Satellite Sound Broadcasting Around 1 GHz

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Abstract — This paper presents the technical factors affecting the design of a geostationary satellite sound broadcasting system operating around 1 GHz to serve low-cost consumer-quality portable and automobile receivers. The technical characteristics for such a system are under study in a number of countries in preparation for the 1985/1988 ITU Space Services Planning Conference. The first session will make appropriate recommendations to the second session on the future regulatory provisions for the service.

A medium-quality monophonic or stereophonic service would be provided using frequency modulation. Signals would be received using a simple circularly polarized omnidirectional antenna. Link margins to serve indoor portable receivers and automobile receivers in rural and urban areas are discussed.

Building penetration loss for single family dwellings is expected to be about 11.8 dB in 90 percent of the houses not using foil-backed insulation or shadowed by trees, increasing to over 17 dB with foil-backed insulation. Shadowing by trees increases the loss by 12–15 dB. Apartment and commercial building penetration loss is expected to approach 20 dB.

Automobile reception in rural areas will be primarily affected by foliage attenuation due to trees. At a 30° elevation angle, an attenuation of about 15 dB with probability of 0.90 is expected. In situations where the line-of-sight path is unobstructed, multipath fading of 2.8 dB at 0.90 probability is the predominant source of degradation. Automobile reception in urban areas requires operating margins of 24–30 dB because of shadowing and multipath by large buildings.

Based on the foregoing considerations, an e.i.r.p. from 66 to 79 dBW is required from a geostationary satellite to serve low-cost portable and automobile receivers in rural and urban environments.

INTRODUCTION

CONTINUED development of high-power satellite technology and launch-vehicle technology has fostered renewed interest in the development of satellite systems to directly deliver sound programs to the general public through low-cost portable and vehicular receivers. Studies and limited experiments were conducted in Europe in preparation for the 1979 World Administrative Radio Conference (WARC'79) for the purpose of providing the technical basis for a frequency allocation for the service [1],[2]. Although WARC'79 did not adopt such an allocation, it did, primarily at the urging of the developing countries, adopt Resolution 505 calling for administrations to conduct studies and perform experiments so that an allocation could be made at a future competent WARC [3]. The next such competent conference is the two-session Space Services Planning Conference, the first session of which is to be convened in 1985 and the second session in 1988.

The sound broadcasting system envisioned in Resolution 505 would consist of a geostationary satellite providing national or regional sound broadcasting service to low-cost consumer-quality portable and vehicular receivers. Transmission parameters would be similar, if not identical, to those used in the terrestrial FM broadcasting service. Receivers would be capable of receiving from medium-quality to high-quality stereo programs in urban, suburban, and rural areas. Receiving antennas would be simple and require neither tracking nor any special pointing.

The remainder of this paper addresses the questions of suitable frequency bands, system performance objectives and characteristics, and propagation effects related to satellite sound broadcasting to portable and vehicular receivers.

SUITABLE FREQUENCY BANDS

Suitable frequency bands for this service lie generally in the range from 500 to about 2000 MHz. This frequency range is referred to in Resolution 505 and is the subject of international study [4]. The lower limit is set by considerations of man-made noise and by the present limits on deployable spacecraft antennas. The upper limit is determined by currently available medium- to high-power spacecraft transmitters (or reasonable extrapolations thereof) and by available spacecraft primary power. These parameters increase with the square of the operating frequency as a consequence of the fixed gain antenna used on the receiver.

The total amount of bandwidth required for this service is estimated at 45 MHz. This would provide for five 250 kHz channels with 150 kHz interleaving for each of the approximately 60 administrations of Europe and Africa [4].

SYSTEM CHARACTERISTICS

Example link calculations are given in Table I for an operating frequency of 1 GHz. These calculations are predicated on serving portable receivers located within homes and vehicular receivers in urban and rural areas. As will be discussed subsequently, the shadow and multipath loss margin is based on ensuring that the receivers will be above a 10 dB threshold with probability 0.90 over 90 percent of the particular type of service area. A relatively simple receiving antenna with a hemispherical pattern has been assumed.

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A geostationary satellite antenna beamwidth of 1.6° has been used because it is representative of the beamwidth required to provide national coverage to small countries and to accommodate regional differences in large countries (see, for example, [5]). The resulting E.I.R.P. and transmitter power are substantial, ranging from about 66 dBW and 420 W up to 78.7 dBW and 7.1 kW, respectively.

Table II summarizes the transmission parameters and the signal quality for the receiver operating at threshold. The transmission parameters are those associated with conventional monophonic FM broadcasting in the VHF/FM band. For monophonic reception, the output test tone-to-weighted noise ratio is about 41 dB. For stereophonic reception, the test tone-to-weighted noise ratio is some 8–12 dB less [6].

