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COMMUNICATIONS SATELLITE SYSTEMS:

A COMPUTER MODEL AND RELATED ANALYSIS

Volume II: The Model and Its Use

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VOLUME II

THE MODEL AND ITS USE

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VOLUME II

THE MODEL AND ITS USE

PART ONE. DESCRIPTION OF THE MODEL

GENERAL

The Technical Operations communications satellite model, programmed for the IBM 7090/7094, consists of six major routines and one associated subroutine.[1/] The major routines are the LAUNCH, ORBIT, COVERAGE, ASSIGNMENT, QUEUE, and COST routines. The subroutine, which performs certain functions to be described below in relation to the ASSIGNMENT and QUEUE routines, is the DEMAND subroutine. Documentation of the previous phase of work under NASA sponsorship discussed an additional routine,[2/] the FREQUENCY routine, which was considered then to be a luxury item since it did not directly contribute to generation of primary measures of cost effectiveness, and which was deleted from the model for that reason. Also discussed was a Ground Location model, the purpose of which was to define a minimum cost ground network. This problem, admittedly interesting, was not felt to be germane to the question of satellite evaluation and was only one factor in the choice of ground stations. We were not so concerned with the question of minimizing networking costs in a given region as we were with the total regional economic and political problem. The former is fundamentally a local problem. However, the total regional (national and international) problem is given careful consideration in Volume III of this report, and networking is cited where relevant.

1/Each of these is discussed in detail in Volume IV, Programming and Operating Documentation, of this report and, in design form, in Technical Operations, Inc. Report No. TO-W62-5, Models for Simulation of Communications Satellite Systems, June 1962.

2/William P. Murden and William G. Howe, Models for Simulation of Communications Satellite Systems, TO-W62-5, June 1962.

Our purpose here is to describe each segment of the model, from a functional viewpoint primarily, but with some mention of how each function is accomplished (see Figure 1).

THE LAUNCH ROUTINE

The purpose of the LAUNCH routine is the placement into orbit of the planned number and types of satellites. This routine has the design capability of cycling, so that as failures occur, during boost or after injection and operation (even for a prolonged period of time), satellites are replaced. Thus, in short, the LAUNCH routine ensures that functioning satellites are kept in orbit for the duration of the system being simulated, and that the ORBIT routine and all other routines in the model consider only functioning satellites at all times.

The LAUNCH routine processes an input launch schedule, which describes each launch in terms of scheduling, launch pad, number of satellites, type, and launch vehicle, and in auxiliary tabular form, a schedule of pad availability (turn-around time) as a function of usage. Distribution tables based upon the normal curve in the model as presently programmed (but held as variable dependent upon future testing and derived data), define eccentricity, altitude, and inclination. These, together with angular spacing between satellites, define the set of initial orbital parameters. Also specified for each launch is the desired orbital plane. A final set of inputs defines probabilities of successful injection into orbit and reliability in orbit as variables; these values and distributions will undoubtedly change with time.

The ability of the LAUNCH routine to cycle, replacing inoperative satellites and rescheduling unsuccessful launches, is basic to the requirement that other portions of the model be able to step chronologically without regard to whether a particular satellite is functioning. Thus, the LAUNCH routine is run initially, and but once, for each simulation, even if in real time the experimenter is examining many years of operation. The desired number of functioning satellites is thereby maintained.

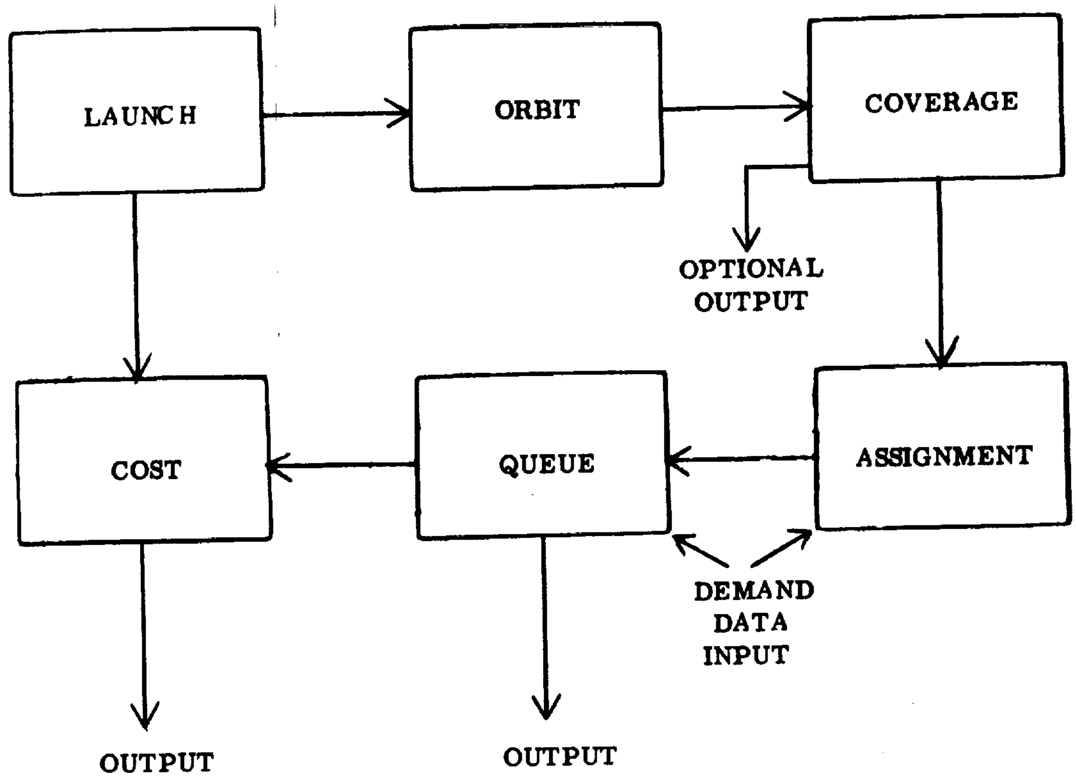

Figure 1. The Model — Data Flow

Replacement policy, that is, the set of criteria that determine when a replacement launch is scheduled, is treated as a variable[1/], a function of desired level of communications service, multiple launch capability, and orbital configuration. The process of replacement is a part of the launch process. Replacement is considered after all initial scheduled launches (and rescheduled launches due to failure to achieve injection) have been accomplished. As in-orbit failures occur, as determined by the relevant failure distribution, they are recorded. When failures sufficient to justify replacement launch have occurred, the launch is accomplished in accordance with the above noted launch pad availability table. Control thus cycles between the launch and replacement sections of the LAUNCH routine until a final pass through the replacement section indicates no further failures during the time of interest.

The LAUNCH routine, even for a system of many satellites and a simulated total system life of several years, takes less than ten seconds of computer time. Output of the LAUNCH routine indicates time of launch and failure, identification, and initial orbital parameters for all orbited satellites, for input to the ORBIT routine, and the same data for all attempted launches plus launch vehicle data, for input to the COST routine.

THE ORBIT ROUTINE

The ORBIT routine has but one purpose: the calculation of future positions of satellites as functions of (1) time and (2) the initial orbital parameters received of the LAUNCH routine.

It was determined early in the study that sophisticated orbital equations, of the kind required to identify an orbiting object or fragment, were not required for the kind of calculation needed in this model. We were interested in positions of satellites relative to points on the earth's surface, and relative to one another,

1/Variation, for some cases, would require minor re-programming to effect a change from our present model, where replacement occurs when three satellites in a given orbital plane have failed, Such changes may easily be accomplished in a day or two, between runs.

not in the precise definition of position and velocity in space. Thus we chose not to use the time-consuming and expensive (from a computer standpoint) computational routines already available, but to design a simpler set of equations of motion, realizing that we must ensure recognition of orbital perturbations and the satellite "clumping" phenomenon.[1/] Output of the ORBIT routine is composed of a listing of satellites, identifying characteristics (channel capacity and type of satellite), satellite coordinates in longitude and latitude, and a minimum ground-station elevation angle.[2/] Thus, the area of visibility for each satellite, varying with time, is defined.

THE COVERAGE ROUTINE

The purpose of this routine is the generation, over time, of a listing of all satellites and all possible communications links, indicating which satellite may provide service to which links at a given time.

One set of input to the COVERAGE routine is the output of the ORBIT routine specified above. The second set of input to the COVERAGE routine is a listing of ground stations with their coordinates.

The COVERAGE routine steps through time examining each satellite and computing the great circle distance from a point directly below the satellite to the most distant surface point at which the satellite is visible. This defines the circle on the earth's surface within which the satellite, allowing properly for elevation angle, is visible. A similar computation quickly ascertains which ground stations lie within this circle, thereby defining the set of possible communications links by means of a single satellite.

The ORBIT and COVERAGE routines together, examining a system of 20 satellites and 12 ground stations, necessitate, dependent upon output, approximately three minutes of computer time for 24 hours of real time. The primary set of output of this routine is the listing indicating, for all time, which satellite

1/Note the discussion in Appendix C where mathematics of the ORBIT routine are shown.

2/The latter, as a variable, enables flexible response to changes in satellite antenna patterns (and power supplies).

is visible to, and may serve, which link. Supplemental, and optional, output indicates the sum of satellite capacities available to a link, thereby enabling direct examination of instantaneous total capacity with its interesting implications.1/

THE DEMAND SUBROUTINE

The DEMAND subroutine is not a separate entity, but consists of portions of both the ASSIGNMENT and QUEUE routines. The ASSIGNMENT routine section is the simple input of raw demand figures, in terms of average voice-channel utilization, to the ASSIGNMENT routine itself for comparison with link capacities and other link/ground station characteristics. The QUEUE routine converts these average channel utilization figures to originating (new) demand for a given time period. For small increments of time, the difference between average channel utilization and new demand can be significant, and it is the latter measure that is required in the QUEUE routine. The DEMAND subroutine thus takes the projection of demand, a basic and vital economic input to the model, and provides it in forms usable in both the ASSIGNMENT and QUEUE routines.2/

THE ASSIGNMENT ROUTINE

The purpose of the ASSIGNMENT routine is the allocation of circuit capacities as afforded by the various satellites to accommodate the demands of the various links. Basic inputs to the ASSIGNMENT routine are the average channel demand figures, plus link capacities as output by the COVERAGE routine.

The ASSIGNMENT problem is quite complex logically and has been subjected to careful, wide-ranging examination over a period of many months. There are many variables involved in this question3/, and what appears at first to be a fairly

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1/Supplemental output significantly raises running time, at present.

2/It is to be noted that the present model makes no provision for direct accommodation of demand that must be relayed through two or more satellites for reason of connectivity. Such demands are assumed to be broken into their single-link component parts.

3/The reader is referred to page 11 for further discussion of this problem and to Appendix A, where certain mathematical formulations are noted.

straight-forward optimization matter, amenable to mathematical programming treatment, turns out to be computationally infeasible even on the machine.

We have programmed an assignment algorithm that, although not optimum, has withstood careful scrutiny. It involves ordered optimizing, or proceeding through an assignment optimizing first on one criterion, then a second, and so forth. The criteria themselves are ordered in importance. This algorithm, noted below, is similar to the procedures suggested in earlier documentation[1/] and in Appendix A:

Step One - Order the links manually, for whatever reason of priority is paramount, or permit the routine to automatically base priority on demand level (and thereby accommodate high-demand links first).

Step Two - Beginning with the top priority link, assign to that link the satellite capable of serving the fewest number of additional links yet able to meet the demand carried on one ground antenna. If there is a choice, assign the satellite with the greatest "time in view".

Step Three - Continue assigning in "chunks" as defined by ground antenna capacity until link demand is satisfied or link capacity is filled. Carry all assignments from one minute to the next[2/] so long as visibility (connectivity) exists.

Step Four - Considering the second priority link, repeat the process, after modifying Step Two so that partially filled satellites are used whenever either all demand may be satisfied or the capacity of a ground antenna fully used. Go on to unused satellites only after partially filled satellites have been checked.

1/William P. Murden and William G. Howe, TO-W62-5.

2/ The minute is the time increment chosen for examination of the system in this model. This in itself is an interesting point, and is looked into briefly on page 19.

Step Five - Continue repeating the above process on down through the link-listing until all links are examined. Begin again, for the next minute, with top priority link.

This is known as the "synoptic" approach, since all links are examined at one time, and differs radically from an assignment algorithm that would step one link through continuous time. The latter approach has also been investigated, but possesses certain notable disadvantages. Priority complications, for example, arise when assignments are made over time without regard for competition from other links.

The ASSIGNMENT routine requires approximately four minutes of computer time for 24 hours of real time for a system of 20 satellites and 12 ground stations. Output of this routine is the assigned capacity available to each ground link in the simulation, as a function of time.

THE QUEUE ROUTINE

The function of the QUEUE routine is the generation of primary measures of effectiveness of the communications satellite system. Demand inputs derive from the DEMAND subroutine portion of QUEUE, still expressed as average channel utilization, and capacity inputs are afforded by the ASSIGNMENT routine.

The logic of the QUEUE routine, too, is complex, and is conditioned by a set of assumptions like those common to queueing analysis as applied to any telephone communications system. These assumptions concern the distribution of call durations (exponential), service priority (first come-first served, with backlog as necessary), and customer impatience (again an exponential distribution, with a constant fraction of the backlog vanishing in each time interval). The reader is referred to Murden and Howe, page 15 and to Volume IV of this report.for further discussions of queueing logic.

Basic to the overall model is the concept of "time slice" , the periodic interval over which the entire satellite-ground system is being examined. We have chosen a time slice of 24 hours, and a time slice of 12 hours, for the initial runs. For the 24-hour time slice, 1440 consecutive minutes are examined, and for the 12-hour time slice, where used, 720 consecutive minutes are checked. In the first case, then, 1440 sets of data are gathered; in the second case, 720 sets are gathered. The primary set of QUEUE routine output derives from the summation over each time slice1/, and an optional set of output indicates the results of each minute's operation within the time slice2/. We may thereby examine, for each ground link, not only how it fared for an entire day's operation, but also, if we wish, where during the day bottlenecks or other troubles occurred. Specifically, these output data are (1) average number of channels in use, (2) percent of demand satisfied, (3) percent of assigned capacity utilized, (4) average backlog of calls, (5) lost calls as percent of demand, and (6) interrupted calls as a percentage of demand. The optional minute-by-minute output includes the above, plus (7) new demand, (8) initial capacity, and (9) excess capacity. We also obtain, as a function of delay time, the number of calls transmitted for each link and summed over the whole system for every time slice. For 15 ground links, the QUEUE routine, without generating the optional output, requires three minutes of computer time for simulation of a 24-hour period. The number of satellites does not effect QUEUE routine running time.

THE COST ROUTINE

The COST routine has as its function the generation of profit and return for each participant in the system. COST routine inputs derive from the QUEUE routine (channel utilization) and from the LAUNCH routine (all launch-associated costs). All other cost data, and revenue data, are input directly into the COST routine.

1/Whenever they occur, and they may occur at any interval, regular or irregular (daily, monthly, yearly, etc.).

2/Optional because of the time required to output 1440, or 720, sets of data per ground-station link.

Satellite and launch vehicle costs, whether for initial establishment of the system or replacement, are treated as investment. The present value of this investment, or value at time zero, is computed for all launches over time. Treated similarly is investment in ground stations. Depreciation is applied to the satellite investment but not the ground station investment.[1] Operating expenses for the Satellite Corporation and for the ground stations are also summed over time and converted to present value. Revenues for the Corporation and each ground station are treated in like manner. Present values of revenue, and of operating expense, plus depreciation, are compared to determine a present value of profit (or loss). The return on investment for each participant is calculated by considering the present value of profits as the present value of a level annuity and thereby computing the corresponding level annual rate of return.

These data are output for each time slice examined in the simulation, and also in summary form reflecting cumulative results over all previous time slices. The COST routine requires less than ten seconds of computer time regardless of the system being simulated.

MODEL OUTPUT

Virtually all of the data described above are transferred internally within the model. However, COST and QUEUE routine output constitutes the essential decision-making potential in the model and is externally output automatically for each run. Output of the COVERAGE routine, both primary and supplemental, may be externally generated at the discretion of the experimenter. Examples of output are presented below, where we discuss the initial runs, and in Appendix D.

1/Note page 16 for further discussion of the depreciation problem.

PART TWO: IMPORTANT FEATURES

GENERAL

Intelligent use of the model as an aid to decision-making requires further discussion of several of its features. These are (1) the assignment problem, (2) the ground antenna problem, (3) political and economic analysis, and (4) the significance of various time factors.

THE ASSIGNMENT PROBLEM

As we have said, this problem has been carefully looked into, over an extended period of time, with the hope of defining a computationally feasible optimizing solution. In addition to the work described in this volume, this question was also investigated under a consulting arrangement.[1/] The minimization of unnecessary changes in satellite-ground link assignment, and the optimization of a weighted function of that objective together with maximization of profits and minimization of unsatisfied demand are both most directly expressible as quadratic functions. The substitution of linear approximation, however, introduces a departure from strict optimization that is impossible of quantitative estimation. Even when the much simpler objective of only maximizing profits is attempted, the simplest linear programming formulation requires approximately 1 1/2 minutes per assignment on the IBM 7090. Since a new assignment computation is required for each minute of system operation,[2/] total time is prohibitive. The attention devoted to the study of this problem has convinced us that a true optimization solution lies beyond the present state of knowledge, and we suggest this to the attention of those readers who seek such a challenging problem.[3/]

1/Dr. Thomas A. Saaty, Office of Naval Research.
2/See page 9, footnote 2.
3/We also briefly attempted structuring within the framework of an inventory problem. The mathematics were feasible, but reality was not achievable within the time available, if at all.

It should be borne in mind that the problem of assigning satellites to ground links is most severe and significant in the case of active, nonstationary satellites. Here both capacities and visibilities are dynamic. In the stationary system, visibility is static and capacity varies only as a function of assignment (or "loading"). In the passive case, although visibility is dynamic, capacity is essentially unlimited (a function of bandwidth available to the system as a whole). The assignment algorithm we have developed was originally designed to handle the active, nonstationary system, and very little additional effort was required to enable it to handle the other two varieties, and combinations, of systems.

In the case of passive systems, we simply raise the capacity of individual satellites so that it essentially becomes unlimited[1/] whereupon ground antennas become the constraint. Mixed systems require only that all satellites are capacity-labeled.

Inherent in the question of assignment is the very important matter of multiple access. Within the assignment algorithm as presently programmed, we make the admittedly optimistic assumption that unlimited multiple access, for active satellites as bound by design capacity, will be achieved. We have only superficially investigated the engineering aspects of this problem, but believe in the feasibility of at least some degree of multiple access. Much attention, certainly, is being devoted to the study of possible solutions.[2/] Programming changes to reflect the most pessimistic situation, i.e., the assignment of but one antenna per ground station to a satellite, would be minor; this is simply a matter of tagging a satellite in the program to prohibit further assignment to it. Changes to reflect varying intermediate degrees of multiple access would be somewhat more difficult to accomplish, yet would require but a few days' reprogramming between runs to vary multiple-access modes.

1/Raised to 4095 voice channels in the passive system runs we have made.

2/Walter Johnson, "Welch, CSC, Defends Stock Offer Timing," Electronic News, 12 August 1963, page 1.

The effect of our treatment of the multiple-access problem in the runs we have made is discussed on page 25.

We believe that the assignment algorithm enbodied in the model represents a good compromise between optimization and reality. It is what might be termed a sequential suboptimization, meaning that optimizing upon several objectives, ordered in importance, is accomplished. It could, with only that variation required to enable real-time use, be turned to the purpose of calculating assignments, at a control center, for a functioning system.

THE GROUND ANTENNA PROBLEM

Closely related to the matter of assignment, yet deserving of separate discussion, is the intriguing matter of specifying an optimum number and capacity of ground antennas for each station.

This is an important question, for ground antennas may be a very real system limitation or they may afford vast amounts of excess capacity. And, of course, they represent a large percentage of system cost to many potential investors.

The problem may be stated as follows: What is the desired number of antennas per station (and link) considering (1) TV (large bandwidth) requirements, (2) bandwidth loss as the number of antennas is increased within a general band, (3) the need for additional antennas for switching or backup, and (4) the objective of being able to divert an antenna to a high-demand link from one that is slack?

It is apparent, from inspection, that the last two of these objectives conflict with the first two; in short, another optimization seems to be called for. The extreme solutions are clear-cut; one is the providing of a single, very-high-capacity antenna per link and the other is the building of many smaller antennas, so that efficient assignment of traffic to the various antennas and links may be accomplished. To the best of our knowledge, the solution of this problem has not been found or, in fact, attempted. The present procedure is simply to derive a required link antenna capacity,[1] provide one high-capacity antenna for that link, and hope that satellite coverage will enable it to serve other links simultaneously. This, unfortunately, guarantees that demand excesses will go unaccommodated and, more important, that significant antenna capacity excesses will develop.

Optimal construction and use of ground antennas is an important facet of the assignment process and deserving of more attention from system designers. The ASSIGNMENT routine is capable of handling any number of antennas per station or link, of all required capacities.

POLITICAL AND ECONOMIC ANALYSIS

An important feature of the model is the absence of quantitative, even probabilistic, direct treatment of political factors. Political analysis is undertaken in Volume III and has resulted in the establishment of tentative conclusions concerning proposed ground station sites. We are not here arguing the merit or demerit of political and strategic gaming; this is interesting but irrelevant. We are only stating that our task was to outline political and economic considerations affecting initial choice of ground stations, and political considerations are best considered external to the computer model. In fact, in our view, it would be totally illogical and wasteful to attempt such analysis on the machine.

Such is not the case, however, where economic analysis is concerned, and economic (and cost) factors appear throughout the model and, of course, as output. Perhaps the most basic economic variable, and the most uncertain and complex, is the projection of demand for communication services. Early in the course of research we had to decide whether to devote time to development of

1/Based upon projected demands and the quality of service desired. For example, "P-.03 Service", which is now provided by the telephone companies for many areas, means that for but 3% of the time during peak periods, will capacity be unable to accommodate demand (based upon informal conversations with representatives of A.T. & T.).

better (hopefully) projections of demand,[1/] or simply ensure that the model could effectively evaluate demand levels, whatever they were hypothesized to be. We determined, because of the uncertainty that would remain no matter how exacting our analysis, that a study of demand in itself would lie beyond the intended scope of our task statement. We had, of course, no assurance that we could develop better demand projections than did the several other research groups. In sum, the significance of demand is best interpreted by the model, and the probability of a given demand is best derived from the reference sources. The model will accept all reasonable demand levels.[2/]

Other economic factors that are taken to be variables within the model, again for reason of the uncertainty that would surround attempts to define limitations, are rate structures,[3/] revenue divisions, and all system component costs. Also important factors to the success of a commercial satellite venture are the level of military demand (and the portion thereof that a commercial system may expect to be allocated) and cable competition, especially post-1965 and in view of high-capacity cable development. The RAND Corporation[4/], has studied military use of communication facilities, and it is generally held that the military, and federal government as a whole, will continue to require a large, and perhaps increasing, proportion of commercial facility.

1/There are many such studies, among them Conrad Batchelder and T. Arthur Smith, Demand for International Telecommunications, TO-W62-3, Technical Operations, Inc., June 1962.

2/Note the discussion on military demand, and cable competition, below.

3/And thereby regulatory practices.

4/Communications Satellites: Technology, Economics, and System Choices, RM-3487-RC, The RAND Corporation, February 1963.

Cable competition, in our view, represents the major doubt. If the development of high-capacity cables progresses as well as it may, the sum of commercial and military demand for satellite facility may fall far short of that required to sustain a commercial effort.[1/] It is possible to derive a table of possible total demand levels for all the various links, and associated probabilities of occurrence, from the various references with revision as deemed appropriate from further economic analysis. Further application runs of the model would make this sort of basic data, even though conjectural, quite desirable. However, the possible impact of cable competition upon these demand levels would remain quite disturbing and could be handled, at best, only in a similar loose probabilistic manner. In sum, the projection of demand is something that could be worked on at great length, but with results that would require, in prudence, that the model be able to test a very wide range of values.

Tied to economic aspects of this problem, and certainly a controversial matter in its own right, is the subject of depreciation. As will be pointed out below in our discussion of initial model runs, depreciation expense is likely to be high, especially for the Satellite Corporation, and its treatment deserves some mention.

There are three possibilities for treatment of satellite expenditures. All may be treated as investment costs, and depreciated; initial launches may be treated as investment and replacements as annual expense; or thirdly, all launches may be treated as annual expense. The arguments against the last two alternatives are powerful. Any consideration of satellite and launch vehicle cost as annual expense could result in wide annual income fluctuations (although stabilizing may occur) as functions of random replacements and the relatively high cost of satellite and launch systems. Furthermore, to the extent annual expense is

1/ The Wall Street Journal, July 18, 1963, among others.

system[1] will increase over time (since no depreciation is incurred), in spite of the totally unproductive nature of the inoperative satellites and destroyed launch vehicles. The argument against treatment as investment cost seems mainly to be that accounting and economic theory sometimes frowns on depreciating assets, such as orbiting vehicles, without any recovery, or salvage, value. There may or may not be precedent for this kind of policy, and regardless, this alternative, given that the satellite dilemna is unique, seems simply to make good business sense.

We therefore treat all launches as investment. Depreciation of satellites and vehicles is calculated on the basis of expected lifetimes as derived from the relevant failure distribution[2] and is then treated as an annual charge. Depreciation also is subtracted from total orbiting system investment, to prohibit this "rate base" from rising disproportionately.

