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SPACE SYSTEMS

NASA CR-72579
15 November 1969

TELEVISION BROADCAST SATELLITE (TVBS) STUDY
TVBS TECHNICAL REPORT
VOLUME III

Prepared For The
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Contract Number NAS 3-9708

GENERAL ELECTRIC COMPANY
SPACE SYSTEMS ORGANIZATION
Valley Forge Space Center
P. O. Box 8555 • Philadelphia, Penna. 19101

GENERAL ELECTRIC

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Contract Number NAS 3-9708

Under The Technical Management Of

R. E. ALEXOVICH

NASA Lewis Research Center

Cleveland, Ohio

Prepared By

R. W. HESSELBACHER

GENERAL ELECTRIC COMPANY

Space Systems Organization

GENERAL ELECTRIC

SPACE DIVISION

Valley Forge Space Center

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PREFACE

The Television Broadcast Satellite (TVBS) study was performed, under NASA Contract NAS 3-9708, from August 1967 through January 1969 by the General Electric Company. The study results are presented in the following three volumes:

- Volume I - TVBS Summary Report
- Volume II - TVBS Research and Technology Implications Report
- Volume III - TVBS Technical Report

The TVBS study was accomplished by the General Electric Company's Space Division under the program managership of R. W. Hesselbacher. The technical work was directed by J. D. Dysinger, System Engineering Manager, and D. E. Foster, Subsystem Engineering Manager.

The following General Electric Space Division engineering personnel comprised the permanent TVBS Study Team and performed the technical work reported in this volur

- D. G. Barringer - Audience and Terrestrial Cost Analysis
- E. C. Conway - Heat Pipe Thermal Control Design
- F. O. Drummond - Satellite Thermal Control Design
- K. L. Hanson - Solar Array Design
- J. H. Hayden - Power Conditioning Design
- P. D. Holthenrichs - Attitude Control Design
- H. Jankowski - Satellite Transmitter Design
- M. C. Jeruchim - Communication Engineering Analysis
- D. A. Kane - Satellite Design and System Trade-off Analysis
- A. Marble - Ground Antenna Design
- R. J. Meier - Satellite Antenna Design
- J. D. Porter - Computer Synthesis Model Software Design
- C. C. Rich - Propulsion Design
- R. E. Roach - Structural Analysis
- I. Rutstein - Technology Evaluation
- M. J. Schmitt - Tracking, Telemetry and Command Design
- S. M. Weinberger - Power Transfer Rotary Joint Design
- O. S. White - Low Cost Ground Equipment Design

The following personnel from General Electric organizations (other than the Space Division) were consultants on the TVBS Study.

- J. Beggs - Research and Development Center - Gridded Tube Transmitter Design
- R. Dehn - Tube Department - Klystron Transmitter Design
- R. H. Dome - TV Receiver Department - TV Receiver Analysis
- R. French - Electronics Laboratory - Satellite Transmitter Design
- J. Hesler - Electronics Laboratory - Ground Signal Converter Design

- R. Hughes - Tube Department - Transmitter Power Amplifier Design
- L. Humphrey - Electronics Laboratory - Propagation Analysis
- E. Kleunder - Communication Products Dept. - Satellite Receiver Design
- W. T. Starr - High Voltage Laboratory - High Voltage Breakdown Analysis

The following recognized authorities comprised the Space Broadcast Advisory Board. This board advised the TVBS Study Team in matters of potential broadcast services, economics, operations, finance, education, and international considerations. The board was chaired by R. W. Haviland, Consulting Engineer, General Electric Company.

- Julius Barnathan, Vice President - Operations and Engineering, American Broadcasting Company.
- George Codding, Jr., Professor of Political Science, University of Colorado.
- Dr. John Ivy, Dean - College of Education, Michigan State University.
- John Gayer, International Broadcast Consultant.
- Gerald Gross, President - Telecommunication Consultants International.
- William Lodge, Vice President - Engineering, Columbia Broadcasting System.
- Dr. Paul MacAvoy, Professor of Economics, Massachusetts Institute of Technology.
- Harry Plotkin, Partner - Arent, Fox, Kintner, Plotkin and Kahn.
- John Renner, Director - Jansky and Bailey Systems Department, Atlantic Research Corporation.
- Reid Shaw - Vice President, GE Broadcasting Company.

This volume, although extensive in scope, represents only a portion of the technical work accomplished by the TVBS Study Team. We have attempted to report significant data without burdening the reader with a great amount of detail data. As such, this volume represents about an order of magnitude reduction of the detail technical data that were prepared and submitted to the NASA Lewis Research Center during the course of the study. For example, over 1,000 parametric trade curves were generated by the ERP/PACES/Cost computer program (See Section 6.1) to permit a thorough broadcast system analysis, but only 17 representative or significant curves are included in this report.

ABSTRACT

This report presents the results of a study of technological and cost factors associated with TV broadcast satellite systems. The cost and performance of the ground and space segments of the system are evaluated as a function of varying the parameters of transmission frequency, modulation, TV picture quality, audience size, size of coverage areas, indigenous noise, and ground receiving modification costs. Satellite conceptual designs are described based upon technology estimates for the early 1970's. Cost comparisons are made with terrestrial methods of delivering transmissions. Significant broadcast satellite technology items are identified and ranked in order of importance, and the following conclusions are made: broadcast satellites are feasible, cost effective, and capable of achieving turnkey operations sooner than terrestrial systems.

SUMMARY

This report encompasses a broad systems and satellite design study, performed under NASA contract NAS 3-9708, which investigated technical and economic factors associated with television broadcasting from space. Variables examined included signal quality, transmission frequency, indigenous noise, audience size, broadcast coverage area, signal modulation, number of channels, and cost of ground receivers. Constraints or assumptions included a 1971 technology base, geostationary orbit, satellite life of two years, continuous payload operation (excluding eclipse), and propagation effects dependent upon latitude and tilt angle from satellite.

Services were divided into two major categories for this study. Direct Service is for use by the general public in the home. For this service the ground investment was restricted to less than $150 per receiver. Special Service is for special groups viewing at a smaller number of selected centers, and for inputs to terrestrial broadcast stations. Here, the range of ground investment was $1000 to $50,000 per receiver.

The costs of the ground and space segments of the system and the effects of variations in technical parameters on these system costs were estimated, resulting in data that permits evaluation of specific mission requirements.

Performance characteristics available in the early 1970's were estimated for satellite and ground system components and subsystems. This data permitted feasibility evaluation of synthesized systems and provided a basis for establishing technology development program recommendations. Significant system parameters (e.g., cost, weight, and varying geometry characteristics) are presented for all satellite and ground subsystems that vary as functions of identified critical design requirements.

Conceptual systems designs were developed for design requirements associated with four representative missions: (1) Community Distribution Services for India, (2) Direct Broadcast Service to Alaska, (3) Instructional TV Service to the U.S., and (4) TVBS Demonstration Mission to the U.S. These designs include link calculations to determine satellite design requirements at the operation point which minimizes the pertinent system costs, preliminary definition of satellite and ground system components, development of feasible launch and orbital satellite configurations, launch vehicle selection, system cost estimation, and program plans and schedules.

The economics of terrestrial methods of providing a TV service were investigated. Different cost models were developed as a function of the type of ownership (commercial or government) and the type of service (broadcast, distribution, or educational). Models were developed for combinations of the above, which provide system costs per unit coverage area as a function of transmitter station spacing. Cost comparisons of satellite and terrestrial methods were made for the four selected systems.

Satellite broadcasting technology was investigated in order to determine those additional programs required to develop or advance the state of the art. Pertinent technologies were identified, their performance improvements with time predicted, and their impact on significant system parameters evaluated. Ranking criteria were established to permit listing the selected technologies in order of recommended priority of allocating development funding for varying satellite power level classifications. The most critical items (for high power TVBS applications) are high efficiency microwave and gridded tube transmitters, components for handling of high voltage and high power, interaction of flexible structures with control systems, deployment of large arrays of solar cells, low cost ground receiving systems, and thermal control of high-power transmitter components.

The study reached several important conclusions: (1) high power broadcast satellites are feasible in the next decade, if current technology and subsystem development is continued; (2) satellite systems are cost effective for large regions with no terrestrial broadcast stations (for regions having ground-based systems, the most cost-effective way of increasing capacity is to supplement the existing system with satellites); (3) turnkey operation can be achieved sooner by satellite than by ground-based systems if the objective is a service to the entire population of a region that possesses neither service.

SECTION 1

INTRODUCTION

The possibility of using space technology to provide television broadcast signals to large land areas of the earth has for some time been an extremely attractive prospect. Of all the applications of today's space program, the Television Broadcast Satellite (TVBS) probably has the greatest potential for directly helping the peoples of the world. In its various forms, the Television Broadcast Satellite can provide mass communication and education where there are none; it can extend and improve them where they exist; and it can accomplish these services more cheaply and quickly than any other means.

The overall purpose of this study is to determine the relationships among the parameters that affect the spacecraft so that NASA can use these results along with those of previous and concurrent studies to determine the technical requirements and assess feasible approache to Television Broadcast Satellite Missions over the full range of possibilities.

The subject matter of this study is relevant to the growing awareness among peoples and national governments of the need to provide education to the large masses of the world population and of the need for better communications among the developed areas and nations. Much current interest in the ways and means of best providing these objectives has been expressed. This study investigated technical and economic factors of satellite systems and compared them to certain alternative terrestrial methods. Sociopolitical, programming, and educational effectiveness factors were not included in this study.

The specific data developed and the system analysis method used provide a workable tool for the cost-effectiveness evaluations. The information in this report has been organized to serve as a reference for government agencies or corporations having interest in television broadcasting or distribution.

Past and present television communication by satellites has been limited to relaying to large, complex ground receiving terminals. Satellites for this type of existing service operate at very low levels of RF power output and low transmitting antenna gain. The current technological state of the art is adequate for the small, low-cost satellite of this type, a fact which has been demonstrated. The earth terminals for this type of service must, however, be extremely complex and costly and require an extensive supporting distribution system on the ground. To achieve attractive costs for a system with a large number of receivers, it is necessary to reduce earth terminal costs by orders of magnitude.

One of the goals of the study was to define total systems that are optimized in terms of specific service needs and projected means of payment. Both the ground and space segments of the systems were examined to ensure that the economics would be evaluated in the proper perspective. Because the number of possible specific services was so large, a wide range of parameters had to be examined. The scope of the satellite design requirements was extended from the low Effective Radiated Power (ERP) levels of the distribution type of service to the maximum ERP values permitted by the range of boosters studied, and the associated payloads, and the desired broadcast coverage areas on the ground.

Specific study objectives were to (1) define and examine in detail the technological and cost factors affecting feasibility of a TVBS in the 1970-75 time period through the synthesis of feasible satellite configurations, (2) develop parametric data for spacecraft subsystems, and (3) develop conceptual system designs. The objectives and scope required development of a large number of satellite and ground system configurations. In order to accomplish the study, a three-phase program was defined: System Technical Analysis, System Protoconcept Design, and Satellite Conceptual Design.

The supporting mission analysis and system synthesis task consisted of mission definition to arrive at potential TV services of value, an audience analysis to define the range of audience size to consider for each type of service, and a cost comparison model to enable comparison of satellite broadcasting with alternative terrestrial methods. A simplified block diagram of the study plan is shown in Figure 1-1, followed by a more detailed discussion of each phase.

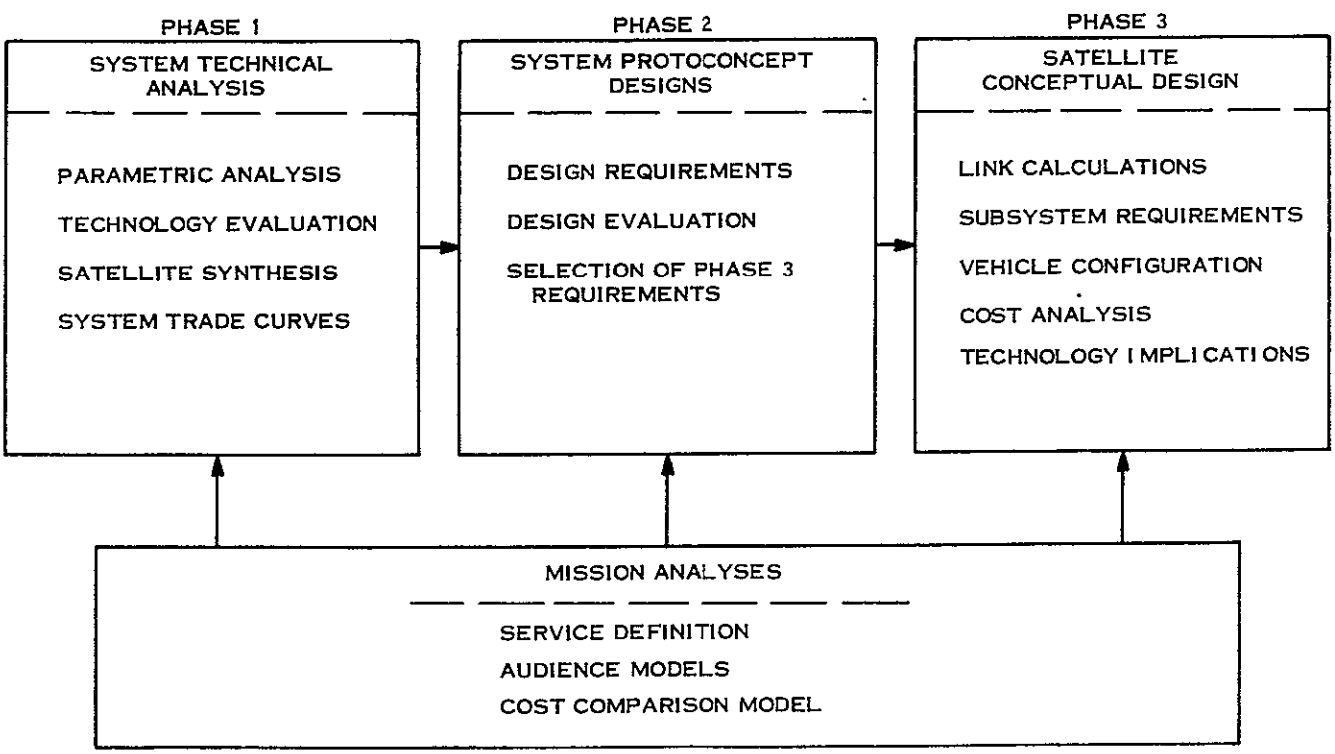


Figure 1-1. TVBS Program Plan

1.1 PHASE 1

Phase 1 was a system technical analysis that included parametric analysis of the ground and satellite subsystems, an evaluation of the current and anticipated state of the art in satellite subsystems, generation of system cost data for trade analysis, and definition of the design requirements for potential television satellite missions.

Phase 1 involved the generation of subsystem performance parameters of significance to the TVBS system (primarily, cost, weight, and power requirements) as a function of the critical design requirements. Where critical subsystem design requirements do not relate directly to broadcast parameters (e.g., structure, attitude control), subsystem design parameters were related to other significant satellite characteristics based on historical design information and engineering judgement. A GE system synthesis computer program was used to develop system cost data necessary for trade analysis.

1.2 PHASE 2

Phase 2 is a system protoconcept design for development of conceptual designs for a relatively large number of potential missions recommended by the GE Space Broadcast Advisory Board. The protoconcept design involved utilization of the results of the system synthesis computer program which generates satellite subsystem parameters and total satellite cost and weight factors. The computer results were modified to incorporate the results of the parametric analysis phase and were used to generate conceptual sketches of the orbital and launch configuration to preliminarily assess overall feasibility. These results were then evaluated by the Advisory Board, which recommended those configurations suitable for further study.

1.3 PHASE 3

Phase 3 is a satellite conceptual design to investigate the satellite aspects with four selected sets of mission requirements. Detailed link calculations were made to arrive at optimized satellite design criteria.

The Phase 3 designs were investigated to sufficient depth to assess design feasibility with respect to the orbital and launch configuration, to define critical technical problems and approaches to their solutions, to estimate development plans and schedules, and to make a detailed cost comparison with alternative methods.

SECTION 2

SUMMARY OF RESULTS

2.1 BOUNDARY CONDITIONS OF STUDY

A listing of the study scope of the contractual effort and of added constraints with respect to the range of parameters is presented in Table 2-1.

Table 2-1. TVBS Study Scope

Subject	Constraints
Launch vehicle	Atlas, Titan, and Saturn 1B class
Orbit	Geostationary
Earth coverage	1/2 to 10 million square miles (Center at subsatellite point)
Effective Radiated Power (ERP)	40 to 80 dBw
Repeater modulation	AM and FM
Transmitter frequency	470 to 890 MHz, 2 to 3 GHz, 8.3 to 8.5 GHz, and 11.7 to 12.7 GHz
Power sources	Any available by 1975
Duty cycle	One to 24 hours per day
Spacecraft life	Two-year minimum
Time period	1970-75
Technology base	1971 state of the art
Man-made noise levels	Urban, suburban, rural
Signal quality	TASO grades 1, 2, and 3 and CCIR relay quality
Audience size	$10-10^8$ receivers
Ground receiver cost	Direct = \$0-\$150 Special = \$1,000 to \$50,000

2.2 SCOPE OF THE STUDY

The scope and depth of the study is illustrated in Table 2-2. Listed are the types of data developed for the subject matter covered in each study phase. The balance of this report describes this data in detail.

Table 2-2. TVBS Study Results

Study Phase	Subject	Type of Data Outputs
Mission Analysis and Cost Models (Phases 1, 2, and 3)	TVBS services	Listing of candidate services
	TVBS audience	Potential receivers per service
	Terrestrial method costs	Cost models for alternative terrestrial methods
System Technical Analysis (Phase 1)	Parametric Data	Cost, weight, and size versus performance
	Ground receiver	Antenna, electronics, and line
	Satellite	Antenna, transmitter, power supply, thermal control, attidue control, propulsion, and structural subsystems.
	System Synthesis	Synthesis of Optimum System by Computer Program
	Ground signal model	Combination of electronics and antenna for given cost which produces minimum ERP requirement
	Satellite model	Synthesis of satellite subsystems requirements as function of ERP required
	System cost model	Satellite selection based on minimum satellite cost total system costs
	Technology Evaluation	State of the art, critical technology items, and ranking
	Ground system	(Modulation and frequency converters)
	Satellite system	Transmitters, antenna, power source, power conditioning, power transfer, thermal, attitude control/structure flexibility
Protoconcept (Phase 2)	Potential TVBS	13 conceptual designs with potential service description
System Conceptual Design (Phase 3)	Selected system conceptual design and description	Optimization analysis, link calculations, launch and orbital general arrangement drawings, satellite subsystem descriptions, program vosts and schedules for four selected systems.

