FINAL REPORT
INFORMATION TRANSFER SATELLITE
CONCEPT STUDY

VOLUME IV • COMPUTER MANUAL

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ADVANCED SPACE SYSTEMS
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FOREWORD

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INTRODUCTION

The Satellite Telecommunications Analysis and Modeling Program (STAMP), developed by Convair, under contract to NASA/Ames provides the user with a flexible and comprehensive tool for the analysis of ITS system requirements. While obtaining minimum cost design points, the program enables the user to perform studies over a wide range of user requirements and parametric demands. The program utilizes a total system approach wherein the ground uplink and downlink, the spacecraft, and the launch vehicle are simultaneously synthesized. A steepest descent algorithm is employed to determine the minimum total system cost design subject to the fixed user requirements and imposed constraints. In the process of converging to the solution, the pertinent subsystem tradeoffs are resolved.

STAMP provides the system designer with the capability to consider a wide variety of communication systems. By appropriate specification of the pertinent input variables, the program can be made to cycle through the various types of subsystem elements and user requirements to be considered. Minimum cost solutions obtained can be compared to determine desired configurations.

STAMP can handle data in any one or combination of four different data types: audio, video, facsimile, and digital data. The program design is such that computations are performed on a per beam basis eliminating the need for assuming a nominal area of coverage and uniform ground system for the case of multiple beams. Each beam may individually handle any of the four previously mentioned data types. The logic also includes a variety of receive and transmit capability options for the ground stations.

The program can be used as a tool in performing required sensitivity analyses. For example, it can be employed to determine the effected change in the total system cost resulting from a perturbation of any of the design parameters, the sizing constraints, and/or the subsystem parameter relationships, as well as the key user requirements such as S/N, frequency, and area of coverage.

This report documents STAMP. Section 2 provides a technical analysis and a description of the principal techniques employed in the program.
2.1 PROGRAM DESCRIPTION

The ITS synthesis program is essentially structured into five major portions: the driver program, the spacecraft system submodels, the uplink and downlink ground system models, the steepest descent iterative process, and other required models such as the signal propagation and sizing models (see Figure 2-1).

In its present form it can handle a list of up to 78 constrained parameters including spacecraft weight, spacecraft volume, spacecraft prime power supply, and transmitter power out/channel at the spacecraft and at the ground uplink facilities. The independent design parameters are chosen from the set of ground antenna gains (diameters) and receiver noise temperatures (noise figures).

The synthesis program is completely modularized in the sense that the various models have been written as separate subroutines and may be modified or interchanged with a minimum amount of effort. The program essentially consists of 35 fixed purpose subroutines representing the various models required to synthesize a communications system. Figure 2-2 illustrates the subroutine breakdown and their main functions. Briefly, the ITS Driver program controls overall execution and essentially performs all of the needed initialization. Subroutine EQUAT maintains control over the computation of the dependent parameter values. This subroutine controls computation of the required transmitter powers and the costs, weight, and volume terms for the various subsystems in addition to sizing the power subsystem in the spacecraft. It computes the cost of the selected launch vehicle and computes total system cost. Subroutine SPCRFT contains the actual logic for the sizing and costing of the various spacecraft submodels. As illustrated, each of the various submodels is represented as a separate subroutine. Also included is a user's diagnostic routine (DIAGN) to provide specific diagnostic messages during execution. These do not include the required general purpose subroutines which are listed in Appendix B.

The general logic flow of the program operation is given in Figure 2-3. Beginning with an initial design point and fixed user requirements, the program first computes
Figure 2-1. Synthesis program block diagram.
ITS DRIVER PROGRAM — CONTROLS OVERALL EXECUTION

INPTX CONTROLS INPUT
AOC ORBIT/OVERAGE MODEL
DIAM COMPUTES SPCRFT ANT SIZE
PARBDS SIZING MODEL
ATTEN SIG. PROP/NOISE MODEL
XBD CHECKS $\bar{X}$ AGAINST BDS
EQUAT COMPUTES $\bar{Y}(\bar{X})$
BNDV CHECKS $\bar{Y}$ FOR BD VIOLATION
OPTMUM (MAXBD) MIN. COST CONVERGENCE ROUTINE
CHANEL COMPUTES CHANNEL REQUIREMENT
CNVRGE CONVERGENCE TEST
OUTPT1, OUTPT2 CONTROLS OUTPUT

EQUAT— COMPUTES $\bar{Y}$

GRDFAC UPLINK/DOWNLINK MODEL FOR CLASS I/II
GDIRCT DIRECT RCVR GRD DWNLNK MODEL
DGDEP ITER SCHEME ON GRD ANT GAIN AND DIAM
DISCR COMPUTES GRD ANTENNA DISCRIMINATION
PXTR COMPUTES REQ'D XMTR POWER/CHANNEL
SPCRFT SPCRFT MODEL
LNCHV LAUNCH VEHICLE
TCOST TOTAL SYSTEM COST

SPCRFT (SPACECRAFT SUBMODELS)

ANTS ANTENNA STNKP ST. KEEPING
ATTCN ATTITUDE CONTROL STRUC STRUCTURE
MANPRV MANNED PROVISIONS THRML THERMAL CONTROL
MTPLXS MULTIPLEXER TLMCMD TELEMETRY & COMMAND
POWER POWER XMTR
RCVRS RECEIVERS (PLACE) SPCRFT TRANSMITTER

MISCELLANEOUS

DIAGN DIAGNOSTIC ROUTINE EXPL
QUAD PARAMETRIC EQ'S.
PFUNC

Figure 2-2. ITS synthesis program subroutine structure.
the required spacecraft antenna size based on the desired frequency and area of coverage. It proceeds to cost the ground systems and to compute the required power out/channel via the link equations. The satellite system is sized and its cost computed. Following this the total system cost is determined. Parameters are checked for boundary violations and the required partial derivatives are found. The optimum design parameter perturbation is computed, and, if convergence has not yet been achieved, the process is repeated with the newly perturbed design point until convergence is achieved. If more cases are to be considered, the program repeats the entire process. The program was designed, tested, and debugged using the CDC 6400 computing facility at Convair Aerospace and eventually modified for use on NASA/Ames IBM 360 system. The IBM version may incorporate the overlay feature to conserve required core space. This overlay is described in Appendix C. Average core requirement on the CDC system is $76000_8$ words including the routines required by the operating system. The IBM 360 version with overlay and use of double precision requires approximately 160 kilobytes of storage. The double precision is necessary because of the shortened word length on the IBM machine, 32 bits/word as opposed to 60 bits/word, and the sensitivity of parts of the system to small perturbations.

$76000_8 = 31744_{10}$
2.2 MATHEMATICAL DESIGN OPTIMIZATION TECHNIQUE

The Convair Aerospace ITS system design optimization program uses a steepest descent iterative process, which is a modified gradient technique, to determine the minimum cost design point for a given system configuration. At each iteration the nominal design point is perturbed in such a way as to cause the maximum rate of decrease in total system cost to be consistent with the design constraints.

The philosophy of the technique is that the direction of steepest descent is given as the direction of the negative cost gradient. When a physical constraint (e.g., satellite weight) is encountered, the new direction is given by the component of the negative cost gradient tangent to the constraint surface. Referring to Figure 2-4, the lowest point D in the valley represents the minimum cost design point; the cost contours represent the increase in cost as the system design deviates from the optimum. The constraint boundary represents a "fence" or physical constraint which prohibits attainment of the specified goal. The process begins at Point A and proceeds iteratively from one contour to the next to Point B, the first encounter with the constraint. It then proceeds along the boundary (in the direction of steepest descent) until it finds the lowest Point C. This represents the lowest achievable point consistent with the imposed constraint.

![Diagram of steepest-descent iterative process](image)

Figure 2-4. Steepest-descent iterative process.
If $\Delta y_j$ is the amount by which the $j$th boundary is violated and $g$ represents the gradient of total system cost, then the perturbation in $\bar{X}$, the vector of independent design parameters, is given by

$$
\bar{X} = -K_c \left[ I - \phi (\phi^T \phi)^{-1} \phi^T \right] g - K_y \phi (\phi^T \phi)^{-1} \Delta y_j
$$

where $\phi$ is the gradient of the constraint relationship. The derivation of this equation is given in Appendix A.

If $K_y$ is set equal to unity, the second term represents, to first order terms, the amount by which $\bar{X}$ must be changed to reduce $\Delta y_j$ to zero. If $K_y$ is less than one, the boundary violation is partially reduced. The first term represents the component of the cost gradient parallel to the constraint boundary and is orthogonal to the second term. For small $\Delta x_1$ (so that the linear approximation is valid), the first term reduces the cost and contributes nothing directly to the boundary violation. If no boundaries are violated, then $\Delta y_j$ and $\phi$ are zero, so that the equation reduces to

$$
\Delta x = -K_c g
$$

which represents a perturbation in the direction of the negative of the cost gradient.

Since $K_c$ is arbitrary, some control over the step-size must be introduced. The principle used in determining the magnitude of the step is that if successive steps have been in the same direction it is desirable to increase the step-size in order to speed up the convergence process. On the other hand, if successive steps have been in opposite directions, it is desirable to decrease the step-size since the optimum design point has been overshot. Furthermore, it appears that larger step-sizes are most desirable in the early iterations to hasten arrival to the vicinity of the optimum design point. Once in the vicinity of the optimum, smaller steps would prove more practical. To afford faster convergence, the step size $S$ is replaced with a vector of dimension $N$. This enables the optimization scheme to scale each component relative to its ability to converge. The modification of the scale factor is based on the following criteria. Let $\Delta X_1$ and $\Delta X_2$ be the two previous perturbations and $\bar{X}$ be the present.

Furthermore, let $C_1 = \Delta X_1 \cdot \Delta X$ and $C_2 = \Delta X_2 \cdot \Delta X$ where the indicated products are vector dot products. Then

- $\text{SCALE} = .5 \times \text{SCALE}$ if $C_1 < 0$,
- $\text{SCALE} = 2 \times \text{SCALE}$ if $C_1, C_2 > 0$,
- $\text{SCALE} = 32$ if $\text{SCALE} > 32$, and
- $\text{SCALE} = .5 \times \text{SCALE}$ if $i \geq 30$ and $\text{SCALE} > 1$ where $i$ = iteration index.
With the step-size, $S_i$, thus specified, the appropriate value of $K_c$ can be determined from

$$K_c = \sqrt{S_i^2 - K_y^2 \cdot \Delta y_j^T (\phi^T \phi)^{-1} \Delta y_j}$$

in the event of a boundary violation. If the solution is unconstrained $K_c$ is determined from

$$K_c = \frac{S_i}{|g|}$$

These are the equations used by the ITS convergence routine. It is important to keep $S_i$ from growing to a point at which a large number of iterations would be required to bring it down. Therefore the upper bound is placed on $S_i$.

