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STUDY OF ORBIT/FREQUENCY UTILIZATION FOR SATELLITE BROADCASTING (Part 1)

by

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This paper is concerned with the technical procedures for determining the effective orbit/frequency utilization for geo-stationary broadcasting satellite different from those of a geo-stationary communications satellite and discusses the factors and the procedures that affect the use of the orbit/frequency, and secondly, the calculation of the co-channel interference ratio resulting from broadcasting satellites using 12GHz band in relation to the minimum angular spacing between the satellites. It also considers an application example of the elemental number of frequency channels required for covering the assumed region of the world. General channel availability to be considered on the world-wide basis is given for three frequency bands at approximately 12GHz, 2.5GHz, and 800MHz.

INTRODUCTION

To save the two important resources of frequency and geo-stationary orbit in the coming space age, the most efficient utilization of these resources, particularly for telecommunications and broadcasting, should be taken into considerations, prior to full exploitation of space services.

Some studies pertaining to an efficient use of the communication satellite orbit have been carried out and they can be applied in part to the case of a broadcasting satellite.

However, another approach should be established to determine an orbital utilización for broadcasting satellites proper, mainly because of the smaller extent of the illuminated area, the simpler receiving installations and their random locations as conspicuous features of a broadcasting system.

In this context the basic technical procedures for determining the minimum angular spacing between broadcasting satellites sharing the same frequency band are discussed mostly for the 12 GHz band.

As a practical application of the study the elemental number of frequency channels which are required for covering the assumed region of the world is calculated for the 12 GHz, 2.5 GHz, and 800 MHz bands.

1. FACTORS AFFECTING EFFICIENT ORBIT/FREQUENCY UTILIZATION

Factors affecting efficient orbit/frequency utilization can be derived from the equation of an interference ratio resulting from satellite broadcasting systems.

The interference ratio $(C/X)_A$ occurring at the receiving point A is given under the consideration of n interfering satellites as follows:

$$(C/X)_A = \sum_{i=1}^{n} \frac{(P.F.D.)w}{(P.F.D.)ui} \cdot \frac{A_w}{A_{ui}} \tag{1}$$

$$= \sum_{i=1}^{n} \frac{P_w}{P_{ui}} \cdot \frac{G_w}{G_{ui}} \cdot \frac{L_{ui}}{L_w} \tag{2}$$

or,

$$(C/X)_Z = P_w \left(\sum_{i=1}^{n} P_i/(G_{e(A-i)} \cdot G_{s(A-i)} \cdot L_{(A-i)}) \right)^{-1} \tag{3}$$

where P_w = e.i.r.p. from the wanted satellite :

P_i = e.i.r.p. from the i-th interfering satellite :

$G_{e(A-i)}$ = ratio of the receiving antenna gain directed towards the satellite to the gain in the direction of the i-th interfering satellite at the point A :

$G_{s(A-i)}$ = ratio of the i-th satellite transmitting antenna gain directed towards the i-th service area to the gain in the direction of the point A :

$L_{(A-i)}$ = path loss ratio of the slant ranges, from point A to the wanted satellite and from point A to the i-th interfering satellite.

The advantages of polarization isolation can be little expected if $n \geq 3$.

The propagation loss due to precipitation is assumed equal for all arriving signals at point A.

Assuming homogeneous satellite systems, $(C/X)_A$ becomes as follows :

$$(C/X)_A = \left[\sum_{i=1}^{n} 1/(G_{e(A-i)} \cdot G_{s(A-i)} \cdot L_{(A-i)}) \right]^{-1} \qquad (4)$$

It is evident from this equation that $(C/X)_A$ can be decided by introducing various geometrical relationships between the orbital positions of the satellites and/or the earth receiving points into the expressions of $G_{e(A-i)}$, $G_{s(A-i)}$, and $L_{(A-i)}$. The expressions of these relationships are described in Appendix I.

Regarding these terms of the equation, the technical factors that affect orbit/frequency utilization for broadcasting satellites can be given as follows :

(1) Radiation pattern of satellite transmitting antenna.
(2) Pointing accuracy of satellite transmitting antenna.
(3) Radiation pattern of earth-station receiving antenna.
(4) Pointing accuracy of earth-station receiving antenna.
(5) Station-keeping accuracy of satellites.
(6) Difference between satellite e.i.r.p.'s.
(7) Type of modulation used, which relates to the protection ratio required for the wanted system.
(8) Polarization discrimination.

The increase of the orbit/frequency utilization will be achieved through technological advancement of the first five items, by effecting system homogeneity regarding the sixth item, and for the seventh item by dispersing, if possible, the concentrated signal energy which may cause harmful interference. A contribution from the eighth item is hardly to be expected, since discrimination due to cross polarization cannot be realized in a broadcasting satellite service area where more than two satellites are in sight of the receiver.