2.3 MISSION ANALYSIS

2.3.1 POTENTIAL SERVICES

The services considered were characterized as being either "broadcasting" or "special service." Broadcasting is restricted to the meaning stated in the ITU/CCIR definition: "... a radio communication service in which the transmissions are intended for direct reception by the general public." Special service encompasses all other potential services that would not satisfy the above definition; it is defined by the ITU/CCIR as "... a radio communication service, not otherwise defined in this article, carried on exclusively for specific needs of general utility, and not open to public correspondence."

A large list of potential TV services with a wide range of transmission parameters was compiled and evaluated by the GE Space Broadcast Advisory Board. The Board is a panel of nine industry and university representatives who are nationally recognized authorities in their diverse fields of interest. Their fields of interest encompass the economic, technical, operational, financial, and educational considerations on an international level. The resultant list of potential (candidate) services is presented in Table 2-3.

2.3.2 AUDIENCE ANALYSIS

An audience analysis was performed to define the range of potential audiences in 1975 for each of the candidate services. Generic models were developed based on the type of service, economic levels, area sizes and population densities. Table 2-4 summarizes the range of results of the audience analysis for the service considered.

Table 2-3. Potential Space TV Services

NAME	GENERAL DESCRIPTION
SPECIAL SERVICES	
ITV	INSTRUCTIONAL TELEVISION FOR FORMAL CLASSROOM USE
"MEDICAL" TV	AN INSTRUCTIONAL SERVICE FOR MEDICAL OR OTHER POST-GRADUATE TRAINING
TV DISTRIBUTION	TO DISTRIBUTE TV SIGNALS FOR RETRANSMISSION BY TERRESTRIAL BROADCAST STATIONS
BROADCASTING SERVICES	
TV BROADCAST FOR THE AMERICAS	TO BROADCAST TV SIGNALS TO THE CONTINENTS OF NORTH AND SOUTH AMERICA
RTV	PROVIDE TV SERVICE TO RURAL, FRINGE AND LOW POPULATION DENSITY AREAS
GTV-D/E	GENERAL PURPOSE TELEVISION FOR DEVELOPING AND EMERGING NATIONS
CTV	CULTURAL TELEVISION FOR DEVELOPED AREAS
URBAN TV	TO PROVIDE TV SERVICE TO URBAN AREAS
UN-TV	WORLDWIDE SYSTEM OF DISSEMINATING UN UNESCO, ETC

Table 2-4. Audience Analysis Results

SERVICE	NUMBER OF RECEIVERS		
	(MINIMUM)	(MAXIMUM)	
BROADCAST			
DIRECT BROADCAST	8500	51,000,000	RECEIVERS
SPECIAL			
INSTRUCTIONAL	3900	282,000	PRIMARY SCHOOLS
	235	42,000	SECONDARY SCHOOLS
	15	2,640	UNIVERSITIES
MEDICAL	60	20,700	HOSPITALS
DISTRIBUTION	5	14,100	TRANSMITTERS

2.3.3 TERRESTRIAL METHOD COSTS

The purpose of the terrestrial cost models was to define the system costs associated with transmitting a television signal from the originating source to the user by terrestrial means. This provided a basis for cost comparisons between terrestrial and satellite systems.

The cost models developed for comparison are based on certain assumptions made to permit modeling; however, the results are respresentative of realistic situations. The model assumes UHF stations transmitting at an ERP level of 1000 kw from antennas 1000 feet above ground. For these systems, the receiver is assumed to be a standard TV set with no preamplifiers; the antenna gain requirement is dependent upon distance from the station. Total system cost is a function of 2 elements: (1) the transmitting station installation and operation, and (2) the receiver installations. Since the receiving antenna installation cost is proportional to the distance from the station (and thereby inversely proportional to the number of transmitting stations and their total cost), there is an operating point for minimum cost dependent upon the number of receivers. In general, the minimum total cost occurs when the coverage radius is extended to a practical maximum by installation of high gain receiving antennas on towers at the fringe areas. Therefore, the coverage radii were established to be 52 miles for a direct service to a home or community receiver and 55 miles for special service receivers. This is based upon receiving antenna heights of 30 feet and 50 feet, respectively. In addition to the coverage radius, the second element determining the required number of stations is the desired portion of the area to be covered. Models chosen for comparison provide 85 percent for home/community coverage and 65 percent for instructional coverage. These values are comparable to existing terrestrial systems.

The initial investment and annual operating costs were determined by first establishing the costs of a single broadcast station and its share of the microwave link. The following variables were investigated in determining the system costs:

1. Type of Ownership. Commercial and governmental ownership was considered. These affect costs in that it is assumed that the government-owned system does not incur indirect costs, such as insurance and amortization of investment.

2. Type of Service. Direct broadcast or distribution services differ from educational services in that quoted microwave link rental rates are lower for educational services.

3. Percentage of Area to be Covered. This directly affects transmitter spacing and number of transmitters required.

4. Number of Channels.

5. Receiving Antenna Height. This also directly affects transmitter spacing.

For the purpose of this study, five unique sets of circumstances that would influence the costs were postulated. These considerations lead to the following models.

Model I: Commercial network with independently owned facilities and rented microwave link

Model II: Government ownership of stations and microwave links

Model III: Government ownership of stations with rental of microwave link at commercial rates

Model IV: Government ownership of stations with rental of microwave link at educational program rates.

Model V: Commercial ownership of stations with joint use of facilities and microwave rental at commercial rates.

The analytical form of the models is presented in Table 2-5, and the associated coefficients are presented in Table 2-6. All that is necessary to use the data is to know the required number of transmitters and transmitter spacing.

Table 2-5. Terrestrial Cost Models

MODEL NUMBER	INVESTMENT COST	OPERATING COST
I	$N\ C_2$	$N\ (D\ K_8+K_3+K_2)$
II	$N\ (D\ C_3+C_1)$	$N\ (D\ K_4+K_1)$
III	$N\ C_1$	$N\ (D\ K_7+K_1)$
IV	$N\ C_1$	$N\ (D\ K_6+K_1)$
V	$N\ C_1$	$N\ (D\ K_8+K_3+K_1)$

Where:

N is the number of broadcast stations required for a system

D is the distance between adjacent transmitters for the specific transmitter, receiving antenna

C is an investment cost associated with the type of ownership and the service of the system

K is an annual operating cost associated with ownership and service of the system

Table 2-6. Summary of Basic Cost Coefficients

	PARAMETER	NUMBER OF CHANNELS 1	2	3	4	5
INVESTMENT COSTS						
BROADCAST STATIONS ($10^3)						
GOVERNMENT OWNED	C_1	549	1021	1481	1941	2871
COMMERCIALLY OWNED	C_2	549	1098		2196	3294
MICROWAVE LINK ($/MILE)						
GOVERNMENT OWNED	C_3	1500	2010		2950	4320
COMMERCIALLY OWNED(1)	C_4	1500	2010		2950	4320
ANNUAL OPERATING COSTS						
BROADCAST STATIONS ($10^3)						
GOVERNMENT DIRECT COSTS	K_1	42	82	113	142	212
COMMERCIAL DIRECT COSTS	K_2	42	85		171	256
INDIRECT COST	K_3	52	99		193	288
MICROWAVE LINK ($/MILE)						
OWNED FACILITIES						
DIRECT COSTS	K_4	150	210		330	450
INDIRECT COSTS(1)	K_5	150	201		295	432
RENTED FACILITIES						
EDUCATIONAL TV	K_6	300	435		680	900
GOVERNMENT	K_7	480	700		1090	1440
COMMERCIAL	K_8	480	960	1440	1920	2880

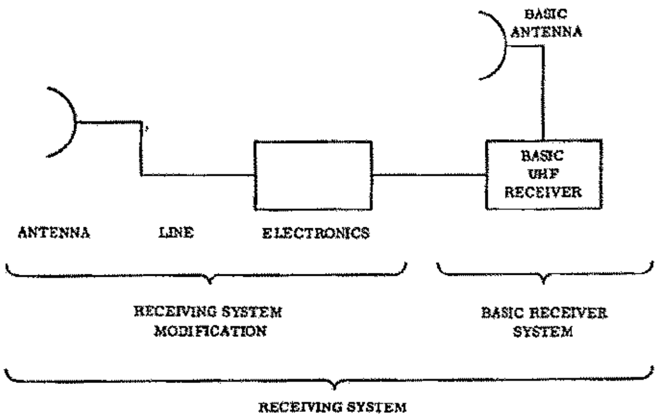
2.4 SYSTEM TECHNICAL ANALYSIS (PHASE 1)

2.4.1 PARAMETRIC DATA

This section presents examples of the subsystem and component data necessary for system cost optimization analysis.

2.4.1.1 Ground Receiver Equipment

In order to examine the cost and performance of the ground segment of the system, it was necessary to compile a set of data related to the portion of the ground receiver system, as shown in the following sketch.



This definition was used to permit relative cost evaluation of a satellite system with a competing terrestrial method; thus, it does not include components that would be common to both systems.

To provide a means of arriving at an optimum cost combination of components (as allocated to antenna or electronics), specific combinations of converter components were selected and cost estimates were made as a function of production quantity for varying performance. The converter components considered include different types of preamplifiers (normal, parametric, and cooled parametric) in combination with frequency and/or modulation converters, as required by the specific transmission case.

An example of the data generated is given in Figure 2-1, which shows the ground electronics data for X-band. Data was developed for the four frequency bands of interest and for the cases of Direct Broadcast or Special Service. To permit optimization of cost, the receiving antenna gain-cost relationship was assumed to be a continuous function. Typical data generated in Figure 2-2, which is for UHF.

2.4.1.2 Satellite Parametric Data

The cost, weight, and other significant characteristics of each satellite subsystem were developed as a function of the critical subsystem parameters that related to the performance requirements of the broadcast service. Example curves of subsystem data developed for weight versus the appropriate parameter are given for the power, attitude control, antenna, and structural subsystems in Figure 2-3 through 2-6. Example curves of the parametric

CONFIGURATION	NF (db)	UNIT COST ($) QUANTITY				
		10	10^2	10^3	10^4	10^5
FREQ CONVERTER + FM DEMOD	9 0	73	44	28	18	13
FREQ CONVERTER + PREAMP + FM DEMOD	5 2	84	51	32	21	14
FREQ CONVERTER + PARAMP + FM DEMOD	1 9	1546	903	528	309	183
FREQ CONVERTER + COOLED PARAMP + FM DEMOD	1 0	38^K	22^K	13^K	8^K	4^K

Figure 2-1. Ground Electronics (8.4 and 12.2 GHz)

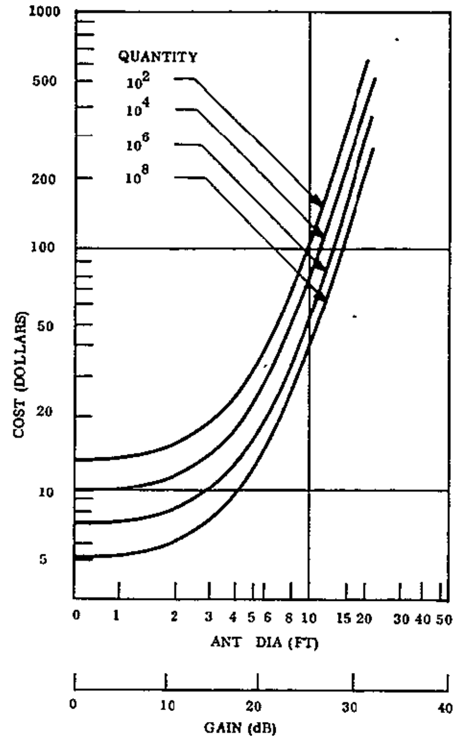


Figure 2-2. 0.8 GHz Ground Antenna Costs

cost data developed are presented in Figures 2-7 through 2-10, for the power, attitude control, transmitter, and heat pipe thermal control subsystem. Examples of additional subsystem parametric data that was necessary for system analysis are shown in Figures 2-11 through 2-14, which show transmitter efficiency, solar array area, and thermal radiator area. The curves are representative of the large amount of parametric data developed during this study and are presented to show the type of results achieved.

2.4.2 SYSTEM ANALYSIS

Extensive system feasibility and cost analysis for the wide study scope was required. A GE computer program developed before the start of the TVBS study contract was applied to the range of parameter requirements (see Table 2-1) to relate system costs to performance requirements. This GE computer program is the Parametric Analysis and Concept Evaluation System (PACES). The major components of this computer model are: (1) a receiver synthesis model, (2) a satellite synthesis model, and (3) a system cost model. The interrelation of these three models is shown in Figure 2-15.

The basic purposes of this computer program are to: (1) determine the lowest cost system to provide any specific service, and (2) to systematically explore the effects of variations of the major system and subsystem parameters on system costs.

