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ANALYSIS AND COMPARISON OF SOME AUTOMATIC VEHICLE MONITORING SYSTEMS

R. Buck
R. Esposito
M. Unkauf

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R. Buck, R. Esposito, M. Unkauf

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16. Abstract
In 1970 UMTA solicited proposals and selected four companies to develop systems to demonstrate the feasibility of different AVM techniques. The demonstrations culminated in experiments in Philadelphia to assess the performance capabilities of each system. The purpose of this report is to analyze and compare those different AVM systems and to answer some specific questions that appear on the FCC Docket No. 18302. These questions are on the performance comparisons of the AVM systems with respect to accuracy, bandwidth, update rate, and data transmission capability. In addition some general considerations on the different AVM systems have been made with respect to performance.

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PREFACE

The analysis and comparisons of the capabilities and characteristics of several Automatic Vehicle Monitoring systems described in this report was performed as part of the Ground Vehicle Communication and Control program. This program is sponsored by the Department of Transportation Office of Telecommunications for the purpose of standardization of AVM systems and of informing the Federal Communication Commission of AVM system radio channel requirements.

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1. INTRODUCTION

In 1968, HUD initiated a program to improve public transportation services. This program was transferred to UMTA of the U.S. Department of Transportation in 1969. The goal of this program was to achieve reliable location and status data for a large fleet of vehicles in an urban area. The specifications for the system are as follows:

1. Fleet size of 1,000 vehicles
2. Vehicle update rate of 1,600 vehicles per min.
3. Location accuracy of 500 ft. or less with 95% confidence
4. Coverage of 10 miles square

In 1970 UMTA solicited proposals and selected four companies to develop systems to demonstrate the feasibility of different Automatic Vehicle Monitoring Techniques (AVM) techniques. The demonstrations culminated in experiments in Philadelphia to assess the performance capabilities of each AVM technique. In addition to these four AVM systems tested in Philadelphia, other AVM systems have been tested. Due to the time schedule only two of these existing systems, Chicago Transit Authority PAVM system and Hazeltine Pulse TAVM system are included in this report.

The purpose of this report is to analyze and compare these various AVM systems, for the purpose of answering some of the specific questions that appear in the FCC Docket #18302. These questions are essentially the performance comparison of the AVM systems with respect to accuracy, bandwidth, update rate and data transmission capability. In addition, some general considerations on the different AVM systems have been made with respect to their performance.

2. DESCRIPTION OF AUTOMATIC VEHICLE MONITORING SYSTEMS

2.1 TELEDYNE

The Teledyne AVM system makes use of the U.S. Coast Guard Loran C navigation system. No spectrum allocation is necessary for the transmitter since the LORAN C transmitters in the band 90-110 kHz are utilized. A LORAN C receiver is used at the base station and at each vehicle. Each of these receivers measures 2 time differences and this information is adequate to determine the position of the vehicle (and the base station) in the LORAN grid. The time differences measured in the vehicle are made available to the vehicle's 2-way FM voice radio for transmission to the base station via an appropriate interface. After reception at the base station the time differences are fed to the computer along with the locally measured time differences. The accuracy claimed is ± 500 ft (95 percent of the time).

The transmission of data share the vehicle transmitter with voice, but it uses a separate pair of channels. Each vehicle is assigned one-to-four time slots for reporting its measurements. The time slots repeat at a frame rate of 1/min and therefore a vehicle can report every 60 sec, 30 sec, 20 sec, or 15 sec. The total number of slots is adequate for 800 vehicles/min or for 200 vehicles/reporting 4 times/min. Each time that a vehicle's slot comes up, the FM radio is switched from the voice channel to the data channel and transmits a digital message comprised of location and telemetry status data. The duration of the digital message is less than 0.1 sec and the interruption of the voice channel is therefore barely noticeable. The base station-vehicle data channel is employed for command and synchronization messages. This transmission is also very short (0.1 sec.). The number of bits transmitted in both directions is as follows:

Vehicle-to-base station

Miscellaneous telemetry data	10 bits
2 time differences	32 bits
LORAN receiver status	6 bits
Coded run number	12 bits
Error correcting and detecting	60 bits
Preamble for synchronization	8 bits
	128 bits

Base Station to Vehicle

Synchronization and command	20 bits
Error correcting and detecting	20 bits
Preamble for synchronization	8 bits
	48 bits

The method of modulation is differential PSK which frequency modulates the RF carrier. The data rate is 2400 bits/sec. The data format includes an 8 msec guardtime before the message and a 5 msec guardtime after the message. The total time allocated to a vehicular transmission is 66.3 msec. This corresponds to 960 messages per minute over a single frequency voice channel. Dividing by 1.6 to take into account the constraints on reporting (80 percent one/minute and 20 percent 4 times a minute), this implies 566 vehicles/channel. So, in essence, this system needs an allocation of two 25 kHz channels for every 1132 vehicles. Each vehicle needs a LORAN C receiver, an interface unit, and an additional duplex FM channel. The Base Station needs 2 separate UHF receivers (if 2 channels are sufficient for the whole fleet) and a LORAN receiver.

2.2 SIERRA

The Sierra AVM system uses phase trilateration, or better, multilateration from a number of sensor stations. The location of vehicles is accomplished from measurements of the difference of the time of arrival of a signal at the sensor stations. The vehicle to be located transmits an audio tone (1.5 kHz) which frequency modulated the carrier of an appropriate transceiver for 10 msec. The signal is received by the receiving sensor stations where it is demodulated and the audio signal is transmitted to the base station via dedicated telephone lines. The base station contains logic circuitry which performs the computation of the vehicle location on the basis of the incoming demodulated tones. The system operates in a time-division mode with a period of 1 min. Each vehicle is allotted a time of 15 msec, i.e., the 10 msec necessary for the tone and a 5 msec guardtime. The system has also the capability of transmitting 10 bits of digital information in appropriate slots, also 15 msec long. The transmitted digital signal is demodulated at the sensor station and the baseband information is sent over the dedicated telephone line to the base station computer. The digital format is designed as follows:

Start of message	2 bits
Message	10 bits
Error detection or space	3 bits
	15 bits

Each period of 1 min is divided in ten equal intervals called cycles. Each cycle is subdivided into 400 slots of 15 msec each. Only two of the ten cycles are data cycles, while the other eight are location cycles. The number of slots allocated to a vehicle depends on whether the vehicle is classified fixed route or random route. Fixed route vehicles are assigned 4 location slots and 1 data slot per minute. Random route vehicles are assigned 8 location slots and 2 data slots per minute. A certain number of slots are reserved for emergencies, synchronization from the base station and calibration. The total number of vehicles that can be handled by this system depends on the percentage of fixed route vs. random route. Two 25 kHz channels will accommodate either 1360 fixed vehicles or 680 random route vehicles. Note, however, that the sampling rate is relatively high. No special channel is required for the synchronization signal from the base station, which lasts for 45 msec and is repeated twice per minute. This synchronization signal is simply sent over the voice channel which is not affected significantly because of the very short duration.

The modulation system used in the transmission of the data is ASK/FM which is essentially FSK with respect to the carrier. Sierra has computed a maximum total error probability per message of the order of 10^{-2}.

The ultimate accuracy which Sierra envisions is ± 500 (95 percent). However, this will require the use of a combination of techniques such as nonlinear least-square filtering, special calibration, mapping of the urban area for signal distribution, increasing of the number of sensor stations and possible use of diversity. It is estimated that 28 sensor stations will eventually be necessary to cover an urban area of 100 square miles.

2.3 CUBIC

The Cubic AVM system uses the phase trilateration approach and includes in addition to the usual voice channels a two-way digital link between the base station and the vehicles. The link between the base station and the vehicles uses a digital voice overlay technique at 3840 Hz with a data rate of 240 bits/sec. The modulation is DPSK/FM. The purpose of this link is both polling and the transmission of digital messages. These messages are simultaneously broadcasted on all the channels in use by the fleet of vehicles. Each low priority vehicle is polled 4 times/min and each high priority vehicle is polled 16 times/min so that each time slot is 9.375 msec and there are 6400 transmission/minute. The fleet is divided in 5 groups of 200 vehicles each: four groups are low priority and the remaining one is the high priority group. The digital messages to each group last 1.75 sec and this is sufficient for about 60 ASCII characters. The rest of the time (0.12 sec) is taken up by short command signals. The link between the vehicle and the base station transmits a tone for trilateration purposes and telemetry. The digital message lasts for 7.5 msec and the format is as follows:

Pre-Synchronization	5 bits
Synchronization	7 bits
Telemetry No. 1	7 bits
Telemetry No. 2	7 bits
Check Sum	7 bits
	33 bits

The data rate is therefore 4400 bits/sec. A guardtime of 1.875 msec is left for timing variations. The frequency of the range tone is 18628 Hz. The whole waveform (telemetry plus range tone plus data clock at 4.6 kHz) frequency modulates the carrier with a modulation index of five. The total RF bandwidth is 320 kHz. A system with FM feedback is envisioned for the receivers. The ranging tone signal is received by several remote stations and relayed to the base station via a microwave link at X-band. In the test only three remote stations were used but a larger number is envisioned for the operational system. Two steps of filtering are used in reducing the raw data: first, successive range differences are filtered over a time period and then a weighted least-squares estimation is performed of the vehicle coordinates, based on the filtered range differences. Note that the experiment was conducted at 220 MHz.

2.4 RCA

The RCA AVM system uses an X-band signpost system where the signposts are low level (50 mW) transmitters at 10.6 GHz mounted on lighting poles at street intersections. Each signpost includes two antennas back-to-back with a gain of 10 dB. The transmission from the two antennas is sequential, in order to utilize only one transmitter and avoid interference. The transmitted message consists of 10 bits, including 1 parity check. The message lasts 0.1 sec and is repeated every 0.24 sec. The modulation method is AM/FSK, with the mark and space frequencies being, respectively, 10 and 12 kHz. Any vehicle passing within the range of the signpost will receive the signal by means of a direct detection receiver followed by the mark and space filters, envelope detection and comparator. If the message is accepted by the receiver it is stored and can be transmitted from the vehicle to a central computer to report location. The estimated number of signposts necessary to cover an area of 100 square miles with the required accuracy of 500 ft is between 10,000 and 20,000.

The AVM system includes a two-way half-duplex voice and data communication link between the vehicles and the base station. Two additional duplex channels (4 frequencies) are required to complement the ordinary FM voice transceiver. The digital communication between base and vehicles contains the identification number of the vehicle to be polled or special messages. The radiated power is 100 watts. The digital format is as follows:

Synchronization	8 bits
Vehicle identification	15 bits
Special messages	6 bits
Error detection	10 bits
	39 bits

The total duration of this message is 32.5 msec and the cycle is repeated every 65 msec, i.e., with a duty ratio of 1/2. The carrier remains on and unmodulated during the remaining 32.5 msec. The data rate is 1200 bits/sec. Thus the base station sends out 923 messages/minute, some of which are scheduled (870 - polling, invitation for request of voice circuit or alarm, invitation for alarm response), and some unscheduled (63 - command to switch to voice channel, acknowledge request for voice circuit, acknowledge alarm). The transmission from the vehicle to the base is either a response to a poll or a response to a special message received from the base station. Voice and data are not simultaneous. The digital format is as follows:

Synchronization	8 bits
Vehicle identification	15 bits
Signpost identification	17 bits
Special responses	10 bits
Error detection	12 bits
	62 bits

The total duration of this message is 51.7 msec, 10 msec is allowed to the transmitter to switch frequency (from voice to data) and 3.3 msec is the guardtime. The data rate is again 1200 bits/sec. The modulation is DPSK/FM and an additional modem is needed to interface with the conventional voice transceiver. The transceiver has an output power of 25 watts and 4 receive only sites, tied to the computer via telephone lines, are needed for full coverage.

2.5 HAZELTINE

The proposed Hazeltine AVM system has three major distinguishing features compared to the majority of proposed AVM systems which are of the narrow-band type. First, it employs wide-band pulses for ranging and requires a spectral occupancy between 5 and 10 MHz. Second, it has a greater location accuracy than the narrow-band systems by a factor of about 3 to 1. Third, it has a larger capacity (in terms of number of vehicles located per minute) than the narrow band systems by nearly 10 to 1.

The Hazeltine AVM system is a wide-band pulse ranging system operating in the 902-928 MHz band. It is a trilateration system and employs a hyperbolic ranging algorithm so that only the return transmission from the vehicle is used for ranging. Modest data transfer is provided between base station and vehicle during each location update.

A time slot is provided for communication with each vehicle. In this time slot, the master station first transmits a timing marker and group of information digits to the vehicle using multiple tone on-off keying. The vehicle then responds by transmitting a series of narrow (2 μs wide) RF pulses to the master station as well as to the relay stations. This first of narrow pulses has a ranging format together with a series of on-off keying (OOK) data pulses. The relay stations verify the reception of a valid vehicle response, suppress one of the range format pulses, and relay the signal to the master station using a spread spectrum modulation technique. At the master station, the hyperbolic ranging is performed using relative range difference information from the relay stations.

The vehicle identifies its time slot by counting the timing "ticks" transmitted by the master station starting from a unique synchronization "tick". The transmission from the base station consists of a preamble (500 μs) for level control and receiver quieting, and three 550 μs bauds consisting of two simultaneous tones out of a four tone alphabet. The first of these bauds is the synchronization pulse or timing "tick" while the remaining two bauds are for information transfer with 9 distinct message combinations possible.

The transmission from the vehicle consists of up to 18 pulses which are about 2 μs wide each. The first two pulses are spaced by 27.5 μs and serve for location. The remaining pulses are spaced by 50 μs and serve for message transmission, emergency status, and message format by their presence or absence in a prescribed position. A total of 15 bits actually convey information for 8,192 different messages. The format is very similar to that used in the present Air Traffic Control (ATC) beacon system except for the much wider pulse-to-pulse spacing proposed in the Hazeltine system. Since the pulse spacing employed is not compatible with standard ATC hardware, a new radio design is required to perform the AVM function at the vehicle.

A time slot of about 4 millisecond duration is required for each vehicle reception and transmission. As a result, 250 vehicles can be accommodated per second or about 4,000 vehicles can be updated every 15 seconds. This capacity is several times larger than that which can be typically achieved in a narrow-band system.

The relatively long time slots per vehicle are necessary to permit practical power levels in the vehicle transmitter and to avoid multipath degradation of the simple waveforms transmitted. Even so, a peak vehicle power of 1 KW is required compared to a lower power of about 25-100 watts in the narrow band systems.

2.6 CHICAGO TRANSIT AUTHORITY

The CTA uses a proximity AVM system to locate its buses. In this system, a 10 bit digital code is transmitted from fixed location "signposts". This transmission has a center frequency of 150 MHz (nominal), 12.5 kHz bandwidth and 100 m watts output power. The digital code, which represents the signpost's location, is detected by the passing buses receiver and stored in memory. Once the bus is outside the detection range of the signpost, an interval timer starts. The number of 12 sec increments of the interval times that have accrued since the bus last passed a signpost is also stored in memory. When the bus arrives within range of the next signpost, the interval times is automatically reset to zero and the previous signpost's digital location code is replaced in memory by the new signpost's code. The buses are interrogated from the base station on a 25 kHz bandwidth channel operating at 450 MHz (nominal).

A once repeated bus identity message totaling 41 digits is used to interrogate the buses. The buses respond on another 25 kHz bandwidth channel operating approximately within 1.8 MHz of the bus stations interrogation channel. The once repeated message from the bus is 45 bits long and contains the signpost's location code and interval times information.

In addition, alarm messages can be transmitted on the bus-to-base channel. Three satellite stations detect the buses transmission and relay this information to the base station via a standard data telephone line. This system has a capacity of 3,300 buses with an update rate of 5 minutes. In addition to the two 25 kHz bandwidth data channels and the 12.5 kHz signpost channel, there is a duplex voice channel to allow simultaneous voice communication between the buses and base station. The total bandwidth is therefore, 112.5 kHz.