The rate of convergence to the minimum cost design point is dependent upon the relative sensitivities of the cost to each of the design parameters. Since the algorithm operates on the most sensitive parameters, convergence to the optimum value of the less sensitive parameters can be slow. For this reason it is often desirable to rescale the units of the design parameters to equalize these sensitivities.

An example of how the process actually converges, consider Figure 2-5 which illustrates a particular case using this technique. In this example, a volume constraint of 170 cubic feet has been imposed on the volume of the solar array. Since the initial design point violates the constraint, several iterations are required to return this quantity to the specified boundary. The process then proceeds along the boundary until the minimum cost solution is achieved. Also illustrated is the interaction of the ground downlink antenna size and the ground downlink receiver noise temperature during the convergence process. The minimum at iteration three actually represents the unconstrained minimum cost design point. The ITS synthesis program is designed to provide a brief summary output at each iteration, so that the user is made aware of such occurrences.

2.3 PARAMETRIC SUBSYSTEM MODELS

The ITS subsystem models include the pertinent elements required to obtain a complete synthesis of the total system. The cost, weight, and volume parametric relationships and fitted curves may be found in the Appendix section of Volume 3.

In general, the curves were fit with one of three types of equations. The forms of these equations is given as one of the following:
Figure 2-5. Illustration of convergence process.
\( y = \frac{10^g(z)}{10} \)

where \( g(z) = a + bz + cz^2 \), \( z = 10 \log P \), and \( P \) represents the value of the parameter determining \( y \),

(2) \( y = a + bx^c \), and

(3) \( y = a + bx + cx^2 \).

Other relations are indicated by either linear or exponential fits or are given as thruput values.

The curves used during this study are applicable over a wide range of parametric values. Where it was impossible to obtain an accurate fit with a single equation, the curve was fit in more than one piece. The breakpoint, in most cases, is variable and is included in the input lists.

The system synthesis incorporates a loss model for both the uplink and downlink portions of the beam, a noise model, and scale factors to account for redundancy in the spacecraft. It contains an orbit and area of coverage model which computes the required beamwidths and a separate model to compute the channel characteristics. Also included is a satellite power subsystem model.

The loss and noise model is discussed in Section 2.6; the area of coverage model in Section 2.5, and the communication links in Section 2.9. A discussion of the redundancy scale factors is in Section 2.8. The cost elements are in Section 2.4. The choice of parameters for the dependent and independent design vectors is discussed in Section 2.10, while the power subsystem model is found in Section 2.7.

2.4 COST MODEL

The ITS cost model summarized in Figure 2-6 illustrates the breakdown per cost element. The model computes the acquisition, non-recurring (development), operation, and maintenance cost to form the total cost.

Table 2-1 is a tabulation of the cost model as implemented in the computer program. The associated array name as used in the program is given together with a descriptive title and whether it is computed from an input curve or is input as a thruput value. It should be noted that each of the individual cost items is dimensioned by the number of beams. The cost-estimating relationships are given in the Appendix section of Volume 3.

In referencing the table, note that the following definitions are provided:
### SATELLITE MODEL:

#### UNIT RECURRING COST
- Subsystem Unit Hardware
  - Structure
  - Electrical Power & Batteries
  - Stabilization & Control
  - Reaction Control
  - Environmental Control
  - Life Support (manned systems only)
  - TT&C/Instrumentation
  - Uplink Antenna, Receiver & Repeater
  - Transmitter
  - Transmitting Antenna & Feed
  - Integration, Assembly & Checkout

#### NONRECURRING COST
- Subsystem Design Development and Test
  - Structure
  - Electrical Power & Batteries
  - Stabilization & Control
  - Reaction Control
  - Environmental Control
  - Life Support
  - TT&C/Instrumentation
  - Uplink Antenna, Receiver & Repeater
  - Transmitter
  - Transmitting Antenna
  - Engineering Test Model or Prototype Hardware
  - System Level Design, Integration, Test & Management
  - NASA Center Support
  - GSE Design Development & Test
  - GSE Hardware
  - Facilities & STE

#### ACQUISITION COST
- Unit Recurring Hardware Cost
- NASA Center Support/Unit
- Launch Operations/Support/Spares

#### OPERATIONS COST
- Replacement Spacecraft Hardware Cost

---

**Figure 2-6.** Cost model for each element.
### Table 2-1. Cost Model

#### I. GROUND UPLINK/DOWNLINK — CLASS I (CLASS II)

**A. Acquisition Cost**

<table>
<thead>
<tr>
<th></th>
<th>Facilities</th>
<th>Terminal equipment (audio)</th>
<th>Terminal equipment (video)</th>
<th>Terminal equipment (facsimile)</th>
<th>Terminal equipment (digital data)</th>
<th>Transmitter (audio)</th>
<th>Transmitter (video)</th>
<th>Transmitter (facsimile)</th>
<th>Transmitter (digital data)</th>
<th>Antenna</th>
<th>Receiver</th>
<th>Standby power</th>
<th>Test equipment</th>
<th>Total acquisition cost — Class I (Class II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Facilities</td>
<td>ACQCl</td>
<td>(ACQC2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TACQC1 (TACQC2) (1, 1) thru TACQC1 (13, 1)</td>
</tr>
</tbody>
</table>

**B. Operations Cost (per year)**

<table>
<thead>
<tr>
<th></th>
<th>Terminal equipment (audio)</th>
<th>Terminal equipment (video)</th>
<th>Terminal equipment (facsimile)</th>
<th>Terminal equipment (digital data)</th>
<th>Transmitter (audio)</th>
<th>Transmitter (video)</th>
<th>Transmitter (facsimile)</th>
<th>Transmitter (digital data)</th>
<th>Receiver</th>
<th>Personnel</th>
<th>Total operation cost — Class I (Class II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OPC1</td>
<td>(OPC2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N_{L} \times \Sigma OPC1 (1, 1) thru OPC1 (10, 1)</td>
</tr>
</tbody>
</table>

\[ \Sigma ACQC1 (1, 1) \text{ thru } ACQC1 (13, 1) \]
### C. Installation Cost

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost Component</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal equipment (audio)</td>
<td>CINST1</td>
<td>$N_6 % \times \text{ACQC1} (2, I)$</td>
</tr>
<tr>
<td>Terminal equipment (video)</td>
<td>CINST1</td>
<td>$N_7 % \times \text{ACQC1} (3, I)$</td>
</tr>
<tr>
<td>Terminal equipment (facsimile)</td>
<td>CINST1</td>
<td>$N_8 % \times \text{ACQC1} (4, I)$</td>
</tr>
<tr>
<td>Terminal equipment (digital data)</td>
<td>CINST1</td>
<td>$N_9 % \times \text{ACQC1} (5, I)$</td>
</tr>
<tr>
<td>Transmitter</td>
<td>(audio)</td>
<td>$N_{10} % \times \text{ACQC1} (6, I)$</td>
</tr>
<tr>
<td>Transmitter</td>
<td>(video)</td>
<td>$N_{11} % \times \text{ACQC1} (7, I)$</td>
</tr>
<tr>
<td>Transmitter</td>
<td>(facsimile)</td>
<td>$N_{12} % \times \text{ACQC1} (8, I)$</td>
</tr>
<tr>
<td>Transmitter</td>
<td>(digital data)</td>
<td>$N_{13} % \times \text{ACQC1} (9, I)$</td>
</tr>
<tr>
<td>Antenna</td>
<td></td>
<td>$N_{14} % \times \text{ACQC1} (11, I)$</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
<td>$N_{15} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Standby power</td>
<td></td>
<td>$N_{16} % \times \sum \text{ACQC1} (2, I)$</td>
</tr>
<tr>
<td>Design, integration, &amp; Mgmt</td>
<td></td>
<td>thru ACQC1 (11, I)</td>
</tr>
</tbody>
</table>

| Total installation cost                    | TINC1          | $\sum \text{CINST1} (1, I)$ thru CINST1 (12, I) |

### D. Maintenance Cost (per year)

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost Component</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility</td>
<td>CMNT1</td>
<td>$M_1 % \times \text{ACQC1} (1, I)$</td>
</tr>
<tr>
<td>Terminal equipment (audio)</td>
<td>CMNT1</td>
<td>$M_2 % \times \text{ACQC1} (2, I)$</td>
</tr>
<tr>
<td>Terminal equipment (video)</td>
<td>CMNT1</td>
<td>$M_3 % \times \text{ACQC1} (3, I)$</td>
</tr>
<tr>
<td>Terminal equipment (facsimile)</td>
<td>CMNT1</td>
<td>$M_4 % \times \text{ACQC1} (4, I)$</td>
</tr>
<tr>
<td>Terminal equipment (digital data)</td>
<td>CMNT1</td>
<td>$M_5 % \times \text{ACQC1} (5, I)$</td>
</tr>
<tr>
<td>Transmitter</td>
<td>(audio)</td>
<td>$M_{12} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Transmitter</td>
<td>(video)</td>
<td>$M_{13} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Transmitter</td>
<td>(facsimile)</td>
<td>$M_{14} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Transmitter</td>
<td>(digital data)</td>
<td>$M_{15} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Antenna</td>
<td></td>
<td>$M_{16} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
<td>$M_{17} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Standby power</td>
<td></td>
<td>$M_{18} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Design, integration, &amp; Mgmt</td>
<td></td>
<td>$M_{19} % \times \text{ACQC1} (12, I)$</td>
</tr>
<tr>
<td>Total maintenance cost</td>
<td>TMNTC1</td>
<td>$N_L \times \sum \text{CMNT1} (1, I)$ thru CMNT1 (12, I)</td>
</tr>
</tbody>
</table>
Table 2-1. Cost Model (continued)

