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ENGINEERING CALCULATIONS FOR COMMUNICATIONS SATELLITE SYSTEMS PLANNING

Charles H. Reilly
Eric K. Walton
Paul Kohnhorst

The Ohio State University
ElectroScience Laboratory
Department of Electrical Engineering
Columbus, Ohio 43212

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Charles H. Reilly, Eric K. Walton, Paul Kohnhorst

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16. Abstract (Limit: 200 words)

In this report, we describe a procedure that we use to calculate minimum required satellite separations based on total-link C/I requirements. We also summarize recent results with our switching algorithm for satellite synthesis problems. We describe analytic solution-value bounds for two of the satellite synthesis models we are studying. Preliminary results from an empirical study of alternate mixed integer programming models for satellite synthesis are presented. Research plans for the near future are discussed.

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I. PURPOSE

The purpose of this grant is to develop methods and procedures, including computer codes, for performing engineering calculations which will be useful for the United States delegations to international administrative conferences concerning satellite communications. Our attention has been directed exclusively toward Fixed Satellite Service (FSS) issues during the interim 12 July 1986 to 14 January 1987, since this service will be a major topic at the World Administrative Radio Conference in 1988 (WARC-88).

II. REQUIRED SATELLITE SEPARATIONS TO ACHIEVE TOTAL-LINK C/I RATIOS

A. Introduction

A communications satellite link in the Fixed Satellite Service (FSS), consists of both an uplink from earth transmitters to the satellite and a downlink from the satellite to receivers on the Earth. Interference from undesired transmissions can occur on either one of these links. The level of interference can be represented by the carrier to interference power ratio (C/I). This is the ratio of the carrier power received from a desired transmission to the total interference power received from other satellite networks.

In the "Delta-S" approach to orbital assignments reported previously, [1,2] the requirements for given C/I protection ratios between satellite networks were transformed into a set of constraints on the orbital locations of the satellites. This was done on a single entry basis; i.e., only the interference between pairs of satellite networks was considered. The minimum required satellite separation was calculated for each combination of two satellites.

These calculations considered only the downlink interference problem. In general, for the FSS, significant amounts of interference may be introduced on both the uplink and the downlink. For this reason, the method of calculating the minimum required separations has been modified to include the effects of both uplink and downlink interference.

B. Procedure

The uplink interference calculations are based on the procedure described in CCIR report 455-3 [3]. The sketch in Figure 1 shows the interference geometry between two satellite networks sharing an uplink frequency. In the sketch, a transmitter in administration 2 is interfering with the uplink transmission from administration 1.

The carrier power received at satellite 1 from the desired transmitter in its service area is found from the Friis transmission formula to be:

$$C = \frac{P_1 G_{ET1} G_{SRI} D_{SRI}(\psi, \psi_o) \lambda_1^2}{(4\pi R_2)^2} \tag{1}$$

The interference power received from a transmitter in the service area of satellite 2 is found from:

$$I = \frac{P_2 G_{ET2} D_{ET2}(\theta, \theta_o) G_{SRI} D_{SRI}(\alpha, \alpha_o) \lambda_2^2}{(4\pi R_2)^2} \tag{2}$$

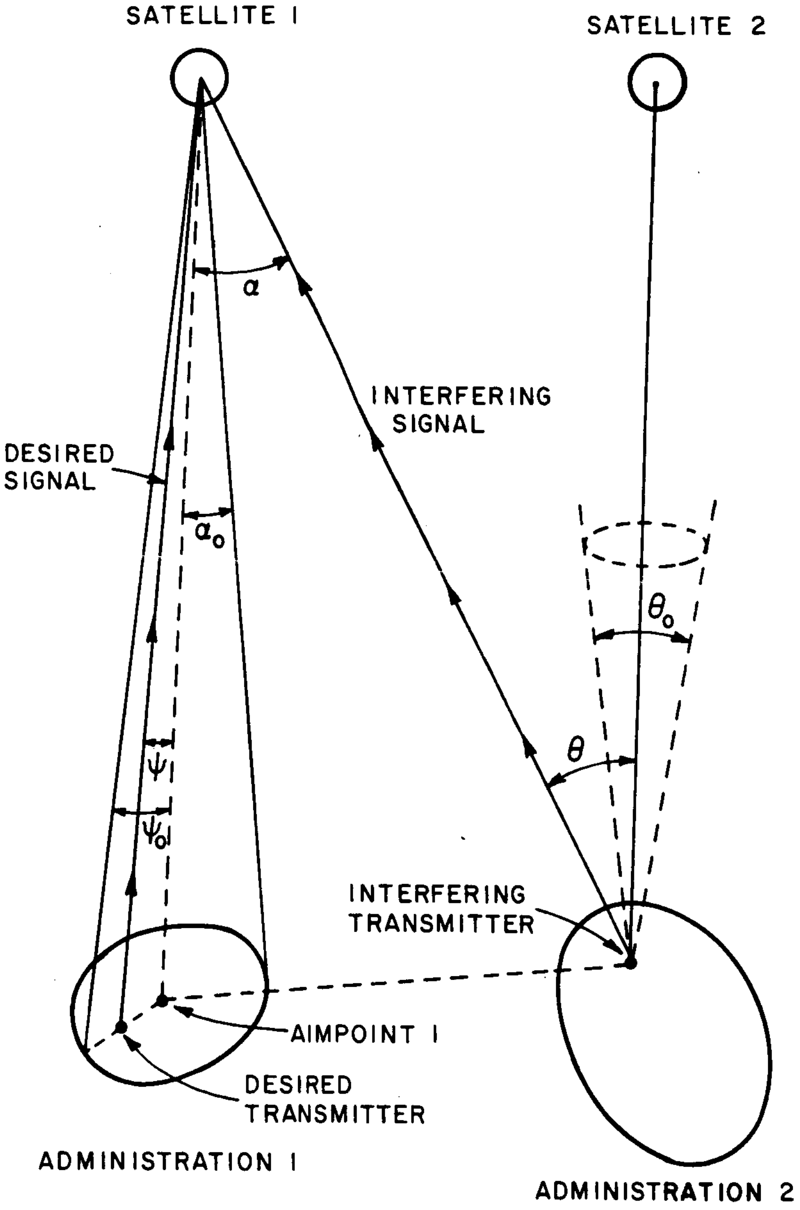

Figure 1. Interference geometry between two satellite networks sharing an uplink frequency.

The following subscripts have been used in the above equations:

E ----- earth station

T ----- transmitting antenna

1 ----- service area from which the desired transmission originates

o ----- denotes the half-power beamwidth of an antenna

S ----- satellite

R ----- receiving antenna

2 ----- service area from which the interfering transmission originates

The variables listed stand for:

P ----- power input to earth transmitter

G ----- on axis gain of an antenna

D ----- relative gain below maximum of an antenna

R ----- range from earth transmitter to satellite

λ ----- wavelength of uplink transmission

The C/I ratio of satellite 1 is then found from:

$$(C/I)_{UP} = \frac{P_1 G_{ET1} D_{SRI}(\psi,\psi_o)(4\pi R_2)^2}{P_2 G_{ET2} D_{ET2}(\theta,\theta_o) D_{SRI}(\alpha,\alpha_o)(4\pi R_1)^2} \qquad (3)$$

In the above relation it has been assumed that the desired and interfering transmissions are on the same frequency and that there is no polarization discrimination between the two signals. In practice, the power received from earth transmitters may fluctuate due to local propagation effects and precipitation which may be different for transmitters located in different geographical regions. To account for the possible reduction of the C/I ratio at the satellite due to these factors, an additional factor, which the CCIR report calls the uplink margin, could be included in the C/I equation. This term has been neglected in the calculations reported here.