It should be noted that because CTA had the bandwidth available, the AVM system manufacturer, Motorola, made no effort to conserve bandwidth. The CTA-AVM system could readily be reduced to 62.5 kHz without affecting the system.

3. RESULTS OF AVM FIELD EXPERIMENTS

The various AVM systems have been tested in the field to determine what their accuracy is in locating vehicles in an urban area. What is basically missing in the field tests is the various systems' capability of transmitting digital data. In general, the companies involved in the AVM field tests only suggested the methods and requirements for digital communication and did not deploy them. Since UMTA specified minimum requirements on the AVM systems digital communication and vehicle update rates, the various companies suggested methods that would at least meet these requirements.

Some AVM systems excluded location calculations on vehicles where the signal-to-noise ratio was below a preset threshold level or where the change in the calculated distance of a vehicle from its preceding location calculation exceeded the distance possible due to the vehicles maximum expected velocity. These exclusions are not included in the tabulations of accuracy and the 95 percentile points.

The accuracy of the four companies, Cubic, Sierra, RCA, and Teledyne, which participated in the Philadelphia AVM tests, were broken down into three categories. These categories were:

1. High rise - downtown Philadelphia
2. Low rise - areas outside the high rise distance of Philadelphia
3. Special cases - areas near power lines, bridges, or tunnels, etc.

The results of these tests are shown in the following table and figures:

Cubic	Table 3-1
Sierra	Figures 3-1, 2, 3, 4, 5, 6
Teledyne	Figures 3-7, 8, 9
RCA	Figures 3-10, 3-11
Hazeltine	Figure 3-12

TABLE 3-1 SUMMARY OF COVERAGE AND ACCURACY

Sample Interval (Seconds)	Number of Attempted Measurements	Number of Successful Measurements (n)	Percent of Measurements Successful	Sample Mean Error		Standard Deviation[1]		RMS Error	Number of Measurements $\Delta R<500$ ft	Percent of Measurements $\Delta R<500$ ft	Total Distance Error		Reference Figure
				$\overline{\Delta X}=\frac{\Sigma\Delta X}{n}$ (feet)	$\overline{\Delta Y}=\frac{\Sigma\Delta Y}{n}$ (feet)	$\sqrt{\frac{\Sigma(\Delta X-\overline{\Delta X})^2}{n-1}}$ (feet)	$\sqrt{\frac{\Sigma(\Delta Y-\overline{\Delta Y})^2}{n-1}}$ (feet)	$\sqrt{\frac{\Sigma(\Delta X)^2+(\Delta Y)^2}{n}}$ (feet)			at 50th Percentile[2] (feet)	at 95th Percentile (feet)	
CATEGORY A - HIGH RISE													
1	268	268	100	-352	-292	1875	1162	2248	77	29	821	4914	1
4	268	267	99+	- 11	+145	1745	1252	2149	64	24	994	4056	2
16	268	221	82	-439	+345	2212	1487	2717	34	15	1255	4963	3
CATEGORY B - LOW RISE													
1	236	236	100	+103	-257	769	940	1243	71	30	813	2071	7
4	236	236	100	+106	-312	932	1281	1615	47	20	887	2821	8
16	236	234	99+	+ 73	-410	1134	1760	2130	40	17	1246	3415	9
CATEGORY C - SPECIAL CASES													
1	80	8	10	+839	-2231	969	3075	3844	0	0	3737	4666	4
4	80	7	9	+1292	-2853	1142	1009	3435	0	0	3765	4151	5
16	80	11	14	+1279	+1762	1969	3831	4648	1	9	3395	7895	6

NOTES: 1. The square of this quantity is the variance. 2. This quantity is also known as Circular Error Probable (CEP).