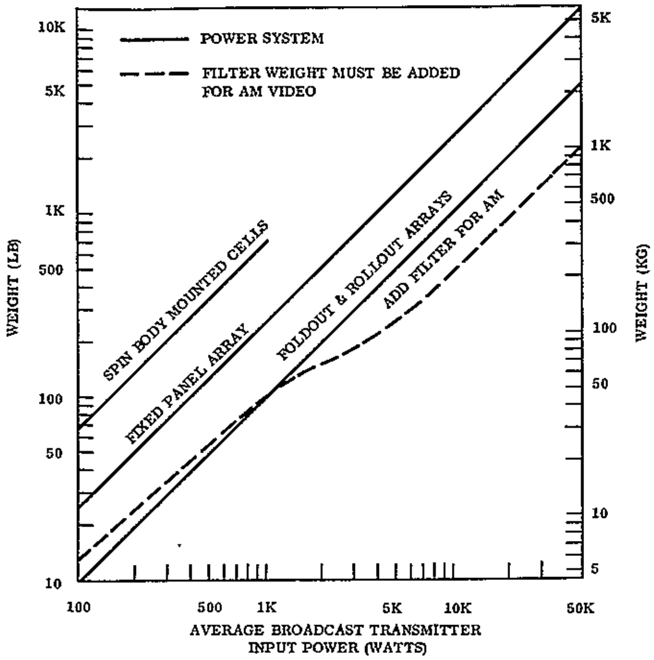


Figure 2-3. Power Subsystem Weight versus Broadcast Transmitter Power

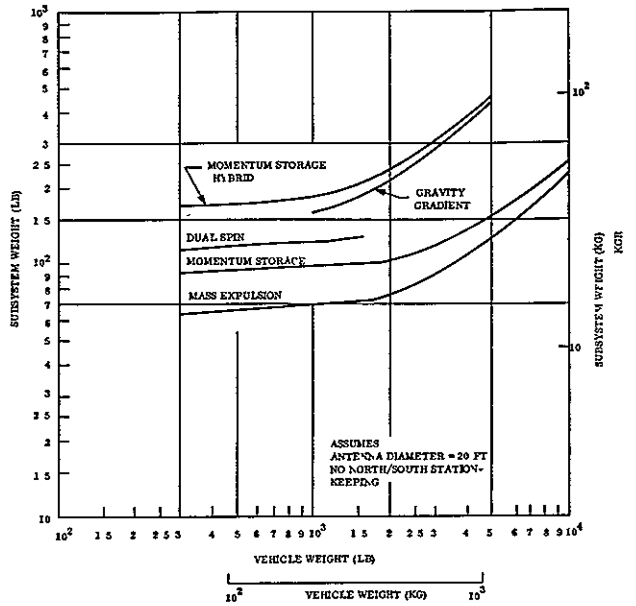


Figure 2-4. Attitude Control Subsystem versus Vehicle Weight

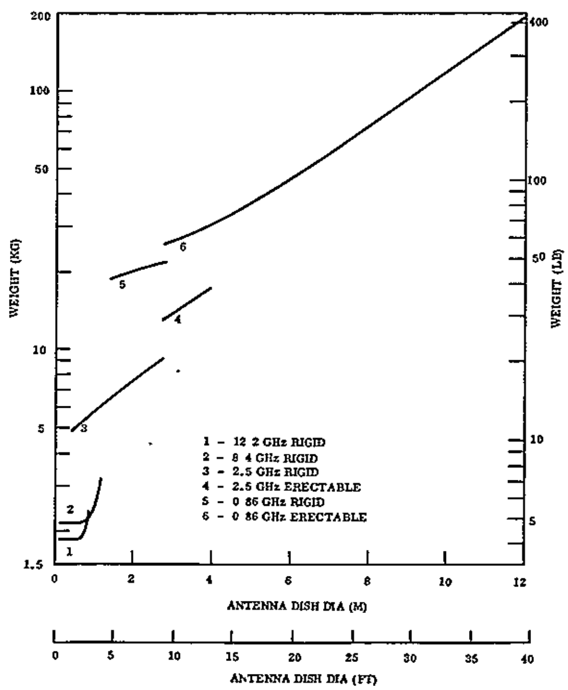


Figure 2-5. Paraboloid Antenna Weight versus Diameter

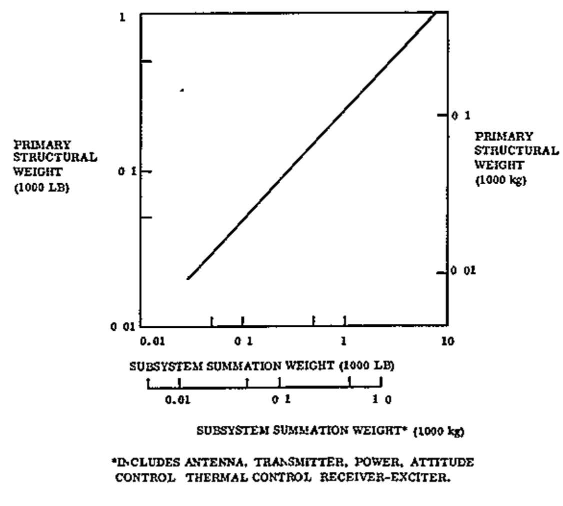


Figure 2-6. Structural Subsystem Weight

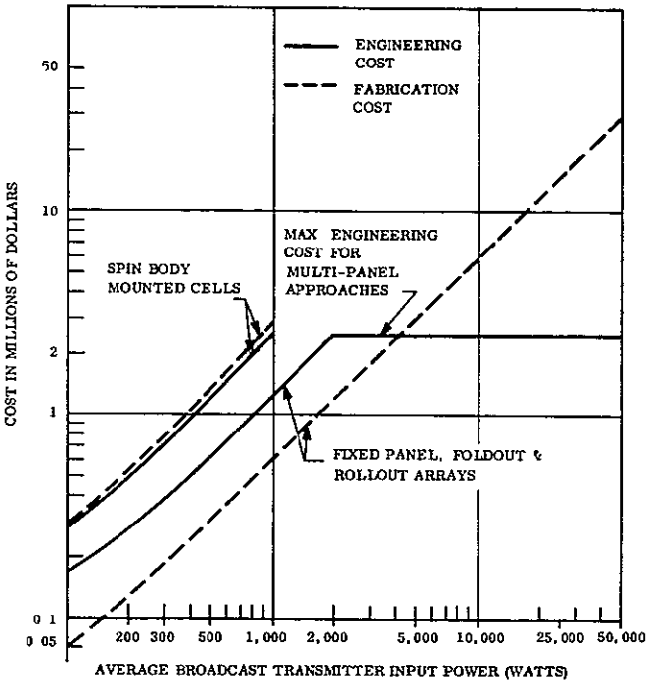


Figure 2-7. Power Subsystem Costs versus Broadcast Transmitter Power

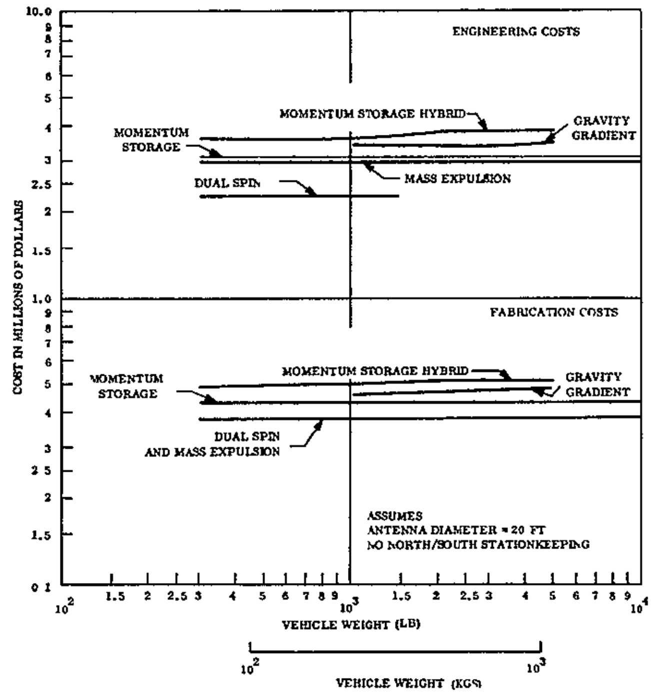


Figure 2-8. Attitude Control Subsystem Costs versus Vehicle Weight

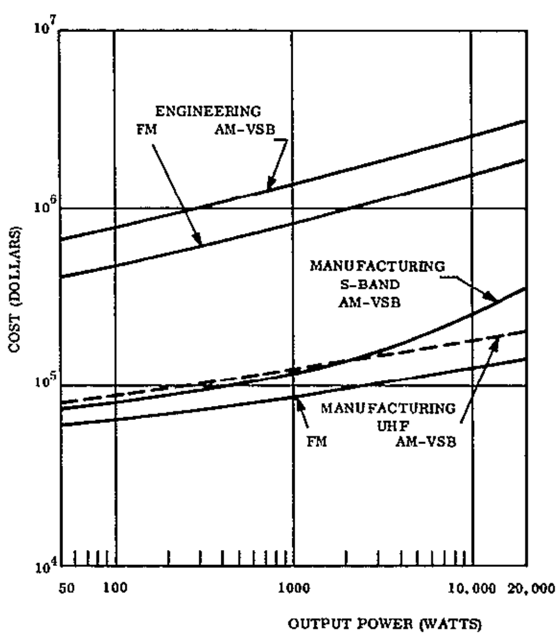


Figure 2-9. CFA TV Transmitter Cost

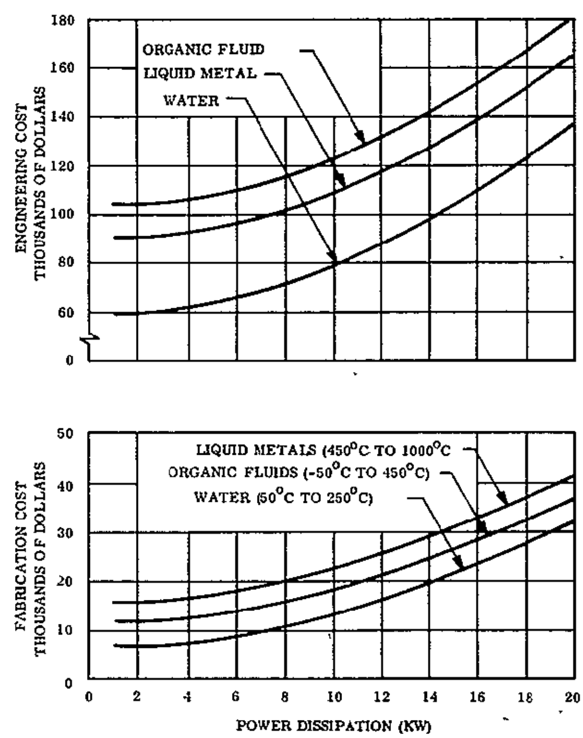


Figure 2-10. Heat Pipe System Cost

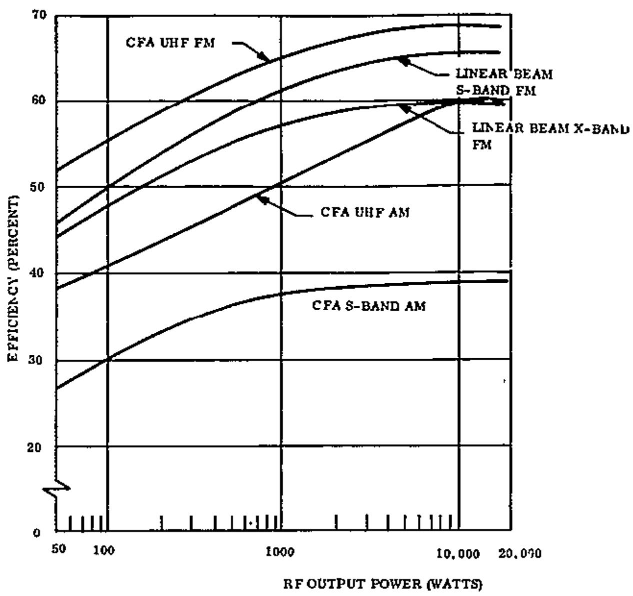


Figure 2-11. Microwave Tube Transmitters Efficiency

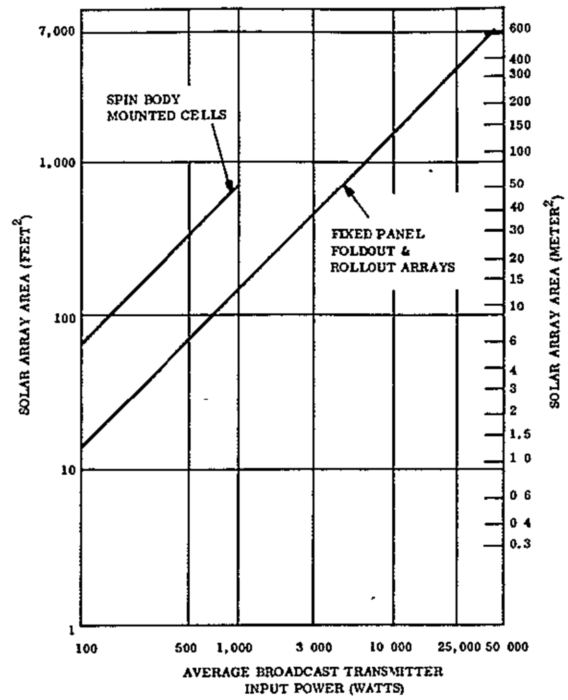


Figure 2-12. Solar Array Area versus Power Requirement

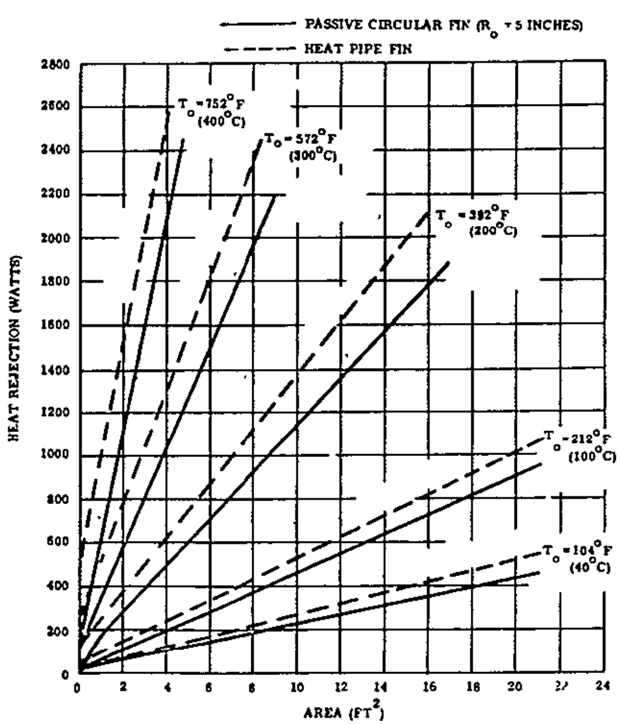


Figure 2-13. Radiator Area Characteristics

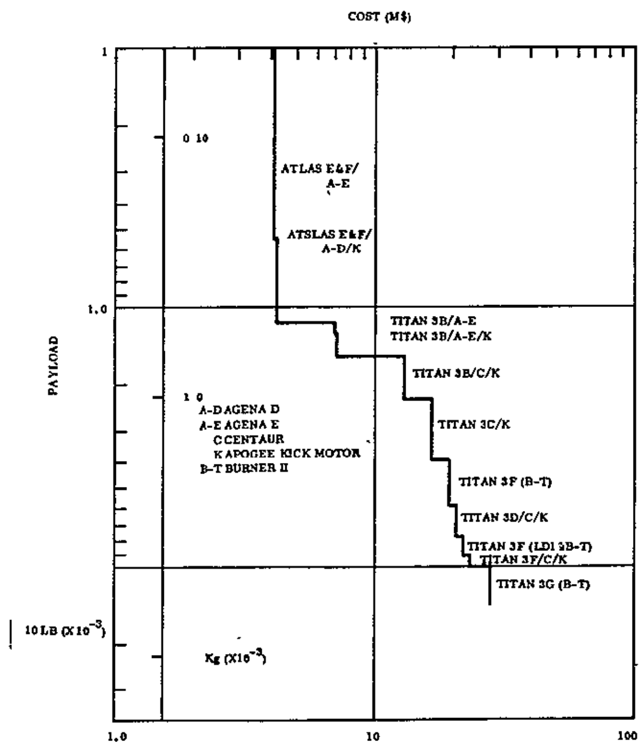


Figure 2-14. Launch Vehicle Cost versus Payload Weight

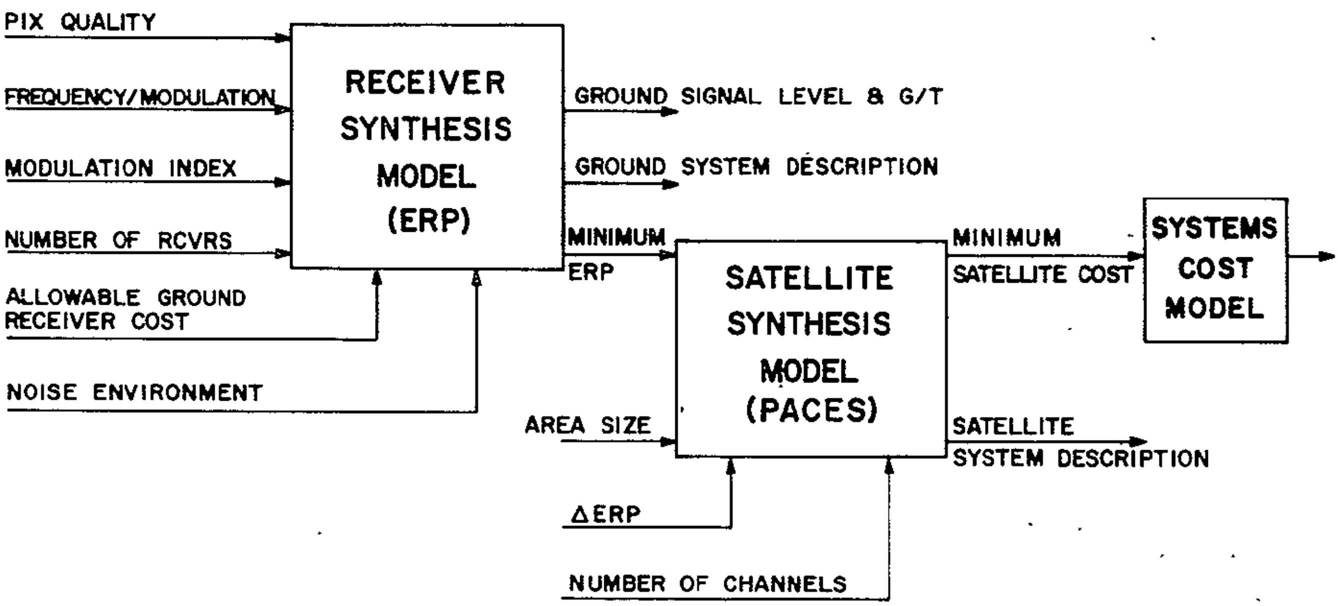


Figure 2-15. PACES Computer Synthesis Model

2.4.2.1 Receiver Synthesis Model

This model defines the maximum performance that can be achieved within a specific ground receiver cost limit. This receiver cost is the installed cost of the antenna, electronics, and the interconnection necessary to receive the satellite signal and supply an output capable of driving standard home television receivers or, in the case of special services, providing baseband output. Maximum performance results in the minimum effective radiated power (ERP) required from the satellite. The model operates on the input parameters of picture quality, frequency/modulation, modulation index, number of receivers, noise environment and the allowable cost per receiver. Where not defined as an input, the model will select that modulation index resulting in the minimum signal level.

The basic aspproach was to solve the link equation associated with RF transmission from synchronous altitude for all possible combinations of input service variables and electronic component performance characteristics. It was necessary to set this up for solution on a digital computer to examine the large number of input cost values desired and to iterate through the variety of electronics components and antenna data for all of the combinations of frequency, modulation audience size, noise location, and picture quality.

One use of this model is to develop curves showing the variation of required ERP as a function of the amount of ground receiver dollars (for each of the values of picture grade, frequency, modulation, noise environment, and number of receivers). Figure 2-16 is an example output for a frequency of 2.5 GHz, AM modulation, an urban noise environment, and 10^6 receiving stations. The model also defines the antenna and receiver electronics performance and cost which results in maximum performance for any specific total ground receiver cost.

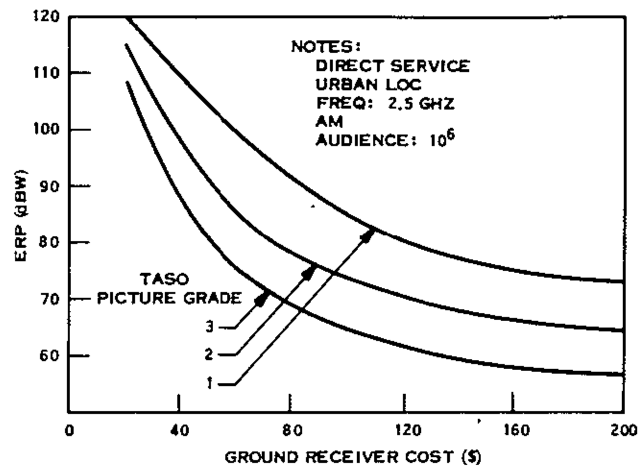


Figure 2-16. Signal Strength Requirements

2.4.2.2 Satellite Synthesis Model

The Satellite Synthesis model operates on the required ERP, the number of video and audio channels, and the desired coverage area size to define the combination of satellite subsystems that meets the performance requirements for minimum cost. It also defines the cost, weight, and performance for each subsystem. In addition, the model accepts inputs to adjust the ERP requirement (ΔERP) to account for the location of the coverage area and ionospheric and atmospheric transmission losses. Satellite subsystems are represented in the model in terms of engineering cost, manufacturing cost, and weight as a function of subsystem performance. The antenna, transmitter, power, attitude control, thermal control, structures, and propulsion subsystems are considered as variables in the model; other subsystems (e.g., TT&C) are treated as fixed points. The model considers antenna pointing accuracy ranges from 0.05 to 5 degrees. For each accuracy assumed, the required antenna beamwidth is defined for the required coverage area. This defines the antenna gain, and, therefore, the RF power output required to supply the defined ERP. The satellite power requirement is then a function of the transmitter dc to RF efficiency. Structural and propulsion subsystem weight requirements are calculated as functions of the summed weight of other subsystems. All the subsystem characteristics, primarily weight and cost, are then summed to represent the total satellite requirements. The minimum size booster capable of launching the satellite into geostationary orbit is selected and the subsystem data are combined to produce the overall satellite cost. Thus, the output of this segment of the computer model is subsystem characteristics, and their summations as required, and selection of the launch vehicle..

2.4.2.3 System Cost Summation Model

Outputs of the ground and space segment models are combined in the systems cost model to derive the system costs, which include management, supporting system investment, operational costs, and amortization. All reasonable combinations of the technical parameters are considered and the resultant costs in various forms are defined. The system costs generated by this model are:

1. Satellite Engineering Development Cost (SEDC) = design, development, and test for spacecraft and design and development of support equipment (i.e., AGE and manufacturing tooling).

2. Satellite Annual Operation Cost (SAOC) = 1/2 (satellite manufacture and launch vehicle), plus support subsystem operation (i.e., uplink, telemetry and control operation), plus 1/10 satellite ground investment (i.e., uplink, AGE, and manufacturing tooling).

3. Total Satellite Cost (TSC) = SEDC, plus 2 SAOC (note: this covers the initial 2 years of operation).

4. Total System Implementation Cost (TSI) = SEDC, plus 10 SAOC, plus unit ground receiver costs times the number of receivers (note: this covers the initial 10 years of system operation).

This cost portion of the program is operated directly in conjunction with the satellite iterative routine for antenna pointing accuracy, and the combination providing minimum SAOC is selected as the synthesized satellite. However, data output for all of the pointing accuracy options examined may be printed out.

2.4.3 SYSTEM TRADE DATA

The primary usage of the PACES computer program was to obtain overall system data to be used for cost-effectiveness analysis of broadcast service parameters. The output was system trade curves (Top Level Trade Curves) in the form of system cost data versus the ground receiving modification costs for varying coverage area size for each desired combination of the following broadcast service parameters: (1) type of service, (2) picture grade, (3) noise location, (4) frequency, (5) modulation, and (6) audience size. The ground receiver modification costs are called delta dollars ($\Delta\$$). More than 4000 Top Level Trade Curves were generated with the combined computer mode.