II. GROUND DOWNLINK — DIRECT

A. Unit Recurring

1. Antenna
2. Receiver (Beam 1)
3. (Beam 2)
4.
5.
6.
7. Receiver (Beam 6)

B. Acquisition Cost

1. Antenna
2. Receiver
3. Total acquisition cost - direct

C. Installation Cost

1. Antenna
2. Receiver
3. Total installation cost - direct

D. Maintenance Cost (per year)

1. Antenna
2. Receiver
3. Total maintenance cost - direct

\[
\text{TACQC3} = \text{ACQC3}(1, I) + \text{ACQC3}(2, I)
\]

\[
\text{TACQC3} = \text{CINST3}(1, I) + 0.5 \times \text{ACQC3}(2, I)
\]

\[
\text{TMNTC3} = N_L \times [(1) + (2)]
\]
Table 2-1. Cost Model (continued)

III. SPACECRAFT SYSTEM

A. Acquisition Cost

1. Prime power
2. Secondary power (batteries)
3. Power conditioning
4. Power distribution
5. Antenna
6. Transmitter
7. Multiplexer
8. Receiver
9. Structure
10. Thermal control
11. Stationkeeping
12. Attitude control
13. Telemetry and command
14. Manned provisions (life-support subsystem)
15. Integration, assembly, & checkout
16. Center support

ACQC4(1) Curve

18. Total spacecraft acquisition

TACQC4 N_s \times N_{L} / N_{LS} \times \\
\Sigma(1) \text{ thru (15)}

B. Research and Development

1. Prime power
2. Secondary power (batteries)
3. Power conditioning
4. Power distribution
5. Antenna
6. Transmitter
7. Multiplexer
8. Receiver
9. Structure
10. Thermal control
11. Stationkeeping
12. Attitude control
13. Telemetry and command
14. Manned provision (life support subsystem)

RDC4(1) Curve

15. Integration, assembly, & checkout

7.5\% \times \Sigma(1) \text{ thru (14)}

16. Center support

15\% \times \Sigma(1) \text{ thru (15)}
B. Research and Development (continued)

15. Prototype
   $\text{RDC4(15) } \Sigma \text{ACQC4(2) thru (14)}$
   $+ 15\% \times \text{ACQC3(1)}$

16. Design, integration, and management
   $\text{RDC4(16) } 50\% \times \Sigma \text{ (1 thru (14)}}$

17. Center support and development
   $\text{RDC4(17) } 5\% \times \left[ \Sigma \text{ (1 thru (14)} + \text{(16)} \right]$

18. Ground support equipment
   $\text{RDC4(18) } 50\% \times \Sigma \text{ACQC4(1) thru (14)}$

19. Total spacecraft R/D
   $\text{TRDC4 } \Sigma \text{(1 thru (18)}}$

IV. LAUNCH VEHICLE

A. Acquisition Cost

   Unit Acquisition
   $\text{N}_S/\text{N}_{SL} \times \text{N}_L/\text{N}_{LS} \times \text{ACQC5}$

   Total Acquisition

B. Research and Development

   R/D Cost
   $\text{Thruput}$

   Total R/D Cost
   $\text{RDC5}$
The thruput cost values indicated for the launch vehicle are calculated external to the program and include the following items:

Non-recurring:
1) Launch vehicle development,
2) Fairings and adapters, and
3) Mission integration.

Unit-recurring:
1) Launch vehicle,
2) Fairings and adapters,
3) Launch services, and
4) Spares.

2.5 ORBIT AND COVERAGE MODEL

The model computes the slant range and elevation angle to the satellite and the off-axis location loss for a nominal ground station. These parameters are used in the propagation and noise models.

To yield better results, the approach during the study has been to make use of a separate model, external to the program, prior to running a particular case. This program (see Figure 2-7) accepts the position of the satellite, the coordinates of the antenna beam center, the azimuth angle of the antenna, the antenna orthogonal beamwidths, and the relative angular positions of the desired radiation levels (e.g., half-power, first sidelobe). Up to ten levels may be handled by the program. The program then computes the contours on the surface of the earth and plots on the SC-4200 plotter together with a mercator projection of the earth as in Figure 2-8. These contours are useful in determining the effectiveness of the coverage and in computing the flux density levels due to transmission. The model in the synthesis program accepts the same parameters to compute the elevation angle, major and minor axes, and location losses for each beam.
Figure 2-7. Orbit and coverage model.

Figure 2-8. Continental United States coverage.
This section presents the various attenuation and noise factors which affect the propagation between the ground uplink station, the satellite, and the ground receiving station and which are incorporated into the program. Associated curves are in the Appendix section of Volume 3.

The basic model is shown in Figure 2-9. Given the elevation angles and the slant ranges for each satellite antenna beam, the attenuation due to clouds, rain, water vapor and oxygen, and the ionosphere as well as circuit losses are determined. Additionally, the noise contributions due to these elements are calculated. Table 2-2 itemizes the terms and equations used in this model. The effective noise seen by the receiver is given by

\[ T_G = T_{ANT} + T_T + T_R \]

where

\[ T_{ANT} = L_{TL} \left( T_{COS} + T_I + T_A + T_C + T_{RN} \right) G_S \]

\[ + T_M G_M + T_E G_E \]

\[ G_S, G_M, G_E \] are relative antenna gains over the three regions — sky, man-made noise, and earth.

The computation of the intermodulation noise for multicarrier operations is also made in this model. The relationship between carrier-to-intermodulation noise \((C/M)\) and transponder backoff for various numbers of carriers is shown in Figure 2-10. For a given \((C/M)\), or determined from the \((C/N)\), the required transponder backoff is computed as a function of the number of carriers.

2.7 POWER AND SPACECRAFT SIZING SUBMODEL

The power subsystem model is depicted in Figure 2-11. The model incorporates the various information types — audio, video, facsimile, and digital data as shown in the figure. Once the transmitter powers required to fulfill the links are determined, the power requirements are traced back to the prime power source considering the efficiency of each element in the system.

The model will allow any number of channels of each type to operate at any duty cycle, and will size the power source and batteries for operation during both the sunlit and eclipse portions of the orbit. Each transmitter and receiver will operate
Figure 2-9. Synthesis program noise and propagation.

Figure 2-10. Transmitter backoff for multi-carrier operation.
Table 2-2. Terms and equations of propagation and noise model.

<table>
<thead>
<tr>
<th>REGION</th>
<th>ATTENUATION</th>
<th>ABSORPTION</th>
<th>AMBIENT TEMPERATURE</th>
<th>EFFECTIVE TEMPERATURE AT RECEIVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSMOS</td>
<td>--</td>
<td>--</td>
<td>T_{COSMIC}</td>
<td>T_{COS} = L_{COS} T_{COSMIC}</td>
</tr>
<tr>
<td>IONOSPHERE</td>
<td>L_{I}</td>
<td>1 - L_{I}</td>
<td>T_{ION}</td>
<td>T_{I} = L_{COS} L_{R} (1 - L_{I}) T_{ION}</td>
</tr>
<tr>
<td>ATMOSPHERE</td>
<td>L_{A}</td>
<td>1 - L_{A}</td>
<td>T_{ATM}</td>
<td>T_{A} = L_{COS} L_{R} (1 - L_{A}) T_{ATM}</td>
</tr>
<tr>
<td>CLOUDS</td>
<td>L_{C}</td>
<td>1 - L_{C}</td>
<td>T_{CLOUD}</td>
<td>T_{C} = L_{R} (1 - L_{C}) T_{CLOUD}</td>
</tr>
<tr>
<td>RAIN-TO SATELLITE</td>
<td>L_{R}</td>
<td>1 - L_{R}</td>
<td>T_{RAIN}</td>
<td>T_{RN} = (1 - L_{R}) T_{RAIN}</td>
</tr>
<tr>
<td>HORIZONTAL PATH</td>
<td>L_{RH}</td>
<td>1 - L_{RH}</td>
<td>T_{RAIN}</td>
<td>T_{RH} = T_{RAIN}</td>
</tr>
<tr>
<td>ENVIRONMENTAL</td>
<td>--</td>
<td>--</td>
<td>T_{MAN}</td>
<td>T_{M} = L_{RN} T_{MAN}</td>
</tr>
<tr>
<td>EARTH</td>
<td>--</td>
<td>--</td>
<td>T_{EARTH}</td>
<td>T_{E} = T_{EARTH}</td>
</tr>
<tr>
<td>TRANSMISSION LINE</td>
<td>L_{TL}</td>
<td>1 - L_{TL}</td>
<td>T_{TL}</td>
<td>T_{T} = (1 - L_{TL}) T_{TL}</td>
</tr>
<tr>
<td>RECEIVER</td>
<td>--</td>
<td>--</td>
<td>T_{RCVR}</td>
<td>T_{R} = T_{RCVR}</td>
</tr>
</tbody>
</table>
Figure 2-11. Power subsystem model.
at its full rate power or in a standby condition (nominally 10 percent full power) according to its duty cycle.

The maximum power input to each transmitter and receiver block is

\[
\begin{align*}
P_a &= \sum_{a}^{N_a} \left( \frac{P_{ta}}{\eta_{ta} \eta_{lca}} + P_{ra} \right) \\
P_v &= \sum_{v}^{N_v} \left( \frac{P_{tv}}{\eta_{tv} \eta_{lcv}} + P_{rv} \right) \\
P_f &= \sum_{f}^{N_f} \left( \frac{P_{tf}}{\eta_{tf} \eta_{lcf}} + P_{rf} \right) \\
P_d &= \sum_{d}^{N_d} \left( \frac{P_{td}}{\eta_{td} \eta_{lcd}} + P_{rd} \right)
\end{align*}
\]

then for maximum rating

\[
P_{pcu} = P_1 + P_a + P_v + P_f + P_d,
\]

where \( P_1 = P_{att} + P_{stk} + P_{mp} + P_{ttc} \),

\[
P_{pc} = \frac{P_{pcu}}{\eta_{pcu}} = \frac{P_1 + P_a + P_v + P_f + P_d}{\eta_{pcu}},
\]

now \( P_b = \frac{P_1 + P_a + P_v + P_f + P_d}{\eta_{pc} \eta_{pcu}} \)

and \( P_{pt_{1}} = \frac{P_1 + P_a + P_v + P_f + P_d}{\eta_{pc} \eta_{pcu}} \).
The total energy output from the batteries in watt-hours is

\[
W_{\text{out}} = \frac{H \cdot P_1 + WH_a + WH_v + WH_f + WH_d}{\eta_b \eta_{pc} \eta_{pcu}}
\]

where

- \( H \) is the total number of hours per day of solar eclipse (1.2 hours for a geostationary orbit).

\[
W_{H_k} = \sum (H - h_j) \left[ \text{BLOCK 'ON' POWER} \right]_j + \sum (h_j) \left[ \text{BLOCK STANDBY POWER} \right]_j
\]

where \( k = a, v, f, d \)

- \( h_j \) is the number of hours during eclipse for standby of the \( j \)th transmitter-receiver block.