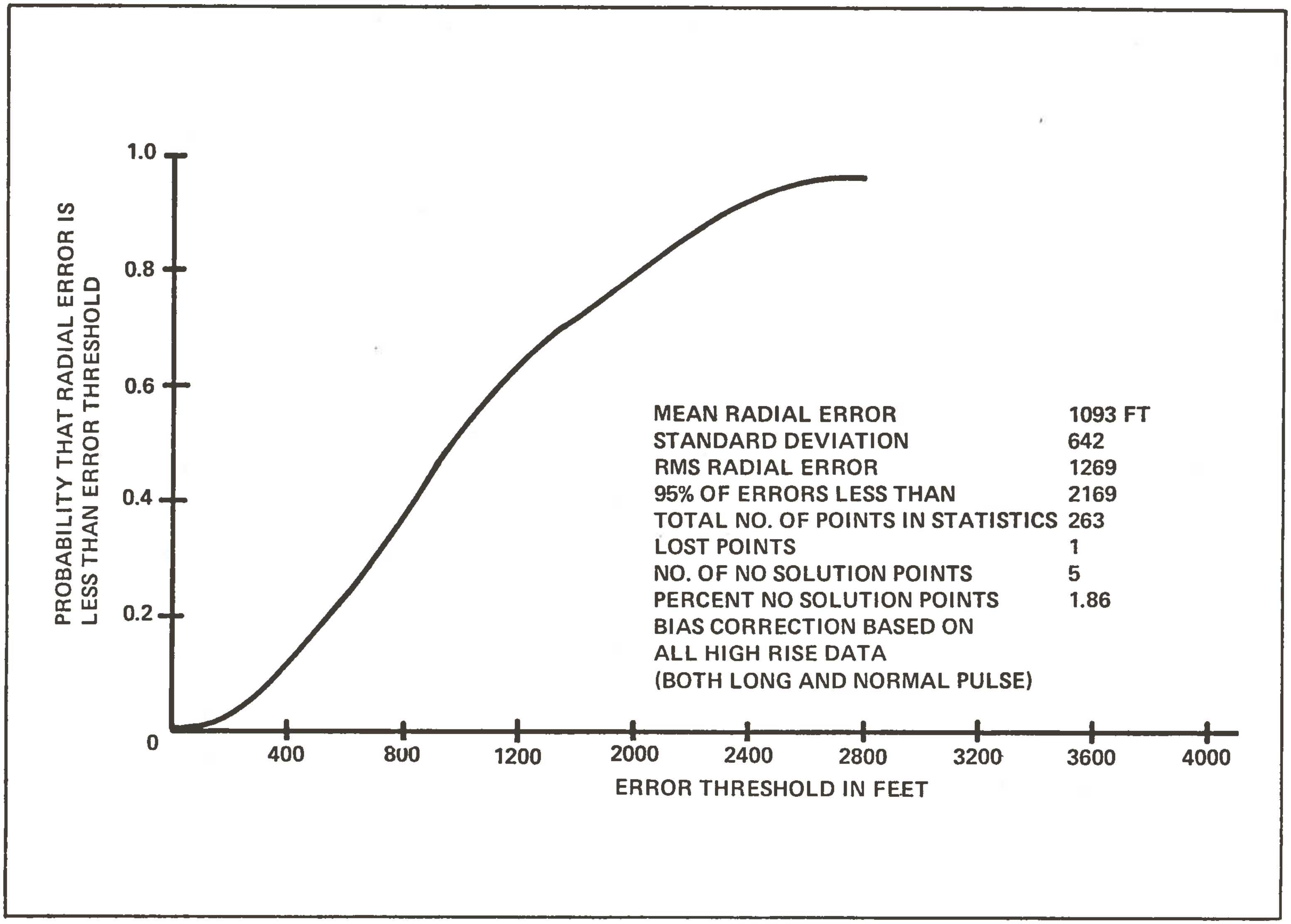


Figure 3-1 Sierra High Rise - Normal Pulse Accuracy

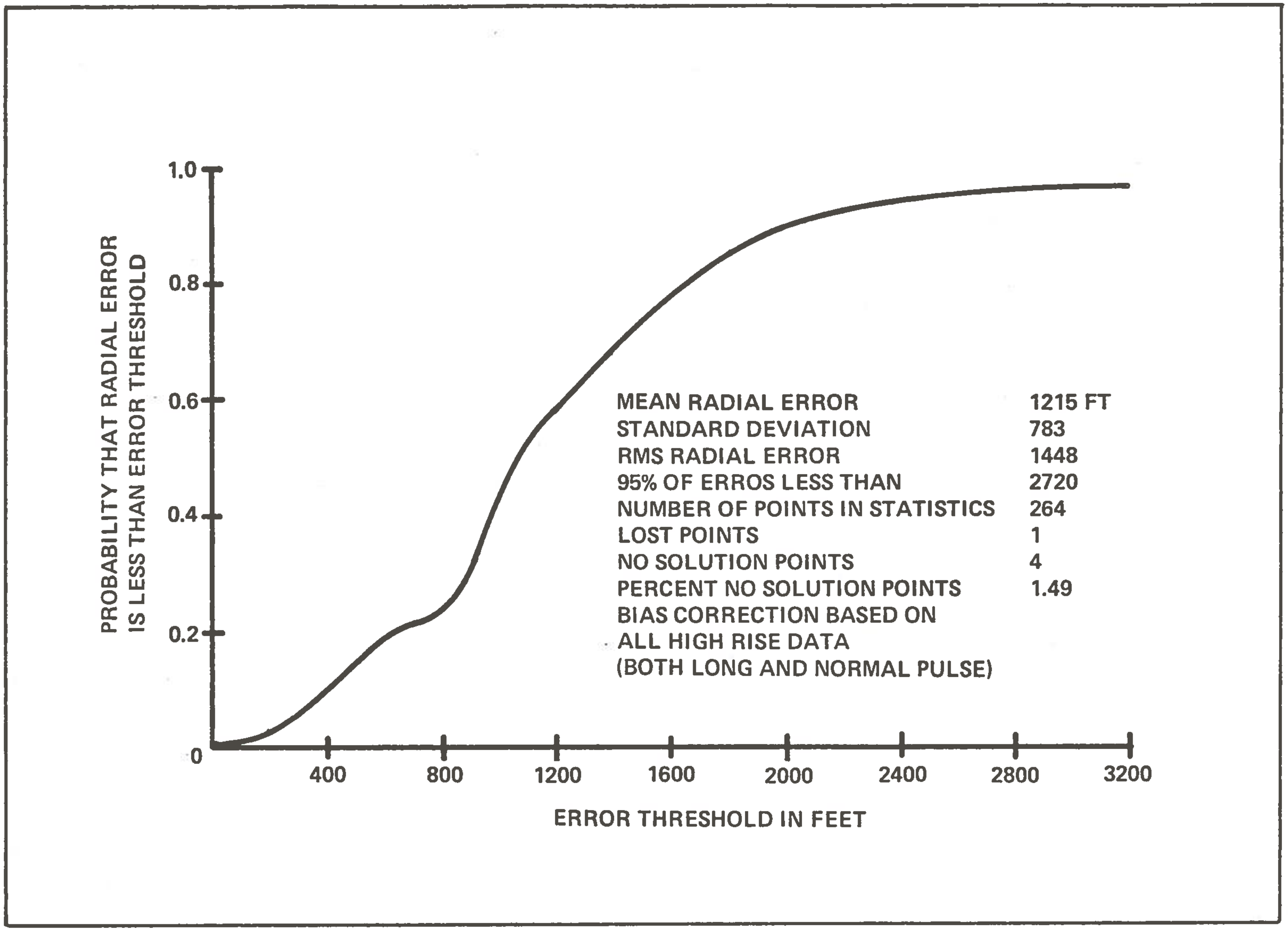


Figure 3-2 Sierra High Rise - Long Pulse Accuracy

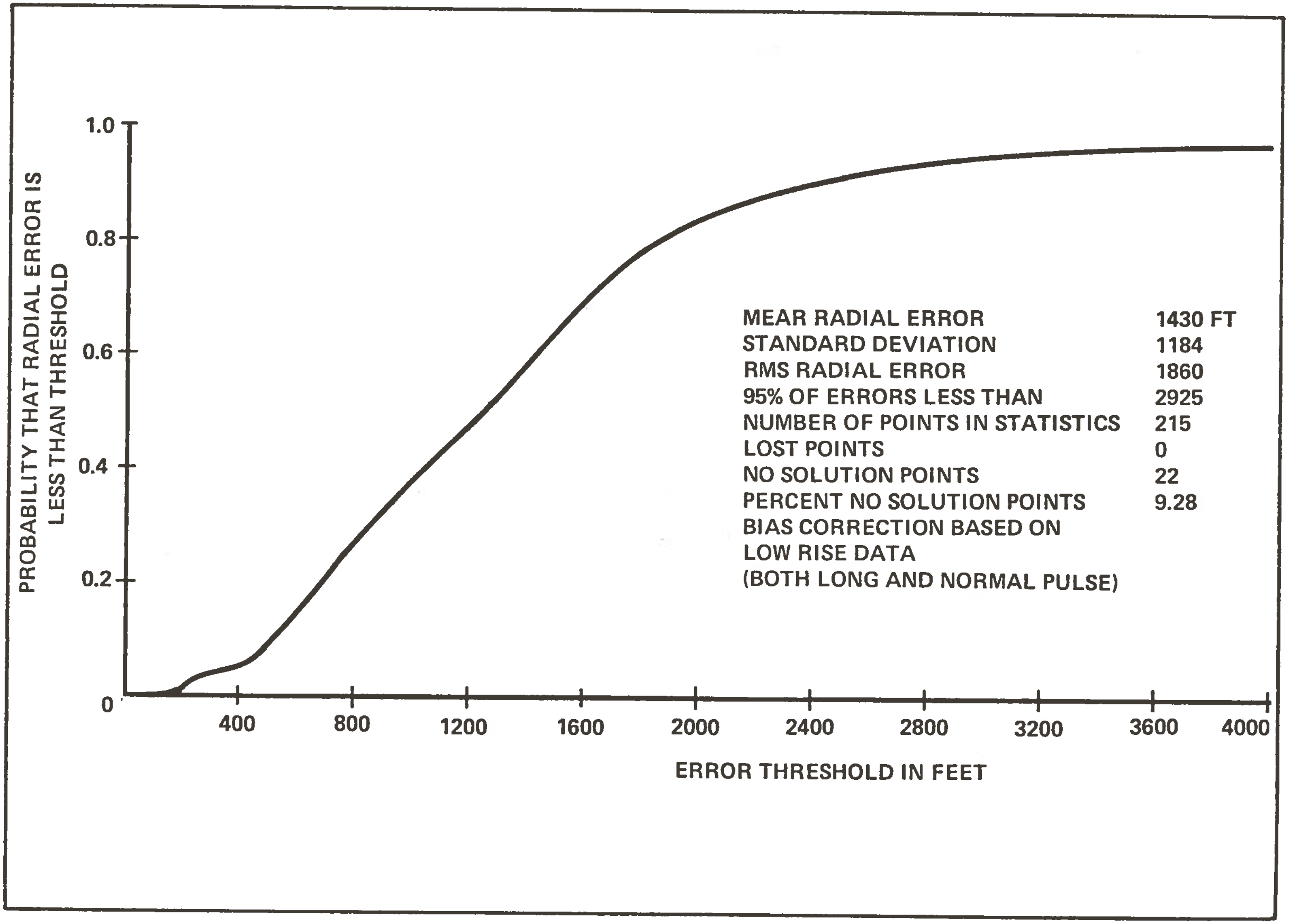


Figure 3-3 Sierra Low Rise - Normal Pulse Accuracy

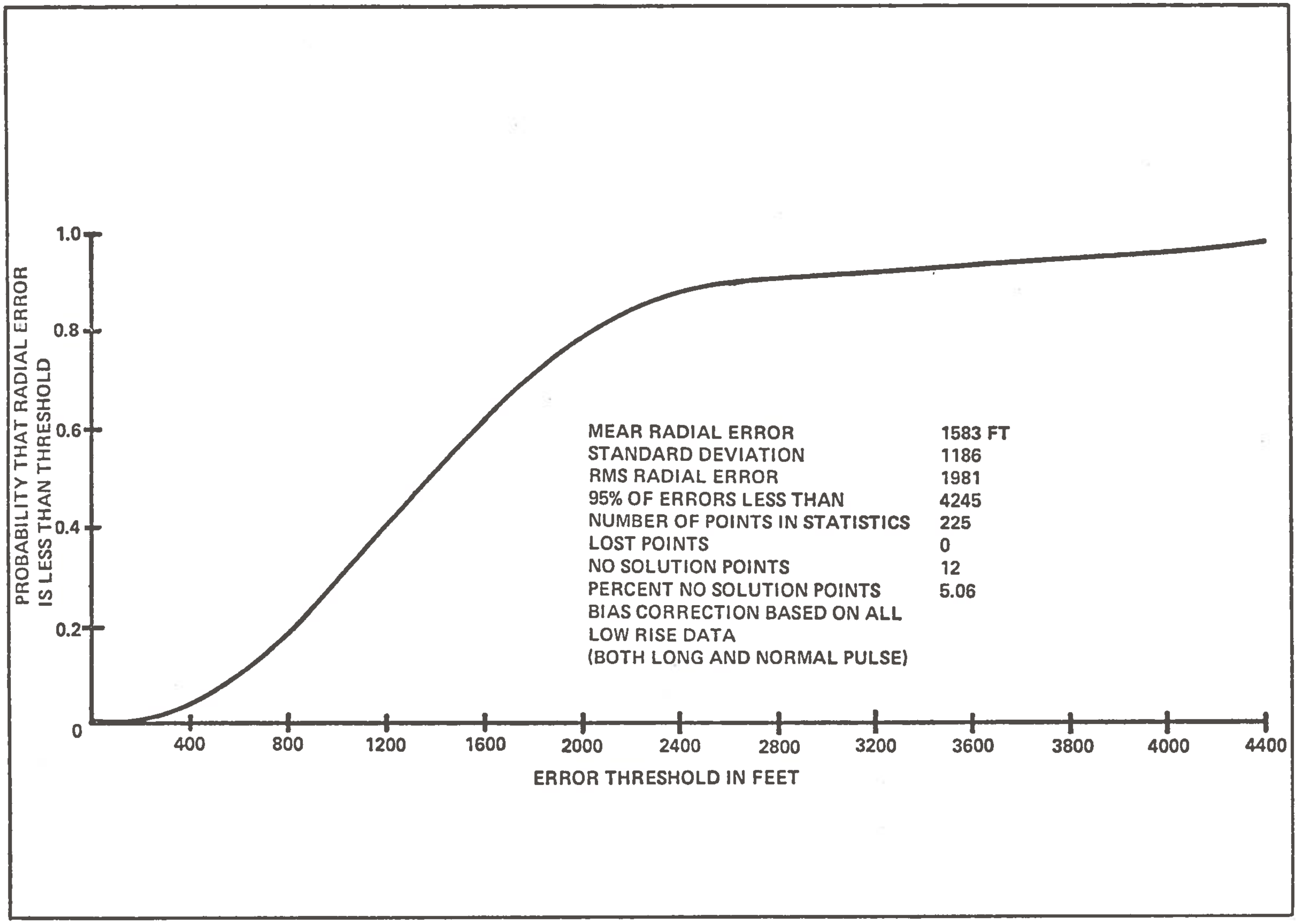


Figure 3-4 Sierra Low Rise - Long Pulse Accuracy

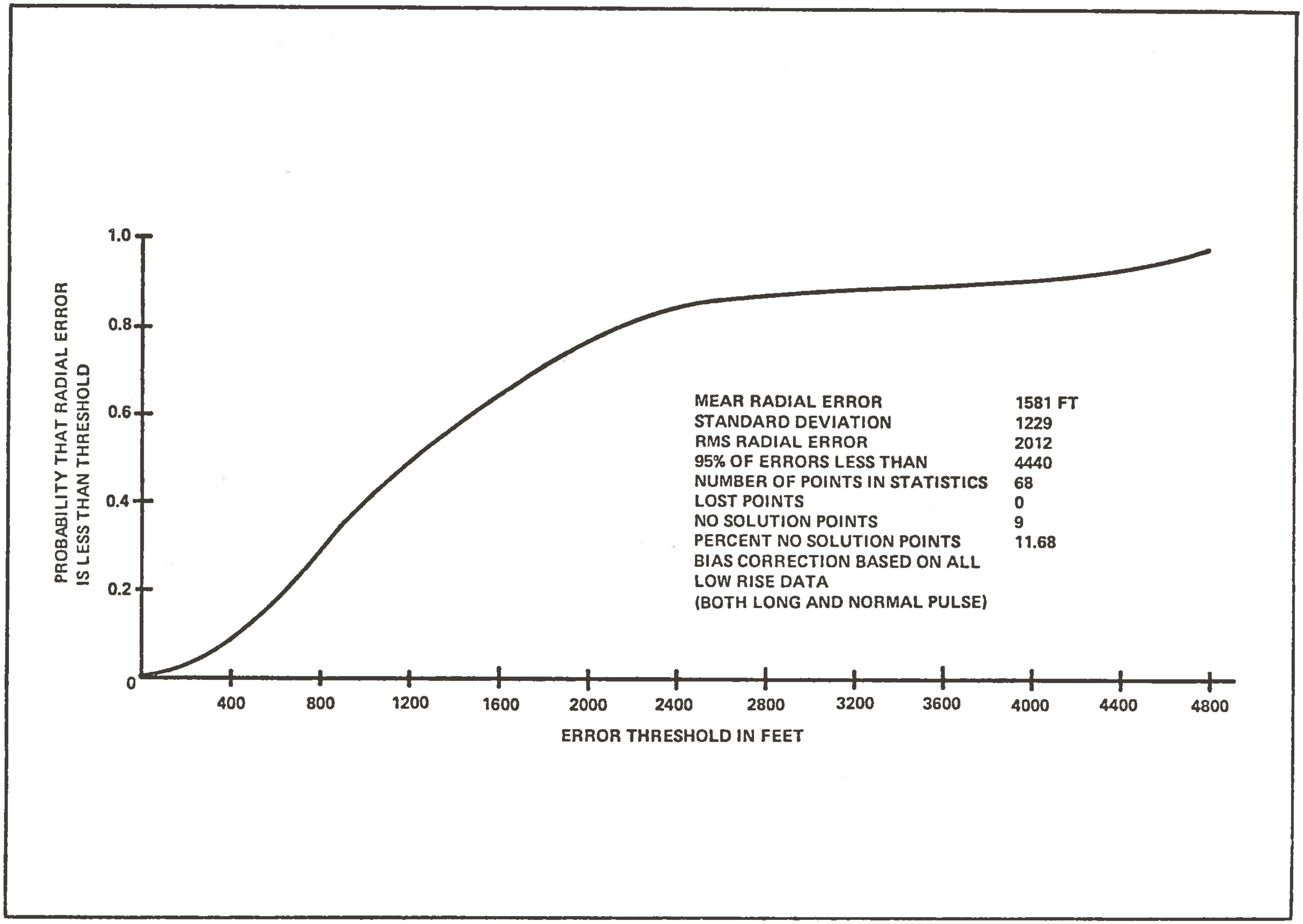
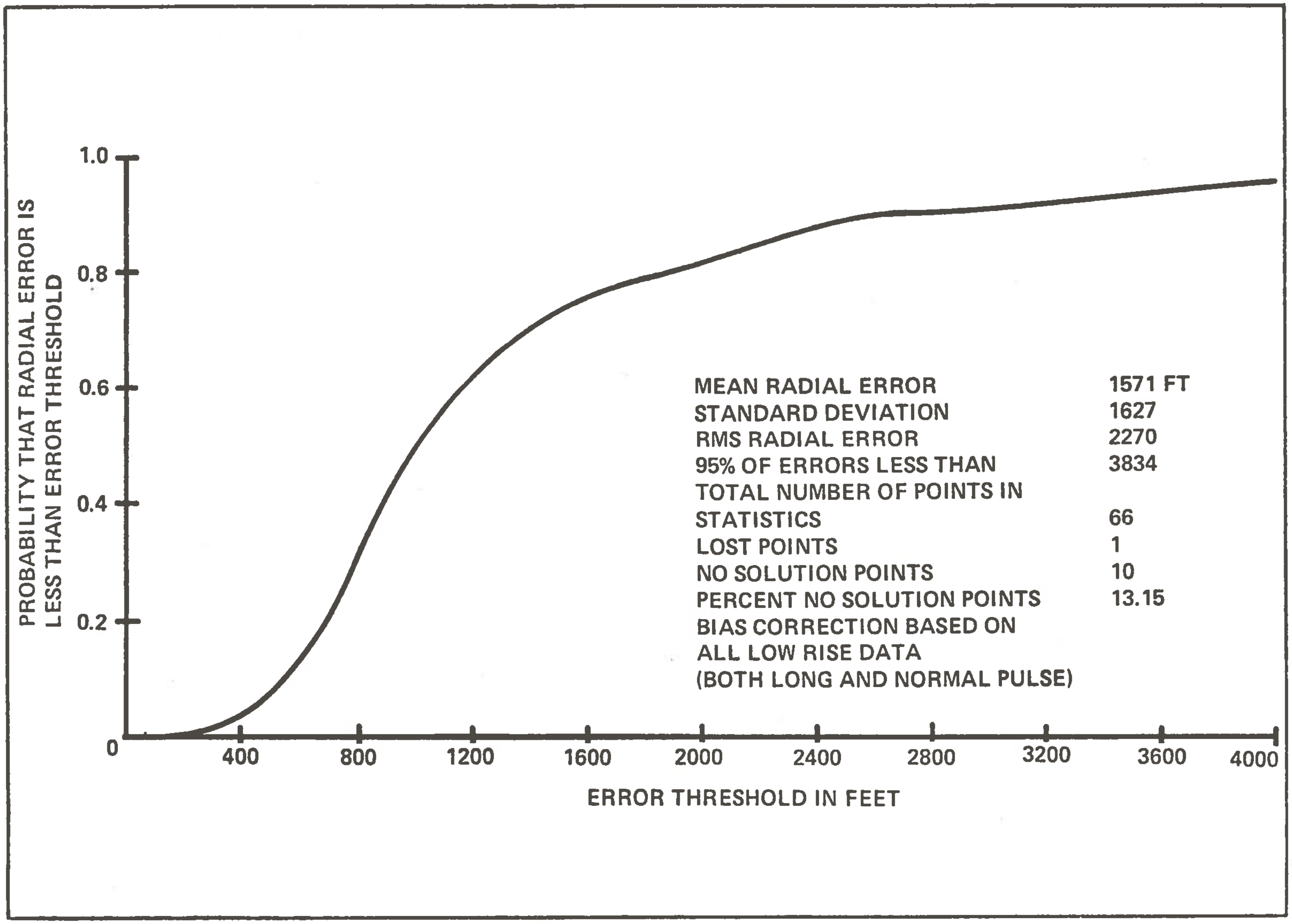
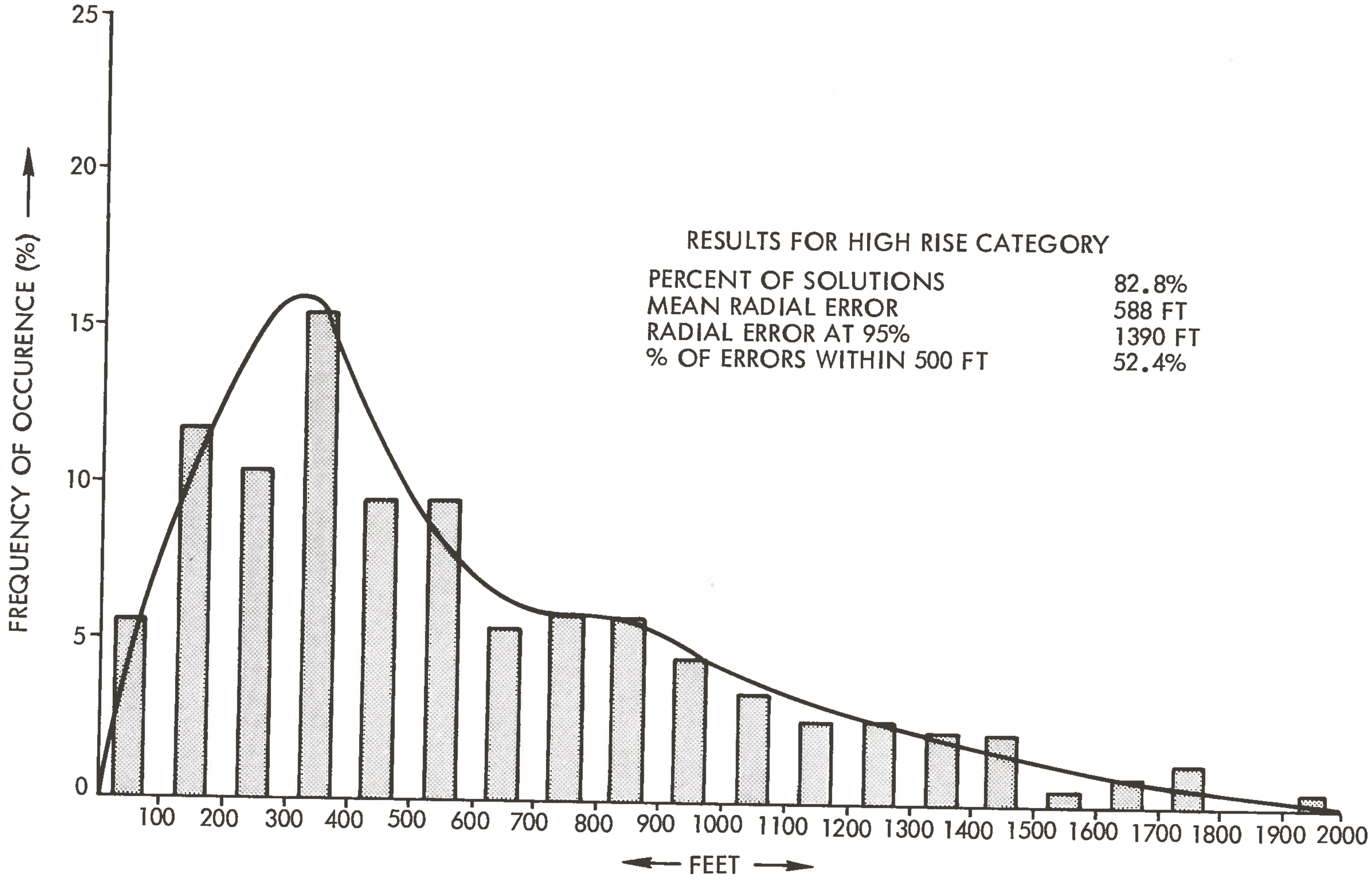


Figure 3-5 Sierra Special Case - Normal Pulse Accuracy



MEAN RADIAL ERROR	1571 FT
STANDARD DEVIATION	1627
RMS RADIAL ERROR	2270
95% OF ERRORS LESS THAN	3834
TOTAL NUMBER OF POINTS IN STATISTICS	66
LOST POINTS	1
NO SOLUTION POINTS	10
PERCENT NO SOLUTION POINTS	13.15
BIAS CORRECTION BASED ON ALL LOW RISE DATA (BOTH LONG AND NORMAL PULSE)	

