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## ANNEX TO VOLUME IV – PART 1

## FIXED-SATELLITE SERVICE

CCIR INTERNATIONAL RADIO CONSULTATIVE COMMITTEE

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SECTION 4D: FREQUENCY SHARING BETWEEN NETWORKS OF THE FIXED-SATELLITE SERVICE - EFFICIENT USE OF THE SPECTRUM AND THE GEOSTATIONARY-SATELITE ORBIT

4D1: PERMISSIBLE LEVELS OF INTERFERENCE

REPORT 455-5

ARCHIVES U.I.T. GENÈVE

# FREQUENCY SHARING BETWEEN NETWORKS OF THE FIXED-SATELLITE SERVICE

(Study Programme 28C/4)

(1970-1974-1978-1982-1986-1990)

## 1. Introduction

The extent to which the same frequencies may be used by different satellite networks of the fixed-satellite service, without causing unacceptable interference, is a subject of considerable importance; bearing as it does on the efficient use of the frequency spectrum and the geostationary-satellite orbit.

Frequency sharing may be affected by:

- the number of satellites sharing a given frequency band channel;
- the orbits in which the satellites move;
- the radiation pattern of the earth-station and space-station antennas;
- any difference in polarization between wanted and interfering signals;
- the relative operating power flux-densities of the wanted and interfering signals, both at the satellites and at the earth stations;
- the interference reduction factor between the input to the space-station, and/or earth-station receiver, and the demodulated output at the earth station;
- the portion of the total noise allowance allocated to interference from other satellite networks.

The problems of frequency sharing between satellite networks are reviewed in this Report.

## 2. Calculation of interference levels

The extent to which satellite networks may share the same frequency band is predicated on the magnitude of the tolerable interfering-to-wanted carrier levels.

### 2.1 *Ratio of wanted-to-interfering carrier levels*

The ratio of down-link wanted-to-interfering carrier powers at an earth station can be expressed as follows:

$$(C/I)_D = R + G_4 - G_4(\varphi) + Y_D \qquad (1)$$

where:

- $(C/I)_D$: the wanted-to-interfering carrier power ratio at the input to the receiving system (dB);
- $R$: the ratio of the power flux-density of the wanted signal to the power flux-density of the interfering signal (dB);
- $G_4$: the receiving gain of the earth-station antenna for the wanted satellite (dB);
- $G_4(\varphi)$: the receiving gain of the earth-station antenna for the interfering satellite (dB);
- $Y_D$: the polarization discrimination of the earth-station antenna against the interfering carrier (dB).

A similar expression can be used to determine the up-link wanted-to-interfering carrier ratio. A method for calculating these ratios for interference between geostationary-satellite networks is given in detail in Annex I.

### 2.2 *Post-demodulation signal-to-interference noise ratio*

In FDM-FM telephone links, the ratio of a 1 mW test tone to the interference power in the worst telephone channel can be expressed as follows:

$$10 \log \frac{\text{1 mW test tone}}{\text{Unweighted interference power in a telephone channel of 3.1 kHz bandwidth}} = \left(\frac{C}{I}\right) + B \qquad (2)$$

where:

$B$ : the interference reduction factor (dB) between the input to the space-station and/or earth-station receiver and the demodulated output at the earth station ($B$ is sometimes called the "receiver transfer factor");

$\left(\frac{C}{I}\right)$ : the wanted-to-interfering carrier power ratio at the input to the receiving system (dB).

The value of the interference-reduction factor, $B$, depends on the type of modulation used on the various carriers. An expression similar to (2) can be used for analogue signals in general if the factor $B$ can be meaningfully applied. Reference should be made to Report 388 for further information.

The case of digital transmission presents a number of difficulties, one of the most important being that the characteristics and performance of digital modulation systems, which may be used for future fixed-satellite networks, are not yet firmly established. Another difficulty is that the nature of digital detection makes it impossible to define the interference performance and the thermal noise performance independently (in contrast to analogue signals above threshold). Reference should be made to Report 388 which sets out the techniques for calculating interference noise in systems carrying multichannel telephony, for the different modulation methods likely to be encountered on wanted and interfering transmissions.

For interference into frequency-modulated television systems reference should be made to Report 449.

### 2.3 *Intermittent exposure to interference*

Generally, in the case of two satellites near to one another (whether they form part of a single system or belong to independent systems), the extent of any resulting interference depends upon whether they both receive signals from their corresponding earth stations at the time of proximity. If they do so, then the form of treatment given in previous sections of this Report will apply. If not, i.e., if one satellite is intentionally energized from the ground and the other only unintentionally, then the effect of any interference will be less marked. This may occur, for example, in an unphased satellite system when the separation between adjacent satellites is temporarily small, or in the case where an interfering satellite is in the vicinity of a geostationary satellite. In these cases, off-beam antenna gain reductions will apply both to the illumination of the interfering satellite and to the reception of its interfering emission. If the output spectral power density of the space-station repeater is a function of the flux illuminating the satellite, the power spectral density produced by the interfering satellite at the earth station would be below its normal operating value. Quite small angular separations between satellites might be tolerable in such situations.

## 3. Permissible levels of interference between networks using geostationary satellites

Interference between networks which use geostationary satellites does not vary greatly with time, and it is feasible to coordinate system characteristics so that the degradation of channel performance due to this interference does not exceed an acceptable level.

### 3.1 *The significance of the level of interference*

Considerable attention continues to be given to the question of what constitutes an acceptable level of interference. It is generally held that the operator of a system should be in essential control of his system's performance and that, therefore, interference should not be a major factor affecting that performance.

However, the gain of earth and space station antennas usually decreases monotonically with increasing angle off the direction of maximum gain. These antenna characteristics may be the only source of isolation between the networks, in which case there is an inverse relationship between the interference level and the separation angles. Thus, the greater the permissible interference between two networks serving more or less the same area on the earth surface, the smaller can be the orbital separation between the space stations of the two networks. Similarly, the greater the permissible interference between two networks whose space stations are in the same, or nearly the same, orbit location and serve different areas on the earth surface through narrow-beam antennas; the closer can those service areas be to each other, and the greater can be the number of times that the frequency band is reused in different parts of the world.

Thus, the greater the permissible level of interference, the higher will be the potential frequency re-use density between networks both on the geostationary-satellite orbit (smaller inter-satellite spacing) and on the earth surface (denser coverage). There is therefore, a conflict between the desire to bound, at relatively low levels, the interference between networks, to maintain reasonable design and operating integrity in a network, and the no less significant need to maximize frequency re-use and, thereby, orbit-spectrum utilization.

Following this theme, during the Plenary period 1986-1990 a number of theoretical and practical studies have been carried out into ways of improving the efficiency of the geostationary orbit, i.e. of increasing the capacity in crowded parts of the orbital arc and spectrum. Some of these studies have shown that there is considerable scope for achieving this end by amending the aggregate and single-entry interference allowances in order to permit more satellites to co-exist in given parts of the arc and operating in the same frequency bands [CCIR, 1986-90]. Further studies are encouraged on this topic, especially those which are based on actual populations of satellites in congested parts of the geostationary orbit, with a view to amending the recommended interference limits during the 1990-1994 Plenary period.

### 3.2 *Permissible levels of interference in FDM-FM telephony transmissions*

It is generally agreed that the maximum level of interference noise from all other satellite networks which may be regarded as permissible lies between 10% and 25% of the total noise recommended for the hypothetical reference circuit (HRC) (Recommendation 353) a further 10% being permitted for interference from terrestrial systems.

If the lower inter-network figure is taken, then the total interference entry from all sources does not exceed 20%; these levels allow the system operator good control over the performance of his system.

If the higher inter-network figure is taken, and if it is assumed that interference from all sources is additive, then it would seem that 35% of the total noise budget is allocated to sources of noise outside the direct control of the system operator. The practical situation may not be quite as severe as this. Thus, at some earth stations there may be far less than the full 10% of interference noise from terrestrial sources, and the maximum entry of interference from other networks may not fall in the same channel as the maximum entry of interference from terrestrial sources. Nevertheless, while such a high interference entry may increase the number of satellites that can be accommodated in the orbit, it has the following disadvantages:

- the loss by the system operator of control of the performance of his system is substantial;
- interference takes various forms and may lead to degradations of types not simply constrainable by a bound on channel noise power; for example impulsive interference might develop;
- the capacity of a satellite is reduced;
- the feasibility of a large measure of frequency re-use within a satellite network, which is in itself a very powerful method of increasing the efficiency of use of the orbit and spectrum, is reduced by the presence of so much external noise.

This is a general area needing further study.

A single entry of interference entering an FDM-FM wanted network will affect some of the carriers of the wanted system more severely than others. The effect of the interference on the various channels of the wanted system is also non-uniform, channels high in the baseband being affected more severely than the others. Thus, the maximum value of interference from the single entry will be experienced by relatively few of the channels in the wanted network. An entry from another network will probably have its most severe effect upon different channels. Thus, the total interference received in any one channel will be less than the sum of the maximum single entry values.

3.3 *Permissible levels of interference in FM-TV transmissions*

For video transmissions the performance specifications in the HRC are given in Recommendations 354 and 567 for the appropriate TV standards. Recommendation 483 recommends that the inter-network interference noise should not exceed 10% of the total noise in the HRC. An increase in this percentage should be studied further.

First, TV-FM transmissions are relatively insensitive high-power transmissions since they have to meet threshold conditions for a relatively large bandwidth. On the whole, a TV-FM transmission is not much more sensitive to interference than a 972-channel FDM-FM telephony carrier and is thus not likely to constitute the limiting case during coordination in which more sensitive carriers need to be protected. This would continue to hold true if an interference criterion were applied which is based on carrier sensitivity as discussed in § 3.2. Thus, there may be no need to increase the interference allowance for video in order to facilitate coordination.

Second, interference effects in an FM-TV transmission are highly dependent upon the character of the interference and it would be desirable for further study to be given to the relationship between baseband noise due to interference, the nature of the interfering signal, and the subjective picture quality which, as in the FDM-FM telephony case, is the ultimate, although not quantifiable, criterion. An increase of the allowable interference noise to 25% of the total baseband noise may well produce objectionable picture quality for some types of interference. The matter is aggravated by the fact that, unlike the FDM-FM telephony case, no trade-off between internal noise and that due to external interference, is possible; a "good" picture tends to be subjectively more sensitive to certain types of interference than a poorer picture.

Thus, a move towards increasing the permissible interference for FM-TV, may on the one hand, not be necessary, and on the other, not be readily possible.

In Annex III, an impairment method to evaluate degradation due to interference is described. Based on a study carried out using NTSC television signals, in the general case it may not be desirable nor appropriate to simply add the different predetection signals on a power basis to attempt to evaluate the degradation of the television signal. However in the case of network quality NTSC signal (Recommendation 567), a close agreement has been shown between the two very different methods: the "objective" method of Report 449 and the "subjective" method of Report 405 and Recommendations 500 and 600 of CCIR Volumes XI-1 and X/XI-2 in carrying out the calculations of Recommendation 483.

Further, in Annex III, results of experiments which related the C/I and S/N resulting in "just perceptible interference" for a variety of carrier types are presented.

3.4 *Permissible levels of interference in digital transmissions*

In the case of digital transmissions, Recommendation 522 gives the performance criterion in terms of the parameter most significant to the user; the bit error ratio. The long-term performance criterion stipulates that the bit error ratio should not exceed the provisional value of one part in $10^6$, 10-minute mean for more than 20% of any month.

To derive an interference criterion which, as before, should reflect a moderate impact of interference on total performance, one could remain in the bit error ratio domain. However, unlike the analogue FDM-FM telephony case, there is no simple linear relationship between contributions to the bit error ratio due to internal noise and that due to interference. As a consequence, one is obliged to relate the interference criterion to the actual performance criterion as a reference. Thus, one could choose as the interference criterion, that interference which would raise the bit error ratio from $10^{-6}/k$ to $10^{-6}$ where $k$ is some positive number which would constitute the allowable *increase* in bit error ratio due to interference. The matter is discussed further in Report 793.

However, since it is necessary to refer to the performance criterion, it has been found to be advantageous to express the interference criterion in terms of a predemodulation parameter which is usually readily available. Having the choice between the wanted-to-unwanted carrier ratio ($C/I$) and the external-to-internal noise ratio ($I/N$), the latter is preferred, because it is largely independent of specific equipment characteristics. The resulting interference criterion is reflected in Recommendation 558. An allowance is also to be made for interference from terrestrial systems where a band is shared with such services.

This criterion has the further advantage that the contributions from various entries may be added in the power domain. In the digital case, as in the analogue FDM-FM telephony case, a trade-off between internal and external noise is possible within reason, and a large digital interference allowance may be considered to facilitate coordination. The effect of interference into digital systems is a function of the amplitude and phase distribution of the interfering carrier. Carrier offset of an interfering signal thus has little effect, as long as the main part of the interference spectrum falls within the wanted channel.

For phase modulated systems using differential encoding and coherent detection, the permissible level of interference can be calculated from the formula:

$$\frac{C}{I} \geqslant 10.8 - \frac{I}{N_{total}} - 20 \log \left[ \sin \left( \frac{180^\circ}{m} \right) \right] + \Delta \qquad \text{dB} \tag{3}$$

where:

$C/I$: ratio of wanted signal power to interference power;

$I/N_{total}$: ratio of the interference power under consideration to the total noise power including all interference power;

$I/N_{total}$: −7 dB (20%), −8.2 dB (15%) or −14 dB (4%) depending on the circumstances of the interference as defined in Recommendation 523; 10.8 dB is the theoretical value ($C/N_{total}$) dB required for BER = $10^{-6}$ for a two-phase system;

$m$: number of phase positions in the PM signal;

$\Delta$: the estimated implementation loss. This will vary according to the demodulator characteristics and the number of phase positions, $m$.

Typical values for $\Delta$ are:

$2.5 + 0.5 \log_2 m$ dB for FDMA systems,

$3.0 + 0.7 \log_2 m$ dB for TDMA systems.

The interference power would be measured in the occupied bandwidth, which will approximate to the Nyquist bandwidth, $B = \frac{R}{\log_2 m}$, where $R$ is the transmission rate in bit/s.

Further research is needed into the conditions under which Recommendation 523 is applicable, with regard to the frequency bandwidth at which the interference level is measured, the modulation characteristics and the performance of the modems.

The method described above for calculating the permissible interference level is based on the assumption that interference has the character of thermal noise. Report 388 contains data which may be used to assess the validity of this assumption for PSK interference.

## 3.5 Results of permissible level of carrier-to-interference ratio

The permissible level of interference has been calculated for various types of carrier combination taken from Table I of Annex III to Report 454. The criteria used for various signal types are summarized in Table I.

The interference calculation has been based on the assumption that the carrier center frequency of the interferred-with carrier coincides with that of the interfering carrier. The spectra of FDM/FM carriers have been assumed to be Gaussian for the purpose of these calculations. Furthermore, due account is taken of the difference in the bandwidths of interferred-with and interfering carriers. When the bandwidth of interferred-with carrier is larger than that of interfering carrier, multiple interference entries with different offsets are considered.

Table II provides the required C/I matrix in which the element (i,j) implies the required C/I to protect the carrier i against the carrier j, in order that it meets a given single entry criterion. For networks published before 1987 the corresponding values would be 1.8 dB higher since the single entry criterion for them was more stringent.

It is to be noted that for the interference to companded FDM/FM carriers the acceptable C/I would be reduced by the amount corresponding to a companding gain.

### 3.6 *Relationship between total allowable interference and individual entries*

The recommended maximum total interference value provides guidance to system designers, who are expected to design their systems to accommodate this level of interference without failing to achieve the required standards of system performance. Thus, the problem is to choose a value for the maximum single entry such that the minimum satellite angular separations will be suitable, and it will be feasible for all the necessary new satellite networks to be accommodated in orbit, as well as ensuring that the total interference in a network will not exceed the recommended value.

For a number of years the single interference entry was limited by CCIR Recommendations to 4/10 of the total allowable. This ratio corresponds approximately to the contribution to the total of each of the two neighbour-satellite networks among a homogeneous equi-spaced population, the satellites of which serve essentially the same area on the Earth surface.

In practice, this single-valued bound has proven unsatisfactory because:

- it is not associated with any given spacing between co-coverage neighbour-satellites and may be claimed for quite large spacings. This tends to be wasteful of orbit; and

- it is an insufficient safeguard to ensure that actual cumulative interference will not exceed the total allowable for which networks have been designed.

To remedy these shortcomings, a strategy may be used which is aimed at producing a reasonably high degree of homogeneity among all networks in a given fixed-satellite service band by imposing emission and sensitivity constraints on the transmit and receive systems respectively, of the earth and space stations in all networks. These constraints would be chosen in such a way that they allow "reasonable" implementation and transmission parameters to be used for acceptable inter-satellite spacing between co-coverage networks (e.g. 4° to 10° of arc). This strategy would be highly effective since it establishes an absolute interference between networks. At the same time, it would be relatively restrictive since the design and operating ranges of the technical parameters in all networks are necessarily bounded.

This strategy is designed to limit the total interference entering a network when all the interfering networks have service areas that overlap with the service area of the wanted network. This is a situation which is typical, for example, of certain arcs of the geostationary-satellite orbit which are extensively used for global coverage satellites. There are additional risks of large total interference levels when some of the networks involved have service areas which do not overlap the service area of the wanted network, and the risks will increase as the orbit becomes crowded with national-coverage satellites using high-performance antennas.

When the satellite network suffering inter-network interference uses FDM-FM emissions of various bandwidths it is unlikely that the maximum interference entries within the network or from other networks will all enter the same wanted channel. Therefore, the total interference in the worst-affected channel will be less than the arithmetic sum of all the separate worst-case single entries of interference. For this reason a ratio of about 1:3 between the maximum permissible single entry and the assumed total level may be valid. Recommendation 466 takes these principles into account in adopting a 2500 pW0p criteria for total inter-network interference, and a 800 pW0p criteria for single inter-network interference entries.

## TABLE I

## SINGLE ENTRY INTERFERENCE CRITERIA

- FDM/FM - Reference: CCIR Recommendation 466-4
  800 pWOp

- SCPC/FM - Reference: CCIR Recommendation AB/4 & others
  - Noise-like interference: C/I* = C/N (operating) + 11.0 (dB)

  - TV/FM interference: C/I** = $13.5 + 2 \log \delta - 3 \log (i/10)$ (dB)
    $\delta$ = bandwidth ratio of SCPC/FM carrier to TV/FM with energy dispersal only

    i = Pre-demodulation interference power in the SCPC bandwidth expressed as a percentage of the total pre-demodulation noise power ($10 \leq i \leq 25$)

- SCPC/PSK - Reference: CCIR Recommendation AB/4 & others***
  - Noise-like interference: C/I* = C/N (BER=$10^{-6}$) + 12.2 (dB)

  - TV/FM interference: C/I = C/N (BER=$10^{-6}$) + 6.4 + $3 \log \delta - 8 \log (i/10)$ (dB)
    $\delta$ = bandwidth ratio of SCPC/PSK carrier to TV/FM with energy dispersal only

    i = Pre-demodulation interference power in the SCPC bandwidth expressed as a percentage of the total pre-demodulation noise power ($10 \leq i \leq 25$)

- Digital - Reference: CCIR Recommendation 523-2
  C/I* = C/N (BER = $10^{-6}$) + 12.2 (dB)

- TV/FM - Reference: CCIR Recommendation 483-1
  C/I* = C/N (operating) + 14 (dB)

Note - Assumed values of C/N are 10.0 dB for SCPC-FM, 15.7 dB for SCPC/PSK and digital carriers, 17.9 dB for TV/FM (17.5 MHz) and 16.0 dB for others.
- Assumed value of i is 20%.

