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January 9, 1995

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FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF SECRETARY

Mr. William F. Caton
Acting Secretary
Federal Communications Commission
1919 M Street, NW, Room 222
Washington, DC 20554

RE: PR Docket 93-61, Automatic Vehicle Monitoring Systems

Dear Mr. Caton:

The attached is submitted on behalf of AirTouch Teletrac. Copies have been provided to David Siddall, Legal Advisor to Commissioner Ness, Bruce Franca, Office of Engineering and Technology, and Rosalind Allen and Ron Netro of the Wireless Bureau. Please associate this material with the above-referenced proceeding.

Two copies of this notice were submitted to the Secretary of the FCC in accordance with Section 1.1206(a)(1) of the Commission's Rules.

Please stamp and return the provided copy to confirm your receipt. Please contact me at 202-293-4960 should you have any questions or require additional information concerning this matter.

Sincerely,

Kathleen Q. Abernathy

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Attachment

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Efficient Spectrum Allocation for Wideband LMS Systems.

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Introduction.

A variety of views have been expressed during the AVM Rulemaking regarding the bandwidth requirements and spectral efficiencies of wideband LMS systems. During this proceeding, the FCC has considered reducing the amount of spectrum to be allocated for each wideband LMS segment from 8 MHz to 6 MHz and potentially less. Southwestern Bell Mobile Systems ("SBMS") has repeatedly encouraged the FCC to subdivide the wideband LMS segments into smaller blocks. To encourage the FCC along this path, SBMS has made claims about spectral efficiency which ignore the fact that location capacity of LMS systems varies as the square of the occupied bandwidth.[1] Additionally, there appears to be a misunderstanding regarding the amount of spectrum necessary to perform location versus that which is sufficient to operate a viable LMS business. Even SBMS, which has claimed that wideband LMS spectrum should be allocated in 2 MHz blocks, plans to use more than one block.[2]

SBMS is the only wideband LMS proponent that could operate in non-contiguous blocks of 2 MHz. A course of action by the FCC that would allow this by splitting up larger more useful frequency blocks would be contrary to the public interest. It would simply favor SBMS above all other major wideband LMS proponents who unanimously

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[1] SBMS cites the Virginia Tech report entitled "Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz ISM Band" dated October 12, 1994 to justify such claims. However, this report ignores the trade-offs involving location performance of LMS (AVM) systems. It deals almost exclusively with the messaging performance of point-to-point communications systems employing code division multiple access. Therefore, it is of little value in assessing the relationship between location performance and bandwidth as SBMS would suggest.

[2] The Ex Parte Comments of Southwestern Bell Mobile Systems, Inc. dated November 9, 1994 state at 10: "Of course, entities (including SBMS) intent on operating with more than two MHz should be able to bid for and acquire multiple two MHz blocks..."

oppose sub-dividing the spectrum.[3] The fact is that if all systems operated in blocks of 2 MHz, as SBMS proposes to do, the result would be far less efficient use of the spectrum compared to the efficiency possible in two blocks of 6 to 8 MHz.

Because of the reduced spectral efficiency associated with smaller blocks, allocating wideband LMS spectrum in segments smaller than 6 MHz would be contrary to the public interest. In order to compensate for the significantly reduced capacity associated with smaller segments, LMS providers would have to raise service fees or sacrifice service quality to recover lost capacity.[4] Unfortunately, lower service quality would only drive the demand for services down. In response, LMS operators would have to raise prices even further to recover their operating costs. Such a cycle that potentially leads to nonviable LMS systems and fallow spectrum is not in the public interest.

Spectral Efficiency of Wideband LMS Systems Increases as Bandwidth Increases.