Figure 3-6 Sierra Special Case - Long Pulse Accuracy



RESULTS FOR HIGH RISE CATEGORY

PERCENT OF SOLUTIONS	82.8%
MEAN RADIAL ERROR	588 FT
RADIAL ERROR AT 95%	1390 FT
% OF ERRORS WITHIN 500 FT	52.4%

Figure 3-7 Teledyne High Rise Accuracy

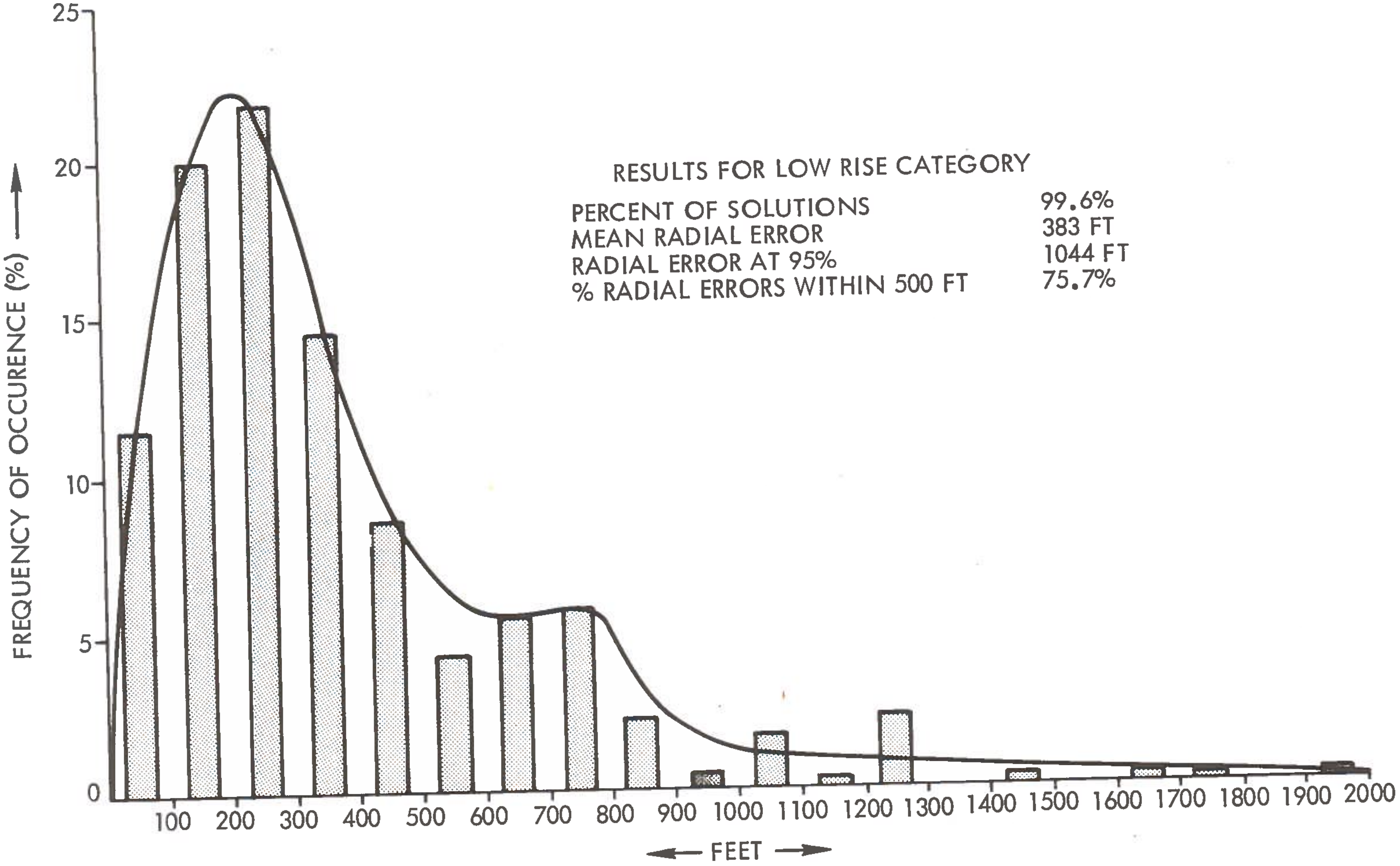
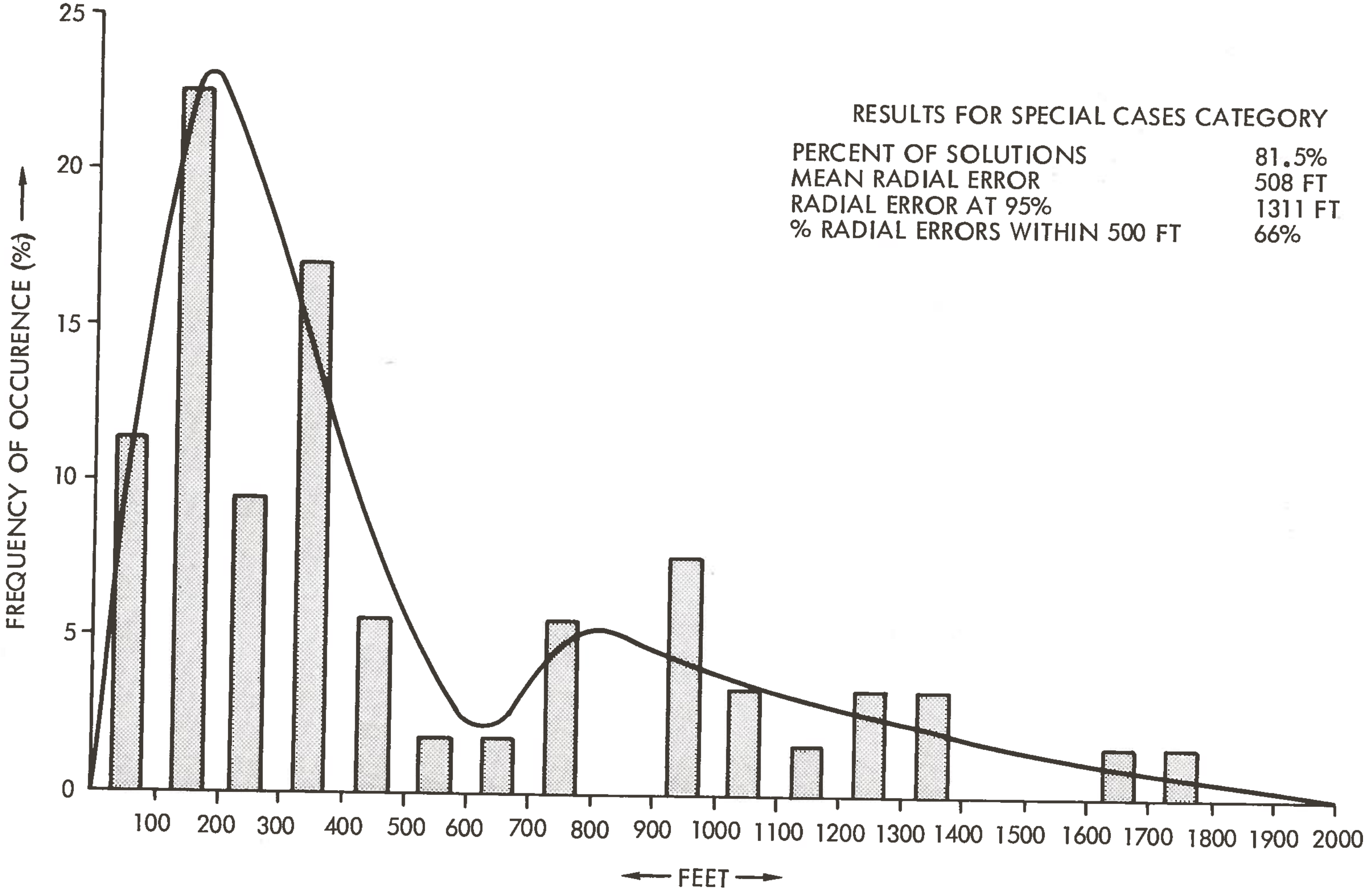