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* I is the interference power contained in the bandwidth of the desired carrier.

** I is the total power of the interfering carrier.

*** The criteria for TV/FM to SCPC/PSK is currently under further study by CCIR.

TABLE II

SINGLE ENTRY CARRIER-TO-INTERFERENCE RATIO (CIR) MATRIX

| WANTED CARRIER ↓ / INTERFERING CARRIER → | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 24.4 | 24.4 | 25.2 | 25.2 | 25.3 | 22.7 | 22.8 | 23.4 | 21.2 | 21.4 | 21.5 | 20.1 | 20.2 | 20.2 | 18.1 | 16.5 | 16.7 | 17.3 | 12.0 | 16.3 |
| 2 | 17.8 | 16.4 | 16.9 | 16.9 | 17.0 | 15.3 | 15.4 | 15.8 | 14.0 | 14.2 | 14.3 | 13.1 | 13.1 | 13.1 | 11.2 | 11.6 | 9.8 | 10.3 | 9.1 | 9.4 |
| 3 | 26.4 | 25.2 | 25.8 | 25.8 | 25.9 | 23.9 | 24.0 | 24.5 | 22.5 | 22.7 | 22.8 | 21.6 | 21.6 | 21.6 | 19.6 | 20.0 | 16.2 | 16.8 | 17.5 | 17.6 |
| 4 | 34.4 | 33.6 | 33.9 | 33.9 | 34.0 | 32.5 | 32.6 | 33.0 | 31.3 | 31.5 | 31.6 | 30.4 | 30.4 | 30.4 | 28.5 | 28.9 | 27.1 | 27.7 | 26.4 | 24.7 |
| 5 | 36.1 | 35.6 | 35.9 | 35.9 | 36.0 | 34.7 | 34.8 | 35.1 | 33.5 | 33.7 | 33.8 | 32.7 | 32.7 | 32.7 | 30.8 | 31.2 | 29.4 | 30.0 | 26.7 | 29.0 |
| 6 | 28.3 | 26.4 | 24.7 | 26.6 | 26.6 | 25.7 | 25.8 | 26.0 | 24.8 | 25.0 | 25.0 | 24.1 | 24.1 | 24.1 | 22.4 | 22.5 | 21.1 | 21.4 | 20.4 | 20.7 |
| 7 | 34.4 | 33.8 | 34.1 | 33.7 | 33.7 | 33.3 | 33.4 | 33.7 | 32.7 | 32.8 | 32.9 | 32.2 | 32.2 | 32.2 | 30.7 | 31.0 | 29.5 | 30.0 | 28.8 | 29.1 |
| 8 | 41.8 | 37.2 | 37.4 | 36.6 | 36.5 | 37.1 | 37.1 | 37.0 | 37.1 | 37.2 | 37.2 | 36.8 | 36.8 | 36.8 | 35.6 | 35.9 | 34.5 | 35.0 | 33.9 | 34.2 |
| 9 | 30.0 | 27.2 | 27.6 | 27.2 | 27.2 | 26.3 | 24.3 | 26.4 | 25.7 | 25.8 | 25.9 | 25.2 | 25.2 | 25.2 | 23.6 | 24.1 | 22.6 | 23.1 | 22.0 | 22.3 |
| 10 | 37.5 | 34.3 | 34.9 | 34.1 | 34.1 | 32.8 | 32.6 | 32.8 | 32.5 | 32.8 | 32.4 | 32.2 | 32.2 | 32.2 | 31.1 | 31.3 | 30.0 | 30.5 | 29.4 | 29.7 |
| 11 | 41.0 | 37.5 | 38.3 | 37.2 | 37.2 | 35.1 | 35.1 | 35.0 | 35.2 | 35.2 | 35.2 | 35.1 | 35.1 | 35.1 | 34.3 | 34.5 | 33.4 | 33.8 | 32.6 | 33.1 |
| 12 | 31.1 | 28.2 | 28.4 | 28.1 | 28.1 | 26.5 | 26.5 | 26.6 | 26.1 | 26.1 | 26.2 | 25.7 | 25.7 | 25.7 | 24.6 | 24.8 | 23.5 | 24.0 | 22.9 | 23.2 |
| 13 | 38.3 | 35.3 | 35.8 | 35.1 | 35.1 | 32.6 | 32.4 | 32.4 | 32.3 | 32.3 | 32.3 | 32.1 | 32.1 | 32.1 | 31.3 | 31.5 | 30.4 | 30.8 | 29.9 | 30.2 |
| 14 | 41.1 | 38.1 | 38.7 | 37.9 | 37.9 | 34.7 | 34.4 | 34.2 | 34.3 | 34.3 | 34.3 | 34.2 | 34.3 | 34.3 | 33.6 | 33.9 | 33.0 | 33.4 | 32.6 | 32.8 |
| 15 | 34.1 | 31.2 | 31.7 | 31.1 | 31.1 | 28.6 | 28.2 | 28.2 | 27.5 | 27.4 | 27.4 | 27.2 | 27.2 | 27.2 | 26.6 | 26.7 | 25.9 | 26.2 | 25.4 | 25.6 |
| 16 | 41.9 | 39.0 | 39.5 | 38.9 | 38.9 | 36.1 | 35.3 | 35.2 | 34.1 | 33.9 | 33.7 | 33.7 | 33.7 | 33.7 | 33.6 | 33.7 | 33.2 | 33.4 | 32.8 | 33.0 |
| 17 | 38.2 | 35.3 | 35.8 | 35.2 | 35.2 | 32.7 | 32.2 | 32.1 | 30.9 | 30.5 | 30.3 | 30.0 | 29.8 | 29.7 | 29.4 | 29.4 | 29.0 | 29.1 | 26.7 | 26.6 |
| 18 | 43.8 | 41.0 | 41.5 | 40.8 | 40.8 | 38.4 | 37.7 | 37.7 | 36.1 | 35.5 | 35.1 | 34.7 | 34.3 | 34.1 | 34.2 | 34.2 | 34.0 | 34.1 | 33.9 | 34.0 |
| 19 | 36.7 | 33.8 | 34.3 | 33.7 | 33.7 | 31.3 | 30.8 | 30.7 | 29.5 | 29.2 | 28.9 | 28.5 | 28.2 | 28.1 | 27.6 | 27.7 | 27.2 | 27.4 | 27.0 | 27.1 |
| 20 | 45.3 | 42.4 | 42.9 | 42.3 | 42.3 | 39.8 | 39.3 | 39.2 | 37.9 | 37.4 | 37.0 | 36.4 | 35.5 | 35.2 | 34.4 | 34.4 | 34.5 | 34.5 | 34.4 | 34.4 |
| 21 | 48.7 | 45.8 | 46.3 | 45.7 | 45.7 | 43.3 | 42.6 | 42.8 | 41.5 | 40.8 | 40.3 | 39.4 | 36.0 | 37.4 | 36.4 | 36.1 | 34.6 | 36.6 | 37.0 | 34.9 |
| 22 | 43.0 | 40.1 | 40.4 | 40.0 | 40.0 | 37.5 | 37.0 | 36.9 | 35.8 | 35.4 | 35.2 | 34.7 | 34.2 | 33.9 | 32.3 | 32.1 | 31.2 | 31.3 | 31.0 | 31.1 |
| 23 | 8.0 | 4.6 | 5.6 | 5.6 | 5.9 | 2.6 | 2.8 | 3.4 | 1.0 | 1.2 | 1.4 | -0.1 | 0.0 | 0.0 | -2.1 | -1.7 | -3.6 | -3.0 | -4.3 | -3.9 |
| 24 | 9.0 | 5.5 | 6.6 | 6.6 | 6.8 | 3.6 | 3.8 | 4.4 | 2.0 | 2.2 | 2.3 | 0.9 | 0.9 | 1.0 | -1.1 | -0.7 | -2.6 | -2.0 | -3.3 | -3.0 |
| 25 | 9.8 | 6.3 | 7.4 | 7.4 | 7.6 | 4.4 | 4.5 | 5.2 | 2.8 | 3.0 | 3.1 | 1.7 | 1.7 | 1.8 | -0.3 | 0.1 | -1.8 | -1.2 | -2.5 | -2.2 |
| 26 | 14.5 | 11.1 | 12.2 | 12.1 | 12.4 | 9.2 | 9.3 | 9.9 | 7.5 | 7.8 | 7.9 | 6.5 | 6.5 | 6.5 | 4.4 | 4.9 | 3.0 | 3.5 | 2.3 | 2.6 |
| 27 | 17.5 | 14.1 | 15.2 | 15.2 | 15.4 | 12.2 | 12.3 | 12.9 | 10.5 | 10.8 | 10.9 | 9.5 | 9.5 | 9.5 | 7.4 | 7.9 | 6.0 | 6.6 | 5.3 | 5.6 |
| 28 | 17.7 | 14.3 | 15.3 | 15.3 | 15.5 | 12.3 | 12.5 | 13.1 | 10.7 | 10.9 | 11.1 | 9.6 | 9.7 | 9.7 | 7.6 | 6.0 | 6.1 | 6.7 | 5.4 | 6.7 |
| 29 | 18.9 | 15.5 | 16.5 | 14.5 | 16.7 | 13.5 | 13.7 | 14.3 | 11.9 | 12.1 | 12.2 | 10.8 | 10.9 | 10.9 | 8.8 | 9.2 | 7.3 | 7.9 | 6.6 | 4.9 |
| 30 | 23.7 | 20.2 | 21.3 | 21.3 | 21.5 | 18.3 | 18.4 | 19.1 | 16.6 | 16.9 | 17.0 | 15.6 | 15.6 | 15.6 | 13.6 | 14.0 | 12.1 | 12.7 | 11.4 | 11.7 |
| 31 | 26.7 | 23.2 | 24.3 | 24.3 | 24.5 | 21.3 | 21.4 | 22.1 | 19.7 | 19.9 | 20.0 | 18.6 | 18.6 | 18.7 | 16.6 | 17.0 | 15.1 | 15.7 | 14.4 | 14.7 |
| 32 | 29.7 | 26.2 | 27.3 | 27.3 | 27.5 | 24.3 | 24.5 | 25.1 | 22.7 | 22.9 | 23.0 | 21.6 | 21.7 | 21.7 | 19.6 | 20.0 | 18.1 | 18.7 | 17.4 | 17.7 |
| 33 | 29.0 | 27.7 | 27.9 | 27.9 | 27.9 | 27.0 | 27.1 | 27.4 | 25.9 | 26.1 | 26.2 | 25.1 | 25.1 | 25.1 | 23.2 | 23.6 | 21.8 | 22.4 | 21.1 | 21.5 |
| 34 | 30.0 | 27.9 | 27.9 | 27.9 | 27.9 | 27.5 | 27.5 | 27.7 | 24.7 | 26.8 | 26.9 | 25.9 | 25.9 | 24.0 | 24.2 | 24.4 | 22.9 | 23.4 | 22.2 | 22.5 |
| 35 | 30.9 | 28.0 | 28.5 | 27.9 | 27.9 | 27.7 | 27.8 | 27.8 | 27.1 | 27.3 | 27.3 | 26.5 | 26.6 | 26.6 | 25.0 | 25.3 | 23.7 | 24.2 | 23.0 | 23.3 |
| 36 | 34.4 | 31.5 | 32.0 | 31.4 | 31.4 | 28.9 | 28.4 | 28.3 | 27.9 | 27.9 | 27.9 | 27.8 | 27.8 | 27.8 | 27.3 | 27.5 | 26.5 | 26.9 | 26.0 | 26.3 |
| 37 | 34.4 | 31.5 | 32.0 | 31.4 | 31.4 | 28.9 | 28.4 | 28.3 | 27.9 | 27.9 | 27.9 | 27.8 | 27.8 | 27.8 | 27.3 | 27.5 | 26.5 | 26.9 | 26.0 | 24.3 |
| 38 | 37.5 | 34.6 | 35.1 | 34.5 | 34.5 | 32.0 | 31.5 | 31.4 | 30.3 | 29.9 | 29.7 | 29.2 | 28.7 | 28.5 | 27.9 | 27.9 | 27.6 | 27.9 | 27.6 | 27.7 |
| 39 | 39.9 | 37.0 | 37.5 | 36.9 | 36.9 | 34.5 | 34.0 | 33.9 | 32.8 | 32.4 | 32.2 | 31.7 | 31.2 | 30.9 | 29.5 | 29.3 | 27.9 | 28.0 | 27.9 | 27.9 |
| 40 | 40.5 | 37.4 | 38.1 | 37.5 | 37.5 | 35.1 | 34.4 | 34.5 | 33.4 | 33.0 | 32.8 | 32.3 | 31.7 | 31.8 | 30.1 | 29.9 | 28.5 | 28.6 | 27.9 | 27.9 |
| 41 | 40.4 | 37.5 | 38.0 | 37.4 | 37.4 | 34.9 | 34.4 | 34.4 | 33.2 | 32.8 | 32.6 | 32.2 | 31.6 | 31.4 | 30.0 | 29.6 | 28.4 | 28.4 | 27.9 | 27.9 |
| 42 | 41.5 | 38.6 | 39.1 | 38.5 | 38.5 | 36.0 | 35.5 | 35.4 | 34.3 | 33.9 | 33.7 | 33.2 | 32.7 | 32.5 | 31.1 | 30.9 | 29.4 | 29.5 | 26.6 | 26.5 |
| 43 | 46.1 | 43.2 | 43.7 | 43.1 | 43.1 | 40.7 | 40.2 | 40.1 | 39.0 | 38.6 | 36.4 | 37.9 | 37.4 | 37.1 | 36.7 | 35.5 | 34.1 | 34.2 | 33.5 | 33.2 |
| 44 | 46.5 | 43.6 | 44.1 | 43.5 | 43.5 | 41.1 | 40.6 | 40.5 | 39.4 | 39.0 | 38.8 | 38.3 | 37.7 | 37.5 | 36.1 | 35.9 | 34.5 | 34.6 | 33.9 | 33.5 |
| 45 | 47.8 | 44.9 | 45.4 | 44.8 | 44.8 | 42.3 | 41.6 | 41.8 | 40.6 | 40.3 | 40.0 | 39.6 | 39.0 | 36.8 | 37.4 | 37.2 | 35.6 | 35.8 | 35.2 | 34.6 |
| 46 | 43.8 | 40.9 | 41.4 | 40.8 | 40.8 | 38.4 | 37.8 | 37.8 | 36.6 | 36.3 | 36.0 | 35.6 | 36.0 | 34.8 | 33.4 | 33.2 | 31.9 | 31.9 | 31.9 | 31.9 |
| 47 | 42.5 | 39.4 | 40.1 | 39.5 | 39.5 | 37.0 | 36.5 | 36.5 | 35.3 | 34.9 | 34.7 | 34.3 | 33.7 | 33.5 | 32.1 | 31.9 | 30.5 | 30.5 | 30.0 | 30.0 |
| 48 | 44.2 | 41.3 | 41.8 | 41.2 | 41.2 | 38.8 | 38.3 | 38.2 | 37.1 | 36.7 | 36.5 | 36.0 | 35.5 | 35.2 | 33.8 | 33.6 | 32.2 | 32.3 | 31.6 | 31.3 |
| 49 | 44.2 | 41.3 | 41.8 | 41.2 | 41.2 | 38.8 | 38.3 | 36.2 | 37.1 | 36.7 | 36.5 | 36.0 | 35.5 | 35.2 | 33.8 | 33.6 | 32.2 | 32.3 | 31.6 | 31.3 |
| 50 | 44.5 | 41.6 | 42.1 | 41.5 | 41.5 | 39.1 | 38.6 | 38.5 | 37.4 | 37.0 | 36.6 | 36.3 | 35.8 | 35.5 | 34.1 | 33.9 | 32.5 | 32.6 | 31.9 | 31.6 |

TABLE II (continued)