The ground stations are treated in a straightforward manner; they are simply depreciated on a straight-line basis over a 15-year period beginning with the operational date. Asset value is not considered to decrease over time, as it would if depreciation were subtracted as incurred, because return would increase inordinately as asset value tended toward zero. Moreover, there may well be recurring repairs and replacements which, if capitalized, would stabilize asset value.

We cannot now predict how the F.C.C., the Communications Satellite Corporation, and any or all of the other participants may decide to treat this controversial matter. In due course all relevant elements of depreciation and investment theory will undoubtedly be examined.[3] Since orbiting elements have no

1/ This is plant, and the dollar value, in our runs, accounts for over 90 percent of corporate expenditures. It is difficult to picture it as anything but investment.

2/ As presently programmed, the Weibull distribution (Appendix B).

3/ See "Depreciation, Market Valuations, and Investment Theory," by Vernon L. Smith, Management Science, July 1963, for a concise treatment of this general problem, some discussion of various depreciation policies, and comment on the ambiguous and frequently more important, relation of depreciation to investment policy.

market value unless they are functioning, and since reinvestment (replacement) policy based upon a future stream of income is relatively clear-cut (complete failure means replacement; only the partials are questionable), the depreciation procedure decided upon may well be akin to the straight-line, original cost, capital recovery method we have outlined. It is to be noted, however, that the depreciation section of the model, a portion of the COST routine, is not complex from a programming viewpoint and may be readily revised.

SIGNIFICANT TIME FACTORS

Time is important, first, in terms of requirements for the computer. The IBM 7090/7094 system is expensive, and whenever time spent on the machine can reasonably be pared, it should be. We have attempted to build the model efficiently, without sacrificing performance, yet are convinced that an application phase could see the model run, for a given system, in but half the time presently required.1/ Of course, the length of time spent on the machine, for a given system, may bear directly upon statistical confidence in a given set of output; but only in a series of application runs, with associated sensitivity analysis, can these confidence factors be developed.

The variables which most directly influence required computer time are number of ground links, number of satellites, frequency of changes in either (because a time slice or "picture" of the system is required for each change), length of a time slice (e.g., a half-day, one day, two days) and desired output. The minimum number of time slices is dictated by changes to satellite or ground link configuration (or, in fact, by any change in the communications satellite system that causes the system to function differently after the change)2/. The maximum number would be based upon statistical evidence that no system vagaries are being overlooked.

1/We have run a three year system in one hour, with good results, and a six year system in 1 1/2 hours, also with good results.
2/Or the number of years being simulated, whichever is greater.

For the three and the six-year real-time simulations, we used, respectively, four 24-hour time slices and eight 12-hour time slices. We are reasonably convinced that no coverage difficulties were experienced, either in terms of recurring frequent (daily and weekly, for example) outages, or longer term clustering outages. This is treated in some detail on page 29 where we discuss the effort to determine the best length and number of time slices.

Another time factor of significance within the time slice is the minute. The minute is the length of time between successive looks at the system. Thus, as noted on page 9, there are 1440 checks of the system (assignments and other compilations of data) in a time slice of 24 hours. We considered examining the system at greater intervals, particularly for the higher altitude systems where coverage is less dynamic, but believe the process of rechecking to determine when coverage did change (once a change is uncovered) would be as time-consuming as minute-to-minute computation.[1/] We do not, at any rate, consider this factor to be significant in machine time required for the present model. Input and output of data, for example, are far more likely to afford real opportunity for future time savings.

1/For example, checking the system every ten minutes. If a change occurred, one would search back from minute to minute looking for the time of change. This approach, we understand, is undertaken in similar models.

PART THREE: RESULTS OF INITIAL RUNS

GENERAL

We were able to obtain useful data from five runs, as noted in Tables 1 through 3. It is most important to bear in mind, as we talk of these runs, that our purpose was not to define either a "best" communication satellite type, or a "best" world-wide ground station configuration. If this can be done within the framework of a contract calling for "at least three" runs of the model, then the problem is so trivial as to not require a model in the first place. [1/] It is the purpose, then, of this section to draw such conclusions as are proper from the initial set of runs; these conclusions to be interpreted carefully by the reader.

RESULTS OF SATELLITE CORPORATION OPERATIONS

From an examination of Table 1 certain facts stand out. The Communications Satellite Corporation showed a profit in but two runs. It is apparent, in comparing Runs 1 and 4, that the distribution of revenues is quite significant. In spite of the fact that more ground links were involved, and a simulated lifetime three times as long run, Run 1 generated but twice the revenue of Run 4 for the Corporation. And Run 4 showed a profit while Run 1 did not.

A comparison of Runs 3, 4 and 5 is indicative of the impact of the coverage factor. This, of course, is well explored in the literature [2/], and its importance is borne out in Table 1, where a comparison of revenue and profit is as expected, and in Table 2 where the effect of coverage upon demand accommodated is clearly

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1/ Our essential purpose was to build and demonstrate the potential usefulness of the model.

2/ A Study of Passive Communication Satellites, R-415-NASA, and Communications Satellites: Technology, Economics, and System Choices, RM-3487-RC, both The RAND Corporation, February 1963.

shown for certain links and is reflected in the revenues given in Table 1. It is important to note that no changes other than in the orbiting system were made between Runs 3, 4, and 5. Every other variable was held constant, insofar as Corporation operations were concerned.

TABLE 1
SATELLITE CORPORATION – FINANCIAL RESULTS

	Run 1	Run 2	Run 3	Run 4	Run 5
Type of Satellites	6000 mile active	2000 mile passive	2000 mile passive	6000 mile active	6000 mile active, and stationary
Simulated Time	6 years	3 years	2 years	2 years	3 years
Number of Satellites	18	18	18	18	12 random, 3 stationary
Number of Ground Links	10	8	8	8	8
Distribution of Revenue	1/3 Sat. Corp., 1/3 ea ground Station	80% to Satellite Corp., 10% to each ground station			
Total Investment (x 10^6)	\$192	\$59	\$52	\$83	\$151
Total Operating Expense (x 10^6)	\$11	\$5	\$3	\$3	\$5
Total Depreciation (x 10^6)	\$85	\$24	\$12	\$26	\$58
Total Revenue (x 10^6)	\$79	\$20	\$10	\$38	\$107
Profit (x 10^6)	-	-	-	\$9	\$44
Level of Annual Return	-	-	-	9%	19%

TABLE 2

PERCENT OF DEMAND SATISFIED 1/

	Run 3	Run 4	Run 5
London to Andover	14%	21%	66%
Paris to Andover	18%	23%	33%
San Francisco to London	1%	23%	69%
Rome to Andover	9%	25%	29%

Runs 2 and 3 were run essentially as a check upon one another, and inspection of Table 1 indicates that results seem to be as expected, allowing that Run 2 was for 3 years and Run 3 for 2 years. Exhibit B of Appendix D is the actual computer output of Run 2 at the end of the second year and the results, but for rounding, are quite close to those shown in Table 1 for Run 3.

Table 1 indicates, also, how important decreciation may become to the "book" profit of the Communications Satellite Corporation. This is not really intriguing in itself, but is pointed out because of the magnitude of investment in satellites and the interesting argument that may be evoked concerning the most suitable depreciation policy (see page 16).

1/ Taken from summary output of the QUEUE routine, automatically printed for every run. An example of actual output is given in Appendix D as Exhibit A.

RELATION OF MULTIPLE ACCESS TO CORPORATION'S OPERATIONS

Referring to Exhibits A and C of Appendix D, in no case did we find an indication that a satellite visible to a link was unavailable to that link because of prior assignment. And we did assume fairly high levels of demand over the various links, as may be noted in Appendix E. Capacity was assigned on an average channel utilization basis, and the assumed relation between incoming demand, call length, and backlog was such that utilization of assigned capacity for all links tended to stabilize near 60 per cent. The summation of demand over the North Atlantic links during peak periods is approximately 250 voice-channels, less than one half the stated capacity of one 6000-mile random satellite. In sum, we feel we have here further indication of something already reasonably well-established: that if multiple access is achievable the prime difficulty is simply in-service (coverage) time, and capacities of 600 voice-channels per satellite for narrow band transmissions seem excessive in spite of the fact that many links may "crowd in". If multiple access is not achieved, at least partially, we would have needed many more satellites and launches to derive the same Corporation revenue. In the initial years, if multiple access proves difficult, and if satellite cost reductions are worthwhile, it will undoubtedly be best to construct lower capacity satellites for the narrow band (non-television) transmissions. 1/

To review the procedure for making this determination, it is simply a matter of comparing QUEUE routine minute-by-minute data, 2/ QUEUE routine summary data, with COVERAGE routine supplemental output (also optional, therefore it too must be requested). The fact that sensible assignments were made is thereby established. To show that assignments were not capacity-limited, simply estimate total maximum channel requirements and compare it with Exhibit C (supplemental portion) of Appendix D. An example of QUEUE routine minute-by-minute output is given as Exhibit D of Appendix D.

1/ Barring unpredictably high demand levels.

2/ Optional output.

RESULTS OF GROUND STATION OPERATIONS

Shown in Table 3 are the financial data for the ground stations participating in Runs 1, 2, and 5. These data were taken from output similar to that of Exhibit B of Appendix D. The program numbers the stations consecutively from the southernmost, beginning with Number 1; thus, for our hypothesized network, Santiago-de-Chile was 1, Rio was 2, and so forth (data given in Appendix E).

A most striking indication, from examination of Table 3, is once again the influence of the division of revenues. Of course it is not surprising that the percentage of revenues awarded participants can either "make or break" the operation, and this is what we attempted to verify in this first effort at finding a vital input variable. The model output shows clearly that given equal divisions of revenues, many stations can recover their investments quickly (Run 1), and when most of the revenue is awarded the Corporation (Runs 2 and 5) only a satellite system affording excellent coverage (Run 5) will permit even the high demand stations to earn a profit. With demand as uncertain as it is, it would seem to behoove participants to initially settle upon a flexible, periodically reviewed, revenue division schedule; only in this manner may gross inequities be avoided.

Comparison of the various revenue figures of Runs 2 and 5 again strengthens the conclusion concerning coverage. Run 2, a low-altitude simulation, evidenced far more outage time than Run 5 where little outage after launch of the stationary satellites was experienced.1/ Revenues for Run 5 clearly show this.

SUMMARY

It would not be proper to attempt to draw further conclusions from the five runs we made. Other thoughts come to mind, such as the importance of assumed rates, of reliabilities of satellites in orbit, and of launch vehicle success probabilities, but these factors were not tested, except in the aggregate, in the initial runs.

1/ Where we simulated a mixed system, we caused the stationary satellites to be launched after one year in order to have "before" and "after" coverage indications. Some outage was experienced during run 5 because of satellite drift.

TABLE 3

GROUND STATIONS — FINANCIAL RESULTS

Run 1, 6 years

Station	Revenue Distribution	Investment (x 10^3)	Depreciation (x 10^3)	Operating Costs (x 10^3)	Revenue (x 10^3)	Profit (x 10^3)	Return
Rio	Each Station Receives 1/3	$2909	$ 732	$2757	$3095	-	-
Lagos	of the Revenue Derived from	2188	252	950	446	-	-
Beirut	its Links	4167	481	1776	4289	2030	11.0%
Tokyo		2909	732	2757	1550	-	-
San Francisco		5545	1397	5170	36051	29484	122.1%
Rome		6100	1763	6523	23661	15395	57.0%
Andover		6100	1763	6523	44346	36060	138.9%
Weilheim		5545	1397	5170	8089	1522	6.2%
Paris		6100	1763	6523	7224	1/	-
London		6100	1763	6523	25517	17231	64.8%

Run 2, 3 years

Station	Revenue Distribution	Investment (x 10^3)	Depreciation (x 10^3)	Operating Costs (x 10^3)	Revenue (x 10^3)	Profit (x 10^3)	Return
Rio	Satellite Corp.	$5003	$ 576	$1893	3	-	-
Tokyo	Receives 80%, each	5003	576	1893	22	-	-
San Francisco	Ground Station 10%	6822	788	2840	554	-	-
Rome		7500	1239	4466	908	-	-
Andover		7500	1239	4466	1628	-	-
Weilheim		6822	788	2840	195	-	-
Paris		7500	1239	4466	1068	-	-
London		7500	1239	4466	702	-	-

Run 5, 3 years 2/

Station	Revenue Distribution	Investment (x 10^3)	Depreciation (x 10^3)	Operating Costs (x 10^3)	Revenue (x 10^3)	Profit (x 10^3)	Return
Rio	Satellite Corp.	$5004	$ 577	1893	1344	-	-
Tokyo	Receives 80%, each	5004	577	1893	355	-	-
San Francisco	Ground Station 10%	6824	788	2841	5074	1445	8.4%
Rome		7500	1238	4463	3339	-	-
Andover		7500	1238	4463	7278	1577	8.5%
Weilheim		6824	788	2841	463	-	-
Paris		7500	1238	4463	4028	-	-
London		7500	1238	4463	4871	-	-

1/ Certain links involving Paris were not input to the simulation for this run. Paris revenues, however, have generally approximated those of Rome and London given our demand data.

2/ Ground station costs are somewhat higher here than may be expected.

These, and the entire range of variables tabulated in Appendix E and in the following discussion on continued use of the model, were either held constant from run-to-run or varied but slightly.[1/] In short, an attempt to use the model to generate meaningful points on a response surface, i.e., to begin a sensitivity analysis, was really beyond the scope of this work. We do feel, however, that these preliminary runs did verify the significance of revenue divisions, multiple access, coverage patterns, demand levels, and, to accountants at least, depreciation policy.

1/ Even satellite reliability in orbit, probably an important factor, showed little significance where generated revenues are most important and active satellites are given competitively long lifetimes.

PART FOUR: CONTINUED USE OF THE MODEL AS AN AID TO DECISION MAKING

GENERAL

This section is devoted to a discussion of one of the two remaining tasks if the effort involved in the design, building, and preliminary demonstration of this model is to bear fruit. Here we discuss intelligent use of the model; in Appendix F we discuss the actual card-by-card structure of the deck in the setting up for a run. It is our purpose to provide all the guidance required to permit the use of the model by any interested organization.

FURTHER APPLICATIONS AND SENSITIVITY ANALYSIS

This simulation is like others; it is designed to enable an experimenter to run replications of system tests and vary input parameters in a fashion directed by sound application of principles of experimental design. [1] We do not propose to discuss these principles in detail since the literature abounds with discussions of them, but rather we will briefly outline a procedure that could be followed in attempting to define a relationship between coverage and the length of the time slice chosen for a given run. This general technique would be relevant to the establishing of relations between many other system variables.

In attempting to determine a "best" length of time slice, or period for compilation of data, we are immediately struck by the importance of getting typical coverage patterns. This is important, too, in determining how many time slices, over long periods of time, are required to ensure that no long-term coverage patterns are being overlooked or, equally bad, considered typical when they are atypical.

The factors that seem most important in choosing time-slice length are orbital period and number of orbital planes. It is important, in other words, that the

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[1] The model also permits all randomly generated parameters to be held constant, if desired, from run-to-run by simply treating the random number generator starter as a constant.

earth track, or coverage areas, of satellites be a true common denominator when multiplied over the length of time being simulated. We chose time slices of a half day (720 minutes) and of a full day (1440 minutes); outage time patterns may be derived from these. A means of expected value comparison is available from the literature[1] for certain ground links. Outage (and coverage) times are quickly calculated for a given link, from the data typified by Exhibit D of Appendix D, and this may be compared with the expected value outage times, to check for accuracy, and from run-to-run to check for consistency. Unfortunately, we were not able to collect sufficient data of this sort from the initial runs to do more than a preliminary analysis, but considering the orbital periods and number of planes involved (approximately 2 and 6 hours, and 2 to 4 planes) we believe the time slices were sufficiently long. Certainly it would seem that the 24-hour time slice will generate proper coverage patterns. Nevertheless this may easily be checked within the framework of subsequent runs.

This procedure is typical of the fractional factorial approach[2] to replication, where the following two conditions are met:

1. Almost all of the output variance is attributable to main effects and two-factor interactions.
2. The logical structure of the system being analyzed permits the intelligent rejection of many two-factor interactions.

In application, this technique often provides some built-in check on the accuracy of the above assumptions, in this case that orbital period and number of planes are important main-effect and two-factor variables, interacting with one another and with length of time slice. Only, of course, is the effect of time slice examined in the experiment we have outlined.

1/ Communications Satellites: Technology, Economics, and System Choices.

2/ Herein applied to a variable internal to the model, rather than to a variable of the communications satellite system itself. The fractional factorial design is well-explored in many statistical texts.

Before leaving the subject of time slice and coverage we should note that we believe that all coverage patterns are properly considered by the model. Long-term, non-recurring, clustering is automatically detected and considered by the orbital equations and thereby in the COVERAGE routine. Very long-term clustering is practically precluded, anyway, by satellite failure rates; as failures occur, satellites are replaced in initial positions. Recurring, shorter-term fluctuations in coverage, due to randomization of initial orbital parameters, should be uncovered in the kind of experiment outlined above where the results for a given link, for consecutive time slices, may be compared. [1] Care should be taken to compare proper satellite networks. In addition, a minor reprogramming effort could effectively bypass certain orbital calculations and preclude coverage instabilities, if it becomes desirable to assume, rather than calculate, coverage patterns. This is particularly relevant to runs involving stationary satellites; in Run 5, for example, we permitted stationary satellites to drift, resulting in outages that may easily be avoided.

It is important to realize that much sensitivity analysis with regard to many variables inherent in the model [2] may be accomplished without recourse to a computer run for an answer to each question. This, then, is the essence of this section of the report; efficient, intelligent use of the model absolutely requires the application of sound statistical technique. Anything less is quite likely to spend more money, in the long run, than appears to be saved by rapid running and re-running of the model.

Having derived a set of systems data, like that in Appendix E, for a given run, one may turn to Appendix F for guidance in transposing this data to punched-card input.

1/ These fluctuations, of course, are considered in the orbital equations.

2/ In particular, the choice of ground stations in view of whatever political considerations are then relevant.

APPENDIX A

AN EXPLORATORY STUDY OF COMMUNICATIONS SATELLITE SYSTEM PROGRAMMING

Note: This appendix covers basic concepts of the assignment problem. The algorithm finally chosen for the model is similar to the synoptic algorithm discussed here.

AN EXPLORATORY STUDY OF COMMUNICATIONS SATELLITE SYSTEM PROGRAMMING

With misleading simplicity the problem central to this study may be described as finding the best way to use a given set of satellites for providing communications among a given set of ground stations. Upon the slightest inquiry, simplicity and brevity quickly vanish. In their place will be presented (1) a statement of purpose and an analysis of the scheduling problem (2) statements of a number of computational algorithms which have relevance to the problem and (3) conclusions as to their applicability and power.

PURPOSE

To fulfill the purpose of this study the simulation must be capable of providing unbiased measures of system effectiveness for a variety of system types. The simulation necessarily deals with two different classes of events: (1) those controlled or defined by the physical nature of the system under consideration, and (2) those controlled by the plan of action which directs the system's operation. The first class of events is fixed once a particular system configuration has been selected, and orbits are defined (by simulated launch). The latter class, however, is in essence a second variable in the system under evaluation. It is desirable that the simulation produce judgments of the relative values of a number of proposed systems of hardware. In making these judgments the investigator's view must not be clouded by the effect of an inadequate plan of action which accentuates the good points of a mediocre system while failing to recognize the strong points of a better system. In this respect an absolute standard of comparison is desirable. If it were possible to combine in the simulation a satellite system description with that plan of action which would ultimately be used with it, a highly realistic measure of the worth of the combination could be generated. At this time little is known about the nature of the plans of action which might ultimately be employed, yet system comparisons are required. The choice seems to lie between making system comparisons based in part on an arbitrary and potentially biasing plan of action or on an optimally limiting plan of action. The absolute nature of an optimizing scheduling scheme is attractive for at least two good reasons. First, it seems likely in view of the high cost of any satellite system, no matter what system is installed, that much effort will be applied to optimizing its scheduling. The last bit of performance will be squeezed out of whatever system is built. It is, therefore, likely that the best or nearly the best possible system schedule is the one which will ultimately be used. Secondly, effort devoted now to the problem of schedule optimization can lead to suggestions for system design modifications allowing operational improvements. Note, for example, the discussion on ground antennas earlier in this volume.

The purpose of this short duration study, then is to consider the problem of scheduling satellite capacity usage with primary emphasis on the development of optimal assignment schemes appropriate for inclusion in the simulation.

This Appendix presents findings in regard to the scheduling problem. In summary, there seems to be available at this moment no technique which is so structured and sufficiently powerful to be used to solve the unabbreviated scheduling problem in the operational environment. Problem simplification, abbreviation, or partitioning is called for, and it is recognized that a deeper understanding of the essential system interactions must be acquired before the needed problem modifications can be achieved. Nevertheless, a number of possibilities exist for dealing with the assignment problem in the simulated environment.

PROBLEM ANALYSIS

The communication system's primary objective is to provide ground-based users with the ability to communicate economically. If the term 'economically' is loosely used, the preceding may account for foreign policy as well as business considerations. Mathematical deference to foreign policy will be adequately observed if an externally supplied measure of data importance is allowed to modify the business costs of the system. Thus, in proposed scheduling schemes the use of priorities or policy values which might be arbitrarily assigned by governmental authority are acceptable. For instance, Ghana-U. S. communications might be considered to bring twice the revenue per word as Australian-South African communications even though their actual rates might be in the opposite relationship.

Within this framework an optimal schedule is one that maximizes effective system revenue over some stated interval of time. In other words an optimal schedule is one that produces:

$$\text{Max} \sum_{i,j,T} W_{i,j} R_{i,j} Q_{i,j,T}$$

where

$W_{i,j}$ is a factor of importance of communication between points i and j

$R_{i,j}$ is an estimated actual revenue rate for communications between points i and j

$Q_{i,j,T}$ is the revenue traffic transmitted between points i and j during time period T.

Limitations are imposed on the scheduling function by the equipment in the satellite as well as the ground-based equipment and its plan of action. A satellite may be either an active repeater or it may be passive. It may be in a high orbit or a relatively low one. In any case a single parameter, capacity, is sufficient to characterize the satellite's ability to relay the signals which it receives. A satellite's capacity to transmit between ground stations i and j vanishes (or becomes infinitely costly) when either of the paths, i to satellite or satellite to j, becomes infeasible for transmission. This can occur when a signal-to-noise ratio reaches an unacceptable level or when the path crosses the radio horizon. Capacity may be stated as a maximum information rate in bits per second or words per minute. For this problem a more aggregated unit is appropriate because a larger unit can reduce the computational difficulty of assignment schemes.

The differences between the ground-based antennas and other equipment required by active and passive satellite systems may be so pronounced as to preclude the use of part or all of one system's equipment with the other system. If complete independence is required or if only one type of system is built in quantity, the problem of optimal scheduling is vastly reduced. Where approximating algorithms are used, the partial overlapping of equipment capabilities is not too likely to cause trouble but when true optimization is sought overlapping capabilities are almost certain to bring computational infeasibility.

In the following discussions a scheduling problem is dealt with that is not complicated by partially interchangeable ground equipment; either a one-type system or one in which there is complete interchangeability is considered. Nevertheless, some of the algorithms that are presented are applicable, if suitably modified, to even the partial overlap problem.

Also the system is arbitrarily restricted to a deterministic sort of scheduling system—one by which a schedule might be calculated for distribution well in advance of its time of use.

The problem of a responsive scheduler is not considered—one that would change its assignments to conform to unpredicted demand fluctuations or the lengths of customer queues.

The elements which are central to the scheduling problem appear at first glance to fall neatly into the linear programming format wherein satellites are said to have capacities and predicted levels of desired point-to-point communications considered as demands. Other restrictions result from the number of antennas at sites and the inability of one antenna to point simultaneously to more than one satellite.

PROBLEM FORMULATIONS AND SOLUTION ALGORITHMS

Two rather different approaches to the problem of schedule optimization have been attempted. The first is based on a static instantaneous assignment optimization and approaches an over-all schedule optimization via a sequence of optimized assignments. The second approaches over-all schedule optimization by considering simultaneously all assignments which might be made during some meaningfully long interval of time (the synoptic approach).

STATIC OPTIMIZATION. As an illustration of static optimization the following simple problem formulation is given along with applicable solution algorithms. Later, attempts to generalize the formulation and solution algorithms are described. The first problem formulation is one which can be quickly solved and, despite its simplicity, it may be of value in making comparisons of proposed systems.

A static optimization has direct applicability to systems which change little with time or systems whose changes have little implication to cost effectiveness. If there were no important cost associated with shifting transmission paths from one satellite to some other, the only system "cost" of interest in scheduling a given system would be the loss in revenue resulting from not satisfying a demand. In that situation maximizing the usage of available satellite capacity would result in minimum system "cost". Since in this situation the assignment in one time period need not bear any relation to that in the preceding period, it is only necessary to develop an algorithm which optimizes the assignment for a specified set of demands and capacities independently and use that algorithm over and over to achieve complete optimization. In actuality this algorithm need only be used to determine schedules at those times when either a system demand or capacity is changed, for unless some input changes, an optimal assignment will remain optimal.

Inputs to the Problem. For the simple problem which is now being considered the problem inputs are completely specified for any time of interest by two tables, one relating to demands for transmission at that time and the other dealing with capabilities to transmit at the same time.