Figure 3-8 Teledyne Low Rise Accuracy



RESULTS FOR SPECIAL CASES CATEGORY

PERCENT OF SOLUTIONS	81.5%
MEAN RADIAL ERROR	508 FT
RADIAL ERROR AT 95%	1311 FT
% RADIAL ERRORS WITHIN 500 FT	66%

Figure 3-9 Teledyne Special Cases

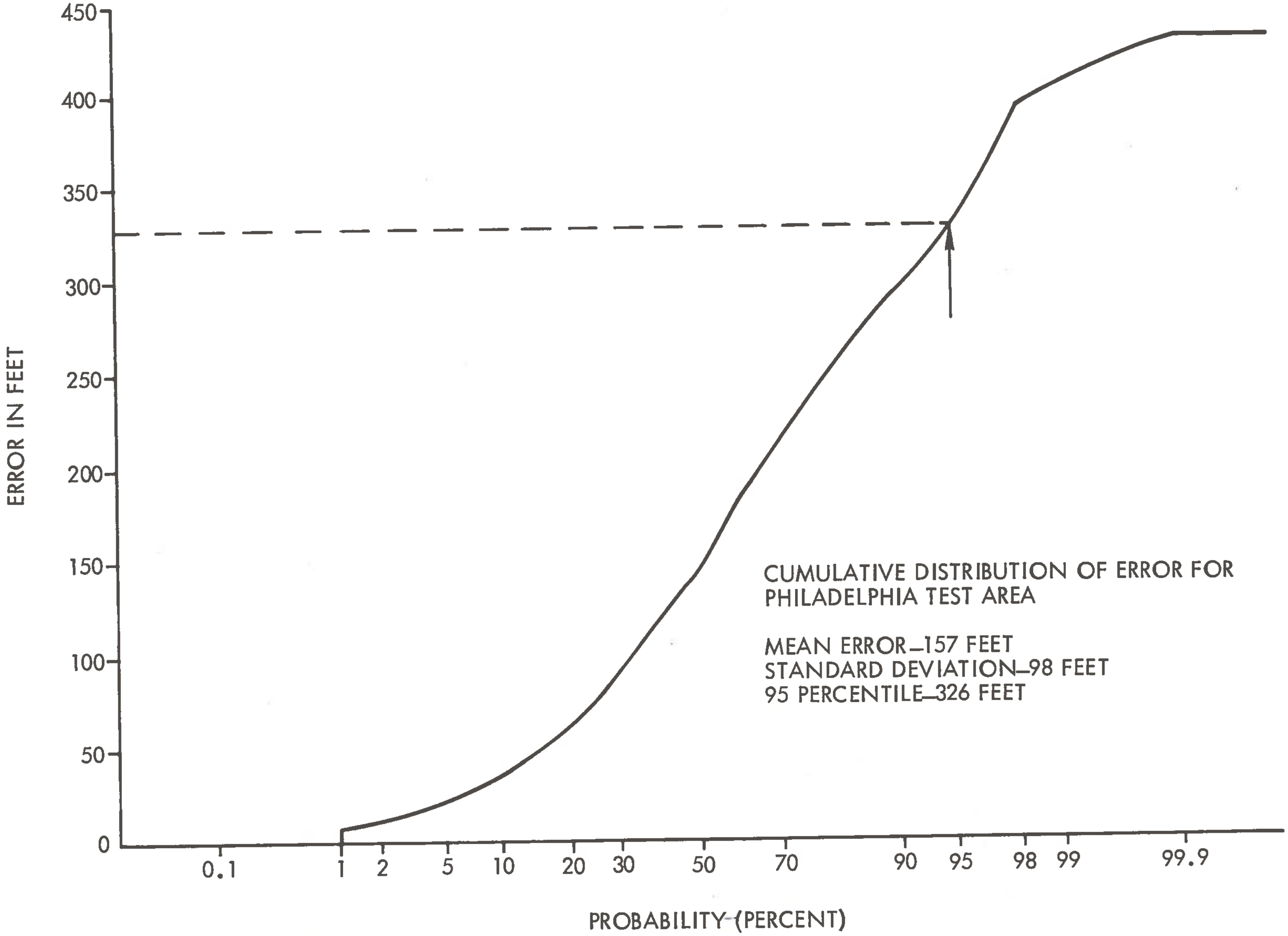


Figure 3-10 RCA Cumulative Distribution of Error

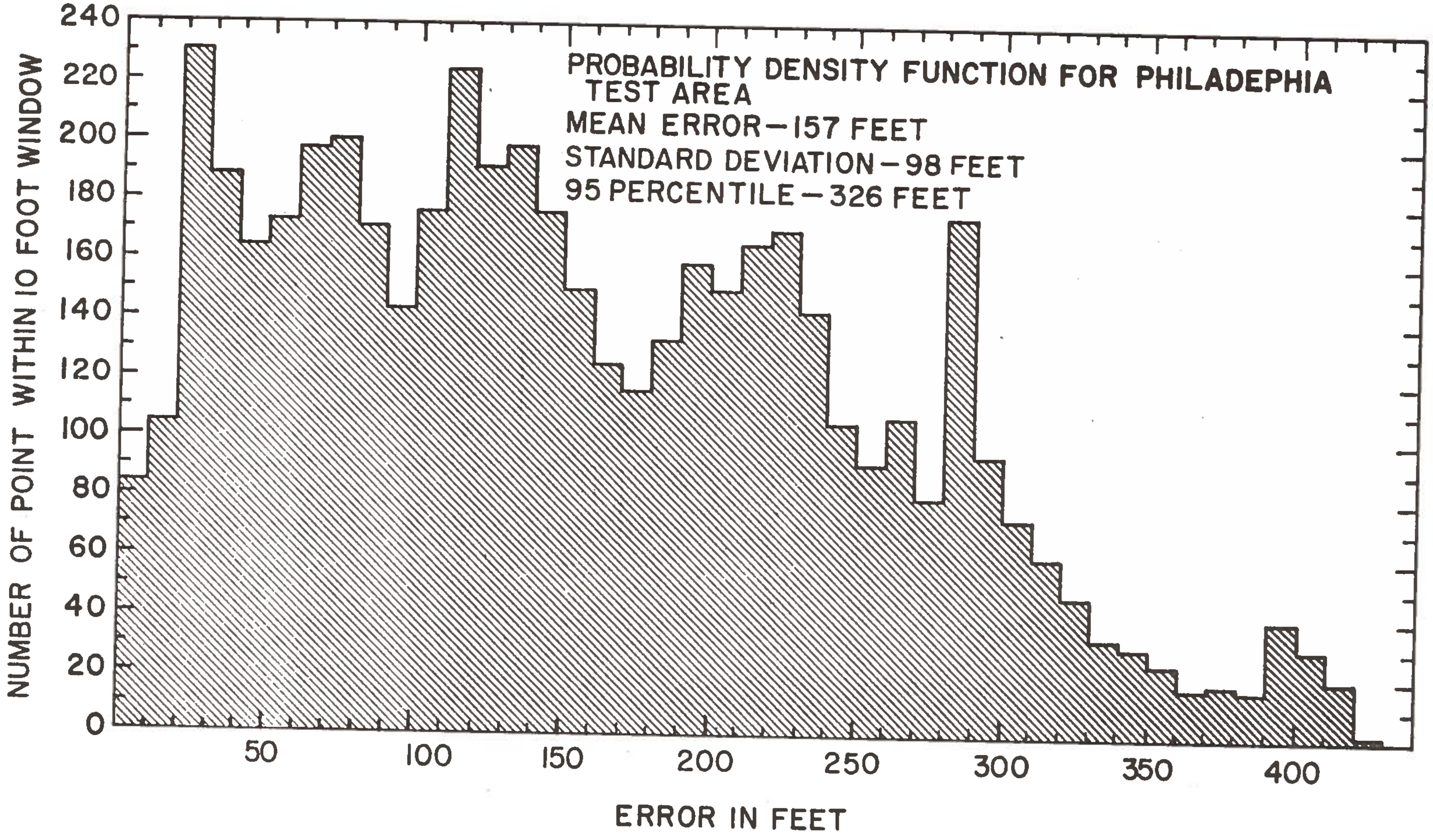


Figure 3-11 RCA Probability Density Function Accuracy

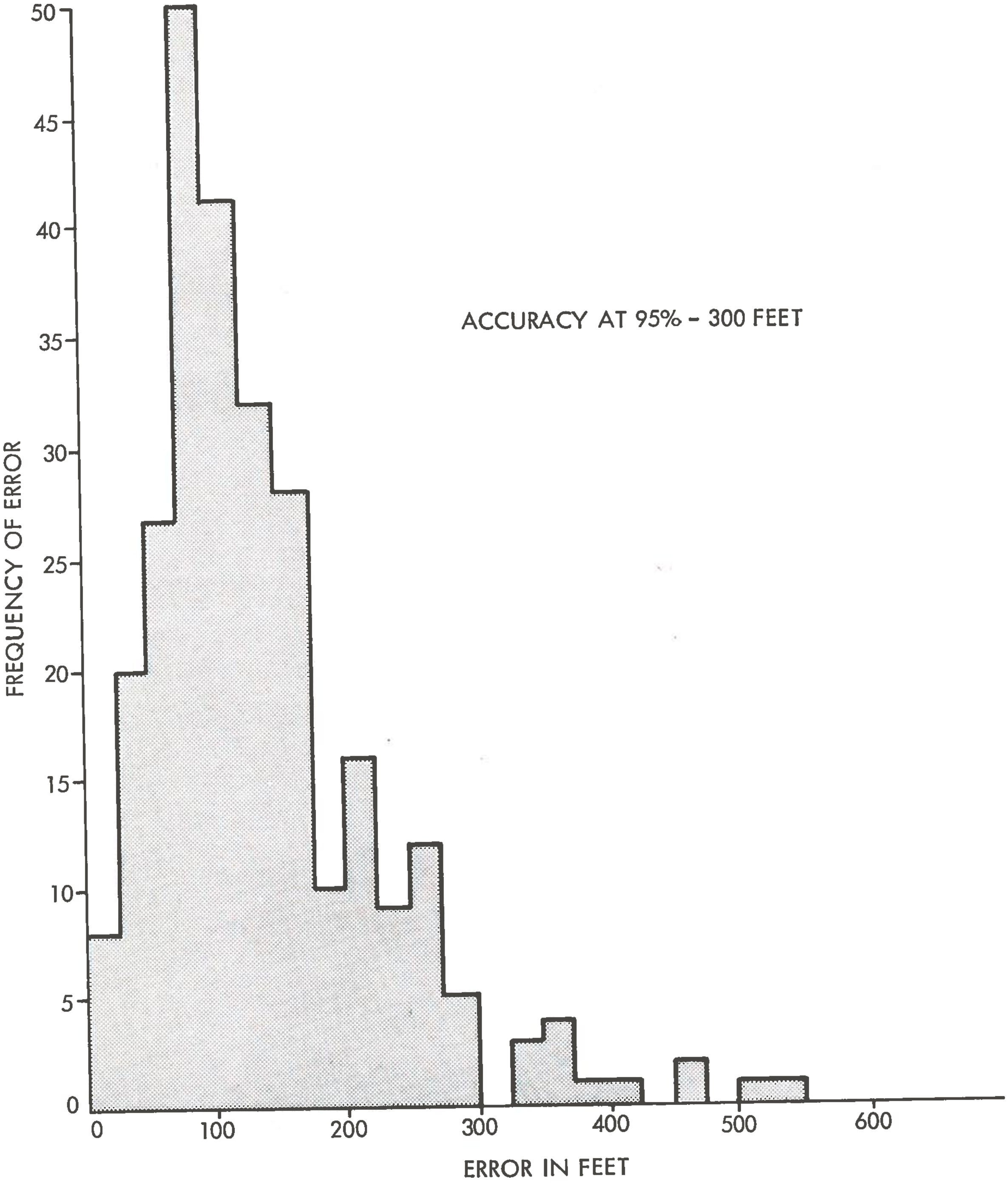


Figure 3-12 Hazeltine Accuracy; Distribution of Magnitude of Vector Error

Sierra used two different pulse lengths on their phase tone ranging measurements. These lengths were 70 ns and 35 ns. Actually only the 35 ns phase tone pulse lengths could be used for their 1000 vehicle per minute update rate AVM system.

RCA accuracy tests were conducted without a base station or digital data links. Their measurement was conducted within the test vehicle by comparing its real location to test location equipment readouts located in the vehicle. Hazeltine performed their accuracy tests within a one mile square area in downtown Manhattan, a high rise area.

The CTA proximity AVM system differs from all the other AVM systems tested with the exception of RCA because the accuracy is a function of the location and number of signposts used and is not affected by the noise and multipath characteristics of the urban environment. The difficulty encountered in the CTA AVM system was the vehicle low reply rates to base station interrogation. These low reply rates were due to faulty equipment, human factors, and multipath fading of the data channel. It is felt that all of these can be improved upon to produce a reply rate of 95%. The approximate 80 day life term of vehicle equipment can obviously be improved upon. The human factors, which deal with the fact that some bus drivers do not want "big brother" watching them, will occur in all AVM systems. Effects of multipath fading of the data channel can be overcome by increasing transmitter power, space diversity of antennas, and improving data link modems. It should be noted that of all the replies received from the AVM vehicle, essentially 100% were correct to within the accuracy allowed by the signpost locations. The CTA AVM system used a total bandwidth of 112.5 kHz. This bandwidth was for the following:

12.5 kHz for signpost transmission

50 kHz for duplex voice channels

50 kHz for duplex data channels.

This bandwidth can readily be reduced to 62.5 kHz without affecting the system. The Motorola Corporation designed the system to operate using the 112.5 kHz bandwidth only because the CTA had the bandwidth available.

The present CTA AVM system has a capability of updating 3,3000 vehicles every 5 minutes. There is no reason that modems similar to other AVM systems could be used to obtain identical interrogation rates (1,000 vehicles/min).

4. THEORETICAL CONSIDERATIONS OF AVM SYSTEMS

4.1 SPECTRUM OCCUPANCY

From the point of view of spectrum occupancy, it is useful to divide the AVM systems presently under development in two categories: proximity systems and trilateration systems. In the first category the location function is performed by signposts, whose radiation is generally very low level and moreover, often at frequencies where no significant spectrum crowding problem exists. Thus in such systems, bandwidth is only required for the two-way communication link between base station and vehicles. In a sense the LORAN C system also belongs to this class. In the second category, instead, bandwidth is used for both purposes of location and communication. It is therefore mostly to this category that this is addressed to our attention.

The structure currently envisioned for an AVM system of the class mentioned includes at least two essential functions: that of locating and tracking vehicles and the communication (one-way or two-ways) between the vehicles and a base station. The AVM system, in its most general form, is thus a combination of a radar-type system (although with a generally cooperative target) and a communication system. In describing the location and tracking functions, the criteria of performance are the accuracy of location, the location up-dating rate and the number of vehicles that can be conveniently handled, whereas for the communication system, which is assumed to be digital, the criterion of performance is the probability of incorrect reception of a single bit or of a whole message. Note that in most of the systems currently being developed the location information is part of the digital message so that the two systems are interrelated. The bandwidth used for each of the two functions plays, of course, a critical role with respect to the criteria of performance just mentioned. The technology of AVM systems has developed along two quite different directions from the point of view of the required bandwidth and these approaches are labeled, for brevity, the narrowband

AVM and the wideband AVM. In the former, which is generally envisioned at VHF or in the lower UHF band (450 MHz) where spectrum crowding is most acute, the location and communication functions are both accommodated (with the notable exception of the Cubic system) in conventional 25 kHz FM channels which, however, have to be specially allocated for this new function. In the latter, instead, which is planned in the neighborhood of 1 GHz where the spectrum is much less crowded, the bandwidth envisioned is almost two orders of magnitude higher. Furthermore, while in the narrowband approach most of the equipment design is centered around existing land-mobile transceivers, the designer of a wideband system enjoys much more freedom since the technology is very different from the one conventionally used in land-mobile applications.

In order to assess the advantages and disadvantages of one approach versus the other, one must consider in some detail the channel in which the system operates. The urban channel can be conveniently modeled as a fading dispersive channel where the additive noise is mainly man-made. Although several studies are currently in progress to improve our knowledge of this channel, one can safely say that the impulse response at a given time consists of a discrete number of continuous paths which can, however, merge together and whose total duration can extend up to 15 μsec although larger values have occasionally been observed. This structure of the impulse response is due to multiple reflections from the complex structure of the different areas of a city illuminated by the transmitter, and generally changes when the vehicle moves. The fading, or change in the propagation characteristics whose most visible effect is a change in signal strength, is in fact, due to the movement of the vehicle through the nonuniform spatial distribution of energy induced by the multiple reflections. The order of magnitude of the smaller scale spatial wavelength is of the order of λ, the wavelength of the transmitted signal so that the maximum fading rate (or Doppler spread) is of the order of $4v/\lambda = 4vf/c$ where v is the velocity of the vehicle and c the velocity of light. In view of this simple channel characterization it is possible to discuss the communication and location performance in rather general terms.

4.2 CHANNEL-CAPACITY CONSIDERATIONS

It is well known that the celebrated Shannon formula for channel capacity

$$C = W \log_2 \left(1 + \frac{P_s}{N_o W}\right) \tag{1}$$

is only valid for white Gaussian noise and for a channel with fixed parameters. The calculation of channel capacity for an arbitrary fading channel is a formidable problem and not much progress has been achieved toward its complete solution although a few interesting results are available, especially in the Soviet literature, as pointed out in a recent survey article by Dobrushin.[1] A good summary of the progress achieved can be found in a survey paper by Siforov.[2] Some of the most relevant results are reported here. We note, first of all, that although the noise in the urban channel is not Gaussian, the consideration of a Gaussian noise in the computation of channel capacity will yield a lower bound for this quantity since, as is well known, Gaussian noise is the worst possible type of disturbance and a processing gain larger than one is always realizable, in principle, if the noise is not Gaussian. In the evaluation of fading channels it is important to introduce the concept of self-capacity which is defined as the limit approached by the capacity when the signal power goes to infinity. In other words the self-capacity is the maximum capacity which can be obtained when the signal-to-noise ratio is large and when the coding is the best possible. As is clear from Equation (1) the self-capacity is infinite for channels with constant parameters. Fading channels are called type 1 if their capacity has the same behavior of Equation (1), whereas they are of type 2 if their capacity approaches a definite limit when the signal grows without bounds. In channel of type 1 it is also important to know how the capacity approaches infinity. The following results apply:

1. If the channel fades very slowly, so that a quasi-static approximation is appropriate, the fading channel is of type 1, and its capacity, where the fading is Rayleigh, is modified by a factor η whose value is a function of the average signal-to-noise ratio

   $$\beta = \frac{P_m}{WN_o}$$

   where P_m is the average power of the signal taken over a large time. The value of η, for any value of β, is never less than 0.83. This means that the degradation of channel capacity is never higher than 17 percent.

2. If the total bandwidth for the frequency spectra of statistically independent random variations in the amplitudes and propagation times of signals in all paths of a channel having a finite number of paths in less than its frequency bandpass, then the capacity of the channel will increase without bound for an unbounded reduction of the additive noise level.

   Moreover, it turns out that for this type of multipath channel, the capacity is actually longer than that of the equivalent channel with invariant parameters.

The rate of variations of parameters in an urban channel can be easily estimated, at least in an order of magnitude sense. The worst case, of course, is when both the frequency of the signal and the speed of the vehicle are high. Assume f = 1 GHz and v = 30 m/sec. The resulting Doppler spread per path is 400 Hz. Even if we consider 10 path, the maximum total spread will be 4 kHz and therefore lower than the bandwidth used in conventional FM transceivers. This means that if we use Shannon's formula for computing the channel capacity of any urban channel we will have, generally, a conservative estimate. If, however, the channels variation are so slow that a quasi-static approximation is warranted, then the error in computing the capacity is, at most 17 percent. Note that this condition will very seldom exist in an urban channel.

We will briefly discuss data transmission in the context of Equation (1). We concentrate our attention on the link between vehicle and sensor stations or base station and therefore ignore the possible link between the sensor station and the central station. Such a link uses generally a dedicated telephone line or a microwave link and its constraints are different from the ones of interest to us. We are ultimately concerned with the question of spectrum utilization and therefore discuss the role played by the bandwidth. The significance of Equation (1) is the implicit tradeoff between output SNR and bandwidth. It can be easily shown[3] that if $z = P/N_oW$ is the input SNR and b the ratio between the bandwidth occupied by the signal and the information bandwidth, the relation between the output SNR $(S/N)_D$ and these parameters, i.e., the tradeoff relation mentioned above is

$$\left(\frac{S}{N}\right)_D = \left(1 + \frac{z}{b}\right)^b - 1 \cong \left(\frac{z}{b}\right)^b \quad \text{if } z/b >> 1 \quad . \qquad (2)$$

Thus, from the point of view of information theory one expands the bandwidth only if the signal-to-ratio available is not adequate. Practical systems, such as analog FM have a similar behavior as shown in Figure 4-1 which is plotted for a specific value of $(S/N)_D$, i.e., 50 dB. The behavior of digital communication systems of common use is also similar. See, for example.[4]

An interesting graph taken from[4] is reported in Figure 4-2 which shows the spectrum efficiency of various digital modulation systems. It is useful to add that conventional binary FSK modems that a rather inefficient bits/cycle ratio of at most 0.5 and therefore they can transmit 10 K bits in 20 kHz. Thus, there is certainly room for improvement: For example, at an SNR of 15 dB the optimum FSK modem (which would be an 8 level

