the data obtained over the plains with the van moving showed more pronounced spatial variation and a gradual decrease in median level until only an occasional peak of signal level was observed. Time runs at these distances showed the effects of atmospheric condition on the signal. In the morning when the atmosphere is more likely to be calm and stratified, fairly stable signals were received but as time passed during the morning and the ground warmed up, the stratification would tend to break up and the signal level was observed to decrease gradually, sometimes to below the receiver noise level. Figures A-16 and A-17 show plains data with the vehicle stationary and with the vehicle moving as noted on the figures. On all of the data sample figures, the top trace (and bottom trace), "Wideband Receiver rf RSL," is contaminated by interference that disabled the receiver from time to time. These periods were removed by software routines from the magnetic tape data analysis.

A.2.1.2 Foothills Data

The foothills data differed from the plains data chiefly in that the foothills data could include the effects of apparent terrain reflections. This means that even for short paths along the foothills, large rapid excursions in received signal level were observed as the transmitter van moved. This proved to be true for path distances as short as a few kilometers. In addition, the more abrupt terrain features typical of the foothills paths led to larger broad scale changes in signal level over shorter distances than were observed over the plains paths. These effects are shown in Figure A-18 which shows data taken with the transmitter van in motion at the approximate distance from the receiver location as noted on the figure. Since most of the foothills paths were short, no extended period time runs were made except for samples of a few seconds to a few minutes duration (obtained when the transmitter van was stopped in traffic) showed that the signals were fairly stable over these time intervals.

A.2.1.3 Mountain Data

The data obtained as the transmitter van travelled over the mountain routes showed the greatest variation. Since the radio path between the transmitter van and the receiver was almost never line-of-sight, the signal levels were low and showed constant variation with change in transmitter location and frequently dropped below the receiver noise level. On the other hand, data taken with the transmitter van stopped showed that the received signal was generally constant with time, at least over the periods observed. Examples of received signal level with the transmitter in motion and stopped at mountain locations are shown in Figures A-19 and A-24.

The most noteworthy changes of received signal level with time were observed on the longest mountain path for which the transmitter was located at Rustic in the Poudre Canyon west of Loveland. The transmitter van remained at this site for several hours and during most of this time the signal level was below receiver noise. However, several periods were observed when the signal level was enhanced enough that the receiver was able to pick up the data messages from the transmitter. The character of these signal enhancements is shown in Figures A-21 through A-24, which also show how many 10-character blocks and 130-character messages (if any) were received during the high-signal periods.

A.3 CALIBRATION

Two kinds of calibration were needed: the first involved the calibration of the receiving system, and the second involved the transmitter and its antenna. The receiver calibration provided the relationship between the receiver AGC voltage and the signal power at the input of the receiver. This, of course, was done for both receivers.

The second calibration was performed because the transmitter power and both antenna gains were uncertain. This calibration was done by choosing a test transmit site that would provide a clear, line-of-sight, propagation path to the receiver. This path was 15.3 km long with a free-space, basic transmission loss of 90.0 dB. If we make the arbitrary assumptions that the radiated power is 50 watts and the (logarithmic) sum of the antenna gains is 10 dB, we predict a received signal level of -33.0 dBm. The actual measurement on the test path was -48.4. This means we must include a 15.4 dB calibration constant (or correction factor) when analyzing the data, and we must also use the radiated power and antenna gains to be what was assumed above.

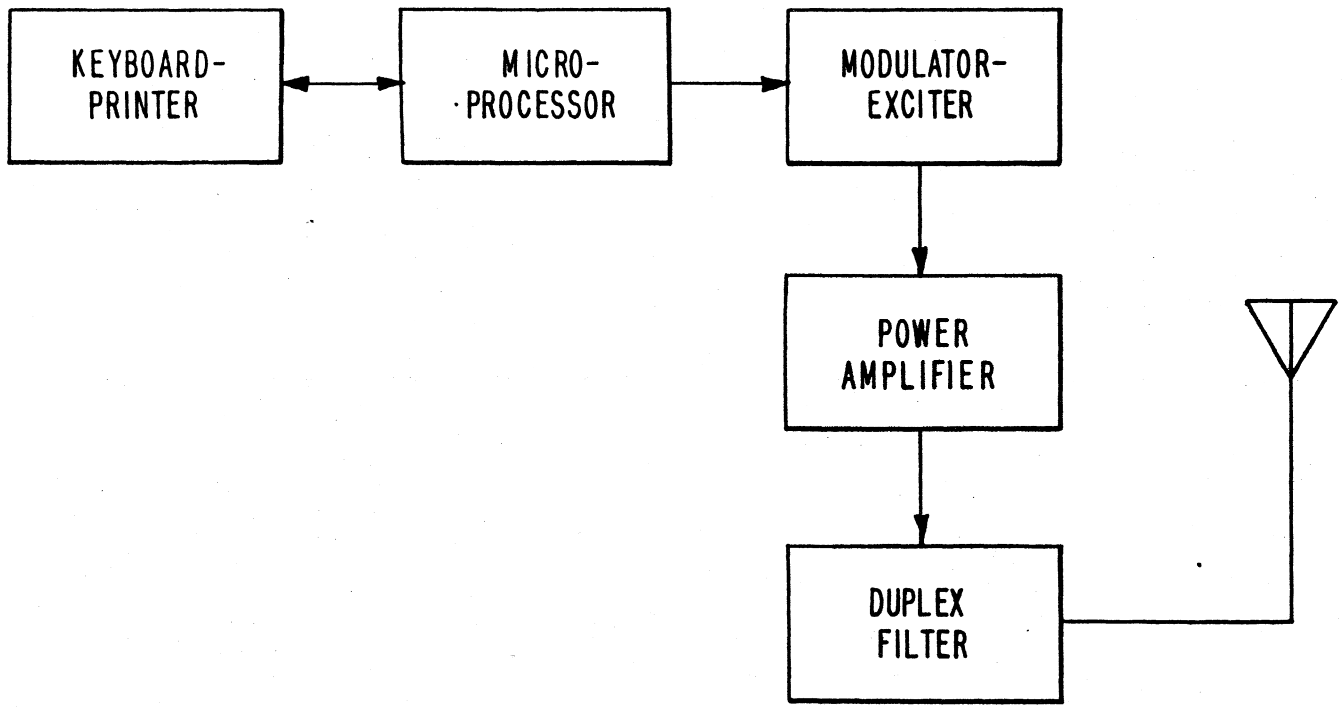

Figure A-1. Block diagram of the transmitting system mounted in the mobile unit (van).

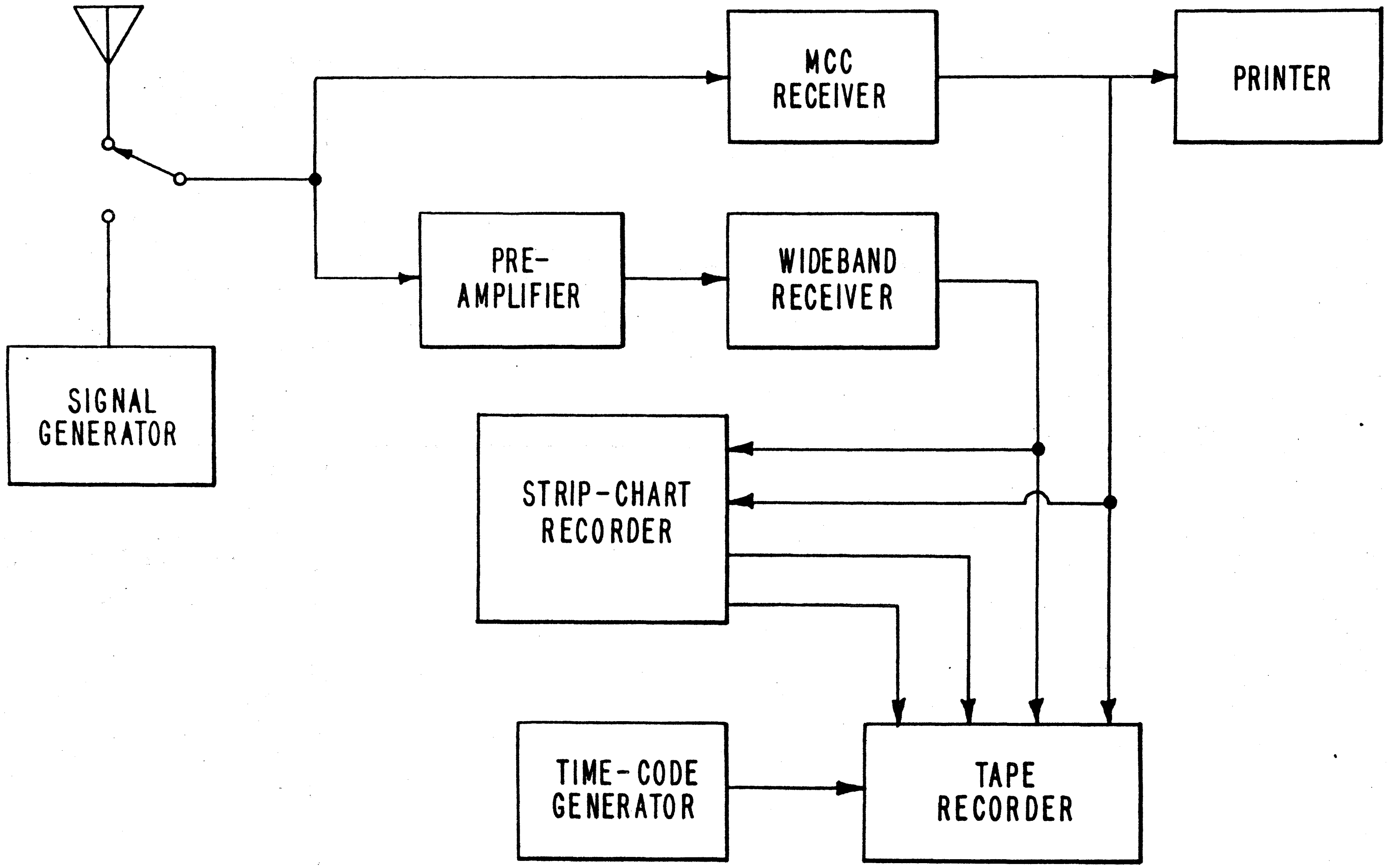

Figure A-2. Block diagram of the receiving system.