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 16.7 | 13.8 | 42.5 | 41.5 | 40.7 | 35.9 | 32.9 | 39.7 | 38.5 | 33.7 | 30.7 | 29.2 | 23.9 | 22.8 | 21.9 | 16.5 | 16.5 | 15.4 | 12.9 | 12.3 |
| 2 | 9.8 | 7.0 | 35.6 | 34.6 | 33.8 | 29.1 | 26.1 | 32.8 | 31.6 | 26.9 | 23.8 | 20.8 | 16.8 | 15.9 | 15.1 | 11.6 | 11.6 | 6.5 | 6.1 | 5.5 |
| 3 | 18.2 | 15.4 | 44.0 | 43.0 | 42.2 | 37.5 | 34.5 | 41.2 | 40.0 | 35.3 | 32.3 | 29.3 | 25.4 | 24.4 | 23.5 | 20.0 | 20.0 | 16.9 | 14.5 | 13.9 |
| 4 | 27.1 | 24.3 | 52.9 | 52.0 | 51.2 | 46.4 | 43.4 | 50.1 | 49.0 | 44.2 | 41.2 | 38.0 | 34.2 | 33.3 | 32.4 | 28.9 | 28.9 | 25.8 | 23.4 | 22.8 |
| 5 | 29.4 | 26.6 | 55.2 | 54.3 | 53.5 | 48.7 | 45.7 | 52.5 | 51.3 | 46.5 | 43.5 | 40.3 | 36.4 | 35.6 | 34.7 | 31.3 | 31.3 | 28.2 | 25.7 | 25.1 |
| 6 | 21.1 | 18.3 | 47.0 | 46.0 | 45.2 | 40.5 | 37.5 | 44.2 | 43.0 | 38.3 | 35.2 | 32.2 | 28.4 | 27.4 | 26.2 | 23.0 | 23.0 | 19.9 | 17.5 | 16.9 |
| 7 | 29.5 | 26.8 | 55.5 | 54.5 | 53.7 | 48.9 | 45.9 | 52.7 | 51.5 | 46.7 | 43.7 | 40.7 | 36.9 | 35.8 | 34.3 | 31.5 | 31.5 | 28.4 | 25.9 | 25.3 |
| 8 | 34.5 | 31.9 | 60.6 | 59.6 | 58.8 | 54.1 | 51.1 | 57.8 | 56.6 | 51.9 | 48.8 | 45.8 | 42.0 | 41.0 | 40.1 | 36.6 | 36.6 | 33.5 | 31.1 | 30.5 |
| 9 | 22.6 | 20.0 | 48.7 | 47.7 | 46.9 | 42.2 | 39.2 | 45.9 | 44.7 | 39.9 | 36.9 | 33.9 | 30.1 | 29.0 | 26.2 | 24.7 | 24.7 | 21.6 | 19.1 | 16.4 |
| 10 | 30.0 | 27.5 | 56.3 | 55.3 | 54.5 | 49.7 | 46.7 | 53.5 | 52.3 | 47.5 | 44.5 | 41.5 | 37.7 | 36.4 | 35.7 | 32.2 | 32.2 | 29.2 | 26.7 | 26.1 |
| 11 | 33.4 | 30.9 | 59.8 | 58.8 | 58.0 | 53.2 | 50.2 | 57.0 | 55.8 | 51.0 | 48.0 | 45.0 | 41.2 | 40.1 | 39.2 | 35.7 | 35.7 | 32.7 | 30.2 | 29.6 |
| 12 | 23.5 | 21.0 | 49.8 | 48.8 | 48.0 | 43.2 | 40.2 | 47.0 | 45.8 | 41.0 | 38.0 | 35.0 | 31.2 | 30.1 | 29.2 | 25.7 | 25.7 | 22.7 | 20.2 | 19.6 |
| 13 | 30.5 | 28.1 | 57.0 | 56.0 | 55.2 | 50.5 | 47.4 | 54.2 | 53.0 | 48.2 | 45.2 | 42.2 | 38.4 | 37.3 | 36.4 | 32.7 | 32.7 | 29.9 | 27.4 | 26.6 |
| 14 | 33.0 | 30.9 | 59.8 | 58.8 | 58.0 | 53.3 | 50.2 | 57.0 | 55.8 | 51.0 | 48.0 | 45.0 | 41.2 | 40.1 | 39.2 | 35.3 | 35.3 | 32.7 | 30.2 | 29.6 |
| 15 | 25.9 | 23.8 | 52.8 | 51.9 | 51.1 | 46.3 | 43.3 | 50.0 | 48.9 | 44.1 | 41.1 | 38.1 | 34.3 | 33.2 | 32.3 | 28.6 | 28.6 | 25.7 | 23.3 | 22.7 |
| 16 | 33.2 | 31.5 | 60.6 | 59.7 | 58.9 | 54.1 | 51.1 | 57.9 | 56.7 | 51.9 | 48.9 | 45.9 | 42.1 | 41.0 | 40.1 | 36.7 | 36.7 | 33.5 | 31.1 | 30.5 |
| 17 | 29.0 | 27.5 | 56.9 | 55.9 | 55.1 | 50.4 | 47.4 | 54.1 | 52.9 | 48.2 | 45.1 | 42.1 | 38.3 | 37.2 | 36.4 | 32.9 | 32.9 | 29.5 | 27.4 | 26.8 |
| 18 | 34.0 | 32.9 | 62.6 | 61.6 | 60.8 | 56.0 | 53.0 | 59.8 | 58.6 | 53.8 | 50.8 | 47.8 | 44.0 | 42.9 | 42.0 | 38.6 | 38.6 | 35.0 | 33.0 | 32.4 |
| 19 | 27.2 | 25.9 | 55.5 | 54.5 | 53.7 | 48.9 | 45.9 | 52.7 | 51.5 | 46.7 | 43.7 | 40.7 | 36.9 | 35.8 | 34.9 | 31.5 | 31.5 | 28.4 | 25.9 | 25.3 |
| 20 | 34.5 | 33.8 | 64.0 | 63.0 | 62.2 | 57.5 | 54.4 | 61.2 | 60.0 | 55.2 | 52.2 | 49.2 | 45.4 | 44.3 | 43.5 | 40.0 | 40.0 | 36.9 | 34.4 | 33.8 |
| 21 | 36.8 | 36.9 | 67.5 | 66.5 | 65.7 | 60.9 | 57.9 | 64.7 | 63.5 | 58.7 | 55.7 | 52.7 | 48.9 | 47.8 | 46.9 | 43.5 | 43.5 | 40.4 | 37.6 | 37.5 |
| 22 | 31.1 | 30.6 | 61.7 | 60.7 | 59.9 | 55.2 | 52.1 | 58.9 | 57.7 | 52.9 | 49.9 | 46.9 | 43.1 | 42.0 | 41.2 | 37.7 | 37.7 | 34.6 | 32.1 | 31.2 |
| 23 | -3.5 | -6.4 | 22.2 | 21.2 | 20.4 | 15.7 | 12.7 | 19.4 | 18.2 | 13.4 | 10.4 | 7.4 | 3.6 | 2.6 | 1.7 | -1.8 | -1.8 | -4.9 | -7.3 | -7.9 |
| 24 | -2.6 | -5.5 | 23.2 | 22.2 | 21.4 | 16.6 | 13.6 | 20.4 | 19.2 | 14.4 | 11.4 | 8.4 | 4.6 | 3.5 | 2.7 | -0.6 | -0.6 | -3.9 | -6.4 | -7.0 |
| 25 | -1.8 | -4.7 | 24.0 | 23.0 | 22.2 | 17.4 | 14.4 | 21.2 | 20.0 | 15.2 | 12.2 | 9.2 | 5.4 | 4.3 | 3.4 | 0.0 | 0.0 | -3.1 | -5.6 | -4.2 |
| 26 | 3.0 | 0.1 | 28.7 | 27.8 | 27.0 | 22.2 | 19.2 | 25.9 | 24.8 | 20.0 | 17.0 | 14.0 | 10.2 | 9.1 | 8.2 | 4.8 | 4.8 | 1.7 | -0.6 | -1.4 |
| 27 | 6.0 | 3.1 | 31.7 | 30.8 | 30.0 | 25.2 | 22.2 | 29.0 | 27.8 | 23.0 | 20.0 | 17.0 | 13.2 | 12.1 | 11.2 | 7.8 | 7.8 | 4.7 | 2.2 | 1.6 |
| 28 | 6.1 | 3.3 | 30.7 | 29.7 | 28.9 | 24.2 | 21.1 | 27.9 | 26.7 | 21.9 | 18.9 | 15.9 | 12.1 | 11.0 | 10.2 | 6.7 | 6.7 | 3.6 | 1.1 | 0.6 |
| 29 | 7.3 | 4.4 | 31.9 | 30.9 | 30.1 | 25.3 | 22.3 | 29.1 | 27.9 | 23.1 | 20.1 | 17.1 | 13.3 | 12.2 | 11.4 | 7.9 | 7.9 | 4.8 | 2.3 | 1.8 |
| 30 | 12.1 | 9.2 | 36.7 | 35.7 | 34.9 | 30.1 | 27.1 | 33.9 | 32.7 | 27.9 | 24.9 | 21.9 | 18.1 | 17.0 | 16.1 | 12.7 | 12.7 | 9.6 | 7.1 | 6.5 |
| 31 | 15.1 | 12.2 | 39.7 | 38.7 | 37.9 | 33.1 | 30.1 | 36.9 | 35.7 | 30.9 | 27.9 | 24.9 | 21.1 | 20.0 | 19.1 | 15.7 | 15.7 | 12.6 | 10.1 | 9.5 |
| 32 | 18.1 | 15.2 | 42.7 | 41.7 | 40.9 | 36.1 | 33.1 | 39.9 | 38.7 | 33.9 | 30.9 | 27.9 | 24.1 | 23.0 | 22.2 | 18.7 | 18.7 | 15.6 | 13.1 | 12.5 |
| 33 | 21.9 | 19.0 | 46.5 | 45.5 | 44.7 | 39.9 | 36.9 | 43.7 | 42.5 | 37.7 | 34.7 | 31.7 | 27.9 | 26.8 | 26.0 | 22.5 | 22.5 | 19.4 | 16.9 | 16.3 |
| 34 | 22.9 | 20.1 | 47.5 | 46.4 | 45.8 | 41.0 | 38.0 | 44.8 | 43.6 | 38.8 | 35.8 | 32.8 | 29.0 | 27.9 | 27.0 | 23.6 | 23.6 | 20.5 | 18.0 | 17.4 |
| 35 | 23.7 | 20.9 | 48.4 | 47.4 | 46.7 | 41.9 | 38.9 | 45.6 | 44.4 | 39.7 | 36.7 | 33.6 | 29.8 | 28.8 | 27.9 | 24.4 | 24.4 | 21.3 | 18.9 | 18.3 |
| 36 | 26.5 | 24.2 | 51.9 | 50.9 | 50.1 | 45.3 | 42.3 | 49.1 | 47.9 | 43.1 | 40.1 | 37.1 | 33.3 | 32.2 | 31.4 | 27.9 | 27.9 | 24.8 | 22.3 | 21.8 |
| 37 | 26.5 | 24.2 | 51.9 | 50.9 | 50.1 | 45.3 | 42.3 | 49.1 | 47.9 | 43.1 | 40.1 | 37.1 | 33.3 | 32.2 | 31.4 | 27.9 | 27.9 | 24.6 | 22.3 | 21.6 |
| 38 | 27.8 | 26.7 | 55.0 | 54.0 | 53.2 | 48.4 | 45.4 | 52.2 | 51.0 | 46.2 | 43.2 | 40.2 | 36.4 | 35.3 | 34.5 | 31.0 | 31.0 | 27.9 | 25.4 | 24.8 |
| 39 | 27.9 | 27.7 | 57.4 | 56.5 | 55.7 | 50.9 | 47.9 | 54.7 | 53.5 | 48.7 | 45.7 | 42.7 | 38.9 | 37.8 | 36.9 | 33.5 | 33.5 | 30.4 | 27.9 | 27.3 |
| 40 | 27.9 | 27.8 | 58.0 | 57.1 | 56.3 | 51.5 | 48.5 | 55.2 | 54.0 | 49.3 | 46.3 | 43.3 | 39.5 | 38.4 | 37.5 | 34.0 | 34.0 | 31.0 | 28.5 | 27.9 |
| 41 | 27.9 | 27.8 | 57.9 | 56.9 | 56.1 | 51.4 | 48.4 | 55.1 | 53.9 | 49.1 | 46.1 | 43.1 | 39.3 | 38.3 | 37.4 | 33.9 | 33.9 | 30.8 | 28.4 | 27.6 |
| 42 | 28.0 | 27.9 | 59.0 | 58.0 | 57.2 | 52.4 | 49.4 | 56.2 | 55.0 | 50.2 | 47.2 | 44.2 | 40.4 | 39.3 | 38.5 | 35.0 | 35.0 | 31.9 | 29.4 | 28.6 |
| 43 | 32.7 | 31.1 | 63.6 | 62.7 | 61.9 | 57.1 | 54.1 | 60.9 | 59.7 | 54.9 | 51.9 | 48.9 | 45.1 | 44.0 | 43.1 | 39.7 | 39.7 | 36.6 | 34.1 | 33.5 |
| 44 | 33.1 | 31.5 | 64.0 | 63.1 | 62.3 | 57.5 | 54.5 | 61.2 | 60.0 | 55.3 | 52.3 | 49.3 | 45.5 | 44.4 | 43.5 | 40.0 | 40.0 | 37.0 | 34.5 | 33.9 |
| 45 | 34.3 | 32.8 | 65.3 | 64.3 | 63.5 | 58.8 | 55.8 | 62.5 | 61.3 | 56.4 | 53.5 | 50.5 | 46.7 | 45.7 | 44.8 | 41.3 | 41.3 | 38.2 | 35.6 | 35.2 |
| 46 | 31.9 | 31.7 | 61.3 | 60.4 | 59.6 | 54.8 | 51.8 | 58.5 | 57.3 | 52.6 | 49.6 | 46.6 | 42.7 | 41.7 | 40.8 | 37.3 | 37.3 | 34.2 | 31.8 | 31.2 |
| 47 | 30.0 | 29.9 | 60.0 | 59.0 | 58.2 | 53.5 | 50.5 | 57.2 | 56.0 | 51.2 | 48.2 | 45.2 | 41.4 | 40.4 | 39.5 | 36.0 | 36.0 | 32.9 | 30.5 | 29.9 |
| 48 | 30.8 | 30.0 | 61.8 | 60.8 | 60.0 | 55.2 | 52.2 | 59.0 | 57.8 | 53.0 | 50.0 | 47.0 | 43.2 | 42.1 | 41.2 | 37.8 | 37.6 | 34.7 | 32.2 | 31.6 |
| 49 | 30.8 | 30.0 | 61.8 | 60.8 | 60.0 | 55.2 | 52.2 | 59.0 | 57.6 | 53.0 | 50.0 | 47.0 | 43.2 | 42.1 | 41.2 | 37.8 | 37.6 | 34.7 | 32.2 | 31.4 |
| 50 | 31.1 | 30.0 | 42.0 | 41.1 | 40.3 | 55.5 | 52.5 | 59.3 | 58.1 | 53.3 | 50.3 | 47.3 | 43.5 | 42.4 | 41.5 | 36.1 | 36.1 | 36.0 | 32.5 | 31.9 |

## TABLE II (continued)

| | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 12.5 | 11.4 | 6.7 | 6.3 | 5.1 | 22.5 | 22.5 | 19.4 | 19.4 | 22.5 |
| 2 | 5.6 | 4.5 | -0.1 | -0.5 | -1.8 | 15.6 | 15.6 | 12.6 | 12.6 | 15.6 |
| 3 | 14.0 | 12.9 | 8.3 | 7.9 | 6.6 | 24.0 | 24.0 | 21.0 | 21.0 | 24.0 |
| 4 | 22.9 | 21.9 | 17.2 | 16.8 | 15.5 | 32.9 | 32.9 | 29.9 | 29.9 | 32.9 |
| 5 | 25.2 | 24.2 | 19.5 | 19.1 | 17.8 | 35.2 | 35.2 | 32.2 | 32.2 | 35.2 |
| 6 | 17.0 | 15.9 | 11.3 | 10.9 | 9.6 | 26.6 | 26.6 | 24.0 | 24.0 | 26.6 |
| 7 | 25.5 | 24.4 | 19.7 | 19.3 | 16.0 | 34.5 | 34.5 | 32.4 | 32.4 | 34.5 |
| 8 | 30.6 | 29.5 | 24.9 | 24.5 | 23.2 | 38.8 | 38.8 | 37.6 | 37.6 | 38.8 |
| 9 | 18.7 | 17.6 | 13.0 | 12.6 | 11.3 | 27.3 | 27.3 | 25.6 | 25.6 | 27.3 |
| 10 | 26.2 | 25.2 | 20.5 | 20.1 | 18.8 | 34.0 | 34.0 | 33.0 | 33.0 | 34.0 |
| 11 | 29.8 | 28.7 | 24.0 | 23.6 | 22.3 | 36.5 | 36.5 | 36.3 | 36.3 | 36.5 |
| 12 | 19.8 | 18.7 | 14.0 | 13.6 | 12.4 | 27.6 | 27.6 | 26.4 | 26.4 | 27.6 |
| 13 | 27.0 | 25.9 | 21.2 | 20.8 | 19.6 | 33.6 | 33.6 | 33.1 | 33.1 | 33.6 |
| 14 | 29.8 | 28.7 | 24.0 | 23.6 | 22.4 | 35.5 | 35.5 | 35.6 | 35.6 | 35.5 |
| 15 | 22.8 | 21.8 | 17.1 | 16.7 | 15.4 | 28.7 | 28.7 | 28.2 | 28.2 | 28.7 |
| 16 | 30.6 | 29.6 | 24.9 | 24.5 | 23.2 | 34.9 | 34.9 | 35.0 | 35.0 | 34.9 |
| 17 | 26.9 | 25.8 | 21.2 | 20.8 | 19.5 | 30.9 | 30.9 | 30.8 | 30.8 | 30.9 |
| 18 | 32.6 | 31.5 | 26.8 | 26.4 | 25.2 | 35.2 | 35.2 | 35.4 | 35.4 | 35.2 |
| 19 | 25.4 | 24.4 | 19.7 | 19.3 | 18.0 | 29.2 | 29.2 | 29.0 | 29.0 | 29.2 |
| 20 | 34.0 | 32.9 | 28.2 | 27.8 | 26.6 | 35.3 | 35.3 | 35.5 | 35.5 | 35.3 |
| 21 | 37.4 | 36.4 | 31.7 | 31.3 | 30.0 | 36.4 | 36.4 | 37.0 | 37.0 | 36.4 |
| 22 | 31.3 | 30.5 | 25.9 | 25.5 | 24.3 | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 |
| 23 | -7.8 | -8.9 | -13.5 | -13.9 | -15.2 | 8.6 | 8.6 | 8 | 8 | 8.6 |
| 24 | -6.8 | -7.9 | -12.6 | -13.0 | -14.2 | 8.8 | 8.8 | 8.2 | 8.2 | 8.8 |
| 25 | -6.0 | -7.1 | -11.8 | -12.2 | -13.4 | 8.9 | 8.9 | 8.3 | 8.3 | 8.9 |
| 26 | -1.3 | -2.3 | -7.0 | -7.4 | -8.7 | 9.9 | 9.9 | 9.3 | 9.3 | 9.9 |
| 27 | 1.7 | 0.7 | -4.0 | -4.4 | -5.7 | 10.5 | 10.5 | 9.9 | 9.9 | 10.5 |
| 28 | 0.7 | -0.4 | -5.1 | -5.4 | -6.7 | 14.5 | 14.5 | 13.6 | 13.6 | 14.5 |
| 29 | 1.9 | 0.8 | -3.9 | -4.2 | -5.5 | 18.1 | 18.1 | 16.3 | 16.3 | 18.1 |
| 30 | 6.7 | 5.6 | 0.9 | 0.5 | -0.8 | 21.0 | 21.0 | 19.1 | 19.1 | 21.0 |
| 31 | 9.7 | 8.6 | 3.9 | 3.5 | 2.3 | 22.8 | 22.8 | 21.0 | 21.0 | 22.8 |
| 32 | 12.7 | 11.6 | 6.9 | 6.5 | 5.3 | 24.6 | 24.6 | 22.8 | 22.8 | 24.6 |
| 33 | 16.5 | 15.4 | 10.7 | 10.3 | 9.1 | 26.5 | 26.5 | 23.5 | 23.5 | 26.5 |
| 34 | 17.5 | 16.5 | 11.8 | 11.4 | 10.1 | 27.5 | 27.5 | 24.5 | 24.5 | 27.5 |
| 35 | 18.4 | 17.3 | 12.7 | 12.3 | 11.0 | 27.9 | 27.9 | 25.4 | 25.4 | 27.9 |
| 36 | 21.9 | 20.8 | 16.1 | 15.8 | 14.5 | 27.9 | 27.9 | 27.9 | 27.9 | 27.9 |
| 37 | 21.9 | 20.8 | 16.1 | 15.8 | 14.5 | 27.9 | 27.9 | 27.9 | 27.9 | 27.9 |
| 38 | 25.0 | 23.9 | 19.2 | 18.8 | 17.6 | 27.9 | 27.9 | 27.9 | 27.9 | 27.9 |
| 39 | 27.4 | 26.4 | 21.7 | 21.3 | 20.0 | 28.0 | 27.9 | 27.9 | 27.9 | 27.9 |
| 40 | 28.0 | 27.0 | 22.3 | 21.9 | 20.6 | 28.6 | 28.0 | 27.9 | 27.9 | 27:9 |
| 41 | 27.9 | 26.8 | 22.2 | 21.8 | 20.5 | 28.5 | 27.9 | 27.9 | 27.9 | 27.9 |
| 42 | 29.0 | 27.9 | 23.2 | 22.8 | 21.6 | 29.6 | 29.0 | 27.9 | 27.9 | 27.9 |
| 43 | 33.6 | 32.6 | 27.9 | 27.5 | 26.2 | 34.2 | 33.6 | 31.9 | 31.9 | 31.6 |
| 44 | 34.0 | 33.0 | 28.3 | 27.9 | 26.6 | 34.6 | 34.0 | 32.3 | 32.3 | 32.0 |
| 45 | 35.3 | 34.2 | 29.6 | 29.2 | 27.9 | 35.9 | 35.3 | 33.5 | 33.5 | 33.3 |
| 46 | 31.3 | 30.2 | 25.6 | 25.2 | 23.9 | 31.9 | 31.9 | 31.9 | 31.9 | 31.9 |
| 47 | 30.0 | 28.9 | 24.3 | 23.9 | 22.6 | 30.6 | 30.0 | 30.0 | 30.0 | 30.0 |
| 48 | 31.8 | 30.7 | 26.0 | 25.6 | 24.4 | 32.3 | 31.8 | 30.0 | 30.0 | 30.0 |
| 49 | 31.8 | 30.7 | 26.0 | 25.6 | 24.4 | 32.3 | 31.8 | 30.0 | 30.0 | 30.0 |
| 50 | 32.0 | 31.0 | 26.3 | 25.9 | 24.6 | 32.6 | 32.0 | 30.3 | 30.3 | 30.0 |