A further simplification in the C/I equation results from assuming that the power input to each earth station transmitter is adjusted to achieve a specified power flux density at the satellite serving the earth station. Thus,

$$\frac{P_1 G_{ET1}}{4\pi R_1^2} \cong \frac{P_2 G_{ET2}}{4\pi R_2^2} \tag{4}$$

and

$$(C/I)_{UP} \cong \frac{D_{SRI}(\psi,\psi_o)}{D_{SRI}(\alpha,\alpha_o) D_{ET2}(\theta,\theta_o)} \tag{5}$$

The term, $D_{SRI}(\psi,\psi_o)$ reflects the position of the desired transmitter within the serivce area of the desired satellite. Since the locations of the transmitters are always chosen at the borders of the administration's service area, this term could be approximated as 0.5 (or -3 dB).

The denominator of the equation determines how closely the two satellites can be located to achieve the desired C/I. The term $D_{SRI}(\alpha,\alpha_o)$ reflects the geographical separation of the 2 service areas.

The closer the interfering transmitter is to the -3 dB contour on the earth of the desired satellites receiving antenna, the greater the interference will be. The term $D_{ET2}(\theta,\theta_0)$ reflects the longitudinal separation of the two satellites as seen from the interfering satellites. It is this term can be adjusted during the orbital assignment process to insure adequate C/I margins for all satellites.

The reflective gains below maximum of the earth station and satellite antennas are determined from the reference pattern envelopes shown in Figures 2 and 3. These patterns are found in the CCIR recommendations [4,5].

For purposes of comparison, the earth station gain pattern is shown at both the transmitting frequency of 6 GHz and the receiving frequency of 4 GHz. The patterns shown are for 4.5 m parabolic dishes. The increase in the effective size of the antenna for the uplink results in approximately 3 dB more discrimination for the same satellite separation. For this reason, the worst uplink C/I ratio for each service area tends to be greater than the worst downlink C/I ratio.

The current version of the computer program to compute the minimum required separations for all pairs of satellites, works to satisfy a specified total link C/I ratio. The link C/I ratio for each service area is found by first fnding the worst uplink and downlink C/I ratios for each area. The worst uplink C/I is found by performing an uplink calculation for all combinations of desired transmitter locations in a satellite's service area and all interfering transmitter locations in the interferng satellite's service area. Similarly, the worst downlink

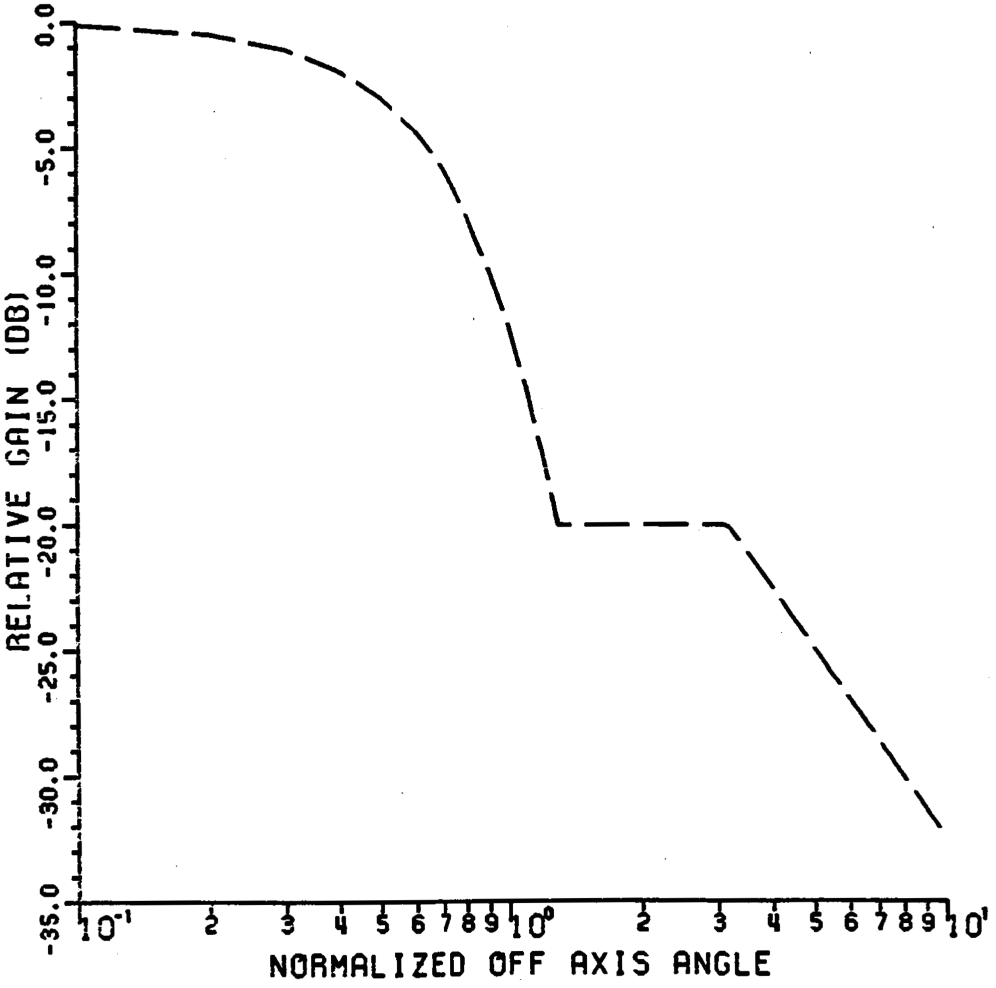

Figure 2. Satellite receiving antenna reference pattern envelope.