### Building Penetration Loss

For receivers with built-in antennas operated within houses or other types of buildings, allowance must be made for absorption and scattering of the signal due to walls, ceilings, and roofs. Measurements of the mean signal within single family dwellings using ATS-6 have shown that the penetration loss is a function of frequency, receive antenna polarization, type of construction of the house (wood siding or brick veneer), the extent of thermal insulation (ceiling and walls), and the proximity of the room to an outside wall [7]. The penetration loss was virtually independent of elevation angle. The measurements indicated that the distribution of the penetration loss for each type of house is approximated by the normal distribution when expressed in decibels. Table III summarizes the factors contributing to the mean penetration loss. The standard deviation for any house of a particular type was found to be 3 dB. This included the random measurement error (on the order of 1.5 dB or less) and the variability associated with the house [7].

The link calculations presented in Table I for the average house assume that it has a brick veneer, that it is fully insulated, and that the receiver is located in an inside room. For an operating frequency around 1 GHz, the
TABLE II

FM TRANSMISSION PARAMETERS AND SIGNAL QUALITY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier-to-noise ratio (dB)</td>
<td>10</td>
</tr>
<tr>
<td>Peak deviation (kHz)</td>
<td>75</td>
</tr>
<tr>
<td>Noise bandwidth (kHz)</td>
<td>250</td>
</tr>
<tr>
<td>Maximum baseband frequency (kHz)</td>
<td>15</td>
</tr>
<tr>
<td>Test tone frequency (kHz)</td>
<td>1</td>
</tr>
<tr>
<td>Test tone-to-noise ratio (dB)</td>
<td>38.0</td>
</tr>
<tr>
<td>De-emphasis time constant (μs)</td>
<td>75</td>
</tr>
<tr>
<td>Test tone reduction due to de-emphasis (dB)</td>
<td>0.9</td>
</tr>
<tr>
<td>Noise weighting factor (I) (dB)</td>
<td>4.5</td>
</tr>
<tr>
<td>Output test tone-to-weighted noise ratio (dB)</td>
<td>41.6</td>
</tr>
</tbody>
</table>


TABLE III

BUILDING ATTENUATION PARAMETERS (FROM [7])

<table>
<thead>
<tr>
<th>Average</th>
<th>6.10 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td></td>
</tr>
<tr>
<td>2869 MHz</td>
<td>1.16</td>
</tr>
<tr>
<td>1550 MHz</td>
<td>0.19</td>
</tr>
<tr>
<td>860 MHz V</td>
<td>-1.25</td>
</tr>
<tr>
<td>860 MHz H</td>
<td>0.14</td>
</tr>
<tr>
<td>Construction</td>
<td></td>
</tr>
<tr>
<td>Wood siding</td>
<td>-0.50</td>
</tr>
<tr>
<td>Brick veneer</td>
<td>0.58</td>
</tr>
<tr>
<td>Insulation</td>
<td></td>
</tr>
<tr>
<td>Blow-in ceiling</td>
<td>-0.80</td>
</tr>
<tr>
<td>Ceiling and walls</td>
<td>0.80</td>
</tr>
<tr>
<td>Room position</td>
<td></td>
</tr>
<tr>
<td>Exposed walls</td>
<td>-0.30</td>
</tr>
<tr>
<td>No exposed walls</td>
<td>0.30</td>
</tr>
</tbody>
</table>

mean building penetration loss is 8.0 dB. To account for the variability in 90 percent of the houses of this type, an additional 3.8 dB has been added. The resulting margin of 11.8 dB applies to houses of the particular construction assumed and which are not shadowed by other buildings and trees. For houses in which “sheetrock” (gypsum wallboard) backed with aluminum foil is used for the interior walls and ceiling, the average penetration loss will be increased to over 17 dB. Similarly, for houses surrounded by large trees, there is an additional loss of about 12–15 dB [7].

Building penetration loss data for satellite systems serving multistory apartment houses and office buildings will be estimated on the basis of terrestrial data. Measurements taken at 940 MHz indicate that for typical steel, concrete, and stone buildings, the building penetration loss is again approximated by a normal distribution when the loss is expressed in decibels. On the ground floor of such buildings, the mean and standard deviation of the distribution are 10 and 7.3 dB, respectively [8]. For 90 percent of the buildings of this type, the building penetration loss is 19.3 dB or less.