However, for wide-band digital systems, all the various interference entries within the pre-demodulator bandwidth of the wanted system will be added together on a power basis and will affect all channels in the system; there will be no randomization of the incidence of interference between different channels. In these circumstances it can be clearly foreseen that the total interference level will be substantially greater and a higher ratio between the maximum permissible single entry and the recommended total interference level should be assumed. Also, it appears to be necessary to differentiate between the permissible total inter-network interference levels where frequency re-use is and is not employed, but this is a subject for further study. Recommendation 523 for digital telephony adopts a lower value of total inter-network interference for frequency re-use in satellite networks because a given level of external interference will have more impact on the capacity of such a network than the same level would have on a network that does not use frequency re-use techniques. If the single entry maximum appropriate for the case where frequency re-use is not used were applied also to the frequency re-use case, there is some possibility that the total level of interference from other satellite networks in some of the channels will exceed the applicable criteria. This might occur when the arc of the orbit close to the wanted satellite is heavily loaded. However, if different single entry maxima were recommended in the two cases, the process of frequency coordination would be made more complex and for that reason the same value is used.

Recommendation 466 recommends a lower value of total inter-network interference for frequency re-use satellite networks (2000 pW0p) because a given level of external interference will have more impact on the capacity of such a network than the same level would have on a network that does not use frequency re-use techniques for which the allowance is for 2500 pW0p.

If the single entry maximum appropriate for the case where frequency re-use is not used were applied also to the frequency re-use case, there is some possibility that the total level of interference from other satellite networks in some of the channels will exceed 2000 pW0p when the arc of the orbit close to the wanted satellite is heavily loaded. However, if different single entry maxima were recommended in the two cases, the process of frequency coordination would be made more complex and for that reason the same value is used.

It is clear that any attempts to increase the current levels of maximum interference must be accompanied by safeguards which ensure that cumulative actual interference does not exceed the increased total allowance materially and continuing study is required.

**A number of studies have been made with respect to the ratio of aggregate interference to single-entry interference. A description of these studies and the results obtained are given in Annex IV .**

Finally, there are certain transmissions which are quite incompatible with each other as regards mutual interference on a co-channel basis. An example is the interference which a high density carrier such as TV-FM with insufficient carrier energy dispersal, or a low-index high-capacity FDM-FM carrier, may cause in a low capacity carrier such as an analogue or digital SCPC transmission. Juxtaposition of such incompatible transmissions would produce extreme imbalance in the characteristics of two networks and should be avoided by convention or in coordination.

## 4. Relationship between ΔT/T ratios and single-entry interference criteria

Annex V to Report 454 presents the results of calculations of the ΔT/T ratios that correspond to the single-entry interference criteria applicable to the different types of systems. Annex III of Report 454 contains a description of a method for calculating interference which is based on Appendix 29, appropriately modified to give accurate results.

## 5. Technical means to facilitate coordination between networks using geostationary satellites

When two satellite networks are coordinated from a mutual interference standpoint, a number of parameter adjustments may be made in either or both networks in order to meet mutually acceptable interference levels. These adjustments can include changes in link parameters which result in changes in power density and sensitivity levels.

Report 453 identifies, conceptually, four-power density constraints, namely:

- the up-link power density ($P_u$);
- the interference power density to which a satellite receiver is afforded protection ($I_u$);
- the down-link power density ($P_d$); and
- the interference power density to which an earth station receiver is afforded protection ($I_d$).

It may be possible to achieve coordination on this basis, i.e agreed limits on these four parameter values.

Rearrangement of transponder accesses to minimize the effect of differences in earth station antenna gains or $G/T$ may also be employed to achieve coordination on the above four parameter bases.

If during the coordination process between two systems evidence is provided that the interference criteria cannot be met over the entire band then it may be necessary to consider segmenting the frequency band and thereby enabling the coordination of more homogeneous bandwidth segments. The ($P_u/I_u$) and ($P_d/I_d$) values may be considerably reduced by a frequency band segmenting procedure whereby coordination may be achievable with different values for the four parameters in different segments of a band. Particular attention should first be given to interference from high spectral density carriers such as FM television. Whenever possible these carriers should be limited to a segment of the RF band free of highly sensitive transmissions such as SCPC telephony. If similar transponder arrangements are used for both networks this could be achieved by allocating different transponders for each type of transmission. If coordination is performed at an early design stage, another possibility could be to arrange the transponder frequency plans so that the filter cross-over bands of one network fall within the usable bandwidth of the other. This makes it possible to locate the highest spectral density carriers of one network within the guard bands of the other.

If this is not possible it may be necessary to reduce the interfering spectral density by improving the TV energy dispersal technique. Conventional spreading of a TV carrier, such as is presently employed to alleviate interference in low capacity multichannel carriers, is relatively ineffective in protecting an SCPC transmission since it is based on uniform dispersal of the often otherwise undeviated TV carrier at the video frame rate, i.e. 50 or 60 Hz. The TV carrier, dispersed at such a low rate and over one or, at most, a few MHz, is seen by an SCPC carrier much like pulsed interference of the full TV carrier power with a duty cycle equal to the ratio of the SCPC occupied bandwidth to the peak-to-peak dispersal deviation.

To achieve improved interference reduction for this case, a spreading technique for analogue FM-TV has been proposed and tested by analysis and measurement. This technique simply uses a higher dispersal frequency, ideally of the same order of magnitude as the information element rate of the SCPC signal. In practice, this is approximated by a dispersal frequency at the video line rate. It has been shown that the video signal, for line rate dispersal, does not require additional RF bandwidth. The interference effect on SCPC is then much more like that of a white noise signal uniformly distributed over the dispersal bandwidth, because the SCPC receiver filter can no longer respond to the actual sweeping TV carrier but rather, sees it as occupying an appreciable instantaneous bandwidth. The use of line-frequency dispersal thus results in a $C/I$ ratio comparable to that obtained with other types of transmissions.

Both triangular and sawtooth spreading are effective, and either spreading waveform is easily removable at the receiver. For additional information, see Annex II of Report 384.

It should be noted that single-frequency dispersal of analogue FM-TV at the video line rate may prove unattractive for the reduction of interference into FDM-FM multichannel telephony or other analogue FM-TV carriers since the dispersal frequency may appear in the baseband of other carriers sharing common elements of the transmission system with the dispersed carrier.

For either line rate or frame rate energy dispersal, if the separation between the SCPC and TV carrier frequencies is slightly greater than one half of the sum of the energy dispersal bandwidth and the low frequency peak-to-peak TV carrier deviation, interference at the full TV carrier level cannot occur.

Frequency interleaving could be another means to facilitate the coordination procedure. The extent to which closer satellite spacing and improved orbit/spectrum utilization may be achieved by interleaving the carrier frequencies of one satellite with those of a neighbouring satellite, is critically dependent on the type of modulation (e.g. FM or PSK) and the satellite multiple-access technique (e.g. single carrier or FDMA) applied to the wanted and interfering carriers. The achievable reduction in satellite spacing may be expressed in terms of an improved tolerance to RF interference which, depending on the modulation and satellite multiple-access techniques applied, may vary from about 0 to 12 dB.

For the case of frequency-modulated FDM telephony an improvement in required carrier-to-interference ratio is obtained when interleaved carrier frequencies are used. This is of interest in considering the efficiency of use of the orbit. The improvement is found to be up to about 12 dB, depending upon the modulation indices.

In the case of systems employing a variety of modulation and satellite multiple-access techniques, the maximum interleaving advantage may only be achieved by appropriate coordination and the allocation of traffic or transmission modes to specific satellite RF channels. However, this may not be possible in practice because of the difficulty in accurately forecasting traffic requirements or new applications and the loss of flexibility in reassigning traffic. As noted above in § 3.4, there will be little improvement in satellite spacing requirements to be obtained by interleaving digital signals in such cases, but this is not likely to be a limiting factor, since the spacing required by analogue signals will usually be greater.

In view of the above considerations, the advantages of frequency interleaving between satellites may, in practice, be restricted to relatively few applications.

Coordination may be facilitated by rearrangement of carriers among transponders to minimize mutual interference. Computer techniques for optimum carrier arrangements have been developed for this case.

Coordination may also be facilitated by adjustment of the positions of carriers within each transponder. Techniques to optimize this type of carrier rearrangement have also been developed.

However, it should be noted that such coordination by carriers in an FDMA network would cause substantial operational difficulties due to inability to respond to changes in user requirements. Nevertheless, the pressure of new systems may make such detailed coordination necessary in the future.

A simple method of presenting interference calculations for two adjacent satellite systems is described in Annex II.

## 6. Separation of satellites in space and time domains

### 6.1 *Introduction*

Frequency sharing between satellites of different networks is feasible if sufficient angular separation exists between their satellites, or if the transmitter of one is turned off when sufficient angular separation is not available. The methods for establishing the required spatial and temporal separations for geostationary and non-geostationary satellites are indicated in the following paragraphs.

### 6.2 *Separation angles between geostationary satellites*

Calculations made in [CCIR, 1966-69] show that the required separation angles between satellites are not unreasonable (of the order of 1° to 6°) in most cases. Larger separations are, however, required in the case of multi-channel systems with low modulation indices, or single-channel systems.

### 6.3 *Interference between geostationary and non-geostationary systems*

#### 6.3.1 *Separation in the space domain through orbit gaps*

Angular separation between satellites with inclined orbits and geostationary satellites can be maintained in the space domain only if parts of the goestationary-satellite orbit are reserved for the equatorial crossings of moving satellites.

This approach puts a limit on the number of geostationary satellites that can be employed.

#### 6.3.2 *Separation in the time and space domains*

Separation between satellites in the space and time domains means that, during periods of insufficient spatial separation, temporal separation is achieved by terminating transmissions from one of the satellites causing mutual interference.

The entire system using non-geostationary satellites includes hand-overs, antenna reorientations, and tracking, as part of the normal operating procedures. The need to transfer traffic from one satellite about to be turned off for interference reasons, to another, will not add unduly to the complexity of the overall system.

Figure 1 represents the zone within which interference between geostationary and non-geostationary satellites is possible. This is the volume limited by the surface of revolution around the axis of the Earth formed by straight lines tangent to the Earth and intersecting the plane of the equator at the geostationary orbit altitude.

Interference between geostationary and non-geostationary satellites can be prevented by terminating transmissions from one of them when insufficient angular separation exists for earth stations communicating via these satellites. If earth stations working with a non-geostationary satellite are designed for tracking hand-overs, and rapid antenna reorientations, then technically it should be feasible to cease transmissions from such a satellite when sufficient spatial separation is not available between it and a geostationary satellite. When the geostationary satellite orbit becomes fully utilized, this could mean that non-geostationary satellites should technically be capable of ceasing transmissions when they are in the zone of interference as shown in Fig. 1. However, this is a question which would need to be decided by the administrations concerned.

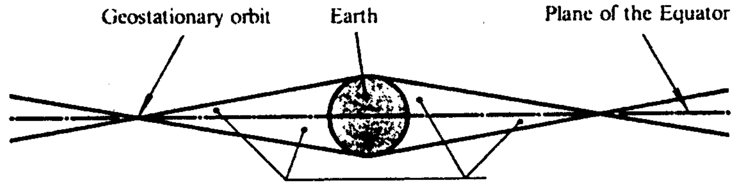



FIGURE 1 — *Zone of interference between geostationary and non-geostationary satellites*

## 7. Summary

This study shows that the minimum angular separation between satellites depends on the acceptable level of interference noise contributions in the baseband channels from other satellites and earth stations.

Frequency sharing between geostationary-satellite networks is feasible if sufficient angular separation is present. The actual spacing required for satellites in the geostationary-satellite orbit depends on system parameters such as e.i.r.p., radiation pattern of earth-station antennas, etc., and cannot be defined in general terms at this time.

Frequency sharing between the networks of geostationary and moving satellites is feasible if one of the satellites is turned off when sufficient angular separation is not provided. The decision on which satellite to turn off will have to be made by the administrations affected.

The actual spacing required between satellites also depends upon the permissible level of total interference and on the way in which this total is built up from the interference entries from individual satellites. The optimization of these levels and the determination of means for regulating them is an important matter for further study under Study Programme 28A/4.

REFERENCES

CCIR Documents

[1966-69]: 4/348 (USSR)
[1986-90]: 4/324 (IWP 4/1 report); 4/342 (U.K.); IWP 4/1 - 1506 (U.K.)

# ANNEX I

## METHOD OF CALCULATING THE WANTED-TO-INTERFERING CARRIER RATIOS IN GEOSTATIONARY-SATELLITE NETWORKS

### 1. Introduction

The amount of interference experienced between two satellite networks depends on the operating parameters of the networks involved. To assess the interference between radiocommunication-satellite networks it is usual to divide the computation process into two stages. The first stage of the calculation is to determine the wanted-to-interfering carrier ratios between any two potentially interfering carriers, at the appropriate receiver input terminals. The second stage is then to relate these ratios to the noise power in the baseband channel. This Annex provides the method for calculating the wanted-to-interfering carrier ratios. For the second stage, reference should be made to Report 388.

### 2. Method

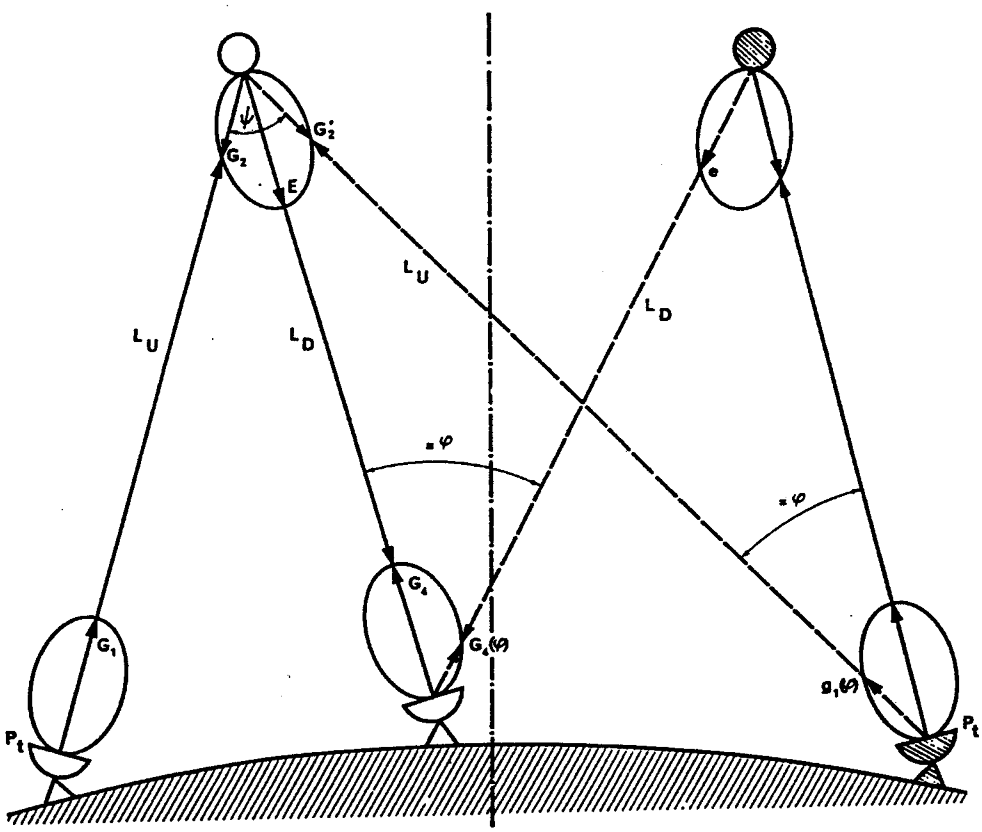
The interference geometry between two satellite networks is shown in Figs. 2a and 2b. The minimum topocentric (as seen from a point on the Earth) satellite spacing angles should take into account the nominal geocentric satellite spacing angle, the satellite position uncertainties (longitude of the orbit nodes and orbit inclinations) and the geographical locations of the earth stations. The use of the geocentric angular spacing, $\varphi$, instead of the topocentric satellite spacing angle, is simpler for the computation and its use is justified by the fact that the two angles are nearly equal. Also, the topocentric spacing angle is always greater than the geocentric spacing angle and hence the calculations based on geocentric spacing angles are conservative.

Radiocommunication satellites require frequency assignments in two frequency bands, one for the up link and the other for the down link. It is current practice for frequency bands to be associated in pairs, one band being used for up links and the other for down links. Case I below, is concerned with the possibility of interference between two networks which have been assigned frequency bands in this way; thus interference from an up link enters the wanted up link and interference from a down link enters the wanted down link. However, it should also be feasible to use a pair of frequency bands in the reverse sense, for some networks, the up-link band for one network being the same as the down-link band for the network using an adjacent satellite; in these circumstances interference from an up link enters the wanted down link and interference from a down link enters the wanted up link. This is Case II.

