# REPEATER REQUIREMENTS FOR PAN-EUROPEAN SATELLITE DIGITAL BROADCAST SERVICES

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## ABSTRACT

Satellite systems represent a cost-effective means of providing broadcast services over very large areas, but shadowing from buildings reduces availability in built-up areas. In order to provide a high quality-of-service, therefore, a hybrid network, which includes terrestrial repeaters, is attractive. The number of repeaters required depends on a large number of parameters and must therefore be analysed carefully. This paper describes a technique for achieving this by collecting building statistics over a small area and extending their use to the whole of the required coverage area. The approach is exemplified by determining the required number of repeaters for three satellite configurations: single GEO, dual GEO and HEO. In each case the network is required to provide high service availability over the whole of Europe to mobile receivers. It is shown, based on specified assumptions and data, including the use of time diversity, that a HEO satellite broadcast system will require close to zero terrestrial repeaters to provide ubiquitous coverage over a large part of Europe, while a GEO satellite broadcast system is likely to require up to about 4200 terrestrial repeaters for the same target coverage area.

## INTRODUCTION

Three potential satellite systems are under investigation here:

- 1 GEO: A single Satellite Geostationary Earth Orbit (GEO) at 25° E, providing an elevation angle in London of about 27°
- 2 GEO: The 1 GEO satellite plus a second GEO at 15° W.
- HEO: A constellation of Highly Elliptical Orbit (HEO) satellites for which elevation angle in London varies between 76° and 88°.

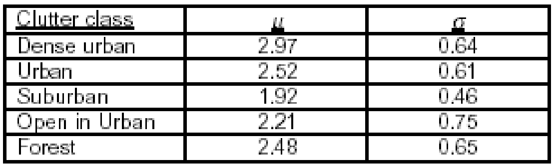
It is desired to provide a required service availability of 99% of both time and location. The satellite availabilities will first be calculated in isolation to determine whether they meet this performance, and if not, the required number of repeaters will be determined in each case to cover the majority of European countries.

## SATELLITE AVAILABILITY

The systems under analysis here provide insufficient link margin to permit operation when the line-of-sight path is blocked by buildings. Availability can therefore be found by determining the statistics of building heights and street widths, and then by using appropriate geometrical analysis to determine the overall blocking probability for the relevant elevation angles. The methodology adopted here is derived from that described in (1) and (2). For the current study, building height data and clutter data were obtained for a sample area within London, together with clutter statistics for the whole of London. For the purposes of this study, London is defined as the area within the North and South Circular roads (383 km$^2$). The building height data is in the form of a 2 m raster, with heights relative to ground and accurate to ±1 m, and processed to remove trees and other non-building features. The clutter dataset is a 50 m resolution raster (i.e. 50 m pixels) with 10 clutter classes, covering the same area as the building raster data. Of these 10 classes, 5 represent the built environment:

- dense urban (DU)
- urban (U)
- suburban (SU)
- industrial
- village

An "L"-shaped sample area of 10 km$^2$ was chosen for analysis. This area is judged to be representative of the clutter classes of interest, and extends from the city of London, with a high proportion of dense urban clutter, westwards and northwards to areas with a high proportion of suburban clutter. Building height statistics were determined for buildings within each of the five categories given above. The parameters determined for each clutter class, assuming a lognormal distribution of the building height $h$, are given in Table 1, where $\mu$ and $\sigma$ are the mean and standard deviation of $\ln(h)$ respectively.



| Clutter class | $\mu$ | $\sigma$ |
|---|---|---|
| Dense urban | 2.97 | 0.64 |
| Urban | 2.52 | 0.61 |
| Suburban | 1.92 | 0.46 |
| Open in Urban | 2.21 | 0.75 |
| Forest | 2.48 | 0.65 |

**Table 1: Building height statistics for London**

Two different approaches to determining the street width (spacing between building faces) were used; in one a constant street width of 25m was assumed, and in the other street width parameters were extracted from the building data and fitted to a lognormal distribution.

