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THE ROLE OF SERVICE AREAS IN THE OPTIMIZATION OF FSS ORBITAL AND FREQUENCY ASSIGNMENTS

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16. Abstract (Limit: 200 words)

A relationship is derived, on a single-entry interference basis, for the minimum allowable spacing between two satellites as a function of electrical parameters and service-area geometries. For circular beams, universal curves relate the topocentric satellite spacing angle to the service-area separation angle measured at the satellite. The corresponding geocentric spacing depends only weakly on the mean longitude of the two satellites, and this is true also for elliptical antenna beams.

As a consequence, if frequency channels are preassigned, the orbital assignment synthesis of a satellite system can be formulated as a mixed-integer programming (MIP) problem or approximated by a linear programming (LP) problem, with the interference protection requirements enforced by constraints while some linear function is optimized. Possible objective-function choices are discussed and explicit formulations are presented for the choice of the sum of the absolute deviations of the orbital locations from some prescribed "ideal" location set.

A test problem is posed consisting of six service areas, each served by one satellite, all using elliptical antenna beams and the same frequency channels. Numerical results are given for three "ideal" location prescriptions for both the MIP and the LP formulations. The resulting scenarios also satisfy reasonable aggregate interference protection requirements.

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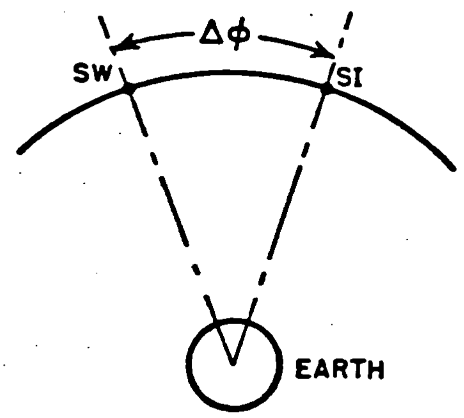
I. INTRODUCTION

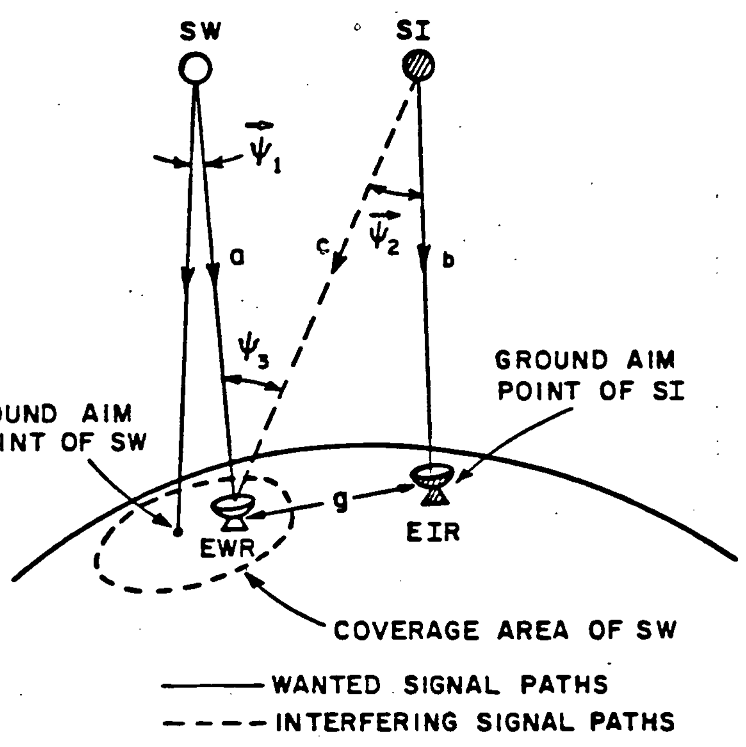
Satisfactory scenarios of orbit and spectrum allocations for communications satellites must achieve sufficient protection for the desired signals relative to interfering ones. Since the protection ratio is a highly non-linear function of the satellite locations and the frequencies to be assigned, it is natural to formulate the optimization of these assignments in terms of non-linear programming techniques [1-4]. The resulting codes place heavy demands on computational resources [5]. Here we shall introduce an intermediate step: from an estimate of the required single-entry protection we shall first calculate the required satellite separations and then use these as constraints in a linear-programming optimization, which should require less computational effort. To do so, it is first necessary to derive quantitative relationships between the required satellite separations, the service-area geography, the protection ratios, and other system parameters.