### 2.1 *Case I*

The following propagation conditions are assumed to apply to the up-link and down-link wanted-to-interfering carrier ratios:

- due to propagation effects and local precipitation both the wanted and the interfering signals which are transmitted by earth stations situated at different points on the Earth's surface will fluctuate. Unless the e.i.r.p.s of the earth stations are adjusted so that the levels received by the satellites are always the same, a margin should be introduced in calculating the mean interference value to the up-link equation;
- the ratio of the wanted signal level to the interference level on the down link does not vary with time. Any interference strong enough to have an appreciable effect would be caused by other satellites close to those of the wanted network so that the discrimination due to the directivity of the earth-station antenna is insufficient to separate the wanted from the interfering signals. Hence the wanted and interfering signals will be attenuated to the same degree when propagation conditions vary, since they will travel through the same disturbed areas. Consequently, fluctuations caused in the received wanted signal will have no significant effect on the level of interference produced in the baseband and, therefore, a down-link margin may usually be neglected.



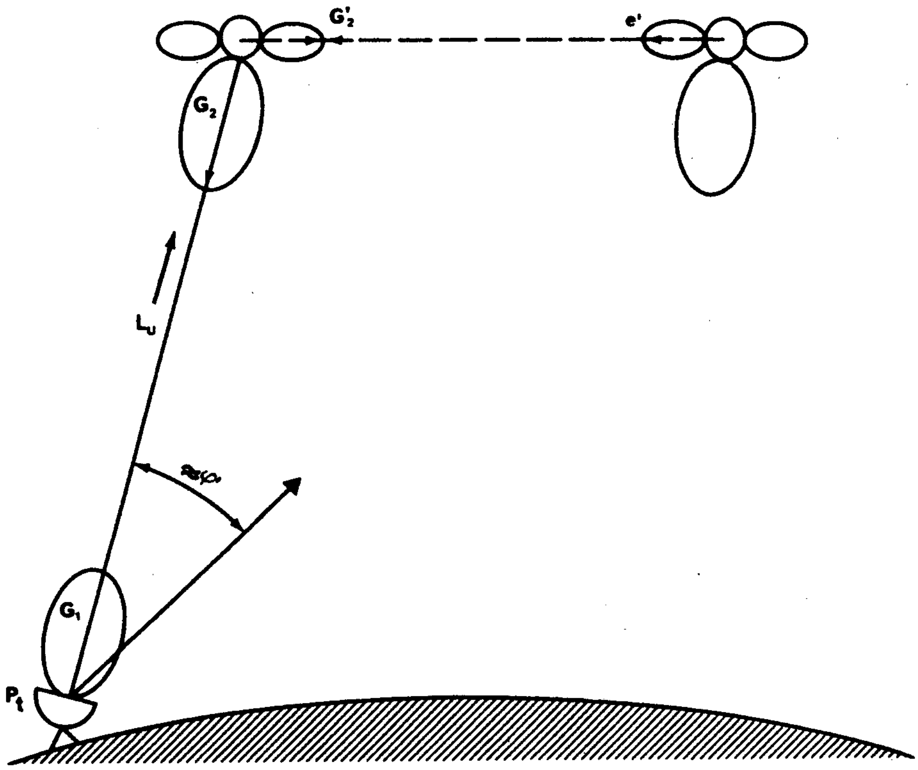

Interfered-with network Interfering network

$$G_2 - G'_2 = \Delta G_2(\psi)$$

——— Wanted signal paths

– – – – Interfering signal paths

FIGURE 2a – *Interference geometry between two satellite networks. Case I – up link of wanted network sharing frequencies with up link of interfering network.*




Interfered-with network

Interfering network

$$G_2 - G'_2 = \Delta G'_2$$

——————— Wanted signal paths

– – – – – Interfering signal paths

FIGURE 2b – *Interference geometry between two satellite networks, Case II – up link of wanted network sharing frequencies with down link of interfering network*

The first stage of the computation procedure requires solution of the two equations:

$$(C/I)_U = P_t + G_1 - \Delta L_U - M_U - p_t - g_1(\varphi) + \Delta G_2 + Y_U \qquad \text{dB} \qquad (4)$$

and

$$(C/I)_D = E + G_4 - \Delta L_D - e - G_4(\varphi) + Y_D \qquad \text{dB} \qquad (5)$$

where:

- $(C/I)_{U,D}$: up- and down-link wanted-to-interfering carrier ratios (dB);
- $P_t$, $p_t$: transmit powers of wanted and interfering carriers delivered to the associated earth-station antenna (dBW);
- $G_1$, $G_4$: transmit and receive antenna gains of one or more wanted earth stations (dB);
- $\Delta L_U$: path loss differential in the up link to the wanted satellite from the two earth stations, $\Delta L = L_{wanted} - L_{interfering}$ (dB);
- $\Delta L_D$: path loss differential in the down link to the wanted earth station from the two satellites, $\Delta L$ as above (dB);
- $M_U$: up-link margin in the wanted network (dB);
- $g_1(\varphi)$: antenna gain component at the unwanted earth station towards the wanted satellite (dB);
- $(\varphi)$: geocentric minimum angular satellite spacing at the interfering earth station;
- $\Delta G_2$: differential in receive antenna gains at the wanted satellite toward the two earth stations, $\Delta G_2 = G_{2\,wanted} - G_{2\,interfering}$ (dB);
- $Y_U$: minimum polarization discrimination between interfering up-link carrier and wanted satellite receive antenna (dB);
- $Y_D$: minimum polarization discrimination between interfering down-link carrier and wanted earth-station receive antenna (dB);
- $E$, $e$: e.i.r.p. of the wanted and interfering carriers in the direction of the wanted earth station (dBW);
- $G_4(\varphi)$: antenna gain component at the wanted earth station toward the interfering satellite (dB).

*Notes on some of the factors in the above equations:*

- Powers and antenna gains associated with the wanted network are in capitals, those associated with the interfering network use lower case letters. Suffixes associated with the various antenna gains follow the signal path, viz: 1 = earth-station transmit, 2 = satellite receive, 3 = satellite transmit, 4 = earth-station receive.
- The antenna gains $g_1(\varphi)$ and $G_4(\varphi)$ should, if possible, be computed using measured earth-station antenna patterns. However, for preliminary calculations, the generalized earth-station antenna radiation pattern given in Recommendation 465 may be applied.
- For very precise calculations the topocentric angles may be used in the expressions for $g_1$ and $G_4$.
- The terms $\Delta G_2$, $E$ and $e$ should, if possible, be computed using measured satellite antenna patterns. Variations of path geometry with time may affect these terms; however, these variations are likely to be small and may usually be neglected.
- In the absence of information on satellite antenna polarization, the factors $Y_U$ and $Y_D$ must be set at 0 dB. The subject of polarization discrimination is discussed in Reports 1141 and 555.

### 2.2 *Case II*

When a given up-link frequency assignment in a wanted network is the same as the down-link frequency assignment in an interfering network, the up-link carrier-to-interference ratio in the wanted network may be approximated by:

$$(C/I)'_U = P_t + G_1 - M_U + \Delta G'_2 - e' + Y' + 20 \log \varphi' - 35.2 \qquad \text{dB} \qquad (6)$$

where (in addition to the preceding definitions):

- $\Delta G'_2$: differential in receive antenna gains at the wanted satellite, in the directions of the wanted transmitting earth station and the interfering satellite, $\Delta G'_2 = G_{2\,wanted} - G_{2\,interfering}$ dB;

$e'$ satellite e.i.r.p. of the interfering carrier in the direction of the wanted satellite (dBW);

$Y'$ : minimum polarization discriminations between the interfering-satellite carrier and the wanted-satellite receive antenna (dB);

$\varphi'$ : geocentric minimum angular satellite spacing for the wanted earth station (degrees).

The calculation of interference from an unwanted up link to the wanted down link, that is, from an earth-station transmitter into the wanted earth station receiver should be based on the techniques discussed in Reports 448 and 388. However, it should be possible to reduce such interference to a negligible level by a careful choice of earth station sites.

2.3 *Link wanted-to-interfering carrier ratio*

– For Case I, the overall wanted-to-interfering carrier ratio is obtained by combining the results of equations (4) and (5) using the following:

$$C/I = -10 \log \left[ 10^{-\frac{(C/I)_U}{10}} + 10^{-\frac{(C/I)_D}{10}} \right] \quad \text{dB} \qquad (7)$$

– For Case II, the wanted-to-interfering carrier ratio* is obtained directly from equation (6).

## 3. Interference

Section 2 provides the formula for calculating the wanted-to-interfering carrier ratio. The specific effects on system service will depend on many additional factors such as: (1) type of service, e.g., telephony, television, data, etc., (2) type of modulation used, e.g., digital, FM, AM, (3) modulation parameters, and (4) desired carrier-to-system thermal noise ratio. Many different types of interfering signal interactions are possible. This is a subject of continuing investigation.

The most common types of transmission used for systems in the fixed-satellite service are: *(a)* FM telephony, *(b)* frequency-modulation television, and *(c)* digitally modulated carriers. The effect at baseband of interference between similar and dissimilar signal types is required in order to predict overall link performance and establish allowable interference guidelines. This Annex presents only a method for calculating the wanted-to-interfering carrier ratios which serve as an input parameter to such calculations.

## 4. Summary

A step-by-step method for the calculation of interference levels between two satellite networks for one set of parameters encompasses the following:

4.1 designate one satellite as the "wanted", the other as the "interfering" satellite;

4.2 choose the parameters required to solve equations (4), (5) or (6) for one of the potential interference entries and designate the parameters in accordance with § 4.1 above;

4.3 solve, for the set of parameters chosen, equations (4), (5) or (6);

4.4 determine the network wanted-to-interfering carrier ratio in accordance with § 2.3 of this Annex, as applicable.

4.5 using the result of § 4.4, and the modulation and frequency spacing data pertaining to the carriers under investigation, determine, by means of Report 388 the interference noise power in the interfered-with carrier;

4.6 repeat the above steps with the designations of "wanted" and "interfering" satellites reversed, wherever applicable;

4.7 repeat the above steps for all combinations of carrier and earth station which might be expected to cause interference in the two networks.

*Note.* – In some cases a given carrier will be subject to interference from more than one interfering carrier. In such cases, it seems permissible to add interference noise contributions on a power basis.

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* Interference between earth stations needs to be considered separately since different propagation conditions and different criteria apply.

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ANNEX II

A METHOD OF PRESENTING INTERFERENCE CALCULATIONS FOR TWO ADJACENT SATELLITE SYSTEMS

This method is based on the definition of two parameters of inhomogeneity between the two adjacent satellites, and a parameter of compatibility between the two satellite systems (including the respective earth stations). The satellites are assumed to serve the same geographical area and to use exactly the same up and down frequency bands. These restrictions can be removed later.

Consider first the case that the satellite system B interferes with the satellite system A. Define the receive inhomogeneity $U_{BA}$ and the transmit inhomogeneity $V_{BA}$ of the satellite B in respect to satellite A:

$$U_{BA} = P_B - P_A \tag{9}$$

$$V_{BA} = E_B - E_A \tag{10}$$

where:

$P_A$, $P_B$ are the power flux densities (in dB) required for reception at the satellite indicated by the subscript, and $E_A$, $E_B$ are the e.i.r.p. values (in dB) of the satellites, respectively. Note that, due to the assumptions above, the wanted values of one system are simultaneously the interfering values in the other system.

Define the compatibility factor $K_{BA}$ (in dB) of system B in respect to system A:

$$K_{BA} \triangleq -10 \log \left\{10^{0.1\,[U_{BA} - \Delta G_B (f_{up})]} + 10^{0.1\,[V_{BA} - \Delta G_A (f_{down})]}\right\} \tag{11}$$

where:

$\Delta G_A$, $\Delta G_B$: the differences between the maximum gain and the side-lobe gain value at $\varphi = 1°$ calculated from the reference radiation pattern (including the correction for $D/\lambda$ for small antennas) of Report 391, for the earth stations in the system indicated by the subscript. (Note that for small antennas the side-lobe gain thus calculated is theoretical only):

$f_{up}$, $f_{down}$: up- and down-link frequencies.

It can then be shown that:

$$25 \log \varphi_{BA} = \left(\frac{C}{N}\right)_A - 10 \log \left(\frac{q}{1-q}\right) - K_{BA} \tag{12}$$

where:

$\left(\frac{C}{N}\right)_A$: the nominal carrier/noise ratio (in dB) at the input of the receiver of the earth station in system A:

$q$: the allowed single entry interference ratio (e.g. $q = 0.04$ for the 4% criterion) and

$\varphi_{BA}$: that angular spacing (as seen from the earth station) between the satellites, at which the single entry criterion is exactly satisfied for interference from system B to system A (account is taken for both up- and down-link interference).

$K_{BA}$ is called the compatibility factor because an increase in $K_{BA}$ makes the angular distance smaller (B is more tolerable to A).

It is illustrative to plot curves of constant $K_{BA}$ using $U_{BA}$ and $V_{BA}$ as coordinate axes. Figure 3 shows an example, where the contour of $K_{BA}$ = + 11.3 dB for antenna diameters $D_A$ = 5 m and $D_B$ = 1 m, $f_{up}$ = 14 GHz and $f_{down}$ = 12.5 GHz, is seen in the lower left-hand quadrant. In the shaded area $K_{BA}$ > 11.3 dB. $K_{BA}$ was chosen so as to correspond to $\theta_{BA}$ = 5° in a system for which $(C/N)_A$ = 15 dB and $q$ = 0.04, as can be verified from equation (12). It is then clear that, if the satellites are spaced at 5°, the single entry criterion in the system A is satisfied everywhere inside the shaded area in the $U_{BA}$, $V_{BA}$ plane.

Interference from system A to system B can be treated in the same manner. Only the subscripts are interchanged. It is noted that $U_{AB} = - U_{BA}$ and $V_{AB} = - V_{BA}$. For that reason the contour of $K_{AB}$ can be plotted in the same figure, as shown in the upper right-hand corner of Fig.3 . If $(C/N)_B$ = 15 dB and $q$ = 0.04, then again $K_{AB}$ = 11.3 dB corresponds to 5° angular distance, and at that distance the single entry criterion is satisfied for the system B inside the curve. It is seen that, in this case, there are no values of $U$ and $V$ which would satisfy the single entry criterion simultaneously for both systems, at a 5° spacing between the satellites.

Figure 4 shows the same case as above except that contours have been drawn also for $D_B$ = 2 m and $D_B$ = 3 m. The allowable limits for the inhomogeneities between the satellites can at once be seen, for each choice of $D_B$, from the plot.

The restrictive assumption that the satellites serve the same geographical area and occupy exactly the same frequency bands can be removed by introducing an additive correction factor to both $U_{BA}$ and $V_{BA}$. Both the effect of the antenna pattern of the satellite antennas and the only partly overlapping frequency bands can be included in these correction factors.

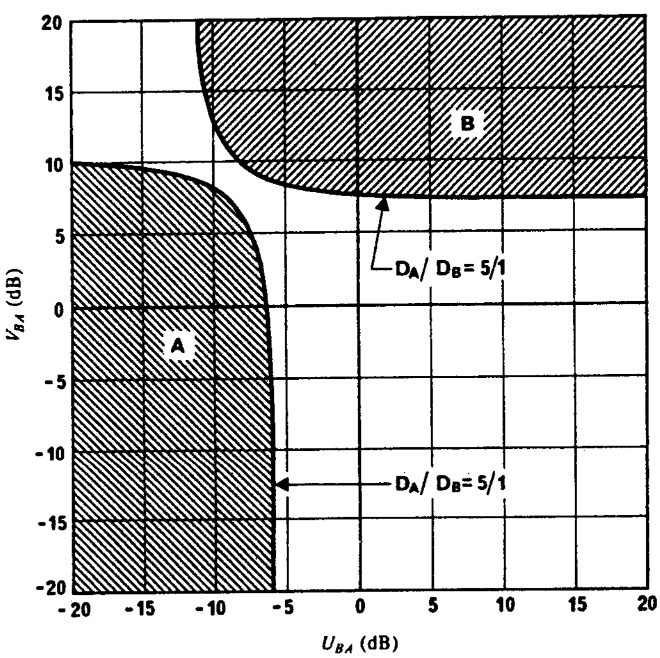



FIGURE 3 – *Principle of the single entry interference plot*

A: Single entry criterion satisfied for system A
B: Single entry criterion satisfied for system B

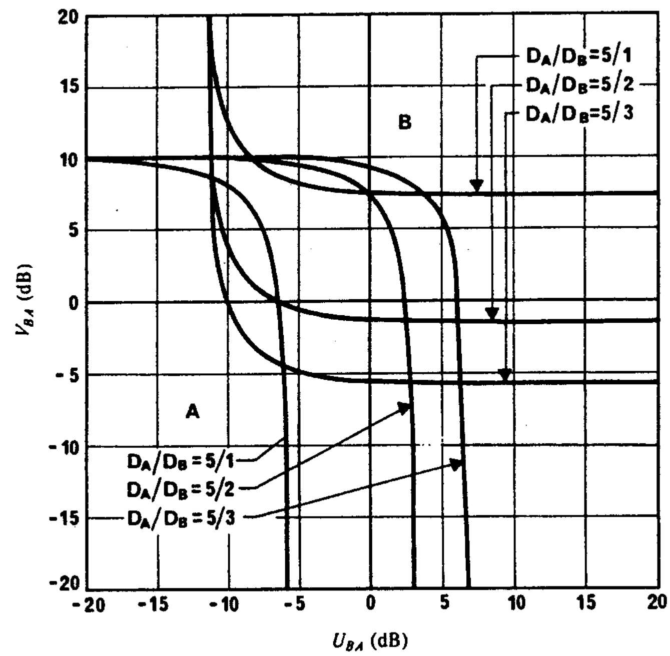



FIGURE4 – *Example of a single entry interference study. Angular spacing of satellites 5°. C/N = 15 dB (both systems), q = 0.04*

A: Single entry criterion satisfied for system A
B: Single entry criterion satisfied for system B

## ANNEX III

## INTERFERENCE INTO ANALOGUE TV SYSTEMS

Recommendation 483 specifies the permissible level of interference into a television channel as a percentage of the total noise and interference in that channel. Section D.3.2.1 of Recommendation 567 specifies the video signal-to-weighted-noise level in a hypothetical reference circuit carrying an analogue television signal. There are two very different methods to determine the pre-detection carrier to interference ratio (C/X) which would give results consistent with both of these recommendations. These are:

a) the "objective" method that is described in section 3 of Report 449, and

b) the "subjective" method, described here, based on CCIR Report 405, CCIR Recommendations 500 and 600 , and work done in Canada [Bouchard G. et al, 1984].

When using the objective approach the carrier-to-interference ratio(C/X) is related to the video signal-to-interference ratio (S/I) by the relationship.

$$(S/I) = (C/X) + Bv \qquad \text{(in dB)} \qquad (1)$$

where Bv is the video interference reduction factor. For an analogue frequency modulated NTSC television signal interfered with by a similar signal, Bv is approximated by the empirical relation

$$Bv = 6 + 20 \log_{10} (\Delta f) \qquad \text{(in dB)} \qquad (2)$$

where $\Delta f$ is the peak-to-peak frequency deviation of the wanted signal. When using the subjective approach, i.e. the approach based on tests of television signal acceptability by viewers, a more indirect route must be followed. In this approach the basic unit is "impairment" of the television signal on the screen, rather than "interference" measured within the equipment.