RURAL AREAS

Vehicular reception in rural areas is primarily affected by multipath and shadowing losses. Both of these mechanisms result in fluctuations of the received carrier power at a rate proportional to the velocity of the vehicle. Which mechanism dominates depends on the type of environment. In areas characterized by flat terrain with low-standing vegetation, multipath predominates. Shadowing predominates in forested areas and in areas in which trees line the roadway.

Multipath is intrinsic to satellite communication systems employing low-gain user antennas which cannot effectively discriminate between the line-of-sight signal and signals reflected from the surface of the earth. The reflected signal consists of a coherent component and a Rayleigh distributed component. The relative magnitude of each component depends on the roughness of the reflecting surface. The Rayleigh roughness criterion provides a useful measure of the characteristics of the reflected signal

\[ g = \frac{4\pi\sigma_h}{\lambda} \sin \xi \]  

(1)
where \( \sigma_t \) is the standard deviation of the surface height about the local mean value within the first Fresnel zone (meters), \( \lambda \) is the wavelength at the operating frequency (meters), and \( \xi \) is the grazing angle measured with respect to the tangent to the surface (essentially the the elevation angle in flat terrain) \[9, [10]. A surface may be considered smooth for \( g < 0.3 \). For an operating frequency of 1 GHz and an elevation or grazing angle of 30°, the standard deviation of the surface height must be less than 1.4 cm in order for it to be classified as smooth.

The relative amplitude of the specular component \( \rho_s \) may be approximated by \[10\]

\[
\rho_s = R e^{-\sigma_t^2/2}
\]

where \( R \) is the effective reflection coefficient for a circularly polarized wave, \( R_v \) is the reflection coefficient for a vertically polarized wave, and \( R_h \) is the reflection coefficient for a horizontally polarized wave. For very rough surfaces, \( (2) \) tends to underestimate the magnitude of the specular component. More accurate models are, however, available \[11\].

Evaluation of (1)–(3) for a surface with a standard deviation of 10 cm, an operating frequency of 1 GHz, an elevation angle of 30°, and an average earth as the reflecting surface (conductivity = \( 3.5 \times 10^{-2} \) S/m and a relative permittivity of 15 \[12\]) yields 0.6 for \( R \) and about 0.066 for \( \rho_s \). Thus, for what might be considered a relatively smooth surface and with no antenna discrimination, the envelope of the received signal will fluctuate by about \( \pm 0.6 \) dB relative to the line-of-sight signal due to the specularly reflected component. Variations of this order have been observed on bridges over water during a recent series of propagation measurements \[13\]. Clearly, for the general case of vehicular receivers in rural areas, specular multipath is not a significant problem.

The diffuse component of the reflected signal arises from scattering over an area larger than that encompassed by the first Fresnel zone. There is no simple expression in the literature to estimate the magnitude of the diffuse component \[10\]. It is zero for smooth surfaces and maximum for very rough surfaces. Experimental measurements indicate that the diffuse signal component is statistically random with an envelope exhibiting a Rayleigh distribution and a uniformly distributed phase. Over bare ground or the sea, the rms value of the diffuse component has been found to be between 5 and 11 dB less than the rms value of the line-of-sight component \[10\].

The distribution of the rms envelope of the sum of a line-of-sight component and the Rayleigh-distributed multipath component is given by the Rice–Nakagami density function \[14, [17]\]

\[
p(r) = \frac{2r}{\sigma_r^2} I_0 \left( \frac{2r\sqrt{P}}{\sigma_r^2} \right) e^{-\left( r^2 + P \right)/\sigma_r^2}\]

where \( r \) is the rms amplitude of the instantaneous received carrier, \( P \) is the power in the line-of-sight component, \( \sigma_r^2 \) is the total power in the diffuse multipath component, and \( I_0 \) is the modified Bessel function of the first kind of zero order.

The link margin necessary to ensure that the receiver operates above threshold with a specified probability is obtained from

\[
P(r > R_0) \approx \int_{R_0}^{\infty} \frac{2r}{\sigma_r^2} I_0 \left( \frac{2r\sqrt{P}}{\sigma_r^2} \right) e^{-\left( r^2 + P \right)/\sigma_r^2} \, dr.
\]  (5)

Equation (5) has been solved numerically with the results shown in Figs. 1 and 2. Plotted in Fig. 1 is a family of exceedance probability curves for the rms value of the

![Fig. 1. Distribution function for the Rice–Nakagami distribution (from [14]).](image)