II. REQUIRED SATELLITE SEPARATIONS

Consider the single-entry interference between two down-link satellite communications circuits. The up-link calculation has been shown to be dual, i.e., of precisely the same form [6]. The geometry is shown in Figure 1. The following notation is used: S - satellite, E - earth station, W - wanted network, I - interfering network, T - transmit, R - receive. These symbols will also be used as subscripts in the equations below. It should be noted that the angle $\vec{\psi}_1$ is a



(a) Overall geometry



(b) Detail with Earth radius exaggerated for clarity

Figure 1. Interference geometry between down-link networks.

two-dimensional vector since, for elliptical or shaped beams, not only its magnitude is important, but also the orientation of its plane with respect to the plane defined by the beam axis and the beam-maximum (or other reference) direction, e.g., the ellipse major axis for elliptical patterns. Similarly the angle $\vec{\psi}_2$ is a vector, but ψ_3 can be treated as a scalar since there is no incentive for earth stations to use non-circular beams.

The carrier and interference powers can be determined by means of the Friis transmission formula [7] and combined to give a well-approximated single-entry carrier-to-interference ratio

$$(C/I)_{EWR} = \frac{E_{SWT}}{E_{SIT}} \frac{D_{SWT}(\vec{\psi}_1, G_{SWT})}{D_{SIT}(\vec{\psi}_2, G_{SIT}) D_{EWR}(\psi_3, G_{EWR})} \quad (1)$$

where E denotes effective isotropic radiated power, D antenna discrimination relative to the beam maximum, and G antenna gain in the beam-maximum direction [8]. For satisfactory performance the carrier-to-interference ratio must equal or exceed the required protection ratio, which is the product of a co-channel protection ratio P and a relative protection ratio p(f), where f denotes the frequency offset from co-channel [9]. Therefore Equation (1) shows that the minimum allowable satellite spacing is implied in

$$R_{DN}^{-1} = D_{SIT}(\vec{\psi}_2, G_{SIT})\, D_{EWR}(\psi_3, G_{EWR}) \quad (2)$$

where

$$R_{DN} = P\,p(f)\,E_{SWT}^{-1}\,E_{SIT}\,D_{SWT}^{-1}\,(\vec{\psi}_1,\,G_{SWT}) \quad . \tag{3}$$

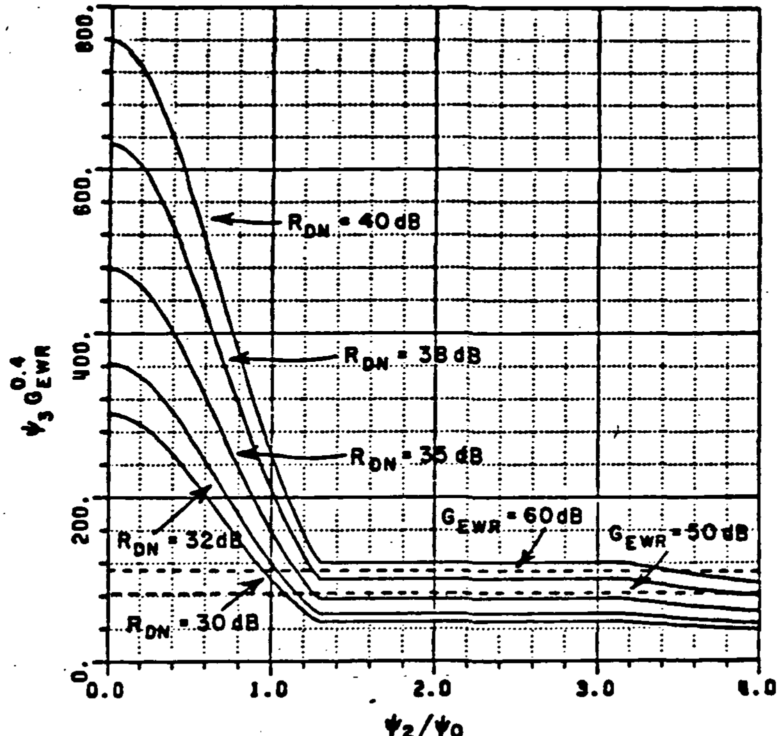
The first four factors in R_{DN} are known system parameters. Also since calculations will always be performed at test points on the boundary of a service area and since, in practice, satellite beams will be shaped to give a reduction of approximately 3 dB at these test points, one can set $D_{SWT}(\vec{\psi}_1,G_{SWT}) \approx 1/2$. The left side of Equation (2) can therefore be considered known in an orbit synthesis procedure.

It is important to note that Equation (2) is an implicit equation relating the required satellite separation to the separation of the two service areas. The existence of such a relationship has long been recognized qualitatively [10,11]. Equations (2) and (3) state quantitatively that, when frequency isolation is insufficient, the system requires antenna discrimination to achieve a required protection level, and that this is obtained as the product of the earth and satellite antenna discriminations.