The demand table gives for each transmitter-receiver combination [1/] the amount of traffic which users desire to send at the time of interest. This infor-

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[1/] Demands are described at this stage as though they were demands for simplex transmission.

mation is indicated by the quantity, $D_{i,j}$, which may be interpreted as the level of demand for transmission between the i^{th} transmitter and the j^{th} receiver at the time of interest. In the capacity table, (C_k) indicates the total capacity of each satellite. Both $D_{i,j}$ and C_k are to be stated in terms of an integral number of data channels of specified information rate which are desired or available respectively.

No consideration is given to limitations on the number of transmitting, receiving, or multipurpose antennas which are located at each ground station. It is assumed for this example that sufficient antennas are in place and as a result it is possible to relax the simplex restriction and consider demands to be given as either simplex, duplex or both.

Optimal schedules are defined as those which minimize a broadly interpreted cost criterion. However, at this point the only cost considered is that loss in system revenue resulting from an insufficiency of system transmission capacity.

A linear programming transportation array may now be formed as illustrated by the following diagram (Figure A-1).

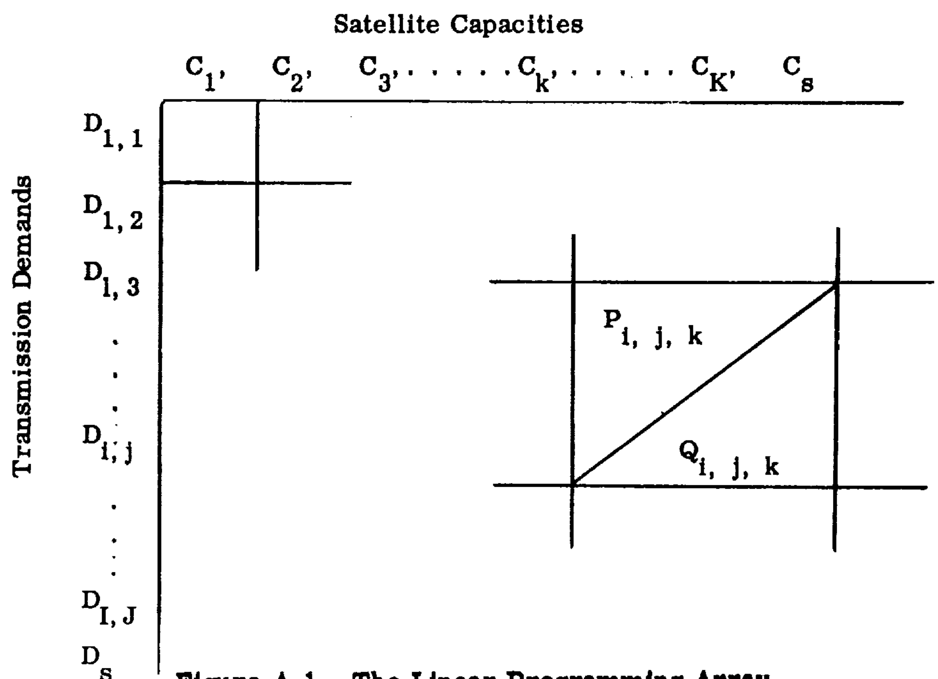

Figure A-1. The Linear Programming Array

In Figure A-1 the symbol C_s denotes the capacity of a "slack" satellite and D_s denotes a slack demand. $P_{i, j, k}$ denotes the cost penalty associated with the transmission of a unit of the demand, $D_{i, j}$, by means of satellite k. $Q_{i, j, k}$ denotes an assignment by indicating the number of units of demand, $D_{i, j}$, which are scheduled to be sent via satellite k.

The costs or penalties, $P_{i, j, k}$ will be effectively infinite when it is not physically possible to transmit any of demand $D_{i, j}$ via satellite k. The cost of transmitting a unit of demand $D_{i, j}$ via the slack satellite will be entered as the cost (loss in revenue plus good will or what have you) resulting from not transmitting that unit of demand at all. Since the cost of not transmitting is likely to be considerably less than infinity and since slack satellite capacity will be essentially unlimited, the linear program algorithm will never schedule any transmissions over infeasible routes. For the simple problem chosen, it is recognized that $P_{i, j, k}$ will be zero for all physically feasible routes, i-k-j.

At this stage it is recognized that the problem as stated may be greatly simplified when the costs are the same for all physically feasible routes ($P_{i, j, k}=K_1$) and are the same ($P_{i, j, k} = K_2; K_2 > K_1$) for all slack routes. When total real demand is less than total real capacity, any schedule which fulfills all real demands via feasible routes will be as desirable as any other. At the other extreme when total real demand exceeds total real capacity, any schedule which completely utilizes all available capacity will be as desirable as any other and all such schedules will be optimal. In either of the cases, however, real capacities and demands may be overlapped in such a way that it is impossible to either completely utilize capacity or completely satisfy demands or both. In such cases (and in general) those schedules which maximize the use of real capacity to satisfy real demands will be optimal schedules. The costs, $P_{i, j, k}$ of Figure A-1 now all have one of three values—K_1 for feasible routes, K_2 for slack routes, and K_3 for infeasible routes where these constants are in the relations,

$$K_1 < K_2 < K_3 \simeq \infty.$$

The so-called "Hungarian method" [1/] of linear programming might now be applied to effect a relatively rapid and efficient integer solution. In this problem, however, the regularity of the cost matrix allows a further simplification based on the matrix reductions of the Hungarian method. That simplification is desdribed by the following algorithm:

1. Begin with a matrix having a column for each real satellite and a row for each real demand and in the notation of Figure A-1 calculate:

$$A = \sum_k C_k - \sum_{i,j} D_{i,j}$$

   All $P_{i,j,k}$ in this matrix are either K_1 or K_3. Substitute $K_1 = 0$ for all K_1 in this matrix.

2. Next, modify the original matrix by adding a slack demand of magnitude A if A is positive or by adding slack of magnitude $|A|$ if A is negative. The $P_{i,j,k}$ for the slack just added are all K_2.

   It is recognized at this point that for an optimal solution to exist within the framework of the Hungarian method there must be at least one zero in each row and column. Since a row or column has just been added which contains no zero, a further matrix transformation must be performed. We subtract K_2, the smallest cost in the row or column just added, from each cost $P_{i,j,k}$ of the row or column just added and the result is a complete row or column of zeros. Enter all $P_{i,j,k}$ for slack rows or columns as zeros and do not bother with K_2 until a later time.

3. Now calculate row weights and column weights as required by the Hungarian method. To be specific:

$$a_{i,j} = \sum C_k \text{ for those k for which } P_{i,j,k} = 0$$

$$b_k = \sum D_{i,j} \text{ for those i, j for which } P_{i,j,k} = 0.$$

4. Test the Hungarian method's condition for optimality:
   If all $a_{i,j} \geq D_{i,j}$

   and all $b_k \geq C_k$

1/ Ackoff, R. L., Progress in Operation Research, John Wiley and Sons, Inc. New York (1961). P. 134.

and one or more of these inequalities is a strict inequality, an optimal solution exists in the zeros of the matrix. Even beginning with a matrix of K_3's and zeros, and adding a slack vector of only zeros, an optimal allocation may not be indicated. If the Hungarian method's condition for optimability is not met, an additional pair of slack vectors must be added to keep the problem square while allowing simultaneously for certain unsatisfied demands and unused capacities. The magnitude of slack demand and capacity in these two vectors must be the smallest amount which will cause the condition for optimality to indicate that an optimal solution exists. To achieve this, find the greatest negative $(D_{i,j} - d_{i,j})$ or $(C_k - b_k)$ and introduce a slack capacity and slack demand of that absolute magnitude into the matrix. Since slack capacity cannot be allowed to ever satisfy slack demand, enter all $P_{ss} = K_3$ and all other slack costs as zeros. An optimal solution will now be indicated by the matrix, and only the problem of selecting the solution from the matrix remains.

The following selection algorithm is proposed to perform the selection. In this algorithm the index ℓ is substituted for the two indices i and j as used previously to simplify the notation. The elements of a complete row of the matrix can now be viewed as:

$$D_\ell, i_\ell, j_\ell, (P_{\ell,k} Q_{\ell,k} \text{ for } k = 1, K), P_{\ell,s} Q_{\ell,s}.$$

All other symbols are as previously defined. Primed variables act as temporary storage registers corresponding to unprimed variables of the same symbol.

Selection Algorithm.

1. $\ell = k = 1$
2. Calculate row and column weights a_ℓ and b_ℓ respectively. Note that upon first entry to this algorithm an initial set of weights is nearly available.
3. If $P_{\ell,k} \neq 0$, go to (6); otherwise:
   $Q'_{\ell,k} = \text{MIN}(D_\ell, C_k)$
   $D'_\ell = D_\ell - Q'_{\ell,k}$
   $C'_k = C_k - Q'_{,k}$
4. Calculate new row and column weights, a'_ℓ and b'_k, on the basic of D'_ℓ and C'_k for all rows and columns that are effected. This is a maximum of (K + L) calculations.

Check the altered weights to see if the Hungarian method's condition for optimality still indicates an optimal solution. If an optimal solution would still exist after installing Q'_{ℓ}, substitute all primed variables for their unprimed counterparts and proceed to (5); otherwise:

$$Q'_{\ell,k} = Q'_{\ell,k} - 1$$

If $\quad Q'_{\ell,k} < 0$, go to (6).

Otherwise:

$$D'_{\ell} = D'_{\ell} + 1$$
$$C'_{k} = C'_{k} + 1$$

Go to (4).

5. If $C_k = 0$, $P_{\ell,k} = K_3$ for all ℓ.

   If $D_{\ell} = 0$, $P_{\ell,k} = K_3$ for all $_k$ and then go to (7); otherwise go to (6).

6. $k = k + 1$.

   If $k > K$, go to (7); otherwise go to (3).

7. $\ell = \ell + 1$

   If $\ell > L$, stop with an optimal assignment.

   Otherwise $k = 1$. Go to (3).

From the preceding description it is obvious that the algorithm might do a great deal of unnecessary checking of the existence of an optimum as selections are made.

Although the complete testing operation on a 100 by 250 matrix has been estimated to take only 3 seconds[1/] of 7090 time per test, an undesirable delay might still result. It must be recognized that more efficient selection schemes than that shown here can be devised to take advantage of two facts. First, not all weights need be checked on each successive test since only those that have changed can indicate a loss of optimality. Second, particularly in the beginning of the selection process, the possibility of making groups of selections before testing for optimality could reduce the number of required tests. If all selections but one were made without testing and then a test indicated the existence of an optimal solution in the remaining matrix, we would have eliminated nearly all testing with no ill effect (and also been very lucky). A well-designed

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1/ This estimate is based upon a 7090 machine language code which executes approximately 10 instructions per matrix element and 10 instructions per matrix row.

search scheme seems appropriate if greater efficiency is called for. That scheme is largely a matter of computer programming and so will not be discussed further.

When considering the effect of a single change to a matrix for which initially an optimal solution exists, an even more important realization exists in that it is not necessary to reprocess all matrix elements. A total of (L + K - 1) elements must be examined and at worst all L + K row and column weights must be reduced by a constant.

As an off-hand estimate of the computation time required to (1) put the matrix in memory, (2) create an optimal set of zeros, (3) select an optimal assignment, and (4) put it into some usable form, a maximum of one minute and a minimum of twenty seconds would be required depending upon the effort put into program optimization.

Relaxation of Restrictions. The two most important kinds of restrictions imposed by the simple problem formulation and solution method just presented can be classed as antenna limitations and time-phasing limitations. The consideration of antenna limitations is possibly of greater interest as part of the operational problem. Yet, the design question of how many antennas (of what type) to provide at each ground site must be answered. The simulation can help to provide this answer. The antenna question is an economic one that is very closely related to the scheduling problem. Optimal attainable use of a given set of antennas should be at the heart of the antenna decision.

A number of attempts were made to deal with antenna restrictions but success was limited. The efforts and applicable algorithms are described in the following section which is entitled "antenna limitations."

By time-phasing limitations we refer to the difficulties removed from the previous problem by the assumption that there was no cost or penalty associated with shifting from one system assignment to another. In reality shifting transmission paths too frequently can reduce system effectiveness by using up effective transmission time, and/or increase system cost by requiring unnecessarily large numbers of spare antennas. Certain approaches to dealing with this problem via static optimization are discussed in the subsequent section on time-phasing limitations.

Antenna Limitations. For the simple problem discussed previously it was assumed that the number of antennas at each point would always be sufficient to provide all connectivity required by any capacity-optimal schedule. An attempt will be made to relax that assumption and deal with schedules that are both capacity and antenna optimal.

To set the stage for the following discussions, consider an assignment matrix whose row and column constraints are real and slack capacities and demands and whose cost zeros indicate the existence of an optimal assignment. Let this matrix have the smallest amount of slack which can result in the optimality condition on the basis of capacity. The basic problem of the antenna limitation may be described as selecting out of the zeros of this matrix a capacity optimal subset of zeros such that the number of zeros associated with unique paths from or to (or both) each point does not exceed the number of antennas at that point. It must be recognized that the desired subset of zeros may or may not exist within the initial set. If it does, it may only be necessary to select it, but if it does not, first add an amount of slack (both capacity and demand) sufficient to cause the desired subset to exist.

If there were a computationally feasible algorithm to determine the existence of a combined antenna and capacity optimum in a set of zeros, the second need would be of minor importance. The selection of that particular set would also be made easy by a modification of the earlier procedure described as the selection algorithm.

Unfortunately, no direct algorithm with the desired properties has been found. A number of different possibilities have been considered for developing approximations to the optimal solution. All of the approximation methods considered begin with the minimum slack square matrix which can be capacity optimal.

Random Selection Search Algorithm. This algorithm selects at random an antenna-feasible set of zeros from the original set and then determines the amount of additional slack required to make that set capacity-optimal. Iterating while keeping track of the assignment that required the smallest amount of additional slack will eventually result in the selection of the best assignment.

The following is a somewhat more precise statement of the random selection search algorithm:

1. Initialize a random number generator and record its initializing parameter(s). Assuming the complete transmission feasibility matrix is available, choose at random a row and a column. If a zero is at the intersection, install it, if possible, in a test matrix and make the appropriate reductions to the lists of antennas available for transmitting and receiving.
   Note: Selections of the same zero more than once can be eliminated by either removing zeros from the matrix once they have been chosen or by some other device.

2. Continue the random selection process until either all antennas are used or all zeros have been considered, whichever occurs first.
   Note: When all zeros in any row or column have been considered, that row or column should be removed from consideration in such a way as to make the selection procedure as efficient as possible.

3. When the selection procedure has ended, a trial connectivity matrix will exist. The matrix testing routine must then be applied to generate a measure of effectiveness and compare this measure with the best of all preceding tests.
   Note: We need save only the initializing parameter(s) used to cause the random generator to produce the best matrix in order to be able to reconstruct it at the end of the procedure.

This selection and testing procedure will in its first iteration determine an antenna-feasible connectivity matrix and will then search for other such matrices which perform better than that one last selected. There is no definite end point to this process of selection. Either a time limit, an arbitrary numerical limit, or a statistically derived numerical limit must be imposed to halt it. The running time of the random selection algorithm is estimated to be about four times as long as the evaluation algorithm and the total running time per iteration is then about 30 seconds. The number of iterations required to produce an acceptable solution might be large.

The goodness of the assignment will generally appear to converge, but the power of this algorithm lies only in the nature of the statistically based statements which can be made about the best assignment which has been found after a specified number of random selections. As in the random statistical experiment with numerous variables, it will take a relatively small number of selections (16 or so) before there will be high likelihood (80%) that the best solution will lie in a best part (20%) of the full selection realm.

Best Addition Algorithm. At this point it is recognized that optimizing the assignment of satellites may be considered as finding that selection order with which zeros are chosen from the transmission feasibility matrix and placed into the connectivity matrix. If the correct ordering is found, whether by the random procedure described previously or by some more direct procedure, an optimal assignment will result.

Consider now a relatively direct procedure for selecting zeros for inclusion in the connectivity matrix. This algorithm selects that zero whose installation can result in the greatest satisfied demand. The zero is "installed" if possible and an accounting of antenna use is made. To be possible it means merely antenna feasibility since capacity feasibility may be guaranteed by slacks. The procedure continues until no more assignments can be made and then an evaluation of the assignment may be performed via the previously described evolution algorithm.

In somewhat more precise terms this algorithm scans the zeros of the capacity optimal set and selects that one whose use can bring about the largest satisfaction of demand. If sufficient antennas are available for the use of this zero, the assignment is made, demands and capacities are adjusted and again the best zero is selected. This procedure continues until no more selections can be made because either all antennas are used or no unallocated antenna can satisfy any additional demand.

This algorithm is not an optimizing algorithm although under appropriate conditions it can select an optimal assignment. Its principal advantage is that it attempts to find greatest demand satisfaction per connection made and therefore will tend toward optimal use of available antennas. It is also likely to be rather speedy in making its assignment. As described, however, it cannot make more than one assignment and therefore cannot be used without modification to investigate other assignments whose generating sequences are closely related to that described above.

Modification of a Capacity Optimum. When the assignment made without consideration of antenna limitations is one which breaks the antenna restriction in only a small proportion of its assignments, a slight modification of that assignment may yield a quite acceptable solution. If the antenna restriction were not broken for any ground station, the capacity optimal solution would be an over-all optimum. If a very small number of assignments were beyond the antenna restriction, ignoring the smallest excess assignments might nevertheless give a true optimum or a near optimum. Yet, if the assignment is not a true optimum the possibility exists that the satellite capacity scheduled for use by an excess (non-existing) antenna might be put to use to satisfy a real demand via an available antenna. The following algorithm is proposed for use in that situation.

1. Begin with an assignment schedule based upon consideration of capacity alone.
2. Remove from it all those assignments which are in excess of available antennas. Select for removal those assignments which satisfy the smallest demand per antenna.
3. Restore real satellite capacity in conformance with the assignments removed but do not restore demands.
4. Determine if any real satellite can satisfy any demand which is being satisfied in the assignment via a slack satellite and can do so via a real antenna. If possible, make the assignment(s) and stop. Note that if there are too many possible secondary assignments, the reassignment problem has the same appearance as the original assignment problem.

Time-phasing Limitations. If in addition to the elements of the original formulation is added a cost or penalty associated with rerouting a transmission path from one satellite to some other, a somewhat more realistic formulation results. The following paragraphs describe attempts to consider such a cost.

Two problems which are different in appearance but actually are closely related must be dealt with if this revised formulation is to optimize the assignment. First, is the theoretical problem of selecting a cost or penalty whose use can drive the static optimization algorithm to or toward a dynamic (time-inclusive) optimum. Second, is the problem of computational feasibility and computation time.

Cost Estimators. Begin with an assignment in effect at time t and consider that assignment to be made for the time t + 1. Note that as before the time indexing need refer only to times at which either a demand or a capacity are changed.

The following observations are at the heart of this treatment of rerouting costs. First, no rerouting cost is encountered if a route being used at time t is continued in use during time t + 1. Note that here is a route as it pertains to a single point-to-point demand, not as it relates to the antenna-satellite allocations. This is necessary since even when no antenna allocations are changed, rerouting costs may be encountered if the message routing is changed. Second, when a satellite route ceases to exist, a shift must be made, and no variable cost is encountered. Since this cost is fixed, it need not explicitly enter the optimization process. Third, it is realized that when a change is made before a route ceases to exist the cost of shifting is, in general, being incurred unnecessarily early.

For an assignment to be truly optimal over some time interval it must minimize the sum of the costs of fulfilling all demands of the interval and the costs of rerouting. Obviously, both of these kinds of costs must be stated in the same units. For the moment consider only the rerouting costs.

If a series of assignments satisfies all demands during some interval and if the absolute minimum number of message shifts are made, the assignment series will be an over-all optimum. Under these conditions, no assignment series that involves a larger number of message shifts can be optimal. Stated in a slightly different way, no assignment series that involves a greater average number of shifts per message transmitted can be optimal. This realization suggests an algorithm that attempts sequentially to minimize the average number of message shifts per message. The following example explains how that algorithm might operate.

Consider a minimum-slack square cost matrix in the previously described format. Now in the place of the zeros of the matrix substitute positive $P_{i,j,k}$ which may be unique for each route i-k-j. These penalties are to be calculated to include the effect of path feasibility changes over time.

Where the feasible route i-k-j is currently carrying a unit of demand $D_{i,j}$, the current cost rate (rerouting component) associated with that route is given by:

$$P_{i,j,k} = \frac{K_4}{t_f - t_b}$$

Where K_4 is a cost constant associated with a unit rerouting,

t_b is the time at which transmission over route i-j-k was begun and,

t_f is the time at which transmission over the route i-j-k must cease because transmission feasibility ends.

Where the feasible route i-k-j is not currently carrying any of demand $D_{i,j}$, the current cost rate (rerouting component) associated with that route is given by:

$$P_{i,j,k} = \frac{K_4}{t_f - t}$$

where K_4 and t_f are as previously described, and

t is the current time.

Thus as the time remaining for transmission over some currently unused route decreases, the effective cost of using it increases. As a result a shift to such a route will only be justified on face value when the new route will be available for a longer time than the old route's original availability time. Of course, even an increase in cost rate may be justifiably scheduled by the linear programming algorithm if by so doing a lower grand total cost rate is achieved.

The suggestion has been made that a weighting factor be applied to the calculated cost rate used for routes which are currently in use. This weighting factor would act to make rerouting less likely soon after an assignment is made and more likely toward the end of the transmission period. The following diagram (Figure A-2) illustrates this weighting concept by showing as a solid line an unweighted cost rate and as a crossed line the same cost rate weighted by a hypothetical continuous weighting function.

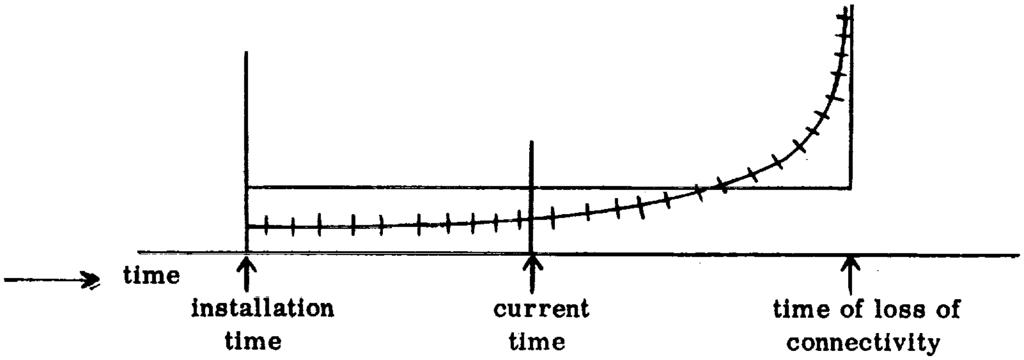


Figure A-2. A Weighted Cost Function

With this formulation we have introduced in effect a system of double accounting wherein one set of costs is as realistic as possible and the other set is used to make decisions.

One can easily visualize other sorts of continuous weighting functions and even step functions or combinations of step and continuous functions used as weights. Both theoretical and pragmatic arguments can be produced to try to justify the use of a wide variety of weighting systems. For instance, the system in which no assignment would be changed until at least M minutes after it was made would in a way be a very practical system to use. But, no matter how adept one's mind is at creating new weighting schemes, the real question to be considered is "what function or combination of functions can produce the best schedules." Unless an analytic insight into this question can be had and a proof of optimality discovered, simulation with various proposed weighting functions seems to be the most direct method for obtaining an answer.

One argument in favor of weighting functions relates to the first part of a transmission's duration. Here as shown in Figure A-2 the weights would be less than one and an assignment, once made, would tend to remain. The constant cost rate, it is argued, might result in too many shifts too early and a reduced effective cost rate would tend to reduce that danger. There is also merit in this argument. The following example will illustrate it and show an approach to evaluating the weighting function:

> Consider an assignment (i-j-k_i) which was just made on the basis of cost rate P_i. After a small time increment Δt, another route k_2 becomes available at the cost rate $P_2 = P_i - \Delta P$. All other things being equal, a shift would be made. Now, if these happenings were to recur at each Δt, a very large number of undesired shifts would be made. From a different point of view, if an assignment of expected duration L is made and its cost rate is to be bettered by an immediate shift (after Δt), it can be argued that the replacement's duration must be at least 2L. This extra shift's cost plus the first shift's cost must be spread over a period of time, and the new rate must be better than the old. For a shift to be made we obtain the conditional relation:
>
> $$\frac{2K}{L'} \le \frac{K}{L}$$
>
> $$L' \ge 2L$$
>
> where L' is the duration of the replacement route. This, of course, implies that the initial weight for any newly installed assignment ought to be 0.5 or less.

It should be noted that the condition described above is a limiting condition. It relates to the earliest time at which a change might be justified on the basis of its cost rate. However, the same cost minimum will be achieved in the case described above if the switch is not made until the end of the first transmission interval, L. Since some lower cost route might become available in the interim, the waiting game is much preferred.

It has been observed that if rerouting costs are the only costs being considered, and if there is at all times sufficient capacity available to satisfy all demands, the weighting function which is zero for any ongoing installed assignment will be optimal. This is true (if costs are positive quantities) since any other weight would tend to result in earlier switches and earlier switches necessarily lead to larger numbers of switches.

When considering other cost rates, such as the revenue loss for non-transmission in addition to rerouting costs, it appears that switches should be made to improve the instantaneous cost rate whenever an uninstalled assignment's total cost rate (rerouting component plus other applicable costs) is less than the total other costs for some installed assignment.

Another point in favor of the use of a weighting function is the bird-in-hand argument. So long as the cost of not fulfilling a demand is important, a scheduler should strive for transmission continuity and should as a result err on the side of switching too early rather than running the risk of having nothing to switch to when the current route terminates. Since the capacity to which an early switch is made must come from somewhere, there appears to be no merit in the bird-in-hand argument unless a complicated and time-consuming accounting is made of the effects of the relative worths of different message streams.