2. TECHNICAL PROCEDURES FOR DETERMINING THE MINIMUM SATELLITE SPACING

The procedures pertaining to an efficient use of the communication satellite orbit can be applied in part to a broadcasting satellite, even though the efficient use has primarily been treated from the viewpoint of global coverage by single-beam satellites. However, the objective of pursuing the orbit/frequency utilization for a broadcasting satellite seems to cover as many countries as possible in addition to regions, if favoured, using the least total frequency bandwidth without causing any harmful interference. Furthermore, the use of small earth-station receiving antennas and the installation of a large number of receivers within the service area are the conspicuous features different from those in communication satellite systems.

The following is considered as the technical procedure for accomplishing this objective of the broadcasting satellite study.

(1) Determine the minimum angular spacing between co-channel broadcasting satellites in general, the service areas of which are along the longitude of the sub-satellite point, for example.

(2) Determine the minimum orbital arc necessary for regions congested with countries, where orbit/frequency trade-off should be taken.

In making an effective arrangement of the satellites around the earth a combination of both the above would be suitable. The pursuit of these items would result in making clear an elemental number of frequency channels which are needed for covering the entire world or the specified region of the world.

3. EXAMPLES OF CALCULATION OF MINIMUM SATELLITE SPACING

3.1 Single-beam Satellite System

The minimum angular spacing between single-beam broadcasting satellites sharing the same frequency band, the service areas of which are assumed to lie along the longitude of the sub-satellite point, can be derived through the calculation procedure mentioned in 2.

Using the notation written in Appendix 1, each term in Equation (4) can be expressed by the following:

$$G_{e(A-i)} = G_{eo} - \left\{ 30-20 \log (\alpha_{ij}) \right\} \text{ (in relative gain, dB)} \qquad (5)$$

$$G_{s(A-i)} = 1+ (2\beta_{ji}/\phi_o)^{3.7} \text{ (in relative gain)} \qquad (6)$$

$$L_{(A-i)} = 2L_{ji} \text{ (dB)} - 2L_{jj} \text{ (dB)} \qquad (7)$$

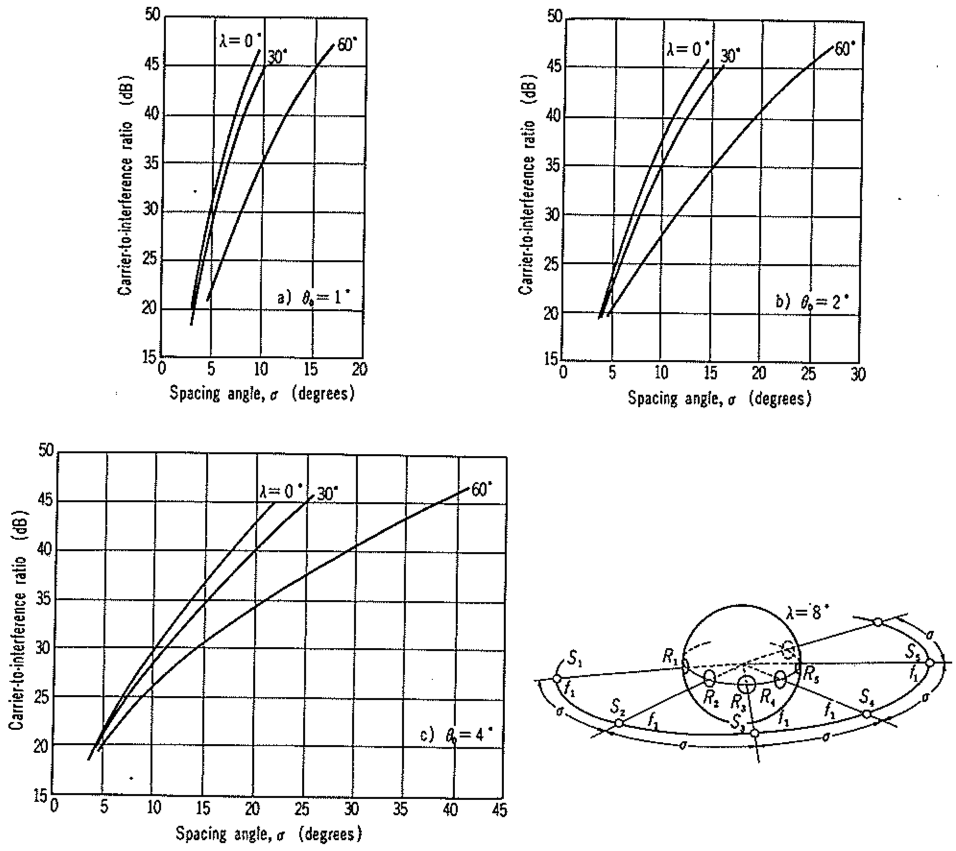
where G_{eo} = maximum gain of the earth-station receiving antenna.