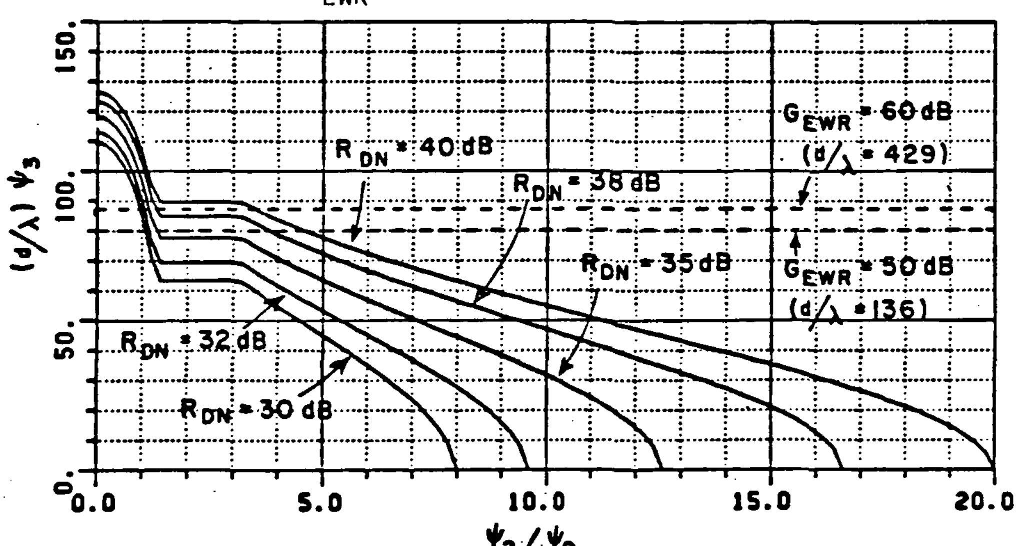
III. SEPARATIONS FOR CIRCULAR BEAMS

For circular beams, the angle $\vec{\psi}_2$ in Equation (2) becomes scalar and it is possible to solve explicitly for ψ_3 as a function of ψ_2 when the discrimination patterns D_{SIT}, D_{EWR} are specified. The relationship can be plotted conveniently as a universal set of contour curves, with R_{DN} as parameter and normalized values of ψ_2,ψ_3 as coordinates. The need for normalization is implied in Equation (2) by the presence of the gains G as arguments in the antenna discriminations. For example, when G_{EWR} is large, corresponding to a narrow Earth-station beam, a given value of D_{EWR} is reached with a smaller value of ψ_3 than when G_{EWR} is small. The universal curves are shown in Figure 2 for discrimination pattern envelopes recommended by the CCIR for co-polarized FSS antennas [12,13]. Unfortunately, no corresponding cross-polarized patterns have been recommended as yet. Two sets of curves are required because of the piecewise specifications of $D(\psi_3)$. At first sight it might appear that four sets would be required since four "pieces" are used in the CCIR specification of Earth-station discrimination. However, it turns out that the far side-lobe and back-lobe regions imply so much discrimination that the interference can be neglected, while the constant part of the pattern, representing the near-sidelobe envelope, is accounted for by the discontinuity in the ψ_3 values which results from switching between Figures 2a and 2b in accordance with the directions given below them.

The expression of the universal curves in terms of the antenna-centered "off-axis" angles ψ_2 and ψ_3 is natural and also useful: for example, it shows that the "separation" of service areas, measured by ψ_2, is rigorously the distance from the aimpoint of the interfering satellite antenna to that test point of the area suffering interference which is on the highest discrimination contour of the interfering satellite antenna pattern on the Earth surface. For circular beams and high satellite elevations this would be the test point nearest to the interfering satellite aim point. Nevertheless, for many system



(a) Use for $\psi_3 > 26.3\ G_{EWR}^{-0.3}$ degrees or above appropriate Earth station antenna gain line. Unless dB are specified G_{EWR} means the numerical gain value.



(b) Use for $\psi_3 < 20\ (d/\lambda)^{-1}[5.35 + 5\log_{10}(d/\lambda)]^{1/2}$ or below appropriate Earth station antenna gain line

Figure 2. Universal curves for the minimum allow-able satellite spacing angle ψ_3 as function of the normalized off-axis angle ψ_2. ψ_0 is the half-power beam width of the satellite antenna, d/λ the diameter-to-wavelength ratio of the EWR antenna.

calculations it is more useful to find the geocentric satellite separation $\Delta\phi$ instead of the topocentric angle ψ_3, directly as a function of the longitude differences and latitudes of EWR, EIR, and SI instead of ψ_2. Actually the angle ψ_3 turns out to be a rather good approximation for $\Delta\phi$, which can be improved sufficiently for all practical purposes by

$$\Delta\phi = \psi_3 \, [1.023-0.302 \cos(\phi_M-\phi_E)\cos\theta_E]^{1/2} \text{ rad} \qquad (4)$$

where ϕ_M is the longitude of the midpoint between the wanted and interfering satellites (SW,SI) and ϕ_E, θ_E are the longitude and latitude of the test point (EWR), respectively.