In summary, suffice it to say that there appears to be a strong possibility that the time-phasing formulations can be made fruitful for both the simulation and the operational environment. Nevertheless, additional investigation of the method is required before a specific best formulation can be selected.

Computational Feasibility. The question of computational feasibility is made less complex by the small extent of the change from the previous formulation. The primary difference between the two computational problems is that it is now necessary to consider a larger number of cost levels than previously. Earlier only three costs were mentioned: $K_1 < K_2 < K_3 \simeq \infty$. Now considering the cost 1/, K_1, as a continuous variable results in a complete transportation problem.

1/ Where now the restricting relation becomes:

$K_1 < K_3 \simeq \infty$.

$K_2 < K_3$.

While the complete Hungarian algorithm might be incapable of producing answers in an acceptable amount of time, it has great promise if we modify the assumption of a continuous cost function, K_1. When costs are continuous, an absolutely worst case for the Hungarian algorithm will exist when all costs are unique and are arranged so that with each matrix operation only one new zero is introduced. In this case an optimal solution can be guaranteed only after N matrix operations, where N is the number of matrix rows. However, when there is only one level of real cost, K_1, one implicit matrix operation uncovers all feasible route zeros. From this, it can be seen that when the number of levels of cost (real and slack) represented in a cost matrix is A, the maximum number of Hungarian matrix operations which could ever be required by any optimal solution is also A and a saving of M - A operations results.

This implies a great advantage to be accrued from using a regular discrete cost system with as large a defining increment as is reasonable in view of the cost relationship being described. In this particular case the cost $K_3 \simeq \infty$ need not be considered as affecting the number of cost levels involved.

Now, if limitations on the number of antennas are not considered, the Hungarian algorithm can lead to an optimal assignment. The trade-off between computation time and the descriptive precision of the discrete cost system can be made explicit and considered objectively. Obviously, further work is needed on this point.

The consideration of antenna limitations simultaneously with a discrete cost function for feasible routes is another matter. Previously, the problem now faced did not exist since in the first matrix operation all feasible (real) routes became zero cost routes. In the current problem the optimal solution zeros of the matrix may relate to some slack routes while not including all real routes. The possibility, therefore, exists that some real route might enter a solution at a cost lower than an additional slack to convert a capacity-optimal solution to a capacity- and antenna-optimal solution.

While the problem of finding an over-all optimum under these conditions is recognized as important and challenging, its further treatment is deferred both because of the press of time and because any forthcoming solution method is very likely to be computationally unacceptable for the simulation. Even the Hungarian solution of the time-phased cost system problem may require more computation than can be justified if the needed number of cost levels is too great.

A SYNOPTIC ALGORITHM FOR THE ASSIGNMENT PROBLEM. A second and basically different approach to over-all schedule optimization is one that in essence simultaneously treats all assignments that can be made during a scheduling interval. In this case a scheduling interval is intended to be on the order of 24 hours or more. The assumption is made that from one scheduling interval to the next the shifting of assignments (at the interface) is not important. This assumption can be made to be operationally tenable primarily by causing the interface to occur infrequently. Another mechanism for suppressing the interface difficulty is the modification of the demand and capacity series to reflect the tail of the previous schedule.

Considering some limited scheduling interval for which demands, $D_{i,j}$, and capacities, C_k, are known time series, the synoptic algorithm iteratively schedules the satellite transmission that yields during its feasibility interval a minimum cost, P, per unit of information transmitted. In theory, antenna limitations may also be dealt with by the same basic selection scheme. If the selection process of this algorithm is to be meaningful to the problem at hand, the costs, penalties or net revenue per message unit transmitted during a transmission interval, using a specified relay route, must be estimable and should be, after technical feasibility, the primary variable effecting schedule goodness. While we recognize that:

$$\sum \text{MIN } P \neq \text{MIN} \sum P$$

because of interaction between links, it is likely because of the similarity between this algorithm and the proven algorithm of Zaphyr [1] that this algorithm can yield schedules that are reasonably good and yet do so with a relatively small computational expense.

---

[1] Zaphyr, P. A., Analysis and Redesign of Teletype Circuits by Computer, Case Report 59-2007, Westinghouse Corporation, East Pittsburgh, Pa. April 17, 1959.

The synoptic algorithm is described by the following sequency of instructions. The symbology is generally the same as that used previously, but note the difference in the usage given to the subscript t when used with the variables P and ΔT.

1. Calculate all $P_{i,j,k,t}$

$$P_{i,j,k,t} \simeq \frac{K}{\Delta T_{i,j,k,t}}$$

where [1/] $P_{i,j,k,t}$ is the penalty factor per unit of demand $D_{i,j}$ transmitted via the k^{th} satellite during the interval of transmission feasibility beginning at time t.

$\Delta T_{i,j,k,t}$ is the length of the transmission feasibility interval which begins at time t.

K is a constant but may be K_i, K_j, or $K_{i,j}$.
Note that at this stage one penalty factor has been calculated for each transmission feasibility period that exists any time during the scheduling interval.

2. Place all $P_{i,j,k,t}$ approximately identified into a penalty table in order of increasing value.
Note that at this stage, if it is desired, the majority of the penalty table may be moved out of the computer's quick access memory and put on tape if it is arranged to be called back in order of increasing penalty.

3. Select MIN $P_{i,j,k,t}$ from the table. If there are no $P_{i,j,k,t}$ in the table, or if all demands have been satisfied, go to (7).

4. If the assignment corresponding to $P_{i,j,k,t}$ cannot be made, go to (6).
Note that an assignment cannot be made if its effective feasibility interval has been changed from what it was when the penalty factor

---

1/ When $D_{i,j}$ and C_k are not constant over the interval $\Delta T_{i,j,k,t}$ or when some other route cost is also to be considered, a more complex expression is required.

was last calculated.

Note also that if an antenna feasibility check is to be made, it should be made at this point.

5. Make the assignment corresponding to $P_{i,j,k,t}$
   a. Remove $P_{i,j,k,t}$ from further consideration by either removing it from the table or marking it appropriately.
   b. Remove a demand equal to the smaller of $D_{i,j,t}$ or $C_{k,t}$ from $D_{i,j,t}$ and from $C_{k,t}$ for all t during the interval, $\Delta T_{i,j,k,t}$.
   c. Go to (3).

6. Recalculate the $P_{i,j,k,t}$ in question and merge it into the penalty table in the appropriate place. This calculation is of the same form as it was originally (step 1). Go to (3).

   Note that if an assignment is infeasible because of antenna limitations over all of its transmission interval, it may be removed from consid- ation. Otherwise a more complicated recalculation and/or redefinition is required.

7. The schedule is now complete. STOP.

In summary this algorithm first calculates a single penalty factor pertaining to each unique period of feasible transmission, then iteratively selects and installs the transmission which has the smallest penalty rate. It takes into account the effect that one installed assignment might have on other non-installed assignments by recalculating the effected factors. Since no penalty factor can ever be decreased as the result of the installation of another, a computational saving is obtained by recal- culating penalties only when the previous penalty of the assignment involved has the lowest value of any uninstalled assignment.

The justification for a synoptic algorithm lies mainly in the fact that when viewing all possible assignments at once, it can choose those which are most desirable and not run the risk of having them precluded by some conflicting prior time assignment.

This algorithm is not optimal. While the problem of optimizing this formulation brings visions of a computational task of mammoth proportions, the computational problem implied by the synoptic algorithm itself is not so large. If we consider a 24-hour scheduling interval, one and a half hour orbits, and assume that an average satellite is capable of transmitting between a total of only 50 per cent of the demanding ground stations during its full orbit, we can obtain an estimate of the computational problem. If there are 50 satellites and 200 demands we obtain:

$$0.50 \times 200 \times 16 \times 50 = 80,000$$

possible assignments during the interval. If an average of 300 executed instructions were to suffice to process an average assignment, the time [1/] estimate becomes:

$$0.8 \times 10^{5} \times 3 \times 10^{2} \times 12 \times 10^{-6} \approx 288 \text{ seconds}$$

or about 6 minutes.

Even for a fully extended system of 100 satellites and 250 demands the running time is only about 15 minutes for a simulated or real schedule interval of 24 hours. It appears that this algorithm is time-feasible for simulation purposes.

[1/] Based on a representative execution time for the IBM 709. IBM 7090 execution time, of course, would be less.

APPENDIX B

SURVIVAL FUNCTIONS FOR COMMUNICATION SATELLITES

APPENDIX B

SURVIVAL FUNCTIONS FOR COMMUNICATION SATELLITES

INTRODUCTION

The problem discussed in this appendix is the determination of analytical expressions for the survival functions for three communication satellites. The survival function of an item or system is sometimes called the reliability of the system and, for our problem, it is the probability that a satellite has not failed by a given time. It is therefore a function of operating time, where operating time originates at the time the satellite is placed in orbit. Table B-1 is the reliability data given for the three satellites. In terms of this data the problem is to construct continuous reliability functions that take on values close to the tabulated values. Additional requirements are that the continuous reliability function chosen have some engineering justification and be relatively easy to compute.

TABLE B-1

Given Reliability Data for Three Satellites

Satellite Type	Probability That Satellite Has Not Failed By:					
	0 Months	1 Month	12 Months	24 Months	36 Months	60 Months
Stationary	1	0.95			0.50	
Active	1	0.95		0.50		
Passive	1		0.95			0.50

MATHEMATICAL BACKGROUND

Let T be a non-negative random variable called the failure time or age of failure of the satellite. In our problem T is in units of months. Since T is a random variable it has a probability density function, say, f(t) defined by:

$$(1)\qquad \begin{cases} f(t) = \lim\limits_{\Delta t \to 0^+} \dfrac{\Pr\{t < T \le t + \Delta t\}}{\Delta t} & \text{for } t \geq 0, \\ f(t) = 0 \text{ for } t < 0, \end{cases}$$

and

$$(2)\qquad \int_0^\infty f(t)\, dt = 1.$$

In approximate terms, $f(t)\Delta t$ is the unconditional probability that a satellite will fail in the interval $(t, t + \Delta t)$. The corresponding cumulative distribution function F(t) is defined as

$$(3)\qquad F(t) = \Pr\{T \le t\} = \int_0^t f(u)\, du,$$

and is the probability that a satellite will fail before age t. F(t) has the properties $F(t) \nearrow$, $F(0) = 0$ and $F(\infty) = 1$

By (1) and (3),

$$f(t) = \lim_{\Delta t \to 0^+} \frac{\Pr\{t < T \le t + \Delta t\}}{\Delta t}$$

$$= \lim_{\Delta t \to 0^+} \frac{F(t + \Delta t) - F(t)}{\Delta t} = \frac{d\,F(t)}{dt},$$

so that

$$(4) \qquad f(t) = \frac{d\,F(t)}{dt}\,.$$

Now let R(t) be the reliability function defined as:

$$(5) \qquad R(t) = 1 - F(t) = \Pr\,\{T > t\} = \int_t^{\infty} f(u)\; du.$$

Thus, R(t) is the probability that a satellite has not failed by time t and has the properties $R(t) \swarrow$, $R(0) = 1$, and $R(\infty) = 0$. From (5) and (4) we obtain the relation

$$(6) \qquad f(t) = -\frac{d\,R(t)}{dt}\,.$$

Consider now the function m(t) defined as

$$(7) \qquad m(t) = \lim_{\Delta t \to 0^+} \frac{\Pr\,\{t < T \le t + \Delta t \mid t < T\}}{\Delta t}\,.$$

The function m(t) is variously called the age-specific failure rate, the force of mortality or the hazard function. From its definition (7), it is evident that m(t) is a conditional density function of failure probability with time and is the instantaneous probability rate of failure at time t conditional upon non-failure prior to time t. It is useful for interpreting the physical causes of failure in terms of probability distributions.

By the definition of conditional probability:

$$\Pr\,\{t < T \le t + \Delta t \mid t < T\} = \frac{\Pr\,\{(t < T \le t + \Delta t) \cap (t < T)\}}{\Pr\,\{t < T\}}$$

$$= \frac{\Pr\,\{t < T \le t + \Delta t\}}{\Pr\,\{t < T\}}\,.$$

Using this in (7) yields

$$m(t) = \lim_{\Delta t \to 0^+} \frac{\Pr\{t < T \le t + \Delta t\}}{\Delta t} \cdot \frac{1}{\Pr\{t < T\}}$$

$$= \frac{1}{\Pr\{t < T\}} \cdot \lim_{\Delta t \to 0^+} \frac{\Pr\{t < T \le t + \Delta t\}}{\Delta t}$$

$$= \frac{1}{R(t)} \cdot f(t).$$

The last equality coming from (1) and (5). Thus

$$(8) \qquad m(t) = \frac{f(t)}{R(t)} .$$

Figure B-1 shows the general shapes of F(t) and R(t) for a general f(t). Figure B-2 shows two simpler possibilities for m(t). If m(t) is an increasing function of t, there is positive ageing; the older the item, the more probable it is to immediate failure. If m(t) is a decreasing function of t, there is negative ageing; the older the item, the less probable it is to immediate failure. In some cases, items display a combination of increasing and decreasing hazards as well as constant hazard rates. We will show later that if m(t) is a constant, then the probability density function f(t) is exponential, and conversely.

From (8) and (6) we have

$$m(t) = \frac{f(t)}{R(t)} = - \frac{1}{R(t)} \cdot \frac{d}{dt} R(t) = - \frac{R'(t)}{R(t)} .$$

This equation can be taken as a definition of the mortality function instead of the definition given by (7). It is instructive to do this since the procedure is intuitively meaningful. From the survival curve it is obvious that the intensity of mortality varies at each moment of age of the satellite. The slope of the survival curve at any point is related to the intensity of mortality at that point since the steeper the slope the faster the failures are occurring. A measure of the slope of R(t) is the derivative of $R(t)$ with respect to time, say $R'(t)$. Since the reliability curves are all monotone decreasing the value of $R'(t)$ will be negative. To facilitate the comparison of several curves it is convenient to have positive values. Thus, $-R'(t)$ can be taken as a rough measure of the intensity of mortality. One further property of a measure for the intensity of mortality is necessary — the dimension of the measure should be a rate. This is accomplished by dividing $-R'(t)$ by $R(t)$. Thus, the complete definition for the intensity of mortality is

$$m(t) = -\frac{R'(t)}{R(t)}.$$

It is possible to show that $-R'(t)/R(t)$ is the same as the right-hand side of equation (7).

$$-\frac{R'(t)}{R(t)} = \frac{F'(t)}{R(t)} = \frac{f(t)}{R(t)} = \frac{1}{R(t)} \lim_{\Delta t \to 0^+} \frac{\Pr\{t < T \leq t + \Delta t\}}{\Delta t}$$

$$= \frac{1}{\Pr\{t < T\}} \lim_{\Delta t \to 0^+} \frac{\Pr\{t < T \leq t + \Delta t\}}{\Delta t}$$

$$= \lim_{\Delta t \to 0^+} \frac{\Pr\{t < T \leq t + \Delta t \mid t < T\}}{\Delta t}$$

$$= m(t).$$

The theorem stating the result of taking the derivative of the natural logarithm of a function gives the relation

$$-\frac{R'(t)}{R(t)} = -\frac{d}{dt} \ln R(t),$$

where $\ln R(t) = \ln_e R(t)$. Thus, $m(t)$ can be written as

$$m(t) = -\frac{d}{dt} \ln R(t). \tag{9}$$

Using (9) and integrating produces the following relations:

$$\int_0^t m(u)du = -\int_0^t \frac{d}{du} [\ln R(u)]\, du$$

$$= - [\ln R(u)]_0^t$$

$$= - \ln R(t) + \ln R(0)$$

$$= - \ln R(t) + \ln 1$$

$$= - \ln R(t).$$

Thus

$$\ln R(t) = - \int_0^t m(u)\, du,$$

so that,

$$R(t) = \exp \left[- \int_0^t m(u)\, du \right]. \tag{10}$$

Using (10) and (8) gives

$$f(t) = m(t) \exp \left[- \int_0^t m(u)\, du \right]. \tag{11}$$

If we start with f(t), then by (5) we know R(t) and hence by (8) we know m(t). If we start with R(t), then by (6) we know f(t) and again by (8) we know m(t). If we start with m(t), by (11) we know f(t) and by (10) we know R(t). In other words the function f(t), F(t), R(t), and m(t) are mathematically completely equivalent.

As an example of this last sentence, suppose that T has the exponential distribution with parameter b

$$f(t) = b \exp(-bt) \tag{12}$$

for $t \geq 0$ and zero otherwise. Then by (5)

$$R(t) = \int_t^{\infty} b \exp(-bu) du = \exp(-bt),$$

and by (8),

$$m(t) = \frac{b \exp(-bt)}{\exp(-bt)} = b.$$

Conversely, if $m(t) = b$, then by (11) we have

$$f(t) = b \exp\left[-\int_0^t b\, du\right] = b \exp(-bt).$$

A number of failure distributions used in reliability theory were used in an effort to fit the data in Table B-1. Most of the distributions were rejected because they gave mortality curves with negative ageing or no ageing. It is felt that the distribution used should show positive ageing, be general, and be fairly easy to use in computations. The distribution selected that satisfies these requirements is the Weibull distribution whose probability density function is

(13) $$f(t) = \lambda \alpha t^{\alpha - 1} \exp(-\lambda t^{\alpha}); \alpha > 0, \lambda > 0, t > 0.$$

Using (3) and (13), the corresponding cumulative distribution function is

(14) $$F(t) = 1 - \exp(-\lambda t^{\alpha}),$$

and the reliability function is then

(15) $$R(t) = \exp(-\lambda t^{\alpha}).$$

By (8), the mortality function is

$$m(t) = \alpha \lambda t^{\alpha - 1} . \tag{16}$$

The parameter λ is termed the scale parameter and α the shape parameter. From (16), if $\alpha > 1$, there is positive ageing with m(t) varying from zero to infinity as t increases. If $\alpha < 1$, there is negative ageing. If $\alpha = 1$, $m(t) = \lambda$ and the probability density function is exponential.

One further result will be useful in our computations. The expectation of the random variable T distributed according to (13) is

$$E(T) = \int_0^\infty \lambda \alpha t^{\alpha} \exp(-\lambda t^{\alpha}) \, dt.$$

In this, make the change of variable $u = t^{\alpha}$ to get

$$E(T) = \int_0^\infty \lambda u^{\frac{1}{\alpha}} \exp(-\lambda u) \, du.$$

The above integral can be written in terms of the Γ - function so that

$$E(T) = \Gamma\left(\frac{1}{\alpha} + 1\right) \lambda^{-\frac{1}{\alpha}} . \tag{17}$$

COMPUTATIONS

Two approximation methods will be given for estimating the reliability function (15). It should be emphasized that the data in Table B-1 are very rough approximations so that some liberties can and have to be taken with the data. Thus if, for one of the satellites, t_1, t_2, $R(t_1)$, and $R(t_2)$ are taken directly from Table B-1, the estimates for α are all less than 1. This implies negative ageing. By keeping t_1 and t_2 fixed and varying $R(t_1)$ and $R(t_2)$, it is possible to compute the resulting α's and λ's to select the first α larger than 1. This procedure is difficult to describe and apply. In both of the methods shown below, the d, t_1 and t_2 are fixed in advance and the resulting $R(t_1)$, and $R(t_2)$ and λ computed. For both procedures, the computed R(t) values are reasonably close to those tabulated in Table D-1.

METHOD 1. Let t_1 and t_2 be the two non-zero times in Table B-1. That is, for the: stationary satellite $t_1 = 1$, $t_2 = 36$; active satellite $t_1 = 1$, $t_2 = 24$; passive satellite $t_1 = 12$, $t_2 = 60$. Choose some value of α larger than 1 and label it $\bar{\alpha}$. The reliability function given by (15) for the two times becomes

$$(18) \qquad \begin{cases} R(t_1) = \exp\left(-\lambda t_1^{\bar{\alpha}}\right) \\ \\ R(t_2) = \exp\left(-\lambda t_2^{\bar{\alpha}}\right). \end{cases}$$

Since $t_1^{\bar{\alpha}}$ and $t_2^{\bar{\alpha}}$ are now constants in (18), the λ can be varied and for each λ the corresponding $R(t_1)$ and $R(t_2)$ values computed. The λ producing R(t) values reasonably close to those in Table B-1 is taken as the best estimate for λ. The method is illustrated for the three satellites for a value of $\alpha = 3/2$.

Stationary Satellite.

$t_1 = 1,\ t_2 = 36$

$t_1^{\bar{\alpha}} = 1,\ t_2^{\alpha} = 36^{3/2} = 216$

$R(1) = \exp(-\lambda)$

$R(36) = \exp(-216\lambda)$

λ	R(1)	R(36)
.0100	.99004	.11532
.0050	.99501	.33960
.0030	.99700	.52309
.0025	.99750	.58275
.0028	.99720	.54618
.0029	.99710	.53451

Take $\lambda = 0.0030$ as the best fit for R(t). Using $\alpha = 1.5$ and $\lambda = 0.0030$ yields for the stationary satellite the reliability and mortality functions:

$$\begin{cases} R_s(t) = \exp\left[-0.0030\, t^{1.5}\right] \\ m_s(t) = 0.0045\, t^{0.5} \end{cases}$$

Active Satellite.

$t_1 = 1$

$t_2 = 24$

$t_1^{\bar{\alpha}} = 1$

$$t_2^{-\alpha} = 24^{3/2} = 119.75518$$

$$R(1) = \exp(-\lambda)$$

$$R(24) = \exp(-119.755\lambda)$$

λ	R(1)	R(24)
.0100	.99004	.30191
.0040	.99600	.61940
.0050	.99501	.54947
.0060	.99401	.48695
.0070	.99320	.43244
.0065	.99352	.45914
.0055	.99451	.51752
.0058	.99422	.49927
.0059	.99411	.49331

Take λ = 0.0059 as the best fit for R(t). For λ = 0.059 and α = 1.5, the reliability and mortality functions for the active satellite are:

$$\begin{cases} R_A(t) = \exp(-0.0059t^{1.5}) \\ m_A(t) = 0.0089t^{0.5} \end{cases}$$

Passive Satellite.

$$t_1 = 12$$

$$t_2 = 60$$

$$t_1^{\bar{\alpha}} = 12^{3/2} = 41.5645$$

$t_2^{\bar{\alpha}} = 60^{3/2} = 464.7600$

$R(12) = \exp(-41.56\lambda)$

$R(60) = \exp(-464.76\lambda)$

λ	R(12)	R(60)
.0010	.95925	.62826
.0020	.92026	.39475
.0015	.93960	.49802
.0014	.94346	.52168
.0013	.94743	.54651

Take $\lambda = 0.0014$ as the best fit for R(t). For $\lambda = 0.0014$ and $\alpha = 1.5$, the reliability and mortality functions for the passive satellite are:

$$\begin{cases} R_p(t) = \exp(-0.0014t^{1.5}) \\ m_p(t) = 0.0021t^{0.5} \end{cases}$$

METHOD 2. Again let t_1 and t_2 be the two non-zero times as given in Table B-1 and take $\alpha = 3/2$ for each satellite. Now make the assumption that the expected value of the time to failure, given by (17), is equal to the median of the probability density function (13). The median is the value of t that makes $R(t) = 0.50$. For the three satellites the assumption is that $E_s(T) = 36$, $E_A(T) = 24$, and $E_p(T) = 60$. Knowing α and E(T) then permits the calculation of λ. Equation (17) can be solved for λ to give

$$\lambda = \left[\frac{\Gamma(\frac{1}{\alpha} + 1)}{E(T)} \right]^{\alpha} \tag{19}$$

Taking the logarithm to the base 10 of equation (19) gives

$$\log \lambda = \alpha \left[\log \Gamma(\frac{1}{\alpha} + 1) - \log E(T) \right]$$

Since α is taken to be 1.5 for all three satellites and $\Gamma(1.5 + 1) = 0.9033$, we have

$$\log \lambda = 1.5 \; [9.95583\text{-}10 - \log E(T)].$$

Stationary Satellite.

$$E(T) = 36$$

$$\log E(T) = 1.55630$$

$$\log \lambda = 1.5 \; [9.95583\text{-}10 - 1.55630]$$

$$= 1.5 \; (8.39953\text{-}10) = 12.59930\text{-}15$$

$$\lambda = 0.003975$$

$$\begin{cases} R_s(t) = \exp \; [-0.0040 \; t^{1.5}] \\ m_s(t) = 0.0059t^{0.5} \end{cases}$$

Active Satellite.

$E(T) = 24$

$\log E(T) = 1.38021$

$\log \lambda = 1.5 \,[9.95583\text{-}10 - 1.38021]$

$= 1.5\,(8.57562\text{-}10) = 12.86343\text{-}15$

$\lambda = 0.007302$

$$\begin{cases} R_A(t) = \exp\,[-0.0073\, t^{1.5}] \\ m_A\,(t) = 0.011 t^{0.5} \end{cases}$$

Passive Satellite.

$E(T) = 60$

$\log E(T) = 1.77815$

$\log \lambda = 1.5\,[9.95583\text{-}10 - 1.77815]$

$= 1.5\,(8.17768\text{-}10)$

$= 12.26652\text{-}15$

$\lambda = 0.001847$

$$\begin{cases} R_p(t) = \exp\,(-0.0018 t^{1.5}) \\ m_p(t) = 0.00277 t^{0.5} \end{cases}$$

COMMENTS

Figures B-3 and B-4 are plots of the reliability and mortality equations obtained by using the first estimation method. The two sets of curves are consistent with the data given in Table B-1. Extreme values for the reliability functions were limited by the accuracy of the tables used to evaluate exp (-x). The functions can be extended to further values by further approximation formulae. The value of 3/2 for α was chosen for computational convenience. Any value for α greater than one can be used. Since the analytic expressions for the R(t) functions are simple, there is no need to approximate the R(t) curves by step functions.