The total energy supplied to the batteries is

\[
W_{\text{in}} = \frac{W_{\text{out}}}{\eta_b} = \frac{H \cdot P_1 + WH_a + WH_v + WH_f + WH_d}{\eta_b \eta_{pc} \eta_{pcu}}
\]

and the required power is

\[
P_{pt_2} = \frac{W_{\text{in}}}{24 - H} = \frac{H \cdot P_1 + WH_a + WH_v + WH_f + WH_d}{(24 - H) \eta_b \eta_{pc} \eta_{pcu}}
\]

The batteries are sized assuming a 50 percent depth-of-discharge requiring a capacity twice the output energy, \( W_{\text{out}} \).

Now the output of the power transfer is

\[
P_{pt} = P_{pt_1} + P_{pt_2} = \frac{P_1 + P_a + P_v + P_f + P_d}{\eta_{pc} \eta_{pcu}} + \frac{H \cdot P_1 + WH_a + WH_v + WH_f + WH_d}{(24 - H) \eta_b \eta_{pc} \eta_{pcu}}
\]
and finally the required power source output is

$$\eta_{pt} = \frac{P_{pt}}{\eta_{pt} \eta_{pc} \eta_{pcu}} \left[ \frac{1 + P_a + P_v + P_f + P_d + H \cdot P_a + WH_a + WH_v + WH_f + WH_d}{(24-H) \eta_b} \right].$$

Because of the interdependence among the various satellite subsystems, an explicit solution of attitude control and stationkeeping parameters is precluded. The attitude control weight, volume, and power are a function of the solar array area and the stationkeeping characteristics are determined by the total of all of the remaining subsystem weights. Due to these relationships, an implicit solution is dictated as shown in Figure 2-12. The parametric values for each subsystem which is independent are determined and remain constant throughout the process. A nominal estimate is made for the parameters of the other subsystems — attitude control, stationkeeping, thermal control, and structure. The power subsystem is sized for these initial conditions. The structure is then sized as a function of the contained equipment; the thermal control requirements are determined for the required power dissipation. The attitude control subsystem parameters are computed for the solar array area and the stationkeeping subsystem is sized as a function of the weight of all other subsystems. The process is continued iteratively using the present state of values as the nominal until the difference in successive prime power requirements is sufficiently small.

2.8 REDUNDANCY MODEL

The program computes factors which scale the affected weight, volume and cost terms to reflect the redundant elements required for additional spacecraft life.

Let

- $t_S$ = life of the satellite
- $t_I$ = life of the equipment in question
- $\rho$ = a scale factor such that $0 \leq \rho \leq 1$

If $d = \frac{t_S - t_I}{t_I}$, then

the scaling factor $S$ is given by $S = 1 + \rho \cdot d$.

The same scale factor is used for weight, volume, and cost terms.
Figure 2-12. Iterative process for sizing satellite subsystems.
The list of equipment for which redundancy is provided includes the following:

a) downlink transmitter  
b) spacecraft receiver  
c) power transfer unit  
d) power conditioning unit  
e) power control unit  
f) L/C filter

Each requires that the lifetime $f$ and the scaling factor $\rho$ be input.

2.9 COMMUNICATION LINKS

The communication links are modeled using the relations shown in Figure 2-13 where

$$G \text{ is Antenna gain}$$
$$P \text{ is Transmitter power}$$
$$L \text{ is System attenuation}$$
$$N \text{ is System noise}$$
$$\frac{C}{N} \text{ is Carrier-to-noise ratio}$$
$$A \text{ is Satellite transponder gain}$$

Indicated subscripts are defined as follows:

U indicates uplink (at frequency $f_U$)
D indicates downlink (at frequency $f_D$)
G indicates ground based
S indicates Satellite
1 indicates Station 1
2 indicates Station 2

The receiver carrier-to-noise ratio of the signal transmitted by Station 1, transponded by the satellite, and received by Station 2 for a constant gain transponder is

$$\frac{C}{N} \bigg|_2 = \frac{P_G G_{UG_1} L_U G_{US} A G_{DS} L_D G_{DG_2}}{N_G + N_{IM} + N_S A G_{DS} L_D G_{DG_2}}$$
Figure 2-13. Communications link analysis.

\[
\frac{C}{N} = \frac{P_G \cdot G_{UG} \cdot L_U \cdot G_{US} \cdot A \cdot G_{DS} \cdot L_D \cdot G_{DG}}{N_G + N_{IM} + A \cdot G_{DS} \cdot L_D \cdot G_{DG} \cdot N_S}
\]

\[
\frac{C}{N} = \frac{(P_S - A N_S) \cdot G_{DS} \cdot L_D \cdot G_{DG}}{N_G + N_{IM} + A \cdot G_{DS} \cdot L_D \cdot G_{DG} \cdot N_S}
\]
where $N_{IM}$ is the intermodulation noise due to multicarrier operation through one transponder.

For the constant power transponder, the equation relating satellite transmitter power and carrier-to-noise ratio is

$$\frac{C}{N} = \frac{(P_S - A_N S) G_{DS} L_D G_{DG_2}}{G_2 + N_{IM} + N_{DS} A_G L_D G_{DG_2}}$$

In both equations, the total noise is composed of three terms: receiving system noise, intermodulation noise, and noise on the downlink due to the uplink.

For the reverse link — station 2 to station 1 — the numerical subscripts are reversed.

2.10. SELECTION OF DEPENDENT AND INDEPENDENT DESIGN PARAMETER VECTORS

In this application, the choice of parameters for the dependent and independent vector varies with the case under consideration. Essentially, there are nine cases which the program will consider. The distinct cases are determined by the choice of transmit and receive capability of the Class I and/or Class II facilities and whether or not any direct receiving facilities are to be used. Figure 2-14 depicts the nine options which can be considered. Modifications to increase this number can be done with minimum effort.

The choice for the components of $\mathbf{Y}$, the vector of dependent parameters, is given as:

$y(1)$ — total satellite weight (lb)
$y(2)$ — total satellite volume (cu ft)
$y(3)$ — volume of the satellite equipment module (cu ft)
$y(4)$ — satellite prime power supply (watts)
$y(5), y(6), \ldots, y(28)$ — spacecraft transmitter power, power out/channel (watts)
$y(29), y(30), \ldots, y(52)$ — Class I transmitter power, power out/channel (watts)
$y(53), y(54), \ldots, y(76)$ — Class II transmitter power, power out/channel (watts)
$y(77)$ — direct ground antenna diameter or ground antenna diameter for selected dependent facility (ft)
$y(78)$ — direct ground antenna diameter (ft)

For the components of the independent design parameter vector, the choice is:

$x(1)$ — Class I or Class II ground facility antenna diameter (ft)
<table>
<thead>
<tr>
<th>OPTION NO.</th>
<th>CLASS 1 STATION</th>
<th>CLASS 2 STATION</th>
<th>DIRECT STATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>1</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>2</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>3</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>4</td>
<td>T/R</td>
<td>T/R</td>
<td>R</td>
</tr>
<tr>
<td>5</td>
<td>T/R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>6</td>
<td>T/R</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>7</td>
<td>T/R</td>
<td>R</td>
<td>T/R</td>
</tr>
<tr>
<td>8</td>
<td>T/R</td>
<td>T</td>
<td>T/R</td>
</tr>
<tr>
<td>9</td>
<td>T/R</td>
<td>T/R</td>
<td>T/R</td>
</tr>
</tbody>
</table>

Figure 2-14. Synthesis program ground system options.
x(2) — Class I, Class II, or direct ground antenna diameter (ft) or Class I receiver noise figure

x(3) — Class I, Class II, or direct receiver noise figure

x(4) — Class II or direct receiver noise figure

For the nine cases, the vectors are illustrated in Figures 2-15 and 2-16. The notation used in the charts is given by the following:

\[ W_t = \text{total satellite weight} \]

\[ V_t = \text{total satellite volume} \]

\[ V_{em} = \text{volume of satellite equipment module} \]

\[ P_{ps} = \text{prime power supply (satellite)} \]

\[ P_{tr} = \text{transmitter power (satellite)} \]

\[ P_{g1} = \text{transmitter power (Class I)} \]

\[ P_{g2} = \text{transmitter power (Class II)} \]

\[ D_1 = \text{antenna diameter (Class I)} \]

\[ D_2 = \text{antenna diameter (Class II)} \]

\[ D_3 = \text{antenna diameter (direct)} \]

\[ N_{f1} = \text{receiver noise figure (Class I)} \]

\[ N_{f2} = \text{receiver noise figure (Class II)} \]

\[ N_{f3} = \text{receiver noise figure (direct)} \]

In cases six through nine the choice of the independent antenna diameter is made on the basis of which class requires the largest value for C/N. The remaining antenna diameter reverts to being a dependent parameter.