Figure 2-17 is an example of the trade curve analysis, which shows how optimum operating points may be precisely located. The curves show SAOC and TSI plotted for two values of audience size as functions of Ground Receiver Cost, and with varying size of coverage area. The particular broadcast service would be a Special Service operating at 8.4 GHz/FM and would be providing 18 channels of CCIR Relay quality. The satellite annual operating cost decreases rapidly with receiver cost increase until about $5000 expenditure, at which point the satellite is at near minimum in power requirements. The total system costs parallel the satellite costs for the low audience number (100) reflecting the domination of satellite costs. Ground costs clearly dominate the 1000 receiver case, where the total system costs increase rapidly with receiver cost at about $ 5000. This indicates the false economy of using low power satellites and large expensive ground stations.

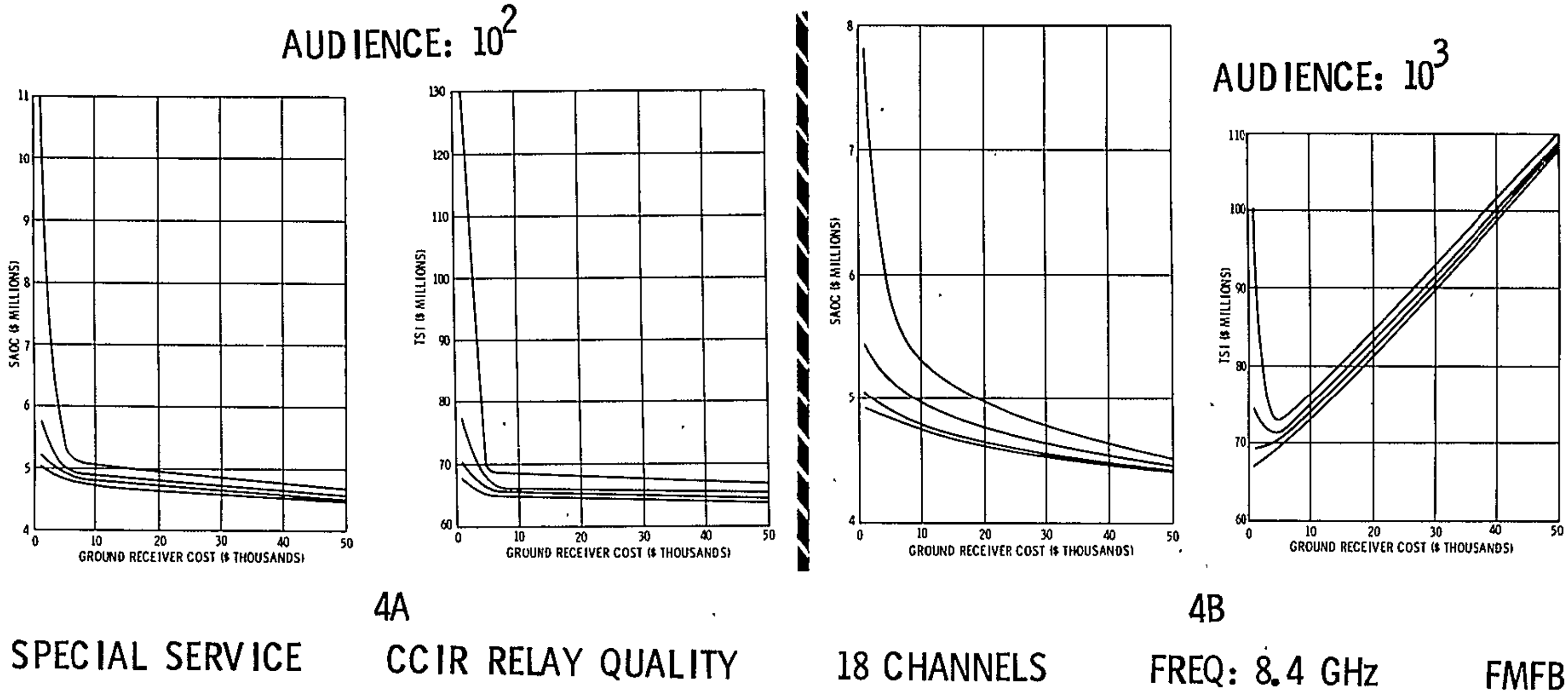


Figure 2-17. Television Broadcast Satellite Systems Cost Curves

2.5 SYSTEM PROTOCONCEPT DESIGNS (PHASE 2)

The general types of potential TV broadcasting services and parameter ranges of interest are listed in Table 2-1. Specific parameter values from Table 2-1 for selected services are shown in Table 2-6. These served as a basis for the generation of the TVBS protoconcept designs. All of the specific combinations were run on the PACES computer program, and the output data was compared with the purpose of selecting the minimum cost combinations consistent with all other criteria.

Table 2-6. TVBS Operational Requirements.

Service Name - Example Target Area	Area $X10^6$	Audience	Number Channels V - A	Signal Grade	Loc.	$Δ	Freq GHz	Modulation	ΔERP
DIRECT SERVICE									
*UN - Africa	10	10^6	1-4	3	U	50	0.8	AM	1.38
Cultural - USA	3	10^6	1-1	2	U	150	2.5	FM	0.83
*Cultural - USA	3	10^6	1-1	2	U	150	0.8	AM	0.80
Cultural - USA	3	10^6	1-1	1	U	150	12.2	FM	2.11
*Cultural - USA	3	10^6	1-1	1	U	100	12.2	FM	2.11
Americas - Cent. & So. America	3	10^6	1-2	3	S	50	0.8	AM	1.04
Rural/Suburban - Australia	3	10^6	1-1	3	S	50	0.8	AM	0.34
*Rural/Suburban - Australia	3	10^6	3-1 ea	3	S	50	0.8	AM	5.66
*Gen. Purpose (Community) - India	1	10^6	1-4	2	U	50	0.8	AM	1 38
*Urban - W. Europe	1	10^8	1-4	1	U	100	0.8	AM	2.48
*Urban - W. Europe	1	10^8	2-4 ea	1	U	100	0.8	AM	5 64
Urban - W. Europe	1	10^8	1-4	1	U	100	12.2	FM	3.64
*Urban - W. Europe	1	10^8	1-4	1	U	65	12 2	FM	3 64
Urban - W. Europe	1	10^8	1-4	2	U	50	0.8	AM	2.48
*Community - India	1	10^6	1-4	2	U	50	0.8	FM	1.38
SPECIAL SERVICE									
*Instructional - All USA	$2\text{-}10^6$	10^4	(6-1 ea)/Area	1	R	1K	2.5	AM	12.95
Instructional - All USA	$2\text{-}10^6$	10^4	(6-1 ea)/Area	1	U	1K	12.2	FM	14.86
*Professional (Medical) - USA	1/2	10^3	1-1	0	U	5K	12.2	FM	2.11
*TV Distribution - All USA	3-1/2	10^3	(6-1 ea)/Area	0	U	5K	8.4	FM	16.07
TV Distribution - USA	3-1/2	10^3	(6-1 ea)/Area	0	U	2K/3.5K	8.4	FM	14 1
*Americas - Cent. & So. America	10	10^3	1-2		R	5K	2.5	FM	1.07
Americas - Cent. & So. America	10	10^3	1-2	0	U	1K	8.4	FM	1.48

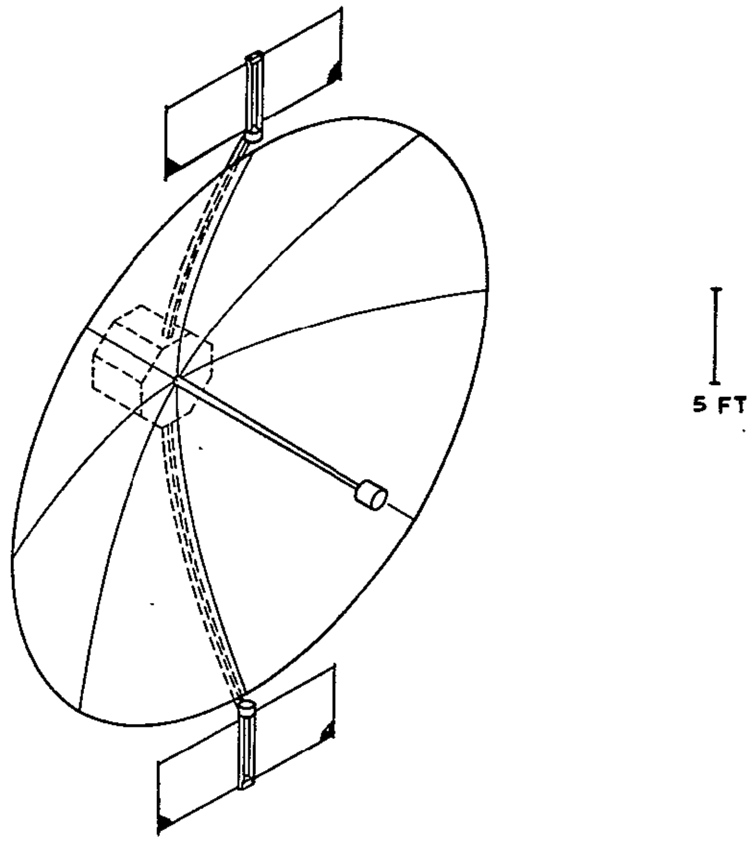
NOTE: V = Video Channel

A = Audio Channel

* = Selected for Protoconcept Design

Examination of the PACES results indicated that specific sets of satellite design parameter combinations would satisfy more than one desired mission, this "commonality" principle then permitted reduction of the number of protoconcepts to 13.

The protoconcept design phase then resulted in the evolution of 13 conceptual designs compatible with the requirements. The basic objective was to assess the feasibility of attaining practical satellite launch stowage and orbital configurations. An example of one of the designs is presented in Figure 2-18, along with a description of the potential mission.



(BROADCASTING SERVICE) COMMUNITY TELEVISION

A COMMUNITY TELEVISION SERVICE IS INTENDED PRIMARILY FOR USE IN EMERGING COUNTRIES THAT COULD NOT HAVE A NATIONAL TELEVISION SERVICE BY OTHER MEANS. EXTENSIVE USE OF RECEIVERS LOCATED AT COMMUNITY CENTERS, RATHER THAN IN HOMES, WOULD BE MADE. BECAUSE OF ITS SPECIALIZED AUDIENCE, COMPATIBILITY WITH EXISTING TELEVISION IS LESS IMPORTANT THAN COST.

THE SERVICE IS A COUNTRYWIDE EXTENSION OF THE "TELECLUBS" WIDELY USED WHEN TELEVISION IS BEING INTRODUCED, AND IS ALSO AN EXTENSION OF THE INFORMAL COMMUNITY VIEWING COMMON WHERE TELECLUBS ARE NOT FORMALLY ORGANIZED.

PROGRAMMING CHARACTERISTICS WOULD BE IDENTICAL TO THOSE FOR GENERAL TELEVISION.

Figure 2-18. TVBS Protoconcept Configuration

2.6 SYSTEM CONCEPTUAL DESIGN (PHASE 3)

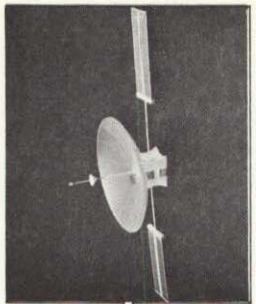
Four representative TVBS systems were examined to sufficient depth to establish feasibility, estimate cost, and compare costs to alternative terrestrial systems. Three of the systems were considered representative of operational TVBS systems. These were selected as a result of the evaluation of Phase 2 protoconcept designs. The fourth system (demonstration mission) was defined to encompass a wide range of mission requirements that would demonstrate a corresponding range of subsystem performance parameters.

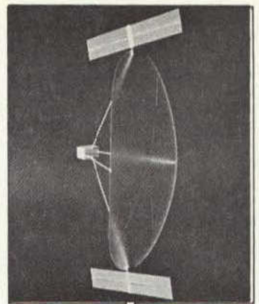
The three satellite systems selected as representative of operational TV space broadcasting were (1) a direct community TV service to India with an added distribution service, (2) a direct rural/suburban TV service to Alaska and, (3) a special instructional TV service to the continental United States. The demonstration satellite system is to provide a TV signal to interested technical and user audiences in the U. S. The baseline requirements for the four systems are shown in Table 2-7. The design description of the resulting systems is shown in Table 2-8. Descriptions of the example services and the key results of the design analyses follow.

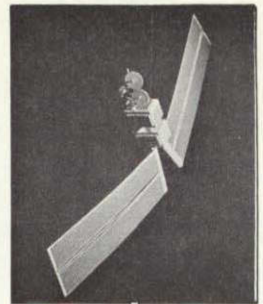
Table 2-7. TVBS Phase 3 Baseline Requirements

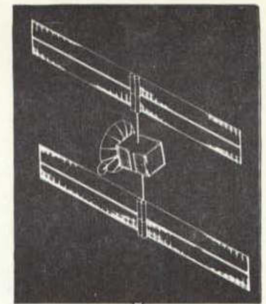
SERVICE DESCRIPTION	FREQUENCY (GHz)	MODULATION	COVERAGE AREA	SIGNAL QUALITY	RECEIVER COST ($)	NUMBER OF CHANNELS
COMMUNITY-DIRECT	0.8	FM	INDIA	2	< 50	1V/4A
REBROADCAST-SPECIAL	8.4	FM	INDIA	CCIR RELAY	1000-5000	1V/4A
RURAL/SUBURBAN-DIRECT	0.8	AM	ALASKA	2	<100	3
INSTRUCTION-SPECIAL	12.2	FM	USA	1	1000	6 EA TO 2 AREAS
DEMONSTRATION SATELLITE	2.5	FM	45°N-10°S	0/1	5000/150	2
	2.5	AM	45°N-10°S	0	1000	1
	12.2	FM	45°N-10°S	0/1	5000/1000	2

Table 2-8. Baseline Requirements for Four Possible Systems









	CASE I COMMUNITY/DISTRIBUTION SERVICE TO INDIA		CASE II DIRECT SERVICE TO ALASKA	CASE III INSTRUCTIONAL SERVICE TO U.S.	CASE IV DEMONSTRATION MISSION TO US
SATELLITE WEIGHT, LBS.	752		2043	983	2036
BOOSTER (CAPABILITY, LBS.)	ATLAS E/AGENA D/KICK (910)		TITAN 3B/CENTAUR/KICK (2260)	ATLAS E/AGENA E/KICK (910)	ATLAS (SLV-3C)/CENTAUR/KICK (2267)
SATELLITE DESCRIPTION	FIG. 7		FIG. 9	FIG. 11	
SI SOLAR CELL PANELS	2 AT 72 FT^2		4 AT 171 FT^2	2 AT 145 FT^2	4 AT 2.00 FT^2
TOTAL CELL AREA (FT^2)	124		621	259	779
POWER LEVEL AFTER 2 YRS (KW)	1.1		5.5	2.3	7.0
ANTENNA TYPE & SIZE	2 CONCENTRIC PARABOLAS 21 FT (0.8 GHz), 2 FT (8.4 GHz)		ELLIPTICAL SEGMENT OF PARABOLOID 29 FT x 80 FT	4 PARABOLAS 2 AT 1.4 FT; 2 AT 2.25 FT	2 PARABOLAS 9.0 FT (2.5 GHZ); 1.4 FT (12.2 GHZ
CONSTRUCTION	DEPLOYABLE (UMBRELLA) AND RIGID		INFLATABLE WIRE GRID	RIGID	RIGID
GAIN & HPBW	BOTH 4.1° CIRCULAR/32 DB		1.1° x 3.1°/39 DB	4.1° CIRC./32 DB; 2.5° CIRC./36.3 DB	3.0° CIRC./34.5 DB; 4.1° CIRC./32 DB
BEAM POINTING (.05° ACCURACY)	ANTENNA ELECTRICAL AXIS USING RF INTERFEROMETER		FEED TRANSLATION USING RF INTERFEROMETER	ORBIT INCLINATION FOR ELEVATION CONTROL, RF INTERFEROMETER FOR AZIMUTH POSITIONING	ORBIT INCLINATION FOR ELEVATION CONTROL, RF INTERFEROMETER FOR AZIMUTH POSITIONING
TRANSMITTER TYPE	CFA	TWT	CFA (SEPARATE VIDEO AND AUDIO)	TWT	CFA (S-BAND AM)(SEP. VID.& AUD.)
AVG RF POWER OUTPUT CH (W)	416	20	505	70 (MAX)	1830
OVERALL EFFICIENCY OF TRANSMITTER SYSTEM (%)	58	35	42	34	37
ATTITUDE CONTROL TYPE	3 AXIS ACTIVE-MOMENTUM WHEEL		3 AXIS-MOMENTUM WHEEL (FLYWHEEL AUGMENTED)	3 AXIS ACTIVE-REACTION CONTROL SYSTEM AUGMENTED WITH PITCH FLYWHEEL	3 AXIS ACTIVE-REACTION CONTROL SYSTEM AUGMENTED WITH PITCH FLYWHEEL
PERFORMANCE					
SATELLITE ERP/CH. (DBW)	58	45	71	50 (MAX)	71
FIELD STRENGTH ($\mu V/M$)	122	18	420	24	437
(REQ'D/ACT.) COVERAGE AREA, 10^6 MI^2	1.1/2.3		0.6/≈1.2	3/≈7.6	–/≈3.0
PICTURE QUALITY (TASO GRADE/S/N)	2/39.5 DB	CCIR RELAY/56.5 DB	2/39.5 DB	1/50.5 DB	1
AUDIENCE SIZE	0.5×10^6	100	10^5	10^5	
GROUND STATION COST ($)	50	2885	100	1100	2110
COST COMPARISON - TOTAL 10 YEAR PROGRAM					
SATELLITE ($ M)	87		155	95	NOT APPLICABLE
TERRESTRIAL ($ M)	151		325	1284	
TERR. TO SAT. RATIO	1.7		2.1	13.5	

2.6.1 COMMUNITY/DISTRIBUTION SATELLITE FOR INDIA

2.6.1.1 General System Considerations

This system would provide a greatly needed instructional, educational, and information dissemination service for developing nations. By providing a simple community receiving system (minimal operation and maintenance requirements), audio-visual presentation can be implemented rapidly by utilization of broadcast satellites. India is a good example of this type of nation because its population is clustered in villages and spread over a large area. Because this type of service is directed toward nations in which use of the RF spectrum is now minimal, the broadcast service parameters can easily be optimized on a cost-effectiveness basis. A distribution service, at 8.4 GHz, was added in this satellite to deliver signals to ground television stations in the major cities.

The community service is the more demanding of the two services; thus, it is selected as the critical design condition for optimum satellite performance. Minimization of TSI cost is the optimization criterion used, since one entity would be likely to bear the entire cost. Figure 2-19 shows that TSI cost is minimized at an expenditure of approximately $50 on the ground receiver equipment, operating at UHF with frequency modulation. (Estimates are based on U. S. costs. Adjustments may be needed for other countries to obtain absolute values, but the relationships shown would remain constant.) A description of the selected ground receiver equipment is presented in Table 2-9 for the two services.