Blocking probabilities were then evaluated as described in (2) for each clutter class. Blocking probabilities are obtained for the city as a whole by taking a weighted average of the probabilities for each clutter class, with weights determined by the proportion of London occupied by each clutter category. Mobile users are assumed to be in street-centred vehicles with 1.5m antenna height. Azimuth angles are assumed uniformly distributed over 0° to 360°.The resulting satellite availabilities, $A_s$, are shown in Table 2 for each of the satellite constellations for the three most built-up clutter classes (DU, U & S). It is clear that none of the three systems achieves the required availability of 99%, although HEO succeeds everywhere except in dense urban clutter. A sensitivity analysis was performed to determine the impact of vehicles off street centres and the overall effect was found to be small.

| | | As | |
|---|---|---|---|
| Sat. config. | street width: | 25m | variable |
| 1 GEO | Dense urban | 30.4% | 30.4% |
| | Urban | 48.0% | 46.8% |
| | Suburban | 80.7% | 79.1% |
| 2 GEO | Dense urban | 55.8% | - |
| | Urban | 77.6% | - |
| | Suburban | 98.6% | - |
| HEO | Dense urban | 98.8% | 96.6% |
| | Urban | 99.8% | 99.4% |
| | Suburban | 100.0% | 100.0% |

**Table 2. Satellite availabilities in London**

## EFFECT OF RECEIVER BUFFER

It is common practice in modern digital receivers to provide a data buffer to minimize the impact of signal outages. The performance of such buffers depends on the spatial statistics of the blocking encountered and on the speed of the mobile receivers. In order to analyse this effect, we have used data for building outlines and street centrelines coincident with the areas used to obtain building height statistics for Table 1.

Randomly selected areas were selected from each of the three clutter classes were used in the repeater range analysis above. These are assumed to be globally representative of the relevant clutter class. Obstruction of the satellite to vehicle path is simulated by moving the vehicle in 1 m steps along each street centreline.

Blockage has been calculated at each vehicle location by first identifying all building edges intersected by the vertical plane through the satellite-to-receiver path. The path is assumed blocked if the vertical angle to any of these building edges is greater than the satellite elevation angle.

The length along the street of each blockage, $L_b$, is then determined as the vehicle moves down the street. The overall blockage probability, $P_b$, is also obtained by dividing the total length of all blockages by the total street length. To simulate the effect of uniform azimuth, azimuth angles from 0º to 330º in 30º steps have been used.

Blockages were put into bins from 1 to 300 m blockage length, with 1 m bin width, creating a histogram of occurrences versus bin width, for each clutter class and elevation angle. Figure 1 shows an example histogram.

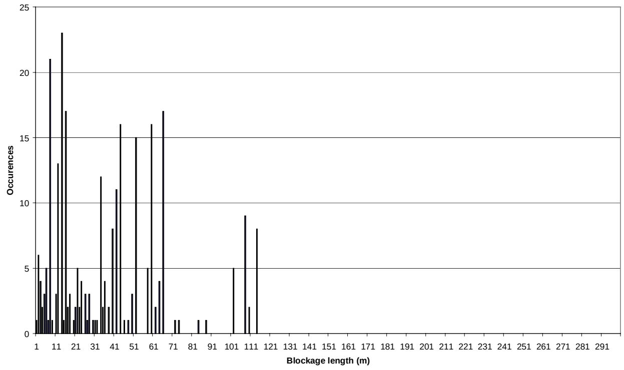


**Figure 1:Histogram of blockage lengths in London for Dense Urban clutter and 27° elevation angle**

A buffer duration of 4 s has been assumed, with vehicle speed dependent on clutter class as given in Table 3. Each combination of vehicle speed and buffer duration corresponds to a critical blockage length, $L_c$, also shown in Table 3. It is assumed that service is lost if the blockage length $L_b$ is greater than $L_c$. The length (in m) of outage is ($L_b$ - $L_c$).

| Clutter class | Speed (mph) | Buffer duration (s) | Critical blockage length (m) $L_c$ |
|---|---|---|---|
| Dense Urban | 10 | 4 | 17.9 |
| Urban | 10 | 4 | 17.9 |
| Suburban | 30 | 4 | 53.6 |