Then we have an interference ratio at location A from Equation (4) as

$$(C/X)_A = \sum_{i=1}^{n} \left\{ G_{eo}-(30-20 \log\alpha_{ij}) \right\} \left[10 \log \left\{ 1 + (2\beta_{ji}/\phi_o)^{3.7} \right\} \right] 2(L_{ji}-L_{jj}), \text{ (dB)} \qquad (8)$$

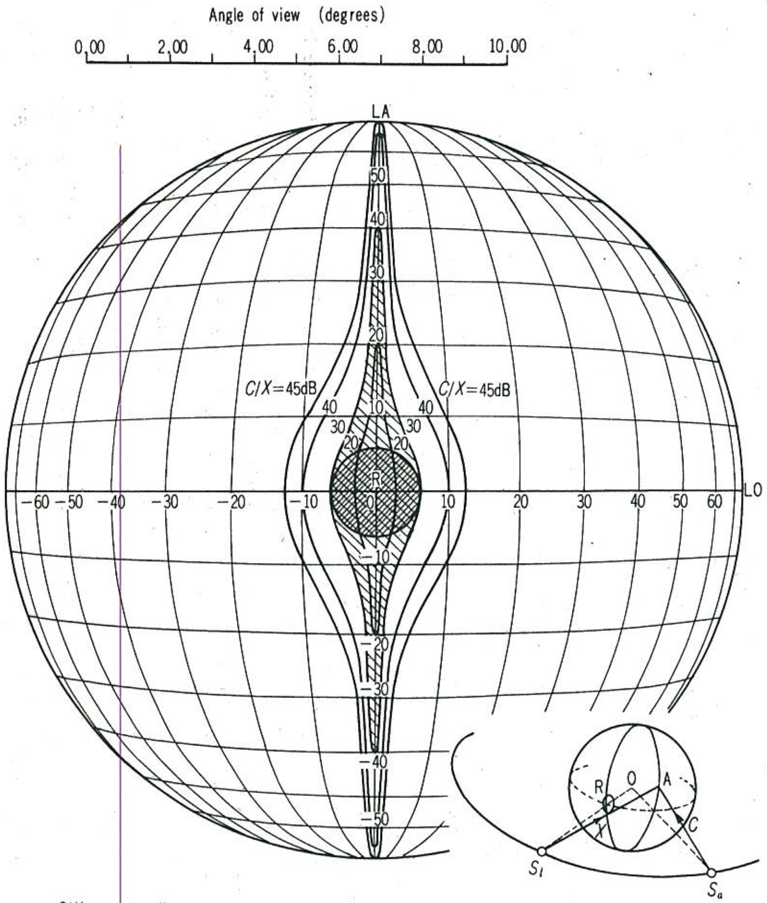
Fig.1 shows the results of wanted-to-interfering signal ratio $(C/X)_A$ in a 12 GHz band at the centre of the service area as a function of satellite spacing, on the assumption that the homogeneous satellite systems are repeatedly prepared for serving along the specified latitude which is taken as a parameter in the figure.

Fig.2 is a modified expression from Fig.1 and shows a two-dimensional interference effect by projecting the interference ratio onto the Earth viewed from the satellite. In this figure an assumption is taken that the interference is caused by only one adjacent satellite. It is understood from this figure that more satellites may be placed along the orbit to cover the less interfered area in the Earth such as 30°N or S latitude,



λ : latitude of the centre location of the service area
θ_0 : satellite antenna beamwidth
S_n : satellite, R_n : service area
f_1 : co-channel frequency, 12GHz
Diameter of ground receiving antenna : 1m
Assumed radiation pattern of satellite antenna : $1/(1+(2\theta/\theta_0)^{3.7})$
Assumed sidelobe pattern of ground receiving antenna : $30-20\log\theta$(dB)
θ : angle from beam axis

Fig. 1 Carrier-to-interference ratio at the centre of each service area equidistantly located along the specified latitude.