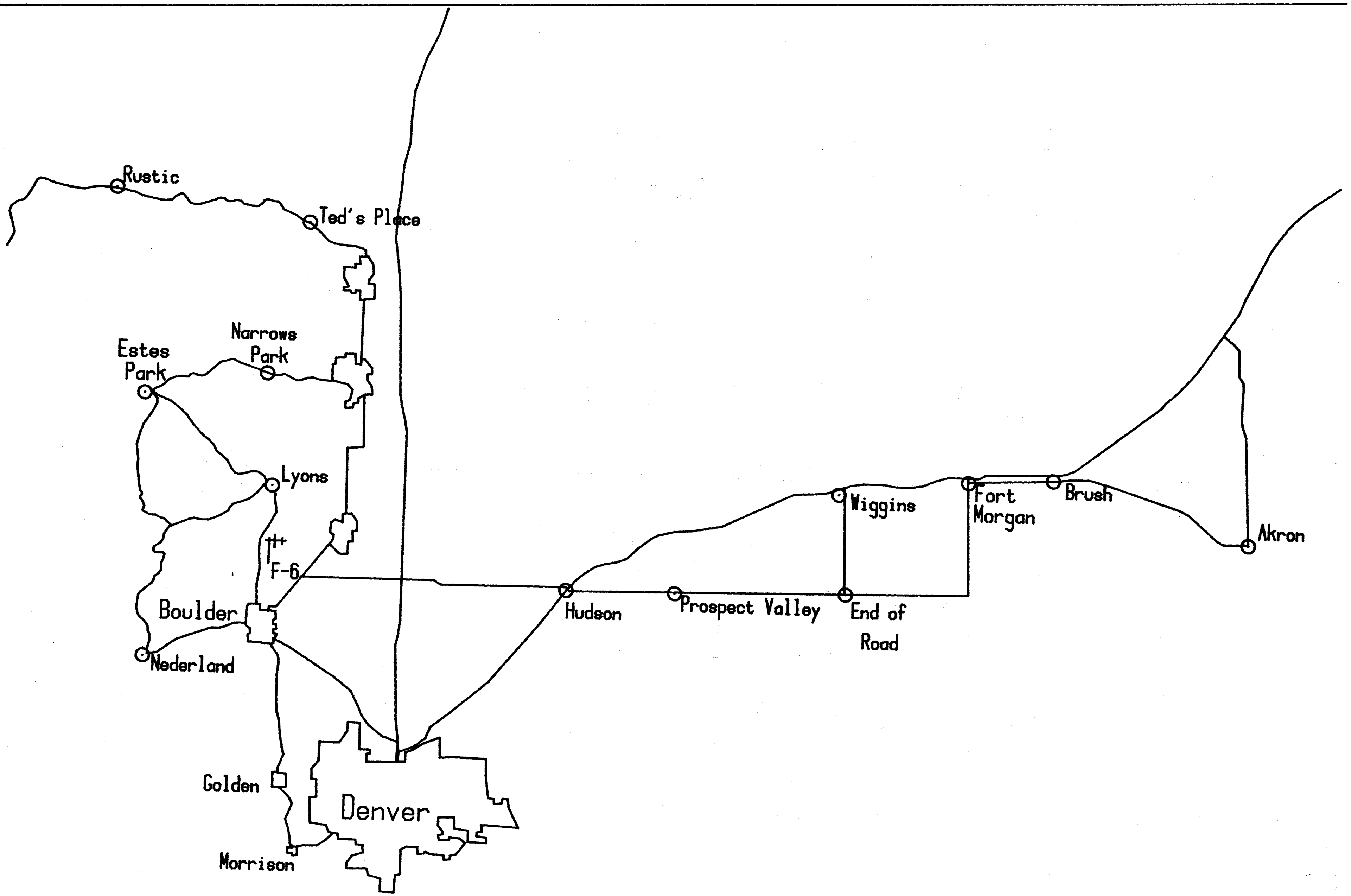

Figure A-3. Map of the measurement area.

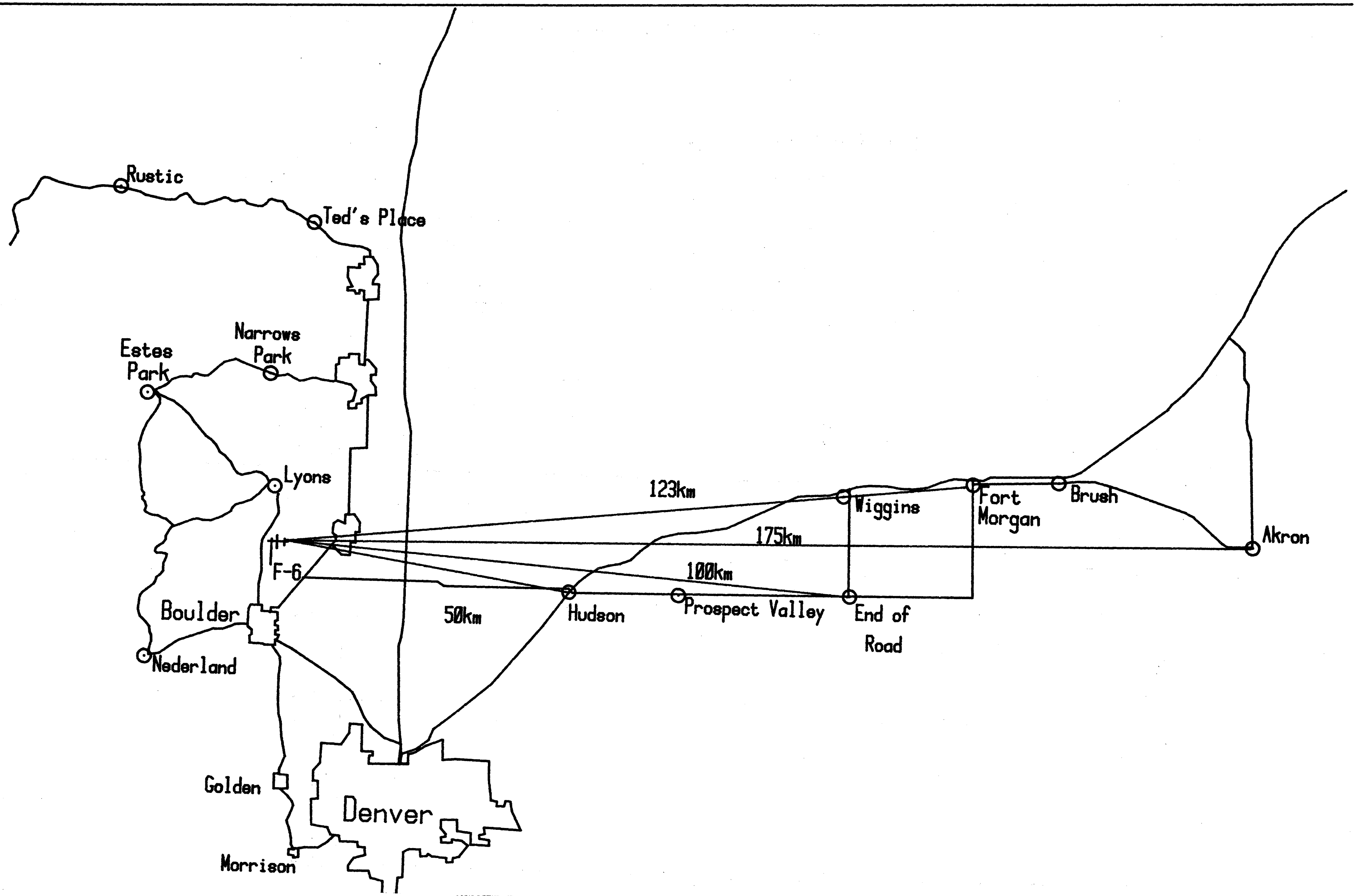

Figure A-4. Map showing plains path.

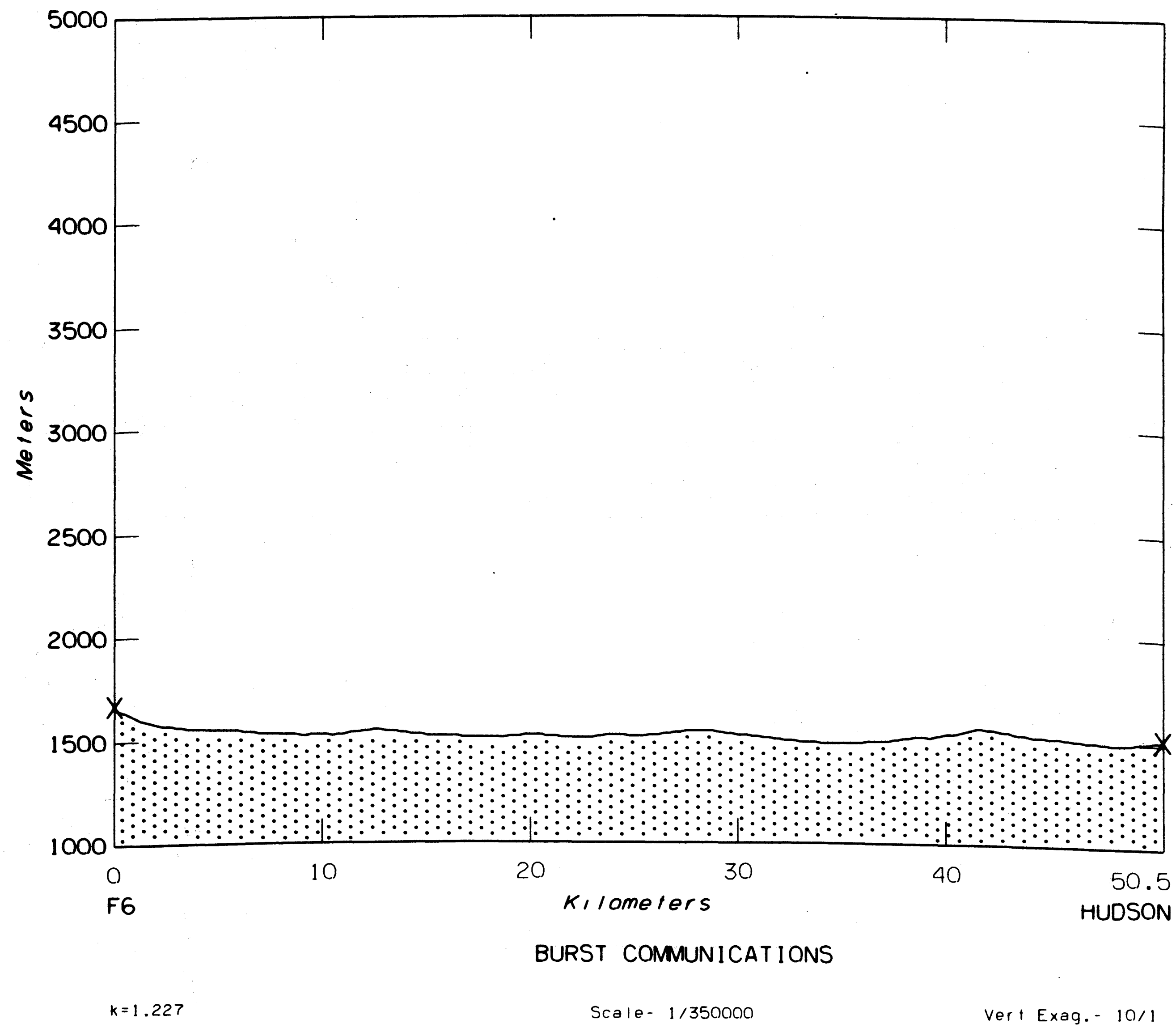

Figure A-5. Terrain profile between Table Mountain (F6) and Hudson.

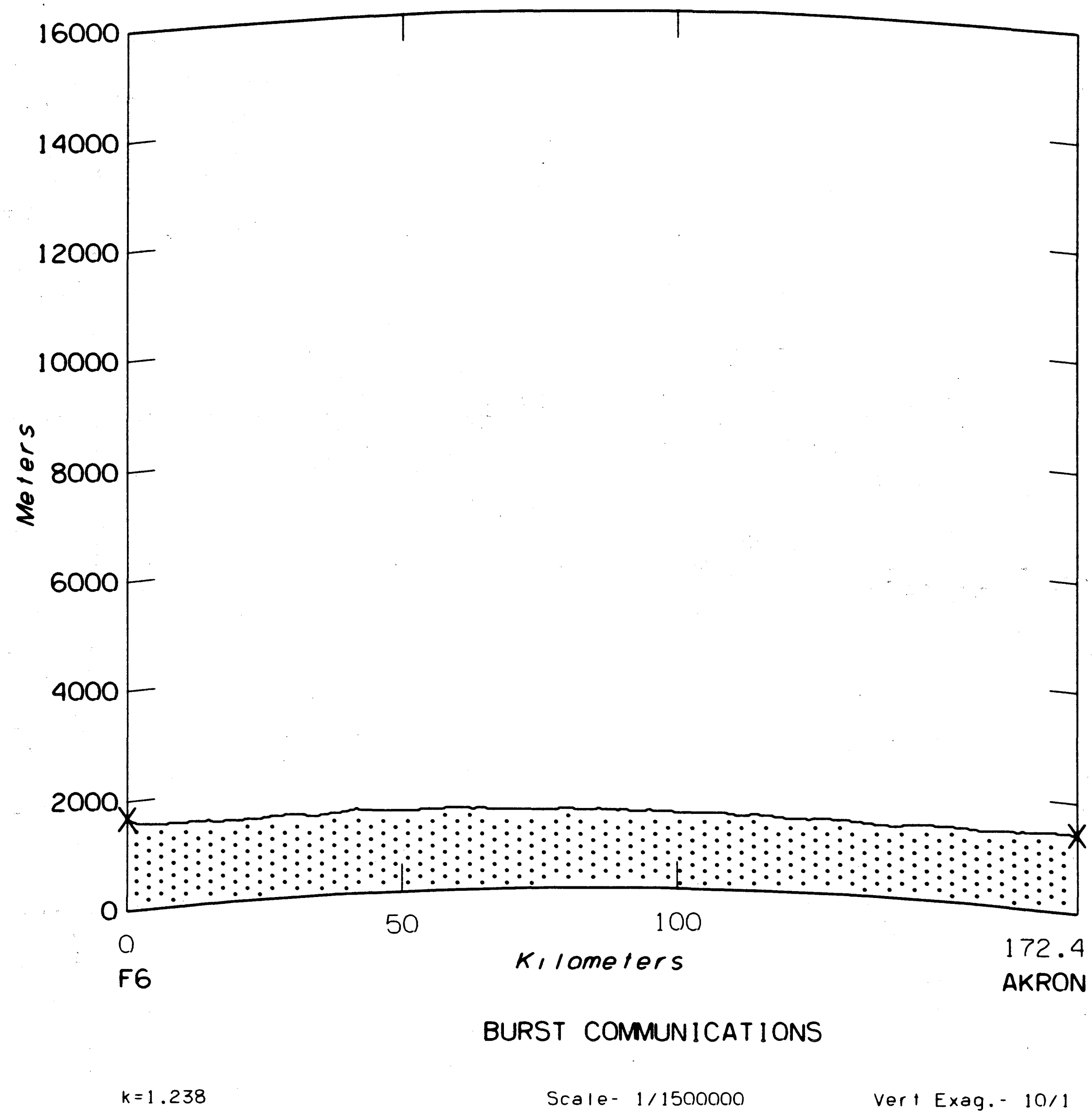

Figure A-6. Terrain profile between Table Mountain (F6) and Akron.