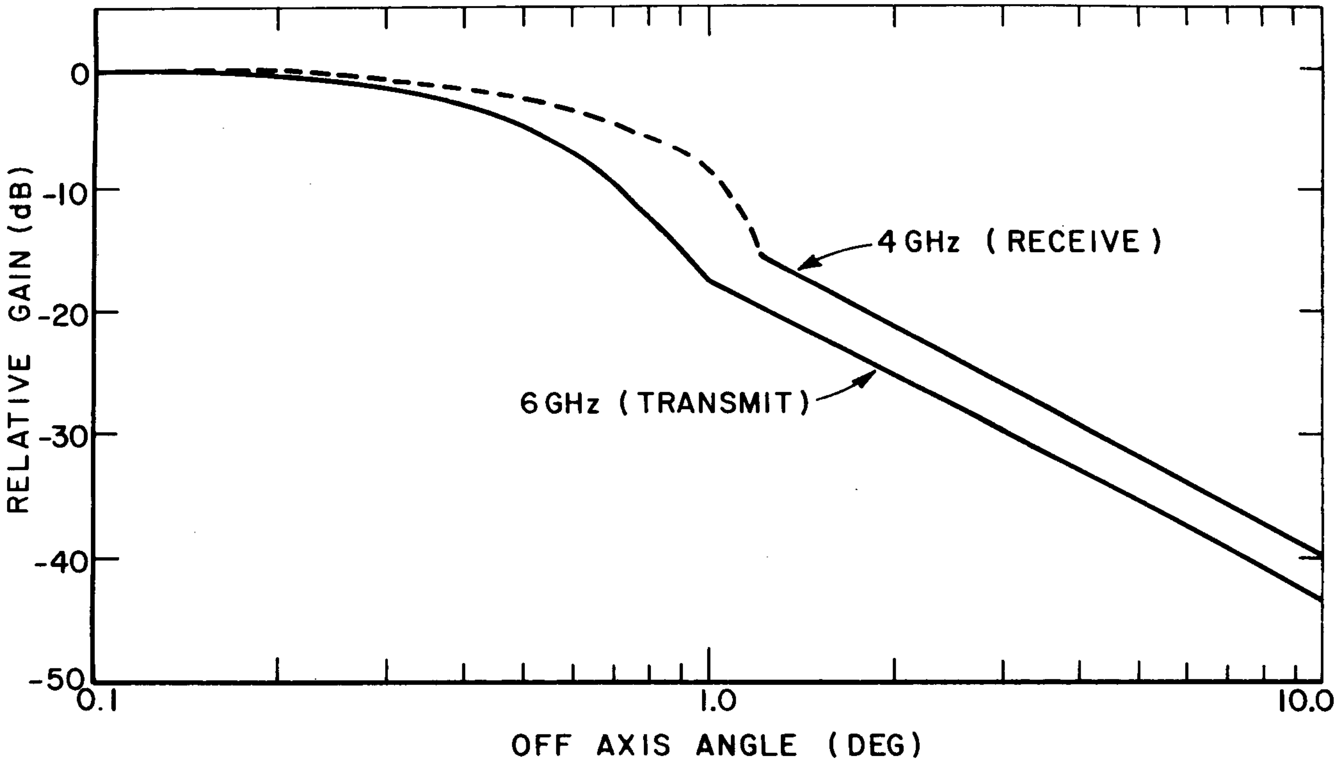

Figure 3. Earth station antenna reference pattern envelopes for receiving and transmitting antennas.

C/I is found by performing a downlink calculation at each receiver location in the satellite's service area. The link C/I ratio is then found by assuming that the C/I ratio on the transmission from the satellite is the same as that which is received by the satellite. This results in the following expression.

$$(C/I)^{-1}_{LINK} = (C/I)^{-1}_{up} + (C/I)^{-1}_{DOWN} \qquad (6)$$

The flow chart displayed in Figure 4 illustrates the procedure used in the program. A binary search is used to locate the minimum required separation at each orbital location considered. It is assumed that for small changes in the locations of the satellites that the only angle used in the C/I calculations which will change significantly is the angle of separation between the two satellites as seen from the earth stations. This is a reasonable approximation since the coverage patterns of the satellite antennas change very slightly as the location of the satellite is changed slightly. Thus, only the angle labeled θ in Figure 1 needs to be recalculated during each iteration.

C. Results

The curves displayed in Figures 5-7 illustrate the variation of the minimum required satellite separation values over the extent of the feasible arc common to both administrations. The administrations in question are all in South America. The curves are parametric in (C/I),

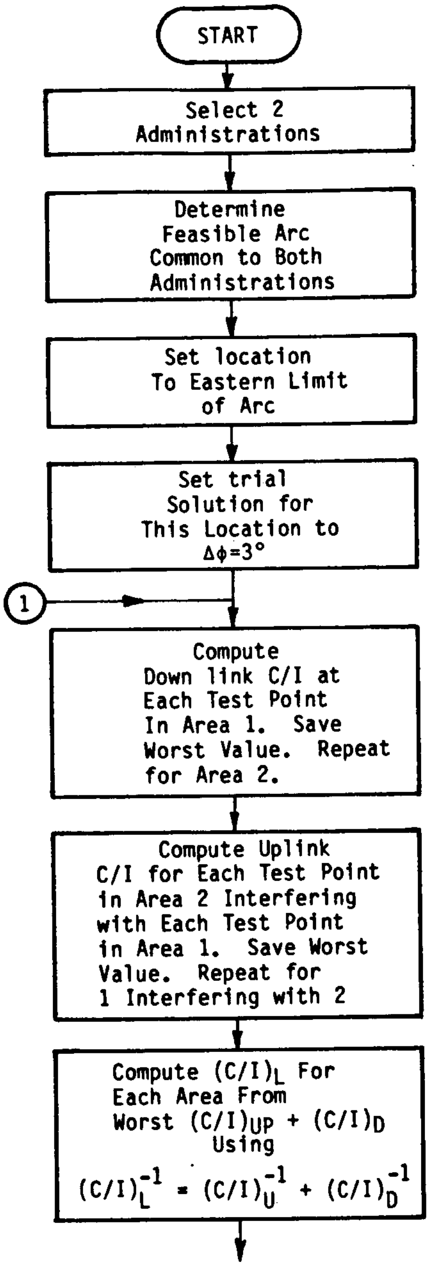

Figure 4. Flow chart illustrating modified procedure for the required separation calculation.