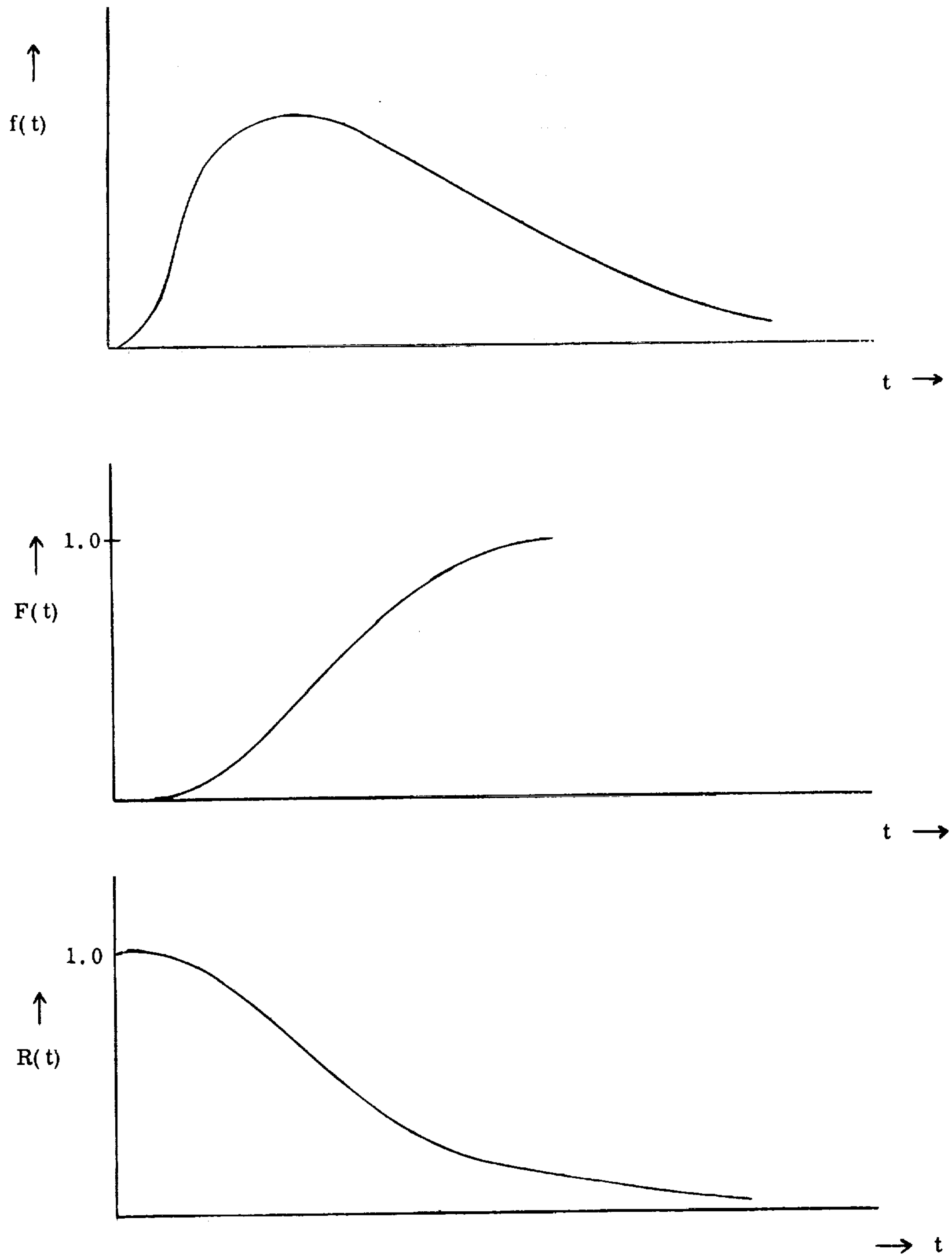


Figure B-1. The functions f(t), F(t), R(t) for a typical distribution

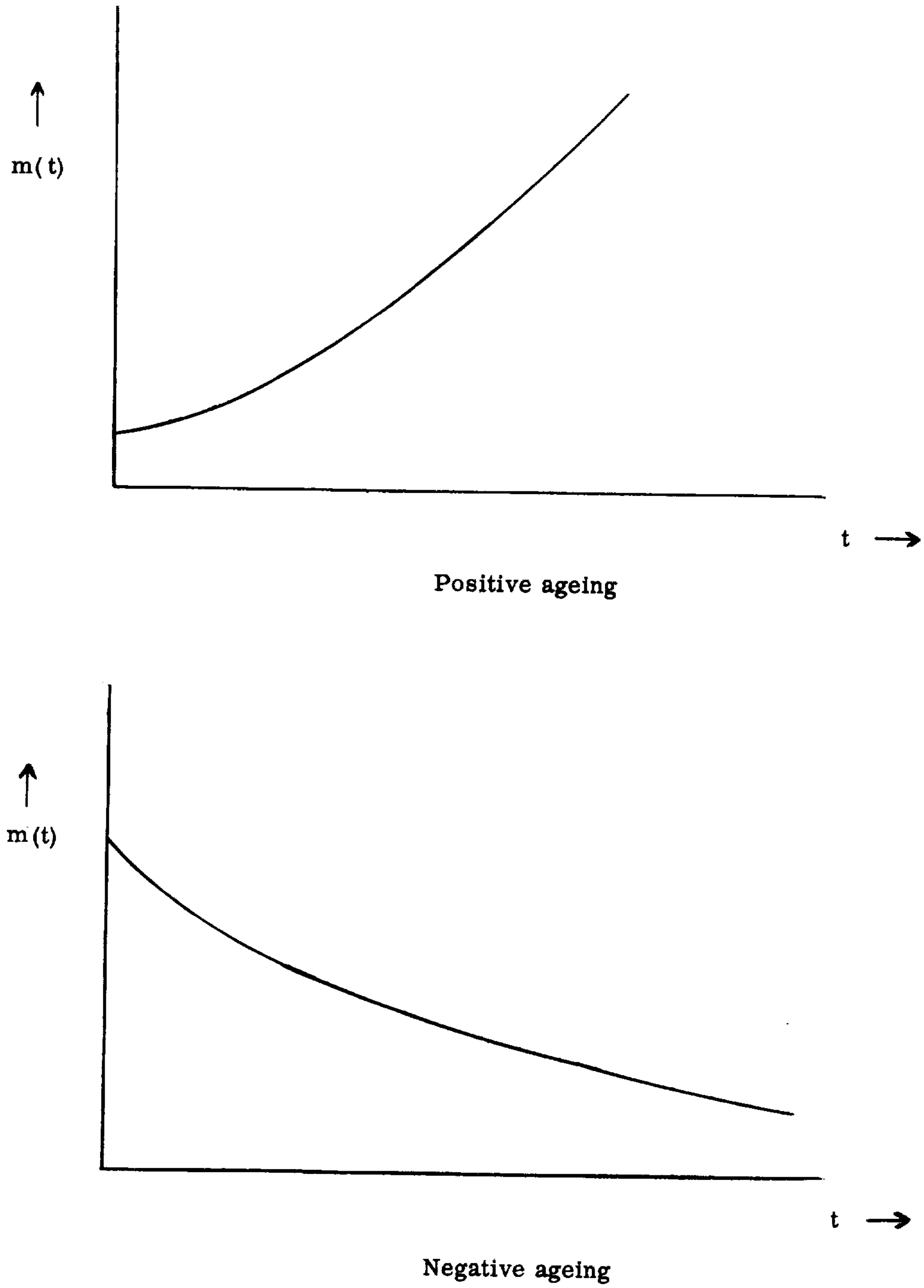


Figure B-2. Some typical age-specific failure rates (mortality functions) m(t)

Figure B-3. Plots of fitted reliability functions (Method 1)

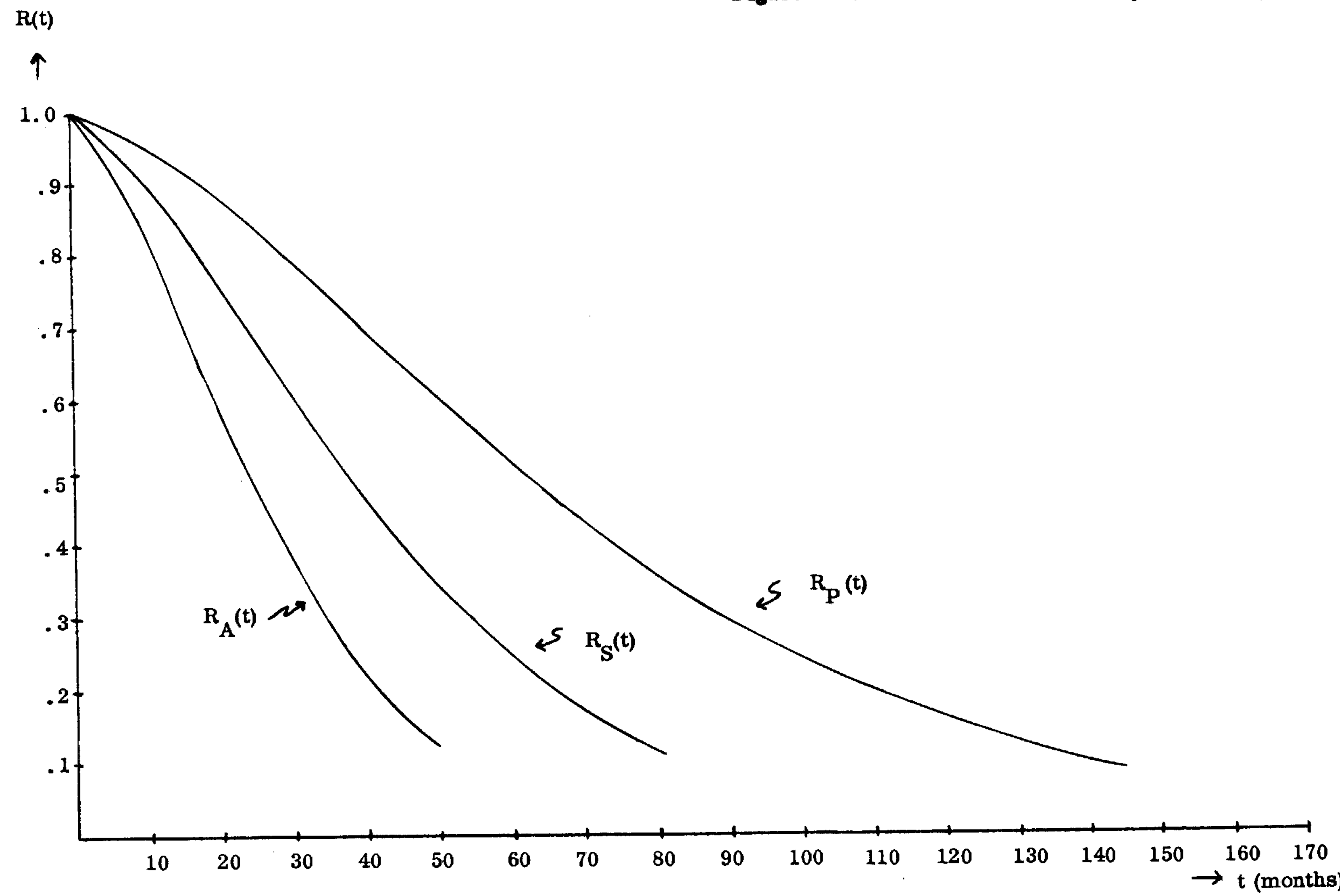
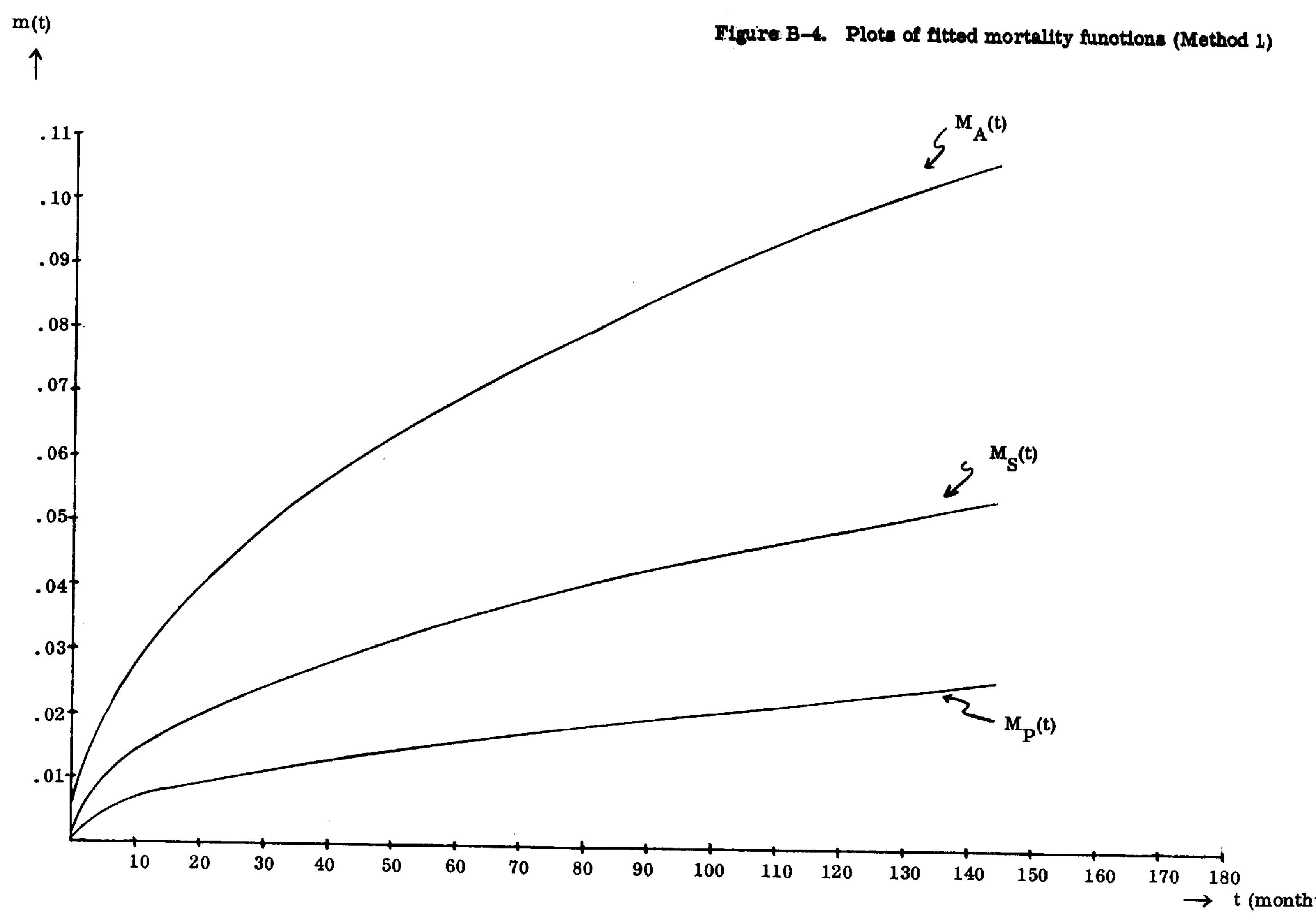


Figure B-4. Plots of fitted mortality functions (Method 1)



APPENDIX C

AN ANALYTICAL METHOD OF DETERMINING SATELLITE LOCATIONS

APPENDIX C

AN ANALYTICAL METHOD OF DETERMINING SATELLITE LOCATIONS

INTRODUCTION

This Appendix presents a solution to the problem of determining the location of a satellite at any point in time, given the orbital parameters of the satellite for some previous orbital passage. The solution of this problem is the task of the ORBIT routine of the model.

The method assumes the satellite is of negligible mass and moves in the force field of a spherical homogeneous earth without atmosphere. Perturbing effects caused by earth oblateness, specifically, regression of the nodes and precession of the position of perigee, are taken into consideration.

Two basic steps are taken in arriving at the solution. These are as follows:

1. Given the time for which the satellite position is being found, the geographical longitudes of the nodes preceding and following the desired position are determined. In addition, the location of perigee is calculated.
2. The location of the satellite is calculated by relating the position of the actual satellite to the position of a hypothetical satellite in a circular orbit with equal period. The geographical coordinates for the position of the hypothetical satellite are calculated. The angular difference in position of the real and hypothetical satellites, assuming simultaneous nodal passage, then enables calculation of the geographical coordinates of the position of the actual satellite. Altitude is then calculated.

In the following, the above steps will be discussed in order. First, however, a description of the orbital parameters and coordinate systems to be used in the analysis is presented.

ORBITAL PARAMETERS AND COORDINATE SYSTEMS

The motion of a satellite in a force field of a homogeneous spherical earth without atmosphere takes place in a plane called the orbital plane. The path of the satellite will be an ellipse with one focus at the center of the earth.

To define the characteristics of a satellite orbit, six parameters are required: three to define the position of the ellipse in the orbital plane; two to define the position of the orbital plane with respect to an arbitrary xyz coordinate system; and one of time. This is illustrated as follows.

Define a right-hand orthogonal xyz coordinate system fixed in space such that the xy plane contains the earth's equatorial plane (see Figure C-1). The orbital plane of the satellite will intersect the equatorial plane along the line NN' called the line of nodes. The ascending node is the point on NN' at which the satellite passes through the equatorial plane going from south to north. The required six parameters are then defined as:

1. The angle, Ω, between the x-axis and the ascending node; called the longitude of the node.
2. The angle, ω, between the ascending node and the point of perigee; called the longitude of perigee.
3. The angle, i, the inclination of the orbital plane with respect to the equatorial plane.
4. The semi-major axis, a, of the orbital ellipse.
5. The eccentricity, e, of the orbital ellipse.
6. A reference time, τ_0, taken to be the time of perigee passage.

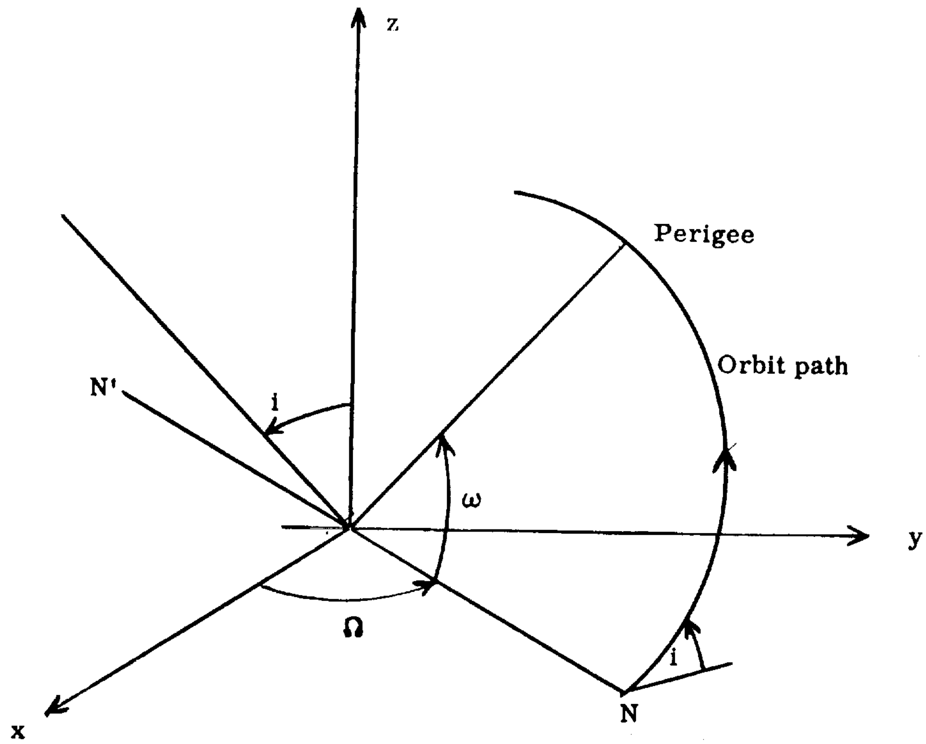


Figure C-1. Basic Parameters and Coordinate Systems

Solutions to the equations of motion for a satellite under the assumptions stated above (see reference 1 and 4) are usually given by

$$r = \frac{a(1 - e^2)}{1 + e \cos \theta}$$

and

$$r^2 \frac{d\theta}{dt} = \text{constant},$$

where r and θ are as shown in Figure C-2.

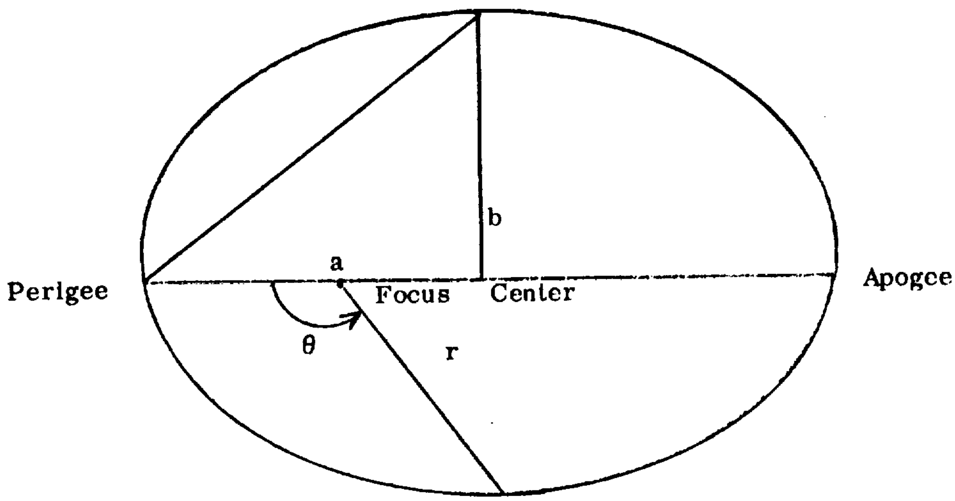


Figure C-2. Motion in the Orbital Plane

To relate the position of the satellite in its orbit to a point on a rotating earth requires the introduction of a second, rotating, coordinate system. Let x'y'z' be a coordinate system fixed within the earth, such that the z'-axis is coincident with the z-axis of the previously defined system, with the x'-y' plane rotating at an angular velocity of $\overline{\omega}$. See Figure C-3.

The following additional parameters are now defined.

Ω': the longitude of the ascending node in the x'y'z' system.

ψ_p: the geographical longitude of perigee in the xyz system.

ψ'_p: the geographical longitude of perigee in the x'y'z' system.

ϕ : the geographical latitude of perigee in both systems.

λ_0: the initial position of the x' axis at reference time τ_0.

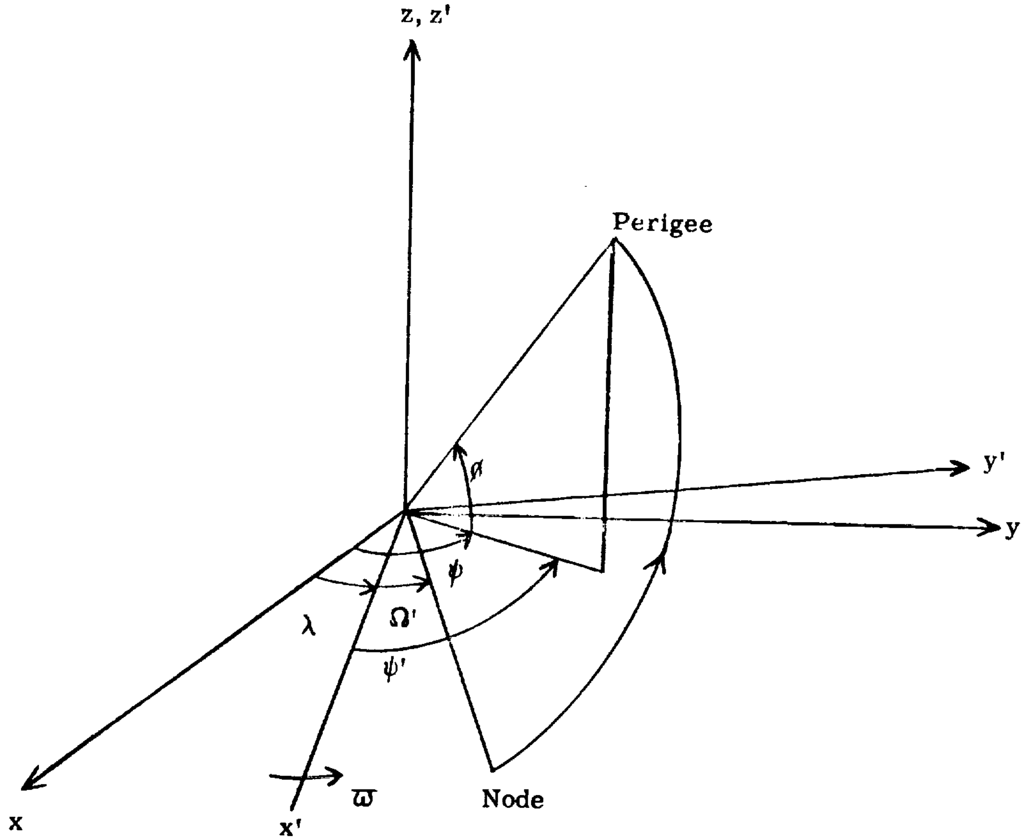


Figure C-3. Fixed and Rotating Coordinate Systems

DETERMINATION OF FUTURE NODE POINTS

Given the orbital parameters as described on page 86, the first task is to determine the initial and future positions of the nodal passages 1/, and the longitudes of perigee.