The relationship between ψ_2 and the geocentric variables can be found by substituting suitable expressions obtained from Figure 1 into the cosine law

$$\cos\psi_2 = (b^2+c^2-g^2)/2bc \quad , \qquad (5)$$

but for many purposes the relationships

$$\frac{g}{6.54R_E} < \psi_2 < \frac{g}{5.62R_E} \text{ rad} \quad , \qquad (6)$$

where R_E is the earth radius, give a sufficiently good estimate. The correct value is close to the upper limit for high satellite SI elevations and to the lower for low elevations, as viewed from the aim point EIR. The variation of the required separation $\Delta\phi$ for various system parameters and configurations in terms of longitude and latitude is shown in Figures 3 and 4. From these and more such computations the following results emerge [14]:

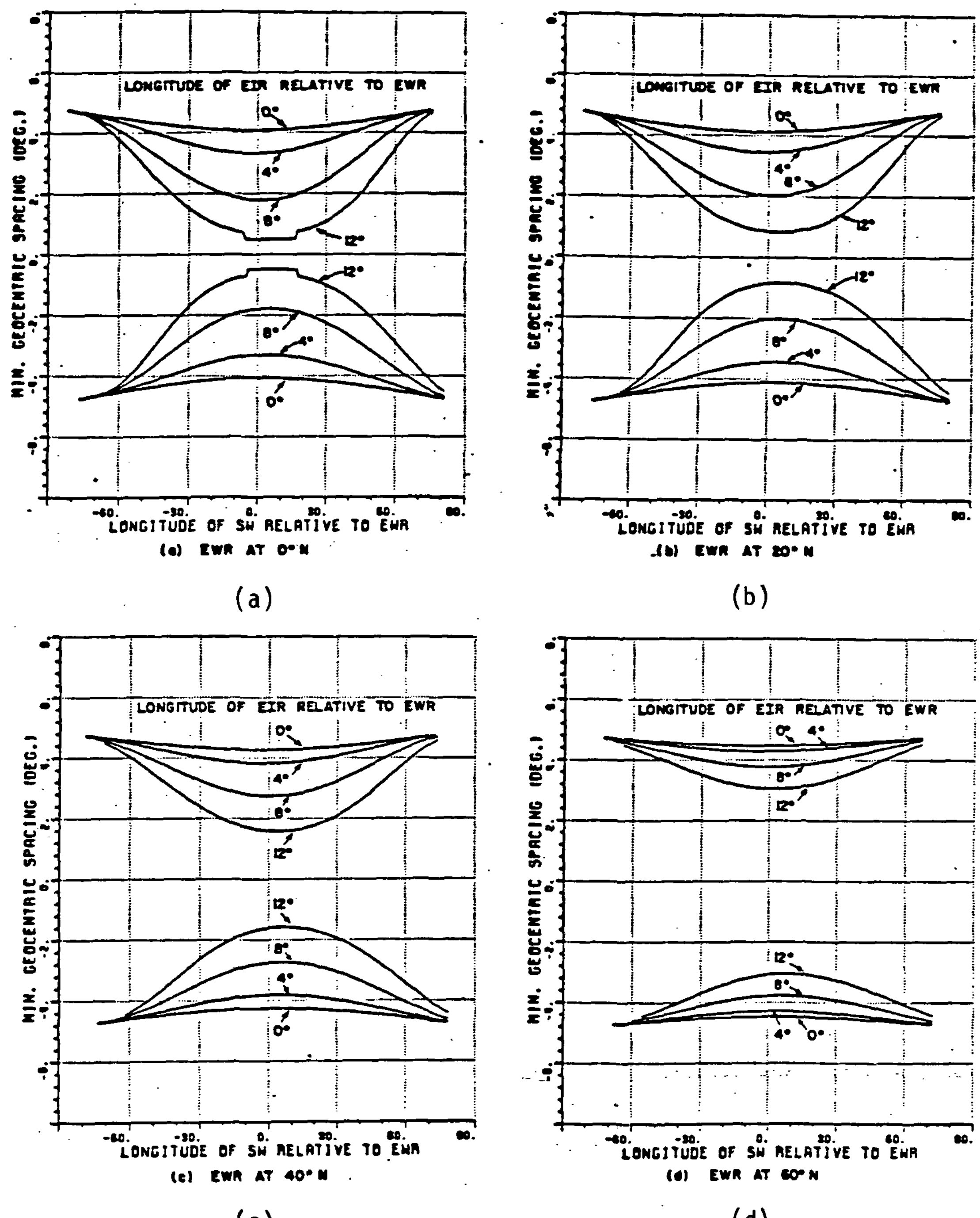


Figure 3. Minimum geocentric satellite spacing when earth stations are separated in longitudinal direction. R_{DN} = 35 dB, G_{SIT} = 40 dB, G_{EWR} = 50 dB.