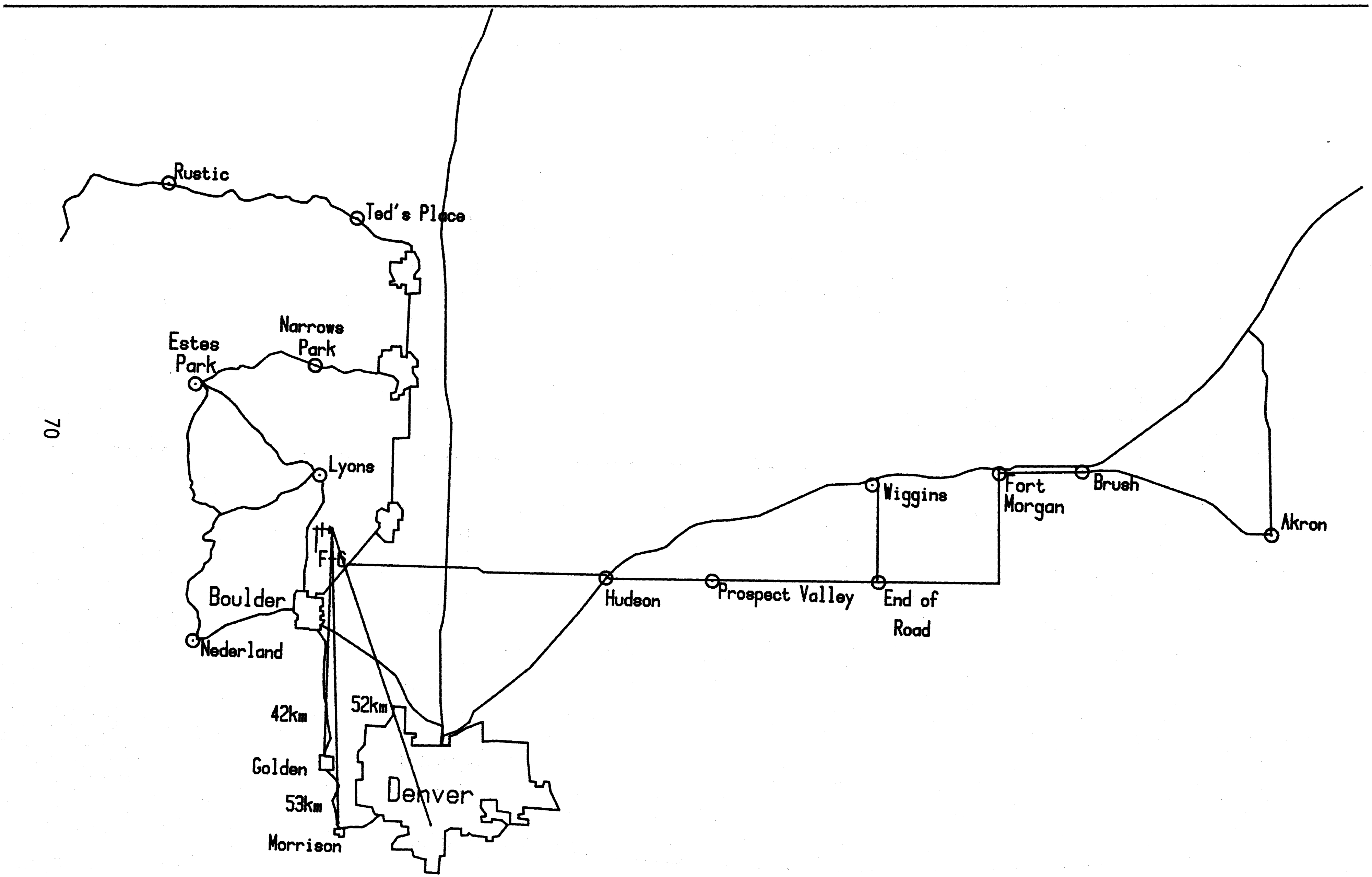

Figure A-7. Map showing foothills paths.

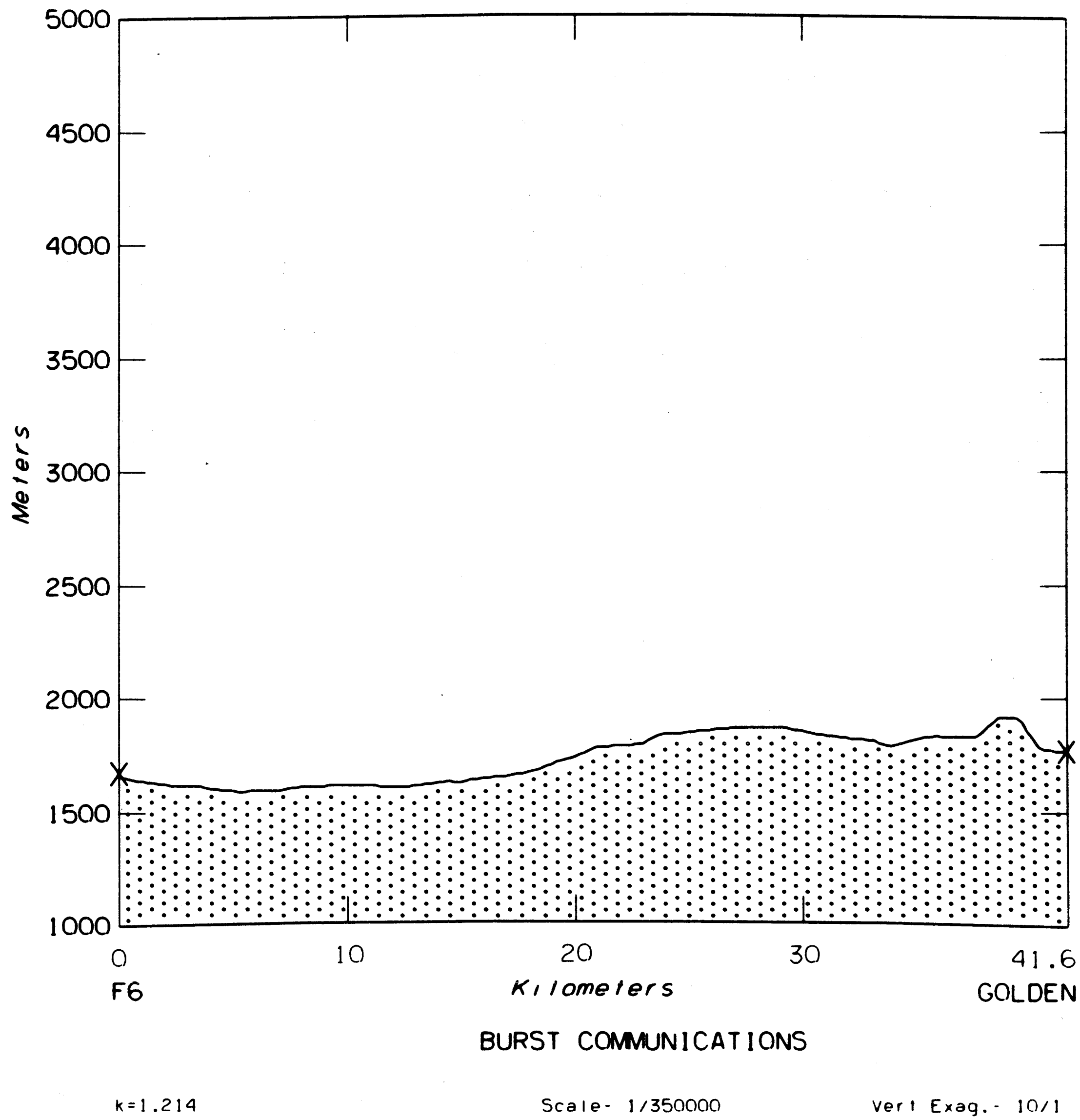

Figure A-8. Terrain profile between Table Mountain (F6) and Golden.

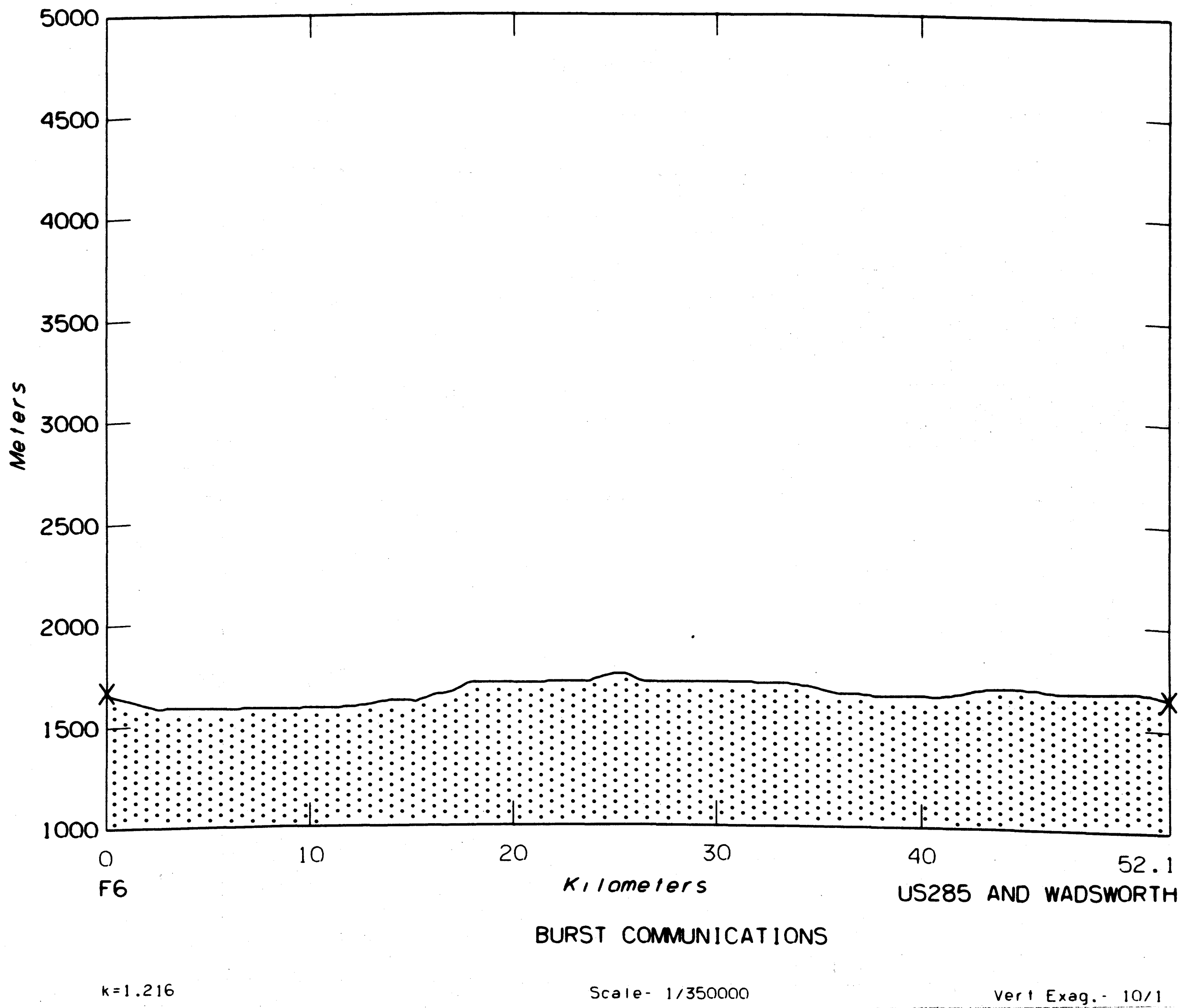

Figure A-9. Terrain profile between Table Mountain (F6) and Denver (RT. 285 and Wadsworth).