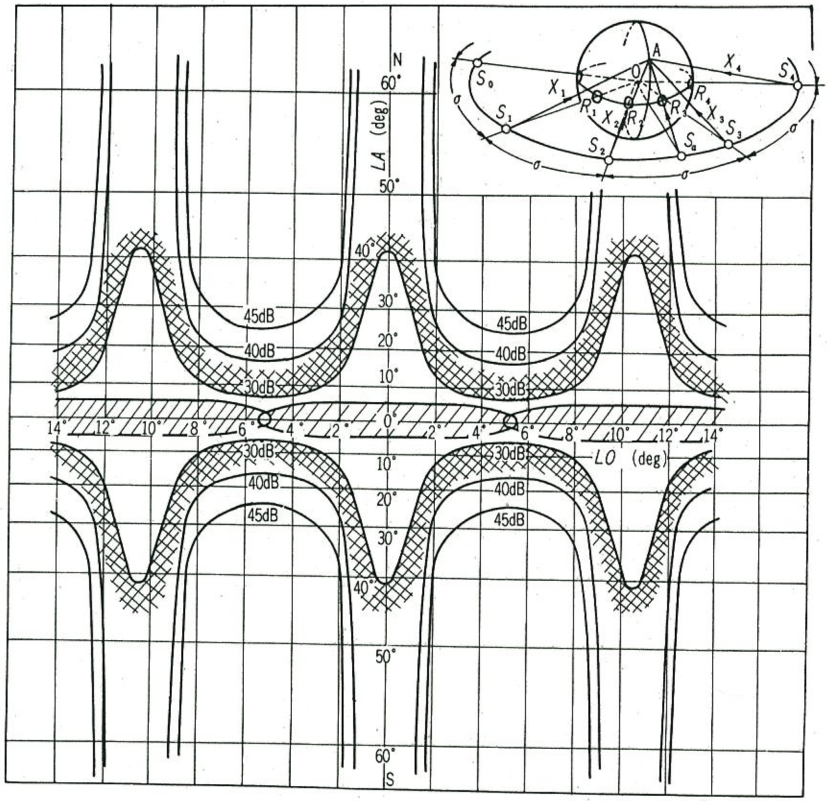
C/X at arbitrarily-selected location A;

C; The wanted-signal from satellite (S_a), the sub-satellite point of which coincides with the longitude of location A

X; The interfering signal from satellite (S_1), the service area (R) of which is centred at the location (0° rel. longitude, 0° latitude)

Diameter of ground receiving antenna : 1m
Satellite antenna beamwidth : 2°
Antenna pattern : see Notes to Fig. 1
Frequency : 12GHz
LO: relative longitude
LA: latitude

Fig. 2 Contour of the carrier-to-interference ratio resulting from two satellites projected on the earth from the satellite.



C/X at arbitrarily-selected location A;

C; The wanted-signal from the presumed satellite (S_a), the longitude of which coincides with that of location A

X; The sum of each interfering signal from other satellites ($S_0, S_1, S_2, \cdots$), the service area centres of which are located at the sub-satellite point (service areas hatched)

C/X at the fringe of each service area : 30dB Frequency : 12GHz
Satellite antenna beam width : 2°
Diameter of ground receiving antenna : 1m
Areas with double hatches ($C/X>30$dB) : no interference occurs where frequency re-use is seen feasible
Other notes : see Fig. 2

Fig. 3 An example of the contour of carrier-to-interference ratio resulting from equidistant distribution of the service areas along the equator.

10°E or W relative longitude and so forth.

A detailed example of Fig.2 is shown in Fig.3, which represents equidistant service areas along the equator and the amount of the interference on the other parts of the world, to make clear the possibility of frequency re-use for serving other latitude areas. Further study should be made on this point for accomplishing the minimum angular spacing.

3.2 Multi-beam Satellite System

The calculation of the minimum satellite spacing for multi-beam satellite systems is not so simple; thus the required angle of beam separation between any two beams from satellites is presented here for a two-beam satellite system and for a three-beam satellite system.

The interference ratio at the edge of the service area concerned is dependent only on radiation patterns of satellite transmitting antennas without regarding those of earth-station receiving antennas. Thus,

$$(C/X)_A = \sum_i \frac{G_{sw}}{G_{sui}} = \sum_i \frac{1/2}{1 + \left(\frac{2\theta i}{\theta_{oi}}\right)^{3.7}} \qquad (9)$$

where G_{sw} = gain of the wanted antenna in the direction of the service area edge (A)

G_{sui} = gain of the i-th antenna in the direction of A

$\theta_i = \theta_{sep\cdot i} - \theta_o/2$ (see Fig.4)

$\theta_{sep\cdot i}$ = beam separation angle between the two main beam axes of the i-th and wanted antennas

θ_{oi} = half power beamwidth of the i-th antenna

For the homogeneous antenna systems,

$$(C/X)_A = \sum_i \frac{1/2}{1 + \left(\frac{2\theta_i}{\theta_o}\right)^{3.7}} \qquad (10)$$

where θ_o = half power beamwidth of the wanted antenna.

By calculating Equation (10) Fig.5a furnishes the details for the wanted-to-interfering signal ratio as a function of a beam separation angle in the two-beam satellite system. The identical beamwidth for the two antenna beams, which is taken as a parameter in the figure, is assumed. Fig.5b shows a three-beam satellite system. It is understood that a multi-beam broadcasting satellite sharing the same frequency band for different programmes may practically be restricted to one with an antenna beamwidth as narrow as 1° or less, if antenna radiation patterns are assumed as in this paper.