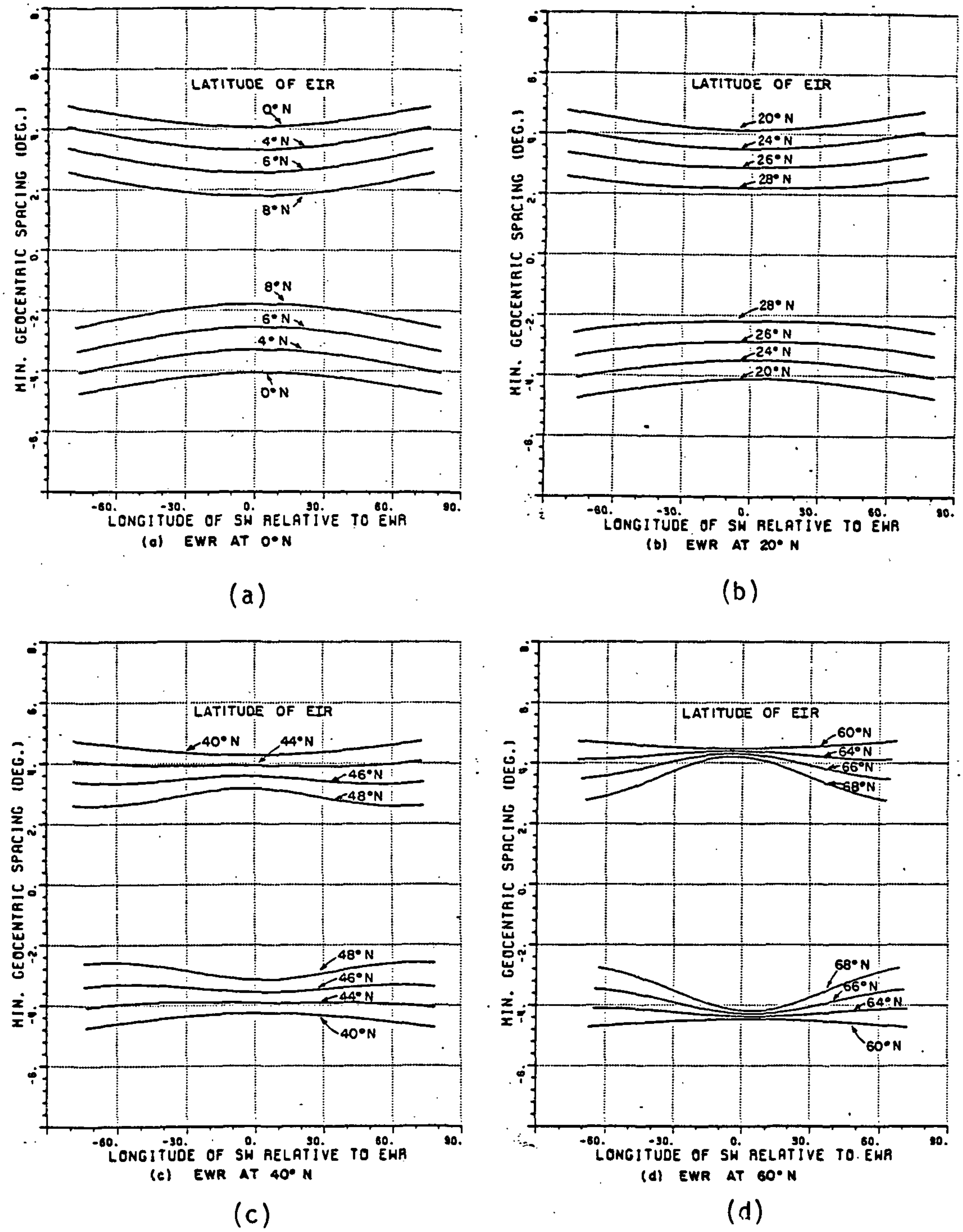


Figure 4. Minimum geocentric satellite spacing when earth stations are separated in latitudinal direction. R_{DN} = 35 dB, G_{SIT} = 40 dB, G_{EWR} = 50 dB.

(a) the smallest required separation occurs for practical geometries when the wanted satellite is near the longitude of the center of its service area,

(b) for a substantial range of orbital locations about this longitude the required separation varies little.

This last result, which appears to be true also for elliptical beams (see Section IV), is very important in the synthesis procedure discussed in Section V, because it reduces or eliminates the need to recalculate the required satellite separations as satellite orbit assignments are changed.