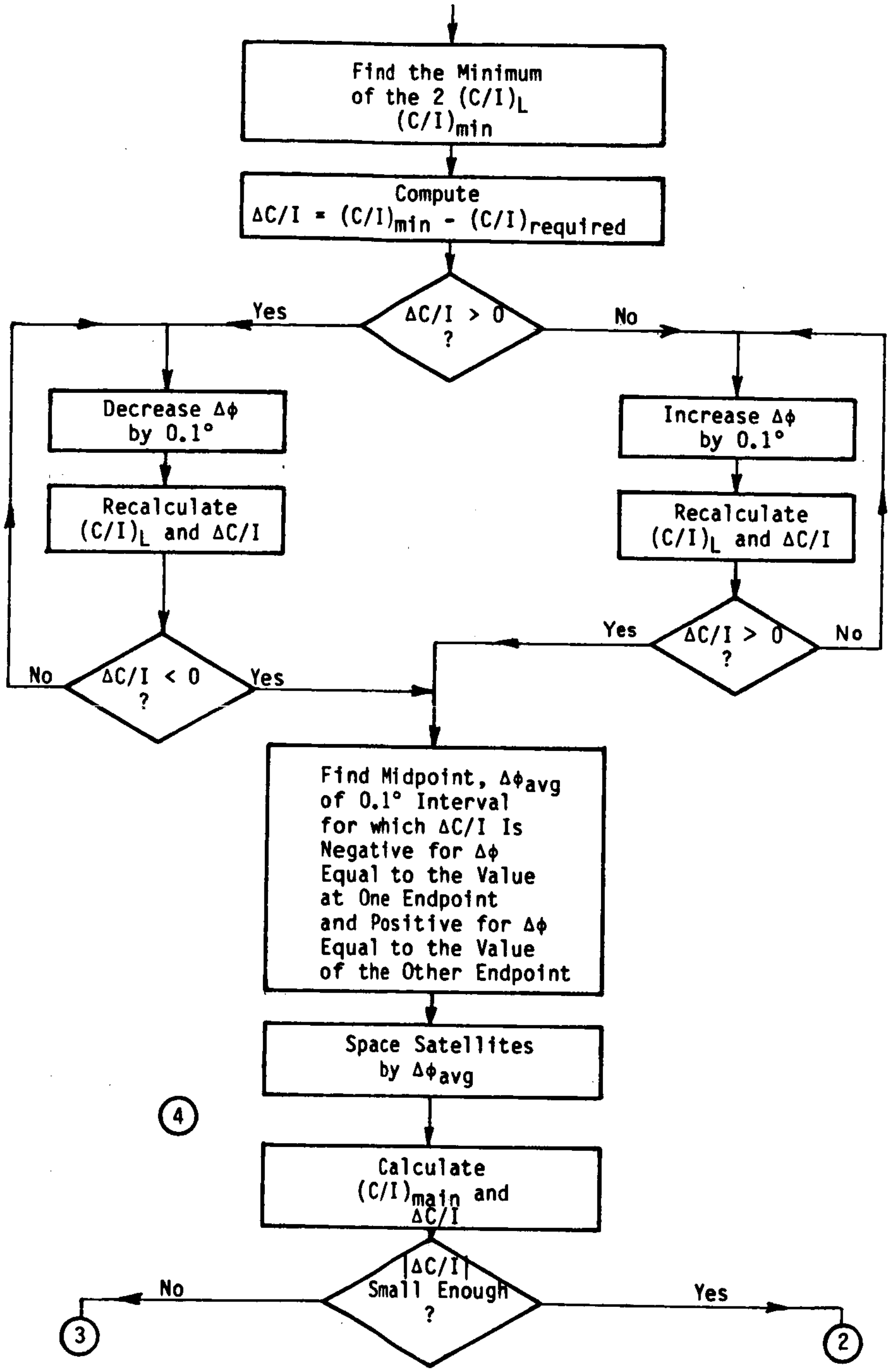

Figure 4. Continued.

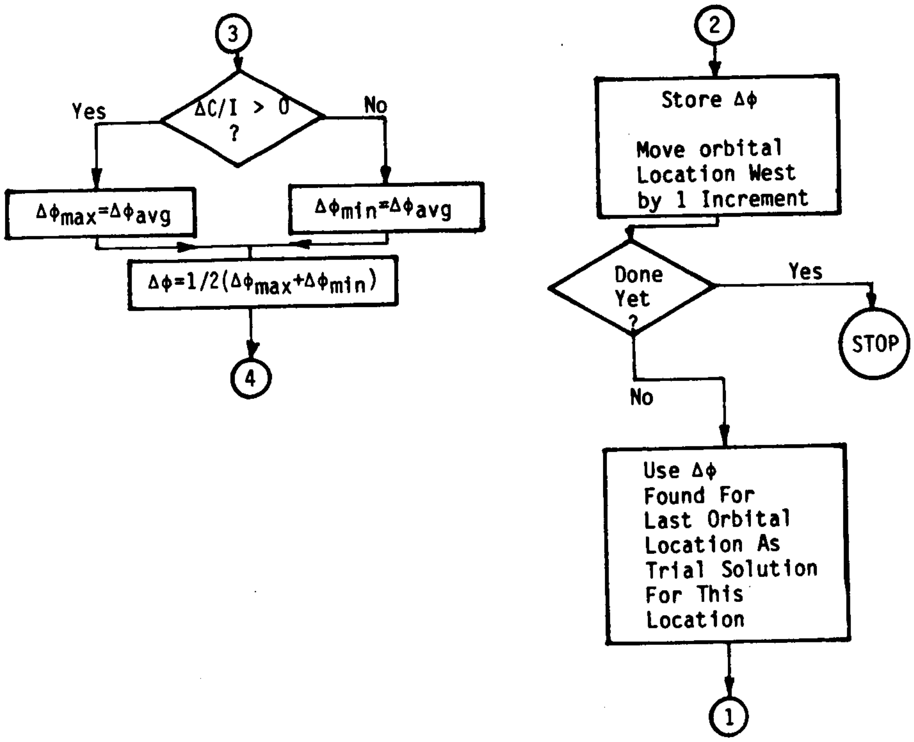

Figure 4. Continued.

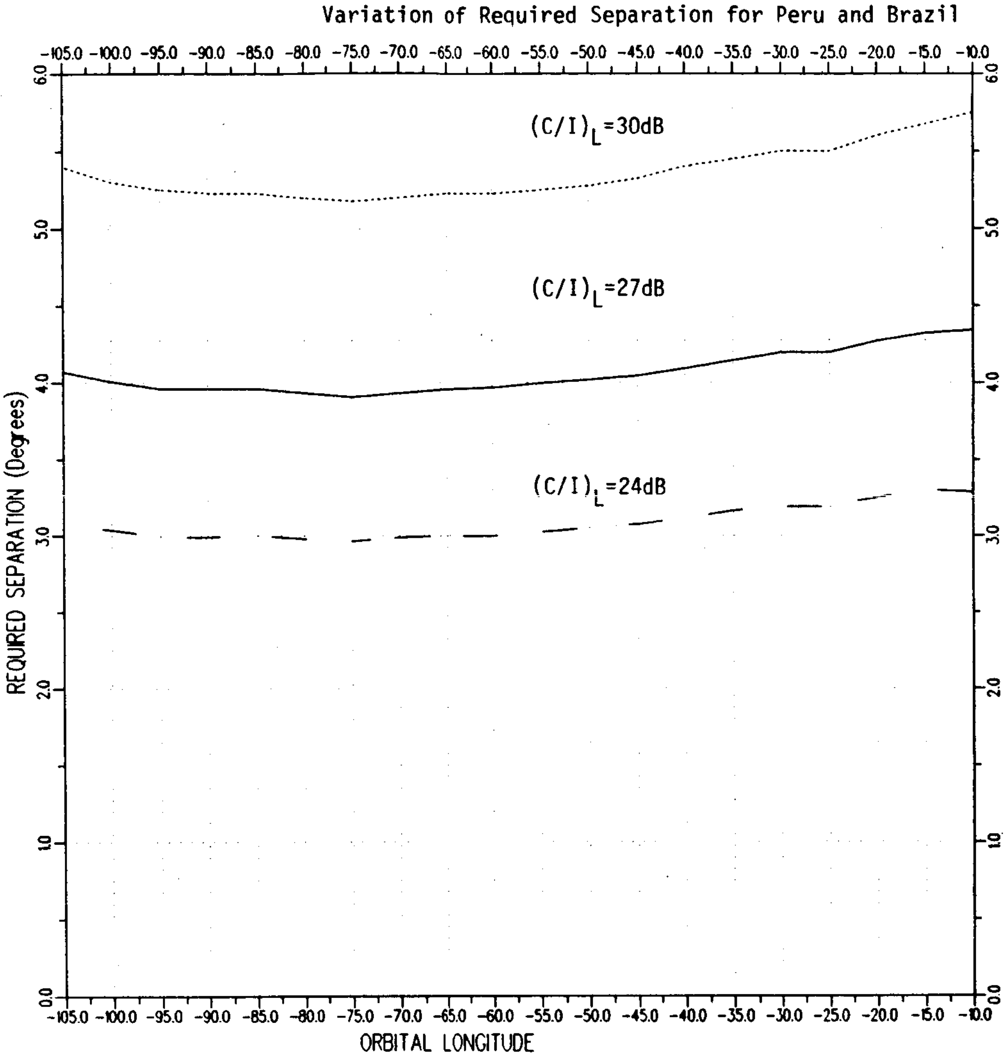

Figure 5. Variation of required separation over the orbital arc for satellites serving Peru and Brazil.