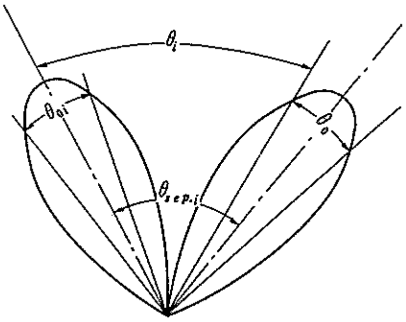
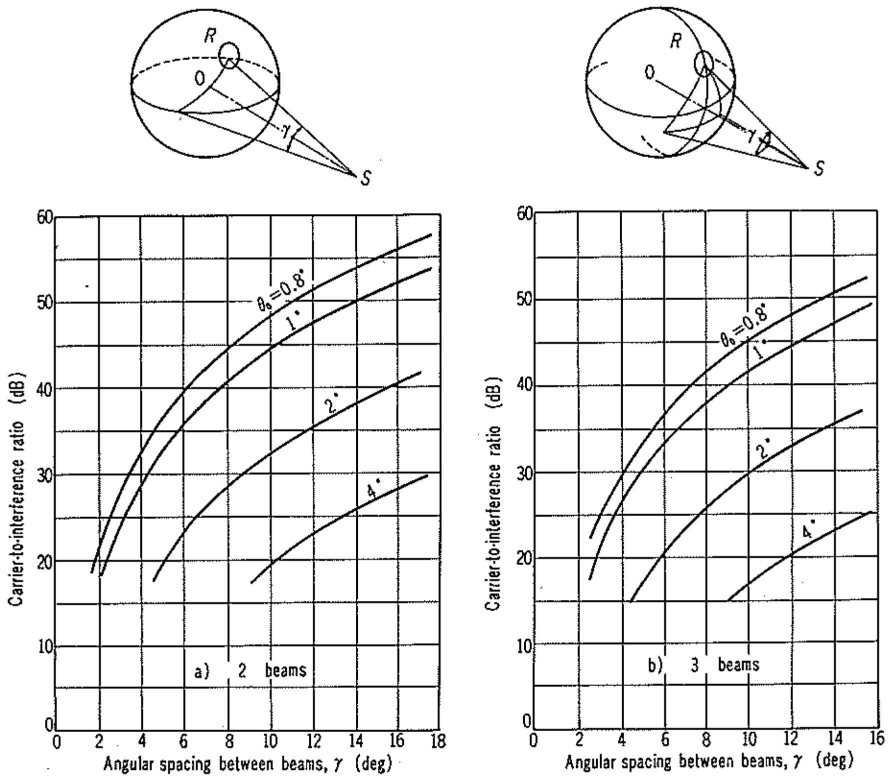


Fig. 4 Relationship among beam angles.



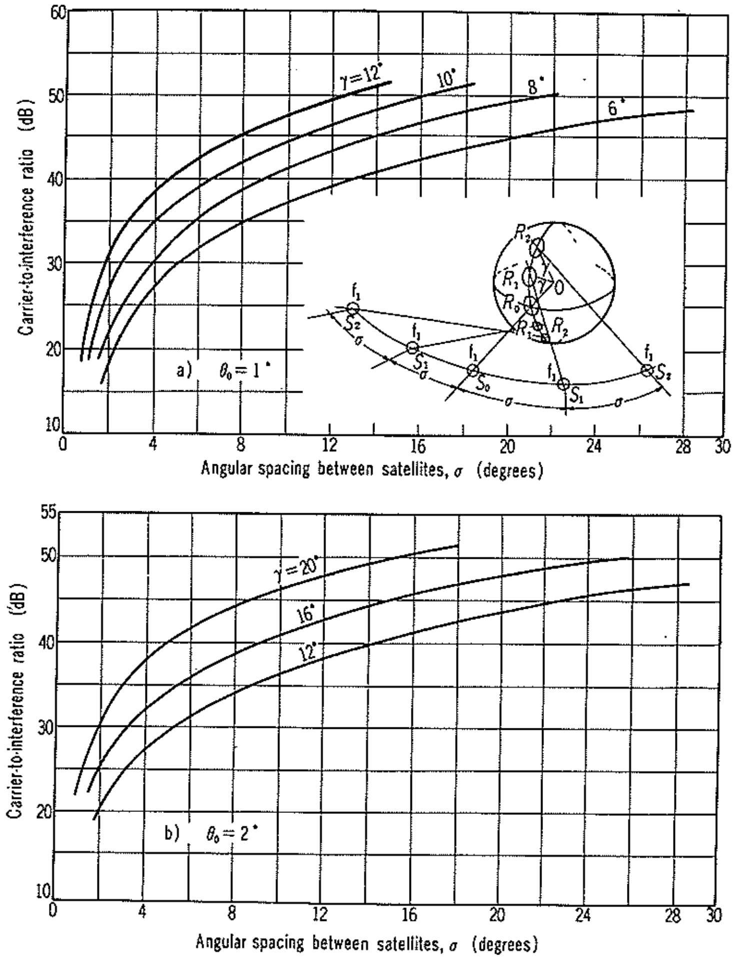
θ_0 : satellite antenna beamwidth
S : satellite
R : service area
Satellite antenna pattern : see notes to Fig. 1, identical for multi-antennas

Fig. 5 Minimum carrier-to-interference ratio in each service area illuminated by a multi-beam satellite.