IV. SEPARATIONS FOR ELLIPTICAL BEAMS

For elliptical beams, the required satellite separations can be calculated by the following procedure:

(1) For each service area choose test points on the periphery and calculate the orientation and axial ratio A_r of the minimum projected ellipses which enclose them, using 2° increments in satellite longitude [15].

(2) Choose a wanted and an interfering satellite and a longitude within the orbital arc under consideration, and consider the desired and interfering satellites collocated at that longitude. By incrementally increasing $\Delta\phi$, with the satellites located symmetrically on each side of the initially chosen central

longitude, calculate the required satellite separation from Equation (2) with

$$D_{SIT}(\vec{\psi}_2, G_{SIT}) = D_{SIT}\left[\frac{\psi_2}{\psi_0}(\cos^2\theta + A_r^{\,2}\sin^2\theta)^{1/2}\right], \qquad (7)$$

where ψ_0 is the half-power beamwidth in the direction of the major axis and θ is the angle between the plane in which ψ_2 is measured and the plane determined by the SIT beam axis and the SIT ellipse major axis. Equation (5) is used for evaluating ψ_2 in this calculation.

(3) Repeat step (2) for other central longitudes. The result for the worst test point for each service area shown in Figure 5 is shown in Table 1 for a sequence of central longitudes. For each pair of satellites two separation values can be obtained, depending on which service area is considered protected, with the satellite of the other area considered interfering. The larger of these appears as $\Delta\phi$ in Table 1. Notice the slow variation of $\Delta\phi$ with the mean satellite longitude, provided that this longitude is not too different from that of the protected service area. One satellite per service area was assumed in these calculations.

(4) Choose the largest of all the $\Delta\phi$ values obtained in this process over the allowable orbital arc for each satellite pair and denote it Δs. The triangular matrix of Δs elements corresponding to Table 1 is shown in Table 2 for all satellites constrained to the

Figure 5. Geography of the six-service-area scenario. Dots indicate test points.

TABLE 1

$\Delta\phi$ VALUES IN DEGREES

Single-entry protection ratio = 30 dB. The discrimination patterns of refs. 16,17 were used for the Earth antennas with d/λ = 60 and 0.6 aperture efficiency. Those of ref. 18 were used for the satellite antennas with beam width as determined by the minimum ellipse. It was assumed that SW and SI produce the same power density at their respective aim points, corresponding to $R_{DN} \approx 33$ dB.

Satellite pairs		Mean Satellite Longitude				
		70°W	80°W	90°W	100°W	110°W
ARG	BOL	4.00	4.02	4.05	4.12	4.17
ARG	CHL	4.18	4.05	4.00	4.02	4.19
ARG	PRG	4.24	4.28	4.32	4.28	4.32
ARG	PRU	0.94	1.04	1.15	1.25	1.41
ARG	URG	4.18	4.14	4.06	4.06	3.94
BOL	CHL	4.13	4.20	4.28	4.39	4.57
BOL	PRG	4.00	3.99	4.00	4.03	4.04
BOL	PRU	3.87	3.95	3.99	4.10	4.26
BOL	URG	0.39	0.38	0.38	0.84	0.94
CHL	PRG	1.08	1.14	1.25	1.46	2.00
CHL	PRU	3.84	3.83	3.85	3.89	3.94
CHL	URG	0.42	0.41	1.03	1.28	1.59
PRG	PRU	0.49	0.49	0.50	0.85	1.10
PRG	URG	2.16	2.19	2.20	2.34	2.46
PRU	URG	0.40	0.37	0.37	0.33	0.32

80°W to 110°W orbital arc. These separations will be used as constraints in the synthesis procedures of the next section.

TABLE 2

Δs VALUES IN DEGREES

	BOL	CHL	PRG	PRU	URG
ARG	4.17	4.19	4.32	1.41	4.14
BOL		4.57	4.04	4.26	0.94
CHL			2.00	3.94	1.59
PRG				1.10	2.46
PRU					0.37

V. LINEAR PROGRAMMING FORMULATION

The FSS synthesis problem can now be formulated as a linear program with a set of nonlinear side constraints. The set of satellite locations which satisfy the constraints constitutes the feasible region. A variety of linear functions can be selected to be optimized. Three functions have occurred to us:

(a) to search only for some point in the feasible region by setting the function to be minimized equal to zero;

(b) to minimize the occupied orbital arc;

(c) to minimize the sum of the absolute deviations of the satellite locations from a specified set of locations.

The last objective has been implemented in the formulation described below. The following parameters and non-negative variables are used:

$e_j(w_j)$ - easternmost (westernmost) feasible location for satellite j, in °W,

d_j - desired location for satellite j,

Δs_{ij} - required minimum separation between satellites i and j, as in Table 2,

x_j - relative location (in degrees west of e_j) of satellite j,

$x_j^+(x_j^-)$ - degrees west (east) of d_j that satellite j is located,

$p_{ij}(n_{ij})$ - degrees west (east) of satellite j that satellite i is located (defined for $i < j$).