SBMS claims that wideband LMS systems that use less spectrum are inherently more efficient simply because they use less spectrum and that sub-dividing the wideband LMS segments would be in the public interest. Both of these claims ignore the disproportionate reduction in location capacity that accompanies a reduction in bandwidth and the negative impact this would have on LMS operations.[5]

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[3] See Comments of Pinpoint Communications, Inc. on Ex Parte Presentations dated March 15, 1994 (at 20) stating, "... the more-than-linear increase in throughput ... as bandwidth increases argues convincingly in favor of a band plan accommodating ... much wider bandwidths than those Southwestern Bell proposes." See Further Comments of MobileVision, L.P. dated March 15, 1994 (at 25) stating, "... splitting the 8 MHz band into two 4 MHz bands will reduce location capacity <u>by a factor of four</u> and data capacity by a factor of two." and "fragmentation of the frequency band reduces significantly the ability of the LMS system to resolve multipath signals and ensure reliability of location functions."

[4] Service quality includes location accuracy, response time (or latency), system coverage, and location reliability (or success rate). As shown in the Appendix, there is a trade-off between these parameters and location capacity.

[5] SBMS continues to advocate these views despite the fact that the Virginia Tech report dated October 12, 1994, submitted by SBMS as an ex parte submission on October 19, 1994, states (at 6 and 7) that the arguments made by Dr. Raymond Pickholtz (in Comments of North American Teletrac and Location Technologies, Inc. dated June 29, 1993) regarding the relationship between location performance and bandwidth are "essentially correct".

The spectral efficiency of LMS systems is determined by how many locations per unit time per MHz can be performed. Simply looking at how much bandwidth a system occupies does not reveal how efficient it is. To understand this, it is useful to compare the actual location capacities of two wideband LMS systems: the SBMS system and the Teletrac system. These systems occupy 2 MHz and 4 MHz, respectively. Based on available information, the SBMS system can perform about 45,000 locations per hour.[6] In just twice the bandwidth (4 MHz), the currently operating Teletrac system can perform over 200,000 locations per hour[7]. These figures represent 22,500 locations per hour per MHz for SBMS and 50,000 locations per hour per MHz for Teletrac. In relative terms, Teletrac's system is more than twice as efficient as SBMS's system since it provides over 4 times the capacity in only double the bandwidth. Two SBMS systems operating in the same overall bandwidth occupied by Teletrac's system would only provide half the capacity of one Teletrac system. In the future, Teletrac can achieve even greater efficiencies by using the authorized bandwidth (presently 8 MHz) more fully to increase capacity, performance, and the variety of services as customer loading and market demands dictate.[8]

This comparison illustrates the fact that location capacity increases as the square of the bandwidth which is reaffirmed by the theoretical analysis contained in the Appendix. Clearly, using less spectrum for wideband LMS systems is not inherently more efficient. The opposite is true: using more spectrum allows a wideband LMS system to be more efficient.

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[6] Mr. Wayne Watts of SBMS claimed a capacity of 45,000 locations per hour at a round table meeting held by Commissioner Ness on December 7, 1994. This is consistent with technical data available which shows that the SBMS system uses location bursts of just over a quarter second (about 14,000 locations per hour) and can achieve frequency reuse of 5 times at low system loading levels. 45,000 locations per hour represents about 64% loading with a reuse factor of 5.

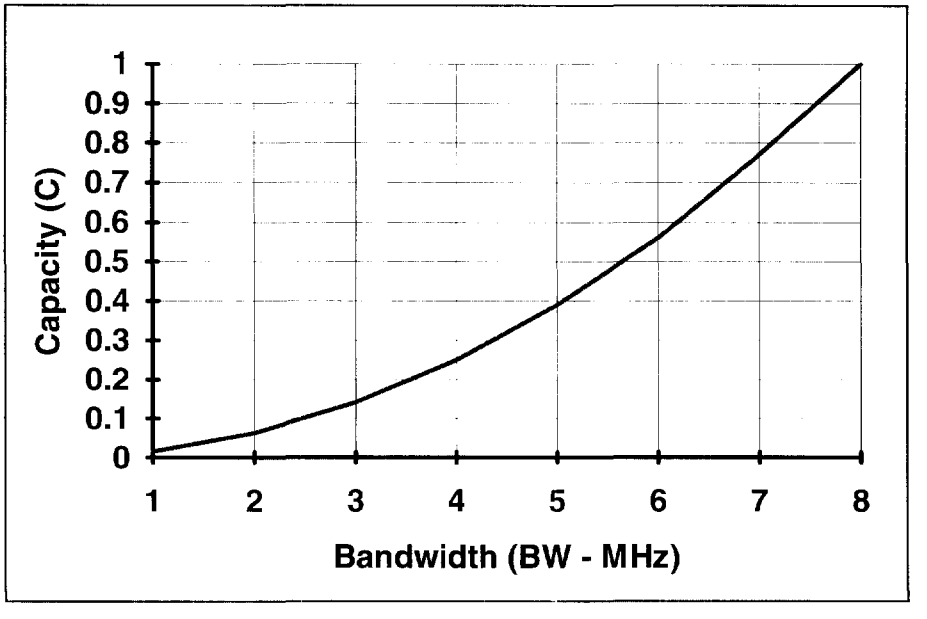
[7] Without frequency reuse.