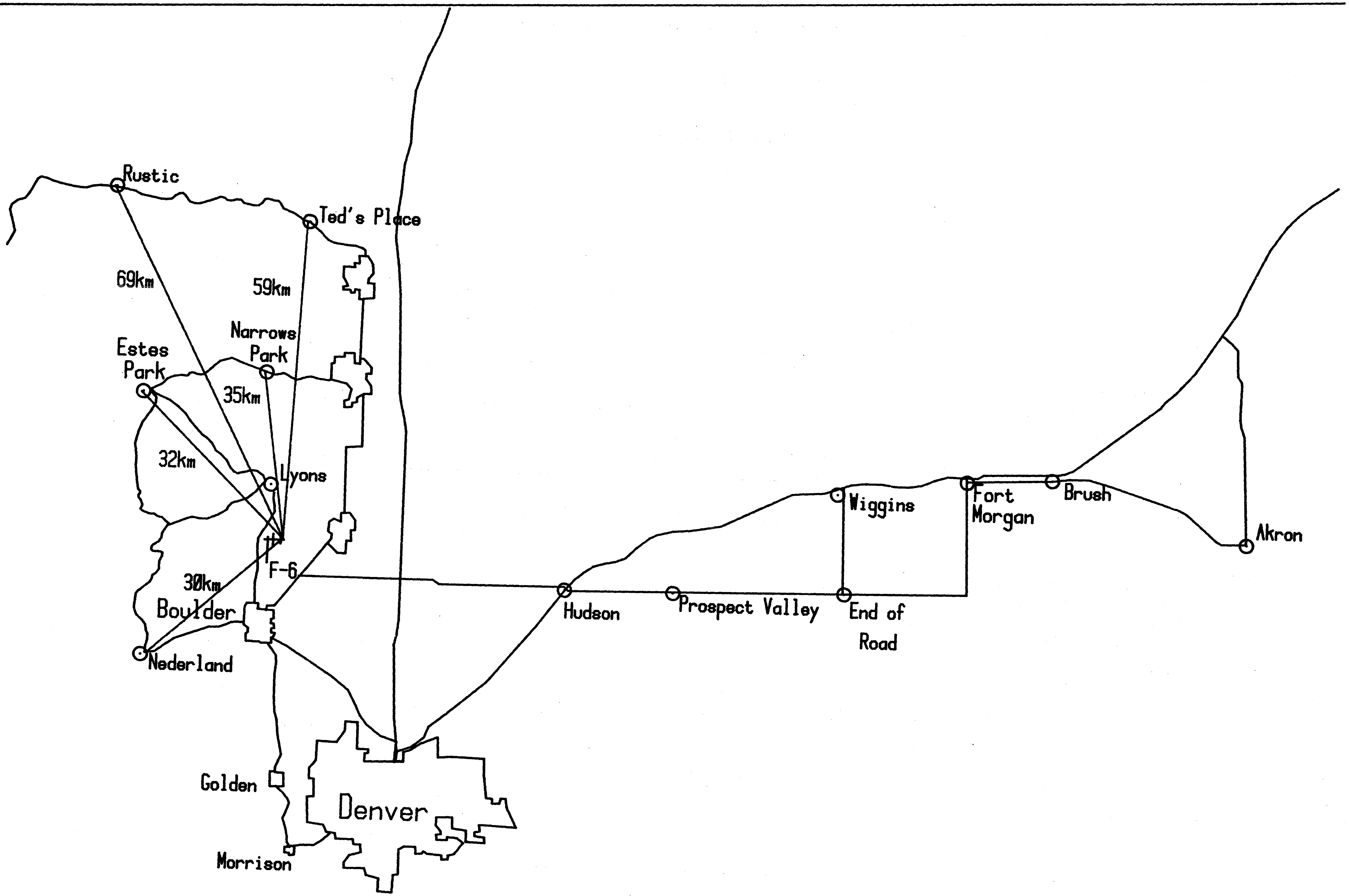

Figure A-10. Map showing mountain paths.

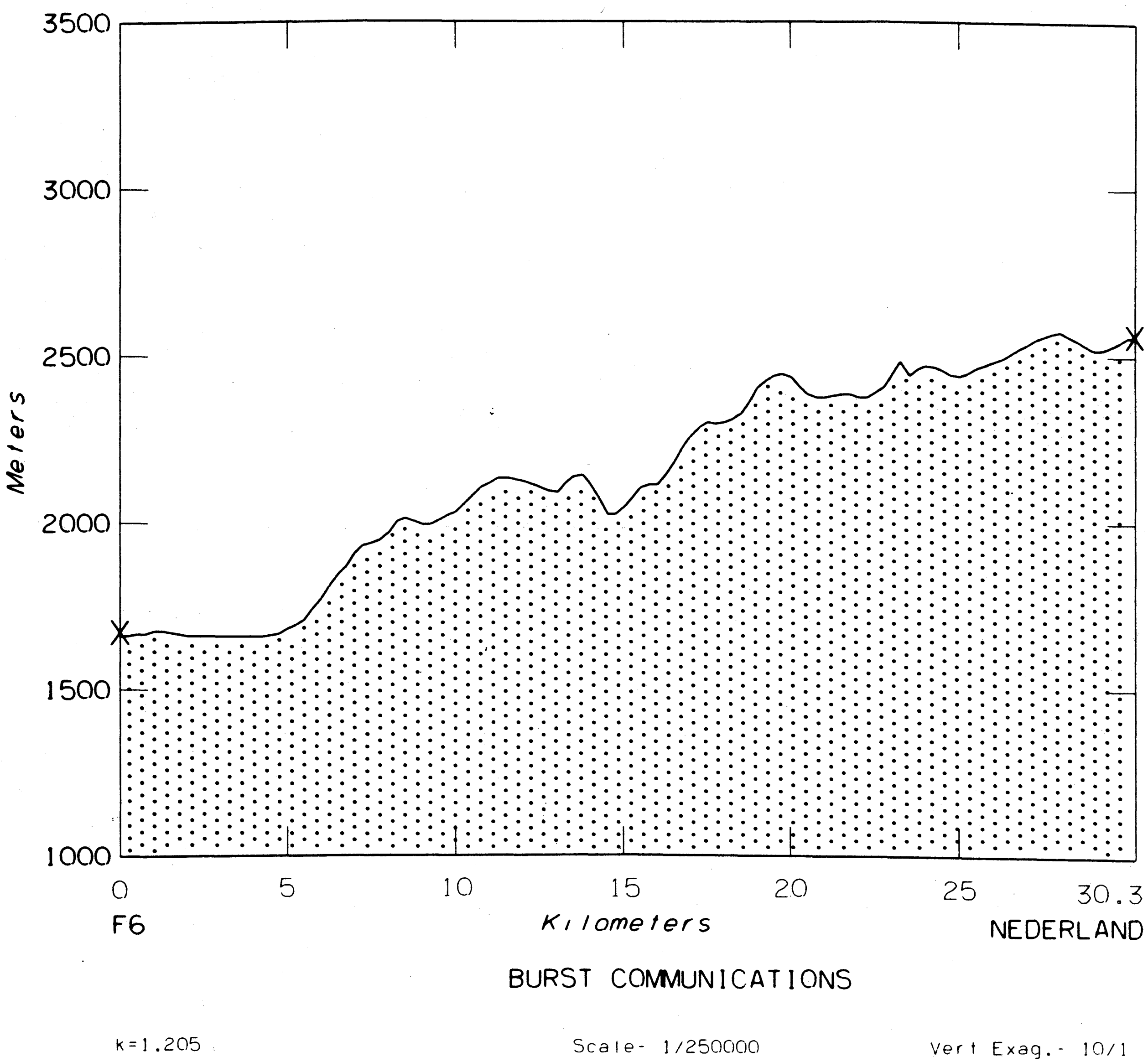

Figure A-11. Terrain profile between Table Mountain (F6) and Nederland.

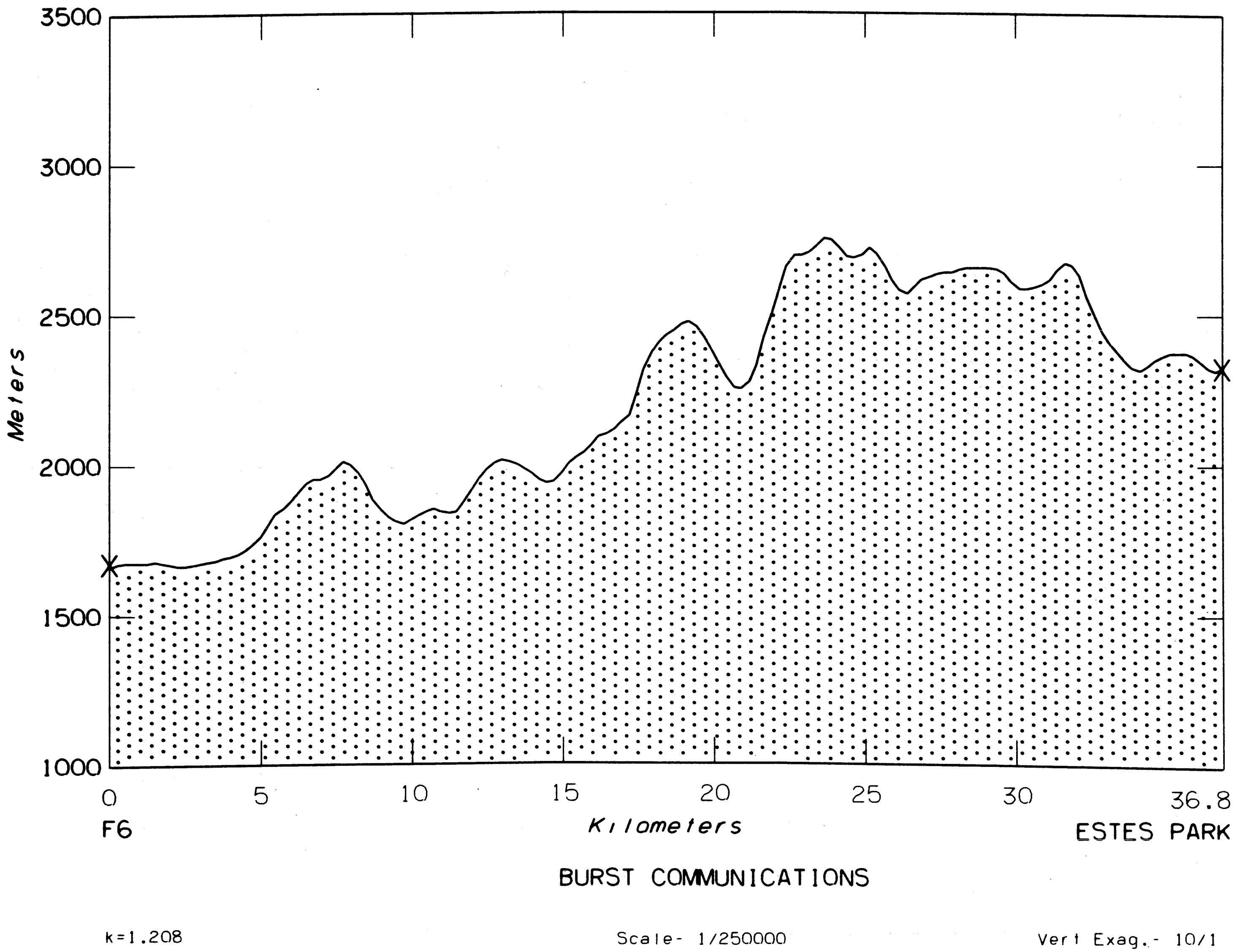

Figure A-12. Terrain profile between Table Mountain (F6) and Estes Park.