The FSS orbit assignment synthesis is then formulated as follows:

Minimize

$$z = \sum_j (x_j^+ + x_j^-) \tag{8}$$

subject to

$$x_j - x_j^+ + x_j^- = d_j \quad \text{for all } j , \tag{9}$$

$$x_i - x_j - p_{ij} + n_{ij} = 0 \text{ for all } i,j \text{ where } i < j , \tag{10}$$

$$p_{ij} + n_{ij} \geq \Delta s_{ij} \quad \text{for all } i,j \text{ where } i < j , \tag{11}$$

$$x_j < w_j - e_j \qquad \text{for all } j , \qquad (12)$$

$$x_j,\ x_j^+,\ x_j^- > 0 \qquad \text{for all } j , \qquad (13)$$

$$p_{ij},\ n_{ij} > 0 \qquad \text{for all } i,j \text{ where } i < j , \qquad (14)$$

and

$$p_{ij} \cdot n_{ij} = 0 \qquad \text{for all } i,j \text{ where } i < j . \qquad (15)$$

The objective function, Equation (8), computes the sum of the absolute deviations of the prescribed satellite locations (x_j's) from the desired or ideal locations (d_j's). These absolute deviations are measured in the first set of constraints, Equation (9). The actual separations between all pairs of satellites ($p_{ij} + n_{ij}$) are computed in the second set of constraints, Equation (10), and are compared to the minimum required satellite separations in the third set of constraints, Equation (11). The constraints of Equation (12) guarantee that the location prescribed for each satellite is feasible. Constraint Equations (13) and (14) indicate that all of the variables in the problem are restricted to non-negative values. Finally the complementary relationships between pairs of variables p_{ij} and n_{ij} are enforced by the constraints of Equation (15).

Linear programs are much more readily solvable than nonlinear programs and integer programs. They are most often solved by the simplex method [19]. This technique examines a sequence of basic solutions to the constraints of the linear program. Each solution examined has an objective function value no less favorable than that of the previous solution. The algorithm terminates when it is determined that no improved solution can be found.

The presence of the nonlinear side constraints of Equation (15) prevents us from using the simplex method in its most common form. The method can be modified to handle these additional constraints through the use of *restricted basis entry:* p_{ij} can *not* be a basic variable *if* n_{ij} is a basic variable, and vice versa [20]. When employing the simplex method with restricted basis entry, we are certain to find a local, but not necessarily a global, optimum. As formulated, the problem has m(m+2) variables, where m is the number of satellites, and m^2 constraints, not counting the simple bound constraints of Equations (12) to (14) and complementarity constraints of Equation (15). The formulation is similar to one suggested by Ignizio for the N-job, single-machine scheduling problem [21].

VI. MIXED INTEGER PROGRAMMING FORMULATION

The same problem can also be formulated as a mixed integer program [22]. A global optimum is guaranteed when this formulation is employed. However, the computational effort required to find a final solution can be immensely greater than it would be with the linear programming formulation. In any case, this formulation is helpful in assessing the quality of the solutions found using the linear programming formulation on small test problems.

To complete this formulation, we need the following definitions:

$$e = \min_j \{e_j\} \quad , \tag{16}$$

$$w = \max_j \{w_j\} \quad , \tag{17}$$

$$x_{ij} = \begin{cases} 1 & \text{if satellite } i \text{ is located west of satellite } j. \\ 0 & \text{otherwise} . \end{cases} \tag{18}$$

The objective function and the constraints (9), (10), (11), (13) and (14) appear in this formulation precisely as they did in the linear programming formulation. The complementarity constraints (15) are replaced by two new constraints:

$$(e-w)x_{ij} + p_{ij} \leq 0 \tag{15a}$$

$$(w-e)x_{ij} + n_{ij} \leq (w-e) \tag{15b}$$

which, together with the nonnegativity restrictions on p_{ij} and n_{ij}, constraints (14), guarantee that either $p_{ij} = 0$ or $n_{ij} = 0$ for all pairs of satellites i and j.

If there are m satellites, the mixed integer formulation entails $m(m+2)$ continuous variables, $m(m+1)/2$ binary variables, and $2m^2-m$ constraints specified by Equations (9), (10), (11), (15a), (15b). The time required to solve an FSS synthesis problem with this formulation will be most heavily dependent upon the number of binary variables. For large problems (many satellites), this formulation may involve prohibitive solution times.