[8] See Teletrac Comments dated June 29, 1993, Appendix 4 and Teletrac Reply Comments dated July 29, 1993 (at 30 - 31).

The Interim Wideband AVM Band Plan Provides the Greatest Spectral Efficiency.

The FCC provided 16 MHz for wideband LMS under Interim Rules and after further consideration in this rulemaking informally proposed in August of 1994 to reduce this to 12 MHz.[9] In both cases the Commission proposed two separate wideband LMS segments. More recently the Commission has considered proposals to allocate three sub-bands of 6, 6 and 2 MHz in a total of 14 MHz of spectrum. If 14 MHz is to be allocated to wideband LMS systems, two 7 MHz segments rather than the three smaller segments would be a more efficient spectrum allocation.

The figure and table below illustrate how, in a given amount of spectrum, allocating fewer segments yields much higher capacity (efficiency) for wideband LMS. Figure 1 shows the capacity of wideband LMS segments versus bandwidth. The capacity ("*C*") is scaled from that of a maximal 8 MHz segment ($C = 1$) according to the square of the bandwidth ("*BW*") by the equation: $C_{BW\ MHz} = C_{8\ MHz} \times (BW/8)^2$, where *BW* is in MHz.



[9] This represents a significant reduction in bandwidth from the two segments of 10 MHz each recommended in the "Petition of Hazeltine Corp. for the Establishment of a New Radio Service", RM-1734, filed December 24, 1970. This view was supported by other commenters during the Rulemaking leading to the Interim Rules. See "Summary of the Rulemaking Proceedings Leading to Adoption of the 1974 Interim AVM Rules, 47 C.F.R. Sect. 90.239" filed as Appendix 5 to Teletrac Comments dated June 29, 1993.

Figure 1. Capacity vs. Bandwidth for Wideband LMS.

Note the rapid decline in capacity with only moderate reduction in bandwidth. At 6 MHz the capacity is almost reduced by half. To illustrate the effect of this phenomenon on potential band plans, Table I shows several potential wideband LMS band plans in order of decreasing overall capacity. Note that for a given overall bandwidth, band plans made up of two segments are more efficient (have higher capacity) than those that accommodate more segments. In fact 2-segment plans have higher capacity than 3 and 4-segment band plans that occupy more spectrum. For each band plan, the overall capacity is computed by: 1) dividing the total bandwidth into the appropriate segments, 2) selecting the value of *C* from Figure 1 for each segment; and 3) summing the individual capacities of all segments in each band plan.

Table I. Relative Capacity of Various Potential Band Plans.

Band Plan	Segment 1		Segment 2		Segment 3		Segment 4		Overall		Lost
Description	BW	C	BW	C	BW	C	BW	C	BW	C	Capacity
Interim Rules (2x8)	8.0	1.00	8.0	1.00	-	-	-	-	**16**	**2.00**	**0%**
2x7 Plan	7.0	0.77	7.0	0.77	-	-	-	-	**14**	**1.54**	**22%**
2x6 + 2 Plan	6.0	0.56	6.0	0.56	2.0	0.06	-	-	**14**	**1.18**	**41%**
8/94 Informal 2x6 Plan	6.0	0.56	6.0	0.56	-	-	-	-	**12**	**1.12**	**44%**
SBMS 4x4 Proposal	4.0	0.25	4.0	0.25	4.0	0.25	4.0	0.25	**16**	**1.00**	**50%**
12/94 METS Proposal[10]	5.5	0.47	5.5	0.47	2.0	0.06	-	-	**13**	**1.00**	**50%**
SBMS 6x2 Proposal*	2.0	0.06	>	>	>	>	>	>	**12**	**0.36**	**82%**

* Segments 2 through 6 are identical to Segment 1.