1/ Nodal passage will mean "ascending nodal passage".

It will be assumed that motion between any two successive nodal passages will be confined to a plane. However, considerations of the effects of oblateness make necessary the following: If the orbital parameters of the kth orbit are

$$\left[a,\ e,\ i,\ \Omega_k,\ \omega_k,\ \mathcal{T}_k\right],$$

then the orbital parameters of the k + 1th orbit are

$$\left[a,\ e,\ i,\ \Omega_k - \Delta\Omega,\ \omega_k + \Delta\omega,\ \mathcal{T}_{k+1}\right],$$

where $\Delta\Omega$ and $\Delta\omega$ account for regression of the nodes and precession of perigee, respectively.

Reference 2 gives the following:

$$\Delta\Omega = \frac{2\pi J}{\left(1 + \frac{h}{R_E}\right)^2 \left(1 - e^2\right)^2} \cos i \qquad \text{(rad./rev.)}$$

$$\Delta\omega = \frac{2\pi J}{\left(1 + \frac{h}{R_E}\right)^2 \left(1 - e^2\right)^2} \left(2 - \frac{5}{2} \sin^2 i\right) \text{(rad./rev.)}$$

where the $\Delta\omega$ is measured with reference to previous node point. J is a dimensionless constant representing a measure of the oblateness of the earth. h is the mean altitude of the orbit. In terms of initial conditions, therefore, the orbital parameters of the kth orbit are:

$$\left[a,\ e,\ i,\ \Omega_0 - k\,\Delta\Omega,\ \omega_0 + k\,\Delta\omega,\ \mathcal{T}_k\right].$$

If the location of a satellite at a given time T after T_0 is desired, the nodal passage preceding T must be located. The period of the satellite is given by

$$P = 2\pi \left(\frac{a^3}{\mu}\right)^{1/2},$$

where μ, a constant, is the gravitational parameter.

1/ Reference time.

Therefore the nodal passage preceding T, defined to be k_T, is the first integer less than or equal to T divided by P; therefore

$$k_T = \frac{T}{P} - \epsilon$$

where k_T is an integer and $0 \leq \epsilon < 1$.

Then the orbital elements for the satellite during the k_Tth orbit are:

$$\left[a, e, i, \Omega_o - k_T \Delta\Omega, \omega_o + k_T \Delta\omega, \mathcal{T}_{k_T}\right].$$

Next, the geographical longitudes corresponding to the $k_T^{\underline{th}}$ nodal passage must be found.

At the initial nodal crossing the angular relationships between the x-axis, the x'-axis and the node point are as follows (see Figure C-4):

$$\psi_o' = \Omega_o - \lambda_o .$$

Because of earth rotation only, the next nodal crossing will be

$$\psi_1' = \psi_o' - \Delta\psi' ,$$

where

$$\Delta\psi' = \overline{\omega} P .$$

But because of oblateness the nodal crossing is

$$\psi_1' = \psi_o' - (\Delta\psi' + \Delta\Omega).$$

Therefore the k_T^{th} nodal crossing will be given by

$$\psi_{k_T}' = \left|\left[\psi_o' - k_T (\Delta\psi' + \Delta\Omega)\right]\right| - 2\pi C,$$

where the C is an integer such that

$$0 \leq \psi_{k_T}' \leq 2\pi .$$

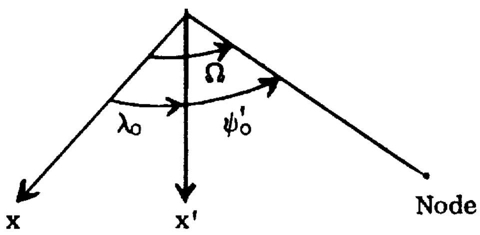


Figure C-4. Initial Longitudes

The remaining task is now to locate the position of the satellite at time T, knowing the location of the nodal point preceding T.

LOCATION OF THE SATELLITE IN ORBIT (AFTER THE k_Tth NODAL PASSAGE)

The geographic longitude of the k_Tth node having been derived, the next task is to compute the position of the satellite at time T. To accomplish this task the concept of an equivalent circular orbit is introduced. For a given elliptical orbit, an equivalent circular orbit is a circular orbit having the same period.

POSITION IN AN EQUIVALENT CIRCULAR ORBIT. The geographical longitude and latitude of a satellite in a circular orbit can be found as a function of the geographic longitude of the node, the true anomaly, and the inclination as follows.

Let γ'_c, ϕ'_c, θ'_c, be defined as Figure C-5.

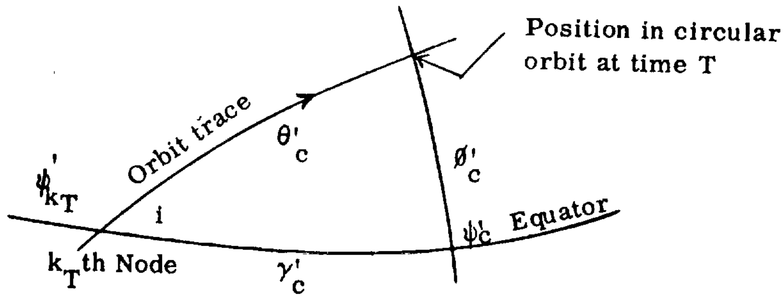


Figure C-5. Location of Satellite in Circular Orbit at Time T

ψ'_{k_T} is the geographic longitude of the k_Tth node, and ψ'_c is the geographic longitude of the satellite in a circular orbit at time T. ϕ'_c, is then the geographic latitude at time T. θ'_c is the true anomaly at time T measured from the node.

From the figure it is seen that

$$\psi'_c \begin{cases} \psi'_{k_T} + \gamma'_c\,, & \text{for} \left(\psi'_{k_T} + \gamma'_c\right) \leq 2\pi \\ \psi'_{k_T} + \gamma'_c - 2\pi, & \text{for} \left(\psi'_{k_T} + \gamma'_c\right) > 2\pi. \end{cases}$$

ψ'_{k_T} was determined on page 89, and γ'_c is given by Reference 3 as

$$\gamma'_c = \tan^{-1} (\cos i \tan \theta'_c) - \frac{\theta'_c P}{2\pi R_E},$$

where the term, $\theta'_c P/2\pi R_E$, accounts for earth rotation.

The latitude ϕ'_c is then given by

$$\phi'_c = \sin^{-1} (\sin i \sin \theta'_c).$$

θ'_c is given by

$$\theta'_c = \frac{2\pi (T - T_{k_T})}{P},$$

where T_{k_T} is the time of the k_Tth nodal passage.

POSITION IN THE ELLIPTICAL ORBIT. Assuming simultaneous nodal passage, the position of the satellite in the elliptical orbit at time T will be displaced from the position derived on page 92 by increments $\Delta\phi'$, $\Delta\gamma'$, and will be located at latitude and longitude, ϕ'_E, and ψ'_E.

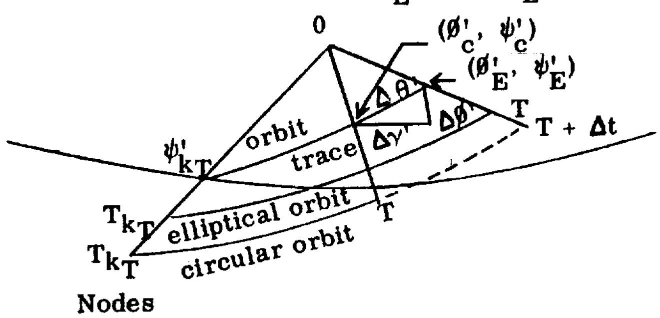


Figure C-6. Location of Satellite in Elliptical Orbit at Time T

But this will be the approximate position of the satellite in the circular orbit at time T + Δt, as shown in Figure C-6. To derive the exact location the amount of displacement caused by earth rotation in the time Δt must be accounted for.

Therefore,

$$\gamma_E' = \tan^{-1}(\cos i \tan \theta'_E) - \frac{\theta_E' P}{2\pi R_E} + \frac{\Delta\theta' P}{2\pi R_E}$$

$$\psi_E' = \begin{cases} \psi_{k_T}' + \gamma_E' & , \text{ for}\left(\psi_{k_T}' + \gamma_E'\right) \leq 2\pi \\ \psi_{k_T}' + \gamma_E' - 2\pi & , \text{ for}\left(\psi_{k_T}' + \gamma_E'\right) > 2\pi \end{cases}$$

$$\phi_E' = \sin^{-1}(\sin i \sin \theta'_E)$$

$$\theta'_E = \frac{2\pi\left[(T + \Delta t) - T_{k_T}\right]}{P} .$$

Now

$$\Delta t = \frac{\Delta\theta' P}{2\pi}$$

and the remaining task is to calculate $\Delta\theta'$.

Utilizing Equation 3-32 in Reference 1 (see also Reference 4, page 171), and noting that $\Delta\theta' = \theta'_E - \theta'_c$,

$$\Delta\theta' = 2e \sin M + \frac{5e^2}{4} \sin 2M - \frac{e^3}{12}(3 \sin M - 13 \sin 3M) -$$

$$- \frac{e^4}{96}(44 \sin 2M - 103 \sin 4M) + \ldots .$$

where $M = \left(\frac{\mu}{a^3}\right)^{1/2}(T - \mathcal{T}_{k_T})$, $\mathcal{T}_{k_T}$ being the time of perigee passage.

The altitude at time T, h_T, is then calculated using Equation 3-7 in Reference 1 as

$$h_T = \left\{ a\left[1 - e \cos M + \frac{e^2}{2} (1 - \cos 2M) + \frac{3}{8} e^3 (\cos M - \cos 3M) + \frac{e^4}{3} (\cos 2M - \cos 4M) + \dots \right] \right\} - R_E .$$

This completes the problem.

REFERENCES TO APPENDIX C

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4. Moulton, F. R., Celestial Mechanics, New York: The MacMillan Company, 1914.

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APPENDIX D
EXAMPLES OF COMPUTER OUTPUT

EXHIBIT A

Summary Link Output of the QUEUE Routine, Run 4

LINKR	LINKS	INTERRUPTS AS PERCENT OF DEMAND	LOST CALLS AS PERCENT OF DEMAND	UTILIZATION OF CAPACITY (PERCENT)	PERCENT OF DEMAND SATISFIED	AVERAGE BACKLOG	AVG. NUMBER OF CHANNELS IN USE
2	15	0	30	28	0	1	3
9	10	0	8	7	0	0	3
10	15	1	44	49	1	5	13
11	12	2	35	52	9	3	75
11	14	3	19	63	50	1	448
11	15	3	25	62	31	2	279
12	13	3	32	54	10	2	86
12	14	4	37	63	18	5	245
12	15		30	51	14	2	116

Each block (except the last) is followed in the printout by the lines:

OBJECT QFFBAR VERSION QVRGNF
OBJECT QFFBAR VERSION QVRGNF
PAGE 1
PAGE 1

Note: The numbers in the two left-most columns indicate the ground stations.

EXHIBIT A (continued)

Summary Link Output of the QUEUE Routine, Run 5

```
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMAND       BACKLOG   OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)     SATISFIED              IN USE
0   2   15        2            24          53            15          1          80
4   OBJECT OFFBAR    VERSICN QVRGNF                                                     PAGE  1
1   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMAND       BACKLOG   OF CHANNELS
             OF DEMANC    OF DEMAND    (PERCENT)     SATISFIED              IN USE
0   9   10        2            3           60            58          0          65
4   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
1   OBJECT QFFBAR    VERSICN CVRGNF                                                     PAGE  1
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMAND       BACKLOG   OF CHANNELS
             OF DEMANC    OF DEMAND    (PERCENT)     SATISFIED              IN USE
0  10   15        1            32          66            23          3         232
4   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
1   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMAND       BACKLOG   OF CHANNELS
             OF DEMANC    OF DEMAND    (PERCENT)     SATISFIED              IN USE
0  11   12        1            27          64            25          2         202
4   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
1   OBJECT QFFBAR    VERSICN CVRGNF                                                     PAGE  1
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMAND       BACKLOG   OF CHANNELS
             OF DEMANC    OF DEMAND    (PERCENT)     SATISFIED              IN USE
0  11   14        1            16          62            56          1         492
4   OBJECT QFFBAR    VERSICN CVRGNF                                                     PAGE  1
1   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMANC       BACKLOG   OF CHANNELS
             OF DEMANC    OF DEMANC    (PERCENT)     SATISFIED              IN USE
0  11   15        1            18          67            46          1         404
4   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
1   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMAND       BACKLOG   OF CHANNELS
             OF DEMANC    OF DEMAND    (PERCENT)     SATISFIED              IN USE
0  12   13        2            23          60            35          2         282
4   OBJECT QFFHAR    VERSICN QVRGNF                                                     PAGE  1
1   OBJECT QFFBAR    VERSICN QVRGNF                                                     PAGE  1
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMAND       BACKLOG   OF CHANNELS
             OF DEMANC    OF DEMAND    (PERCENT)     SATISFIED              IN USE
0  12   14        1            36          67            23          4         320
4   OBJECT OFFBAR    VERSICN QVRGNF                                                     PAGE  1
1   OBJECT CFFBAR    VERSICN CVRCNF                                                     PAGE  1
OLINKR LINKS INTERRUPTS   LCST CALLS   UTILIZATICN   PERCENT OF   AVERAGE   AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY   DEMAND       BACKLOG   OF CHANNELS
             OF DEMANC    OF DEMAND    (PERCENT)     SATISFIED              IN USE
0  12   15        2            29          60            21          2         179
```

EXHIBIT A (continued)
Summary Link Output of the QUEUE Routine, Run 6

```
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0   2   15        C           15           49           64          0        309
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0   9   10        0            0           61          176          0        232
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  10   11        1           37           68           15          4        186
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  10   12        0            0           78           98          0       1959
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  10   14        1           40           80           18          7        328
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  10   15        0           15           68           69          1        829
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  11   12        1           24           63           29          2        242
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  11   14        0            0           66           98          0        888
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  11   15        C            0           63           97          0        852
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  12   13        1           23           68           33          2        283
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  12   14        1           30           70           33          4        449
4   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
1   OBJECT OFFBAR    VERSION OVRGNF                                                  PAGE   1
OLINKR LINKS INTERRUPTS   LOST CALLS   UTILIZATION  PERCENT OF   AVERAGE  AVG. NUMBER
             AS PERCENT   AS PERCENT   OF CAPACITY  DEMAND       BACKLOG  OF CHANNELS
             OF DEMAND    OF DEMAND    (PERCENT)    SATISFIED             IN USE
0  12   15        0           15           57           66          1        526
```

EXHIBIT B

Financial Data of Run 2, An Example of COST Routine Output
(End of 12 Months, 18 Months, and 2 Years)

EXECUTION OF PROCESS   QREWA6
EXECUTED MLT-LC STATEMENT NUMBER- 4
1 OBJECT SQINFO VERSION PAGE 1
0 CUMULATIVE RESULT OF SATELLITE CORPORATION OPERATIONS

	INVESTMENT($1000)	OPERATING EXPENSE($1000)	REVENUE($1000)	DEPRECIATION($1000)	PROFIT($1000)	RETURN(10THS OF PC)
0	31062	1792	5601	6867	0	0

0 CUMULATIVE RESULTS OF GROUND STATIONS OPERATIONS

	INVESTMENT($1000)	OPERATING EXPENSE($1000)	DEPRECIATION($1000)	REVENUE($1000)	PROFIT($1000)	RETURN(10THS OF PC)
0 1	0	0	0	0	0	0
11	7500	1626	451	389	1688	249
12	7500	1626	451	364	1713	252
14	7500	1626	451	394	1683	248
15	7500	1626	451	249	1828	269
16	0	0	0	0	0	0

4 OBJECT SQINFO VERSION PAGE 1
1 OBJECT SQINFO VERSION PAGE 1
0 CUMULATIVE RESULT OF SATELLITE CORPORATION OPERATIONS

	INVESTMENT($1000)	OPERATING EXPENSE($1000)	REVENUE($1000)	DEPRECIATION($1000)	PROFIT($1000)	RETURN(10THS OF PC)
0	52662	2329	7121	9750	0	0

0 CUMULATIVE RESULTS OF GROUND STATIONS OPERATIONS

	INVESTMENT($1000)	OPERATING EXPENSE($1000)	DEPRECIATION($1000)	REVENUE($1000)	PROFIT($1000)	RETURN(10THS OF PC)
0 1	0	0	0	0	0	0
2	5003	514	156	0	670	100
9	5003	514	156	0	670	100
10	6822	771	214	5	980	107
11	7500	2397	665	441	2621	252
12	7500	2397	665	505	2557	255
13	6822	771	214	44	941	103
14	7500	2397	665	470	2592	259
15	7500	2397	665	305	2757	275
16	0	0	0	0	0	0

4 OBJECT SQINFO VERSION PAGE 1
1 OBJECT SQINFO VERSION PAGE 1
0 CUMULATIVE RESULT OF SATELLITE CORPORATION OPERATIONS

	INVESTMENT($1000)	OPERATING EXPENSE($1000)	REVENUE($1000)	DEPRECIATION($1000)	PROFIT($1000)	RETURN(10THS OF PC)
0	52662	2819	8972	12384	0	0

0 CUMULATIVE RESULTS OF GROUND STATIONS OPERATIONS

	INVESTMENT($1000)	OPERATING EXPENSE($1000)	DEPRECIATION($1000)	REVENUE($1000)	PROFIT($1000)	RETURN(10THS OF PC)
0 1	0	0	0	0	0	0
2	5003	991	301	0	1292	143
9	5003	991	301	1	1291	143
10	6822	1487	413	10	1890	160
11	7500	3113	864	542	3435	264
12	7500	3113	864	650	3327	256
13	6822	1487	413	72	1828	154
14	7500	3113	864	573	3404	262
15	7500	3113	864	380	3597	277
16	0	0	0	0	0	0

4 OBJECT SQINFO VERSION PAGE 1
END OF RUN. PRINT NEXT FILE.
1

Note: Profit and return have no significance if profit is negative (loss), and ground stations are denoted by numbers in the left-hand column.

EXHIBIT C

An Example of Primary Output of the COVERAGE Routine*

```
OBUFNO BTOTNO BITIME
0     7       7     43
0      FINAL TIME      INITIAL TIME   GROUND  GROUND  SATELLITE
    OF CONECTIVITY OF CONECTIVITY STATION STATION  NUMBER
0 1          44             43         12      13        3
  2          47             43         10      15       17
  3          51             43         12      15       17
  4          55             43         10      15       10
  5          60             43         12      15       10
  6          64             43         13      14        3
  7          64             43         13      15        3
4     OBJECT    BUFR      VERSION    COVR
1     OBJECT    BUFR      VERSION    COVR
OBUFNO BTOTNO BITIME
0     6       6     47
0      FINAL TIME      INITIAL TIME   GROUND  GROUND  SATELLITE
    OF CONECTIVITY OF CONECTIVITY STATION STATION  NUMBER
0 1          47             47         10      14       17
  2          51             47         12      14       17
  3          55             47         10      14       10
  4          60             47         12      14       10
  5          65             47         14      15       10
  6          67             47         14      15       17
4     OBJECT    BUFR      VERSION    COVR
1     OBJECT    BUFR      VERSION    COVR
```

*Not externally output unless specifically requested; normally input directly to the ASSIGNMENT Routine.

EXHIBIT C (continued)

An Example of Supplemental Output of the COVERAGE Routine*

```
0 VTIME
0572530
0    GROUND   GROUND   NUMBER OF SATELLITES TOTAL CAPACITY NUMBER OF SATELLITES
     STATION  STATION  VISIBLE OVER LINK      OVER LINK    REQUIRED FOR LINKAGE
0 1     1        1             0                  0              1
 01     9       13             1               4095              1
 02     9       14             1               4095              1
 03     9       15             1               4095              1
 72    11       12             1               4095              1
 73    11       13             3              12285              1
 74    11       14             2               8190              1
 75    11       15             2               8190              1
 09    12       13             1               4095              1
 10    12       14             1               4095              1
 11    12       15             1               4095              1
 46    13       14             7              28665              1
 47    13       15             7              28665              1
 83    14       15             7              28665              1
 76     0        0             0                  0              0
4    OBJECT SATSPM     VERSION GORDUN                                          PAGE    1
1    OBJECT SATSPM     VERSION GORDUN                                          PAGE    1
0 VTIME
0572531
0    GROUND   GROUND   NUMBER OF SATELLITES TOTAL CAPACITY NUMBER OF SATELLITES
     STATION  STATION  VISIBLE OVER LINK      OVER LINK    REQUIRED FOR LINKAGE
0 1     1        1             0                  0              1
 01     9       13             1               4095              1
 03     9       15             1               4095              1
 72    11       12             1               4095              1
 73    11       13             3              12285              1
 74    11       14             2               8190              1
 75    11       15             2               8190              1
 09    12       13             1               4095              1
 10    12       14             1               4095              1
 11    12       15             1               4095              1
 46    13       14             6              24570              1
 47    13       15             7              28665              1
 83    14       15             6              24570              1
 76     0        0             0                  0              0
```

*Must be requested if desired as external output.

EXHIBIT D

Minute-by-Minute Output of the QUEUE Routine — London/Andover Link*

0	INITIAL CAPACITY	DEMANC	CHANNELS IN USE	BACKLOG	LOST CALLS	INTERRUPTS	REMAINING CAPACITY	PERCENT UTILIZATION OF CAPACITY	PERCENT DEMAND FILLED
350	20	1	12	0	0	0	8	60	100
351	20	2	12	0	0	0	8	60	100
352	20	4	14	0	0	0	6	70	100
353	20	2	13	0	0	0	7	65	100
354	20	4	14	0	0	0	6	70	100
355	20	2	13	0	0	0	7	65	100
356	20	5	15	0	0	0	5	75	100
357	20	5	17	0	0	0	3	85	100
358	20	3	17	0	0	C	3	85	100
359	20	6	20	0	0	0	0	100	100
360	20	4	20	0	0	0	0	100	100
361	0	1	C	1	0	16	0	0	0
362	10	0	C	0	0	0	10	0	0
363	10	0	0	0	0	0	10	0	0
364	10	1	1	0	0	0	9	10	100
0	OBJECT QAAMIN		VERSICN QVRGNA						PAGE 8
1	OBJECT QAAMIN		VERSICN QVRGNA						PAGE 9
0365	10	0	1	0	0	0	9	10	100
366	10	0	1	0	0	0	9	10	100
367	10	1	2	0	0	0	8	20	100
368	10	1	3	0	0	0	7	30	100
369	10	C	2	0	0	0	8	20	100
370	10	C	2	0	0	0	8	20	100

*Links designated by number as in Exhibit A not shown here. This output if desired must be specifically requested. The "minute" is given in the left-hand column.

APPENDIX E

SYSTEMS DATA FOR THE FIVE INITIAL RUNS

Page

APPENDIX E

SYSTEM DATA FOR THE FIVE INITIAL RUNS

BACKGROUND

In fulfillment of the requirement to apply the computer simulation to at least three specific satellite system configurations, the systems described in detail below were established for the initial model demonstration runs. System characteristics and parametric values (numbers of satellites, reliabilities, capacities, costs, pad availabilities, etc.) were coordinated with NASA, and many of the chosen values, especially costs, were taken from RAND's RM-3487-RC[1/] of February 1963 in accordance with our attempts to use RAND's work whenever possible. The Federal Communications Commission was helpful in suggesting procedures by which costs and revenues were apportioned. Demand levels are derived from previous Tech/Ops work, which in turn was largely based upon earlier estimates of the Ad Hoc Carrier Committee, the RAND Corporation, and Booz, Allen and Hamilton.[2/]

The parametric values chosen are not to be considered fixed in any sense, nor even "most reasonable", but only indicative of possible systems. The experimenter may vary all of the values and certain of the procedures of these demonstration runs in designing future runs as outlined in other sections of this report.

We have, nonetheless, chosen variables in a fashion to begin to point out functional differences between the three generic communications satellite systems. We have, for example, held constant for the five runs such things as ground station locations, demand levels, cost and revenue breakdowns, and rate structures. Satellite systems may thereby be compared against a solid common denominator. It should be recognized, however, that in specifying inputs we are not attempting to depict the total analysis cycle. The choice of inputs for these runs was based upon the research of previous studies rather than upon sensitivity and correlation analysis as applied to output in the choice

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1/ Communications Satellites: Technology, Economics, and System Choices, February 1963.

2/ Conrad A. Batchelder and T. Arthur Smith, Demand for International Telecommunications, TO-W62-3, Technical Operation, Inc., June 1962.

of variable values for subsequent input. This latter phase of analysis, as explained earlier in this volume, was somewhat beyond the scope of this work and must await application runs of the model.