Impairment can be related to the television picture quality Q by the relationship

$$Im = (5 - Q) / (Q - 1) \qquad (3)$$

Analysis of the subjective measurements reported in [Bouchard G. et al, 1984] suggests that for NTSC the impairment Im of (3) can be related to the video weighted $S/N_w$ ratio of Recommendation 567 by the empirical expression

$$Im = \exp[30.9 - 8.41 \log_e (S/N_w)] \qquad (4)$$

and that the impairments from different sources, i.e., from thermal noise, interfering signals, etc. can be added, i.e.

$$(Im)_r = (Im)_n + (Im)_i \qquad (5)$$

Further, the impairment due to an interfering NTSC frequency modulated signal can be related to the pre-detection carrier-to-interference ratio (C/X) of these signals by the equation

$$(C/X) = 16.9 - 8.7 \log_{10} (Im)_i - 20 \log_{10} (\Delta f/12) \qquad (6)$$

where $\Delta f$ is the same peak-to-peak frequency deviation of the wanted signal that appears in equation (2). Use of equations (5) and (6) together with either (3) or (4) to specify the performance of the hypothetical reference circuit will produce the required C/X, the same quantity that is specified in a very different way by the equations (1) and (2).

It is instructive to compare the required C/X values from these two very different approaches. To do this numerically, it is necessary to assume a typical set of system characteristics. Let us assume that the video signal to noise ratio due to thermal noise alone is 53 dB as specified by Recommendation 567-2, and $\Delta f$ = 20 MHz. The results using the two approaches are shown in Table III.

TABLE III - Required pre-detection carrier-to-interference ratio (C/X)

| Interference or impairment as a percentage of the total link budget | Estimate Using objective Approach | Estimate Using Subjective Approach | Difference |
|---|---|---|---|
| 10%<br>20% | 30.5 dB<br>27.0 dB | 30.17 dB<br>27.11 dB | 0.33 dB<br>0.11 dB |

The difference between the estimates of required C/X using the two approaches is quite small, given that they were both arrived at in different ways involving the use of empirical formula based on very different types of laboratory measurements. This very close agreement when typical values of fixed satellite systems are considered for CCIR network-quality transmission (S/N = 53 dB) leads to the conclusion that the simpler method described in section 3 of Report 449 may be used in applying Recommendation 483.

Since the measurements described in Report 449 were carried out using NTSC desired and interfering signals, equations (1) and (2) provide accurate estimates of the interference environment for this combination of interfering and interfered-with signals.

**Where the network under consideration has a performance significantly different from that indicated in Recommendation 567-2, it should be noted that the two methods may not lead to the same permissible C/X ratio. Application of equations (1) to (6) for various values of weighted signal to noise ratios yields the C/X values indicated in Figure 5 for the two methods. From the results, it may be observed that the two methods give a very close (C/X) ratio in the range of (S/N) value from 51 to 55 dB. For other (S/N) values, the difference in the required pre-detection carrier to interference ratio between these two approaches becomes significant. Hence, we can conclude that the objective method can be used in confidence when calculating the required (C/X) ratio in the (S/N) range of 51-55 dB but the difference becomes significant outside that range.**

An experiment was performed to estimate Bv for various other interfering carrier types [CCIR, 1986-90]. The object of this measurement program was to determine protection ratios that corresponded to "just perceptible interference" and $S/N_w$ for the existing three analogue video standards when interfered with by various capacity FDM/FM carriers or a 120 Mbit/s TDMA carrier. The protection ratios, actually the C/I, when the interference effect just became perceptible, were measured as a function of the frequency offset between the center frequencies of the interfering and victim carriers. The $S/N_w$ was determined only for the situation where the two carriers were co-frequency. The victim carrier was modulated with a colour bar waveform with sufficient amplitude to produce a peak-to-peak video deviation of 15 MHz.

The victim carrier was then combined with an interfering carrier, bandpass filtered with a 20 MHz filter and demodulated. This demodulated waveform was displayed on a picture monitor which was viewed under the reference conditions set out in Report 634. The perceptability of the interference was determined by an expert observer so that the level of picture impairment is equivalent to an approximate rating of 4.75 out of 5.0. Throughout the measurements, the carrier to thermal noise ratio C/N was held constant at 17 dB. This level corresponds to the nominal level maintained at that time in the INTELSAT System for half transponder video transmission.

Measurements were made for the following types of interfering carriers:

a) Color Bar Modulated FM TV (same TV standard as the victim carrier)

b) Frame Rate Energy Dispersal Frequency (EDF) Modulated FM (1 MHz peak-to-peak deviation)

c) 24 channel/2.5 MHz bandwidth FDM

d) 60 channel/5.0 MHz bandwidth FDM

e) 132 channel/10.0 MHz bandwidth FDM

f) 252 channel/10.0 MHz bandwidth FDM

g) 252 channel/15.0 MHz bandwidth FDM

h) 432 channel/15.0 MHz bandwidth FDM

i) 972 channel 36.0 MHz bandwidth FDM

j) 120 Mbit/s QPSK TDMA

The resulting values of Bv are presented in TABLE IV.

TABLE IV - Measured interference reduction factors, Bv (dB), for various interfering carrier types

| | NTSC | PAL | SECAM |
|---|---|---|---|
| $S/N_w$ without interference | 48.9 dB | 50.4 dB | 50.5 dB |
| Color Bar | -- | 31.7 | 27.7 |
| EDF | 27.2 | 23.7 | 30.8 |
| 24/2.5 | 23.3 | 26.5 | 27.1 |
| 60/5 | 28.0 | 25.3 | 22.6 |
| 132/10 | 27.0 | 26.3 | 22.1 |
| 252/10 | 23.8 | 22.2 | 22.7 |
| 252/15 | 27.2 | -- | 26.5 |
| 432/15 | 27.0 | 27.0 | 24.7 |
| 972/36 | 32.0 | 27.5 | 22.0 |
| TDMA continuous | 31.5 | 27.9 | 27.3 |
| TDMA burst | 31.3 | 28.9 | 28.0 |

Further work may be required to determine the value of Bv for other combinations of interfering and interfered-with signals. It would be useful to develop an empirical formula for Bv to simplify the calculations.

Note - The information in this annex should be taken into account in future considerations of Recommendation 483.

## REFERENCES

BOUCHARD M. , CHOUINARD G. and TRENHOLM R.,[December, 1984] "Subjective Evaluation of the Effects of Noise and Interference on Frequency Modulated NTSC Television Signals", CRC Report No. 1367, Department of Communications, Ottawa, Canada.

CCIR Documents

[1986-90]: 4/312 (USA) and 4/314 + Add.1 (Canada).

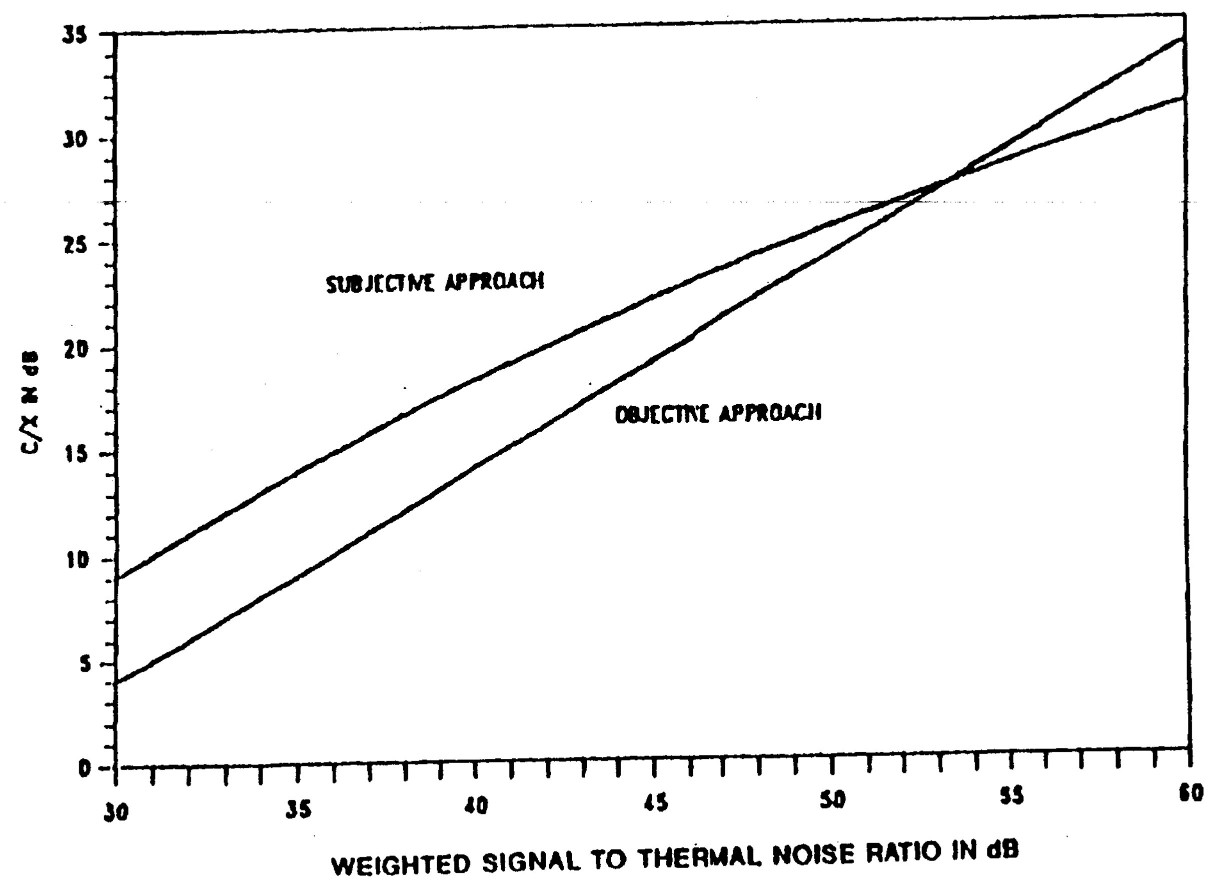



FIGURE 5: Graph of C/X versus S/N for FM/TV reception with interference equal to 20% of the total link budget

ANNEX IV

The relationship between aggregate and single-entry interference levels

## 1. Introduction

Inter-system interference between geostationary satellite networks depends to a great extent on the side-lobe characteristics of earth station antennas for co-coverage situations and on the characteristics of satellite antennas outside the coverage area when the coverage areas are separated. An optimum or judicious mix of satellite and earth station antenna discrimination is necessary for the efficient utilization of orbit/spectrum resources. An important aspect of this process is the determination of the interference effects of a number of satellite networks as compared to a pair of adjacent satellite networks. A comparison of single-entry versus aggregate interference effects is related to the determination of appropriate interference limits for such CCIR Recommendations as 466 and 523.

This annex presents several analyses [CCIR 1986-90a-e] involving a variety of satellite arrangements and interference conditions and provides the results obtained for the relationship between single-entry and aggregate inter-satellite interference.

## 2. Homogeneous model-variable satellite antenna discrimination

### 2.1 General

Various degrees of satellite antenna discrimination can exist between satellite networks depending on the respective coverage areas of the satellite antennas. When the coverage areas overlap (co-coverage) little or no discrimination exists and network isolation is achieved with only earth station antenna discrimination. For separated coverage areas adequate discrimination can be achieved by a combination of earth station and satellite antenna discrimination. When the coverage areas are far apart most, if not all, of the discrimination can be provided by the satellite antenna.

These situations are combined in a homogeneous model which assumes an array of equally spaced satellites in which satellites with antenna discrimination are placed between co-coverage satellites. With this model estimates of the aggregate to single-entry interference ratios may be made.

### 2.2. Simplified model

This model assumes that the earth station antenna discrimination is proportional to $\varphi^{-2.5}$; i.e., the satellite spacing is greater than the off-axis angle corresponding to the first side-lobe plateau of the earth station antenna. No satellite station keeping or earth station pointing tolerances are included. Where satellite antenna discrimination exists it is assumed to be the same for all satellites.

A series of satellite networks are postulated; A, B, C etc. where satellite antenna discrimination can exist between each but no discrimination exists between individual A's, B's, C's, D's etc. Sequences can be postulated in which a number of satellites with antenna discrimination are placed between co-coverage satellites.

The equations which relate the multiple entry (ME) to single-entry (SE) ratio, (ME/SE) are of the following form in which all parameters are dimensionless numerical ratios:

$$ME/SE = W + X/\alpha \qquad : \alpha \geq \alpha_c \tag{1a}$$

$$ME/SE = Y\alpha + Z\alpha \qquad : \alpha \leq \alpha_c \tag{1b}$$

The parameter ($\alpha$) is the satellite antenna discrimination and ($\alpha_c$) is the value of discrimination which results in the highest value of (ME/SE).

Equation (1a) is the case where the highest single-entry is the adjacent satellite, and the minimum separation angle ($\varphi_1$) is determined by that entry. Equation (1b) is the case where the minimum separation angle is determined by the nearest satellite with no satellite antenna discrimination; ($\varphi_1$) being the angle between the nearest co-coverage satellite divided by the number of intervening satellites plus one. Thus, ($\varphi_1$) varies when $\alpha \geq \alpha_c$ and is constant when $\alpha \leq \alpha_c$.

Assuming 24 entries (twelve on either side of an interfered with network), constants for the above equations are.

| Number of satellites between co-coverage satellites | W | X | Y | Z | $\alpha_c$ |
|---|---|---|---|---|---|
| 1 | 2.1928 | 0.4601 | 12.404 | 2.6027 | 0.1768 |
| 2 | 2.4896 | 0.1632 | 38.809 | 2.5440 | 0.06415 |
| 3 | 2.5752 | 0.0776 | 82.406 | 2.4832 | 0.03125 |
| 4 | 2.6107 | 0.0421 | 145.943 | 2.3546 | 0.01789 |
| 5 | 2.6261 | 0.0267 | 231.574 | 2.3545 | 0.01134 |

This model can also be used for the co-coverage cross-polarization case where satellites with opposite polarizations are interleaved. In this case, the intervening number of satellites is one.

The ratio ME/SE equals W + X for the co-coverage co-polar situation ($\alpha = 1 = 0$ dB). The ME/SE varies from two with one interfering satellite on each side of the interfered with satellite to 2.65 for 12 satellites on each side as shown in Figure 6.

Equation (1) is plotted in Figure 7 as a function of ($\alpha$) and (ME/SE) for various sequences. The highest value of (ME/SE) is achieved for one unique value of satellite discrimination ($\alpha_c$) and drops rapidly for higher or lower values. This occurs when the nearest satellite entry with proper discrimination is equal to the nearest satellite entry with no discrimination. Also it is noted that the value of ($\alpha_c$) is a function of the sequence. It would appear highly unlikely that four equal level single-entries would occur in practice and thus a single-entry level based on the highest (ME/SE) shown in Figure 7 could be quite conservative.

Figure 7 is also useful in determining the satellite antenna discrimination required to make the contributions from adjacent satellites relatively small compared to the co-coverage satellites. A value of 25 dB of satellite antenna discrimination for the first side-lobe plateau would effectively isolate up to four intervening satellites between a pair of co-coverage satellites.

## 2.3 Model with complete earth station antenna patterns and tolerances

Homogeneity is again assumed. However, due to the segmented earth station antenna pattern and the manner in which tolerances are accounted for, the equations given for the simplified model cannot be used. For the following analyses, the assumptions are:

1) the earth station antenna discrimination is determined using Annex VII of Appendix 29 patterns which removes the restriction of being beyond the first side-lobe plateau of the earth station pattern;

2) the required composite earth station and satellite antenna discrimination is 30 dB;

3) the satellite station keeping tolerances are ± 0.1 degrees and the earth station pointing accuracy is assumed to correspond to the -1 dB relative gain angle.