The last column shows the percentage of capacity lost from that provided by the Interim Rules caused by sub-dividing or reducing the spectrum. Note that this lost capacity cannot be recovered once the segments are allocated. These examples show the dramatic penalty in overall capacity paid by sub-dividing the limited available spectrum beyond two segments. The only way to avoid this penalty and accommodate more providers is to allocate additional spectrum for wideband LMS systems.[11] Clearly,

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[10] See MobileVision Ex Parte filed on December 22, 1994 suggesting a band plan consisting of two 5.5 MHz segments plus a 2 MHz segment.

[11] Time-sharing has been advocated by Pinpoint as a means of accommodating more providers. However, sharing of wideband LMS segments would also cause losses in capacity and because of the coordination overhead associated with time-sharing its loss would be comparable to that of frequency sub-division. Time-sharing would have the added penalty of unreasonable complexity and oversight. Comments opposing time-sharing have been

approaches that seek to simultaneously reduce the overall spectrum and create more than two segments would severely reduce efficiency and should be avoided.

Sub-Dividing the Wideband LMS Segments is not in the Public Interest.

There seems to be confusion between the spectrum necessary to perform location and that which is sufficient to operate an LMS business and offer viable services. Although an LMS system may be able to perform locations in as little as 2 MHz, the customer base and the variety of location services needed to sustain a viable LMS business cannot be accommodated without more spectrum. Based on extensive technical and economic analysis, Teletrac believes between 6 and 8 MHz is necessary to sustain an LMS business at the levels of service quality and pricing the market demands.[12]

Although, allocations as small as 6 MHz may provide adequate capacity to meet projected market demands, wideband LMS providers would incur added risk compared to 8 MHz allocations. By reducing the segments from 8 to 6 MHz, service providers will be forced to provide the quality of service and meet the price points expected by the public in less spectrum. Having sufficient capacity to operate profitably becomes less likely when the authorized bandwidth is reduced.

Since the driving cost factors for operating an LMS business are coverage area and service quality, the fixed costs of operating an LMS business are independent of the number of providers or the size of the customer pool.[13] Given the disproportionate reduction in capacity that comes with reduced bandwidth, there would be added risk that infrastructure and operating expenses could not be recouped at price points the public

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repeatedly filed by all other major wideband LMS proponents: by Teletrac on June 29, 1993, July 29, 1993, March 15, 1994 and March 30, 1994; by SBMS on June 29, 1993, March 15, 1994 and March 29, 1994; and by MobileVision on June 29, 1993, March 15, 1994 and March 29, 1994.

[12] See Teletrac Comments filed on June 29, 1993: Appendix 1, "Engineering Analysis of Cochannel Pulse-Ranging LMS Systems, by Professor Raymond Pickholtz (at 34); Appendix 3, "The Economics of Co-Channel Separation for Wideband Pulse Ranging Location Monitoring Systems", by Professor Richard Schmalensee and Dr. William E. Taylor (at 32 - 34); and Appendix 4, "Declaration of Paul Jansen", McKinsey & Company, Inc.

[13] See Teletrac Comments dated June 29, 1993, Appendix 3 (at 12 - 13).

would be willing to pay. The reduction in bandwidth would also inhibit the introduction of more capable or more accurate services since the added risk would translate into less investment in deployment in LMS systems and development of new services.

By allocating the limited spectrum to more providers, the overall cost for infrastructure would be increased (because of duplication of facilities) but the total number of customers that could be served by all providers combined would be less and the variety of services would be reduced. As a group, LMS providers would have to recoup more expenses from a smaller customer base with less capable services. This would only drive the cost of service up and the quality down. Neither of these conditions offers a viable long term business environment nor are they in the public interest.