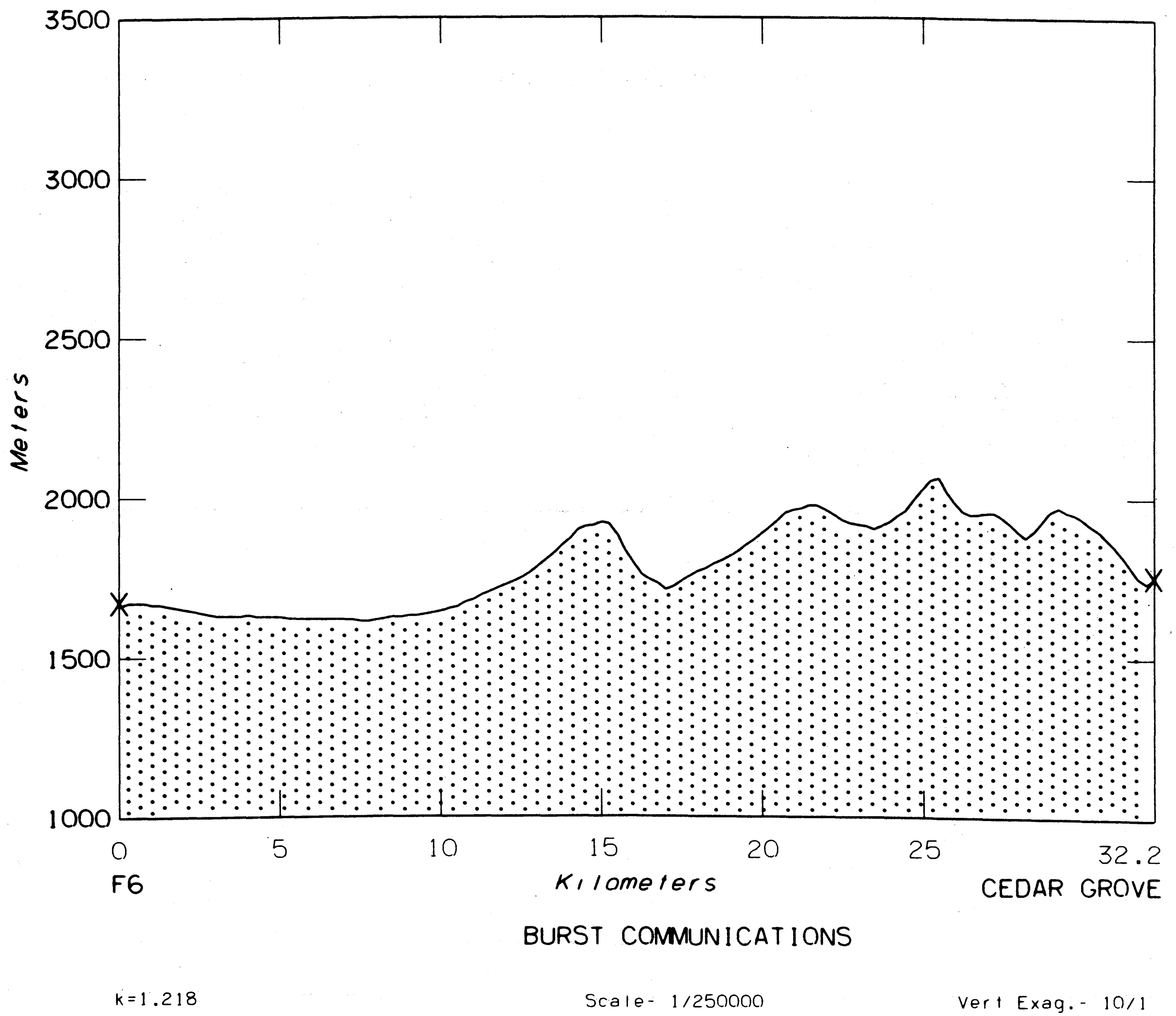

Figure A-13. Terrain profile between Table Mountain (F6) and Cedar Grove.

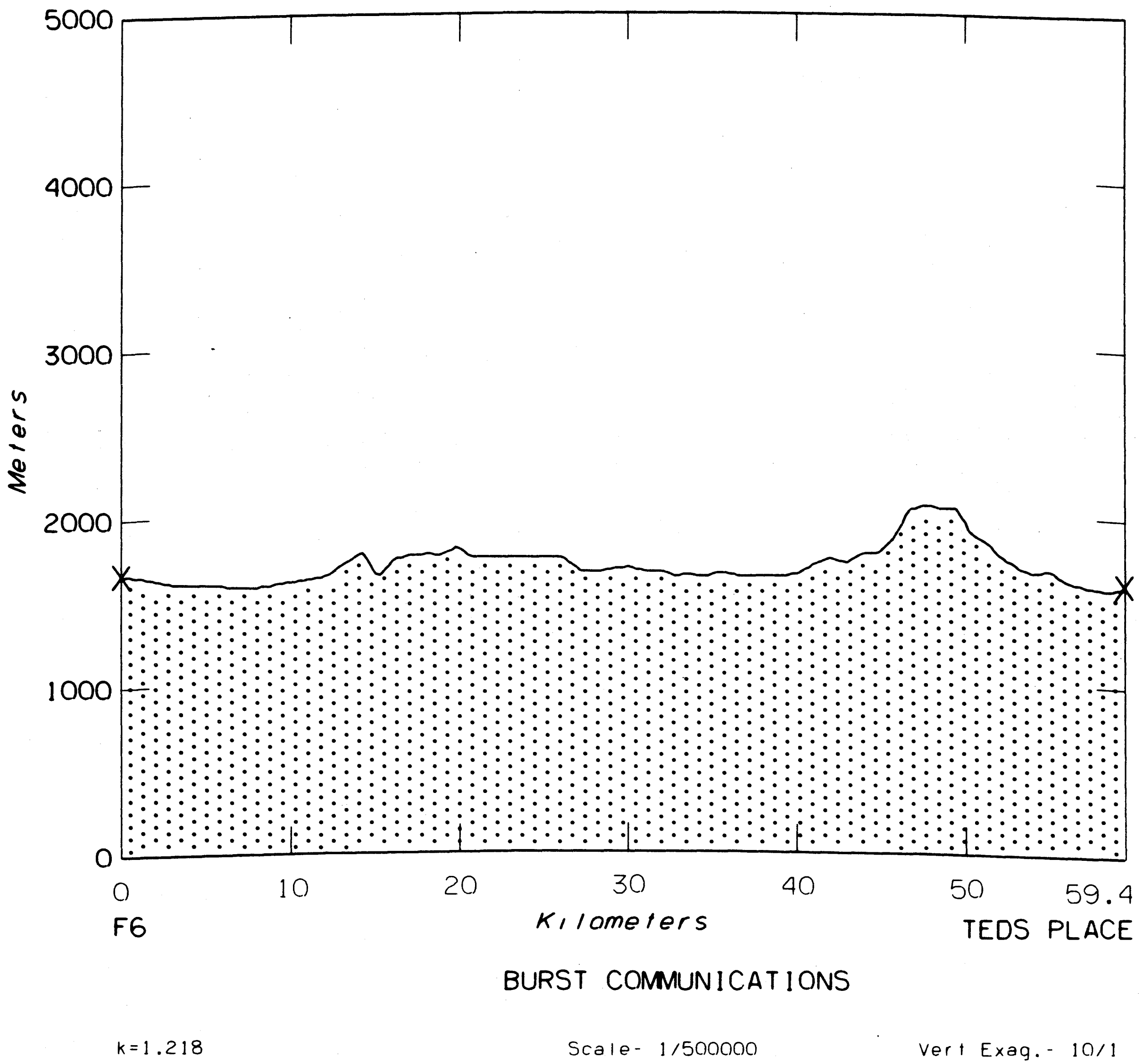

Figure A-14. Terrain profile between Table Mountain (F6) and Ted's Place.

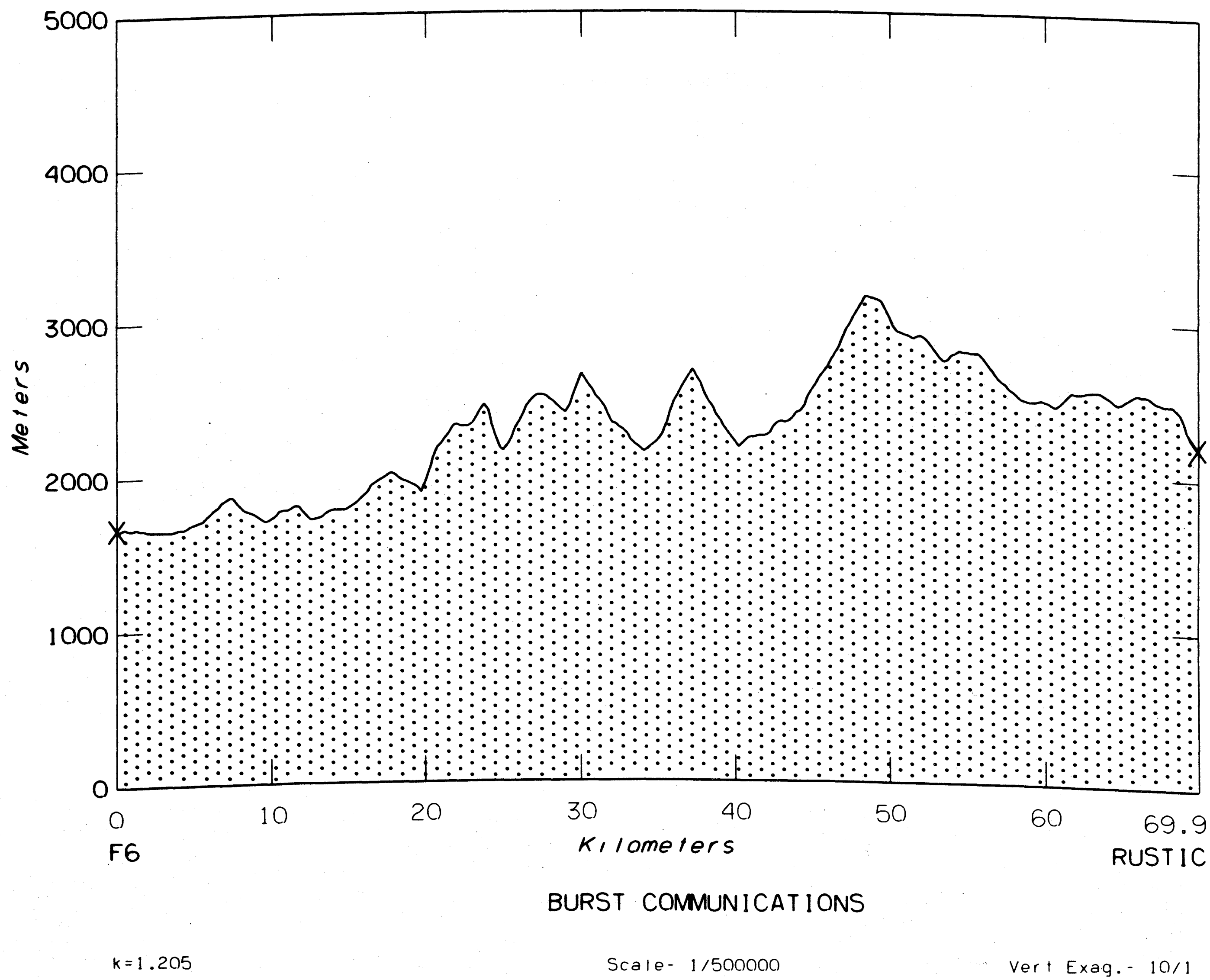

Figure A-15. Terrain profile between Table Mountain (F6) and Rustic.