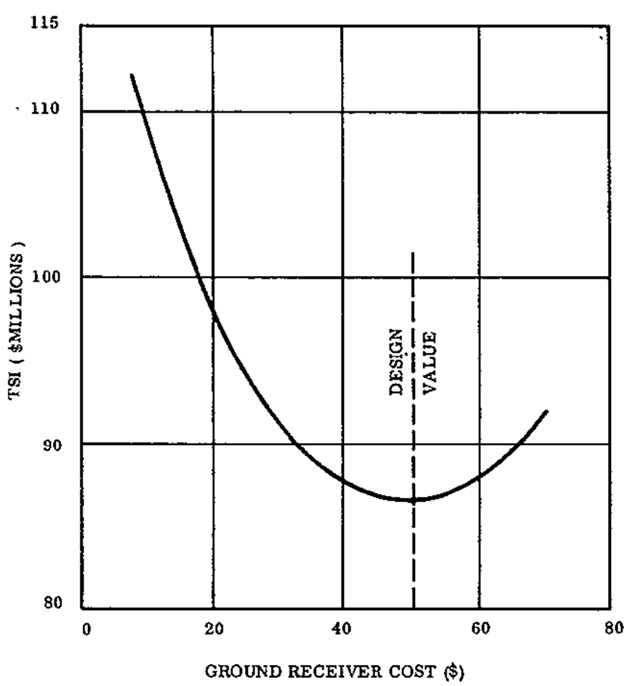


Figure 2-19. System Implementation Costs-Community Service

Table 2-9. Receiver Component Characteristics for TV Service to India

COMPONENT	DESCRIPTION	
	COMMUNITY SERVICE	DISTRIBUTION SERVICE
ANTENNA		
TYPE	HELIX	PARABOLOID
SIZE	12 INCH × 5 INCH DIA	13.9 FT DIA
HPBW (DEGREES)	49	0.59
GAIN (dB)	10	48.4 NOM (47.1 NET)
COST-INSTALLED ($)	37.00	2045.00
ELECTRONICS		
TYPE	PREAMP + MODUL CONV	PARAMP + FREQ AND MODUL CONV
NOISE FIGURE (dB)	3.0	1.9
COST ($)	10.50	903
TRANSMISSION LINE	30 FT TWIN LEAD COSTING $2.50	

The satellite longitudinal positioning selected was the stable point at $77^{\circ}E$ (which is within 2 or 3 degrees of the optimum location for India). The half-power beamwidth (HPBW) coverage provided is shown in Figure 2-20, with the beam centered at $79^{\circ}E$, $20^{\circ}N$. To cover the portion of India between E. Pakistan and Burma (Assam), the transmitting antenna would have to be of HPBW = 5°; but the rest of India can be conveniently covered by a HPBW = 4°, as shown. It was decided to provide the basic coverage to the major portion of India and increase ground receiving sensitivity in the Assam region. The cost of the additional ground antenna gain to provide the 4 to 5 dB for the extreme off-axis location in Assam is about $10 per antenna. With about 20,000 villages in Assam, the additional increment on the ground system cost would be $200,000. The cost of providing 1.9 dB (0.5 kw) additional power on the satellite would be about $1.8M for a 10 year period; thus, the trade is much in favor of the selected approach.

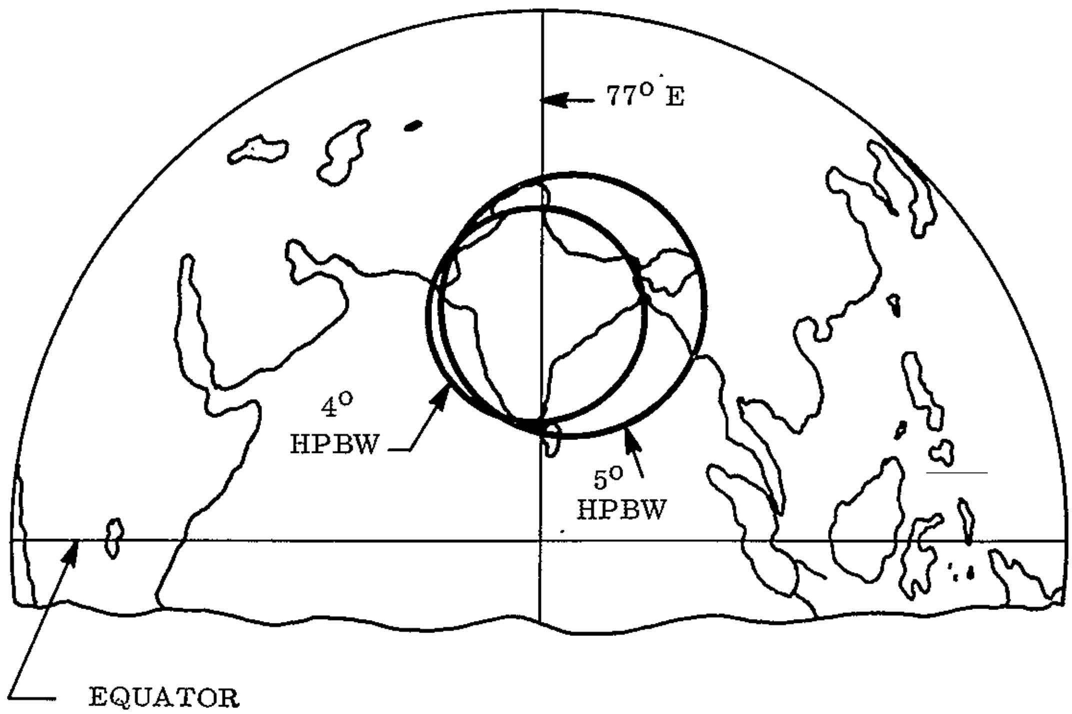


Figure 2-20. Community Service to India Beam Coverage

2.6.1.2 Satellite Configuration

The satellite for this service to India employs a sun orbit-normal reference system to fully orient the solar array to the sun and a cooperative ground beacon for pointing and transmitter to the desired location on the earth. This requires a full 360° per day rotation of the solar array assembly with respect to the antenna/body module and is accomplished with low voltage dc slip rings. Seasonal inclination of the solar array to track the sun would be accomplished by a $\pm 23\ 1/2^{\circ}$ motion, using a flex harness. The satellite antenna package consists of a deployable 21-foot diameter UHF antenna with a concentric X-band antenna (8.4 GHz) mounted on the back of the prime focus feed is accomplished by error signal detection from an RF interferometer system. CFA and TWT power amplifiers are used for the UHF and X-band systems, respectively. Total orbital weight of the satellite is 752 pounds. Because the booster selected (Atlas E or F/Agena D/AKM) has a payload capacity of 910 pounds, there is a weight margin of 21 percent. The AKM (Apogee Kick Motor) was assumed to be a nominal design of the Surveyor-type, employing a mass fraction of 0.9 and an I_{sp} of 290 seconds. The satellite configuration is shown in Figure 2-21 with pertinent characteristics. A cost breakdown of the satellite system and supporting systems is presented in Table 2-10.

Table 2-10. System Costs-Community Service to India

COST CATEGORY / ITEM	COST (MILLIONS $)			
	DEVELOPMENT/ ENGINEERING	FABRICATION, OR REPLACEMENT	ANNUAL OPERATION	INVESTMENT
SATELLITE SYSTEM	13.3	3.4	---	---
LAUNCH VEHICLE	10	4.2	---	---
SUPPORTING SYSTEMS	5	---	.8	1.3
GROUND RECEIVERS	---	---	---	25.0

SAOC = 1/2 (3.4 + 4.2) + .8 + 1/10 (1.3) = 4.7

SEDC = 13.3 + 1.0 + 5 = 14.8

TSI = 10 (4.7) + 14.8 + 25.0 = 86.8

2.6.2 DIRECT BROADCAST-TO ALASKA

2.6.2.1 General System Considerations

This service provides general purpose television to sparsely populated remote regions. The advantages of this type of service would be (1) ready acceptance by inhabitants with available resources to purchase the needed equipment and (2) maintenance would be provided. The example target area is Alaska; three channels are provided.

The development and installation of this type of satellite system is likely to be borne by the U.S. government, the ground system installation cost borne by the user, and the operation conducted by a broadcasting company. This implies that either the satellite annaul operating cost and/or the receiver cost be the governing cost for minimization. For this service, it was decided to restrict operation to the current UHF/AM standards of terrestrial broadcast.

In this case, the cost factor evaluated was the sum of the amortized costs of the ground receiving equipment (using a 10-year amortization) and the satellite annual operating cost. As shown in Figure 2-22, this value decreases rapidly with increasing ground receiver cost up to about \$100. The ground cost of \$100 was chosen for this system because increases do not significantly reduce the total cost and would tend to make the service less attractive to the user. Ground receiving equipment for this service consists of an outdoor antenna, a preamplifier, and transmission line. The equipment characteristics are presented in Table 2-11.

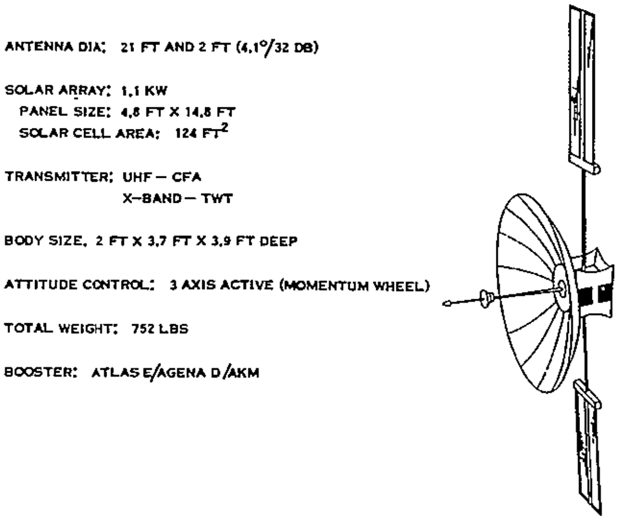


Figure 2-21. TVBS Community/Distribution Service-India, Satellite Configuration and Pertinent Characteristics

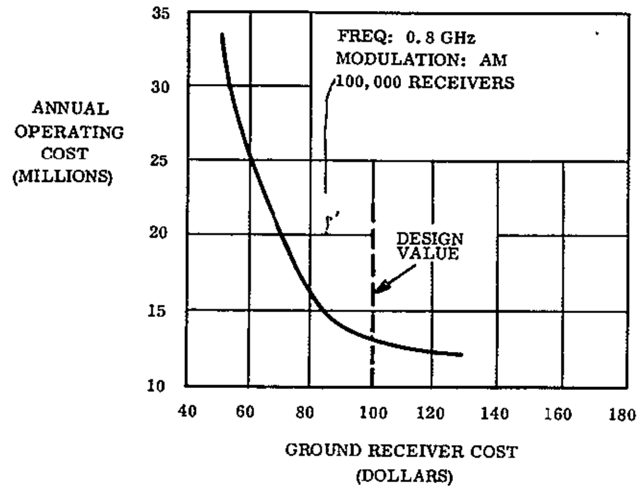


Figure 2-22. System Operation Cost-Direct Service To Alaska

Table 2-11. Receiver Component Characteristics for Direct Broadcast to Alaska Service

COMPONENT	DESCRIPTION
ANTENNA	
TYPE	PARABOLOID (PRIME FOCUS)
SIZE (FT DIA)	5.2
HPBW (DEGREES)	16.5
GAIN (dB)	19.5 NOMINAL (18.9 NET)
COST-INSTALLED ($)	85.00
ELECTRONICS	
TYPE	PREAMPLIFIER
NOISE FIGURE (dB)	3.3
COST ($)	12.50
TRANSMISSION LINE	30 FT TWIN LEAD COSTING $2.50

Longitudinal positioning of 135°W for the satellite was selected so that the satellite can receive an uplink from the Western U. S. and be able to transmit to any portion of Alaska, excluding the Aleutian chain. A more easterly location would be desirable so that the satellite could easily receive uplink transmission from the Eastern U. S., but the local time in Alaska precludes this. At 120°W, which would accommodate an Eastern U. S. uplink, the satellite eclipse at equinox would occur at approximately 9:30 PM, local Alaska time. Because 9:30 is too early, the satellite was positioned at 135°W to extend cut-off time to 10:30 PM.

The RF radiation pattern for Alaska should be squinted to compensate for the extreme latitude, because a circular beamwidth would give excess spillover in the N-S direction and result in inefficiency. A 3^{o} beamwidth in the E-W direction will adequately cover the region from Ketchikan to the Alaskan peninsula, and, if the beam is aywed, the N-S coverage can be achieved with a 1^{o} beam. Therefore, a $1^{o} \times 3^{o}$ elliptical beam was selected, with the resultant coverage shown in Figure 2-23 for a 60°N, 145°W beam center location.

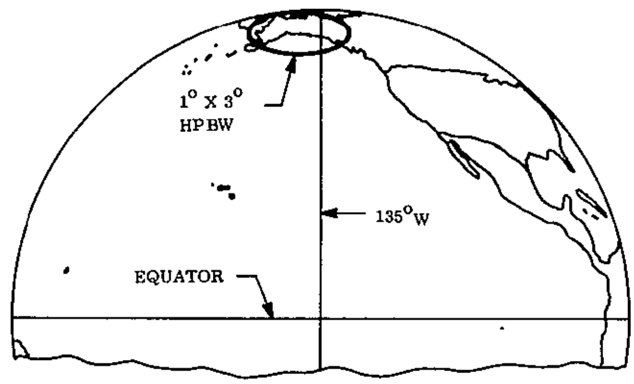


Figure 2-23. Direct Service to Alaska Beam Coverage

2.6.2.2 Satellite Configuration

Direct Service to Alaska would require significant increase in power levels and size from present day satellites. One reason for this is that broadcasting is done with existing standards, using AM modulation. This requires much higher power levels (≈5.5 kw). The other reason is that the restriction to UHF as the carrier frequency causes the squinted narrow-band antenna to be extremely large (29 feet by 80 feet). It may be possible to reduce the size of the antenna without paying a significant system penalty.

A large elliptical dish to track the earth is, therefore, required with the long axis approximately parallel to the satellite pitch axis. The high power level requires fully-oriented solar arrays that rotate about the pitch axis one revolution per day with respect to the antenna.

The size, orientation, and rotation requirements impose a serious constraint on the satellite configuration, because existing and proposed shroud dimensions require a deployable antenna and deployment of the solar array to a position beyond the antenna extremities. The configuration shown in Figure 2-24 includes an inflatable antenna reflector and two symmetrical solar arrays deployed with four telescoping tube assemblies. The satellite body is located in the vicinity of the antenna focal point, so that the feed location can be controlled from a sensor platform which is not separated from the feed by a "soft" structural link.

The solar arrays are articulated and rotated by independent drive assemblies at the junction of the array with the antenna. In addition, separate propulsion units are located at this junction to provide for balancing of torque during thrusting modes.

The satellite accomplishes attitude control with a constant-speed pitch flywheel to provide orbit normal stabilization, a modulation flywheel for pitch control, sun sensors at the solar array for full orientation, and an RF interferometer for pointing of the antenna in a "closed-loop" mode.

ANTENNA 29 FT X 80 FT ELLIPTICAL PARABOLOID
(1.1° X 3.1°) 39 DB

SOLAR ARRAY: 5.5 KW
PANEL SIZE 7.3 FT X 23.3 FT
CELL AREA 621 FT^2

BODY SIZE 4 FT X 7.3 FT X 6 FT DEEP

TRANSMITTER- CFA
AVE RF POWER/CH - 505 W

ATTITUDE CONTROL: 3 AXIS - MOMENTUM WHEEL
(FLYWHEEL AUGMENTED)

WEIGHT: 2043 LB

BOOSTER TITAN 3B/CENTAUR/AKM

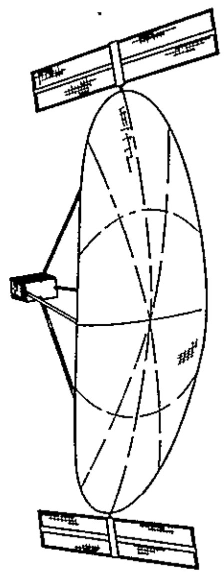


Figure 2-24. TVBS Direct Service-Alaska Satellite Configuration and Pertinent Characteristics

The weight totals 2043 pounds and is summed by subsystem in Figure 2-24. The booster selected for minimum cost was a Titan 3B/Centaur/AKM, which provides an in-orbit payload of 2260 pounds. This provides a 217-pound weight margin (about 11 percent). A cost breakdown of the system is shown in Table 2-12.

Table 2-12. System Costs, Direct TV to Alaska Service

COST CATEGORY / ITEM	COST (MILLIONS $)			
	DEVELOPMENT/ ENGINEERING	FABRICATION, OR REPLACEMENT	ANNUAL OPERATION	INVESTMENT
SATELLITE SYSTEM	20.8	9.2	---	---
LAUNCH VEHICLE	1.0	13.0	---	---
SUPPORTING SYSTEMS	9	---	9	1.7
GROUND RECEIVERS	---	---	---	10.0

SAOC = 1/2 (9.2 + 13.0) + 9 + 1/10 (1.7) = 12.2
SEDC = 20.8 + 1.0 + 9 = 22.7
TSI = 10 (12.2) + 22.7 + 10.0 = 154.7

2.6.2.3 An Alternative Approach for Direct Service to Alaska

The above requirements for a satellite service to Alaska represent extreme conditions and result in a satellite considerably beyond the state of the art. The use of amplitude modulation (to minimize ground receiver cost and RF Bandwidth) requires a very high signal strength to achieve reasonable picture quality and, thus, requires high satellite power levels. The selection of UHF frequency and the necessity to conserve power results in a huge antenna. The india satellite (described in Section 2.6.1) could provide the desired 3-channel service to Alaska, but would sacrifice RF bandwidth and would require a modulation converter at each receiver.

2.6.3 INSTRUCTIONAL TELEVISION SATELLITE FOR THE U.S.

2.6.3.1 General System Consideration

This service would enable developed nations to supplement present educational methods and establish cultural/educational adult community programs. This would be done by utilizing ground receiving stations at discrete centralized locations, such as schools and libraries. High quality teaching instruction could be provided for general and specialized subjects for schools or special interest groups, regardless of local resources.

This service is assumed to require 12 channels (6 to each of two areas). Two beams would be provided to the U. S. during morning and early afternoon hours: one to the eastern region and one to the western region. When the eastern daytime programming is complete, the power used for U. S. transmission would be switched and divided among two previously inactive antennas aimed at Alaska and Hawaii. Daytime instruction for Alaska and Hawaii would then be possible for 5 to 6 hours. Afterwards, power could be switched back to the eastern U. S. the evening cultural/educational programs.