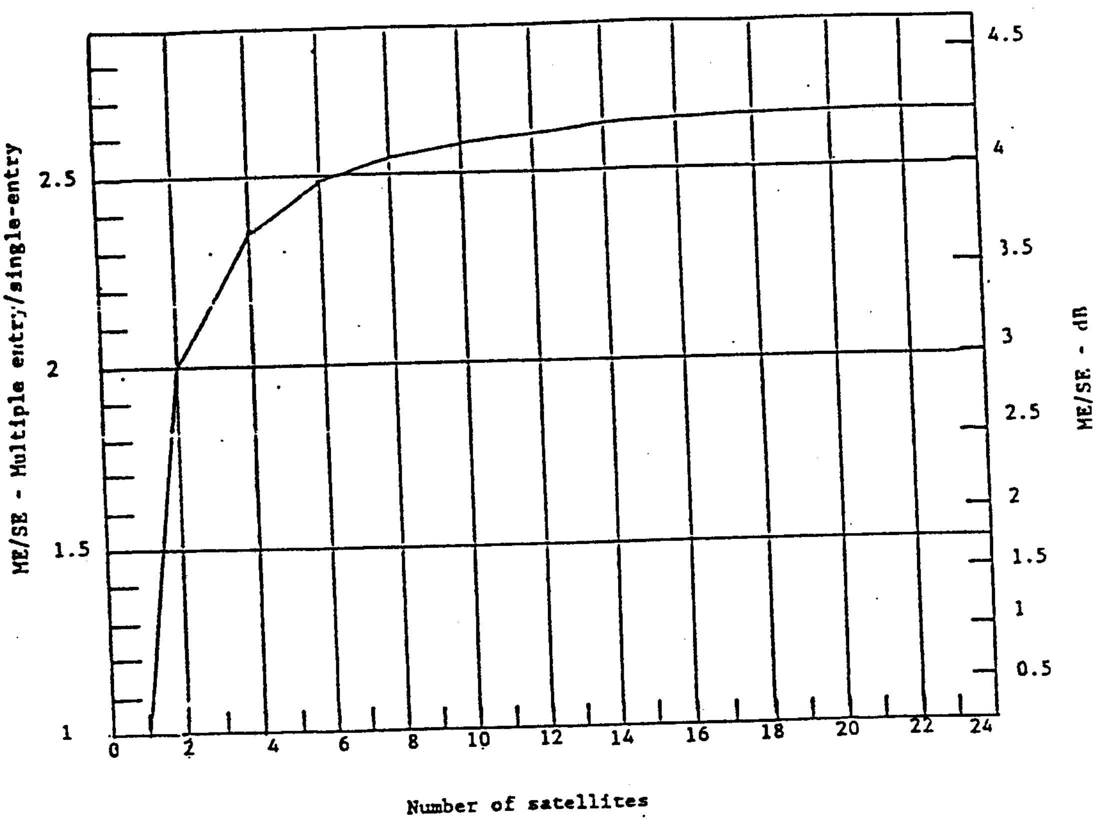



FIGURE 6

ME/SE versus number of co-coverage satellites

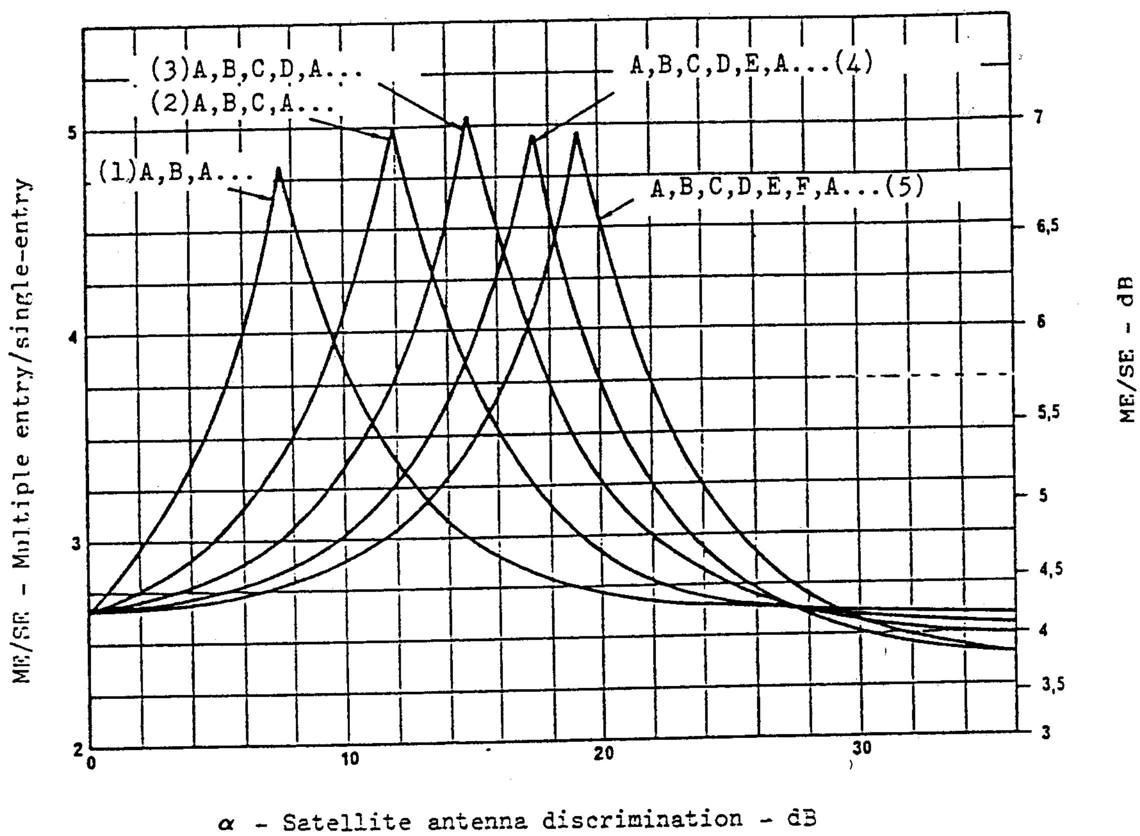


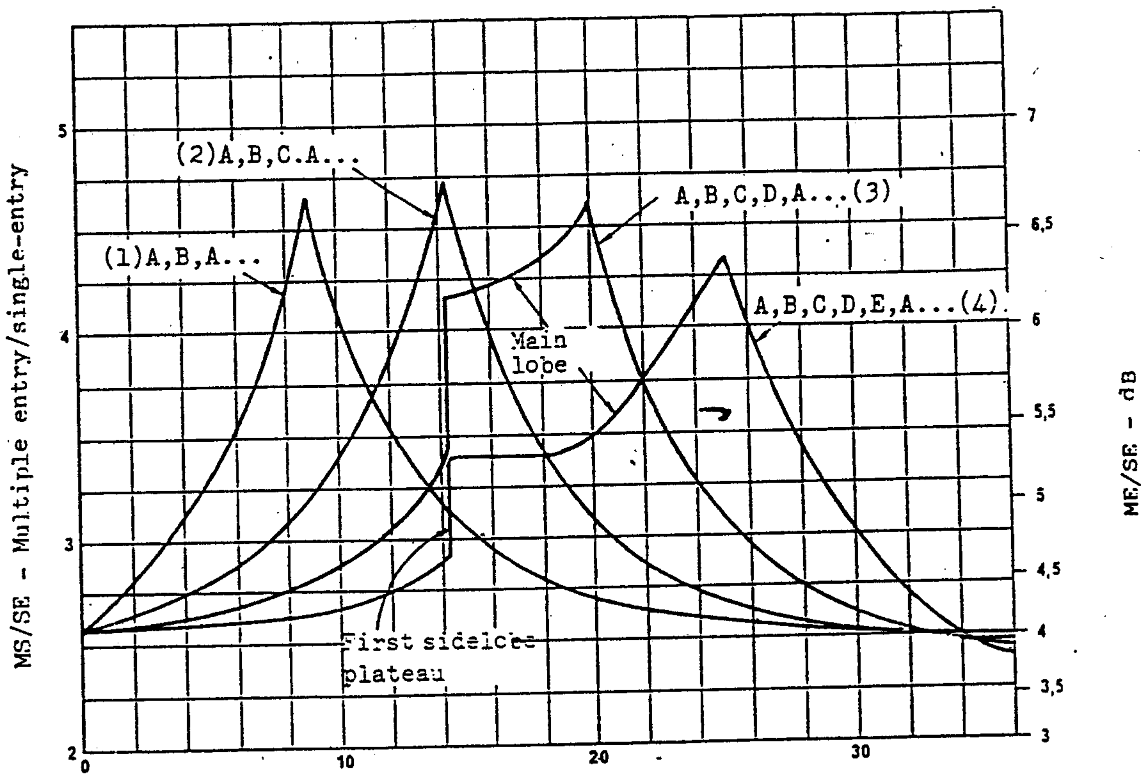

FIGURE 7

ME/SE versus α

Since the spacing between pairs of satellites is determined by worst case SE criteria, the nominal spacing between satellites is the angle where the earth station plus satellite antenna discrimination meets the SE required (30 dB assumed) plus the most unfavourable tolerance situation. For this model, the highest ME/SE will occur when the interfering satellites are at their minimum spacing with respect to the interfered with satellite. This is the condition assumed for these analyses.

Analyses similar to those of the simplified model can be made for various earth station antenna $(D/\lambda)$s and similar results can be obtained. Figure 8 shows the same functions as Figure 7 for an earth station $D/\lambda = 100$. The main-lobe and first side-lobe plateau of the earth station patterns distort the functions when $(\alpha < \alpha_c)$ as compared to the functions of Figure 7. The peak (ME/SE) ratios are somewhat lower than in Figure 7 which is due to the incorporation of the tolerances.

Again, it would appear highly unlikely that the satellite antenna discrimination values required to provide four equal level entries would simultaneously occur in practice. Additionally, it is also highly unlikely that all the interfering satellites would be at their extreme worst case tolerances. If the satellite spacing corresponds to the maximum permissible single-entry level with most adverse tolerances, the ME level, when all satellites are at their nominal positions, may be considerably lower than the worst case condition.




α - Satellite antenna discrimination - dB

FIGURE 8

ME/SE versus α for D/λ = 100

## 2.4 Application

The above analyses do not account for any statistical advantage due to the random placement of interfering carriers with respect to desired carriers. The effective reduction of the ME/SE for FM carriers is significant. However, the effect is generally considered not significant for digital carriers because of their relatively flat spectral densities.

Thus, the above models and results are most applicable to digital carriers.

## 2.5 Summary

Of the two models analyzed the model which includes full earth station antenna patterns and other tolerances is considered more realistic. The following general conclusions are enumerated.

1) The satellite antenna discrimination corresponding to peak multiple entry to single entry ratios is a function of the number of satellites with antenna discrimination that are placed between satellites with no antenna discrimination. The satellite antenna discrimination corresponding to these peaks increases with the number of interleaved satellites. For a satellite antenna discrimination of 25 dB at the first side-lobe plateau, 2 to 3 satellites with this level of discrimination may be placed between co-coverage satellites with little effect on the multiple entry level.

2) The peak values of multiple-entry to single-entry ratios are in the range of 4.5 to 5.0. The peak values occur at specific satellite antenna discrimination values and drop rapidly as the values depart from these specific values. The probability of the specific set of conditions necessary for these peak values occurring in an actual situation is considered to be low and thus lower practical values should be considered. These peaks can also be intentionally avoided. Values less than 4 may be appropriate but further study is needed in this area.

3) Satellite antenna discrimination may not be adequate for co-locating satellites whose coverage areas do not overlap. Even if the satellite antenna discrimination is adequate, it is advantageous to space satellites with antenna discrimination (interleaved between co-coverage satellites) in order to increase the discrimination between satellites.

4) Satellite station keeping and earth station antenna pointing tolerances are a significant factor for closely spaced satellites.

## 3. Aggregate to single-entry interference ratio in a high-capacity orbit-use scenario

The geostationary orbit utilization is maximized when full use is made of spacecraft antenna discrimination, polarization discrimination and earth station antenna discrimination. Figures 8 and 9 of that annex illustrate the theoretical optimum use of the GSO.

It is important to determine the relationship between aggregate and single-entry interference in such an environment. This ratio provides an upper bound to the ratio experienced in practice, just as the same model provides an upper bound on orbit capacity.

In this situation, the interference is produced by a series of adjacent satellites, alternately adjacent coverage and co-coverage. Protection is provided by the earth station antenna, and, in the case of adjacent coverage satellites, the satellite antenna. The resulting interference is shown relative to that caused by adjacent co-coverage satellite. The protection afforded by the satellite antennas is assumed to be 25.5 dB.

Although actual service areas of a satellite network are likely to be fairly complex it is desirable to use as a model a service area configuration which is conceptually simple.

In this case, the model should allow for interference from those transmissions which are intended for the neighbouring areas which surround the "interfered with" area.

Figure 9 shows an array of cells representing the projections of a large number of transmissions on the Earth's surface. The topologically simple regular array has been chosen to simplify calculations showing, with a cross, each area which might be served from one orbital position. As the lines representing transmission to particular cells from one satellite position clutter the diagram, they have been deleted. The served areas are joined with dotted lines to illustrate what is meant, later, by a "shell" of interfering services.

Consideration has been given to interference arising in a situation where the area-to-area distances represent constant regular changes in protection angle at the satellite, but a "row-to-row" variation in down link power density is 4 dB (see e.g. Report 1001, Table I, for potential variations in power density). This condition is represented with alternate "rows" shaded differently. Rows shaded by hatching have the high power level.

Assuming antenna protection follows a -25 log $\varphi$ law. The interference level with respect to the singly-entry level is about 10.8 dB for one shell, 12.1 dB for two shells, and 12.8 dB for three shells.

As the number of shells in a practical situation may, but is unlikely to, exceed 3, the approximate worst condition for three shells may lead to a asymptotic interference level about 13 dB greater than the single-entry value.

Another analysis, based on rectangular cells rather than the hexagonal cells used above, resulted in an asymptotic value for the aggregate interference to single-entry interference ratio of about 11 dB; 10 equal-level entries plus 4 low-level entries. When this model was applied to Region 2 countries, the worst case ratio was found to be about 4 (or 6 dB) for co-channel operation, i.e., there is no statistical advantage due to carrier offsets. More probable situations resulted in aggregate to single entry ratios of three or less.

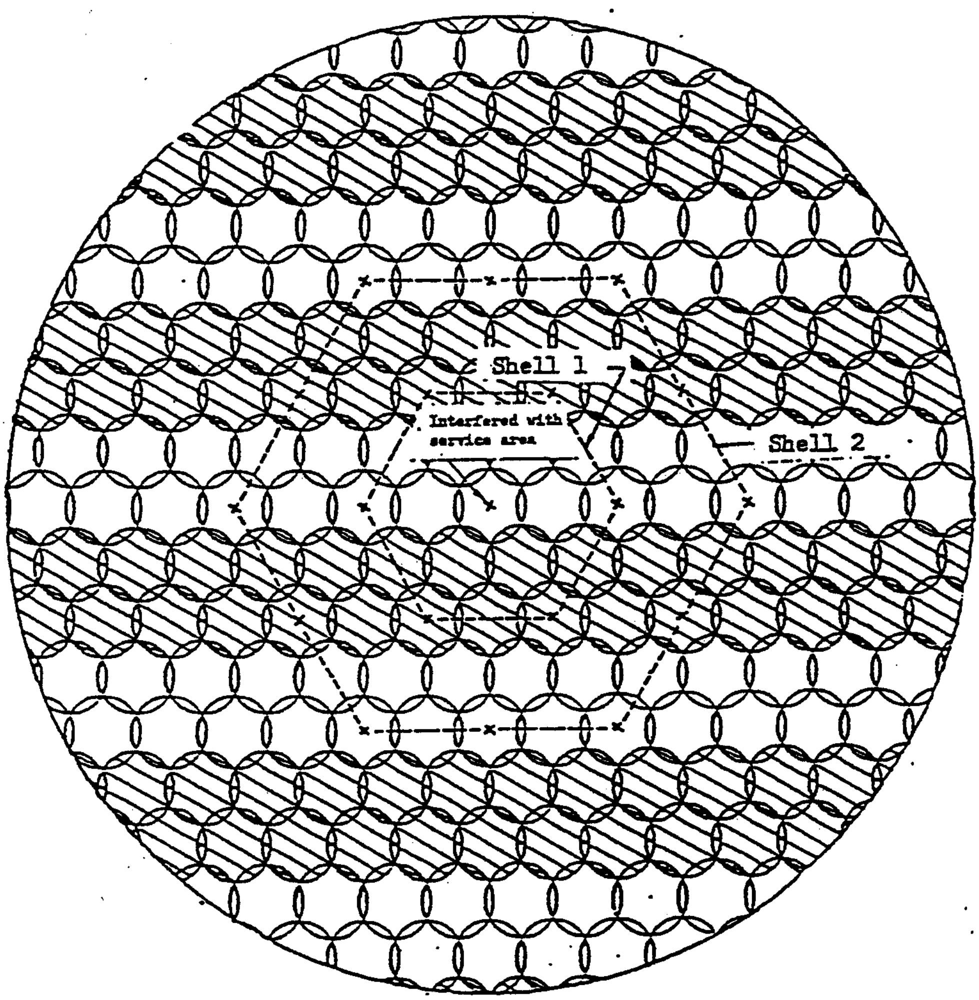



FIGURE 9

Multiple service areas located within subzone

## 4. Statistical estimates of aggregate to single entry interference ratios

The relationships between the maximum single entry interference level and the aggregate interference level for FDM/FM carriers and those for digital carriers have been examined through extensive computer simulation.

A mix of co-coverage and non-co-coverage networks has been considered in order to develop this relationship under a more realistic situation.

In the computer simulation, the aggregate interference into a FDM/FM carrier of a given satellite network due to FDM/FM carriers of other satellite networks is computed. The carriers, which are all equal within each network, have a variety of parameters, and the interfering carrier frequencies relative to the desired carriers are randomly assigned. These interfering carriers are transmitted in networks whose space stations are located at various orbital separations from the satellite with the wanted carrier.

The spacings between satellites are determined based on the co-channel interference assumption which is normally adopted in the course of internetwork coordination. They are determined such that, i) the maximum single-entry interference into every network, as calculated on the co-channel assumption, for all possible combinations of wanted and interfering satellites, does not exceed the applicable single-entry allowance; and ii) the total orbital arc occupied by all the satellites for that ordering is a minimum.

Three single entry levels, i.e. 600 pW0p, 800 pW0p and 1,000 pW0p with the co-channel assumption are considered to determine the spacings between networks. Then the carrier frequencies are randomly shifted so as to simulate the effect of frequency interleaving, and the aggregate interference in each network is evaluated. Therefore, in this interference model the single entry level in any combination of network does not exceed the applicable single-entry criterion.

Figure 10 depicts the cumulative distributions of the aggregate interference thus computed based on 600 pW0p, 800 pW0p and 1,000 pW0p single-entry levels. This figure displays the probabilities with which the aggregate interference exceeds the value on the abscissa after the simulation of random frequency interleavings is taken into account.

It is observed from Figure 10 that, as a result of frequency interleaving, the probability of the aggregate interference exceeding a value of 2.5 times the given co-channel based single-entry level for co-coverage as well as for non-co-coverage networks is less than 1%.

In computing the aggregate interference into digital carriers, another computer simulation was carried out for various types of digital carriers. As in the FDM/FM case, the spacings among networks are determined on the basis of the co-channel interference assumption. A number of satellite arrangements were considered to determine the statistical distribution of aggregate interference. It is noted that, in the case of digital carriers, little advantage due to frequency interleaving is expected.

The single entry criteria considered are 4% and 10% of the total noise power which would correspond to a BER of $10^{-6}$.

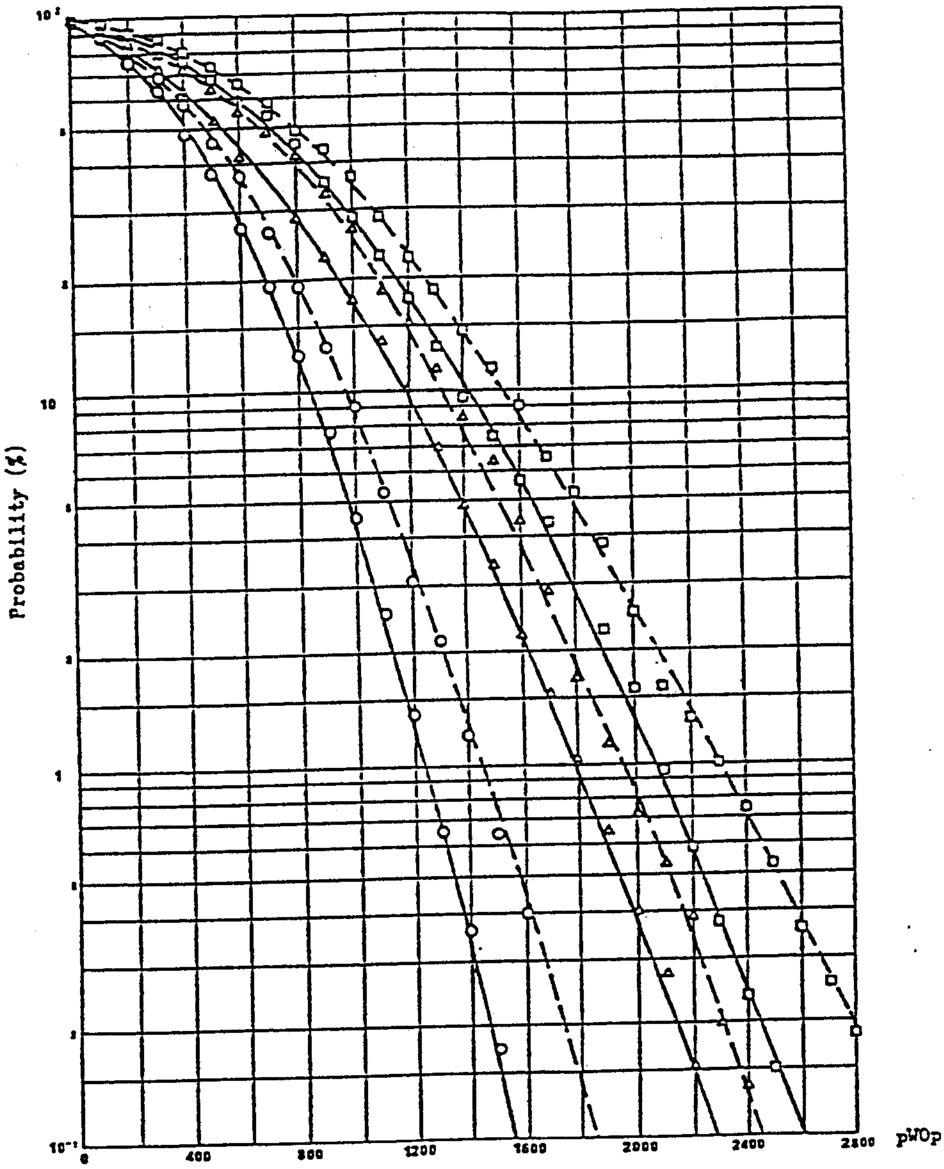



FIGURE 10

Distribution of aggregate interference (FDM/FM carriers)

| | | Single Entry |
|---|---|---|
| ——— | Non-co-coverage | O 600 pWOp |
| | | Δ 800 pWOp |
| — — | Co-coverage | □ 1000 pWOp |

Figure 11 shows the cumulative distributions of aggregate interference calculated, based on the 4% and 10% single-entry interference criteria. The distributions of aggregate interference are expressed in terms of percentage with respect to total noise power.