![Fig. 2. Median value of the Rice–Nakagami distribution relative to the value of the constant component (from K. A. Norton et al., "The probability distribution of the amplitude of a constant vector plus a Rayleigh-distributed vector," Proc. IRE, pp. 1354–1361, Oct. 1955).](image)
envelope of the received carrier relative to the median of the rms envelope as a function of the ratio of the power of the diffuse component to the power of the line-of-sight component. Fig. 2 shows the median value of the envelope normalized to the rms value of the envelope of the line-of-sight component as a function of the ratio of the power in the diffuse component to the power in the line-of-sight component. An estimate of the required margin is obtained in the following way. Assume that the threshold must be exceeded with 0.90 probability and that the power in the line-of-sight component is 10 dB above the power in the diffuse component. From Fig. 1, the rms envelope of the received signal will exceed a level of -2.8 dB relative to the median level with probability 0.90. From Fig. 2, the median value of the envelope is 0.2 dB above the value for the envelope of the line-of-sight component. Consequently, a margin of 2.6 dB is required. Similarly, a 5.8 dB margin will ensure that the received signal will be above threshold with probability 0.99.

Apart from extreme situations such as the vehicle in a tunnel or the line-of-sight component being completely blocked by the terrain (e.g., a cliff), shadowing of the line-of-sight signal by trees is the most severe source of vehicular receiver performance degradation in rural areas. The extent of the shadowing loss may be expected to be a function of frequency, of the kinds of trees, their height, their proximity to the roadway, the presence or absence of leaves, and the azimuth (relative to the azimuth of the roadway) and elevation angle to the satellite. The relationship between the shadowing loss and the constituent parameters has yet to be developed. However, the results of recent measurements around 1 GHz provide an indication of the severity of the shadowing loss due to trees [13], [15]. Measurements reported in [15] were taken in a rural area near Ottawa, Ont., Canada, while the deciduous trees were still in leaf. The area over which measurements were made was about 35 percent wooded while the rest was cleared land. A satellite link was simulated by placing an 870 MHz transmitter in a helicopter, and a receiver and data acquisition equipment were placed in a van and driven over approximately 50 km of roads. The helicopter maintained its altitude, direction, and speed relative to the van so as to simulate a satellite link at an elevation angle of 15°. In the wooded area with the road extending close to the road, the distribution of the received power, when expressed in decibels, was found to be approximated by the normal distribution function

\[ p(P_x) = \frac{1}{\sqrt{2\pi} \sigma_x} e^{-(P_x - m_x)^2/2\sigma_x^2} \]  

where \( P_x \) is the random received power (in decibels, relative to the mean received signal power), \( m_x \) is the mean of the distribution (decibels), and \( \sigma_x \) is the standard deviation of the distribution.

The threshold margin \( M \) for a normal distribution at a specified probability \( P \) may be determined from

\[ M = m_x + k(P)\sigma_x, \quad \text{dB} \]  

where \( k(P) \) is a function of the specified probability. Values of \( k(P) \) for exceedance probabilities of typical interest are given in Table IV.

For the conditions cited previously, the mean and standard deviation of the shadowing loss were about 9.8 and 7.8 dB, respectively. (These values were derived from [15, Fig. 4].)

Measurements reported in [13] are also based on a simulated satellite link. In this case, an 869 MHz transmitter was placed on a stratospheric balloon that rose to an altitude of about 40 km. Measurements were made by a "chase" van driven along various routes to maintain a relatively constant elevation angle. One route was through a pine forest where the elevation angle was about 19°. Neither the distribution of the received signal nor its parameters have yet been determined. However, it is noteworthy that peak-to-peak variations of about 25 dB were measured [13].

Excess path loss measurements to vehicular receivers using the ATS-6 satellite link operating at 860 and 1550 MHz have also been made [16]. Measurements were made in urban, suburban, and rural areas. In particular, measurements were made in the Estes Park, CO, area at a frequency of 1550 MHz. This area exhibited generally unfavorable conditions of deep canyons lined with evergreens. For an elevation angle of 32° an excess path loss of about 15 dB was observed for 90 percent of the time over 90 percent of the area [16].

From the above data, 15 dB is taken as a preliminary estimate of the shadow loss in rural areas with probability 0.90 at an operating frequency of 1 GHz and an elevation angle of 30°. The results of ongoing studies will, of course, be extremely useful in refining this estimate as well as establishing the appropriate shadow loss distribution function and the parameters of the distribution.