2.11 SOLUTION APPROACH

As previously mentioned the link equations are based on the required \( \frac{C}{N} \) and this, in turn, is used to size the spacecraft. The key equations used in the power model are listed below. A more detailed discussion is found in Volume II which elaborates on the link model used in the program.

\[ P_{tr_{ij}} = \frac{C}{N_{ik}} \frac{(\rho_{im} + \rho_{u} + 1) (N_{g_{ikj}})}{(G_{d_{k}}) (G_{ds_{j}}) (T_{d_{kj}})} \]
<table>
<thead>
<tr>
<th>CASE OPTION</th>
<th>y(1)</th>
<th>y(2)</th>
<th>y(3)</th>
<th>y(4)</th>
<th>y(5) - y(28)</th>
<th>y(29) - y(52)</th>
<th>y(53) - y(76)</th>
<th>y(77)</th>
<th>y(78)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W_t</td>
<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>W_t</td>
<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>---</td>
<td>---</td>
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<tr>
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<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>---</td>
<td>---</td>
<td>D_3</td>
<td>---</td>
</tr>
<tr>
<td>4</td>
<td>W_t</td>
<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>P_g_1</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>5</td>
<td>W_t</td>
<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>P_g_1</td>
<td>---</td>
<td>D_3</td>
<td>---</td>
</tr>
<tr>
<td>6</td>
<td>W_t</td>
<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>P_g_1</td>
<td>---</td>
<td>D_1 or D_2</td>
<td>---</td>
</tr>
<tr>
<td>7</td>
<td>W_t</td>
<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>P_g_1</td>
<td>---</td>
<td>D_1 or D_2</td>
<td>D_3</td>
</tr>
<tr>
<td>8</td>
<td>W_t</td>
<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>P_g_1</td>
<td>P_g_2</td>
<td>D_1 or D_2</td>
<td>---</td>
</tr>
<tr>
<td>9</td>
<td>W_t</td>
<td>V_t</td>
<td>Vem</td>
<td>P_ps</td>
<td>P_ps</td>
<td>P_g_1</td>
<td>P_g_2</td>
<td>D_1 or D_2</td>
<td>D_3</td>
</tr>
</tbody>
</table>

Figure 2-15. Choice of parameters for dependent vector, $\bar{Y}$. 
<table>
<thead>
<tr>
<th>CASE OPTION</th>
<th>x(1)</th>
<th>x(2)</th>
<th>x(3)</th>
<th>x(4)</th>
</tr>
</thead>
<tbody>
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<td>$D_1$</td>
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<td>$Nf_3$</td>
<td>---</td>
</tr>
<tr>
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<td>$D_1$</td>
<td>$D_2$</td>
<td>$Nf_2$</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>$D_1$</td>
<td>$D_2$</td>
<td>$Nf_2$</td>
<td>$Nf_3$</td>
</tr>
<tr>
<td>4</td>
<td>$D_1$</td>
<td>$Nf_1$</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
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<td>$D_1$</td>
<td>$Nf_1$</td>
<td>$Nf_3$</td>
<td>---</td>
</tr>
<tr>
<td>6</td>
<td>$D_1$ or $D_2$</td>
<td>$Nf_1$</td>
<td>$Nf_2$</td>
<td>---</td>
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<td>$Nf_1$</td>
<td>$Nf_2$</td>
<td>$Nf_3$</td>
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<tr>
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<td>$Nf_1$</td>
<td>$Nf_2$</td>
<td>---</td>
</tr>
<tr>
<td>9</td>
<td>$D_1$ or $D_2$</td>
<td>$Nf_1$</td>
<td>$Nf_2$</td>
<td>$Nf_3$</td>
</tr>
</tbody>
</table>

Figure 2-16. Choice of parameters for independent vector, $\mathbf{X}$. 

2-32
where \( R = \frac{(G_d)_{ik}}{(T_d)_{kj}} \)

and the subscripts indicated are described as follows:

- \( i \) = data type = 1, 2, 3, 4
- \( j \) = beam number = 1, 2, 3, ......, 6
- \( k \) = fixed, representing independent class = 1 or 2
- \( n \) = fixed, representing dependent class = 1 or 2
- \( \rho_{im} \) = ratio of intermodulation noise/system noise
- \( \rho_u \) = ratio of satellite noise/receiver noise
- \( N_g \) = total noise at the ground receiver
- \( G_d \) = ground antenna downlink gain for class \( k \)
- \( G_{ds} \) = spacecraft antenna downlink gain
- \( T_d \) = total loss down
- \( N_s \) = total noise at the spacecraft
- \( G_u \) = ground antenna uplink gain
- \( G_{us} \) = spacecraft antenna uplink gain
- \( T_u \) = total loss up

Total noise on the ground, \( N_g \), is a function of the effective temperature. The effective temperature at each of the ground receivers is a function of the relative antenna discriminations due to sky, environment, and earth. These discriminations in turn are determined by the downlink gain at each of the receivers. The gain is computed directly as a function of diameter and frequency, except when the diameter is unknown and is given as one of the dependent parameters. In this case, an iteration scheme is used since the equations are of an implicit nature. The iteration scheme is initiated using the value of the gain for the independent class of stations.
The steps describing the approach for each of the case options are given here.

CASE OPTION I

\[ \bar{X} = (D_1, D_3, Nf_3) \]

1. compute satellite antenna characteristics (from frequency and area of coverage),
2a. compute Class I uplink gain, \( G_{u1}' \)
2b. compute direct antenna downlink gain, \( G_{d3}' \)
3. compute antenna discrimination for Class I and direct,
4. compute Class I uplink transmitter power, \( P_{g1} \) and satellite transmitter power, \( P_{tr} \)
5. cost ground facility,
6. size spacecraft and compute associated parameters (weight, volume, power, and cost),
7. cost launch vehicle,
8. compute total cost.

CASE OPTION II

\[ \bar{X} = (D_1, D_2, Nf_2) \]

1. I - 1,
2a. I - 2a,
2b. compute Class II antenna downlink gain, \( G_{d2}' \)
3. compute antenna discrimination for Class I and Class II,
4. I - 4,
5. I - 5 to I - 8.

CASE OPTION III

\[ \bar{X} = (D_1', D_2, Nf_2', Nf_3') \]

1. II - 1 to II - 4,
2. iterate for direct antenna diameter and gain,
3. compute direct antenna relative discriminations,
4. I - 5 to I - 8.

CASE OPTION IV
\[ \bar{X} = (D_1, Nf_1) \]
1. I - 1 and I - 2a,
2. compute Class I antenna downlink gain, \( G_{d1'} \)
3. compute Class I antenna discrimination,
4. I - 4,
5. I - 5 to I - 8.

CASE OPTION V
\[ \bar{X} = (D_1, Nf_1, Nf_3) \]
1. I - 1,
2. compute Class I antenna downlink gain, \( G_{d1'} \)
3. compute Class I antenna discriminations,
4. compute satellite transmitter power to be used in iteration scheme, \( P_{tr}(I, J) \) where \( I = JCLG \) and \( J = IBMG \),
5. iterate for direct antenna diameter, \( D_3' \),
6. I - 2a,
7. compute direct antenna gain, \( G_{d3'} \)
8. compute antenna discrimination for the direct antenna,

CASE OPTION VI
\[ \bar{X} = (D_j, Nf_1, Nf_2) \text{ where } j = 1 \text{ or } 2 \]
1. I - 1,
2. determine independent antenna diameter, \( G_{d1'} \) and dependent antenna diameter, \( G_{dD'} \),
3. compute downlink antenna gain for the independent antenna,
4. compute antenna discriminations for the independent antenna,
5. V - 4,
6. iterate for dependent antenna diameter,
7. I - 2a,
8. compute downlink gain for the dependent antenna,
9. compute the antenna discriminations for the dependent antenna,
10. I - 4 to I - 8.

**CASE OPTION VII**
\[ \bar{X} = (D_j, N_{f1}, N_{f2}, N_{f3}) \text{ where } j = 1 \text{ or } 2 \]
1. VI - 1 to VI - 9,
2. I - 4,
3. III - 2 to III - 4.

**CASE OPTION VIII**
\[ \bar{X} = (D_j, N_{f1}, N_{f2}) \text{ where } j = 1 \text{ or } 2 \]
1. VI - 1 to VI - 9,
2. compute Class II uplink antenna gain, \( G_{u2} \),
3. I - 4,
4. compute Class II uplink transmitter power, \( P_{g2} \),
5. I - 5 to I - 8.

**CASE OPTION IX**
\[ \bar{X} = (D_j, N_{f1}, N_{f2}, N_{f3}) \text{ where } j = 1 \text{ or } 2 \]
1. VIII - 1 to VIII - 5,
2. III - 2 to III - 4.
2.12 OUTPUT

The ITS program provides two forms of output, one a brief summary printed at each iteration, and the second, a comprehensive printout at the conclusion of each case.

A sample of the first type is illustrated in Figure 2-17. This summary is provided for each iteration and provides the program user with indication of the nature of the system at any particular design point during the convergence process and the rate of convergence. The output provides the iteration number, the values of the key dependent parameters, the values of the independent design parameters, the computed perturbation, and the gradient vector. It also provides the number of boundary violations (NBV), the index of the one which violates its constraint by the largest degree (KBV), the number of successive iterations for which the convergence criteria is met (ICV), the number of components of X meeting the convergence criteria (JCV), the computed step size vector for the next iteration, and total system cost.

The variables listed are defined as follows:

- **WSAT** — total satellite weight (lb)
- **VSAT** — total satellite volumes (cu ft)
- **VEM** — volume of the spacecraft equipment module (cu ft)
- **PPS** — prime power supply (watts)
- **D(1) or D(2)** — dependent Class I or Class II ground antenna diameter.
- **PG1** — $4 \times 6$ array of transmitter power out at Class I facilities (watts)
- **PG2** — $4 \times 6$ array of transmitter power out at Class II facilities (watts)
- **PTR** — $4 \times 6$ array of transmitter power out at the spacecraft (watts)

D(3), the direct receiving system antenna diameter is also provided when used.

The formal output at the conclusion of the run is intended to be a comprehensive easy-to-read listing of all pertinent parametric values.

Other than the output and computed values relevant to the user requirements and beam characteristics described in the previous sections, the output routine provides a systematic breakdown of other elements — primarily cost, weight and volume.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER</td>
<td>24</td>
</tr>
<tr>
<td>WSAT</td>
<td>1.3324</td>
</tr>
<tr>
<td>VSAT</td>
<td>110.9</td>
</tr>
<tr>
<td>VEM</td>
<td>68.1</td>
</tr>
<tr>
<td>PPS</td>
<td>243.6</td>
</tr>
<tr>
<td>D(21)</td>
<td>42.3686</td>
</tr>
<tr>
<td>PG1</td>
<td>0.0</td>
</tr>
<tr>
<td>PG2</td>
<td>0.0</td>
</tr>
<tr>
<td>PTR</td>
<td>0.0</td>
</tr>
<tr>
<td>X</td>
<td>20.8755</td>
</tr>
<tr>
<td>DX</td>
<td>0.09465</td>
</tr>
<tr>
<td>G</td>
<td>0.0738</td>
</tr>
<tr>
<td>S</td>
<td>0.5000</td>
</tr>
<tr>
<td>ICV</td>
<td>0</td>
</tr>
<tr>
<td>JCV</td>
<td>1</td>
</tr>
<tr>
<td>NBVIOL</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL COST</td>
<td>345.7633</td>
</tr>
</tbody>
</table>

Figure 2-17. Iterative output summary.
A total system cost summary is provided on an annual cost basis for each of the major subsystems: the Class I, Class II, and direct ground systems, the satellite, the launch vehicle, and the telemetry and command.