Optimum ground station receiver modification cost was based on total system implementation cost, since the project would likely be federally financed. Minimum system costs occur with frequency modulation of either X- or S-band. However, since the cost differences are small between operation at 2.5, 8.4, and 12.2 GHz, operation at 12.2 GHz was chosen, since allocation of spectrum appears more probable in this frequency band. Figure 2-25 shows that the cost minimum point occurs at a ground receiving cost of $1,100. This value was selected as the design point.

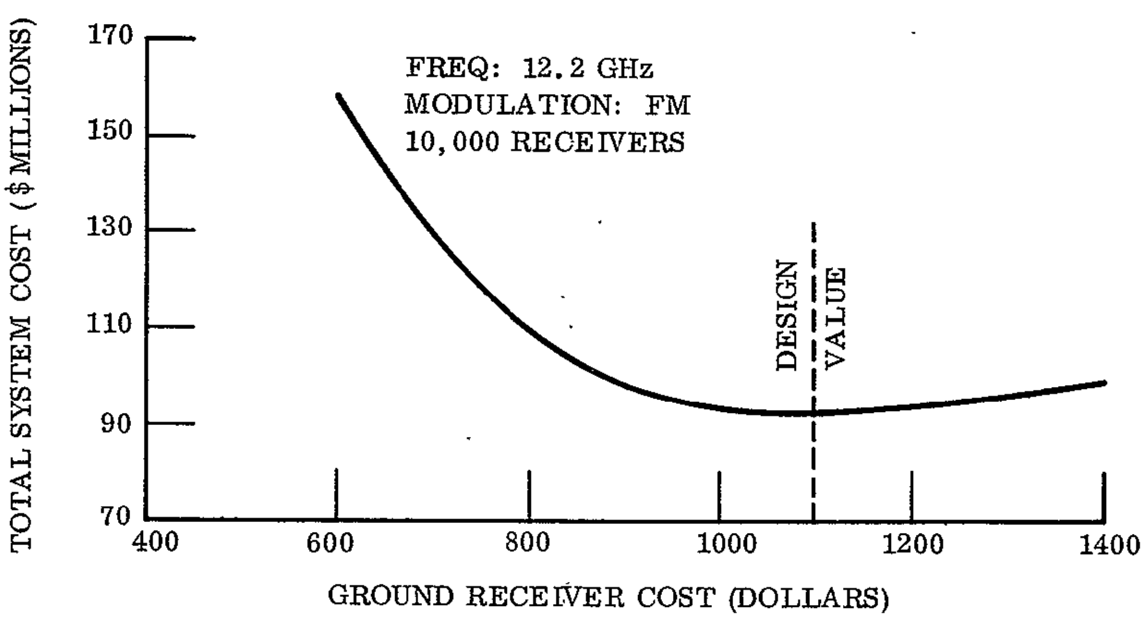


Figure 2-25. System Implementation Costs-Instructional Service

Positioning the satellite involved a trade study considering satellite beamwidth and subsatellite longitude. In many cases, in order to utilize circular beamwidths efficiently, it is desirable to displace the subsatellite longitude from that of the target area. Effective beam shaping is thus gained by creating an elliptical intersection of the conical radiation pattern and the spherical earth. It was determined that the location of 120°W would prevent satellite eclipse during the "prime" evening viewing hours, satisfy all other requirements, and balance out the slant and ground elevation angles between Maine and Alaska. As shown in Figure 2-26, the satellite can achieve coverage of the continental U. S. with two beams of HPBW = 4° and cover Alaska and Hawaii with beams of HPBW = 2.5°. The beam axis coordinates are shown in the following table:

Service	Latitude	Longitude
Eastern U. S.	47°N	68°W
Western U. S.	47°N	88°W
Alaska	72°N	156°W
Hawaii	22°N	162°W

The ground receiving equipment must provide bandwidth requirements for a 6-channel system. The preamplifier is assumed to handle three channels; consequently, the proposed design would use 2 preamplifiers, 2 frequency converters, and 6 demodulators. The resulting price for the 6-channel unit would be $475 for a production quantity of 10^4. The characteristics of the ground receiving system components are presented in Table 2-13.

2.6.3.2 Satellite Configuration

This atellite is a sun/orbit-normal reference system using an RF interferometer system to achieve antenna pointing accuracy of 0.05°. Two fully oriented rollout solar arrays produce a prime power of 2.3 kilowatts. A power conditioning compartment (or module) is fixed relative to the solar array and jointed to the earth-tracking transmitting module through a high-voltage dc-slip ring bearing to provide the daily 360° rotation. Seasonal tracking of the solar array is accomplished by a pivot on the power supply side of the slip ring. The use of dc rather than RF joints means much smaller losses than would be associated with RF joints at the X-band frequencies. The transmitting module contains the reference sensors and tracking electronics, transmitting subsystems for TV broadcasting, TT&C equipment, and a pitch flywheel to "stiffen" the roll and yaw stabilization.

Figure 2-27 shows the satellite configuration and a weight breakdown by subsystem. The broadcast transmitting antennas are fixed to one another, and the TWT power amplifier output will be switched by means of a mechanical RF switch/divider assembly in the waveguide feed system. Subsystem cost breakdowns are shown in Table 2-14.

Table 2-13. Receiver Component Characteristics for Instructional TV Service to U. S.

COMPONENT	DESCRIPTION
ANTENNA	
TYPE	PRIME FOCUS PARABOLOID
SIZE (FT DIA)	8 8
HPBW (DEGREES)	64
GAIN (dB)	47 7 NOM (46 5 NET)
COST-INSTALLED ($)	620 00
ELECTRONICS	
TYPE	PARAMP+FREQ/MODUL CONVERTOR (6 CHANNEL)
NOISE FIGURE (dB)	1 9
COST ($)	475 00
TRANSMISSION LINE	30 FT TWIN LEAD COSTING $2 50

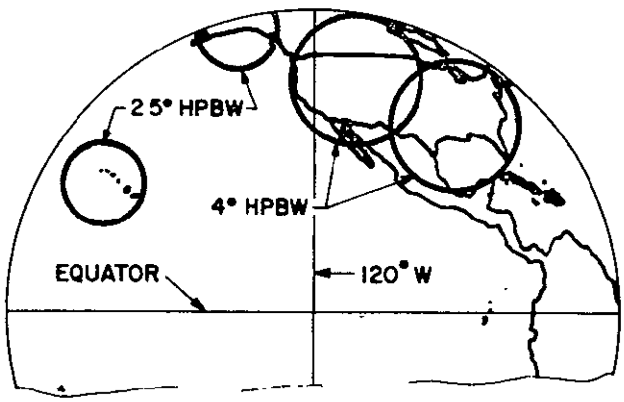


Figure 2-26. Instructional Service Beam Coverage

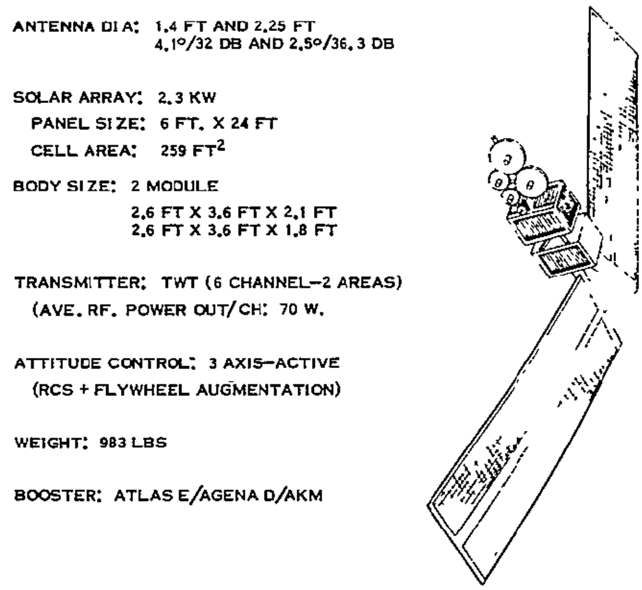


Figure 2-27. TVBS Instructional Service-U. S., Satellite Configuration and Pertinent Characteristics

Table 2-14. System Costs-Instructional TV Service to U. S.

COST CATEGORY / ITEM	COST (MILLIONS $)			
	DEVELOPMENT/ ENGINEERING	FABRICATION, OR REPLACEMENT	ANNUAL OPERATION	INVESTMENT
SATELLITE SYSTEM	22.0	5.9	---	---
LAUNCH VEHICLE	1.0	4.2	---	---
SUPPORTING SYSTEMS	6	---	.8	1.4
GROUND RECEIVERS	---	---	---	11.0

SAOC = 1/2 (5.9 + 4.2) + .8 + 1/10 (1.4) = 6.0
SEDC = 22.0 + 1.0 + 6 = 23.6
TSI = 10 (6.0) + 23.6 + 11.0 = 946

2.6.4 DEMONSTRATION SATELLITE - U. S.

2.6.4.1 General System Considerations

This satellite is postulated as being typical of a satellite that would demonstrate the unique characteristics associated with television broadcasting from space. The primary ground rule for establishment of this system was to select the Atlas-Centaur as the launch vehicle and then establish the prime power available. The two carrier frequencies (2.5 GHz and 12.2 GHz) were selected to be representative of low and high values of the range under consideration, without going to the extreme antenna size associated with UHF. Both AM and FM modulation are included with required S/N_0 ratio established at the receiver for TASO Grade 1 and CCIR Relay Quality pictures.

It is desirable to demonstrate feasibility of critical technology items; the following items are included: (1) multiple channel/feed, (2) deployment of large solar arrays, (3) high dc power rotary joints, (4) high voltage power conditioners, (5) antenna pointing (movable feeds and/or gimbals), and (6) thermal control technology associated with heat pipe transmitter integration.

The demonstration satellite is selected to be centrally located with respect to the U. S., and the specific location is at the west stable point (about 107°W). This causes Maine to be the critical target area, and the three payloads on board were all based on the HPBW coverage extremity being in Maine. The possibility of positioning the satellite eastward exists, because it may be easier to inject at around 92°W; however, total propagation factors would not change appreciably. Beam center-line locations were derived from the coverage plots shown in Figure 2-28 and resultant parameters based on the Maine target area.

2.6.4.2 Satellite Configuration

The U. S. Demonstration Satellite configuration is shown in Figure 2-29. There are two RF carrier frequencies required: 2.5 GHz and 12.2 GHz, but the relative sizes of the antennae would induce unacceptable blockage to the S-band antenna if the X-band antenna were concentric to it; therefore, they are positioned side by side. The large solar array also would resist motion of the entire satellite to achieve antenna pointing; this pointing is accomplished with a gimbal that provides a 2-degrees-of-freedom translational motion.

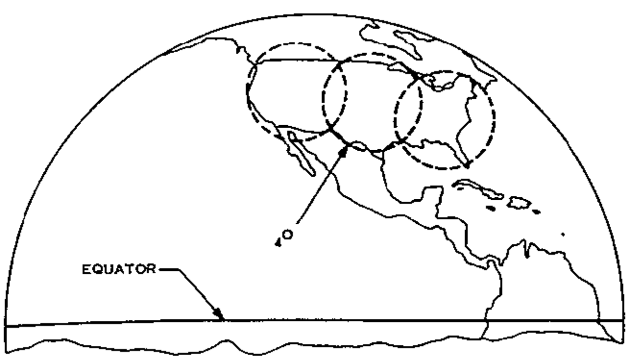


Figure 2-28. TVBS Demonstration Satellite Coverage

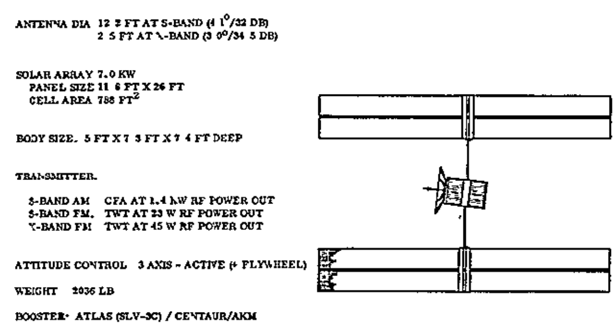


Figure 2-29. TVBS Demonstration-U. S. Satellite Configuration and Pertinent Characteristics

The attitude control and stabilization is accomplished by an earth/orbit normal reference system using a large pitch angular momentum to stabilize the vehicle frame to the orbit normal. The angular positioning required in pitch is derived from an error signal generated by the RF interferometer beacon from the ground target area.

The precise antenna pointing required is accomplished by means of the gimbal system mentioned previously in conjunction with a "closed-loop" control electronics employing the interferometer.

The large solar arrays are four rollout panels, each with almost 200 square feet of area, with a total solar cell area of 779 square feet. These arrays would be nominally oriented normal to the sun line, with seasonal motion requirements accomplished by means of a $\pm 23\ 1/2^{\circ}$ hinge employing flex harness (as for the other configurations).

Thermal control requirements are satisfied by employing four of the six sides for radiating surfaces and internal heat pipe loops to compensate for sun travel around the vehicle in a nominal X-Y plane.

2.6.5 TVBS LINK CALCULATIONS

The details of the calculations made to arrive at required satellite transmitter RF power out are summarized in Table 2-15. In the case of the multiple beam satellites (the Instructional TV-U.S. and the Demonstration Mission - U.S.) only the worst case design condition is shown.

2.6.6 PROGRAM PLANS AND COSTS

In order to display the several parallel and interrelated events on a time scale of the program, a typical summary and project schedule are presented for the U.S. demonstration satellite in Figures 2-30 and 2-31. The NASA Phased Project Planning approach was used as a basis for these schedules, as is noted by the general grouping of tasks on the summary schedules presented. Schedules are assumed to start from the award of a Phase B contract.

In general, an 11-month period is allowed for Phase B, a 24-month period for Phase C/D through Qualification Test, and about 12 months alloted for Phase D flight hardware fabrication, test, prelaunch, and launch. The overall schedule for the space segment of the program encompasses 47 months for the Direct Service to Alaska case, and 41 months for the other three cases. This reduction of 6 months results mainly from overlapping of flight hardware fabrication with final design and qualification test; justification for this would be greater confidence level associated with the smaller size and more straightforward design of these three satellites as compared to the Alaska satellite.

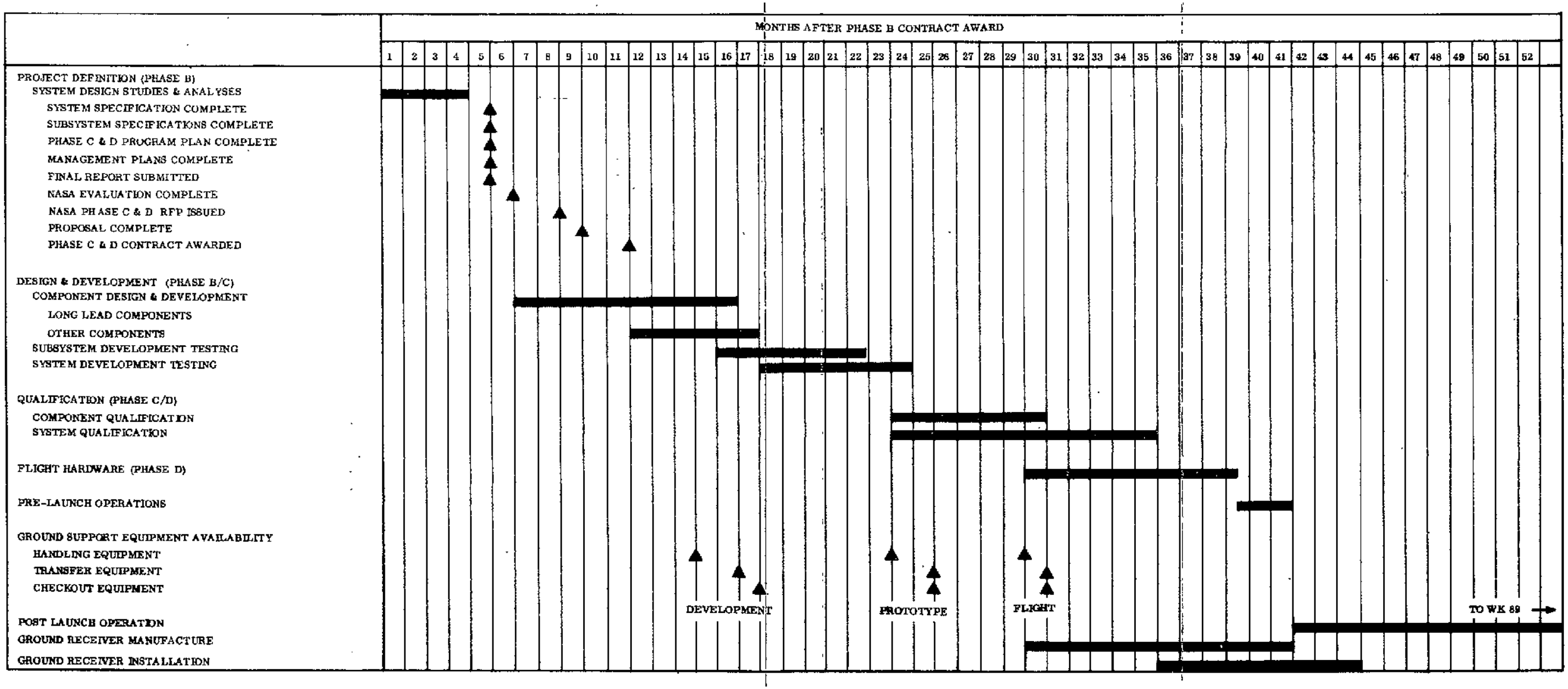
Note that a schedule block to account for postlaunch operation is included on the Summary Schedules. This would extent 48 months from flight date and would include all of the tracking, command, and maintenance activities associated with satellite operation.