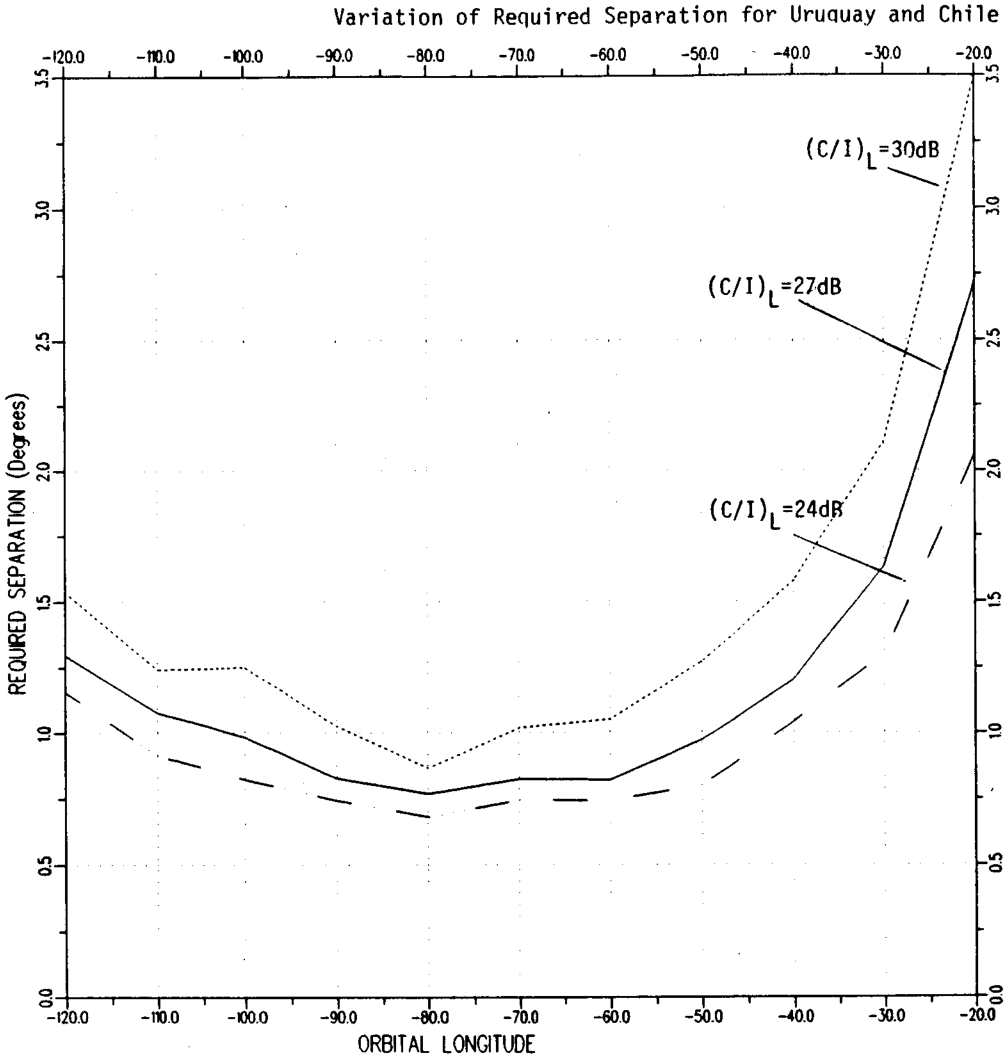

Figure 6. Variation of required separation over the orbital arc for satellites service Uruguay and Chile.

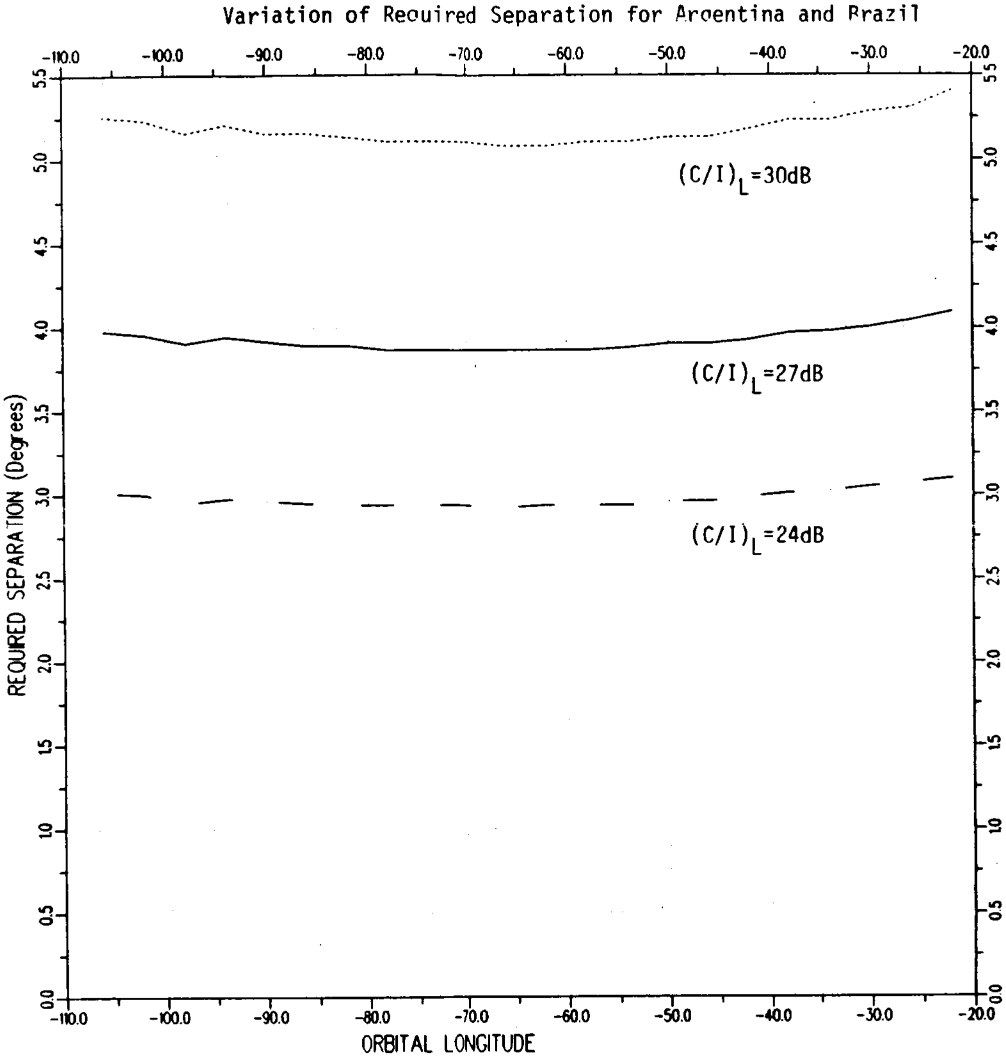

Figure 7. Variation of required separation over the orbital arc for satellite serving Argentina and Brazil.

the minimum required link C/I ratio. These curves exhibit roughly the same variation over the feasible arc as those reported earlier [6,7] in which uplink interference was not considered. That is, the maximum required separation between two service areas generally occurs near the ends of the arc that can be used by satellites of both administrations. At the ends of the arc, the topocentric angle of separation between the two satellites as seen from the earth, is smaller than it is at the center for a given longitudinal, or geocentric angle of separation.

D. Cost-Benefit Curves

As described in an earlier report [8], the margin between the carrier power received from the desired satellite and the total interference introduced from an interfering satellite link over both the uplink and downlink, is determined by two factors. These are the geographical separation of the areas being served by the two satellites and the longitudinal separation of the two satellites. The first factor determines the amount of the satellite transmitting antenna discrimination for the downlink. The second determines the amount of earth station transmitting antenna discrimination on the uplink, and the earth station receiving antenna discrimination on the downlink.