A data service summary is provided for each of the four data categories on a per beam basis. This provides such information as base bandwidth, modulation, modulation index and total of bandwidth. (Figure 2-18)

The ground receiver characteristics are listed for each class of stations and provide a breakdown for each beam requiring that particular class. The information provides the number of channels transmitted and received, EIRP, G/T, S/N, and the total number of facilities for that beam.

The satellite antenna and transponder characteristics are given for each beam. These include the number of channels transmitted and received, G/T, and EIRP. The transponder characteristics list the antenna dimension and gains, beam center, beamwidth, and pattern axes for the uplink and downlink. (Figure 2-19)

A summary of the loss and noise terms are provided for the uplink and downlink beams. The noise terms include sky, earth, and environment, and receiver noise temperatures. The losses provided include free-space, atmospheric, rain, location, polarization, circuit, and pointing losses for the receiver and transmitter. On the downlink those applicable are given for each class of station. (Figure 2-20)

Finally a comprehensive summary is provided for each of the major subsystems: ground, spacecraft, and launch vehicle.

The ground facility summary is provided for each class of station and for each beam. The cost breakdown is given for each cost item comprising the ground system: facility, terminal equipment, transmitters, antenna and multiplexer, receiver, standby power, test equipment, personnel, and design, integration and management. The acquisition, installation, annual operations and maintenance, and total cost are listed for each. Also shown are the number of channels per data category, the required transmitter power, the antenna size and gain, and receiver noise figure. The total cost/facility is shown together with the total number of facilities for that particular beam. (Figures 2-21 and 2-22)

The satellite summary provides the acquisition cost, R/D cost (prorated), total cost, weight, and volume of the various spacecraft subsystems: prime power, secondary power, power conditioning, power distribution, antenna, transmitter, multiplexer, receiver, structure, thermal control, attitude control, stationkeeping, and telemetry/command. Descriptive parameters such as transmitter power and receiver noise figures are provided where pertinent. Also included is the cost
<table>
<thead>
<tr>
<th>USER NO</th>
<th>USER DESCRIPTION</th>
<th>SATELLITE LCAG</th>
<th>UPLINK FREQUENCY</th>
<th>SATELLITE LIFE</th>
<th>DOWNLINK FREQUENCY</th>
<th>TOTAL SYS LIFE</th>
<th>NUMBER OF BEAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>03</td>
<td>EDUCATIONAL/INSTRUCTIONAL TELEVISION DISTRIBUTION (4 BEAMS)</td>
<td>-100.0 DEG</td>
<td>12.00 GHZ</td>
<td>10.0 YEARS</td>
<td>12.20 GHZ</td>
<td>10.0 YEARS</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>USER NO</th>
<th>USER DESCRIPTION</th>
<th>SYSTEM COSTS (MILLIONS/ YEAR)</th>
<th>DIRECT SATELLITE</th>
<th>LAUNCH VEH</th>
<th>TLM/CMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>03</td>
<td>EDUCATIONAL/INSTRUCTIONAL TELEVISION DISTRIBUTION (4 BEAMS)</td>
<td>3684.468</td>
<td>7.015</td>
<td>3647.721</td>
<td>0.000</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>USER NO</th>
<th>SERVICE TYPE</th>
<th>BASE- BAND (MHz)</th>
<th>VEST- BAND (MHz)</th>
<th>NC AUDIO CHANNELS</th>
<th>MODULATION</th>
<th>MDC INDEX</th>
<th>RF BANDWIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>03</td>
<td>COLOR</td>
<td>4.200</td>
<td>0.060</td>
<td>1</td>
<td>FM</td>
<td>FM</td>
<td>2.68</td>
</tr>
</tbody>
</table>

Figure 2-18. Final output — user requirements/major subsystems costs.
Figure 2-19. Final output - ground receiver, satellite transponder, and satellite antenna characteristics.
<table>
<thead>
<tr>
<th>NO</th>
<th>SKY ENVIR EARTH</th>
<th>INTERCBOUICLL TICACLIC NOISE AUDI0 VIDEO FAX DIGIT</th>
<th>UPLINK CONTRIBUCUICA AUDI0 VIDEO FAX DIGIT</th>
<th>CLASS 1 RCVR</th>
<th>CLASS 2 RCVR</th>
<th>DIRECT RCVR</th>
<th>X-UPLINK NOISES-X EARTH RCVR RCVR Ckt</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>83.0</td>
<td>.0 290.6</td>
<td>0.0 0.0 0.0 0.0 0.0</td>
<td>0.0 349.7</td>
<td>0.0 0.0</td>
<td>3377.2 59.6</td>
<td>*95.9 59.6 6.0 0.0 290.0 290.0 59.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>76.1</td>
<td>.0 290.6</td>
<td>0.0 0.0 0.0 0.0 0.0</td>
<td>0.0 349.7</td>
<td>0.0 0.0</td>
<td>3377.2 59.6</td>
<td>*95.9 59.6 6.0 0.0 290.0 290.0 59.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>76.7</td>
<td>.0 290.6</td>
<td>0.0 0.0 0.0 0.0 0.0</td>
<td>0.0 349.7</td>
<td>0.0 0.0</td>
<td>3377.2 59.6</td>
<td>*95.9 59.6 6.0 0.0 290.0 290.0 59.6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>69.9</td>
<td>.0 290.6</td>
<td>0.0 0.0 0.0 0.0 0.0</td>
<td>0.0 349.7</td>
<td>0.0 0.0</td>
<td>3377.2 59.6</td>
<td>*95.9 59.6 6.0 0.0 290.0 290.0 59.6</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2-20.** Final output — loss and noise summary.
# Ground Stations - Beam 1

## Class 1 Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Acquisition (Thousands)</th>
<th>Install (Thousands)</th>
<th>Oper/Year (Thousands)</th>
<th>Maint/Year (Thousands)</th>
<th>Total (Thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility</td>
<td>110.00</td>
<td>-</td>
<td>-</td>
<td>2.20</td>
<td>132.00</td>
</tr>
<tr>
<td>Terminal Equip-Video</td>
<td>120.00</td>
<td>24.00</td>
<td>18.00</td>
<td>12.00</td>
<td>444.00</td>
</tr>
<tr>
<td>Transmitters-Video</td>
<td>111.64</td>
<td>22.33</td>
<td>11.27</td>
<td>11.16</td>
<td>258.30</td>
</tr>
<tr>
<td>Antenna + Mux</td>
<td>30.64</td>
<td>0.00</td>
<td>-</td>
<td>3.06</td>
<td>61.28</td>
</tr>
<tr>
<td>Receivers</td>
<td>4.26</td>
<td>-0.64</td>
<td>-1.21</td>
<td>-3.63</td>
<td>11.79</td>
</tr>
<tr>
<td>Standby Power</td>
<td>77.63</td>
<td>1.55</td>
<td>-</td>
<td>3.88</td>
<td>117.95</td>
</tr>
<tr>
<td>Test Equipment</td>
<td>50.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>50.00</td>
</tr>
<tr>
<td>Personnel</td>
<td>-</td>
<td>-0.60</td>
<td>-</td>
<td>-</td>
<td>39.58</td>
</tr>
<tr>
<td>Design, Integ + Mgmt</td>
<td>-</td>
<td>39.48</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total/Facility</strong></td>
<td><strong>504.16</strong></td>
<td><strong>68.50</strong></td>
<td><strong>79.48</strong></td>
<td><strong>22.73</strong></td>
<td><strong>1714.83</strong></td>
</tr>
</tbody>
</table>

\*NC. CHANS = 6, POWER = 0.080 Kwh, CIA = 15.63, NCISE FIG = 11.02

## Class 2 Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Acquisition (Thousands)</th>
<th>Install (Thousands)</th>
<th>Oper/Year (Thousands)</th>
<th>Maint/Year (Thousands)</th>
<th>Total (Thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility</td>
<td>50.00</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>60.00</td>
</tr>
<tr>
<td>Terminal Equip-Video</td>
<td>120.00</td>
<td>24.00</td>
<td>18.00</td>
<td>12.00</td>
<td>444.00</td>
</tr>
<tr>
<td>Antenna + Mux</td>
<td>3.20</td>
<td>-0.30</td>
<td>-0.26</td>
<td>-0.33</td>
<td>6.75</td>
</tr>
<tr>
<td>Receivers</td>
<td>-0.03</td>
<td>-1.23</td>
<td>0.12</td>
<td>0.08</td>
<td>2.21</td>
</tr>
<tr>
<td>Standby Power</td>
<td>41.25</td>
<td>0.84</td>
<td>-</td>
<td>2.09</td>
<td>63.28</td>
</tr>
<tr>
<td>Test Equipment</td>
<td>25.60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>25.00</td>
</tr>
<tr>
<td>Personnel</td>
<td>-</td>
<td>30.00</td>
<td>-</td>
<td>-</td>
<td>30.00</td>
</tr>
<tr>
<td>Design, Integ + Mgmt</td>
<td>-</td>
<td>18.62</td>
<td>-</td>
<td>-</td>
<td>18.62</td>
</tr>
<tr>
<td><strong>Total/Facility</strong></td>
<td><strong>241.42</strong></td>
<td><strong>43.70</strong></td>
<td><strong>48.64</strong></td>
<td><strong>15.31</strong></td>
<td><strong>520.30</strong></td>
</tr>
</tbody>
</table>

\*NC. CHANS = 2, CIA = 9.95, NCISE FIG = 14.00

Figure 2-21. Final output — ground facility cost summary (1)
Figure 2-22. Final output — ground facility cost summary (2)
breakdown for integration, assembly and checkout, design, integration, and management, center support and ground support equipment. The total/satellite is given for the cost, weight, and volume. (Figure 2-23)

The launch vehicle summary provides the acquisition, R/D (prorated), and total cost for the launch vehicle. Also shown is the weight and volume limits.