Table 2-15. TVBS Link Calculations

ITEM	TV TO INDIA: COMMUNITY	TV TO INDIA: DISTRIBUTION	DIRECT TO ALASKA	INSTRUCTIONAL U.S.(1)	DEMONSTRATION MISSION TO U.S.(3)
FREQUENCY, GHz	0.8	8.4	0.8	12.2	2.5
MODULATION	FM	FM	AM	FM	AM
MAXIMUM DISTANCE, 10^3 NM	20	20	22	21.55	21.20
MIN. GROUND ELEV. ANGLE, (DEGREES)	53	53	7.7	18	24
TV STANDARD, SYSTEM	B	B	M	M	M
PICTURE, TASO GRADE	2	CCIR RELAY	2	1	1
MODULATION INDEX	1.5	6.2	----	5.1	----
IF NOISE BANDWIDTH, MHz	35	101	6	61	6
OUTPUT S/N (WEIGHTED), DB	39 5	56.0	39.5	50.5	50.5
WEIGHTING & DE-EMPHASIS, DB	-16.4	-16.4	-6.0	-12.5	-6.0
MODUL. IMPROV., DB	-15.6	-34.8	----	-32.9	----
REQ'D IF C/N, DB	7.5	4.8	33.5	5.1	44.5
MARGIN, DB	1.5	1.5	1.5	1 5	1.5
ACTUAL IF C/N, DB	9.0	6.3	35.0	6.6	46.0
THRESHOLD, DB	8.8	4.8	----	5.1	----
RECEIVER SYST NOISE TEMP., °K					
RECEIVER AND CABLE	290	175	330	175	114
SKY	35	152	45	202	22
INDIGENOUS (MAN-MADE)	0	0	281 (2)	0	4
EARTH AND OHMIC LOSS	116	32	116	32	46
TOTAL	441	359	772	409	186
SYSTEM NOISE POWER, DBW	-126 9	-123 0	-131 9	-126.9	-138.1
RECEIVING ANTENNA					
GAIN, DB	-10 0	-48.4	-19 5	-47.7	-33.0
POINT LOSS, DB	0.0	0.8	0.1	0 7	0.1
POLARIZATION MISMATCH, DB	0 5	0.5	0.5	0.5	0.5
NET GAIN, DB	-9.5	-47.1	-18.9	-46.5	-32.4
CARRIER POWER REQ'D, DBW	-117.7	-116.9	-96.9	-119 7	-99.2
PROPAGATION LOSS					
IONO., TROPO., & REFR., DB	0 0	0.1	0.2	0.4	0.1
FADING, (DB)	0.0	0.0	0.9	0.0	0.0
CLOUD, (DB)	0.0	3.0	0.0	0.9	0.1
PRECIPITATION, (DB)	0.0	0.4	0.0	4 3	0 0
FREE SPACE, (DB)	182.5	202.5	182.7	206 2	192.3
TOTAL	182 5	206.0	183 8	211.8	192 5
REQUIRED ERP/CHANNEL, DBW	55.3	42.2	68.0	47.3	67.9
ON-AXIS SIGNAL STRENGTH, μV/M	122	18	420	24	437
ON-AXIS POWER DENSITY x 10^{12}, W/M^2	39	0.8	470	1.5	607

(1) WORST CASE SHOWN (EASTERN U.S.) (2) INCLUDES 252°K FOR LOW ELEVATION ANGLE EFFECT ON MAIN LOBE. (3) WORST CASE OF 3 PAYLOADS

A separate block for ground receiver fabrication and installation is shown as a lead item prior to flight date. This is an estimate based upon the desired quantities and is made on the assumption that manufacturing facilities are in place to provide the necessary output.



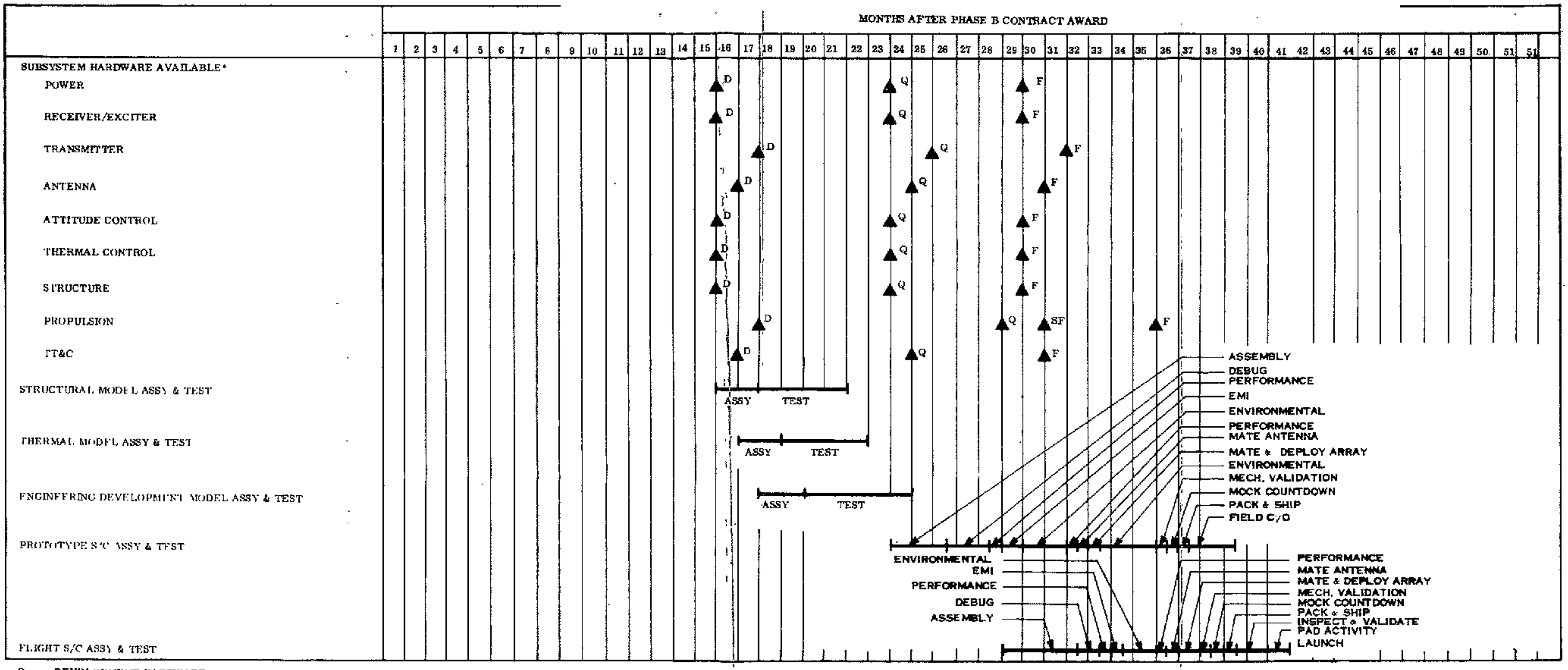
A

FOLDOUT FRAME #1

B

Figure 2-30. TVBS Demonstration-U. S., Summary Schedule

FOLDOUT FRAME #2



D DEVELOPMENT HARDWARE
Q QUALIFICATION HARDWARE
F = FLIGHT HARDWARE
SF = SIMULATED FLIGHT HARDWARE

Figure 2-31. TVBS Demonstration - U.S., Project Schedule

A FOLDOUT FRAME #1

B FOLDOUT FRAME #2

The NASA Phased Project Planning schedules described above are more extended than those that would result from competitive commercial business after the technology had been developed by NASA. To arrive at schedules for operational systems, the Phase B would be eliminated and the Phase C and D tasks would be overlapped. Using these assumptions, the time between contract go-ahead and launch for the operational systems would be as follows:

1. Community Service to India ------------ 24 months
2. Educational TV Service to the U. S. ----- 24 months
3. Direct Service to Alaska -------------- 30 months

Costs of specific subsystems were determined from the parametric performance/cost data, as determined in Phase 1 of the program, to serve as the baseline for cost estimating. The summation of these subsystem costs was then modified by appropriate factors (integration, liaison, and management) and combined with ground receiver costs to develop the total costs.

A summary of the development, investment, and operation cost estimates for the four TVBS systems are presented in Table 2-16.

Table 2-16. TVBS System Cost Summary

Configuration	Satellite Development	10-Year Satellite Operation(2)	Ground Receiver Investment	Total 10-Year Program(1)
Community/Rebroad-cast Service to India	14.8	47.0	25.3	87 1
Direct Broadcast to Alaska	22.7	122.0	10.0	154 7
Instructional TV to U.S.	23.6	60.0	11.0	94.6
Demonstration TV to U.S.	23.3	27.8(1)	Not Applicable	51.1(1)

(1) In the case of the demonstration satellite, the totals are based on a 2-year period.

(2) This allows for 5 launches in the 10 year period.

2.6.7 COST COMPARISONS

The worth of a satellite broadcast system becomes evident when the satellite system is compared to the cost to implement and operate an equivalent terrestrial television system (the alternate approach to providing the TV services). The general terrestrial cost models developed for this study were described in Section 2.3.3. Cost comparisons for the Demonstration Mission are not applicable. The Community Service to India and the Direct Broadcast to Alaska Service were classified as Direct Services providing 85 percent area coverage, while the Instructional TV Service to the U. S. was considered a Special Service providing 65 percent area coverage. These values of area coverage were taken as reasonable estimates for a terrestrial system and will result in substantially lower than 100 percent coverage. Satellite systems will provide 100 percent coverage. The resultant terrestrial costs for the three operational systems are shown in Figures 2-32, 2-33, and 2-34.

2.6.8 SCHEDULE COMPARISONS

One significant advantage of the satellite broadcast system over the terrestrial broadcast system is the shorter length of time required to establish communication signal coverage to a majority of the population of large geographical areas (areas larger than 1/2 million square miles - roughly equivalent to one U. S. time zone).

In the United States, the first terrestrial television channel coverage was obtained in 6 years for 90 percent of the population. It took 16 years before 95 percent of the population had coverage. For developing and emerging nations, the time period for coverage will be extended considerably because they must industrialize before they can install and maintain a terrestrial system.

In contrast, television by satellites offers full national coverage from the beginning of service. The program schedules for establishing a television satellite system is 2 years for design of an operational satellite and 4 years for a satellite requiring development.

In the United States, it took 5-1/2 years to establish a market and distribute television receivers for 50 percent of the population. It took 12 years before 90 percent of the population had receivers, and it was 9 years later before 95% of the population had receivers.

The above time factors lead to the following conclusions:

1. An additional TV channel can be established for 100 percent coverage of the population of a developed nation via satellite in 1/4 to 1/8 of the time required to install an additional terrestrial system for 90 percent to 95 percent coverage of the population.

2. A new satellite TV service can be established for 100 percent of the population of developing and emerging nations many decades before a terrestrial system could be installed and maintained. The time period for the satellite system will be determined by the time selected for production, distribution, and maintenance of the television receivers. This time period can be shortened significantly by designing the system for the simplest of television receivers and by having these receivers produced in a developed nation.

2.7 TECHNOLOGY EVALUATION

The main objective of the technology evaluation was to identify and assess those significant technologies underlying the TVBS requirements to determine additional development programs needed. Candidate technologies for additional development were selected based upon current development programs and upon the expected effect which that development effort might have upon the system cost, weight, life and performance, or subsystem feasibility. The state of the art was assessed for each technology as a further indication of its critical nature and the need for additional development effort. The technologies were ranked according to the degree of system impact, which each improvement would have, and according to the technology development risk and required lead time.

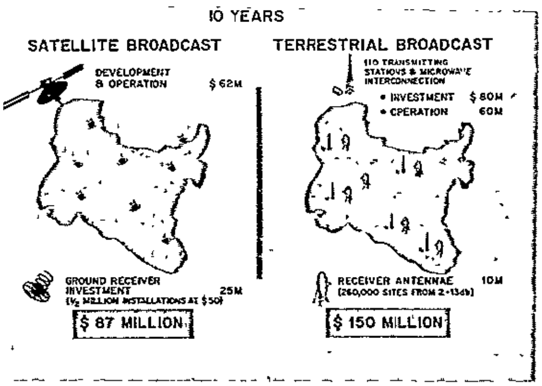


Figure 2-32. Cost Comparison/ Community to India

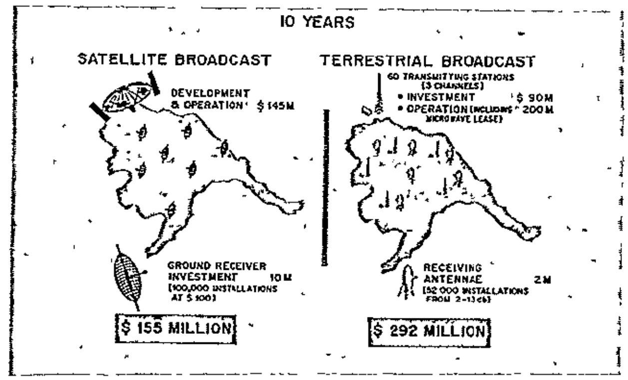


Figure 2-33. Cost Comparison/ Direct to Alaska

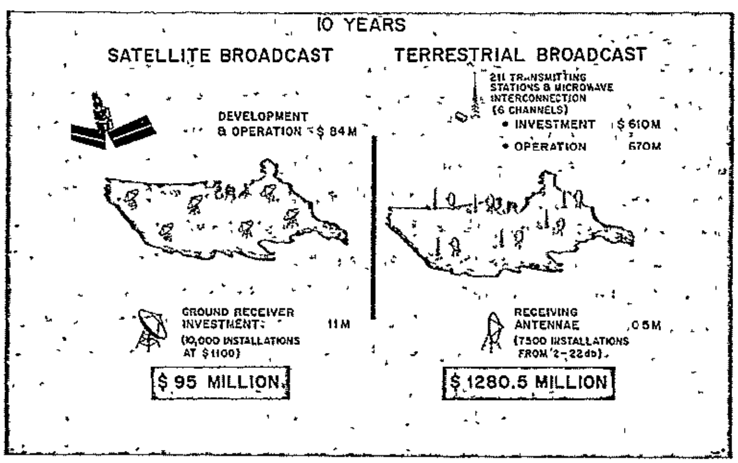


Figure 2-34. Cost Comparison/Instructional to U. S.

The following are the major technological problems associated with the TV Broadcast Satellite requirements:

1. The generation and handling of high dc and RF power and voltage in the space environment

2. The adequate dissipation and control of heat generated as a result of operating at high power levels

3. The deployment and orientation of large flexible structures (such as solar panels), also necessitated by the high power requirement

4. Long life reliability (with 2 to 5 year goals)

2.7.1 STATE OF THE ART FOR TECHNOLOGIES

2.7.1.1 Prime Power

The power subsystem is particularly significant because it represents a relatively high proportion of total system weight, volume, area, and cost. This can be seen by curves showing the percentage allocations of the satellite totals by subsystem as presented in Figures 2-35 and 2-36 for weight and fabrication cost. These curves were developed to aid in the evaluation of technology criticality.

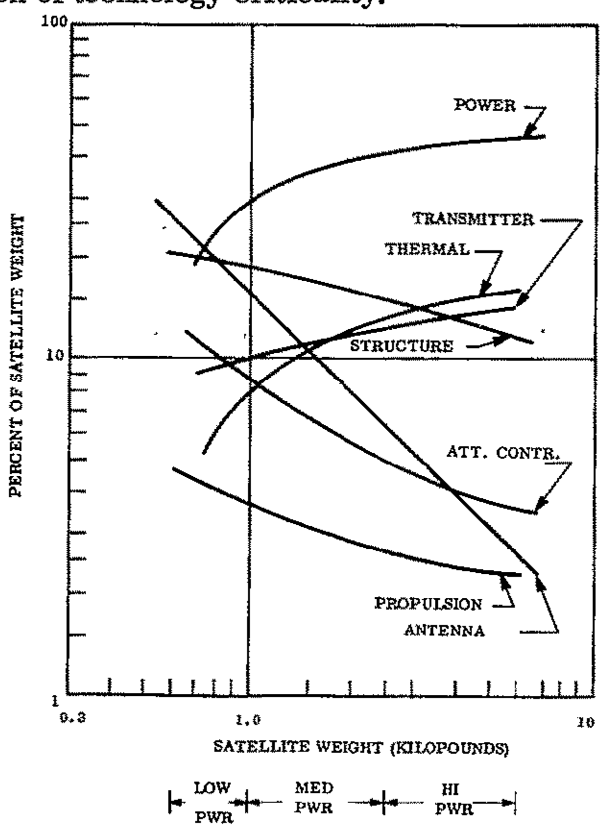


Figure 2-35. TVBS Sensitivity at UHF (0.8 GHz)

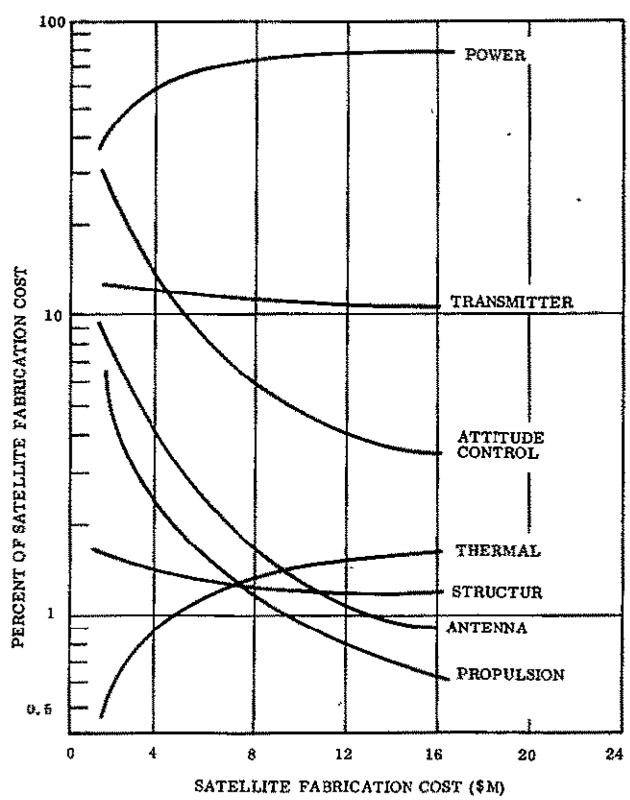


Figure 2-36. TVBS Subsystem Fabrication Cost Sensitivity at UHF (0.8 GHz)

The high labor costs associated with solar array fabrication should motivate the evolution of product techniques for automatic cell manufacture and laydown. System considerations indicate that the development of higher voltage (e.g., over 200 volts) solar arrays could result in easing the power conditioner design requirements.

2.7.1.2 Power Conditioning

Space technology for low-weight power conditioners at levels over 1000 watts and above 2000 volts is not well developed. The general problems associated with high-voltage breakdown of dielectrics need to be solved. The technical feasibility of high-power, high-voltage conditioners in the hard vacuum of space over periods of more than 2 years has yet to be shown. Techniques for greater efficiency and lower weight need to be developed.

2.7.1.3 Transmitter

The transmitter for TVBS applications is required to transmit high power (kilowatt levels) at UHF or higher frequencies in a space environment. High efficiency output devices and associated RF components for such a transmitter are still to be developed and space qualified. High frequency, high power output, high efficiency, linearity, broadband signal handling and thermal dissipation are the prime areas requiring development.

2.7.1.4 Thermal Control

The high values of heat dissipation density and temperature cocurring with high power RF transmitter stages and power conditioners make thermal control a critical technology for broadcast satellites. Heat pipes with over 2-kilowatt capacity need to be investigated for additional data on critical (or burnout) heat flux, so that weight and cost can be reduced by configuration optimization.

2.7.1.5 Antenna

The antenna problems are associated primarily with the stowage, deployment, and orientation of the antenna structure, particularly at the UHF frequencies considered. Beam pointing, beam shaping, and multibeam techniques require development. Very high power levels (greater than 10 kw) may make it necessary to use array antennas for distribution of the power among many feed elements to avoid RF breakdown. Side lobe suppression of multiple and movable feeds is necessary for certain broadcast services.