To provide the greatest public benefit, wideband LMS spectrum should be allocated in the largest blocks possible. Given the limited amount of spectrum and the severe reduction in capacity that accompanies sub-dividing or time-sharing the spectrum, two separate wideband LMS segments is the proper allocation to allow competing services with sufficient spectrum for the quality and variety of services customers demand at the lowest cost possible.

Conclusion.

In balancing the competing needs for spectrum, the evidence shows that the spectrum allocated to wideband LMS must be partitioned as minimally as possible to maximize service capacity, quality and selection A band plan that provides two wideband LMS segments of the maximum size possible is the most efficient use of the spectrum. Therefore, Teletrac continues to favor two 8 MHz allocations for wideband LMS systems as proposed in the NPRM.

Theoretical analysis and real world comparisons show that sub-dividing the available wideband LMS spectrum into smaller segments is not in the public interest. Even though more providers could be accommodated, the overall location capacity of the spectrum would be reduced. The infrastructure costs would be greater for more systems but fewer customers could be accommodated. To overcome this effect, the cost of

services would have to be allocated by each provider to a smaller customer base and the outcome would be higher costs, lower quality, and less variety of services.[14]

Teletrac believes these negative impacts are significant and would present major obstacles to the continued development of wideband LMS businesses. Reducing, subdividing, or time-sharing the available wideband LMS spectrum is inefficient and against the public interest.[15]

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[14] See Teletrac Comments dated June 29, 1993, Appendix 3 (at 32 - 34).

[15] See Teletrac Comments filed on June 29, 1993 (at 23 - 46).

Appendix: Performance, Capacity and Bandwidth of LMS Systems.

by Emmanuel Wildauer
AirTouch Teletrac

Abstract: *This paper analyzes the relationships between the bandwidth and location performance of wideband LMS systems. The analysis shows that simply using less bandwidth is not inherently spectrally efficiency. It also shows that for a properly designed system, capacity increases as the square of the bandwidth thereby allowing wideband LMS systems to be more efficient when using more spectrum. The performance of an LMS system is shown to depend on the complete system design and not just the receiver performance. Finally, Teletrac system parameters are presented to illustrate those of a real world wideband LMS system.*

1. Introduction.

Claims have been made ([1],[2],[3]) that the location capacity of wideband LMS systems does not increase as the square of the bandwidth. In fact, some have tried to claim that capacity does not increase at all with an increase in bandwidth ([1],[2]). This claim is erroneously based on the assertion that operating margin and interference limit the location capacity regardless of the bandwidth used.

This paper underlines the specifics of wideband LMS location and establishes the relationships between bandwidth, receiver performance, receive site density, location performance and location capacity. It shows that location performance can be assessed only at a system level based on three basic aspects of the system design: 1) the parameters of the ranging receiver employed (sensitivity, bandwidth, location burst duration, processing gain, signal-to-noise performance, etc.); 2) the receive site density; and 3) the receive site geometry. Each of these affect the ability to achieve a desired probability of location with a certain accuracy over a given coverage area.

Location accuracy as a function of the system parameters (most notably, receive site density and resulting signal margin) is presented. Then for a given accuracy and system design, the paper shows the relationship between capacity and bandwidth. An example using the parameters of the Teletrac system is presented to demonstrate that the location capacity can be increased fourfold (with the same location accuracy) by doubling the bandwidth utilized.

2. Location Performance (Accuracy and Capacity).

Most, if not all, wideband LMS systems employ the hyperbolic method of location. This method uses the relative differences in signal time-of-arrival (TOA) from several receivers (or transmitters) to determine the location of a mobile transmitter (or receiver). The location accuracy of the hyperbolic location function is related to the TOA estimation accuracy through the following formula ([4]):

$$\sigma_{Loc} = c * GDOP \overline{\sigma_t} \quad , \tag{2.1}$$

where c is the speed of light, σ_{Loc} is the rms location error, *GDOP* is geometric dilution of precision, and $\overline{\sigma_t}$ is the average rms error of the TOA estimations used to compute the location.