4. CALCULATION METHOD OF THE MINIMUM ORBITAL ARC IN ORBIT/FREQUENCY TRADE-OFF

The non-uniform distribution of continents and oceans causes a concentration of countries within particular regions of the world, and for them a maximum number of frequency channels is needed. The trade-off between a number of frequency channels and an orbital arc would be taken in order to solve this congestion at the expense of occupying the orbital positions above the oceans.

Fig. 6 shows the relationship between the wanted-to-interfering signals ratio and the satellite deviation from the original position. In this case each satellite illuminates the corresponding service area along the same longitude.



θ_0 : satellite antenna beamwidth
γ : difference in latitude between centres of adjacent service areas
σ : difference in longitude between adjacent satellites
S_x : satellite
R_x : service area
f_1 : co-channel frequency, 12GHz
Diameter of ground receiving antenna : 1m
Satellite antenna pattern : see notes to Fig. 1

Fig. 6 Estimation of satellite spacing required to allow the carrier-to-interference ratio at one of the service area centres along the specified longitude.

5. EXAMPLE OF A CALCULATION FOR THE DETERMINATION OF THE NUMBER OF FREQUENCY CHANNELS REQUIRED

5.1 Theoretical Evaluation

The elemental number of channels required to cover ideally the whole surface of the Earth can roughly be expressed by the following equation, where the evaluation procedure described in 4.1 is taken into consideration.

$$N = \frac{1}{2}(A-B) / B \qquad (11)$$

where N=elemental number of channels required,

A=interference area with single hatch, and

B=service area with double hatches as shown in Fig.2 respectively.

Table 1 shows the calculation result of Equation (11), which is considered to become an ultimate number of available frequency channels for 12 GHz, 2.5 GHz, and 800 MHz. It is understood from this table that more channels are required for 800 MHz than for 2.5 or 12 GHz when accomplishing the full cover of the Earth with a specified unit of the service area (i.e., 4^{o} satellite antenna beamwidth) because of the existence of a larger interference area in 800 MHz.

5.2 Practical Evaluation

As an illustrative example the elemental number of frequency channels which is required to serve each country with at least one channel is evaluated here. The procedure for this evaluation is as follows :

(1) Determine the extent of the service area and its location centre which correspond to the extent of each country and its geographical location.

(2) The satellite is stationed above the same longitude as that of the centre of the service area.

(3) The interfering signal arriving from all of the interfering satellites should be evaluated for each country concerned.

(4) Determine the necessity of another-frequency channel to ensure the necessary wanted-to-interfering signals ratio for each country concerned.

The interference ratio to be considered is the same as in Equation (8), except that α_{ij}, β_{ji}, and L_{ji} should be decided by the exact values with regard to each target service area and satellite location.

The required number of frequency channels can be derived from considering the different channels for the areas where the interference ratio does not reach the assumed level of protection.

Fig.7a shows an example of the relationship between the elemental number of frequency channels required and the specific wanted-to-interfering signal ratio (C/X) for an illustrated region of the Western Pacific and Asia as shown in Fig.7b, which is viewed from a satellite located above 135°E longitude. It appears that 6 elemental frequency channels at 12 GHz, and 10 channels at 800 MHz may be required to serve each nation for C/X = 30 dB, in satellite broadcasting for frequency-modulation television.

Fig.8 shows a calculated result on a world-wide resquirement for frequency channels at 12 GHz and 800 MHz bands in relation to geographical longitude, where one programme is provided for each service area assumed. It is made clear numerically from this figure that the trade-off between

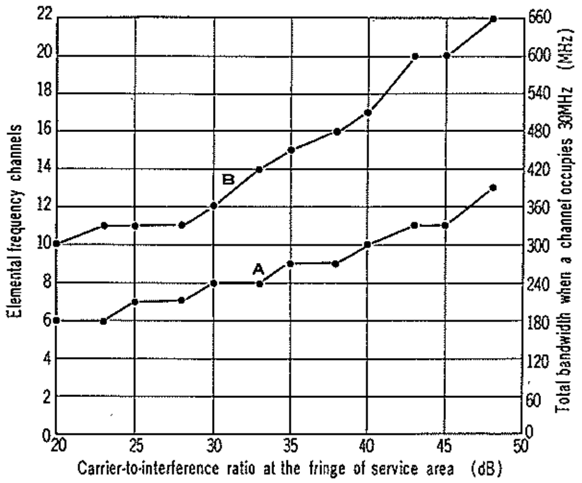
Table 1 Theoretical availability of frequency channels on a world-wide basis