A further breakdown for each beam is listed for the satellite communication subsystem. The summary provides cost, power, efficiency, lifetime for the transmitter, multiplexer, receiver, and antenna and the number of multiple transmitter blocks employed in the satellite.
### Satellite Subsystems Costs

<table>
<thead>
<tr>
<th>POWER SUBSYSTEM</th>
<th>ACQUISITION (MILLIONS)</th>
<th>R&amp;D</th>
<th>TOTAL (MILLIONS)</th>
<th>WEIGHT (LBS.)</th>
<th>VOLUME (CU FT)</th>
<th>TYPE</th>
<th>DESCRIPTIVE PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prime Power</td>
<td>0.15</td>
<td>2.18</td>
<td>4.33</td>
<td>4227.1</td>
<td>272.62</td>
<td>Solar</td>
<td>Power = 29.424 kW</td>
</tr>
<tr>
<td>Secondary Power</td>
<td>0.16</td>
<td>2.23</td>
<td>5.39</td>
<td>9653.6</td>
<td>42.99</td>
<td>MIG-CAP</td>
<td>Capacity = 63.007 kW·m</td>
</tr>
<tr>
<td>Conditioning</td>
<td>0.36</td>
<td>3.32</td>
<td>8.68</td>
<td>2091.2</td>
<td>21.51</td>
<td>4 Beams</td>
<td>H = 10.0</td>
</tr>
<tr>
<td>Distribution</td>
<td>0.90</td>
<td>4.50</td>
<td>1.35</td>
<td>558.8</td>
<td>42.33</td>
<td>TWT</td>
<td>32 Transmitters</td>
</tr>
<tr>
<td>Antenna</td>
<td>0.00</td>
<td>0.04</td>
<td>0.04</td>
<td>44.1</td>
<td>15.51</td>
<td>Waveguide</td>
<td></td>
</tr>
<tr>
<td>Transmitter-Prime</td>
<td>7.26</td>
<td>7.79</td>
<td>8.05</td>
<td>2797.4</td>
<td>109.32</td>
<td>IN-CAO</td>
<td>Capacity = 3.017 kW·m</td>
</tr>
<tr>
<td>Multiplexer</td>
<td>0.31</td>
<td>0.62</td>
<td>1.93</td>
<td>21.4</td>
<td>0.71</td>
<td>ION PROP</td>
<td>AM/L = 6412.6 50 ft</td>
</tr>
<tr>
<td>Receivers</td>
<td>2.22</td>
<td>4.46</td>
<td>6.68</td>
<td>700.0</td>
<td>12.50</td>
<td>LIN TRNS</td>
<td>Noise Fig = 3.0 DB</td>
</tr>
<tr>
<td>Structure</td>
<td>0.16</td>
<td>0.55</td>
<td>0.70</td>
<td>121.1</td>
<td>64.56</td>
<td>HEATPIPE</td>
<td>PMR RAD = 22.620 kW</td>
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<tr>
<td>THERMAL CONTROL</td>
<td>0.19</td>
<td>1.44</td>
<td>1.62</td>
<td>229.6</td>
<td>45.92</td>
<td>ION PROP</td>
<td>M = 3.9, D = 10.0 FT</td>
</tr>
<tr>
<td>Station Keeping</td>
<td>0.59</td>
<td>5.23</td>
<td>5.82</td>
<td>526.1</td>
<td>0.55</td>
<td>ION PROP</td>
<td>AM/L = 6412.6 50 ft</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>0.80</td>
<td>5.09</td>
<td>5.89</td>
<td>108.7</td>
<td>1.38</td>
<td>ION PROP</td>
<td>AM/L = 6412.6 50 ft</td>
</tr>
<tr>
<td>Telemetry + Command</td>
<td>0.17</td>
<td>0.85</td>
<td>1.62</td>
<td>76.0</td>
<td>2.00</td>
<td>ION PROP</td>
<td>AM/L = 6412.6 50 ft</td>
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<tr>
<td>FPGA</td>
<td>-</td>
<td>0.35</td>
<td>0.35</td>
<td>14.41</td>
<td>0.35</td>
<td>1 Protoype</td>
<td>SATELLITE(s)</td>
</tr>
<tr>
<td>INTEG, ASSY + CHECK</td>
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<td>-</td>
<td>1.60</td>
<td>14.41</td>
<td>0.35</td>
<td>SATELLITE</td>
<td>SATELLITE(s)</td>
</tr>
<tr>
<td>Design, Integ + NGMT</td>
<td>-</td>
<td>9.63</td>
<td>9.63</td>
<td>14.41</td>
<td>0.35</td>
<td>SATELLITE</td>
<td>SATELLITE(s)</td>
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<tr>
<td>CENTER SLEPCRT</td>
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<td>1.44</td>
<td>4.88</td>
<td>106.7</td>
<td>1.38</td>
<td>SATELLITE</td>
<td>SATELLITE(s)</td>
</tr>
<tr>
<td>GRD SUPPORT EQUIF</td>
<td>-</td>
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<td>10.67</td>
<td>106.7</td>
<td>1.38</td>
<td>SATELLITE</td>
<td>SATELLITE(s)</td>
</tr>
<tr>
<td>SYSTEM TOTAL</td>
<td>26.37</td>
<td>55.42</td>
<td>81.79</td>
<td>17392.2</td>
<td>1669.12</td>
<td>SATELLITE</td>
<td>SATELLITE(s)</td>
</tr>
</tbody>
</table>

### Launch Vehicle Costs

<table>
<thead>
<tr>
<th>LAUNCH VEHICLE</th>
<th>ACQUISITION (MILLIONS)</th>
<th>R&amp;D</th>
<th>TOTAL (MILLIONS)</th>
<th>WEIGHT (LBS.)</th>
<th>VOLUME (CU FT)</th>
<th>SATURN V</th>
<th>1 SPAS/LAUNCH VEHICLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total/Launch Vehicle</td>
<td>186.20</td>
<td>25.00</td>
<td>213.20</td>
<td>52500.0</td>
<td>6000.00</td>
<td>1</td>
<td>1 Launch Vehicle</td>
</tr>
<tr>
<td>System Total</td>
<td>186.20</td>
<td>25.00</td>
<td>213.20</td>
<td>52500.0</td>
<td>6000.00</td>
<td>1</td>
<td>1 Launch Vehicle</td>
</tr>
</tbody>
</table>

### Satellite Communications Subsystems

<table>
<thead>
<tr>
<th>BEAM NO. 1</th>
<th>UNIT ACQ.</th>
<th>TOTAL ACQ.</th>
<th>TOTAL WEIGHT</th>
<th>TOTAL VOLUME</th>
<th>POWER (WATTS)</th>
<th>EFFICIENCY</th>
<th>UNIT LIFE</th>
<th>MCD</th>
<th>NO. XMT</th>
<th>NO. XMTS</th>
<th>SATELLITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter - TWT</td>
<td>0.05</td>
<td>1.83</td>
<td>708.9</td>
<td>27.34</td>
<td>452</td>
<td>53.7</td>
<td>2</td>
<td>FM</td>
<td>8</td>
<td>5</td>
<td>SATELLITE</td>
</tr>
<tr>
<td>Multiplexer - Waveguide</td>
<td>0.02</td>
<td>5.44</td>
<td>1.0</td>
<td>Loss=1.1 DB</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiver - LIN TRANS</td>
<td>0.07</td>
<td>210.0</td>
<td>3.75</td>
<td>30</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna - RIGID</td>
<td>0.00</td>
<td>11.0</td>
<td>3.80</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-23. Final output — satellite subsystems and launch vehicle summary.
APPENDIX A

DERIVATION OF STEEPEST DESCENT ITERATIVE ALGORITHM

Let \( X \) represent a vector of \( n \) independent system design parameters, \( y(X) \) a vector of \( m \) constrained system parameters, and \( C(X) \) the total system cost. It is desired to determine the minimum value of \( C \) subject to the constraints imposed on \( y \). This solution is to be obtained by iteratively perturbing a nominal design parameter vector \( X_i \) until no further reduction in \( C \) is possible and all constraints are satisfied. At each iteration only those constraints which have been violated need be considered.

Now let \( y \) be a \( k \)-vector whose elements are those parameters whose boundaries have been violated (a subset of the original \( y \) vector). For these parameters the constraint

\[
y(X) - y_{\text{BOUND}} = 0
\]

will be imposed. At a given iteration

\[
Y_i = y(X_i) - y_{\text{BOUND}} \neq 0
\]

Let \( g \) and \( \Phi \) represent the cost and constraint gradients, respectively. That is,

\[
g = \frac{dC}{dx} (X_i) \quad \text{and} \quad \Phi = \frac{dy}{dx} (X_i)
\]

To first order terms

\[
\Delta C(\Delta X) = g^T \cdot \Delta X
\]

and

\[
\Delta Y = \Phi^T \cdot \Delta X
\]

It is desired to determine the vector \( \Delta X \) which minimizes

\[
J = \Delta C(\Delta X) = g^T \cdot \Delta X
\]

while reducing \( \Delta Y \) by some specified amount

\[
\Delta Y = -K_Y \cdot Y
\]
The magnitude of the perturbation is constrained by

\[ S^2 = \Delta X^T \cdot \Delta X \]  

(8)

Applying Lagrange multiplier theory one defines \( J' \) to be

\[ J' = g^T \cdot \Delta X + \lambda \cdot (\Delta X^T \cdot \Delta X - S^2) + \eta^T \cdot (\Phi^T \cdot \Delta X + K_y \cdot Y) \]  

(9)

where \( \lambda \) is an arbitrary constant and \( \eta \) is an arbitrary \( k \)-vector. From Equations 7 and 8 it is clear that \( J \) and \( J' \) are equal, so one can proceed by minimizing \( J' \). This minimum occurs where

\[ \frac{\partial J'}{\partial \Delta X} = g^T + 2 \lambda \cdot \Delta X^T + \eta^T \Phi^T = 0 \]

(10)