The orbital assignment problem for the FSS as presently defined, requires that the satellites cover their service areas with a single elliptical beam. For this reason, the half-power beamwidths of the satellite antennas are essentially fixed, and consequently, the discrimination supplied by the satellite antennas is also fixed. The discrimination supplied by the earth station transmitting and receiving antennas is determined by their half-power beamwidths which may vary from administration to administration.

The capacity of the geostationary orbit, in terms of the number of satellites which can be assigned orbits in a given segment of the arc, can be increased by reducing the amount of the required separation between satellite pairs. Since this required separation is a function of the earth station antennas, it follows that the capacity of a given segment of the arc can be increased through a reduction in the half-power beamwidths of the earth station antennas. The penalty for this increase in orbit capacity will be an increase in the cost of the earth stations for the affected administrations.

In order to examine the tradeoff between increased orbit capacity, in terms of the number of satellites in a given segment of the arc, and the total cost of the satellite system, cost-benefit curves can be generated. In these curves the total cost is defined to be proportional to the square of the inverse of the half-power beamwidths of the earth station antennas. The curves have been calculated on a pairwise basis, with the cost function plotted versus the maximum required separation value over the feasible arcs of the two administrations. The curves show either the effects of reducing the transmitting half-power beamwidth with the receiving half-power beamwidth fixed or vice versa. It is assumed that all earth station antennas in the service areas of both satellites have a uniform beamwidth.

Examples of these curves are shown in Figures 8 and 9. The curves show the extent to which the required separation between Argentina and Brazil can be reduced by reducing the half-power beamwidths of the earth station antennas in these regions. In the first, the receiving half-power beamwidth is held constant at 1.18 degrees (which corresponds to a dish diameter of 4.5 m under the assumptions used in the calculations) while the transmitting half-power beamwidth is allowed to vary. In the second, the receiving half-power beamwidth is allowed to vary while the transmitting value is held at 0.8 degrees (again corresponding to a 4.5 m dish).

The curves indicate that fairly large reductions in the required separation can be achieved by increasing the total cost of the system (as defined here) by 2 to 3 times its initial value. A point is reached, however at which very little further reduction in separation can be achieved even for large increases in the cost of the earth stations. A larger reduction in the required separation can be obtained by increasing the cost of the receiving antennas than can be achieved by increasing the cost of the transmitting antennas.

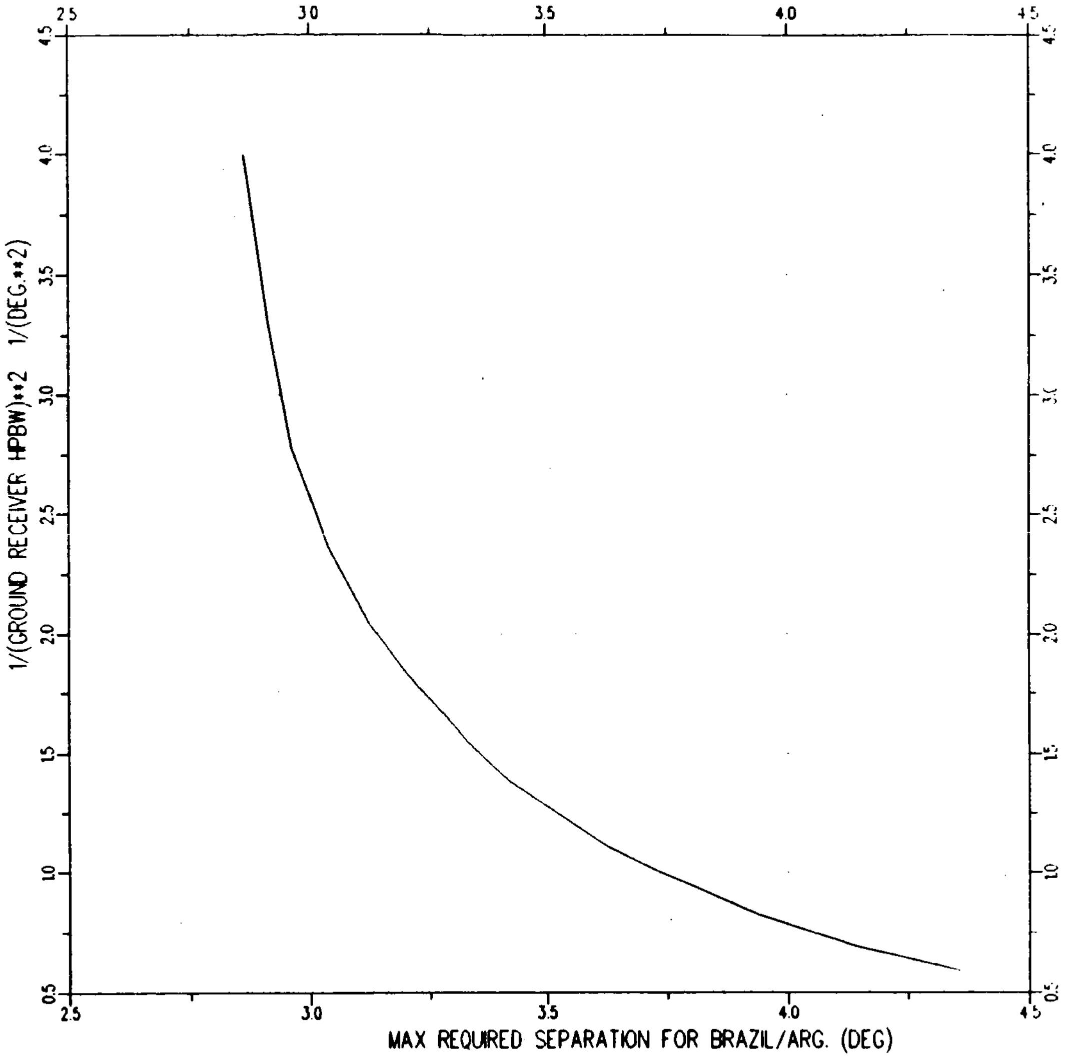

Figure 8. Cost function for ground receiving antennas in Brazil and Argentina versus the maximum required separation for satellites serving Brazil and Argentina.