The mathematical expression for the *GDOP* of a hyperbolic location system is too complex to present here but the reader is referred to [4], (eq. A.18 and A.19), for an explanation. Conceptually, *GDOP* indicates how much the error of a computed location is magnified by the geometry of the receive sites with respect to the object being located. The more evenly distributed the receive sites are around the object being located, the less the error is magnified by their geometry (i.e., the lower the *GDOP*). $\overline{\sigma_t}$ is given by:

$$\overline{\sigma_t} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\sigma_{t_i}^2} \quad . \tag{2.2}$$

Here, N is the number of TOA estimations used in computing the location (i.e., the number of sites that actually received the location burst). The variance of the TOA estimation error ("the variance") at each receiver, $\sigma_{t_i}^2$, is a function of bandwidth, chip rate, burst duration and signal to noise. This variance is given by the Cramer-Rao bound as (see [4], eq. A.24):[1]

$$\sigma_t^2 \geq \frac{T_c}{\alpha^2 B^2 (S/N) T} \quad , \tag{2.3}$$

[1] There is also error due to multipath which will decrease as the bandwidth is increased. For simplicity, this work omits the "treatment" of multipath for the sake of simplicity since it would show even greater benefit on location performance with increased bandwidth.

where α is a constant which depends on modulation and filtering of the received signal (e.g., $\alpha = 2$ for BPSK), B is the bandwidth, (S/N) is the signal to noise ratio at the receiver given $N = BN_o$, T is the location burst duration and T_c is the chip duration. Note that the Cramer-Rao bound only applies, of course, when the received signal is above the receiver threshold (i.e., $(S/N) > (S/N)_{th}$). For simplicity of notation, the variance for a signal of bandwidth kB can be denoted by σ_{kB}^2. Then, the impact on TOA estimation error of doubling the bandwidth can be seen by comparing σ_B^2 and σ_{2B}^2. By definition, $\sigma_B^2 = \sigma_t^2$, where σ_t^2 is given by (2.3). For a signal having a bandwidth of $2B$ (i.e. by doubling the chip rate), the expression for the variance becomes:

$$\sigma_{2B}^2 \geq \frac{T_c / 2}{\alpha^2 (2B)^2 (S/2N) T} \quad . \tag{2.4}$$

Note that the noise observed by the receiver doubles because of the doubling of the bandwidth. As long as $(S/2N)$ is still above $(S/N)_{th}$, equation (2.4) yields:

$$\sigma_{2B}^2 = \frac{1}{4} \sigma_B^2 \quad . \tag{2.5}$$

Notice that by doubling the bandwidth (and chip rate), the variance has been reduced by a factor of 4. In other words, TOA estimation is 4 times as accurate for a system having double the bandwidth and the same location burst duration, T. To take advantage of this improvement, an actual system would have to be designed with at least 3 dB excess link margin to compensate for the doubling of the noise without having to increase signal strength at the receiver.

With the bandwidth doubled, the accuracy improves by a factor of 4 for the same location burst duration, T. By reducing T by a factor of 4, the system capacity could be increased by a factor of 4 while returning the TOA estimation to the same accuracy.

<u>To summarize</u>: *If the Signal to Noise ratio (S/N) is kept above the threshold of the receiver, doubling the bandwidth increases the location capacity four times with the same TOA accuracy. Therefore, doubling the bandwidth can double the efficiency of the system in terms of capacity per MHz occupied.*

3. Parameters of an LMS System Design.

In general, signal margin is a function of the system design, propagation characteristics of the RF channel and interference. A system can be designed such that *S/N* is maintained above the operating threshold of the receiver with some probability given these parameters. As the parameters change, adequate signal margin can be maintained through a variety of measures including increasing the power transmitted, the density of the receive sites, the gain and height of receive site antennas, etc.