### Table IV

<table>
<thead>
<tr>
<th>( P(X/X) )</th>
<th>( k(P) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>0.90</td>
<td>1.28</td>
</tr>
<tr>
<td>0.95</td>
<td>1.65</td>
</tr>
<tr>
<td>0.99</td>
<td>2.33</td>
</tr>
<tr>
<td>0.995</td>
<td>2.56</td>
</tr>
<tr>
<td>0.999</td>
<td>3.09</td>
</tr>
</tbody>
</table>

An assessment of the propagation margin for vehicular receivers operating in an urban environment is based on the results of measurements reported by Hess [16]. The data were acquired along various routes by a specially instrumented van. The signal power received with a quarter-wave whip from 860 and 1550 MHz emissions from the ATS-6 satellite was recorded for subsequent analysis.
Both small-scale and large-scale variations of the received signal were noted. Small-scale variations are those which are observed over distances on the order of several hundred wavelengths. Over these distances the distribution of the envelope fluctuations may be approximated by a probability distribution function whose parameters (mean and standard deviation) are relatively constant. As the measurements were extended over greater distances, but within the same type of environment (e.g., a downtown urban environment), it was found that the parameters of the small-scale distribution changed. The large-scale variations are those associated with the variation in the parameters of the small-scale distribution function.

Hess chose to combine these large-scale and small-scale variations into a single model. The model chosen was the normal distribution for the excess path loss in decibels at a specified small-scale coverage of 90 percent. From the measured data, the mean and standard deviations of the distribution were determined as functions of frequency, elevation angle, direction of travel relative to the satellite azimuth, and the side of the street relative to the direction to the satellite.

For 90 percent small-scale coverage, the mean \( m \) and standard deviation \( \sigma \) are given by

\[
m = 14 - 3.4 \cos(2 \Delta \theta_{az}) + 1.93 f + 0.35 - 0.052 \xi, \quad \text{dB}
\]

\[
\sigma = 6.4 - \cos(2 \Delta \theta_{az}) + 0.054 f + 0.24 + 0.04 \xi, \quad \text{dB}
\]

where \( \Delta \theta_{az} \) is the angular difference between the vehicle's direction of travel and the satellite azimuth, \( f \) is the operating frequency (gigahertz), \( \xi \) is the elevation angle (degrees), and the factors \( \pm 0.35 \) and \( \pm 0.24 \) account for the side of the street the vehicle is on. The minus sign is used if the vehicle is on the side away from the satellite, and the plus sign is used if it is towards the satellite. The excess path loss for a specified large-scale coverage at the 90 percent small-scale coverage level is given by

\[
L = m + k(P) \sigma, \quad \text{dB}
\]

where \( P \) is the large-scale coverage required, and \( k(P) \) is the corresponding factor given in Table IV.

Equations (8) and (9) have been evaluated for an average case and for a worst case for an operating frequency of 1 GHz, an elevation angle of 30°, and for 90 percent large-scale and small-scale coverage. The average case assumes that the relative azimuth and side of the street factor in (8) and (9) average to zero. The worst case assumes that these factors add to the margin. The average excess path loss is 24.1 dB, and the worst case excess path loss is 29.5 dB under the conditions cited above. The average value has been used in the link calculations given in Table I.

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**SUMMARY AND CONCLUSION**

Satellite sound broadcasting to portable and vehicular receivers operating around 1 GHz requires a significant link margin to provide a modest service quality. A system using transmission parameters identical to those used for FM broadcasting in the VHF band will provide a test tone-to-weighted noise ratio of about 42 dB for monophonic reception and between 30 and 34 dB for stereophonic reception. These values pertain to the receiver performance just above threshold.

Link margins have been presented for the cases of a portable receiver operating inside of a house and for vehicular receivers operating in rural and urban environments. These link margins have been derived from limited measured data and are based on a service objective to cover 90 percent of a particular environment with the assurance that the receiver is operating above threshold with 0.90 probability. To serve an average house which is not shadowed by other buildings and trees requires a margin just under 12 dB. With shadowing by trees or the use of metal foil-backed insulation or construction material, the margin will increase to about 25 dB.

The operating margin for vehicular reception in rural areas is dominated by tree attenuation of the line-of-sight signal. It was estimated that a 15 dB margin was required to meet the service objective. Specular and diffuse multipath were shown to be minimal sources of degradation in comparison to tree attenuation.

In urban areas a link margin of about 24 dB was required, on average, increasing to about 30 dB in the worst case.

The margins presented for vehicular reception in rural and urban areas do not take into account the fading characteristics of the signal. For the stated margins there will be areas over which the received signal will drop below threshold at rates proportional to the product of the operating frequency and vehicle velocity. This results in the so-called "picket-fence" effect, which is common to fringe area reception of VHF/FM broadcasting and mobile communications signals. For broadcasting, it may be very annoying. To quantify the degree of annoyance, it would be very desirable to fully characterize the propagation statistics for rural, suburban, and urban areas and, based on these statistics, to conduct subjective listening tests to accurately determine the threshold margin required for a given grade of service.

**REFERENCES**


John E. Miller (M’79), for a photograph and biography, see this issue, p. 202.