**Table 3: Vehicle speed and receiver buffer used for each clutter class and corresponding critical blockage length.**

Satellite unavailability is obtained by numerically integrating the histogram multiplied by ($L_b - L_c$) to give the total outage length, and then dividing by the total street length. $P_o$ is the proportion of blockage length which causes outage. $A_s$ is the satellite availability, which is given by:

$$A_s = 1 - (P_b \times P_o) \qquad (1)$$

$A_s$ is significantly larger in all cases with the buffer (compare Table 2 with Table 4), to the extent that the HEO system does not require any repeaters to avoid building blockage effects.

| Sat. config. | Clutter class | *As* | *At* |
|---|---|---|---|
| 1 GEO | DU | 59.7% | 97.5% |
| | U | 59.9% | 97.5% |
| | S | 87.5% | 92.0% |
| 2 GEO | DU | 87.3% | 92.1% |
| | U | 87.8% | 91.8% |
| | S | 99.7% | 0 |
| HEO | DU | 99.8% | 0 |
| | U | 99.8% | 0 |
| | S | 100.0% | 0 |

**Table 4: Cell edge terrestrial availabilities and repeater ranges in London with receiver buffer**

## JOINT AVAILABILITY OF SATELLITES AND REPEATERS

The system is available if and only if either satellite or terrestrial reception exists. The combined availability depends on the correlation between terrestrial and satellite availability. Some positive correlation is expected (for example terrestrial and satellite availability will both be reduced in narrow streets with tall buildings), although the two have quite different propagation path types. To our knowledge there is no published work on the correlation between satellite and terrestrial reception, and detailed evaluation of the correlation coefficient $\rho$ is beyond the scope of this work. $\rho$ is thought to be between 0 and 1 but much closer to 0 than 1. We have assumed $\rho = 0$, so that the combined availability is given by:

$$A = 1 - ((1 - A_s) \times (1 - A_t)) \qquad (2)$$

Table 4 shows the values of $A_t$ required to give $A = 99\%$. These values are used to derive the repeater range below.

## PREDICTION OF REPEATER RANGE

ITU provide a Recommendation, ITU-R 1546 (3), which gives a detailed methodology for point-to-area prediction of field strength for broadcasting and mobile services, in the frequency range 30 to 3000 MHz, and distance range 1 to 1000 km. This recommendation is designed to apply to rolling landscapes with height variations of around 50 m. It is used extensively by broadcasters and others where terrain data is not required, such as for dimensioning networks, and is well-suited to this work. For area-specific planning, alternative methods would be used together with terrain and clutter data.

The recommendation provides curves of (and formulas for) field strength vs. distance for various nominal frequencies and effective transmitter heights, together with corrections to enable predictions for other frequencies etc. The “effective height” of the transmitting antenna is the height above the terrain averaged over 3 to 15 km distance in the receiver direction. For short paths (less than 15 km) the effective height should be considered as the height above the local clutter.

ITU-R 1546 is only valid for 1% to 50% time, to enable prediction of interfering and wanted field strengths. However over the relatively short paths considered here, 99% time field strengths are likely to be very similar to those at 50% time, hence 50% time curves have been used. The predictions below assume land paths only, although curves for sea and mixed paths are provided in the recommendation.

The curves apply for a receiver antenna height which is equal to the representative clutter height, but a correction is given for other receiver heights. This correction depends on the receiver height and the typical clutter height. Values for the latter have been derived from analysis of the London high-resolution building data, and are given in Table 5.

| Clutter class | Clutter height (m) |
|---|---|
| Dense urban | 22.3 |
| Urban | 13.6 |
| Suburban | 7.1 |

**Table 5: Median clutter heights for each clutter class**

Similarly the curves assume 50% locations, although the recommendation provides a correction for predictions for other required location percentages. The correction is dependent on the standard deviation of location variation, which is given in the recommendation. Note that values are given for urban and suburban clutter classes only. We have assumed that the value for dense urban is the same as for urban.Link budget parameters used in the calculations are given in Table 6.

| | |
|---|---|
| Carrier frequency | 1.5 GHz |
| Repeater EiRP | 36 dBW |
| Minimum receiver signal strength in motion at typical speeds | –96.5 dBm |
| Receiver antenna gain | 0 dBd |
| Receiver antenna height: | 1.5 m above ground |
| Repeater antenna height: | 50 m (Dense Urban & Urban clutter)<br>150 m in Suburban clutter |

**Table 6: Link budget parameters**

The repeater ranges predicted are quite small in some cases, particularly for the GEO configurations with a low effective transmitter height, where a large number of repeaters would be required to cover London. Higher repeaters would help but the service provider would be reliant on existing broadcast structures. For the HEO configuration on the other hand, only dense urban needs to be covered.