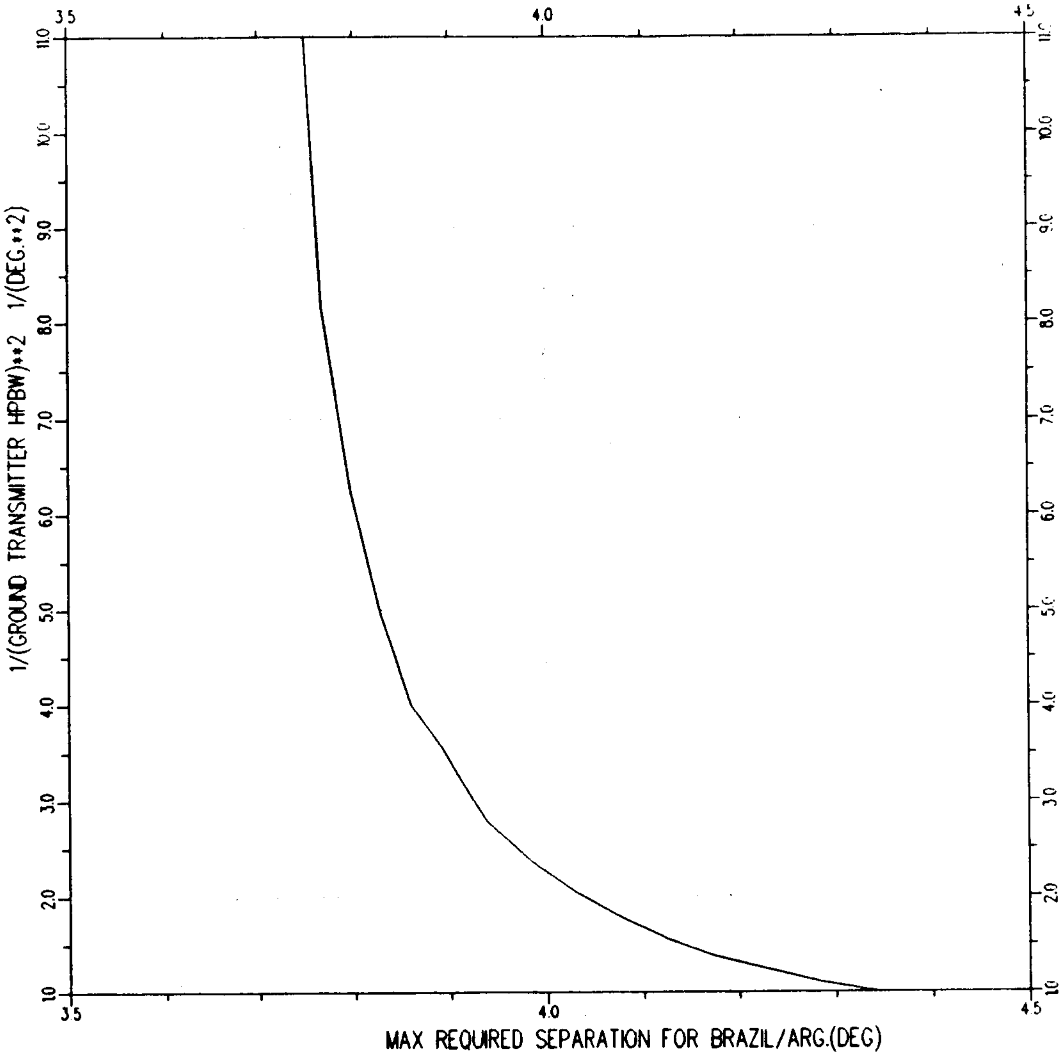

Figure 9. Cost function for ground transmitting antennas in Brazil and Argentina versus the maximum required separation for satellites serving Brazil and Argentina.

III. SWITCHING (PERMUTATION) ALGORITHM RESULTS

In our last interim report, we outlined a new algorithm that has been developed expressly for solving satellite synthesis problems. The new heuristic is a switching, or permutation, algorithm which exploits the observation that a synthesis problem is actually comprised of two problems, an ordering problem and a location problem [9].

The algorithm begins by ordering the satellites, either according to the satellites' assumed desired locations or on the basis of a user-specified ordering. For a given satellite ordering, the mixed integer programming (MIP) synthesis model first suggested in [10] reduces to a linear program. (The objective in this model is to position the satellites in such a way that the sum of the absolute deviations between their prescribed locations and their assumed desired locations is minimized.) The linear program associated with the original ordering is solved. Next, all possible permutations of k adjacent satellites are systematically enumerated and evaluated to determine if any of them would result in a better synthesis solution. The evaluation of the satellite reorderings is performed efficiently, making use of duality theory and sensitivity analysis results for linear programming [11,12]. Any permutations that lead to immediately improved solutions, as measured by the objective function, are made. The method continues until no more groups of k adjacent satellites can switch positions and produce an improved solution. At that time, the method is terminated, or k is incremented and the process is repeated. The switching method has been exercised for k=2, k=3, k=4, k=5, and k increasing from 2 to 5.

It has been our observation that the switching algorithm with the 'increasing k' option produces the best synthesis solutions at the most reasonable expense. It is considerably less time-consuming to examine all possible switches of immediately adjacent satellites (k=2) until no more such switches produce an improved solution, then to examine all switches involving three adjacent satellites, and so on, than it is to always examine switches of five adjacent satellites. The ratio of the time to examine all switches of k+1 adjacent satellites and the time to examine all switches of k adjacent satellites with this algorithm is k. The ratio of times for an iteration with k=5 and an iteration with k=2 is approximately 24. Many switches can be made in iterations where k is small, leading to substantial computational savings. The only switches made with the larger values of k are those that could not be made with smaller values of k. All of the results we report with the switching algorithm are based on computer runs made with the 'increasing k' option.

The switching algorithm has two very distinct advantages over existing exact solution procedures. First, though there is no assurance that the switching algorithm will find an optimal solution to a synthesis problem, the method has found feasible solutions to synthesis problems quickly. Furthermore, the solutions found by the switching algorithm have had objective function values comparable to those found with truncated runs of exact solution procedures. Second, the switching algorithm can use mean-location-dependent satellite separation values instead of the constant worst-case separation values that would be necessary with other solution techniques if signal protection requirements are to be strictly enforced at all possible locations for each satellite. This is made possible in the case of the permutation algorithm because approximate locations of the satellites are known every time the ordering of the satellites is changed slightly. This means that finding solutions to large, tightly-constrained synthesis problems will be made easier.

Recent computer runs made with the switching algorithm and an MIP package are summarized in Table 1. For the three larger scenarios (36, 59, and 81 satellites, respectively), only the switching algorithm was used because we think it is unlikely that the MIP package would have identified a feasible solution for such large problems in two CPU hours, based on our experience with smaller scenarios.

It is encouraging to see that a feasible solution was found for a synthesis problem with 81 satellites in a reasonable time. Though we do not know how good the solution for this large scenario is, the quality of the solutions found for the smaller scenarios can be assessed. In two of five cases, the switching algorithm found a solution that is known to be optimal. In a third case, it found a solution with the same solution value as the best solution found with the MIP package. The differences in the solution values between the switching algorithm and the MIP package were less than nine percent in the other two cases.

Though we have reported similar favorable results for the switching algorithm earlier [14], the fact that the switching algorithm has been able to identify a feasible solution to a synthesis problem with 81

Table 1

Summary of Switching Algorithm Results [13]

Test Problem	Number of Satellites	Best Switching Solution		Best MIP Solution	
		Value	CPU Time[a]	Value	CPU Time[b]
Europe/ North Africa	36	121.79	541	-	-
OASTS2G1	59	443.98	1200[c]	-	-
Western Hemisphere	81	832.46	600[c]	-	-
Eastern Europe[d]	12	52.74	7.34	49.87	613
Western Europe[d]	12	32.29	11.34	29.67*	41.4
South America[d]	13	30.44	11.35	30.44	86.4
North Africa[d]	10	8.65	3.68	8.65*	3.6
Southeast Asia[d]	10	23.05	5.31	23.05*	96.0

Notes: a - Runs made on an IBM 3081-D at The Ohio State University.

b - Runs made on an IBM 4341 at The Ohio State University. (We believe the IBM 4341 is approximately four times slower than the IBM 3081-D.)

c - Run terminated prematurely at user-specified time limit.

d - Worst-case satellite separation values used.

* - Solution is a proven optimum.

satellites in ten CPU minutes is significant. We think that this is truly a large synthesis problem, and it is unlikely that synthesis problems of much greater size will need to be solved, at least for Region 2.

IV. SWITCHING ALGORITHM SOLUTION QUALITY

Because the switching algorithm is an approximate, rather than an exact, procedure, questions about the quality of the solutions found with this method should be addressed. Though we have every indication that the switching algorithm is providing solutions of good quality in a reasonable time, it would be useful to be able to assess the quality of solutions analytically rather than experimentally. Such an assessment of solution quality could also be used as a stopping rule with the switching algorithm or even an exact procedure.