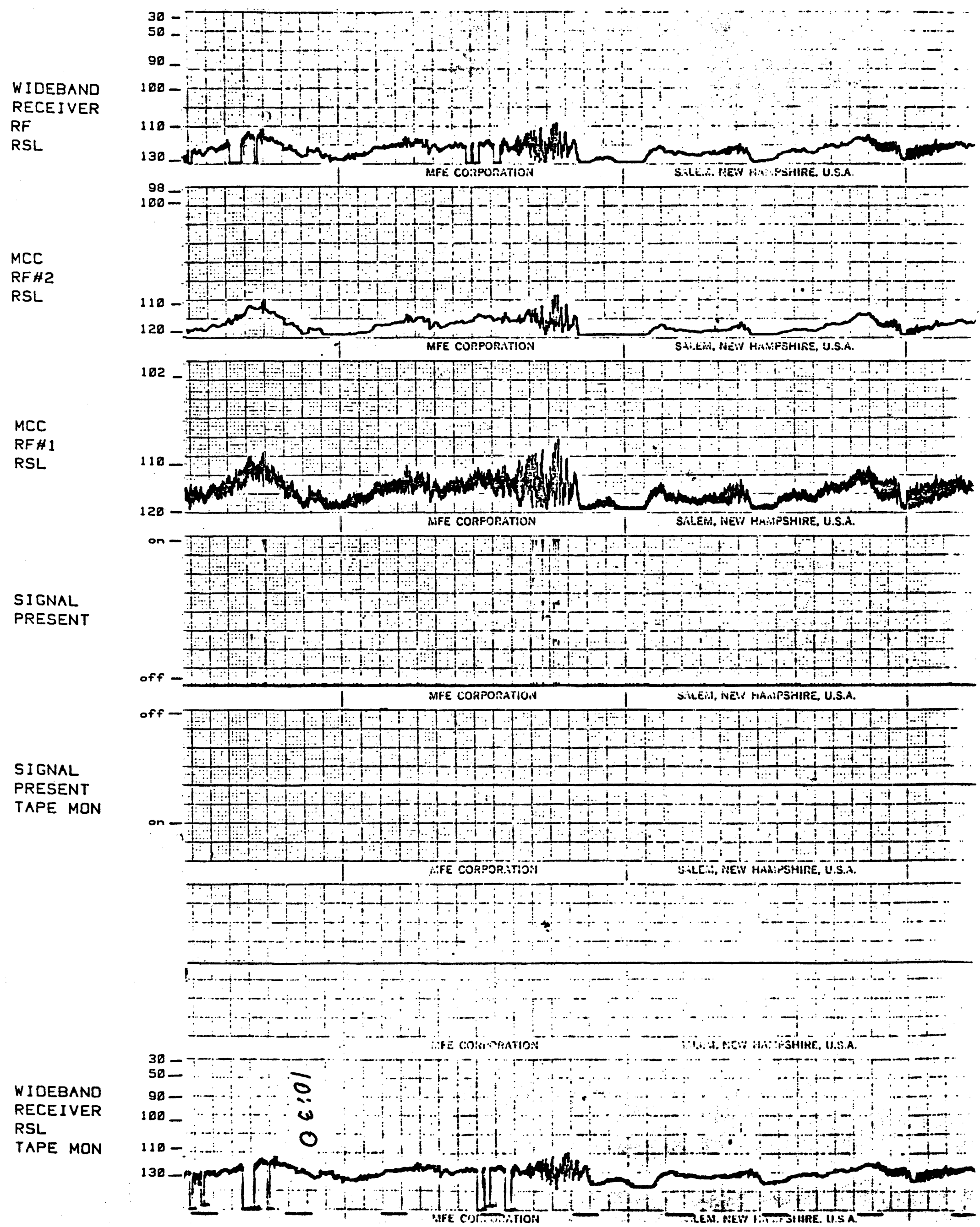

Figure A-16. Sample of data taken in motion between Ft. Morgan and Akron.

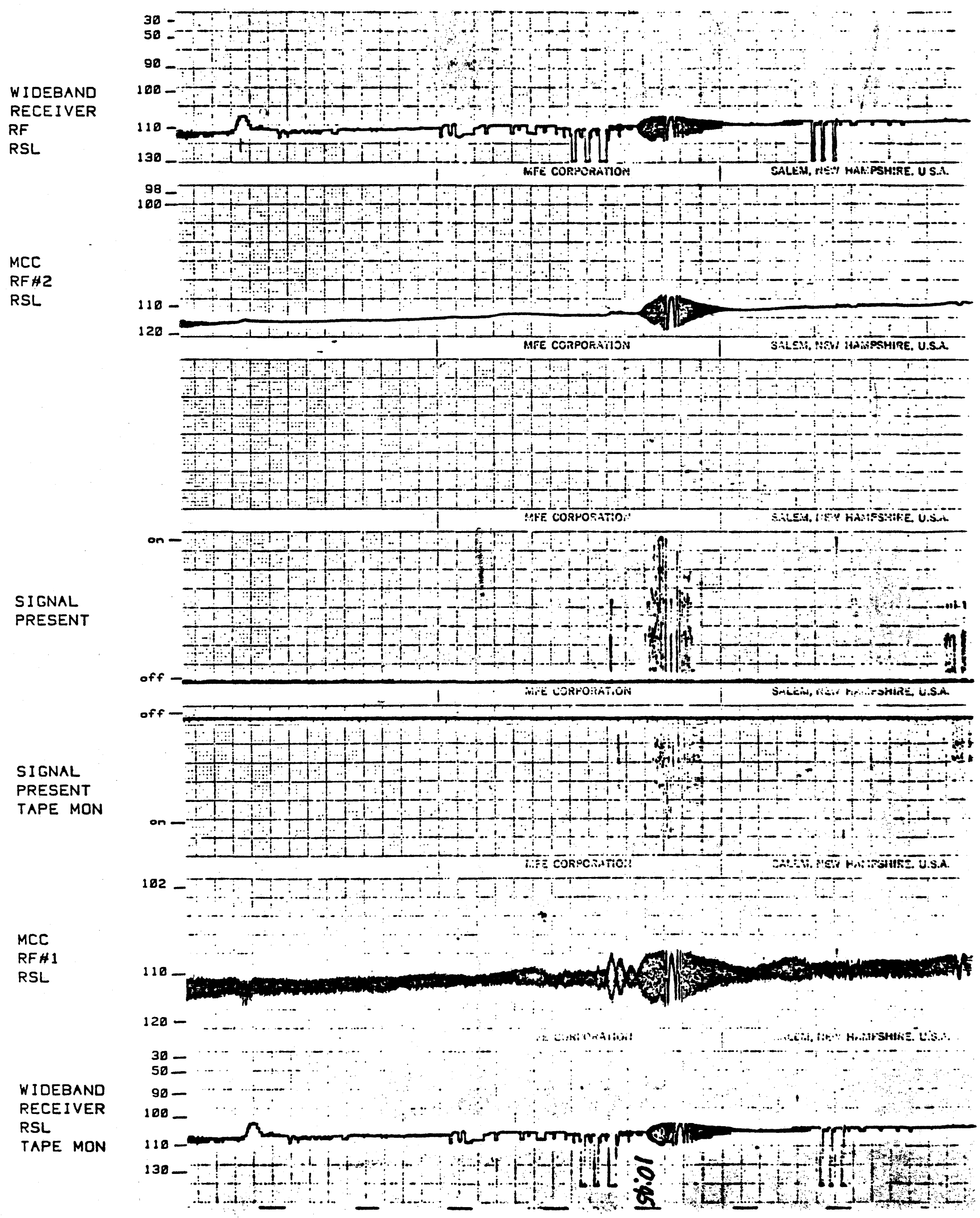

Figure A-17. Sample of data taken while stationary at Ft. Morgan.

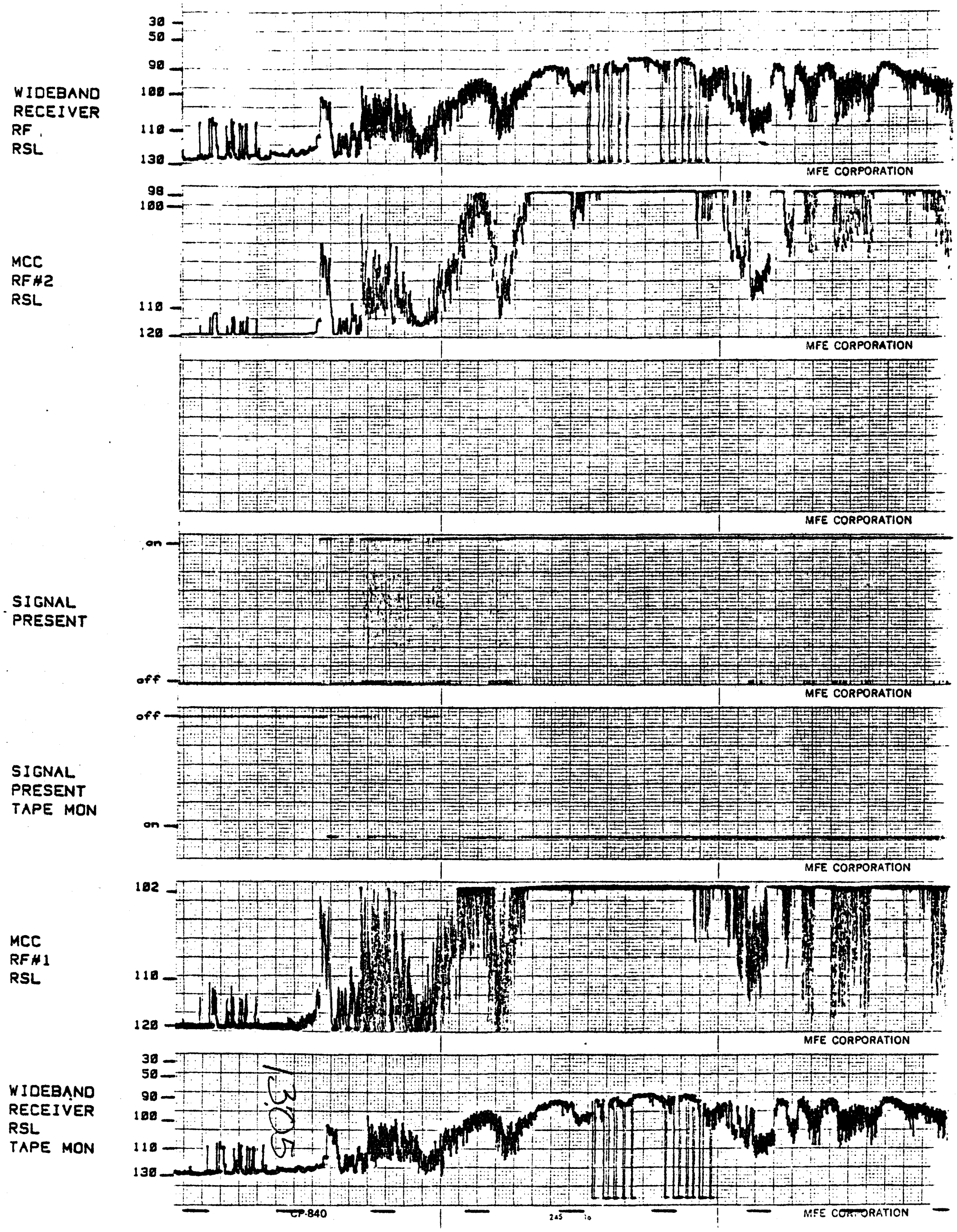

Figure A-18. Sample of data taken in motion near Morrison.