Satellite antenna beamwidth	Items	800MHz		2.5GHz		12GHz	
		FM	AM	FM	AM	FM	AM
1°	Elemental number of channels required *					6	17
	Bandwidth (MHz) **					180	102
2°	Elemental number of channels required *	16	27	8	16	4	9
	Bandwidth (MHz) **	480	162	240	96	120	54
3°	Elemental number of channels required *	11	17	6	11	3	6
	Bandwidth (MHz) **	330	102	180	66	90	36
4°	Elemental number of channels required *	8	21	5	9	3	5
	Bandwidth (MHz) **	240	126	150	54	90	30

Notes :

* The elemental number of channels is defined as the one requiring at least one channel for each unit service area.
C/X = 30dB for FM and C/X = 45dB for assumed amplitude modulation.

** Channel bandwidth of 30MHz for FM and 6MHz for assumed amplitude modulation.



	Curve A	Curve B
Frequency	12GHz	800MHz
Diameter of receiving antenna	0.75m	3.4m
Side-lobe pattern of receiving antenna	$9+20\log(\theta/\theta_0)$	$10.5+25\log(\theta/\theta_0)$
Beamwidth of Satellite antenna	≥0.5°	≥3°

Fig. 7a Elemental number of frequency channels required to cover the assumed service areas in the Western Pacific and Asian region as a function of carrier-to-interference ratio.

an orbital arc and frequency channel is quite effective for the purpose of efficient utilization of frequency/orbit in the areas congested with many countries.

6. CONCLUSIONS

In this paper the basic technical procedures for determining the minimum angular spacing between broadcasting satellites sharing the same frequency band are provided. The related calculation data are shown particularly for the 12 GHz band. Fig.3 shows the two-dimensional evaluation on the influence from the interfering satellite, while Fig.1 gives the limited information about the minimum spacing between the homogeneous satellites illuminating the equidistant service

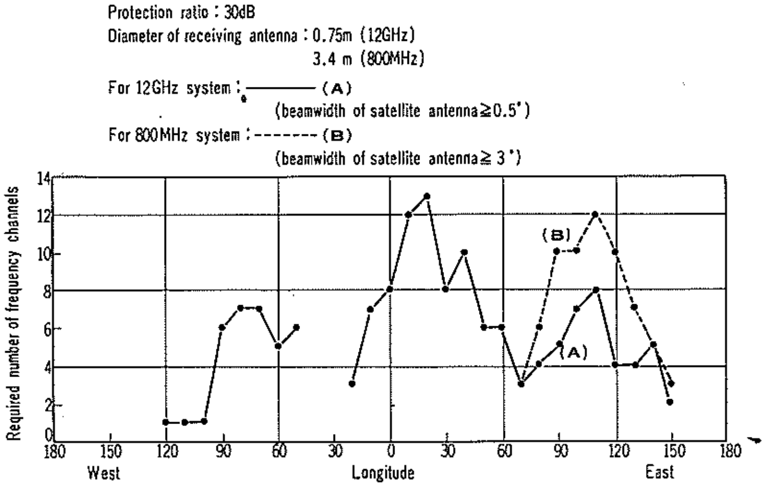
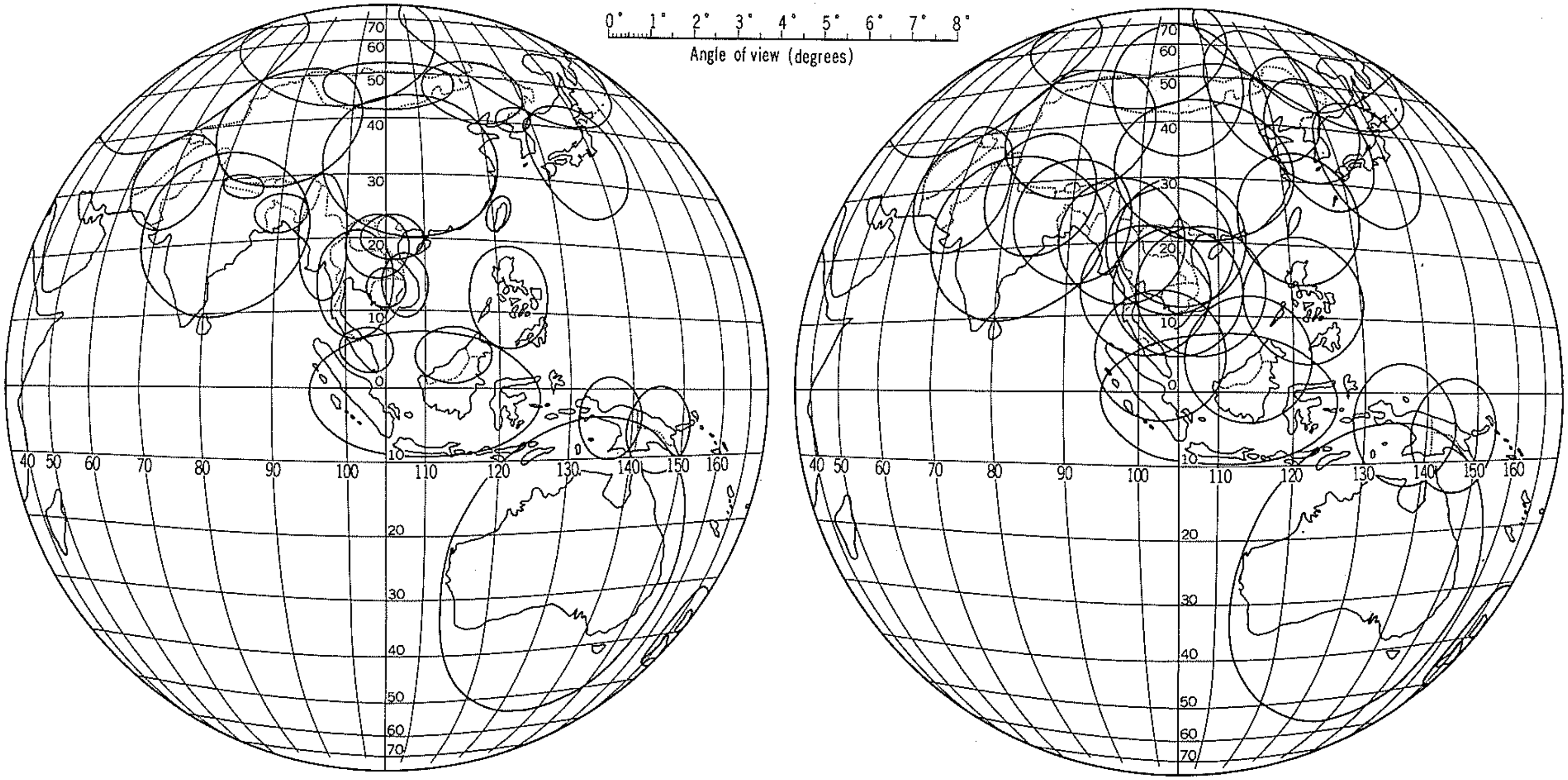