By reference to Figure 11 it is observed that the probability of the aggregate interference exceeding a value of 4.5 to 5 times the applicable single-entry criterion is close to 1%.

## 5. Examples of aggregate to single-entry interference ratios in an orbit-use arrangement similar to the FSS allotment plan

The allotment plan developed at WARC ORB-88 is an example of a high utilization of the geostationary orbit, if all allotments are brought into service as indicated by the Final Acts of the Conference. This is particularly the case for that portion of the GSO serving Region 1. It is useful to use these results of that Conference to examine the statistical characteristics of the ratio "$\gamma$" between the appropriate single-entry interference criterion and the aggregate interference which would be experienced by the satellite networks in such an environment. This information is intended to be complementary to the information provided through the analytical modelling of sections 2 and 3 of this annex and the simulation of analogue networks in section 4.

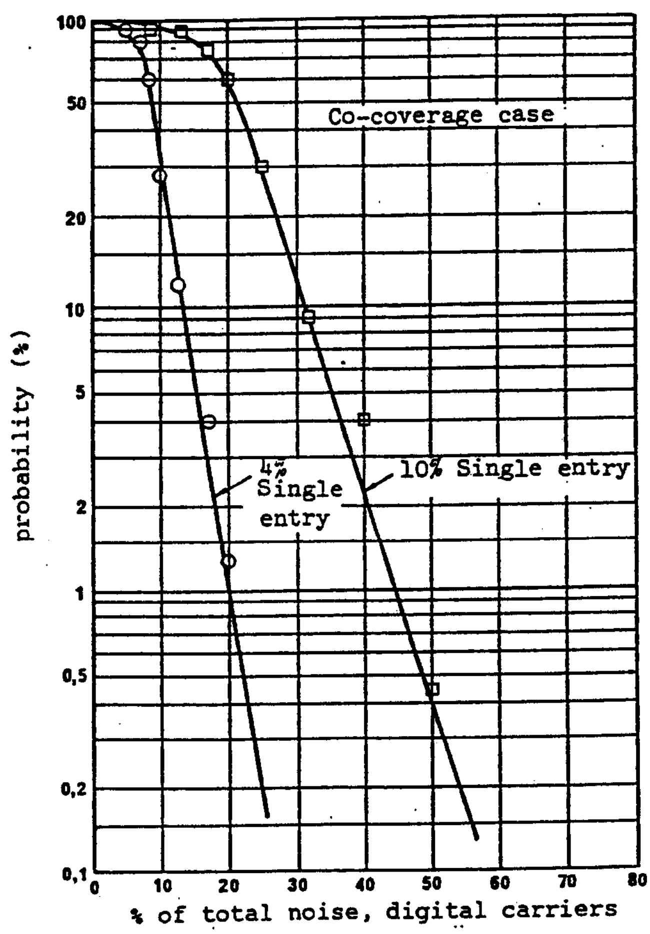



FIGURE 11

Distribution of aggregate interference (% of total noise, digital carriers)

5.1 Simulation example 1

One simulation study using the ORBIT-II computer program as made available by the IFRB in 1988 is reported in [CCIR, 1986-90h]. In this scenario the "requirements" were the 113 satellite beams of Part A of the allotment plan of WARC ORB-88 between 45°W and 50°E. This arc was chosen for examination because it is the most highly utilized orbital arc of the plan.

In this simulation only the "ordering" portion and the "analysis" portion of the ORBIT-II program were used. (The ordering portion is that portion of the program that selects the orbit positions of the required satellites such that all of the single-entry interference levels are less than a specified maximum interference "criteria".) This was done to simulate the situation in which satellite positions are chosen based on single-entry consideration.

The networks accommodated in the simulation had the same technical characteristics as specified in the allotment plan of WARC ORB-88. Specifically, co-channel frequency and co-polarized operation of the networks involved was simulated, representative of networks carrying wideband digital traffic. The one variation from the allotment plan technical parameters imposed on the simulation was that the single-entry (C/I) criterion was increased to simulate a highly-utilized orbit in which the "compression ratio" of the ORBIT-II synthesis result was equal to or slightly greater than unity. Specifically, syntheses with nominal (C/I) single-entry ratios of 33 and 35 dB provided results of a fully-utilized arc, with compression ratios of 1.088 and 1.112 respectively.

The ORBIT-II synthesis program provides several ordering routines, i.e. choices of which network to consider first. The "westerly first" routine was used in the synthesis reported here. Satellites operating in the 6/4 GHz frequency band were simulated.

The analysis portion of the program was used to determine the aggregate interference of each of the 113 networks in the 95° wide arc from 45°W to 50°E, and this aggregate value was compared with the single-entry criterion. The ratio "r" for each entry was calculated in dB and this set of 113 results was used to estimate the statistical characteristics of the random variable r. The estimates of the probability distribution function of this variable are shown in Figure 12 for both the 33 dB simulation and the 35 dB simulation described above. These cumulative histograms are estimates of the probability distribution function of the ratio r, a random variable from one network to the next. In generating the estimates of the probability distribution functions in Figure 12, correction was made for the fact that the compression ratio of the resulting orbital arrangements were greater than unity. The single-entry criterion of the "33 dB" simulation was reduced by 25 $\log_{10}$ (1.088) to 32.09 dB, and the "35 dB" simulation's criterion was reduced by 25 $\log_{10}$ (1.112) to 33.85 dB.

For this scenario, the probability distribution function estimates of Figure 12 may be used to estimate the required single-entry to aggregate interference criterion necessary to ensure that a specified percentage of networks experience an aggregate interference not greater than the aggregate interference criterion, i.e. the aggregate interference level to which they would presumably be designed to accommodate. In this example, if 90% of the networks are to experience aggregate interference levels below the aggregate criterion, the "33 dB" curve of Figure 12 suggests that the ratio between single-entry criterion and aggregate criterion should be in the order of 5.53 dB, and the "35 dB" curve suggests that this ratio be in the order of 5.61 dB.

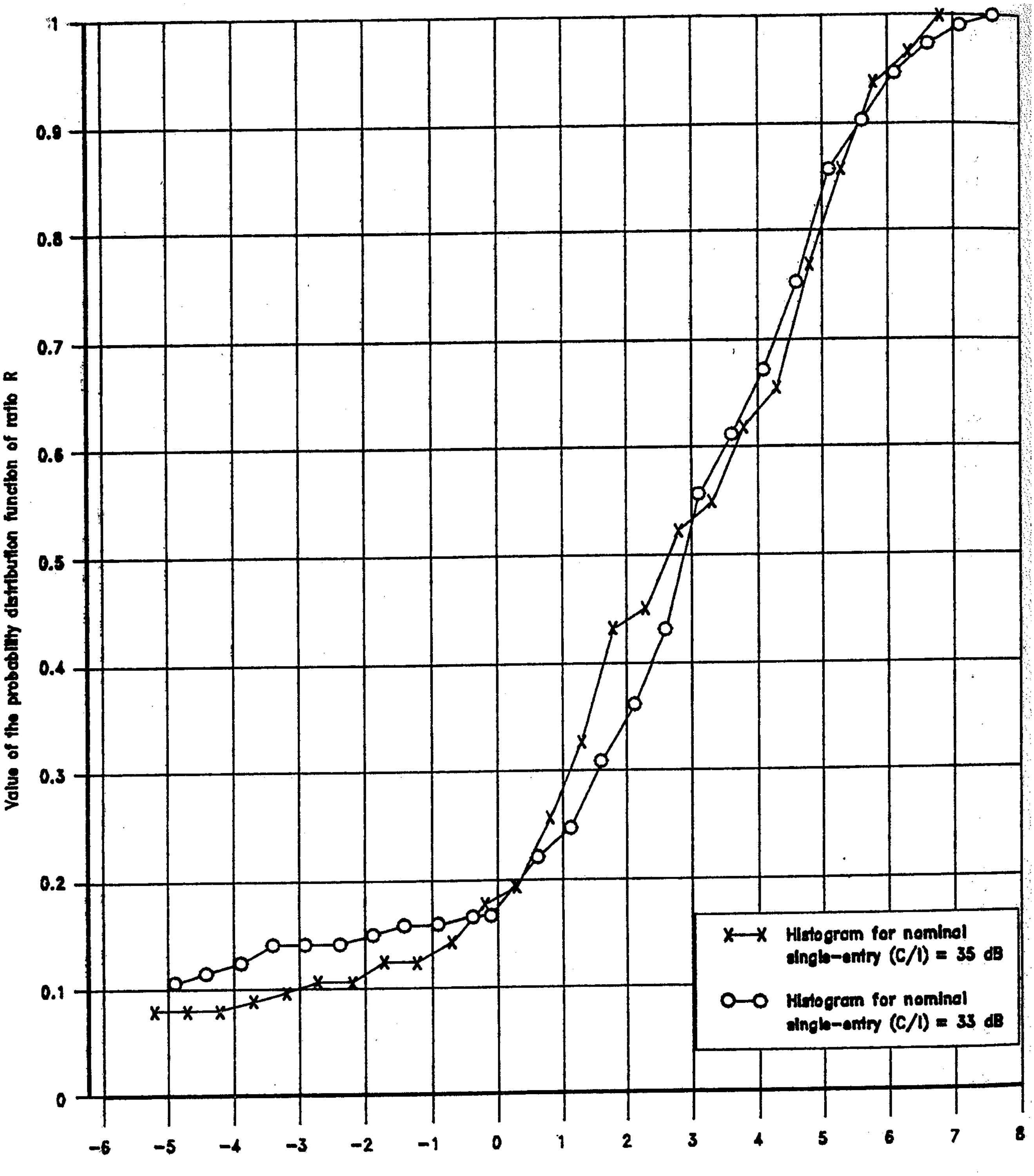



FIGURE 12

Cumulative histograms or estimates of the probability distribution function of the ratio of single-entry (C/I)criterion to experienced aggregate (C/I), R, in dB

5.2 Simulation example 2

In another simulation example, the aggregate interference between digital satellite systems was calculated using one hundred 6/4 GHz beams selected from the requirement for the national allotments in Part A of the Allotment Plan developed at WARC-ORB-88. These one hundred beams were chosen because they represent a highly utilized part of the GSO, i.e. the Europe/Africa region. Systems in Part B, or existing systems, were not included in the calculation.

Technical parameters used, such as carrier-to-noise ratio and antenna diameter, were in accordance with Section A of ANNEX 1 to Appendix 30B of the Radio Regulations. This ANNEX was used in the generation of the Allotment Plan at WARC-ORB-88. QPSK modulation without FEC is assumed in the calculation. By assuming a 2.5dB margin for the QPSK modulation, a C/N of 16 dB (BER $10^{-6}$) was used, which coincides with the operational C/N value adopted in the generation of the plan. Thus, the single entry carrier-to-interference ratio corresponding to 4% and 10% of the total noise level at which the BER equals $10^{-6}$ is 30 dB and 26 dB, respectively. Satellite locations and the length of the total arc to accommodate the satellite systems were determined by using the ORBIT-II programme. The carrier to single entry interference ratio of 30 dB or 26 dB is satisfied for every satellite system.

After the locations were determined, the aggregate interference for each satellite system was calculated and its distribution was analyzed. Since the length of the total arc is adjusted so that the "compression ratio" becomes unity, the correction of the values required in Example 1 is not necessary in this case.

The calculated results are shown in Figure 13. In this example, the ratio of aggregate to single entry interference is not more than 2.8 to 3 (4.4 to 4.8dB) for a 90% probability and not more than 3.8 to 4.5 (5.8 to 6.6dB) for a 99% probability.

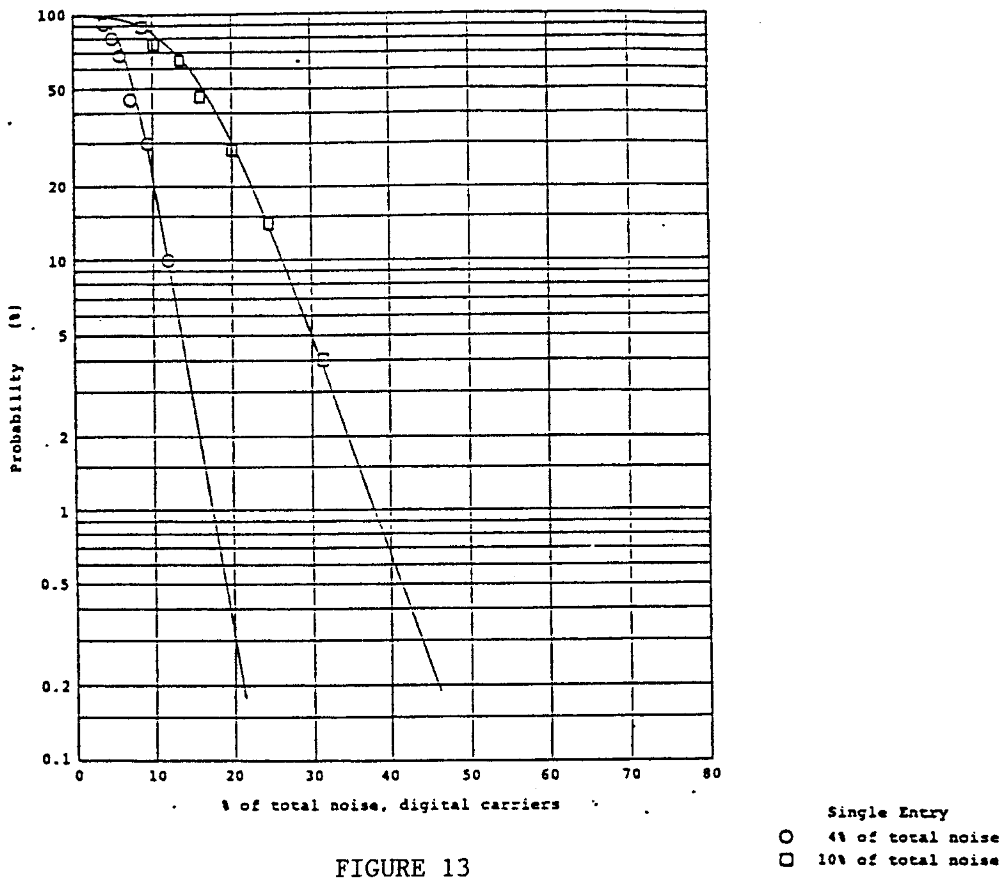



FIGURE 13

Distribution of aggregate interference (% of total noise)

## 5.3 Variations in interference between real satellite networks

The analytical and simulation studies presented in this report depend upon the interference discrimination of earth station and satellite antennas defined by the CCIR Recommendations. These Recommendations depict envelopes of antenna side-lobe gains which usually encompass peak values of these lobes instead of the actual antenna gains at specific off-axis angles. The results of these studies may be conservative in estimating aggregate interference since there are as many "nulls" as there are peaks in the antenna gain patterns. An estimate of actual aggregate interference might include a statistical variation in antenna side lobe gains as well as other non-homogeneous factors, such as variations in antenna beam sizes and RF signal characteristics. The inclusion of these factors may result in lowering the estimates of aggregate interference compared with that shown in the above models. Further study is urgently required.

## 6. Summary

Several models were studied to analyze the factors for determining an appropriate level of aggregate and single entry interference for coordination purposes. It was noted that where many homogeneous satellite networks cover the same or adjacent areas (little or no satellite antenna discrimination exists), the ratio of aggregate to single entry interference (ME/SE) is about 4 dB. In a similar model of homogeneous networks, where satellites with significant satellite antenna discrimination are interleaved between co-coverage (with earth station antenna discrimination) satellites, the ratio (ME/SE) has a sharply peaked value of about 7 dB for unique values of satellite antenna discrimination and considerably lower (ME/SE) ratios for other values of satellite antenna discrimination.

A theoretical study of cellular groupings of service areas, where satellites serving these areas may be co-located in orbit, was made. This study indicated an asymptotic ratio of (ME/SE) of 11 to 13 dB. However, when applied to a practical scenario in Region 2 where the service areas coincided with actual country boundaries, the worst case ratio was 6 dB for co-channel frequency operation. Another analysis, using computer simulations with different types of traffic and frequency offsets between carriers, was applied to a practical mix of co-coverage and non-co-coverage satellite networks. The conclusions in this case were that for FDM/FM carriers, the probability of the ratio exceeding 2.5 or 4 dB, is less than 1%; and for digital carriers the probability of exceeding 7 dB is close to 1%.

Two simulation exercises were performed for a highly utilized part of the GSO based on requirements for the national allotments in the Allotment Plan generated in WARC ORB-88. Both exercises determine satellite positions based on the single-entry interference criteria and analysed the aggregate interference of each satellite system. One exercise shows that 90% of the satellite entries have an aggregate to single-entry interference ratio of less than 5.6 dB. The other exercise shows this ratio to be less than 4.8 dB.

## REFERENCES

CCIR Documents

[1986-90]: a. 4/1(Rev.1) (IWP 4/1); b. 4/47 (USA); c. 4/57 (USA); d. 4/60 (Canada); e. 4/63 (USA); f. 4/269 (Japan); g. 4/324 (IWP 4/1); h. 4/330 (Canada).