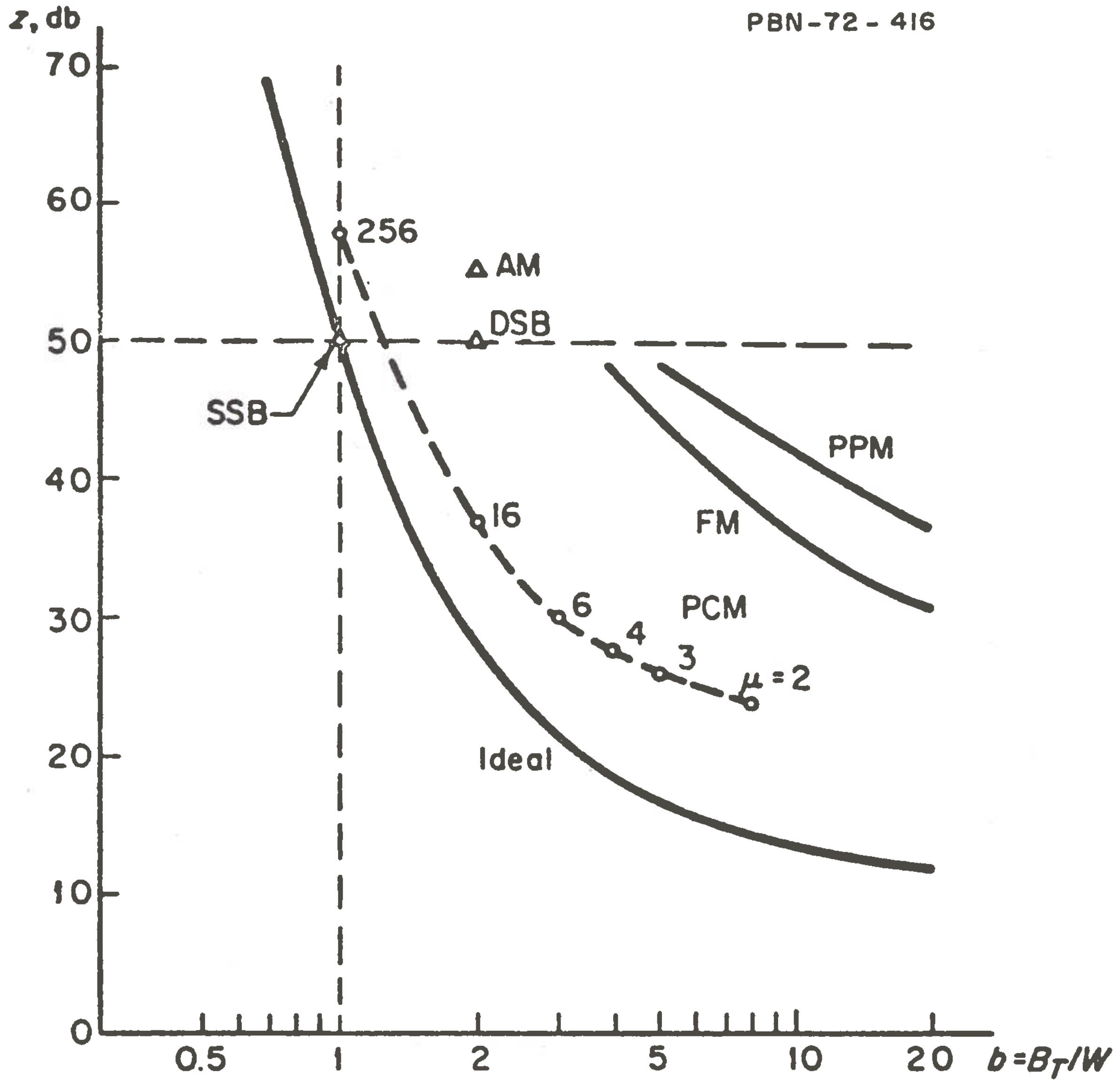


Figure 4-1 Transmitter Power Required as a Function of S/N and Bandwidth

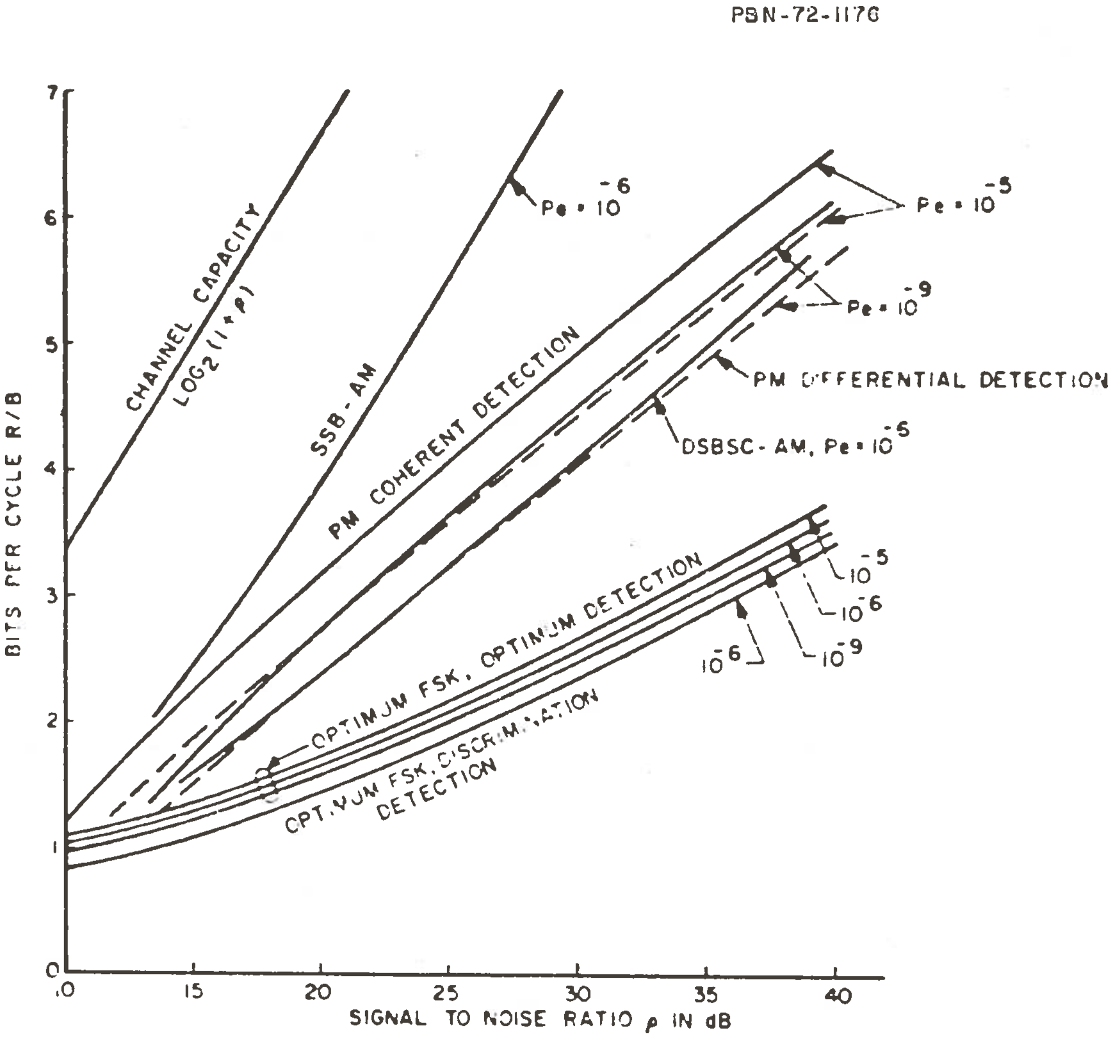


Figure 4-2 Bits/Cycle Versus S/N for Various Modulation Systems

system) would have a bit/cycle ratio of 1.3 while the optimum PSK modem with differential detection (and 4 levels) would yield a bits/cycle ratio of 2. All these systems are rather far from the ideal performance which, for 15 dB, indicates a bits/cycle ratio of 5. It is interesting that four-phase systems with differential detection, whose performance is considerably better than FSK have been recently successfully experimented for land-mobile applications.[5]

In order to evaluate the amount of bandwidth required by an AVM system designed to serve communities of various sizes, one needs an estimate of the number of vehicles that potentially might use such a service and of the number of bits required per vehicle and per sample, together with the up-dating or sampling rate necessary for a given function. Such estimates have been made and are available in the literature. The estimated AVM market is as follows:[6]

Size of Area	Total number of vehicles
Large	7940
Medium	1790
Small	720

If we assume that the sampling rate is 1/min for 80 percent of this number and 4/min for the remaining 20 percent, the number of samples/sec is as follows:

Area	No. of samples/sec
Large	212
Medium	47
Small	19

The number of bits necessary for each transmission is highly variable with the type of AVM, for example those which provide only identity and location and those which also transmit some other information, with the type of vehicle, for example, fixed-route or random-route, and with many other variables. Estimates are, however, available, for example, in,[7] and 60 bits seems to be a reasonable number, both for police cars and semi-random routed vehicles, whereas fixed-route buses may require up to 68 bits to transmit several items of status information. In order to deal with round numbers, let us assume the following maximum number of samples/sec.

Area	No. of samples/sec
Large	250
Medium	50
Small	20

The following table indicates minimum bandwidth requirements for different modulation systems and does not include accessory functions such as synchronization, error correction, guardtime, etc.

50 bits - (S/N) = 15 dB

	FSK binary	FSK optimum	4ϕ PSK (optimum)	Ideal
Large area	25 kHz	10 kHz	6.2 kHz	2.5 kHz
Medium area	5 kHz	2 kHz	1.25 kHz	0.5 kHz
Small area	2 kHz	0.8 kHz	0.50 kHz	0.2 kHz

100 bits

Large area	50 kHz	20 kHz	12.4 kHz	5 kHz
Medium area	10 kHz	4 kHz	2.5 kHz	1 kHz
Small area	4 kHz	1.6 kHz	1.0 kHz	0.4

150 bits

Large area	75 kHz	30 kHz	18.6 kHz	7.5 kHz
Medium area	15 kHz	6 kHz	3.75 kHz	1.5 kHz
Small area	6 kHz	2.4 kHz	1.5 kHz	0.6 kHz

The number of conventional channels necessary can be easily determined since a typical VHF channel of 25 GHz will accommodate a spectrum of about 20 kHz once guardbands are taken into account.

4.3 NARROWBAND DATA COMMUNICATION

We may remark at this point that in all of the existing AVM designs of the communication link there are significant inefficiencies in the use of bandwidth since the maximum data rate envisioned for a 25 kHz channel is of the order of 2400 bits/sec. The main reason for this inefficiency seems to be in the constraint of using the FM modulation capabilities of the conventional mobile transceiver, combined with the relatively modest requirements on system characteristics (number of vehicles to be located, updating rate, digital information to be transmitted, etc.) with respect to the available bandwidth (quantized in blocks of 25 kHz).

Since the AVM systems use a good part of the bandwidth to locate vehicles and to transmit digital messages, it is conceivable that the use of digital communication could take part of the lead off the overcrowded existing voice channels. Some attention to the possibility of improving radio spectrum utilization through this approach has been given by the Advisory Committee for the Land Mobile Radio Services. The study and its conclusions[8] are not too encouraging since the Committee found the replacement of voice by digital messages very seriously hampered by economic and operational constraints. Although the Committee realized that the question deserves further study, it was concluded that only a very small improvement in spectrum utilization could be obtained by adoption of non-voice techniques. A maximum improvement of the order of five percent could theoretically be expected but it is predicated upon the assumption that all the prospective users identified in the study converted their appropriate operations into digital communications. In their opinion, then, "there is no current prospect for anything but trivial overall improvements in spectrum utilization on the use of this concept". In our opinion, however, the question deserves further study because even a saving of the order of a fraction of a percent of the bandwidth currently allocated for voice could make available the few channels which, if an efficient design is implemented, could provide AVM services even to large areas.

4.4 ACCURACY CONSIDERATIONS FOR NARROWBAND AVM

With the exception of the LORAN C system and the signpost system, all the narrowband AVM systems use phase trilateration or multilateration and the delay (corresponding to range) is measured as a phase shift of a tone that modulates the carrier. The frequency of this tone is chosen as to avoid range ambiguities and therefore the corresponding wavelength must be larger than the maximum range of interest. It is well known that if Gaussian noise were the only cause of error the mean-root-square error in the estimation of path delay would be

$$\epsilon_r = \frac{1}{2\pi W(S/N)^{1/2}}$$

where S/N is the energy-to-noise-spectral-density ratio at the receiver and W the bandwidth of the transmitted signal. Since the tone of frequency f_m is generally transmitted as a frequency modulation of the carrier, the relative bandwidth is, if m_f is the modulation index,

$$W \cong 2f_m\ (m_f + 2)$$

and it is easy to see that even modest values of the bandwidth could yield a very low and satisfactory range error if the S/N is high enough. In the urban environment, however, noise is very seldom the main concern and it is the multipath, instead, which causes most of the range errors. Although some analyses have appeared in the literature, for the case, respectively of two discrete paths[9] and of the Young and Lacy experimental data[10], and although they are useful to gain insight into the mechanism of generation of the errors due to multipath, the structure of the urban channel is far too complex to allow a simple analytical treatment. A simulation approach based on actual channel measurements has been pursued by Teknekron 7 (vol. 2, pp. 104 et seq.) with the following results for the range error.

Area	95 Percent point
A	1469' ± 3281'
B	849' ± 1714'
C	156' ± 656'
D	150' ± 475'

The types of areas denominated by A, B, C, D indicate, respectively dense high rise, sparse high rise, metal-frame low rise and wood-frame residences. In this simulation the modulation index was 2. The dependence of the range error on the modulation index and therefore on the bandwidth seems to be very weak. Very little difference has been found in the simulation by increasing the modulation index from 2 to 5. A theoretical explanation of this fact is given in[9] for the case of two paths: it is shown that an increase in the modulation index yields better accuracy only if the difference in the delay of two paths correspond to several degress of the modulation cycle. It is easy to see that for a modulating frequency of the order of a few kHz this does not happen unless the multipath is several microseconds long.

Teknekron has also simulated the location error resulting from the use of the least-square algorithm and several sensors. The results are as follows:

City (similar to San Francisco)	95 Percent radial error
N = 4	1800'
N = 6	1500'
N = 8	1340'
City 2 (similar to Oakland)	
N = 4	1400'
N = 6	1050'

From these and similar simulation results it seems that the law of diminishing returns sets in very quickly when the number of sensors is longer than six. It is therefore evident that the accuracy achievable with phase ranging is relatively limited if the ranging tone frequency is only a few kHz.

A legitimate question is whether, within the constraint of the narrowband approach, the use of a tone which frequency modulates the carrier is the best one can do in terms of resolution, and other considerations such as equipment complexity and instantaneous interference to other users. Although no study seems to have been done of this question, it is quite likely that FM by a tone is a reasonably efficient technique and it is certainly quite simple to implement. The use of a constant level RF also minimizes the average interference to other users.

4.5 THEORETICAL WIDEBAND AVM SYSTEM CAPACITY

It is instructive to consider the maximum capacity of a wideband AVM system according to the fundamental theorems of information theory. This capacity limit is useful to judge the effectiveness of a particular AVM system in the utilization of available resources (power and bandwidth).

The AVM system must provide both position information (ranging) and data transfer. In assessing the capacity limit of the system, the ranging function can be considered as a by-product of the data communication function. The system capacity can then be determined by the average duplex data transfer rate per vehicle, R, the system bandwidth, B, and the signal-to-noise ratio, SNR, at the receiver according to the formula:

$$N = \frac{B}{R} \mathrm{LOG}_2 \ (1 + \mathrm{SNR})$$

where N is the system capacity in number of vehicles. Note that the location update rate does not enter into the capacity calculation for update rates lower than the average data transfer rates.

To determine the system capacity, it is necessary to estimate receiver SNR. The link from vehicle to base station is considered to have the higher data transfer rate and thus limit system capacity. The following list of system parameters is then used to determine performance.

Vehicle to Slave Station

Transmitter Average Power (10W)	40 dBm
Transmitter Antenna Gain (including line losses)	0 dB
Frequency	920 MHz
Path Length	10 Miles
Free Space Path Loss	117 dB
Excess Path Loss	30 dB
Receiver Antenna Gain (including line losses)	8 dB
Receiver Noise Figure	5 dB
Thermal Noise at 20°C	-174dBm/Hz
Urban Man-Made Noise	(negligible at roof-top level)

(Note that an average power of only 10W is assumed. For a vehicle to achieve channel capacity it must employ long and complicated waveforms which do not permit peak power operation.)

The resultant receiver SNR is shown in Figure 4-3 as a function of path length and system bandwidth.

The corresponding theoretical maximum system capacity is shown in Figure 4-4 for several bandwidth-range combinations typical of an AVM system. The average data rate per user depends on the type of user. For police vehicles, data transmission may approach real-time. That is, several tens of bits can be communicated in a period of about 10 seconds resulting in duplex data rates on the order of 10 bps. However, for trucks and buses, the information to be transmitted may be of limited extent such as distress or number of passengers. Such vehicle data rates may be on the order of 0.1 to 1 bps, and would make up the majority of the traffic. Thus, at 1 bps average data rate, the wideband AVM system capacity is in excess of 10^6 vehicles.