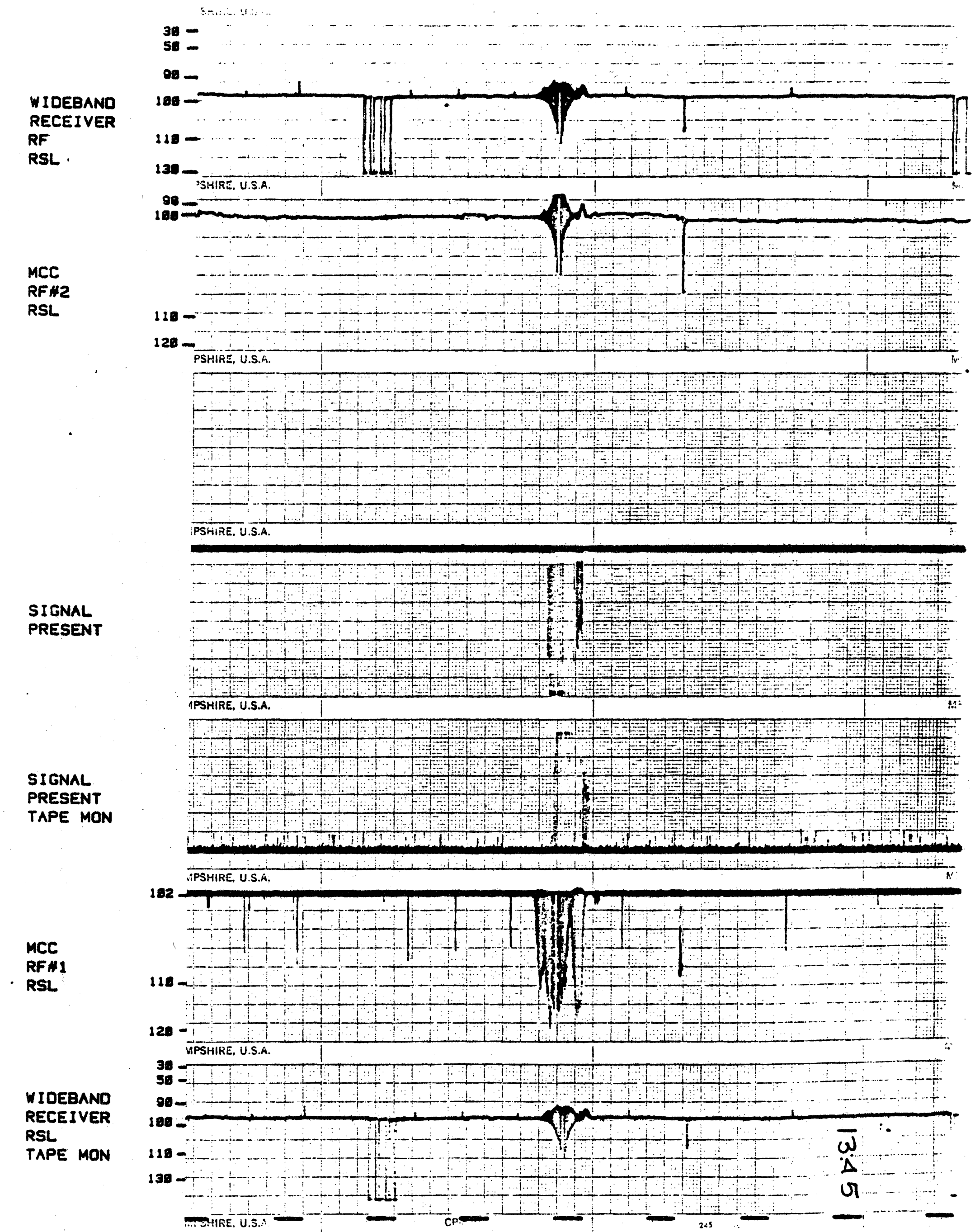

Figure A-19. Sample of data taken while stationary at Narrows Park.

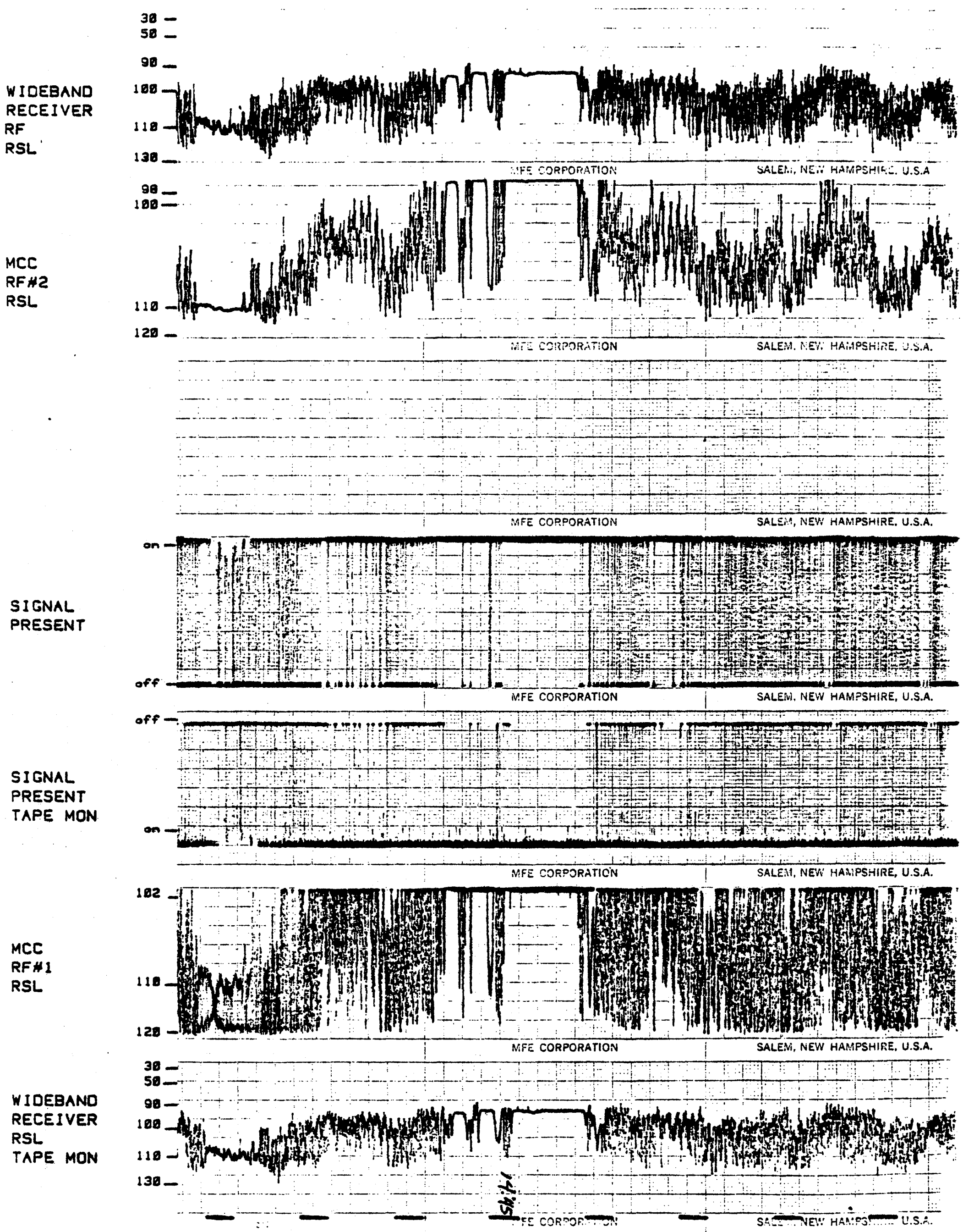

Figure A-20. Sample of data taken in motion between Narrows dam and Estes Park.

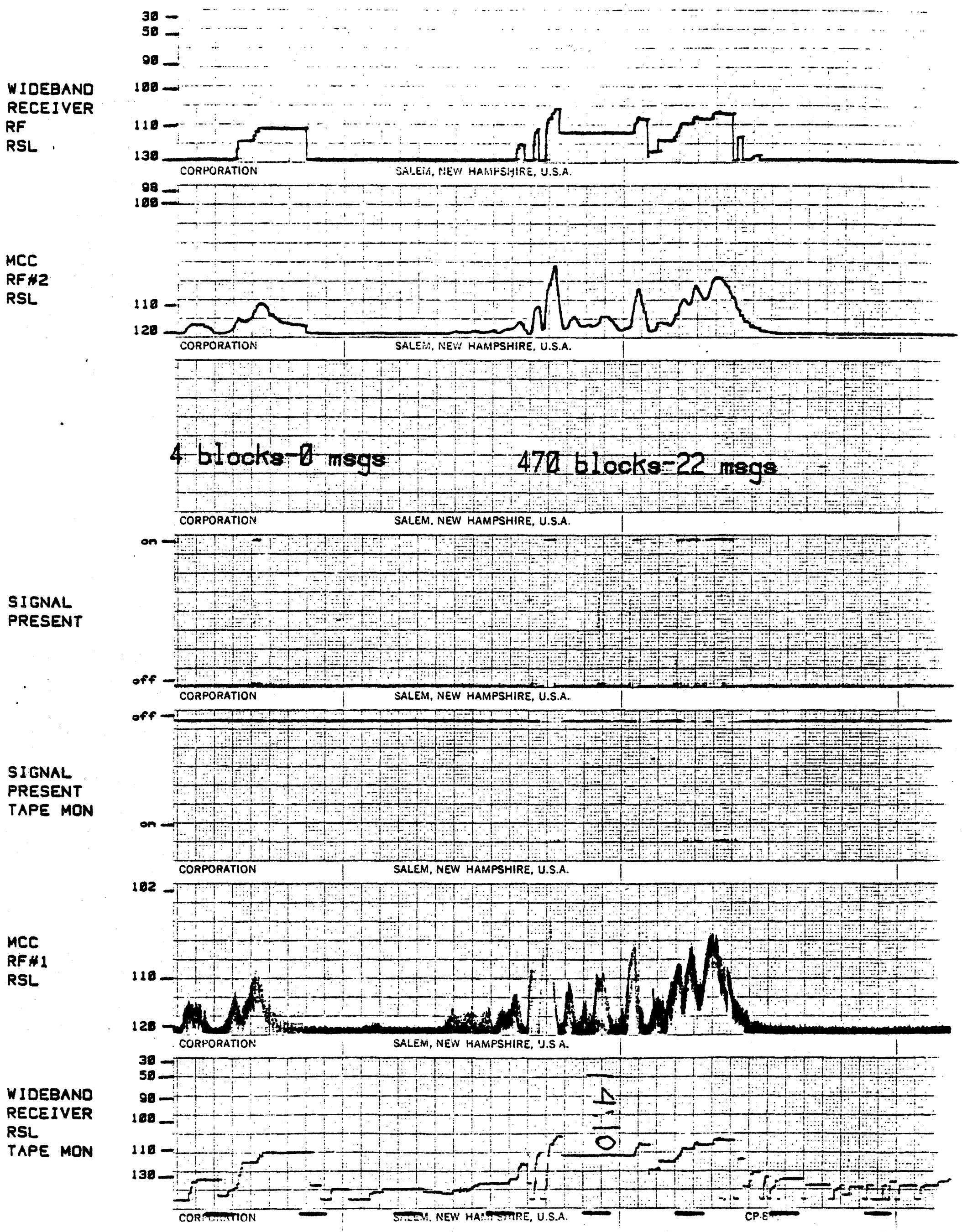

Figure A-21. Sample 1 of data taken while stationary at Rustic.