ORBITING SYSTEMS

We postulated three satellite systems, designated Systems A, B, and C. Runs 1 and 4 involve System A, Runs 2 and 3 involved System B, and Run 5 involved System C. The three systems are described below:

SYSTEM A - 18 SATELLITES (ACTIVE)

Orbit[1/]	Random 6000 n.m., circular polar
Launch Vehicle Reliability	.8
Lifetime in Orbit[1/]	.50 probability for 2 years - .95 for one month
Launch Pad Availability (two pads)	6 weeks' turnaround time; 6 weeks' notice required
Orbital Planes	3 (60^{o} apart)
Costs — Vehicle	\$7.5 million
Costs — Satellite	\$800 K (3/launch vehicle)
Capacities	18 of 600 telephone channels each
Replacement	In threes per plane

[1/] Note distributions, pages 115 and 116

SYSTEM B - 18 SATELLITES (PASSIVE)

Orbit[1]	Random 2000 n.m., circular polar
Launch Vehicle Reliability	.8
Lifetime in Orbit[1]	.95 (one year) - .50 (five years)
Launch Pad Availability (two pads)	6 weeks' turnaround time; 6 weeks' notice required
Orbital Planes	2 (90° apart)
Costs — Vehicle	\$7.5 million
Costs — Satellite	\$150 K (3/launch vehicle)
Capacities	18 of 600 voice-channels each (multiple access implies virtually unlimited total capacity; the capacities given are for a <u>single</u> ground antenna)[2]
Replacement	In threes per plane

[1] Note distributions, pages 115 and 116.

[2] and the total capacity is given by the expression

$$C_T = \sum_{1}^{n} A_s A_N$$

where C_T = total capacity per passive satellite

n = all stations visible to a given satellite

A_s = capacity of a single antenna at station n

A_N = number of antennas at station n

SYSTEM C - 15 SATELLITES (2 TYPES)

	Synchronous (3)	Medium Altitude Active (12)
Orbit[1/]	Stationary	Random 6000 n.m., circular polar
Vehicle Reliability	.7	.8
Lifetime in Orbit[1/]	.95 - 1 month .50 - 3 years	.95 - 1 month .50 - 2 years
Launch Pad Availability	—— 6 weeks, as for Systems A and B ——	
Orbital Planes	Equatorial - 120° separation	4 (45° apart)
Costs — Vehicle	\$8.5 million	\$7.5 million
Costs — Satellite	\$2 million	\$800 K (3/launch vehicle)
Capacities	2400 voice-channels	12 of 600 voice-channels each
Replacement	Singly (no backups)	In threes per plane

[1/] Note distributions, pages 115 and 116.

The probabilities of achieving a given altitude, inclination, or circularity are all based upon the assumption that the distributions defining orbital parameters are normal with parameters as shown:

	Eccentricity - 3σ/apogee-perigee difference of 45 n.m.
System A	Altitude - $3\sigma/\pm$ 50 n.m.
	Inclination - $3\sigma/\pm$ 1^{o}
	Eccentricity - 3σ/apogee-perigee difference of 15 n.m.
System B	Altitude - $3\sigma/\pm$ 50 n.m.
	Inclination - $3\sigma/\pm$ 1^{o}
	Medium Altitude Actives - same as System A
System C	
	Stationary Component:
	Eccentricity - 3σ/ apogee-perigee difference of 75 n.m.
	Altitude - $3\sigma/\pm$ 200 miles
	Inclination - Equatorial ($3\sigma/\pm 2^{o}$)

It would have been desirable to input, for System C, orbital parameters for the stationary component so that these satellites did not change their relative positions over time. However, this was not done for Run 5 and outages that might have been avoided were experienced. It is felt that the engineering capability to provide such a system is proven, and that subsequent runs involving stationary satellites bypass orbital calculations and input positions of such satellites directly to the COVERAGE routine.

LIFETIME DISTRIBUTIONS. From the estimated reliability data furnished by NASA, and with an assumption of positive ageing (i.e., the older the item, the more probable becomes immediate failure), we have determined that the Weibull distribution would serve as a useful first approximation to the highly uncertain lifetime projection.[1] This, of course, is subject to change as knowledge improves, and remains one of the more important variables in the simulation. The Weibull reliability function is $R(t) = \exp(-\lambda t^{\alpha})$, and reliability and mortality curves for the three satellite types are as given in Appendix B.

TIME PHASING OF SATELLITE LAUNCHES.

Systems A and B	—	Every six months beginning at the start of year 1.
System C	—	First launch medium altitude satellites, following same plan as for Systems A and B. Follow with stationary satellites; six months between all established launches.

Replacement launches — The assumption is made, for Systems A and B, that replacements are planned as failures occur so that 6 weeks following the <u>third</u> failure in a given orbital plane, 3 replacements are launched for that plane. Thus, the number of functioning satellites at a selected time may be less than the planned number by reason of insufficient failures to justify replacement. With regard to System C, replacement launches occur six weeks following failure of a single stationary satellite and as noted above for medium altitude satellites. We are thus testing the impact, from the point of view of communications services, of not maintaining a spare stationary satellite in orbit for the mixed system.

---

[1] A number of failure distributions were examined in an effort to fit the given data, but most were rejected because they gave mortality curves exhibiting negative ageing, or no ageing.

GROUND STATIONS, LINKS, AND DEMANDS

Ground Station	Year Established	Antennas		Investment Cost (Millions)		Annual Operating Cost (Millions)	
		No.	Capacity of each	Systems A and C	System B	Systems A and C	System B
London	1	3	600	$6.1	$7.5	$1.5	$1.8
Paris	1	3	600	$6.1	$7.5	$1.5	$1.8
Tokyo	2	3	60	$3.2	$5.5	$0.8	$1.2
Mexico City	7	3	60	$3.2	$5.5	$0.8	$1.2
Rio	2	3	60	$3.2	$5.5	$0.8	$1.2
Bogota	7	2	60	$2.5	$4.1	$0.6	$1.0
Santiago-de-Chile	7	2	60	$2.5	$4.1	$0.6	$1.0
Lagos	5	3	60	$3.2	$5.5	$0.8	$1.2
Beirut	5	3	600	$6.1	$7.5	$1.5	$1.8
Moscow	7	2	60	$2.5	$4.1	$0.6	$1.0
Rome	1	3	600	$6.1	$7.5	$1.5	$1.8
Andover	1	3	600	$6.1	$7.5	$1.5	$1.8
San Francisco	2	3	600	$6.1	$7.5	$1.5	$1.8
Singapore	8	2	60	$2.5	$4.1	$0.6	$1.0
Calcutta	8	2	60	$2.5	$4.1	$0.6	$1.0
Weilheim	2	3	600	$6.1	$7.5	$1.5	$1.8

The costs of ground stations for System C are held to be the same as those of System A for which the stations must also be capable of functioning. The number of antennas per ground station is a complex, as yet undertermined, function of desired service, number of links, bandwidth, and switching and backup requirements, as noted on page 13 of this volume. It is held constant for the three systems. We planned initially to include stations at Moscow, Mexico City, Bogota, Singapore, Calcutta, and Santiago-de-Chile in the five initial runs, but these stations were assumed to begin operation in Year 7 or 8. Since our runs were not set up to go past Year 6, these stations are not reflected in output.

PROJECTED DEMAND SCHEDULE

LINK NO.	YEAR (BEG.)	GROUND STATIONS LINKS FROM	TO	ASSUMED AVERAGE DEMANDS FOR SATELLITE CHANNELS 1965-9	1970-4	ASSUMED % OF PEAK TIME
1	1	LONDON	ANDOVER	25	50	25
4	5	$51^{o}30'$N	BEIRUT	25	40	25
15	8	$00^{o}07'$W	CALCUTTA	--	25	12 1/2
16	8		SINGAPORE	--	7	12 1/2
17	7		MEXICO CITY	--	40	25
2	1		ROME	20	30	33 1/3
3	2		SAN FRANCISCO	30	60	12 1/2
18	2		RIO	15	30	25
19	7		MOSCOW	--	7	25
5	5	PARIS	BEIRUT	25	50	25
6	1	$48^{o}51'$N	ROME	25	50	33 1/3
20	5	$02^{o}20'$E	LAGOS	5	13	33 1/3
7	1		ANDOVER	30	50	25
8	2		SAN FRANCISCO	35	60	12 1/2
21	2		RIO	15	35	25
22	7		MOSCOW	--	10	25
23	2	TOKYO	SAN FRANCISCO	6	15	25
24	7	$33^{o}41'$N	SANTIAGO-DE-CHILE	--	4	12 1/2
25	5	$139^{o}44'$E	BEIRUT	1	2	12 1/2
26	8		CALCUTTA	--	3	33 1/3
17	7	MEXICO CITY	LONDON	--	40	25
27	7	$19^{o}26'$N	SAN FRANCISO	--	30	33 1/3
28	7	$97^{o}07'$W	ROME	--	15	25
29	7		ANDOVER	--	15	33 1/3

PROJECTED DEMAND SCHEDULE (continued)

LINK NO.	YEAR (BEG.)	GROUND STATIONS LINKS FROM	TO	ASSUMED AVERAGE DEMANDS FOR SATELLITE CHANNELS 1965 -9	1970-4	ASSUMED % OF PEAK TIME
18	2	RIO	LONDON	15	30	25
21	2	22°50'S	PARIS	15	35	25
30	5	43°20'W	BEIRUT	15	30	25
31	2		SAN FRANCISCO	10	25	25
32	5		LAGOS	2	3	25
33	7	BOGOTA	SAN FRANCISCO	--	13	33 1/3
34	7	04°38'N	BEIRUT	--	6	12 1/2
35	8	74°06'W	CALCUTTA	--	5	12 1/2
24	7	SANTIAGO-DE-CHILE	TOKYO	--	4	12 1/2
36	7	33°26'S	SAN FRANCISCO	--	6	33 1/3
37	7	70°40'W	BEIRUT	--	4	12 1/2
32	5	LAGOS	RIO	2	3	25
20	5	06°31'N	PARIS	5	13	33 1/3
38	5	03°15'E	BEIRUT	3	7	25
45	5		WEILHEIM	10	15	33 1/3
4	5	BEIRUT	LONDON	25	40	25
5	5	33°53'N	PARIS	25	50	25
25	5	35°30'E	TOKYO	1	2	12 1/2
30	5		RIO	15	30	25
34	7		BOGOTA	--	6	12 1/2
37	7		SANTIAGO-DE-CHILE	--	4	12 1/2
9	5		ROME	25	60	33 1/3
38	5		LAGOS	3	7	25
39	7		MOSCOW	--	4	33 1/3
13	5		ANDOVER	25	60	25
12	5		SAN FRANCISCO	15	35	12 1/2

PROJECTED DEMAND SCHEDULE (continued)

LINK NO.	YEAR (BEG.)	GROUND STATIONS LINKS FROM	TO	ASSUMED AVERAGE DEMANDS FOR SATELLITE CHANNELS 1965-9	1970-4	ASSUMED % OF PEAK TIME
19	7	MOSCOW $55^{o}45'N$ $37^{o}37'E$	LONDON	--	7	25
22	7		PARIS	—	10	25
39	7		BEIRUT	--	4	33 1/3
40	8		CALCUTTA	--	5	25
2	1	ROME $41^{o}52'N$ $12^{o}37'E$	LONDON	20	30	33 1/8
6	1		PARIS	25	50	33 1/3
28	7		MEXICO CITY	--	15	25
10	1		ANDOVER	25	60	25
11	2		SAN FRANCISCO	30	60	12 1/2
41	8		CALCUTTA	--	6	25
9	5		BEIRUT	25	60	33 1/3
1	1	ANDOVER $44^{o}40'N$ $63^{o}36'W$	LONDON	25	50	25
7	1		PARIS	30	50	25
29	7		MEXICO CITY	--	15	33 1/3
13	5		BEIRUT	25	60	25
10	1		ROME	25	60	25
14	2		SAN FRANCISCO	35	60	25
43	2		WEILHEIM	25	50	25
3	2	SAN FRANCISCO $37^{o}45'N$ $112^{o}26'W$	LONDON	30	60	12 1/2
8	2		PARIS	35	60	12 1/2
23	2		TOKYO	6	15	25
27	7		MEXICO CITY	--	30	33 1/3
31	2		RIO	10	25	25
33	7		BOGOTA	--	13	33 1/3
36	7		SANTIAGO-DE-CHILE	--	6	33 1/3
12	5		BEIRUT	15	35	12 1/2
11	2		ROME	30	60	12 1/2
14	2		ANDOVER	35	60	25
42	8		SINGAPORE	--	3	12 1/2

PROJECTED DEMAND SCHEDULE (continued)

LINK NO.	YEAR (BEG.)	GROUND STATIONS LINKS FROM	TO	ASSUMED AVERAGE DEMANDS FOR SATELLITE CHANNELS 1965-9	1970-4	ASSUMED % OF PEAK TIME
16	8	SINGAPORE	LONDON	--	7	12 1/2
42	8	01°18'N, 103°52'E	SAN FRANCISCO	--	3	12 1/2
15	8	CALCUTTA	LONDON	--	25	12 1/2
26	8	22°32'N	TOKYO	--	3	33 1/3
35	8	88°22'E	BOGOTA	--	5	12 1/2
40	8		MOSCOW	--	5	25
41	8		ROME	--	6	25
44	8		WEILHEIM	--	5	12 1/2
43	2	WEILHEIM	ANDOVER	25	50	25
44	8		CALCUTTA	--	5	12 1/2
45	5		LAGOS	10	15	33 1/3

PRIORITIES AND PEAK TIMES – RELATIONS TO DEMAND. The demand levels specified above are taken to be peak-time demands, and non-peak-time demands are to be one-half those values. Peak times, for a given link as a percentage of a day, are a function mainly of longitudes and are specified in the right-most column of the demand tables.

Peak times are scheduled sequentially to conform to the earth's rotation (passage of a day's time), and priorities of links are established as follows:

> Begin with highest level of demand, considering all peak and non-peak-time variations and effect on demand ordering (thereby partially accommodating peak periods).

We thus let demand level establish priorities among links for our runs. It is to be emphasized that this may be overriden and priorities, for any reason, may be manually established.

FINANCIAL MATTERS

INTEREST AND DEPRECIATION. The interest rate for costing purposes is taken to be 10%, with no taxation allowance to permit pre-tax comparisons among participants, local and regional.

Depreciation is assumed to be straight-line. Ground stations are to be depreciated on a system lifetime basis, in this case 15 years, and satellite launchings on an expected lifetime basis, in this case as derived from the Weibull distributions noted above. Depreciation is treated <u>within</u> the model in accordance with the discussion on page 16.[1/]

DIVISION OF REVENUES AND COSTS. Line haul or extension haul deductions may claim a large proportion of the revenues derived from point-to-point overseas telecommunication. These charges provide the means of reimbursing each of the local carriers whose facility is required to tie in calls originating from or directed to regions remote from the endpoints of the overseas links. The amount of this deduction is highly variable, depending primarily upon distances of origination or termination from cable-head (ground station), and negotiated specific agreements. The model permits specific variable link-by-link deductions to be considered as agreements are negotiated. We have, however, assumed the revenues based upon the rates noted below to be divided equally by the satellite entity and the two concerned ground stations.

Costs are to be wholly borne by the entity concerned (i.e., the satellite entity for investment in orbiting systems and corporate operating expense, and

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[1/] It is important to consider unsuccessful launches in the depreciation calculation.

ground station owners for this facility). Ground station costs are noted in the section on ground stations earlier, and operating costs of the satellite corporation are assumed to be as follows:

Year 1	2 million
Year 2	2.5 million
Year 3	3 million
Year 4	3.5 million
Year 5	3.5 million
Year 6	4 million

OVERSEAS RATES. Rate data with regard to overseas telephone calls not involving the United States is difficult to acquire. Even if acquired, interpretation necessitates either conversion of all foreign currencies to a common demoninator or a statement of individual costs in terms of foreign currencies. Either of these alternatives involves certain difficulties from the viewpoint of evaluating, in economic terms, the desirability of participation. We have some basis, however, for estimation the cost of overseas telephone calls (non U.S.) in U.S. dollars, and thus have chosen this path. As analysis proceeds, however, foreign currencies and value, and actual rates for satellite communication should be taken into account.

Charges for communication via overseas cable have traditionally been based primarily upon distance, a factor that very likely will diminish in significance with the coming of satellite communication. We will employ this criterion, making arbitrary allowance for the lessening import of distance, in establishing station-to-station day rate charges for the proposed links. Non-peak rates are derived by subtracting 20 per cent from the day rate. Overtime rates are computed at 75 per cent of the appropriate 3-minute rate. Forty-two links are proposed above, with rates as shown below. This model required the data of the right-hand column[1].

Link	3-Minute Peak-Time Rate	Rate Per Channel Minute
1	$ 9.00	$2.60
2	5.00	1.50
3	11.00	3.10
4	9.00	2.60
5	8.00	2.70
6	5.00	1.50
7	9.00	2.60

[1] Calculated as shown below.

Link	3-Minute Peak-Time Rate	Rate Per Channel Minute
8	$11.00	$3.10
9	7.00	2.10
10	9.00	2.60
11	12.00	3.30
12	14.00	3.90
13	13.00	3.30
14	9.00	2.60
15	11.00	3.10
16	12.00	3.30
17	11.00	3.20
18	11.00	3.20
19	7.00	2.00
20	9.00	2.70
21	11.00	3.20
22	7.00	2.00
23	11.00	3.20
24	14.00	3.90
25	11.00	3.10
26	9.00	2.70
27	7.00	2.10
28	12.00	3.40
29	9.00	2.70
30	13.00	3.30
31	12.00	3.40
32	10.00	3.00
33	10.00	3.00
34	13.00	3.50
35	14.00	3.90
36	12.00	3.50
37	14.00	3.90
38	9.00	2.60
39	8.00	2.40
40	11.00	3.20
41	10.00	3.00
42	13.00	3.60

The rates shown may be considerably less than the present fees for many of the longer distance cable or radio links (after conversion of U.S. dollars). 1/ This is justifiable, not only for reason of the above noted "distance" criterion but also to make the system attractive to foreign participation, assuming some elasticity of demand. The model, of course, can accommodate any rate schedule, including one pegged to present cable and radio rates.

The rate data above in the right-hand column is calculated as shown in the following example:

First, for each given 3-minute rate, calculate average revenue per call. Based upon an average call length of five minutes, this revenue is as given in the next table:

AVERAGE REVENUE PER CALL IN PEAK
AND NON-PEAK TIMES FOR A GIVEN THREE-MINUTE PEAK RATE

Given: Three-Minute Peak Rate	Derived: Average Peak-Time Revenue Per Call	Derived: Average Non-Peak-Time Revenue Per Call
$ 5.00	$ 8.30	$ 6.50
7.00	11.50	9.10
8.00	13.20	10.50
9.00	14.80	11.80
10.00	17.40	13.20
11.00	18.10	14.50
12.00	19.50	15.80
13.00	21.40	17.00
14.00	23.00	18.40

Next, derive the rate per channel-minute as in the following expression:

$$\frac{2\,(\%\text{ Peak Time})\text{ Peak-Time Revenue/Call} + (\%\text{Non Peak-Time})\text{ Non-Peak-Time Revenue/Call}}{2\,(\%\text{ Peak Time}) + \%\text{ Non Peak-Time}}$$

1/ Although we did not have these data, we understand charges for some calls greatly exceed the proposed $14.00 maximum station-to-station initial-period peak rate.

Example: Link 1

$ 9.00 = 3-minute call at peak time

$14.00 = average revenue per call at peak time

$11.80 = average revenue/call at non peak-time

25% = peak period

75% = non peak-period

$$\left[\frac{(25)\ 2\ (\$14.80)\ +\ 75\ (\$11.80)}{2\ (.25)\ +\ .75}\right] \div 5 = \text{Rate Channel Minute (in dollars)}$$

Peak demand is assumed always to be twice non-peak demand, which accounts for the factor of 2.

QUEUING ASSUMPTIONS

Call length and impatience factors are presumed to be given by a negative exponential distribution characterized by a decay rate of 20 per cent. It is further assumed that both call length and willingness to wait (patience) are defined by average values of five minutes. Demand is given by the Poisson distribution characterized by the average values given on page 118 above.

APPENDIX F

PREPARATION OF THE INPUT DECK FOR THE RUNNING OF THE MODEL

APPENDIX F

The discussion that follows covers the preparation of the input deck for the simulation of any system. Control card formats, data card formats and the deck structure are covered. Considerable detail is set forth, in an attempt to minimize future needs for the services of a programmer, yet knowledge of programming could be of real value to the analyst conducting further runs.

Throughout this discussion actual values for any field of a card will be both underlined and in upper case characters.

CONTROL CARDS

Control cards are required in the input deck to communicate requests to the CL-I programming system. The value in columns one through six of a control card is the name of an operation the system is being requested to perform. There are six control card types used in the input deck. For each type, the operation name is punched in columns 1 through 6 and all other information is punched starting in column 12. The MFTPPR, TESTMF, EXCPRC and FINISH control card formats will not be discussed here but will be shown below in the deck structure description.

INPOBJ CONTROL CARD. This control card informs the system that the data cards immediately following, until the first blank card is encountered, contain data to be input to a system object which is to be written on the data input tape. An INPOBJ control card must immediately precede each set of data cards being input. The variable field of the card (column 12 and following) is used to communicate the object name, a version name and other control information. Exact formats are given for each object in the individual object writeups.

OUTOBJ CONTROL CARD. This control card requests the system to format and prepare for printing off-line all objects on the output tape that have the same "name" and "version" as that specified in the variable field of this card. Exact formats are given in the deck structure section.

DATA CARDS

Data used by the simulation model is contained in objects and parameters.[1/] A data set or object is an ordered, structured collection of data or information. The elements of an object are called items. An object has a "name" and "version". The "name" consists of not more than six alphanumeric characters (letters and digits). The "version" is again not more than six alphanumeric characters and may be varied from run to run. Thus, there may exist many versions of an object. Parameters are single-valued items used for communication between the analyst and the model. Parameters have only "names" and values. Each input object, its control card, input data format(s) and associated parameter (if any) are described below. Parameters and their input formats are also described.

Values must be input on data cards for objects in the following manner:

Integer fields - Right justified in the specified column. Leading zeroes may be omitted.

Alphanumeric fields - Left justified in the specified columns with trailing blanks.

Longitude - In the form DDDMMSSδ, where DDD = degrees (000 - 180), MM = minutes (00 - 59), SS = seconds (00 - 59) and δ is E or W for east or west.

For any card type where index number is required, the date cards should first be ordered as described and the sequential (starting at one) numbers be punched in the columns specified for index number.

All values input for parameters must start in column 16 (left justification). Leading zeroes may be omitted.

OBJECT SLNCH. The data input to this object specifies all initial launches and their scheduled times. The parameter SLNCIV must be set to the same value as the version name on the INPOBJ control card. Two data cards must be filled out to describe each launch. The INPOBJ control card for this object has

1/Basic data, for the systems we have simulated, are given in Appendix E. In certain cases, hand calculations (such as the preparation of probability tables) must be accomplished by the analyst upon such data before the card described herein may be prepared. We denote all such cards in this discussion but do not attempt to indicate the mathematics of a particular calculation.

the following format:

INPOBJ SLNCH/version name, TAPE/A5

A data card for each launch is filled out in the following manner and cards are ordered on time of launch.

Card Type 1

Cols. 1 - 3	S11
Cols. 4 - 6	Index number (launch number; 001, 002, ...300).
Cols. 8 - 9	Calandar year of launch (e.g., 65 for 1965).
Cols. 11 - 12	Month of launch (01, 02, . . . 12).
Cols. 14 - 15	Day of launch (01, 02, . . . 31).
Cols. 17 - 18	Hours of launch (00, 01, . . . 23).
Cols. 20 - 21	Minute of launch (00, 01, . . . 59).
Cols. 23 -28	Satellite type identifier (any 6 characters).
Cols. 30 - 35	Launch pad identifier (any 6 characters).
Cols. 37 - 38	Number of satellites in this launch.
Cols. 56 - 58	Launch reference number (usually the same as index number in cols. 4 - 6).

A second data card for each launch is filled out as described below with the index number the same as on card type 1.

Card Type 2 (probably will require manipulation of given systems data).

Cols. 1 - 3	S12
Cols. 4 - 6	Index number (launch number)
Cols. 8 - 10	Starting location (index number) in the object DLOLST for perigee passage information on this launch. This must be specified only when the number of satellites in the launch is greater than one.

Cols. 11 - 18	Longitude of perigee passage next time after the reference time of nodal crossing or blank if longitude is to be randomly generated. This may be specified only when the number of satellites in the launch is one.
Cols. 19 - 21	Starting index in the object DBOLST for nodal crossing information on this launch. This must be specified only if the number of satellites in the launch is greater than one.
Cols. 22 - 29	Longitude of nodal crossing at the reference time of nodal crossing or blank if longitude is to be randomly generated. This may be specified only when the number of the satellites in the launch is one.
Cols. 31 - 38	If the number of satellites in the launch is equal to one this is the reference time of nodal crossing in minutes. If set to zero or blank the reference time will be generated randomly. If the number of satellites in the launch is greater than one, this is the starting location in the object DTLIST for reference time information on this launch.
Cols. 40 - 44	If the number of satellites in the launch is equal to one input the desired altitude in nautical miles or if the number of satellites in this launch is greater than one the starting location in the object DALIST for altitude information on this launch.
Cols. 53 - 54	The number (n) of the curve given by object CRVn to be used for randomizing altitude.

Cols. 56 - 57 | The number (n) of the curve given by object CRVn to be used for obtaining eccentricity.

Cols. 59 - 60 | The number (n) of the curve given by object CRVn to be used for randomizing inclination.

Cols. 62 - 69 | The desired inclination of all satellites in this launch expressed in degrees (0^{o} - $179^{o}59'59''$; i.e., a retrograde orbit is subtracted from 180^{o}). Col. 69 must always contain the character E.