Table 7 shows terrestrial repeater ranges which give a combined availability of 99% at cell edge, for each clutter class and satellite configuration. An effective repeater height of 50m in DU/U clutter and 150m in SU clutter has been assumed, based on practical experience of typical broadcasting mast heights. No buffer has been assumed for terrestrial reception. A correlation coefficient of 0 has been used for terrestrial and satellite blockage. Note that no repeaters are required for the HEO configuration. Repeater ranges are generally large enough to cover all but the largest European cities.

| Sat. config. | Clutter class | Repeater range (km) | |
|---|---|---|---|
| | | H = 50 m | H = 150 m |
| 1 GEO | DU | 7.6 | |
| | U | 9.2 | |
| | S | | 21.1 |
| 2 GEO | DU | 9.4 | |
| | U | 11.2 | |
| | S | | n/a |
| HEO | DU | n/a | |
| | U | n/a | |
| | S | | n/a |

**Table 7. Calculated Repeater ranges to produce 99% combined availability**

The number of repeaters required for London is then calculated using these repeater ranges. Table 8 shows the number of repeaters, $N$, required to completely cover each clutter class, since, subject to the assumption of a uniform hexagonal repeater coverage area:

$$N = \frac{2A}{3\sqrt{3}R^2} \qquad (3)$$

where $A$ is the area to be covered, and $R$ is repeater range. Areas for Dense Urban and Urban in London are derived from the analysis of the clutter data, whilst the total area for London is derived from a population database.

| | Area ($km^2$) | 1 GEO | 2 GEO | HEO |
|---|---|---|---|---|
| DU | 27 | 0.18 | 0.12 | 0 |
| U | 141 | 0.65 | 0.43 | 0 |
| S | 1240 | 1.07 | 0 | 0 |
| Total | 1408 | 1.90 | 0.55 | 0 |
| Estimated | | 3 | 1 | 0 |
| Effective radius (km) | | 13.46 | 23.40 | n/a |

**Table 8:** Required number of repeaters in London and the effective repeater radius used to calculate the repeater requirement for other cities.

Although this analysis suggests that e.g. a total of 1.9 repeaters are required for London for a single GEO, in practice we estimate 3 would be necessary taking account of the actual clutter distribution. Similarly one repeater would clearly be needed for a dual GEO system. It is assumed that no repeaters would be required to cover rural areas for any of the satellite configurations.

## EXTENSION TO OTHER CITIES

Estimated repeater numbers have been used to derive an effective repeater radius which takes account of the clutter distribution. This is equivalent to determining a number of repeaters per $km^2$ required for a city with a similar clutter distribution to London.

Data on the area of 4193 cities in 22 European countries has been used to calculate the number of repeaters required for each city and each satellite configuration. The total number of repeaters needed for to cover all 22 countries is shown in Figure 2, versus the minimum population for a city at which it is deemed viable to install a repeater. Note that 1 GEO requires only very slightly more repeaters than 2 GEO.

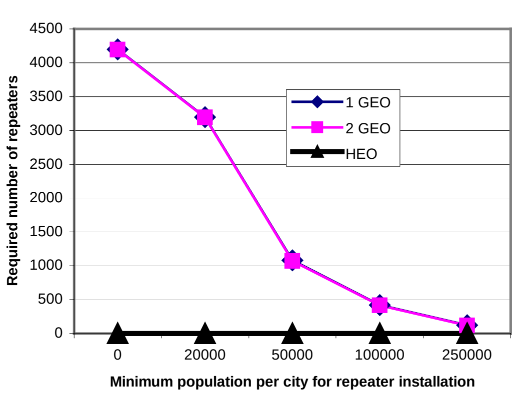


**Figure 2: Required number of repeaters for pan-european coverage versus city population threshold.**

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3 Recommendation ITU-R P.1546: “Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000 MHz” ITU 2001.