Solving Equation (10) for \( \Delta X \) gives

\[ \Delta X = - \frac{1}{2\lambda} \cdot (g + \Phi \cdot \eta) \]

(11)

For convenience define

\[ K_c = - \frac{1}{2\lambda} \quad \text{and} \quad \gamma = - \frac{1}{2\lambda} \cdot \eta \]

(12)

Then

\[ \Delta X = - K_c \cdot g - \Phi \cdot \gamma \]

(13)

Substituting Equation (13) into Equations (5) and (7) gives

\[ \Delta Y = - K_c \Phi^T g - \Phi^T \Phi \gamma = - K_y \cdot Y \]

(14)

Solving for \( \gamma \) gives

\[ \gamma = - K_c \left( \Phi^T \phi \right)^{-1} \cdot \phi^T \cdot g + K_y \left( \Phi^T \phi \right)^{-1} \cdot Y \]

(15)

Substituting Equation (15) into Equation (13) gives

\[ \Delta X = - K_c \left[ I - \phi \left( \Phi^T \phi \right)^{-1} \cdot \phi^T \right] \cdot g - K_y \cdot \phi \left( \Phi^T \phi \right)^{-1} \cdot Y \]

(16)

which is the perturbation equation given in Section 2.2.
The two terms of Equation (16) represent perturbations parallel and perpendicular to the constraint boundaries, respectively. This can be shown by taking the vector inner product (vector projection) of the first term and the constraint gradient

\[
\psi^T \cdot \left[ -K_c \left[ I - \psi (\psi^T \psi)^{-1} \psi^T \right] \right] g = -K_c \left[ \psi^T - (\psi^T \psi) (\psi^T \psi)^{-1} \psi^T \right] g \]

\[
= -K_c \left[ \psi^T - \psi^T \right] g = 0 \quad (17)
\]

The value of \( K_c \) can be determined by substituting Equation (16) into Equation (8) and reducing to

\[
S^2 = K_y Y^T (\psi^T \psi)^{-1} Y + K_c^2 \cdot H^T H \quad (18)
\]

where

\[
H = \left[ I - \psi (\psi^T \psi)^{-1} \psi^T \right] g \quad (19)
\]

Then

\[
K_c = \sqrt{\frac{S^2 - K_y^2 \cdot Y^T (\psi^T \psi)^{-1} Y}{H^T H}} \quad (20)
\]

The step-size \( S \) is controlled to insure rapid convergence to the solution. When the nominal value of \( X \) is "far" from the solution successive perturbations will tend to be in the same direction. Under this condition it is desirable to increase \( S \) for the following iteration. When the nominal \( X \) is "close" to the solution such that a given perturbation overshoots the solution, successive perturbations will tend to be in opposite directions. Under this condition it is desirable to reduce \( S \) to allow the minimum cost solution to be determined to a finer resolution. The logic for implementing this step-size control is given in Section 2.2.
APPENDIX B

GENERAL PURPOSE SUBROUTINES

The ITS computer program requires the following general purpose system routines. Listings for each are provided. For the IBM 360 version, some may be replaced by the appropriate subroutines from the IBM library.

General Purpose Routines

1. Subroutine DSHIFT — to move an N by M matrix A into B
2. Subroutine DZERO — to clear an N by M array
3. Subroutine MTMPY — to form the product of two matrices
4. Subroutine MADD — to form the sum of two matrices

Functions

1. DVMAG — to compute the magnitude of a vector
2. VDOT — to form the vector dot product of two vectors

1. Subroutine DSHIFT
   Purpose: to move an N by M matrix A into B
   Usage: CALL DSHIFT (N, M, A, B)
   where A and B are assumed to be matrices dimensioned N by M

2. Subroutine DZERO
   Purpose: to clear an N by M array
   Usage: CALL ZERO (A, N, M)
   where A is the array to clear and N and M are the dimensions of A

3. Subroutine MTMPY
   Purpose: to form the product of two matrices \( C = A \times B \)
Usage: CALL MTMPY (A, B, C, N, M, L)

where A is an N by M matrix
B is an M by L matrix, and
C is the resultant N by L matrix

Note: A and B may be the same matrix, but C must be a separate matrix.

4. **Subroutine MADD**

Purpose: to form the sum of two matrices \( R = F_1 A_1 + F_2 A_2 \)

Usage: CALL MADD (N, M, A_1, F_1, A_2, F_2, R)

where
- \( A_1 \) and \( A_2 \) are N by M matrices,
- \( F_1 \) and \( F_2 \) are scalar factors of \( A_1 \) and \( A_2 \), and
- \( R \) is the resultant N by M matrix.

5. **Function DVMAG**

Purpose: to compute the magnitude of an N dimensional vector \( V \)

Usage: \( VM = VMAG (V, N) \)

where \( V \) is an N-dimensional vector and \( VM \) is the resultant magnitude

6. **Function VDOT**

Purpose: to compute the scalar product of two vectors \( A \) and \( B \)

\( S = A \cdot B \)

Usage: \( S = VDOT (A, B, N) \)

where \( A \) and \( B \) are N dimensional vectors and \( S \) is the resultant scalar product
The following library functions are referenced:

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIN (X)</td>
<td>Sine × (radians)</td>
</tr>
<tr>
<td>ASIN (X)</td>
<td>Arcsine × (radians)</td>
</tr>
<tr>
<td>COS (X)</td>
<td>Cosine × (radians)</td>
</tr>
<tr>
<td>ACOSD (X)</td>
<td>Arccosine × (degrees)</td>
</tr>
<tr>
<td>TAN (X)</td>
<td>Tangent × (radians)</td>
</tr>
<tr>
<td>ATAN (X)</td>
<td>Arctangent × (radians)</td>
</tr>
<tr>
<td>SQRT (X)</td>
<td>Square root of X</td>
</tr>
<tr>
<td>ALOG10 (X)</td>
<td>Log to the base 10 of X</td>
</tr>
<tr>
<td>EXP (X)</td>
<td>e to the $X^{th}$ power</td>
</tr>
</tbody>
</table>
SUBROUTINE DSHIFT(I,J,A,B)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(I,J),B(I,J)
DO 1 K=1,I
  DO 1 L=1,J
  1 A(K,L) = B(K,L)
RETURN
END

SUBROUTINE DZERO(A,I,J)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(I)
K = 1 * J
DO 1 L=1,K
  1 A(L) = 0.0
RETURN
END

SUBROUTINE DMPY(A,B,C,M,N,L)
C
SUBROUTINE TO FORM THE PRODUCT OF TWO MATRICES
C
A IS AN M BY N MATRIX
B IS AN N BY L MATRIX
C IS THE RESULTANT M BY L MATRIX
C
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(M,N), B(N,L), C(M,L)
DO 20 I=1,M
  DO 20 J=1,L
    C(I,J) = 0.0
  20 DO 20 K=1,N
C(I,J) = C(I,J) + A(I,K)*B(K,J)
RETURN
END

SUBROUTINE DADD(N,M,A1,F1,A2,F2,R)
C
SUBROUTINE TO ADD TWO M MATRICES
C
A1 AND A2 ARE N BY M MATRICES
C
R IS THE RESULTANT MATRICES
C
F1 AND F2 ARE SCALAR FACTORS OF A1 AND A2
C
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A1(1), A2(1), K(1)
M1 = M*N
DO 100 I=1,M1
100 K(I) = F1*A1(I) + F2*A2(I)
RETURN
END
FUNCTION DVMAG(A,N)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(I)
SUM = 0.
DO 10 I=1,N
10 SUM = SUM + A(I) * A(I)
DVMAG = DSQRT(SUM)
RETURN
END

FUNCTION VDOT(A,B,N)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(N), B(N)
S = 0.
DO 1 I=1,N
1 S = S + A(I) * B(I)
VDOT = S
RETURN
END

B-5
APPENDIX C

IBM 360 VERSION OVERLAY STRUCTURE

Since the core storage requirements increase significantly in converting the program from the CDC 6400 version to the IBM 360 version, it is recommended that the overlay feature be used. The increased storage requirement, which could amount to 30% or more, is due to the shortened word length (32 bits/word vs. 60 bits/word) and the need to revert to the use of double precision.

Because of the fact that the major computations are contained within the do-loop system, the number of prospective subroutines to share the same levels is restricted; the philosophy of the overlay feature being to retain in core those modules which are used consistently and flip in and out those which are used with less frequency.

The resident level should then consist of the subroutines which are used for each iteration. This excludes the following list:

Subroutine    INPTX
              AOC
              CHANEL
              DIAM
              ATTNEN
              PARBDS
              XBD

These essentially are initialization routines and hence need not be maintained in core during the executions of the steepest-descent iterative process. For the CDC 6400 version these represent approximately 13% of the allocated core.

Subroutines OUTPT1 and OUTPT2 are used only once per case and need not be resident. These routines comprise approximately 41% of the core.

The remaining ITS program subroutines and system subroutines make up the remainder; the driver routine requiring only 6% of the core requirement. Therefore to implement the overlay, three levels of routines may be considered:
Resident:

Driver routine (6%)

αlevel:

Initialization routines (13%)

INPTX
AOC
CHANEL
DIAM
ATTEN
PARBDS
XBD

βlevel:

System routine (38%)

EQUAT       PXTR       SPCRFT       RCVRS
OPTMUM      DISCR      ANTS        STNKP
BNDV        DGDEP      ATTCN       STRUC
CNVRGE      GRDFAC     MANPRV      TLMCMD
DIAGN       GDIRECT    MTPLXS      THRML
MAXBD       LNCHV      POWER       XMTR
            TOTCST      PLACE

γlevel:

Output routine (41%)

OUTPT1, OUTPT2

Added to these are the required operating system routines.

To accomplish the overlay, only one level is considered — level α. Three separate packages are interchanged during execution.

\[ \alpha_1 = \text{INPTX} \]
\[ \alpha_2 = \text{EQUAT, OPTMUM, BNDV, CNVRGE, MAXBD, PXTR, DISCR, DGDEP, POWER, RCVRS, STNKP, STRUC, TLMCMD, THRML, XMTR, PLACE, GRDFAC, GDIRECT, LNCHV, TOTCST, SPCRFT, ANTS, MANPRV, MTPLXS, ATTN, VDOT, DVMAG} \]
\[ \alpha_3 = \text{OUTPT1, OUTPT2} \]

All else is resident.