This maximum system capacity is for a system of unlimited complexity in terms of signal waveform and signal processing. The capacity of practical communication systems is typically an order of magnitude or more below this capacity limit. Thus, a realistic

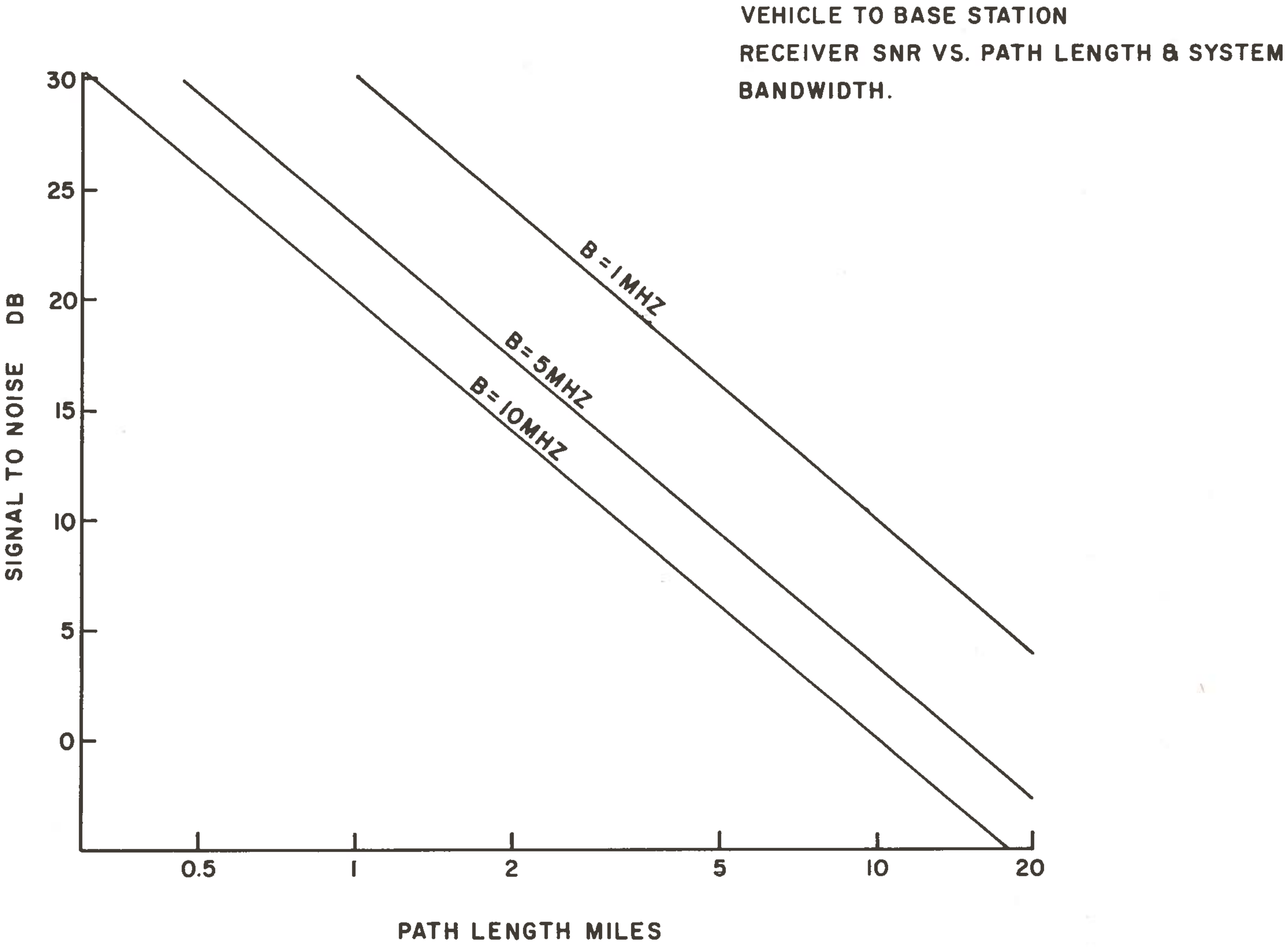


Figure 4-3 Vehicle-to-Base-Station Receiver S/N as a Function of Path Length and Bandwidth

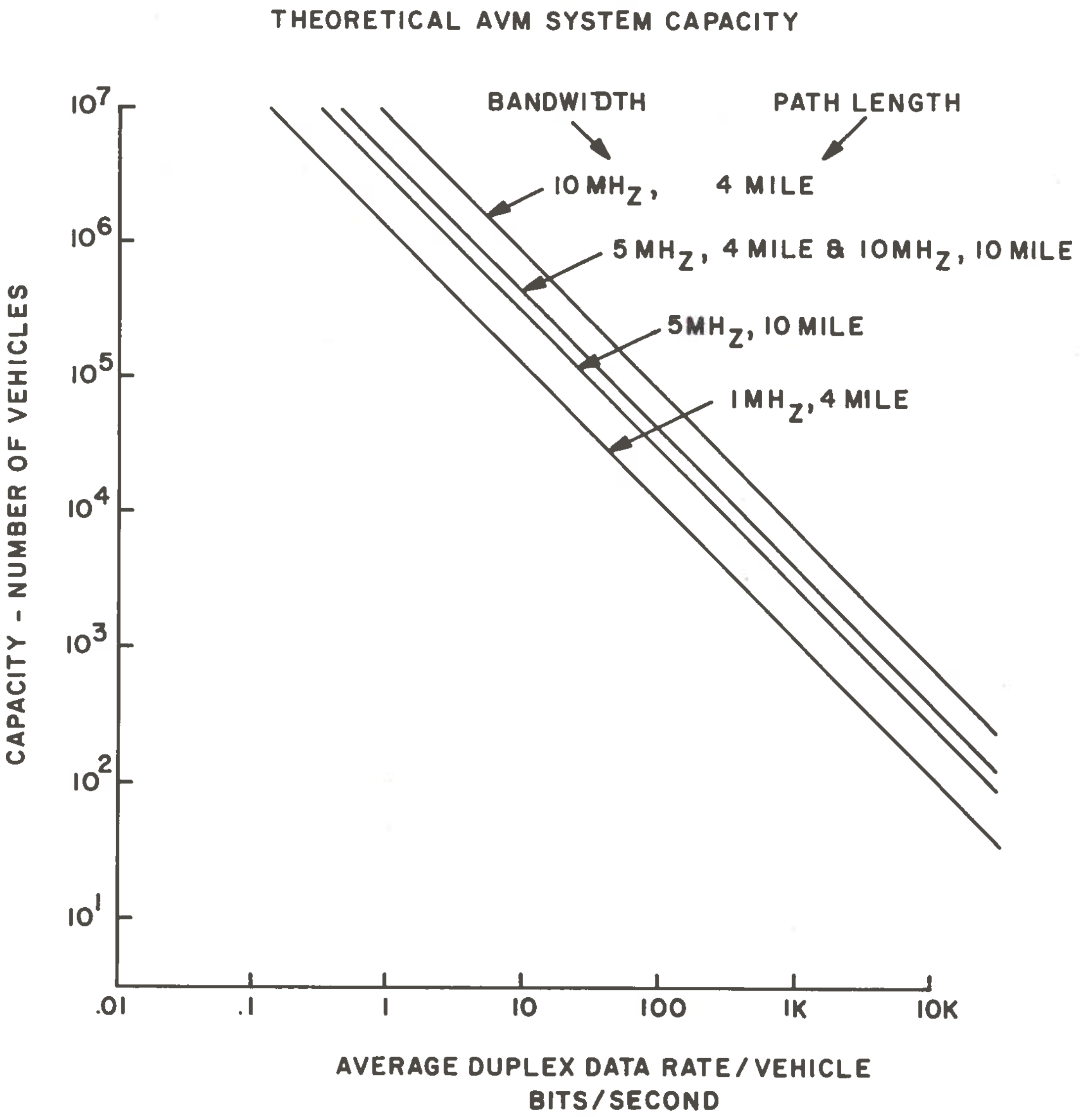


Figure 4-4 Theoretical AVM System Data Capacity

system goal should be a capacity of about 10^5 vehicles at an average duplex data rate of 1 bps or 10^3 vehicles at 100 bps. Such capacity limits should serve the needs of even the largest cities in a single wideband AVM system (less voice communications).

Consider now the addition of voice traffic to the AVM system. The lowest equivalent data rate for voice of reasonable intelligibility and moderate system electronics complexity is about 10 Kbps. At this rate, only about 100 vehicles could be supported in a practical AVM system. However, all 100 vehicles would normally not communicate at once. Each vehicle that does use such two-way voice transmission would add an average data rate of 1 bps to 20,000 other vehicles in the system resulting in a significant reduction in overall capacity. For this and other reasons to be explained later, it is recommended that voice communication be restructed to the existing land-mobile channels.

Consider now the use of slave stations in a typical trilateration system. On the order of 10 stations would be required in a 100 square mile area for adequate coverage and accuracy. The function of these stations is to monitor the vehicle signals and convey their information content to a central processing station for position computation. If these slave stations act as simple relay stations and retransmit the vehicle signals to a common master station in the same frequency band, the AVM system capacity will again be reduced by about one order of magnitude. To retain the maximum AVM system capacity, it will therefore be necessary to isolate the slave to master station transmission from the vehicle transmissions. This isolation can be achieved through the use of a separate communication link at a different frequency (for example, microwave) or through the use of separate highly directive antennas in the same frequency band.

4.6 PRACTICAL WIDEBAND AVM SYSTEM CAPACITY

The previous estimate of maximum system capacity is very exciting since more than 1,000 vehicles would be provided with real-time, full duplex teletype communications (as well as automatic location). However, this estimate was based on unbounded system complexity. Specifically, to attempt to achieve this maximum capacity, it is necessary to allow overlap of the various vehicle transmissions. That is, normally the participating vehicles will be randomly distributed over a large area. In a trilateration system, it is impossible to order the vehicle responses to simultaneously eliminate the need for guardtimes and also prevent signal overlap at all receiving stations. Hence, each vehicle must use some form of spread spectrum coding that will tolerate simultaneous interference from other similar transmission (but with different codes). Since vehicle transmissions can vary in power by 60 dB or more at the receiving sites (due to range and multipath differences), a comparable spread spectrum coding gain would be required. Such high coding gains are not practical for vehicle data rates above about 1 bps and even then, continuous vehicle transmission would be required together with a dedicated decoder at the receiving site for each vehicle.

Taking the closest range as about 0.1 mile (street to rooftop) and longest range as about 10 miles, a 40 dB variation in path loss can be expected. In addition, there is an average excess path loss due to multipath of about 30 dB which is also a variable from vehicle to vehicle. This greater than 60 dB maximum variation in signal strengths received from various vehicles rules out any practical scheme to overlap vehicle transmissions in time. A guardtime must, therefore, be placed between the vehicle transmission in any practical trilateration system to prevent mutual interference.

Under the assumption that the AVM coverage area is about 100 square miles, a maximum range of about 15 miles can be postulated. This maximum range corresponds to about 83 us in propagation delay. To prevent overlap between the nearest and furthest vehicles, it is necessary to allow a guardtime of 2 x 83 = 166 us. That is, in an AVM system where each vehicle responds in fixed time slots which are synchronized to a master station timing marker, the time overlap uncertainty corresponds to twice the vehicle propagation delay. Under these conditions, the maximum number of vehicles per second which can be accommodated is given by

$$N_v = \frac{1}{166 \times 10^{-6} + M_v + M_s} \quad \text{vehicles/second}$$

where M_v is the duration of the vehicle transmission and M_s is the duration of the message from the control station to the vehicle. For zero message lengths, a maximum of 87,000 vehicles can be accommodated with a 15 second update interval.

The message duration to and from each vehicle will essentially increase the system dwell per vehicle and thus reduce capacity. Figure 4-5 shows the resultant system capacity as a function of combined per vehicle duplex message length for various update intervals.

4.7 WIDEBAND RANGING

Measurements have shown that wideband pulse ranging can produce 95% ranging accuracies within about 450 to 750 feet with an average on the order of 550 feet.[6] This accuracy improvement over narrowband systems is due to the ability to often resolve the first multipath echo (shortest return path) in the absence of a direct ray. The accuracy limitations of this approach result from the path length variability of the first echo (due to building height, etc.) and the occasional event of failing to recognize the first echo due to its amplitude fluctuation.

The waveform used for pulse ranging and data transmission can be a simple unmodulated RF burst or a more complicated spread spectrum coded burst. In the absence of multipath, the pulse waveform chosen should permit range resolution to a small fraction of the multipath accuracy limit. In addition, it should also be practical to generate with miniaturized circuitry and require only reasonable transmission power.

The rms accuracy of a single wideband pulse depends on its risetime and SNR and can be approximated by

$$\sigma \simeq \frac{\tau}{\sqrt{2\ \mathrm{SNR}}}$$

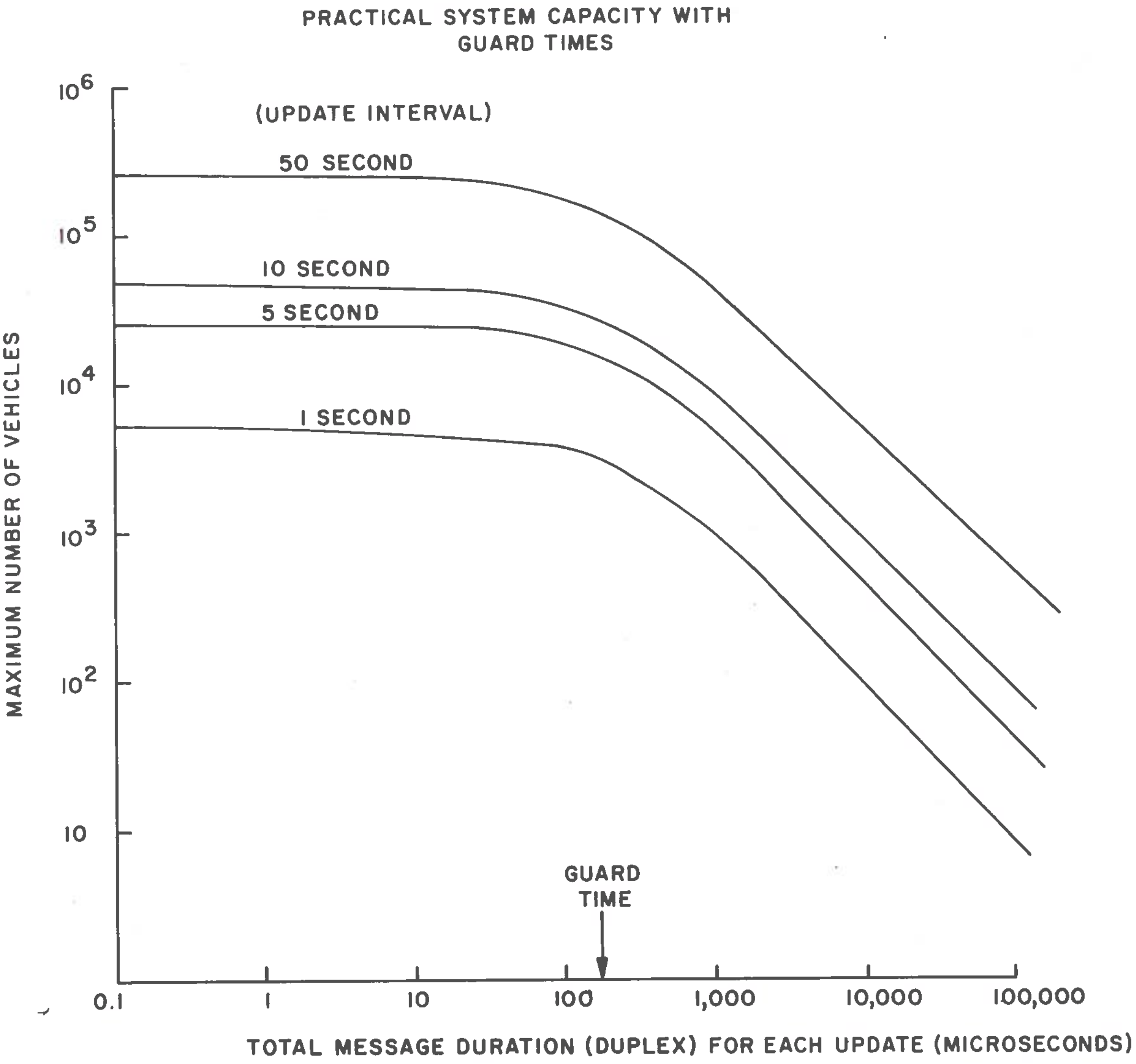


Figure 4-5 Practical System Data Capacity

where τ is the pulse rise time. The difficulty with simple threshold pulse detection is that the pulse SNR must be achieved in a bandwidth large enough to preserve the pulse rise time. As a result, the duration of the pulse contributes very little to accuracy and very high transmission power is required to achieve the SNR. That is, the receiver is optimized for a datum on the order of $1/\tau$ which is several orders of magnitude below the maximum useable pulse rate of system due to multipath limitations. With simple RF location pulses, a vehicle power on the order of 1 KW (peak) is required for reliable performance.

It is well known that for a given bandwidth and message duration, spread spectrum signalling provides the highest ranging accuracy with the lowest transmitter power. If spread spectrum (digital phase coded bursts) pulses were employed, a processing gain advantage equal to the product of the system bandwidth and pulse duration could be achieved. Thus, a 5 MHz bandwidth with a 50 us pulse, for example, would tend to require 250 times less transmit power than for a simple RF pulse. Such techniques should receive further attention in the optimum utilization of energy in the wideband system.