Fig. 8 Required number of frequency channels in relation to geographical longitude where one program is provided for each service area assumed (Satellite is avove the target area).



Beamwidth of satellite antenna≧0.5°
12GHz

Beamwidth of satellite antenna≧3°
800MHz

Fig. 7b Assumed 28 service areas corresponding to figure 7a.

areas along the same latitude. As an illustrative example of a practical channel requirement, Fig.7 shows the elemental number of frequency channels in 12 GHz and 800 MHz for the Western Pacific and Asian regions. A more effective utilization of orbit/frequency could be accomplished through technological advancement of the items mentioned in 2.

APPENDIX I

Equations for determining geometrical relationship with the locations of satellite and terrestrial receivers

Terms in equations	Equations defining the terms in question. (Relative longitude of satellite S_j: ϕ_{sj} Relative longitude and latitude of terrestrial receiving point R_i: ϕ_{ri}, λ_i)
Angle subtended from satellite Sj to two receiving points R_i and R_j : β_{ij}	$\beta_{ij}=\cos^{-1}(L_{jj}{}^2+L_{ij}{}^2-\bar{l}_{ij}\cdot L_{ij})$
Angle subtended from receiving point R_i to two satellites S_i and S_j : α_{ji}	$\alpha_{ji}=\cos^{-1}[(L_{ii}{}^2+L_{ij}{}^2-\bar{s}_{ij}{}^2)/(2L_{ii}\cdot L_{ij})]$
Altitude of geostationary satellite	L_o = 35761.4(km)
Radius of the Earth	R_o = 6378.4(km)
Maximum slant range	$L_{max} = L_o \cdot \sqrt{1+2\cdot F}$ = 41454.3(km)
	$F = R_o/L_o$ = 0.17836, $Q = 2F(1+F)$=0.42034
Slant range between satellite S_j and terrestrial receiving point R_i : L_{ij}	$L_{ij} = L_o \cdot \sqrt{1+Q\cdot\{1-\cos(\phi_{ri}-\phi_{sj})\cdot\cos\lambda_i\}}$
Distance between two receiving points R_i and R_j : $\bar{l}_{ij}$	$l_{ij}=F\cdot L_o\cdot\sqrt{2\cdot\{1-\sin\lambda_i\cdot\sin\lambda_j-\cos\lambda_i\cdot\cos\lambda_j\cdot\cos(\phi_{rj}-\phi_{ri})\}}$
Distance between two satellites S_i and S_j : $\bar{s}_{ij}$	$\bar{s}_{ij} = (1+F)\cdot L_o\cdot\sqrt{2\,\{1-\cos(\phi_{sj}-\phi_{si})\}}$