The relationship between the probability of determining a location with a certain accuracy[2] and the required receive site density, *GDOP* and signal margin leads to the following expression:

$$\rho_{sites} = g[\, P(location|error \leq \sigma_{Loc}),\, M_S, GDOP] \quad , \qquad (3.1)$$

where ρ_{sites} is the required density of receive sites, $P(location|error \leq \sigma_{Loc})$ is the probability of location with a certain accuracy and M_S is the designed signal margin. M_S can also be expressed as:

$$M_S = g^{-1}[\, P(location|error = \sigma_{Loc}),\, \rho_{sites}, GDOP] \quad . \qquad (3.2)$$

Without a loss of generality, a site geometry using redundant sites to give acceptable coverage is assumed to yield constant *GDOP* within the primary coverage area. In that case, a particular density, ρ^*_{sites}, can be selected such that:

$$M_S^* = g^{-1}[\, P(location|error \leq \sigma_{Loc}),\, \rho^*_{sites}] \quad . \qquad (3.3)$$

M_S^* and ρ^*_{sites} are the designed parameters of the LMS system that achieve an rms location error, σ_{Loc}, with probability *P(location)* given the known parameters of the ranging receiver. From this the signal to noise required at the receiver input, $(S/N)^*$, can be expressed (in decibels) as:

$$(S/N)^* = (S/N)_{th} - D + M_S^* \quad , \qquad (3.4)$$

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[2] Probability of location is actually a probability that the mobile signal will be picked up by at least four sites with sufficient strength to achieve required TOA rms error.

where $(S/N)_{th}$ is the receiver threshold and D is receiver desensitization caused by interference. Since $(S/N)^*$ depends on both ρ^*_{sites} and interference, the performance of the system is controlled by both the receiver performance and the system deployment. The effects of interference can be compensated by increasing the site density to gain additional margin.

To summarize: *The designed signal margin, M_S^*, of an LMS system can be achieved by building a system with adequate receive site density, ρ^*_{sites}, given a ranging receiver with known parameters. Proper site density together with proper site geometry (to minimize GDOP) allows a system to achieve a desired location accuracy, limited by σ_{Loc} with probability of location, P(location).*

4. Teletrac - Example of an LMS System Design.

The parameters of the Teletrac LMS system are as follows:

- The receive site density is approximately 1.3 sites per 100 sq. miles.
- The average receiver signal margin with this site density is approximately 10 dB.
- The bandwidth of the present system is approximately 4 MHz.
- Average receiver desensitization (from all interference sources) is about 5 dB.[3]
- The present design accomplishes a location accuracy within the coverage area of 150 feet with probabilities of 0.99 for mobiles transmitting 5 to 10 Watts ERP and 0.95 for mobiles transmitting 1 to 2 Watts ERP.
- The capacity of the system is over 200,000 locations per hour.
- The designed signal margin and available bandwidth authorization of 8 MHz allow the location capacity to be quadrupled without degrading location performance by doubling the location signal bandwidth.

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[3] Average desensitization has decreased since 1991 by nearly 2 dB as a result of migrating isolated sources of harmful interference to other frequencies. See [5] for a summary of the cases of harmful interference experienced.

5. Summary.

- Proper design of an LMS system provides sufficient signal margin at the receiver for reliable and accurate operation.
- With sufficient margin it is possible to double the bandwidth of an LMS system and achieve a fourfold increase in capacity (locations/hour) while maintaining the same location accuracy, thus doubling its location efficiency (locations/hour/MHz).
- The performance of an LMS system depends not only on the performance of a single TOA receiver but on the overall system design as well.
- Receive site density and geometry are essential design parameters that govern the location performance of an LMS system.
- Receive site density establishes the system operating margin and provides a mechanism for compensating degradation in *(S/N)* caused by such factors as increased bandwidth and interference.

References:

[1] Padgett, Jay. E., "Analysis of Teletrac Receiver Performance and Part 15 Interference", October 22, 1993.

[2] Padgett, Jay. E., "Wide Area Pulse-Ranging AVM/LMS: Messaging/Locating System Design Tradeoffs and Part 15 Interference", August 8, 1994.

[3] Southwestern Bell, "AVM/LMS NPRM. Comments on Proposed Rule Making", October 3, 1994

[4] Wildauer, Emmanuel, "Impact of Wideband Co-channel Interference on the Accuracy of Hyperbolic Location", June 22, 1993, Appendix A to Appendix 2 of Teletrac Comments.

[5] AirTouch Teletrac, "Experience with Part 15 Interference", June 21, 1994.