OBJECT DLOLST. The data input to this object is a list of the longitudes of the desired perigee passages the next time after the reference time of nodal crossing for multiple launches and is required input only when one or more launches described in the object SLNCH have more than one satellite and it is not desired to have the longitude randomly generated. Up to 200 values may be input. Cols. 8 - 10 of card type 2 (see SLNCH format) gives the starting index into this object for a given launch. One data card is required for each satellite in a multiple launch. The parameter DLOLSV must be set to the same value as the version name on the INPOBJ control card if DLOLST is input. The INPOBJ control card has the following format:

INPOBJ DLOLST/version name, TAPE/A5, ABMCPD/LSPOOP

Each data card is filled out in the following manner (probably will require manipulation of given data).

Cols. 1 - 5 | DESLO

Cols. 9 - 11 | Index number.

Cols. 13 - 20 | Longitude of perigee passage the next time after reference time of nodal crossing.

OBJECT DBOLST. The data input to this object is a list of the longitudes of the desired nodal crossings at the reference time of nodal crossing for multiple launches and is required input only when one or more launches described in the object SLNCH has more than one satellite and it is not desired to have the longitudes randomly generated. Up to 200 values may be input. Cols. 19 - 21 of card type 2 (see SLNCH format) gives the starting index into this object for a given launch. One data card is required for each satellite in a multiple launch. The parameter DBOLSV must be set to the same value as the version name on the INPOBJ control card if DBOLST is input.

The INPOBJ control card has the following format:

INPOBJ DBOLST/version name, TAPE/A5, ABMCPD/LSPOOP

Each data card is filled out as described below.

Cols. 1 - 5	DESBO
Cols. 9 - 11	Index number.
Cols. 13 - 20	Longitude of nodal crossing at the reference time of nodal crossing.

OBJECT DTLIST. The data input of this object is a list of the reference times of nodal crossing for multiple launches (so as to give the desired number of orbital planes) and is required input only when one or more launches described in the object SLNCH have more than one satellite and it is not desired to have the reference times randomly generated. Any nodal crossing, providing proper spacing between orbits, may be specified. Up to 200 reference times may be input. Cols. 31 - 38 of card type 2 (see SLNCH format) gives the starting index into this object for a given launch. One data card is required for each satellite in a multiple launch. The parameter DTLISV must be set to the same value as the version name on the INPOBJ control card if DTLIST is input. The INPOBJ control card has the following format:

INPOBJ DTLIST/version name, TAPE/A5

Each data card is filled out as described below. (probably will require manipulation of given data).

Cols. 1 - 6	DESTAU
Cols. 9 - 11	Index number.
Cols. 13 - 20	Reference time of nodal crossing in minutes from time zero for the simulation.

OBJECT DALIST. The data input to this object is a list of the desired satellite altitudes for multiple launches and is required input only when one or more launches described in the object SLNCH have more than one satellite. Up to 200 altitudes may be input. Cols. 40 - 44 of card type 2 (see SLNCH format) gives the starting index into this object for a given launch. One data card is required for each satellite in a multiple launch. The parameter DALISV must be set to the same value as the version name on the INPOBJ control card if DALIST is input. The INPOBJ control card has the following format:

INPOBJ	DALIST/version name, TAPE/A5

Each data card is filled out as described below.

Cols. 1 - 6	DESALT
Cols. 9 - 11	Index number.
Cols. 13 - 18	The desired altitude in nautical miles.

OBJECT SCYCLE. The data input to this object furnishes information about the start of the simulation, its duration and each of the "time slices" to be studied. There is one data card for the overall simulation and one for each "time slice". The maximum number of time slices is 50. The parameter SCYCLV must be set to the same value as the version name on the INPOBJ control card. The INPOBJ control card has the following format:

INPOBJ	SCYCLE/version name, TAPE/A5, ABMCPD/LSPOOP

The overall simulation card is filled out in the following manner.

Cols. 1 - 2	SE
Cols. 4 - 5	Starting year for the simulation.
Cols. 7 - 8	Year for time zero of cost calculations.
Cols. 10 - 11	Month for time zero of cost calculations.
Cols. 13 - 14	Day for time zero of cost calculations.
Cols. 16 - 17	Number of years in the simulation.

A data card for each "time slice" to be studied is filled out as described below and ordered on time at beginning of "time slice".

Cols. 1 - 2	SG
Cols. 4 - 5	Year at the beginning of the "time slice".
Cols. 7 - 8	Month at the beginning of the "time slice".
Cols. 10 - 11	Day at the beginning of the "time slice".
Cols. 13 - 14	Hour at the beginning of the "time slice".
Cols. 16 - 17	Minute at the beginning of the "time slice".
Cols. 19 - 23	Length of the "time slice" in minutes.
Cols. 70 - 72	Index number.

OBJECT SABORT. The data input to this object gives the probability of achieving injection into orbit. A maximum of 10 satellite types can be input. The parameter SABORV must be set to the same value as the version name used on the INPOBJ control card. The INPOBJ control card has the following format:

INPOBJ SABORT/version name, TAPE/A5

A data card for each satellite type is filled out in the following manner:

Cols. 1 - 2	S2
Cols. 4 - 9	Satellite type identifier (6 characters).
Cols. 11 - 12	Probability of not achieving injection into orbit (1 - probability of injection).
Cols. 14 - 15	Leave blank (original model design required probabilities for these columns but Cols. 11 - 12 are now all that is required).
Cols. 17 - 18	Leave blank (original model design required probabilities for these columns but Cols. 11 - 12 are now all that is required).

Cols. 71 - 72	Index number.

OBJECT SINTVL. The data input to this object describes for each launch pad the minimum intervals before another launch attempt after 1) an on-pad abort and 2) any launch attempt which did not result in an on-pad abort. Data for one to ten launch pads may be input. The parameter SINTVV must be set to the same value as the version name on the INPOBJ control card. The INPOBJ control card has the following format:

INPOBJ	SINTVL/version name, TAPE/A5

A data card for each launch pad is filled out in the following manner:

Cols. 1 - 2	S3
Cols. 4 - 9	Launch pad identifier (6 characters).
Cols. 11 - 13	Days for minimum interval after on-pad abort.
Cols. 15 - 17	Hours for minimum interval after on-pad abort (zero is acceptable and probably sufficient).
Cols. 19 - 21	Days for minimum interval after a launch attempt which did not result in an on-pad abort.
Cols. 23 - 25	Hours for minimum interval after a launch attempt which did not result in an on-pad abort (zero also acceptable and sufficient).
Cols. 71 - 72	Index number.

OBJECT SETUP. The data input to this object specifies the minimum elapsed time between the decision that a replacement launch is necessary and the physical availability of a replacement for each type of satellite. Data for up to ten satellite types may be input. The parameter SETUPV must be set to the same value as the version name on the INPOBJ control card. The INPOBJ control card has the following format:

INPOBJ SETUP/version name, TAPE/A5

A data card for each satellite type is filled out in the following manner:

Cols. 1 - 2	S9
Cols. 4 - 9	Satellite type identifier (6 characters).
Cols. 11 - 13	Days required for setup.
Cols. 15 - 17	Hours required for setup (zero is probably sufficient).
Cols. 71 - 72	Index number.

OBJECT SFAIL. The data input to this object gives for each satellite type information specifying the probability of failure at time T_n (from launch) and the number of failures before a launch will be undertaken. Up to 100 entries may be made in this object. The parameter SFAILV must be set to the same value as the version name on the INPOBJ control card. The INPOBJ control card has the following format:

INPOBJ SFAIL/version name, TAPE/A5

A data card for each value of T_n for each satellite type is filled out as described below. Cards must be grouped by satellite type and ordered on T_n within any satellite type (manipulation of given data probably required).

Cols. 1 - 2	S8
Cols. 4 - 9	Satellite type identifier (6 characters).
Cols. 11 - 13	Probability of failure by time T_n expressed as an integer percentage.
Cols. 15 - 16	Years from launch to failure.
Cols. 18 - 20	Days from launch to failure.
Cols. 22 - 23	Number of failures before a launch is undertaken.
Cols. 70 - 72	Index number.

OBJECT SDELAY. The data input to this object describes a single curve which is the probability density function reflecting the interval between the scheduled launch time (or time when the launch pad becomes available, if later) and the actual time of launch or abort, T_n. Up to twenty points may be used to describe the curve. Linear interpolation is performed between success points of the cumulative distribution. The parameter SDELAV must be set to the same value as the version name on the INPOBJ control card. The INPOBJ control card has the following format:

INPOBJ	SDELAY/version name, TAPE/A5

A data card for each point is filled out as described and ordered on time of delay (manipulation of given data probably required).

Cols. 1 - 2	S7
Cols. 4 - 6	Probability of the delay time (T_n) expressed as an integer percentage.
Cols. 8 - 10	Hours of delay.
Cols 12 - 13	Minutes of delay (zero possible).
Cols. 71 - 72	Index number.

OBJECTS CRVn, where n = 0, 1, . . . 9. The data input to any of these objects specifies a curve that is used to randomize altitude or inclination or to generate random eccentricity. The object SLNCH references these curves by curve number (n). The curves are input as a series of points and linear interpolation is always assumed. Up to forty points may be specified for any curve. The parameters, CRVnV must be set to the same values as the version names on the INPOBJ control cards. CRVn is considered optional only because it is not necessary that all ten curves be input. Since the object SLNCH references these curves, it is necessary that at least one curve containing as a minimum the points [1, f(1)] (or [0, f(0)]) and [100, f(100)] be input. In fact, it is difficult to see how less than two curves could be input for any realistic model(e.g., one for eccentricity and one for both inclination and altitude). The INPOBJ control cards have the following format:(manipulation of given data required).

INPOBJ	CRVn/version name, TAPE/A5, ABMCPD/LSPOOP

A data card for each point is filled out in the following manner and ordered on cumulative probability.

Cols. 1 - 6	CURVEn
Cols. 8 - 9	Index number.
Cols. 11 - 13	Cumulative probability expressed as an integer percentage.
Cols. 15 - 27	A mixed number (6 integral and 6 fractional digits) is punched in these columns. No decimal point is punched but a point is assumed between cols. 20 and 21. When randomizing eccentricity the function represents the eccentricity. When randomizing altitude or inclinations the function is a multiplier of the desired value.

OBJECT GNDSTA. The data input to this object specifies the location and operational data for each ground station. Up to 30 ground stations may be specified. The INPOBJ control card for this object has the following format:

INPOBJ	GNDSTA/LSTEST, TAPE/A5, ABMCPD/LSPOOP

A data card for each ground station is filled out as described below and must be ordered from southern-most to northern-most latitude.

Cols. 2 - 3	GS
Cols. 4 - 5	Index number.
Cols. 8 - 14	Latitude of this ground station given as DDMMSSV, where DD = degrees, MM = minutes, SS = seconds and V is N or S for north or south respectively.
Cols. 16 - 23	Longitude of this ground station.
Cols. 25 - 31	The beginning operational time of this ground station in minutes of elapsed time from time zero for the simulation.

Cols. 33 - 34	The ground station type indicator (an integer).

OBJECT SACOST. The data input to this object gives for each satellite type the channel capacity, minimum ground station elevation angle, expected life and cost information. One to ten satellite types may be described. The INPOBJ control card for this object has the following format:

INPOBJ	SACOST/VRGABC, TAPE/A5

A data card for each satellite type is filled out in the following manner (some manipulation of data may be required for the depreciation calculation).

Cols. 1 - 2	SB
Cols. 4 - 9	Satellite type identifier (6 characters).
Cols. 11 - 14	Cost of one satellite in thousands of dollars (e.g., a cost of $1,250,000 is input as 1250).
Cols. 16 - 20	Cost of launch vehicle in thousands of dollars (does not include cost of satellites).
Cols. 22 - 25	Annual depreciation for a launch in thousands of dollars.
Cols. 27 - 30	Number of channels capacity.
Cols. 32 - 33	Minimum ground station elevation angle in degrees.
Cols. 35 - 41	Expected life of the satellite in minutes.
Cols. 71 - 72	Index number.

OBJECT ALDA. The data input to this object must describe the demand over every existing link in the system. Up to 435 links can be described. The INPOBJ control card for this object has the following format (note that all cards requiring input in "minutes" will probably require manipulation of given data):

INPOBJ	ALDA/TEST1, TAPE/A5

A data card for every link in the network is filled out as described below. Cards must be grouped and put in ascending order by lower numbered ground station. Within each group the cards should be in ascending order of higher numbered ground station.

Cols. 1 - 4	ALDA
Cols. 6 - 8	Index number (001, 002, . . .)
Col. 9	1 if the link has any demand at any time during the simulation, otherwise 0.
Cols. 10 - 11	Lower ground station number for the link.
Cols. 12 - 13	Higher ground station number for the link.
Cols. 14 - 17	Peak time demand in channels.
Cols. 29 - 32	Beginning of peak demand period in minutes from midnight at the international date line.
Cols. 34 - 37	Length of peak demand period in minutes.
Col. 39	Integer divisor to convert peak to slack demand (set to 2 for initial runs).

OBJECT ANTNNA. The data input to this object specifies the total antenna capacity for each antenna in the system. A maximum of 870 antennas may be specified. The INPOBJ control card for this object has the following format:

INPOBJ	ANTNNA/TEST1, TAPE/A5

A data card for every antenna in the network must be filled out in the manner described below and be ordered on ground station number.

Cols. 1 - 6	ANTNNA
Cols. 8 - 10	Index number (001, 002, . . .)
Cols. 12 - 15	Total capacity for this antenna (channels)
Cols. 17 - 18	Number of the ground station at which this antenna is located.

OBJECT AGSTAT. The data input to this object specified the number of antennas at each ground station and the cumulative number of antennas in the network up to and including the previous ground station. A maximum of 30 entries can be input to this object. The INPOBJ control card for this object has the following format:

INPOBJ	AGSTAT/TEST1, TAPE/A5

A data card for each ground station must be filled out in the manner described below and be ordered on ground station number (index number).

Cols. 1 - 6	AGSTAT
Cols. 8 - 10	Index number (ground station number)
Cols. 11 - 12	Number of antennas in use at this ground station.
Cols. 14 - 16	Total number of antennas up to and including the previous ground station.

OBJECT ADCHGE. The data input to this object specified the long term changes in link demand occurring at a given time (T_n). Up to 435 changes in link demand can be input for the given time. This is an optional input; however, a data set must be input for each time at which it is desired to have changes in demand. The data sets themselves should be in ascending order on time of change in link demand. The INPOBJ control card for this object has the following format:

INPOBJ ADCHGE/TEST1, TAPE/A5

One data card giving the time of the change(s) in demand must be filled out for each data set. The format of this card is:

Cols. 1 - 6	ADCHG1
Cols. 28 - 37	Time of long term change in link demand (T_n) expressed in minutes from time zero of the simulation.

A data card for every link whose demand changes at T_n must be filled out as described below. Cards must be grouped and placed in ascending order by lower number ground station. Within each group the cards should be in ascending order on higher numbered ground station.

Cols. 1 - 6	ADCHG2
Cols. 8 - 10	Index number.
Cols. 12 - 13	Lower ground station number for this link.
Cols. 14 - 15	Higher ground station number for this link.
Cols. 17 - 20	New peak demand (channels) over this link.

OBJECT APRIOR. The data input to this object comprises a list of all existing links in the system in priority order (highest priority first). The beginning time at which priorities change and the time of the next change must be specified as well. For every change in priority a complete data set must be specified. The data sets themselves are ordered on time of change. This object is an optional input in any run. If it is not to be input the parmeter AKEY should be set to 1 to cause internal generation of the priorities. Priority can be described for the maximum number of links, 435. The INPOBJ control card for this object has the following format:

INPOBJ APRIOR/TEST1, TAPE/A5

One data card giving priority change times must be filled out for each data set.

This card has the following format:

Cols. 1 - 3	<u>AP1</u>
Cols. 5 - 14	The beginning time at which priorities change expressed in minutes from time zero of the simulation.
Cols. 16 - 25	Time of next change in priorities expressed as minutes from time zero of the simulation.

A data card must be filled out in the manner described below for ever existing link in the network. These cards must be ordered on priority (highest priority first).

Cols. 1 - 6	<u>APRIOR</u>
Cols. 8 - 10	Index number.
Cols. 12 - 13	Lower ground station number for this link.
Cols. 14 - 15	Higher ground station number for this link.

OBJECT QLKPRT. The data input to this object specified particular links for which the experimenter will want minute-by-minute data output for analysis. A maximum of twenty such links may be specified. This input is optional and if this data is not input the parameter QFLAG may be used to print out the first n links simulated. The INPOBJ control card for this object has the following format:

<u>INPOBJ</u> <u>QLKPRT/QVRGNM, TAPE/A5</u>

A data card for every link for which minute-by-minute output is desired must be filled out as described below. Cards must be grouped and placed in ascending order by lower numbered ground station. Within each group the cards should be in ascending order by higher numbered ground station.

Cols. 1 - 6	<u>QXINDX</u>
Cols. 8 - 10	Index number.

Cols. 12 - 13	Lower numbered ground station of the link.
Cols. 15 - 16	Higher numbered ground station of the link.

OBJECT QCSTBL. The data input to this object supplies information on channel usage, revenue and distribution of revenue data for each existing link in the network. Information for up to 435 links may be input. The INPOBJ control card for this object has the following format (manipulation to reflect revenue per channel per minute probably required):

<u>INPOBJ</u> <u>QCSTBL/QVRGNL, TAPE/A5</u>

A data card for every existing link in the network must be filled out as described below. Cards must be grouped and placed in ascending order by lower numbered ground station. Within each group the cards must be in ascending order of higher numbered ground station.

Cols. 1 - 6	<u>QJINDX</u>
Cols. 8 - 10	Index number
Cols. 17 - 18	Percent of revenue to lower numbered ground station in this link.
Cols. 20 - 21	Percent of revenue to higher numbered ground station in this link.
Cols. 23 - 24	Percent of revenue to the Satellite Corporation.
Cols. 26 - 29	Average revenue per channel per minute expressed in cents and accurate to the nearest ten cents.
Cols. 31 - 32	Lower ground station number for the link.
Cols. 34 - 35	Higher ground station number for the link.
Cols. 36 - 43	Initial operating date of link expressed in minutes from time zero of the simulation.

OBJECT STCOST. The data input to this object gives cost information for each type of ground station. A maximum of ten different types of ground stations may be considered. The INPOBJ control card for this object has the following format:

INPOBJ	STCOST/SYSABC, TAPE/A5

A data card for each ground station must be filled out in the follow manner.

Cols. 1 - 2	SC
Cols. 4 - 5	The ground station type indicator. (An integer that should correspond to the integer input in cols. 33 - 34 of the data card for object GNDSTA for the same ground station type.)
Cols. 10 - 13	Initial investment required to build this type of ground station expressed in thousands of dollars.
Cols. 14 - 17	Annual operating cost for this type of ground station expressed in thousands of dollars.
Cols. 20 - 24	Annual depreciation for this type of ground station expressed in thousands of dollars.
Cols. 71 - 72	Index number.

PARAMETERS. Parameter cards input for a run all have the following format:

Cols. 1 and following	Parameter name.
Cols. 16 and following	Input value for the parameter.

Parameter Name	Value Input
AKEY	0 if link priorities (object APRIOR) are input to the simulation manually. 1 to cause internal generation of priorities based upon demand.

CRVnV(n = Ø, 1, . . . 9)	Version name used on the INPOBJ control card if object CRVn has been input, otherwise the card is not input.
DALISV	Version name used in the INPOBJ control card if object DALIST has been input, otherwise the card is not input.
DBOLSV	Version name used on the INPOBJ control card if object DBOLST has been input, otherwise the card is not input.
DLOLSV	Version name used on the INPOBJ control card if object DLOLST has been input, otherwise the card is not input.
DTLISV	Version name used on the INPOBJ control card if object DTLIST has been input, otherwise the card is not input.
QFLAG	0 if the experimenter wants no minute-by-minute output or he has specified all desired minute-by-minute output in the object QLKPRT. n where n = 1, 2, . . . 435: if minute-by-minute output is desired for the first n links simulated. The value of this parameter may be changed for any "time slice" (see discussion under deck structure).
QF1	An integer representing customer impatience. It is the percent of customers who remain as a backlog waiting to place a call from one minute to the next. The patience (or impatience) function is of the negative exponential form with an average willingness to wait of time 100/(100 -QF1).

QF2

An integer used to generate a population of telephone messages with length negatively exponentially distributed and an average length of 100/(100 - QF2). Thus the value 60 generates a population with an average call length of 2.5 minutes. We input the value QF2 equal to 80 which will generate an average call length of five minutes, although the value 82 necessary to achieve a theoretical 5.5 minutes may be input if desired.1/

RNDNUM

An integer less than $2^{35} - 1$. The starting random number. May be held constant or varied from run-to-run depending upon the desired experimental design. May significantly influence results.

SABORV

Version name used on the INPOBJ control card for the object SABORT.

SCAS

An integer that represents the annual administrative and operating cost of the Satellite Corporation in thousands of dollars. Since the Satellite Corporation is expected to have a bigger job in later years, it is quite reasonable to allow SCAS to increase during the run. The value of SCAS may be changed for any "time slice" (see discussion under deck structure).

SCD

An integer that represents the initial research and development cost in thousands of dollars expended by the Satellite Corporation in developing a functioning system. Because this variable is subject to some interpretation, we have set this value equal to zero for the experimental runs.

1/ 5.5 minutes has been suggested as the expected international call length.

SCYCLV	Version name used on the INPOBJ control card for the object SCYCLE.
SDELAV	Version name used on the INPOBJ control card for the object SDELAY.
SETUPV	Version name used on the INPOBJ control card for the object SETUP.
SFAILV	Version name used on the INPOBJ control card for the object SFAIL.
SINTER	An integer representing the interest rate to be used for the run.
SINTVV	Version name used on the INPOBJ control card for the object SINTVL.
SLNCIV	Version name used on the INPOBJ control card for the object SLNCH.
SPMOUT	0, supplementary coverages measures will not be output. 1, supplementary coverage measure will be output. This parameter may be changed for any or all "time slices" (see discussion under deck structure).

DECK STRUCTURE

Some definitions are in order before an attempt is made to describe the deck structure for the running of the simulation.

An input data set will consist of the INPOBJ control card for the object in question immediately followed by all data cards for this version of the object and terminated by a blank card.

An output data set will consist of four cards. The first card will always have the following format:

Col. 1 - 6	EXCPRC
Col. 12 - 17	QREWA6

The second card must be a blank card, the third card must be the OUTOBJ control card for the object in question and the fourth card must be another blank card.

A "time slice" set consists of parameter cards for each parameter whose value the experimenter desires to change starting at this "time slice" followed by a blank card. If no parameters are to be changed the "time slice" set consists of a blank card. The parameters SPMOUT, SCAS and QFLAG may be changed in any "time slice" set. The "time slice" set for the initial "time slice" must contain the three aforementioned parameter cards in addition to parameter cards for the parameters AKEY, QF1, QF2, RNDNUM, SCD and SINTER.

The deck must be structured in the following manner.

MFTPPR	7
TESTMF	GNDLOC

Blank Card

Input data sets

Input data sets are always required for the following objects.

AGSTAT	QCSTBL	SETUP
ALDA	SABORT	SFAIL
ANTNNA	SACOST	SINTVL
CRVØ	SCYCLE	SLNCH
GNDSTA	SDELAY	STCOST

Input data sets are input for the following objects under the conditions described in the individual object write-ups.

ADCHGE	CRV5	DALIST
APRIOR	CRV6	DBOLST

CRV1	CRV7	DLOLST
CRV2	CRV8	DTLIST
CRV3	CRV9	QLKPRT
CRV4		

The order of the input data sets is optional except in cases where more than one data set is input for an object. The ordering for these data sets is described in the individual object write-ups.

<u>EXCPRC</u> <u>LAUNCH</u>

Parameter Cards

The parameter cards that are always required at this point are:

CRVØV	SCYCLV	SFAILV
RNDNUM	SDELAV	SINTVV
SABORV	SETUPV	SLNCIV

Parameter cards are input at this point for the following parameters under the conditions described in the individual parameter write-ups.

CRV1V	CRV5V	CRV9V
CRV2V	CRV6V	DALISV
CRV3V	CRV7V	DBOLSV
CRV4V	CRV8V	DTLISV

There is no required ordering of the parameter cards.

<u>EXCPRC</u> <u>LOCA</u>

"Time slice" sets

There must be the same number of <u>"time slice" sets</u>

as the number of "time slices" specified in the object SCYCLE.

The parameter cards that are required for the first "time slice" set are the following:

AKEY	QF2	SCD
QFLAG	RNDNUM	SINTER
QF1	SCAS	SPMOUT

For each "time slice" after the first none of the parameters are required, however any or all of the following parameters may be input in each "time slice" set:

QFLAG	SCAS	SPMOUT

There is no required ordering of the parameter cards.

Output data sets — No required ordering. See note below.

FINISH

Note: The OUTOBJ control cards necessary to make up the package of output data sets are listed below:

OUTOBJ	QAAMIN/QVRGNA, TPFILE/A6, REHEAD
OUTOBJ	SATSPM/GOROUN, TPFILE/A6, REHEAD, EXCEPT/NUMVIS
OUTOBJ	QBBDF1/QVRGNB, TPFILE/A6, REHEAD
OUTOBJ	QCCDF2/QVRGNC, TPFILE/A6, REHEAD
OUTOBJ	QDDDF3/QVRGND, TPFILE/A6, REHEAD
OUTOBJ	QFFBAR/QVRGNF, TPFILE/A6, REHEAD
OUTOBJ	SCINFO/, TPFILE/A6, REHEAD
OUTOBJ	SOINFO/, TPFILE/A6, REHEAD