4.8 DATA-TRANSMISSION CONSIDERATIONS

The wideband channel has the capacity for very high speed digital transmission depending on equipment complexity. Simple digital transmissions schemes such as PSK, FSK, and OOK must operate at rates which are less than the "coherent bandwidths" of the channel. That is, channel multipaths will essentially stretch out each bit in time. If the bit rate is too high, enough intersymbol interference will be generated to produce digital errors even in the absense of noise. For the urban channel near 1 GHz, this maximum data rate for simple modulation techniques is on the order of 50 Kbps. Hence, for a system of 16,000 vehicles, about 200 data bits can be transferred during each update. This data can be apportioned between the links to and from the vehicle.

With increased equipment sophistication, (digital modulators and demodulators designed to make use of or avoid multipath distortion), data rates of up to half the channel bandwidths can be achieved. Thus, a maximum data rate of about 5 Mbps is practical in the 10 MHz channel bandwidth. To support this high data requires not only increased equipment complexity (well within the current state-of-the-art) but relatively high vehicle power levels. It is estimated that a vehicle power of about 100 W would be adequate to sustain very high reliability data communications. The implication of this high data rate is that about 20,000 data bits can be transferred by each of 16,000 vehicles at each update. This corresponds to a duplex data rate in excess of 110 bps which is sufficient to provide real-time two-way teletype independently to each vehicle.

5. DIGITAL-VOICE OVERLAY

Narrowband AVM systems of the phase ranging or navigation types will attempt to employ existing land-mobile radio-telephone channels to transfer digital messages and other information between vehicle and base station. Since the number of available land-mobile channels is very limited and the demand for their use is high, it is important to determine whether the AVM waveforms can share the existing vehicle voice channel or whether a new and additional channel assignment will be required for the vehicle. This section is therefore devoted to the study of simultaneous voice and AVM digital traffic in a common 25 kHz channel allocation. Further, only the link from vehicle to base station is considered since its data rate is generally higher than the link to the vehicle and its accuracy requirement is greater.

Previous analysis[11] has demonstrated that a digital data rate of several hundred bits/second can be simultaneous carried on a frequency division multiplex sub-carrier in the FM baseband of the usual voice transceiver. The addition of this digital sub-carrier requires the reduction of the voice baseband bandwidth from 3 kHz to about 2.5 kHz and a small reduction in deviation index. Hence, a small reduction in voice quality results and acceptable digital error rate performance is achieved above FM threshold. This form of digital-voice overlay is adequate for the simultaneous digital transmission from base station to a number of vehicles independently of the voice communications.

The existing transceivers generally employ FM modulation of the voice signals. A deviation index of approximately 2 is employed and the system threshold occurs at about 12 dB Carrier to Noise Ratio (CNR) in the 20 kHz channel bandwidth. The additional data requirements vary between 50 to 150 bits per vehicle update which corresponds to a rate of from 1,333 to 4,000 bits/second in a system with 1600 vehicles updated every minute. To simplify the following comparisons, a digital requirement of 100 bits is assumed at a maximum rate of 2.7 Kbps.

The digital portion of the digital voice overlay transmission technique for the vehicle to base station link must be time shared by a large number of vehicles. Hence, the use of voice transmission by one vehicle must not seriously affect the use of data transmission by another. The only practical approach to this problem in the 25 kHz channel bandwidth is to provide separate digital and analog carriers which are separated in frequency. The problem with this approach is that at the base station receiver, the signal level difference between the analog and digital signals may be as great as 70 to 80 dB due to differences in path length, fading, and excess path losses. Hence, relatively precise filtering must be employed at both the vehicle transmitters and the base station receiver to provide adequate isolation between these signals. For example, if voice FM deviation index is reduced from 2 to 1, an FM bandwidth of 12 kHz is required. Also, if the 2.7 Kbps data stream employs 4-phase digital modulation (QPSK) with suitable pulse amplitude shaping, it can be constrained within a 5 kHz bandwidth. If a 4 kHz frequency guard band is placed between these signals, an occupied bandwidth of less than 21 kHz is achieved.

To obtain adequate isolation between the two signals over an 80 dB dynamic range, sharp cut-off channelizing filters must be employed. A 9 section Chebyshev filter with 0.1 dB ripple and 12 kHz 3 dB bandwidth can be used for the FM signal. Digital pulse amplitude shaping can be employed corresponding to a Bessel filter of 7 sections and 2.5 kHz bandwidth (low-pass). A channelizing filter can then be employed for the digital signal consisting of a 7 section Chebyshev filter with 0.1 dB ripple and 5 kHz 3 dB bandwidth. Similar filters must be employed at both transmitter and receiver with a frequency spacing of 12.5 kHz between center frequencies.

For simultaneous transmission of both digital and analog carriers through a common power amplifier, a back-off of at least 5 to 6 dB in individual carrier power from amplifier saturation is required. This back-off provides reasonably linear operation of the amplifier and negligible intermodulation distortion between carriers. Even with only one carrier present, the back-off must be retained to prevent spectrum spreading due to power amplifier non-linearity. Hence, under these conditions, the voice performance is degraded due to a lower deviations index (6 dB) and a lower carrier power (5-6 dB). As a result, the fade margin of the voice transmission is reduced 11 to 12 dB. While this fade margin could be restored by a corresponding increase in vehicle power output over the 10 W level assumed, such a solution is generally not practical.

At a 10 mile range and for a vehicle power of 10 W, excess path loss of 30 dB, vehicle antenna gain of 0 dB, base station antenna gain of 8 dB, and base station noise figure of 5 dB, a receiver SNR of about 28 dB is achieved even with 5 dB power back-off. Assuming Rayleigh fading of the digital signal, an average digital error rate of about 10^{-3} is achieved at maximum range. The probability of error per message will also be close to 10^{-3} for slow moving vehicles since those vehicles not in a fade will have no digital errors while those vehicles in a fade will have error rates near 50%. This performance should be acceptable in the AVM system.

The modification of an existing land-mobile FM transceiver to accept this additional digital capability would be quite extensive and probably not cost effective. Hence, a new transceiver design and production would be required in the AVM application with a hybrid transceiver cost of 1.5 to 2 times that of the original FM voice only transceiver.

AVM digital data can be transmitted simultaneously with voice using only existing voice land-mobile channels. From a performance viewpoint, about a 12 dB loss in the voice signal fade margin can be anticipated while digital performance should be acceptable. From a vehicle equipment cost viewpoint, there would be little difference in hybrid approach as compared to separate voice and digital transceivers.

It is anticipated that this loss in voice performance of the land-mobile channel would be unacceptable for most users. Hence, a separate land-mobile channel may be required for AVM digital transmission from vehicle to base station in the narrowband systems.

6. CONCLUSIONS

6.1 CURRENT TEST DATA

6.1.1 Accuracy

The various AVM systems have been tested in the field to determine what their accuracy is in locating vehicles in urban areas. The results of these experiments are shown in Table 6-1.

6.1.2 Digital Data Transmission

Although each of the companies which participated in the AVM system location accuracy field tests proposed additional digital data transmission systems, none of these systems were actually tested. The systems that each of the participating companies proposed are shown in Table 6-2.

6.1.3 Bandwidth

The bandwidth required for each of the AVM systems is shown in Table 6-3. These bandwidths listed have taken into consideration the requirements of vehicle location, digital data, voice, relay data links from satellite stations, and signposts. Again, it should be noted that these systems did not include additional digital transmission capability when tested. The additional data transmission and vehicle update rates proposed by each company directly reflects the AVM specifications developed by UMTA. Therefore, most of the proposed systems have similar capabilities with the exception of accuracy.

6.2 EQUIPMENT REQUIREMENTS

The AVM system equipment is conveniently broken down into three categories, base station, satellite stations, vehicles and signposts. In general, the cost and equipment required in the base stations and satellite stations for the different systems are similar. However, there are considerable differences in the required number of satellite stations used by the different AVM systems. Also, some of the AVM systems used X-band data links between the satellite stations and base stations instead of data telephone links. Even though the number of satellite stations used by a system was as high as 28, this would represent a relatively small increase in cost with respect to a complete AVM system. Therefore, the major differences, as far as cost is concerned, are the equipment in the vehicles and the number of signposts used.

Only two of the six different AVM systems analyzed have vehicle equipment that is considerably more expensive than the rest, Teledyne and Hazeltine. Teledyne vehicles use a Loran C receiver which has considerably more complexity than the rest. This receiver will probably cost approximately $1000 to $2000 in large quantities. Hazeltine uses a vehicle transmitter which operates at X-band (10 GHz) and requires microwave components. These components are basically more expensive than UHF components. In addition, the Hazeltine transmitter operates at a output power of 1 KW. This high power requires expensive power supplies and the transmitter lifetime is reduced.

RCA and CTA use a proximity AVM system which involves a large number of signposts. Although individual signpost cost is low, approximately $200, the large number deployed and their maintenance result in increased system costs. Table 6-4 shows the number of base stations, satellite stations and signposts required by each of the six AVM systems to cover an urban area 10 miles square.

6.3 COMPARISON OF WIDE- AND NARROW-BANDWIDTH AVM SYSTEMS

The essential difference between narrowband and wideband AVM systems resides in the accuracy achievable for location and in the amount of digital data which can be exchanged between the base station and the vehicles. This, in turn, represents also the capability of the system in terms of size of the fleet and updating rate. If the system is designed efficiently, there is no inherent difference in effectiveness of channel usage between the wideband

TABLE 6-1 AVM SYSTEM ACCURACY AT NINETY-FIVE PERCENTILE POINT

Company	System	High Rise Accuracy	Low Rise Accuracy	Special Case Accuracy
Teledyne	Loran C	1,390 FEET	1,044 FEET	1,311 FEET
Sierra	Phase TAVM	2,720 FEET	4,245 FEET	3,834 FEET
Cubic	Phase TAVM	4,963 FEET	3,415 FEET	7,895 FEET
RCA*	PAVM	326 FEET	-	-
Hazeltine**	Pulse TAVM	300 FEET	-	-
CTA***	PAVM	500 FEET	-	-

*RCA - Performed only accuracy tests for high rise case.

**Hazeltine - Performed only high rise test case in Manhattan, NY.

***CTA - Did not perform a careful accuracy evaluation; therefore, 500 ft. accuracy is approximate.

TABLE 6-2 ADDITIONAL DIGITAL INFORMATION DATA RATES PER VEHICLE

Company	Vehicle to Base Station	Base Station to Vehicle
Teledyne	10 bits/minute	
Sierra	10 bits/minute	
Cubic*	14 bits/minute	5 bits/minute
RCA	10 bits/minute	6 bits/minute
CTA	-	-
Hazeltine	15 bits/minute	3 bits/minute

*data rate estimated for Cubic System

TABLE 6-3 AVM SYSTEM BANDWIDTH REQUIREMENTS

Company	AVM & Data BW	Satellite to Base Station Data Link BW	Signpost BW	Voice BW	Vehicle Fleet Size	Additional BW/1000 Veh.
Teledyne	50 kHz	-	-	50 kHz	1000	50 kHz (voice)
Sierra	50 kHz	-	-	50 kHz	1000	50 kHz
Cubic	320 kHz	20 MHz	-	50 kHz	1000	320 kHz
RCA	50 kHz	-	20 MHz	50 kHz	1000	50 kHz
CTA*	50 kHz	-	12.5 kHz	50 kHz	3300	-
Hazeltine	5 MHz	10 MHz	-	-	16000	-

*CTA interrogates 3300 buses every 5 minutes

TABLE 6-4 AVM SYSTEM EQUIPMENT REQUIREMENTS

Company	Base Station	Satellite Station	Signposts
Teledyne	1	-	-
Sierra	1	28	-
Cubic	1	6 to 8	-
RCA*	1	-	13200
CTA	1	3	600
Hazeltine	1	9 to 16	

*RCA states that satellite stations might be required for an urban area of 10 miles square.

and the narrowband approach since the bandwidth is related to the specific requirements for system performance. Obviously, the usual criteria apply for the tradeoff between bandwidth and SNR and the bandwidth required must be evaluated in the context of bandwidth availability at the particular center frequency at which the AVM system is designed.

All AVM systems currently under development necessitate the allocation of bandwidth specifically for that purpose and therefore, they represent an additional loading of the available spectrum. None of them is compatible with existing voice and nonvoice communication for any significant size of the fleet monitored. It must be pointed out, however, that potentially, AVM systems have the capability of relieving some of the existing traffic presently carried by voice channels. Although it has been concluded in a recent study that only a very small percentage of the voice traffic could be replaced by digital communication (8), it is possible that even such a marginal saving could produce enough bandwidth to allow the deployment of an efficiently designed AVM system. We recommend, therefore, that this possibility be explored in depth, since it would eventually result in a better usage of the existing voice channels.

Note that for reasonably simple vehicle equipments, the wideband AVM system can accommodate about 16,000 vehicles per minute with a data transfer of about 100 bits. On a per vehicle basis, the data capability and capacity is similar to that of the narrowband system accommodating 1,600 vehicles per minute in a pair of 25 kHz land-mobile channels. Although 10 narrowband AVM systems are required to equal the capacity of one wideband system, the wideband system will still require more than 10 times as much bandwidth as the 10 narrowband systems. The major difference between these systems is thus the improved accuracy of the wideband system (probably a factor of 2 to 3) and the growth capability of the wideband system. This is, by using a more sophisticated signalling technique which permits data transfer rates in excess of the coherent bandwidth of the urban channel, real-time two-way teletype communications can be individually provided for each of the 16,000 participating vehicles. A narrowband system has relatively little growth capability for increased system capacity or data transfer.

6.4 CHANNEL UTILIZATION

A question of importance is whether AVM systems employing data link techniques can be accommodated on the same frequencies used by the licensee for two-way radio telephone systems. Technically, it is possible to accommodate AVM data transmission on the same radio channels used for voice by the licensee. In the data link from base station to vehicle, the relatively low data rate requirements of some narrowband AVM systems (up to 300 bps) can be satisfied by a digital/voice overlay in the voice baseband with only slight degradation of voice quality. In the data link from vehicle to base station, separate digital and voice carriers are required with a substantial (approximately 12 dB) reduction in voice channel performance when both carriers are frequency multiplexed in the same 25 kHz channel bandwidth. Hence, it is recommended that an additional land-mobile channel (one-way) be made available for each AVM licensee for the data link transmission from vehicle to base station.

In the data link from base station to vehicle, the use of the same land-mobile channel used for voice transmission for AVM data transmission also deserves further consideration. This digital voice overlay technique would restrict the digital rate to about 300 bps or only about 10 data bits per vehicle. Less overhead data bits, only a few simple messages could be transmitted to the vehicle. If the AVM system is to have growth potential for the transmission of alpha-numeric characters to the vehicle (8 data bits each), a substantially higher transmission rate is required than can be accommodated in an overlay system. Hence, it is anticipated that in at least some AVM systems, a requirement will exist for an additional land-mobile channel (one-way) for data-link transmission from base station to vehicle. Thus, at most, two new land-mobile channels (one duplex channel) will be required per AVM system. In a large city, as many as 10 AVM systems may be employed for a total requirement of 20 new land-mobile channels. In some AVM systems consisting of about 1,000 participating vehicles, the AVM data link and location capability may partially decrease the amount of voice traffic required. Also, there may be from 1 to 20 full duplex land-mobile channels already assigned to this group of vehicles for voice communication. It may be possible, in some cases, to re-license one of these duplex voice channels to fullfil the AVM data link requirements of the system without reduction of the average voice transmission capabilities of the system. Further detailed study in this area is required to establish the practical overall need for new AVM land-mobile channels.

The need for new land-mobile channels for AVM data link use as described above is not expected to change from one urban area to another or from a large to a small urban area. However, the need to re-license some existing land-mobile channels for AVM data link use may not exist in a small urban area.

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