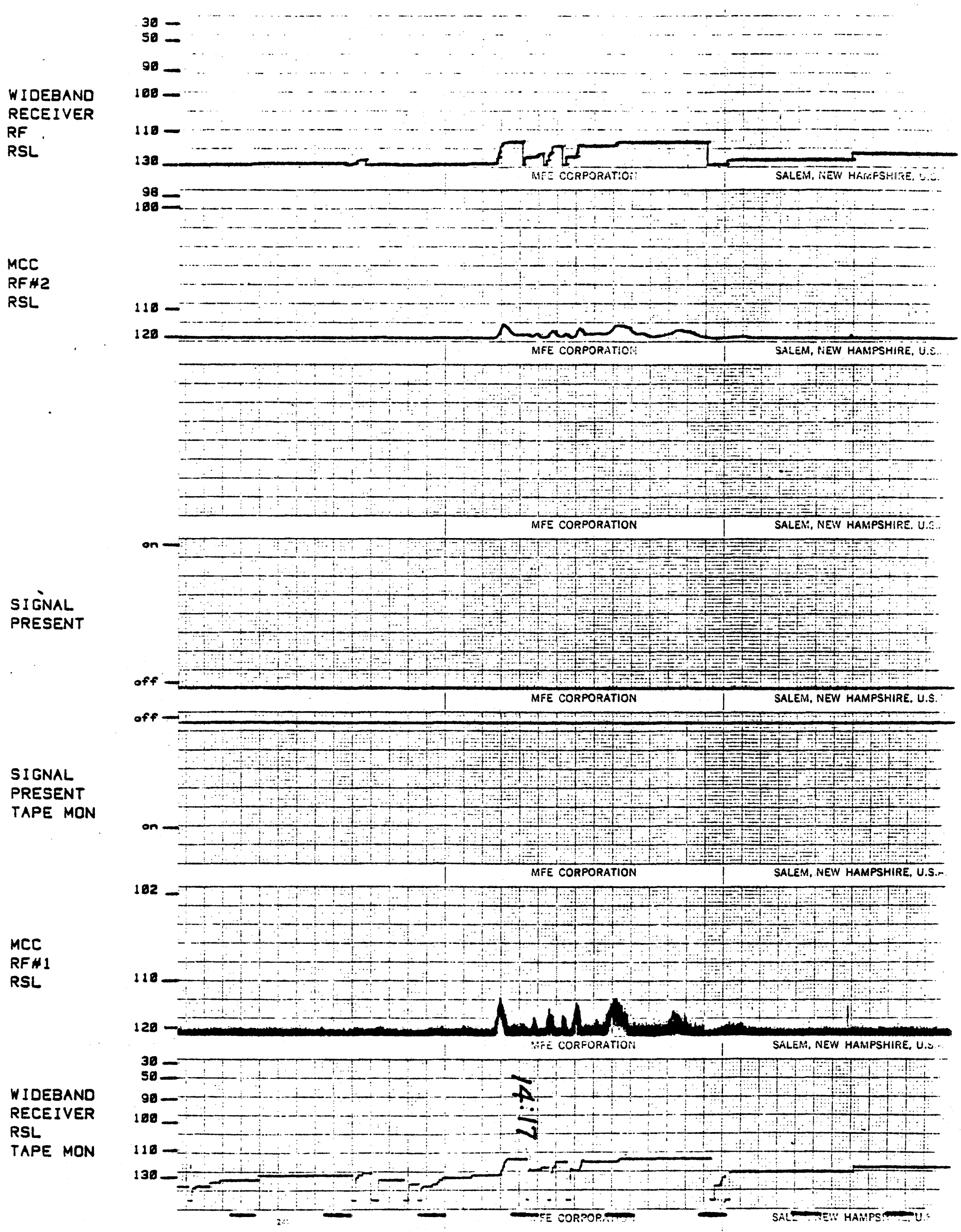

Figure A-22. Sample 2 of data taken while at Rustic.

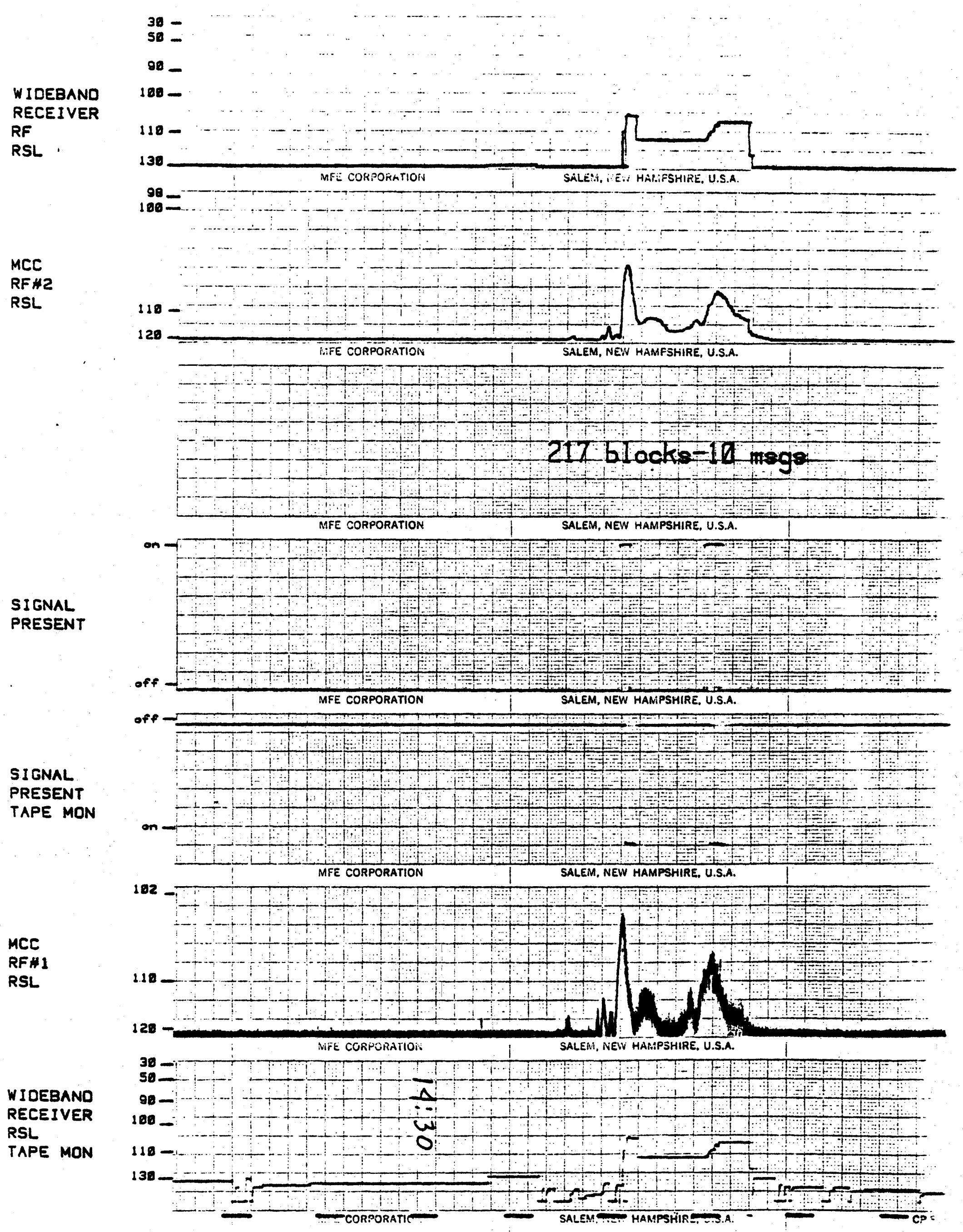

Figure A-23. Sample 3 of data taken while at Rustic.

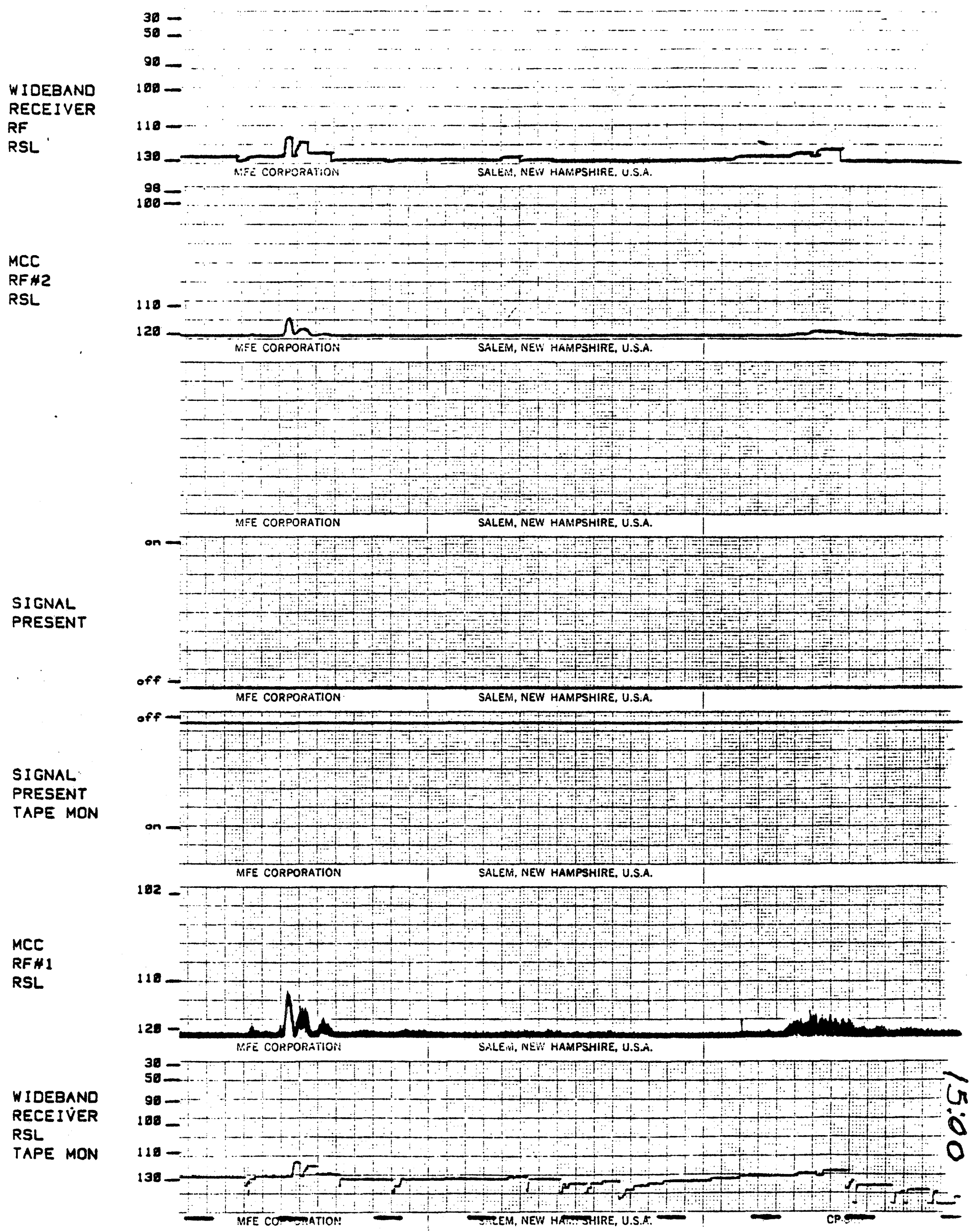

Figure A-24. Sample 4 of data taken while at Rustic.

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Although the use of transmissions that are composed of bursts of information is not new, its application in a terrestrial environment at VHF and UHF is. The usual way of expressing the variabilities in received signal level due to propagation effects for the design of conventional telecommunication systems is inadequate for burst transmission. Instead of using time and location variabilities, the concept of "waiting distance" is introduced and its magnitude is estimated. The waiting distance represents how far one terminal probably must move to have reached a favorable location where a transmitted burst will be successfully received. Acceptance of the waiting distance is a trade-off to achieve an extended range or a power advantage.

This report first examines the concepts of a burst transmission system in the context of using the location variability to estimate the waiting distance, and the associated range extension, in terms of the correlation distance of the

(Continued Next Page)

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received signal level. Using this theory and both previous and current measurements the correlation distance is estimated and, hence, so is the waiting distance. The estimates of the correlation distance range from 200 to 800 m. Recommendations for future efforts are proposed.