VII. NUMERICAL RESULTS

The FSS synthesis minimizing the sum of absolute deviations of orbital positions from a prescribed "desired" set was solved, both as a linear program with the simplex method with restricted basis entry and as a mixed integer program via branch-and-bound [23]. The service areas and test points were those of Figure 5 with one satellite per service area. The available orbital arc for each satellite was specified as 80°W to 110°W. It was assumed that each satellite would carry a full complement of frequency channels, so that a co-channel calculation is appropriate. A single-entry C/I value of 30 dB was chosen with the intent of achieving a 25 dB aggregate co-channel C/I ratio. With these assumptions the Δs values of Table 2 are pertinent. Three problems were run, differing only in the specified "desired" satellite locations. In problem 1, this "desired" location was specified for every satellite as 95°W, the center of the arc. In problem 2, all "desired" locations were specified at 110°W, the westernmost end of the arc. In problem 3, each was specified near the central longitude of the ellipse circumscribing the service area to be served; these "desired" longitudes are indicated in the column labeled DL in Table 3, which shows the solutions obtained for all three problems by both methods. The LP formulations required 48 variables and 36 constraints, while 63 variables, 15 of them binary, and 66 constraints were needed for the MIP formulation.

The solutions to these test problems illustrate some important points. First of all, the solution of a synthesis problem by means of an integer program can require a substantially greater amount of

TABLE 3

SOLUTIONS TO TEST PROBLEMS

LOCATIONS (°W)	Problem 1		Problem 2		Problem 3		
	LP	MIP	LP	MIP	DL	LP	MIP
ARG	105.74	88.68	110.00	101.35	87.5	101.26	88.76
BOL	101.57	99.57	104.33	97.18	92.5	92.5	92.93
CHL	97.00	95.00	99.76	105.54	97.5	97.07	97.5
PRG	95.00	93.00	97.76	107.54	87.5	87.5	84.44
PRU	93.06	91.06	108.59	109.63	102.5	102.67	102.50
URG	92.54	96.59	105.86	110.00	82.5	82.5	81.98
objective function (degrees)	23.71	18.42	33.69	28.76		14.36	5.27
orbital arc length (degrees)	13.20	10.89	12.24	12.82		20.17	20.52
CPU time* (sec)	1.31	25.23	1.30	13.39		1.25	2.86

*IBM-3081 computer

computer time than by means of a linear program. Secondly, the two approaches used can produce strikingly different solutions. (See the results for Problems 1 and 2.) It may also happen that the same solution will be found with both methods, even though this is not evident from the results presented here. Finally, acceptable solutions, in terms of aggregate co-channel C/I ratios, are obtained even when the objective function value for the linear programming solution differs substantially from the mixed integer programming solution, the global optimum. This is not unexpected because the Δs constraints guarantee acceptable single-entry C/I ratios. Table 4 shows the distributions of aggregate co-channel C/I ratios for the two methods and three problems. It will be remembered that a 30 dB single-entry constraint was used to calculate the Δs table on which all these calculations are based.

TABLE 4

NUMBER OF TEST POINTS CORRESPONDING TO A GIVEN AGGREGATE CO-CHANNEL C/I RATIO RANGE FOR EACH PROBLEM AND METHOD

		C/I Interval (dB)				
Problem	Method	<27	27-28	28-30	30-35	>35
1	LP	0	1	8	16	29
1	MIP	0	1	6	18	29
2	LP	0	0	5	20	29
2	MIP	0	4	10	25	15
3	LP	0	0	4	16	34
3	MIP	0	0	9	14	31

VIII. CONCLUSIONS

An implicit relationship has been derived which relates the topocentric separation of two satellites as required for a given level of single-entry protection to the separation and orientation of their service areas. For circular beams and topocentric angles the results are presented explicitly; a computational approach is given for elliptical beams and for use with longitude and latitude variables. It is found that the geocentric separation depends primarily on the service area separation, secondly on a parameter R_{DN} which characterizes the electrical design, and only slightly on the mean orbital position of the satellites. Both linear programming (LP) and mixed integer programming (MIP) algorithms have been implemented, with the sum of the absolute deviations of the orbital locations from a prescribed "ideal" set as objective function. Three "ideal" sets were used. A single-entry protection ratio of 30 dB was specified with the intent of satisfying an aggregate co-channel C/I ratio of 25 dB. The set of orbital locations chosen by the LP and MIP methods differed substantially in two cases and, to a lesser degree, in the third. Still, all six solutions which were found provided acceptable protection ratios at all 54 test points. The worst aggregate co-channel C/I ratio found was 27 dB.

The results are encouraging with respect to applying the LP procedure to larger scenarios. The MIP formulation may result in excessive computation times when many satellites are involved, but it is guaranteed to arrive at a global optimum; it will therefore be useful for evaluating the efficacy of the LP approach via smaller test problems, such as the three presented here.

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