We have devised an analytical lower bound for the optimal solution value to the satellite synthesis problem with the objective of minimizing the sum of the absolute deviations between the prescribed and assumed desired locations of the satellites. We define D_i to be the desired location of satellite i, x_i to be the allotted (optimal) location of satellite i, and Δ_{ij} to be the required minimum separation between satellites i and j. For each pair of satellites i and j, we also define $s_{ij} = \max \{0, \Delta_{ij} - |D_i - D_j|\}$, the minimum possible sum of the deviations between satellite i's allotted location and its desired location and between satellite j's allotted and desired locations. For a two-satellite problem, s_{12} is the optimal objective function value, i.e., $s_{12} = |x_1 - D_1| + |x_2 - D_2|$.

In an n-satellite problem,

$$|x_i - D_i| + |x_j - D_j| \geq s_{ij}$$

and

$$\sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} (|xi - Di| + |xj - Dj|) \geq \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq 1}}^{n} s_{ij}$$

$$2(n - 1) \sum_{i=1}^{n} |x_i - D_i| \geq 2 \sum_{i=1}^{n} \sum_{j=i+1}^{n} s_{ij}$$

$$\sum_{i=1}^{n} |x_i - D_i| > \frac{\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} s_{ij}}{(n - 1)}$$

Hence, a lower bound on the optimal solution value can be calculated using a problem's parameters before any attempt to solve the problem is made. This is a tight bound because it gives the optimal solution value for any two-satellite problem. We have calculated this bound for some of the smaller synthesis example problems we have studied. The bounds calculated in these cases were considerably smaller than the known optimal solution values.

The s_{ij} can also be used to find a lower bound for a synthesis problem with the objective of minimizing the largest of the absolute deviations between prescribed and desired satellite locations:

$$\max_{i} \{|x_i - D_i|\} > \max_{i,j} \{s_{ij}/2\}$$

The solution-value bounds that we have presented here are the result of our first attempt to derive such bounds. It may be quite difficult to construct analytical bounds that are tight for all problem sizes. However, an empirical investigation of the relationships between these bounds and the optimal solution values as a function of problem size might allow us to adjust the bounds on the basis of problem size or characteristics to obtain a better benchmark for assessing solution quality. Though such an approach would not guarantee us a true lower bound, it would provide a simple means for estimating optimal solution values based on problem parameters.

We believe that the calculation of solution value bounds is an important area of research. Bounds not only facilitate the assessment of solution quality, but they also could be useful in establishing stopping criteria for either an exact or an approximate solution procedure.

V. STUDY OF ALTERNATE POINT ALLOTMENT MODELS

Much of our recent effort to solve synthesis problems has been concentrated on the problem of minimizing the sum of the absolute deviations between prescribed and desired satellite locations. The choice of this objective function was made by us at the time we began to study integer programming models for satellite synthesis. Though we think that this objective is a reasonable selection, we realize that there are other reasonable choices. Hence, we are studying several synthesis problems with different objective functions. All of the formulations are similar in form and use the required minimum satellite separations developed by Wang [15].

Specifically, we are studying the following point allotment models:

1. Minimizing the sum of the absolute deviations between allotted and desired satellite locations.
2. Minimizing the sum of weighted absolute deviations between allotted and desired satellite locations, where the weight for each satellite is inversely proportional to the length of its feasible arc. (No feasible arc constraints are enforced.)
3. Minimizing the largest of the absolute deviations between a satellite's allotted and desired locations.
4. Minimizing the distance between the easternmost and westernmost allotted satellite locations.
5. Maximizing the smallest of the satellite separations beyond the corresponding minimum required separation.
6. Maximizing the smallest gap between adjacent satellites.

The second model was selected so it could be determined if there is a computational advantage to using a weighted objective function instead of explicitly enforcing feasible arc constraints as we do in Model 1. Model 3 was chosen because we think that the magnitudes of the absolute deviations will be more nearly equal for all satellites than they would be with either of the first two models. The fourth model is for the same problem studied by Ito et al [16]; however, we use a an MIP model instead of a nonlinear programming model. The fifth model is similar, in terms of its mission, to our earlier nonlinear programming synthesis model because we think it attempts to maximize carrier-to-interference (C/I) ratios. We also expect it to leave room between satellites that could be used to accommodate satellites that are deployed later.

Finally, Model 6 is expected to yield solutions similar to those of Model 5, but the establishment of gaps between satellites is dealt with more directly.

We will use several scenarios with between 10 and 13 satellites in our investigation of these problems. Each model will be solved for each scenario with an MIP package. The solutions will be evaluated on the basis of observed convergence and solution time. We will also investigate the robustness of these models. One model may provide solutions that would be considered good solutions in another model. In such a case, one model might be preferred over another because it can produce good solutions to more than one model at less computing expense.

This investigation is not yet complete, but we can report some preliminary observations. Feasible solutions are found most quickly for Models 1, 2, and 3. These same models also produce more optimal solutions than the other models do in the limited-time runs we have made.

We have also observed that the solutions to Models 1,2, and 3 are good solutions to Model 4 as well. This indicates that our primary integer programming model (Model 1) yields good solutions to the integer programming analog of the nonlinear programming model of Ito et al [17]. The converse is not true. Solutions to Model 4 do not appear particularly good when they are evaluated in Models 1, 2, and 3.

We think that this phenomenon occurs, first of all, because Models 1, 2, 3, and 4 favor solutions in which satellites are positioned at longitudes directly overhead their service areas in test problems like the ones we are using in this study. Furthermore, the service areas in our examples are located near one another. Recall that our default for a satellite's desired location is the midpoint of its feasible arc. If satellites are ordered in such a way that they may be positioned almost directly overhead their service areas (Models 1, 2, and 3) and their service areas are near one another, then the orbital arc segment in which the satellites are positioned would tend to be relatively short (Model 4). But, if the satellites are ordered in such a way that they need a short arc segment in which to reside (Model 4), there is no reason to think that the satellites will be positioned near the midpoints of their feasible arcs (Models 1, 2, and 3).

On the basis of these preliminary observations, we think that our MIP synthesis model is potentially a very useful model. It has been found to be somewhat robust in the sense that it yields solutions that are of good quality in another important synthesis model (Model 4). It is also amenable to solution by a promising heuristic procedure, the switching algortihm that was described in Section III. This investigation will be presented in detail in a master's thesis by Bhasin [18].

VI. PLANS FOR THE NEXT INTERIM

In the interim from 12 January 1987 to 11 July 1987, we will continue our study of FSS system synthesis issues. In particular, we will investigate the use of shaped-beam technology and its potential impact on our synthesis work. At a minimum,the calculation of minimum required satellite separations would have to be modified if we assume satellites may have shaped-beam antennas. We also plan to continue and complete our experimentation with alternate mixed integer programming synthesis models. The switching algorithm will continue to be applied to synthesis example problems. The development of analytical and estimated solution value bounds is to continue so that the quality of the solutions obtained to synthesis problems by the switching algorithm and limited-time MIP runs can be more accurately assessed.

Modifications of the switching program are also planned so that this method can be applied to other synthesis problems. Our intention is ultimately to apply the switching algorithm to the MIP analog of Ito et al's nonlinear programming model [19] and to the problem of allotting arc segments to satellite administrations [20].

If it is determined by NASA that our attention should be shifted to problems of greater immediate importance, we will redirect our efforts accordingly.

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