2.7.1.6 Rotary Joints

The dc rotary joint that might be required between the solar array and the spacecraft involves a number of potential problems related to brush, ring and bearing life, lubricants, outgassing, insulation materials, leakage paths, temperature control, size and weight. Adequate design data for high RF rotary joints between the spacecraft and antenna are lacking, particularly with regard to techniques required to eliminate high power breakdown and multipacting under vacuum conditions. The liquid metal slip ring should be investigated.

2.7.1.7 Attitude Control and Flexible Structures

Attitude control components for TVBS applications are not considered to involve critical technologies. However, significant errors in solar panel orientation and/or antenna pointing angles could result if the effects of motions of large flexible appendages attached to the spacecraft are not investigated and provided for in the attitude control subsystem design.

Flexible structure modes of vibration must be studied and the structure must be defined, in order to adequately assess the interactions of a large flexible structure with its space environment, the stationkeeping system, and an active attitude control system, so that degradation of control accuracy and functional performance can be avoided. A smalll number of configurations representative of deformation mode shapes should be analyzed over suitable ranges of sixes and frequencies to facilitate the selection of flight vehicle configurations, evolve design criteria, and evaluate the feasibility of actual final designs.

2.7.1.8 Ground Receiver Systems

The TV ground installation cost becomes a significant consideration, especially for large audiences, so that low-cost TV converters (frequency and modulation) and ground antennas with adequate gains in the 0.8 to 12 GHz range need to be developed.

2.7.2 RANKING OF TECHNOLOGIES

The initial selection of candidate technologies was based upon current development programs and upon those appearing to have a significant impact upon reduction of system costs, extension of system life, and improvement in system performance. This preliminary candidate list was screened to include only those which were not likely to be designed and constructed within an average two-year design cycle and for which inadequate development work is currently in progress.

Final ranking of the selected candidate technologies was based on criteria, which included the impact upon system weight and cost (using system sensitivity indixes similar to those shown in Figure 2-35 and 2-36), subsystem feasibility, system performance, long life and reliability, development risk, and lead time requirement.

TVBS satellites were grouped into three power level classifications as functions of an assumed launch date. These are shown in Table 2-17. The final priority listing of recommended technology candidates is shown in Table 2-18.

Table 2-17. Satellite Weight and Cost Ranges

	TV Broadcast Satellite Solar Array Power Range (kw)	Approximate Satellite Weight Range (lb)	Est. Satellite Fabrication Cost Range ($M)	Est. Launch Date
Low Power	1 to 3	600 - 1000	2.7 - 5.5	Early 1970's
Med. Power	3 to 10	1000 - 2500	5.5 - 13.6	Mid 1970's
High Power	10 to 30	2500 - 6000	13.6 - 32.0	Late 1970's

Table 2-18. TVBS Subsystem Technology Priority List

SATELLITE CLASS / PRIORITY CATEGORY	LOW SOLAR ARRAY POWER (1–3 KW, EARLY 1970'S)	MEDIUM SOLAR ARRAY POWER (3–10 KW, MID 1970'S)	HIGH SOLAR ARRAY POWER (10–30KW, LATE 1970'S)
FIRST	HIGH EFFICIENCY MICROWAVE TUBE GROUND RECEIVING SYSTEMS HIGH VOLTAGE POWER CONDITIONING HIGH EFFICIENCY GRIDDED TUBE UHF TRANSMITTER CIRCUITS	HIGH EFFICIENCY MICROWAVE TUBE GROUND RECEIVING SYSTEMS HIGH VOLTAGE POWER CONDITIONING ATTITUDE CONTROL OF FLEXIBLE STRUCTURES SOLAR ARRAY DEPLOYMENT HIGH EFFICIENCY GRIDDED TUBE UHF TRANSMITTER CIRCUITS	ATTITUDE CONTROL OF FLEXIBLE STRUCTURES HIGH EFFICIENCY MICROWAVE TUBE GROUND RECEIVING SYSTEMS HIGH VOLTAGE POWER CONDITIONING SOLAR ARRAY DEPLOYMENT HIGH EFFICIENCY GRIDDED TUBE UHF TRANSMITTER CIRCUITS HIGH VOLTAGE HANDLING HIGH VOLTAGE SOLAR ARRAY THERMAL–TRANSMITTER INTERFACE
SECOND	SOLAR ARRAY DEPLOYMENT HIGH VOLTAGE HANDLING THERMAL–TRANSMITTER INTERFACE HEAT PIPES DC ROTARY JOINT RF ROTARY JOINT	HIGH VOLTAGE HANDLING THERMAL–TRANSMITTER INTERFACE HEAT PIPES DC ROTARY JOINT RF ROTARY JOINT HIGH VOLTAGE SOLAR ARRAY HIGH POWER RF COMPONENTS 2–AXIS SOLAR ARRAY DRIVE	HEAT PIPES DC ROTARY JOINT RF ROTARY JOINT HIGH POWER RF COMPONENTS 2-AXIS SOLAR ARRAY DRIVE SOLAR CELL & ARRAY MANUFACTURE REFLECTOR ANTENNA POWER HANDLING REFLECTOR ANTENNA BEAM POINTING REFLECTOR ANTENNA MULTI-BEAMS MICROWAVE TRANSMITTER CIRCUITS
THIRD	HIGH VOLTAGE SOLAR ARRAY HIGH POWER RF COMPONENTS REFLECTOR ANTENNA POWER HANDLING REFLECTOR ANTENNA BEAM POINTING REFLECTOR ANTENNA MULTI–BEAMS MICROWAVE TRANSMITTER CIRCUITS	REFLECTOR ANTENNA POWER HANDLING REFLECTOR ANTENNA BEAM POINTING REFLECTOR ANTENNA MULTI–BEAMS MICROWAVE TRANSMITTER CIRCUITS MECHANICALLY STEERABLE ANT. ARRAY	MECHANICALLY STEERABLE ANTENNA ARRAY ELECTRONICALLY STEERABLE ANTENNA ARRAY

2.8 RESULTS

The TVBS study developed data that resulted in three fundamental conclusions: (1) broadcast satellites are feasible in the next decade, (2) broadcast satellites are more cost-effective than terrestrial systems for large coverage areas, and (3) turnkey operation can be achieved sooner by satellite than by terrestrial systems if the objective is a service to essentially the entire population. The following discussion elaborates on these three conclusions and several corollary conclusions.

2.8.1 FEASIBILITY

High power (1 to 30 kilowatts of solar array power) broadcast satellites are feasible in the 1970's if current technology and subsystem developments already started are continued as planned.

Development of key elements for high powered broadcast satellites is in process. Low cost ground converters are being developed, and solar array power design and development has been under way for many years. High power transmitters, high voltage power conditioners, and special antennas are being designed for broadcast satellites. Experience gained on current space programs is being applied to analyze the attitude control of large flexible vehicles, to develop high voltage and high power components, and to attain long life endurance in space.

2.8.2 COST EFFECTIVENESS

Broadcast satellites utilizing the above technology developments are more cost-effective than terrestrial-based systems for large coverage areas (greater than one time zone of the United States - approximately 1/2 million square miles). This is true for the whole range of missions in direct, community, and special services (e.g., education or distribution). It is important to note that even in cases where the signal is not aimed at direct reception in the home, there is no economic basis for the choice of high cost ground receivers and low performance satellites.

For developing or emerging nations that do not yet possess any terrestrial television channels, the broadcast satellite is clearly the least expensive method for obtaining the initial service.

For developed nations with a sizable dollar and technological investment in ground based television systems, the cost-effectiveness comparison is more complex and was beyond the scope of this study. However, the data developed indicates that expanding television coverage (increasing the number of channels or giving the service to sparsely populated areas) may be done most cost-effectively by supplementing the existing system with broadcast satellites.

2.8.3 EARLY TURNKEY CAPABILITY

For developing or emerging nations that do not yet possess any terrestrial television channels, the broadcast satellite is the quickest method of establishing the initial service. This initial service can be established for essentially the entire population many decades before a terrestrial system could be installed. The time period for the satellite system will be determined by the time selected for production, distribution and maintenance of the television receivers. This time period can be shortened significantly by designing the system for the simplest of television receivers and by having these receivers produced in a developed nation.

For a developed nation, turnkey operations for new channels can be established via broadcast satellite in 1/4 to 1/8 of the time it has historically taken to establish a first or second terrestrial channel for coverage of over 90 percent of the population.

2.8.4 NONTECHNICAL CONSIDERATIONS

Sociopolitical and programming problems associated with space broadcasting were beyond the scope of this study. The literature treats these difficult but soluble problems. As the public becomes aware of the benefits of this application of space technology, many of these problems will disappear.

SECTION 3

MISSION ANALYSIS

This section discusses factors related to the selection and evaluation of TVBS missions.

Section 3.1 presents the considerations relevant to establishing a list of potential TVBS services. It also shows how that list was reduced to the most representative and viable services.

Section 3.2 presents the analysis used to establish the range of audience sizes to be considered for each type of broadcast service. Audience size analysis was necessary to incorporate the quantity-dependence of receiver component cost, to estimate overall system costs, and to establish the range of resultant data to be presented.

Section 3.3 presents the method used to evaluate different combinations of parameters which would satisfy the requirements of a specifice service. It also shows how that parameter combination which would give the lowest system cost was selected.

3.1 REPRESENTATIVE MISSIONS AND SERVICES

The mission of a Television Broadcast Satellite is to provide a television broadcast service. The term, service, is derived from the International Radio Regulations, and is a description for the function provided. The service is one which satisfies social, legal and economic needs. Since, at present, there is no satellite broadcasting, it is not possible to use a historical approach to determine satellite broadcast missions. Accordingly, the purpose here was to determine broadcast services which might utilize satellites in the future.

3.1.1 POTENTIAL SERVICES

Table 3.1-1 is a list of potential services developed from existing television practices, applicable literature, and discussions with representatives from potential operating and using organizations. The services shown are characterized as being either "broadcast" or "special service." In the international regulations, the term "broadcast" has a restricted meaning, namely: "A radio communication service in which the transmissions are intended for direct reception by the general public." In contrast, common usage of the term broadcast follows the dictionary meaning, "spread widely." To allow for the complete range implied by common usage, it was decided that the term "broadcast" would be restricted to the meaning of the international regulations. Potential services which do not satisfy this definition would be designated by the term "special service," which, in the international regulations, is defined as: "A radio communication service, not otherwise defined in this article, carried on exclusively for specific needs of general utility, and not open to public correspondence.

Table 3.1-1. Potential Space TV Services

Name	General Description
ITV (Special Service)	Instructional television for formal classroom use.
"Medical" TV (Special Service)	An instructional service for medical or other post-graduate training
Emergency TV (Broadcast)	To provide television coverage under emergency conditions
American Overseas TV (Broadcast)	To broadcast American TV programs to areas having large American groups.
RTV (Broadcast)	Provide rural television for fringe areas
Cable/Space TV (Broadcast)	To provide general television service when combined with CATV in urban areas
GTV - D/E (Broadcast)	General purpose television for developing and emerging nations.
CTV (Broadcast)	Cultural television for developed areas.
Urban TV - Min (Broadcast)	To provide minimum acceptable TV service to urban areas.
Urban TV (Broadcast)	To provide full service to urban areas.
XTV (Special Service)	Exchange television, networking for areas not having terrestrial connections
American Overseas Distribution TV (Special Service)	To distribute American TV programs to rebroadcasting stations.
UN-TV (Broadcast)	Worldwide system of disseminating UN, UNESCO, etc , proceedings, etc
TV Distribution (Special Service)	To distribute TV signals for retransmissions by terrestrial broadcast stations.
TV for the Americas (Broadcast)	To broadcast TV signals to the continents of North and South America.
Distribution service for Americas (Special Service)	To distribute TV programs within the Americas, to create the Inter-America Network.

The potential services listed do not inherently determine any TVBS system design requirements, since the broadcast parameters are generally independent of the type of service. The broadcast parameters (such as coverage area, receiver noise location, frequency, and modulation) which have appreciable influence on the ability of the satellite to satisfy service needs, and on the cost-effectiveness of the satellite, were treated as independent variables. The range of possible variations of these parameters is very large. However, not all of the parameters may vary for any given service; in any case, a limited number of cases were sufficient to define trends to the accuracy needed. Table 3.1-2 shows the values selected for initial examination.

3.1.2 REPRESENTATIVE SERVICES

Nine representative services were selected for evaluation by the GE Space Broadcast Advisory Board. This board was established to provide high-level guidance and advice to the Company's continuing space broadcasting studies. The guidance of the board was utilized in this study and was applied to economic, technical, operational, financial, educational, and international considerations. The Board is composed of senior, nationally recognized authorities in the required fields of competence. Table 3.1-3 lists the Board members, their advisory roles, and their current positions.

Table 3.1-2. System Design Requirements for Services

Service	Quality on the Ground (0 – CCIR, Other = TASO)	Location* Type (Urban, Suburban, Rural)	$ Δ** Increment Above Receiver	Modulation (AM/FM)-Frequency (GHz)	Area Size (x 10^-6)		Operating Time (Hrs, Per Day Per Area)	No. of Channels
					mi^2	km^2		
BROADCAST SERVICES								
Emergency	3	S	10	AM-0.8	1,3	2 6,7.8	23	1
Americans Overseas	2,3	S	100	AM-0.8, 2.5 FM-11	1,3	2 6,7.8	5	1
Rural	3	R	0,150	AM-0.8, 2.5 FM-11, 0 8	1,3,10	2.6, 7 8, 26	6	1
General Purpose for Developing Emergin Nations	2,3	U,S,R	0, 30, 100	AM - 0 8 FM-11, 0.8	1,3,10	2.6, 7 8, 26	9	1 3
Cultural	1	U	150	AM-0 8, 2 5 FM-11, 0.8	1,3	2 6, 7.8	5	1,2
Urban	3 2 1	U U U	0 30 100	AM-0.8 FM-11, 0.8	0.5,1,3	1.3, 2.6, 7.8	16, 23	1,3
UN	2	U,R	0,40	AM-0.8 FM-11, 0.8	3,10	7.8, 26	12	1
Americas	2 3 3	S R R	100 50 0	AM-0.8 FM-11,0.8	10	26	4,6	1,3
SPECIAL SERVICES								
Instructional	0,1		1K, 2.5K	AM-2.5 FM-2 5, 11 FM-8	0 5, 1,3,10	1 3, 2 6, 7 8, 26	8	1,6
Medical	0,1		1K	AM-2.5 FM-2.5,11 FM-8	0 5,1,3,10	1 3, 2 6	8	1
Exchange	0		10K	FM-11 FM-8	1,3,10	2.6,7 8, 26	18	1,6
Americans Overseas	0,1		10K	FM-11 FM-8	1,3,10	2 6,7.8, 26	5	1
TV Distribution	0		25K	FM-11	0.5, 1	1.3, 2 6	23	6/area
Americas	0		5K	AM-2.5	10	26	4,16,23	1 4

*Use Urban only for frequencies above 0 85 GHz
**Use $Δ = 0 only with AM-0.8 GHz cases

NOTE: See also Table 6.3-1

Table 3.1-3. General Electric Space Broadcast Advisory Board

Consultant	Current Position	Comments
Chairman		
R. P. Haviland	Consulting Engineer, Space Projects Space Division Philadelphia, Pa.	Member U. S Delegation to the ITU, CCIR Committee, Developed Early Concepts of Broadcast Satellites
Operations		
Julius Barnathan (Rep. by G. Milne, Dir. Traffic and Network)	Vice President, Operations and Engineering American Broadcasting Company New York, N Y.	Formerly President, ABC Owned and Operated Stations; Vice President ABC Affiliated Stations
William B. Lodge	Vice President, Engineering CBS Television Network New York, N Y.	Formerly Director, NAB and Director, International Radio and Television Executive Society
Dr John Ivey	Chairman of the Board Midwest Program on Airborne TV Instruction Dean, College of Education Michigan State University East Lansing, Michigan	Formerly Executive Vice President, New York University
Reid L Shaw (Rep. by D. Weise)	Vice President and General Manager GE Broadcasting Co., Inc. Schenectady, N.Y	Manager, GE's TV, FM, AM Stations and The General Electric Cablevision Corp. (CATV)
Economics		
Dr. Paul MacAvoy	Professor of Economics Massachusetts Institute of Technology Cambridge, Mass.	Formerly Senior Staff Economist, Council of Economic Advisors Executive Office of the President
Technical		
John Renner	Director, Jansky & Bailey Systems Department Atlantic Research Corporation Washington, D.C.	Directed Recent NASA Study on Technical and Cost Factors Involved in Television Reception from Broadcast Satellites.
R B. Dome	Consulting Engineer, TV Receivers General Electric Company Syracuse, New York	Nationally Known Pioneer in TV Technology Holds 95 Patents in this Area
National and International Affairs		
Gerald C Gross	President, Telecommunication Consultants International Washington, D.C	Formerly Secretary-General, ITU Geneva, Switzerland
John H. Gayer	International Broadcast Consultant	Formerly IFRB, ITU, Geneva, Switzerland Chairman, Space Radio Communication Conference Many Other International Communication Conferences
George A. Codding, Jr.	Professor, Department of Political Science University of Colorado Boulder, Colorado	Doctor ES Sciences Politiques, University of Geneva, Switzerland Director, Graduate Program in International Studies, University of Colorado
Harry M. Plotkin	Partner Arent, Fox, Kintner, Plotkin & Kahn Washington, D.C.	Formerly FCC Assistant General Counsel for Broadcast Activities

The Advisory Board helped reduce the number of candidate services by ranking the services of Table 3.1-1 as to their potential value. The diverse background, experience, and knowledge of the Board members led to the consideration of relevent aspects. This qualitative evaluation resulted in the list of services, presented in Table 3.1-4 below.

Table 3.1-4. Selected Space TV Services

Name	General Description
	SPECIAL SERVICES
ITV	Instructional television for formal classroom use
Medical TV	An instructional service for medical or other post-graduate training
TV Distribution	To distribute TV signals for re-transmission by terrestrial broadcast stations.
	BROADCASTING SERVICES
TV Broadcast for the Americas	To broadcast TV signals to the continents of North and South America
RTV	Provide TV service to rural, fringe and lightly populated areas
GTV-D/E	General purpose television for developing and emerging nations.
CTV	Cultural television for developed areas
Urban TV	To provide TV service to urban areas
UN-TV	Worldwide system of disseminating UN and UNESCO activities

3.2 AUDIENCE ANALYSIS

The purpose of the analysis was to define the potential audiences in 1975 for each of the services given in Section 3.1. The approach used was to develop generic models based on the type of service, economic levels, area sizes, and population densities.

The range of area sizes considered was 0.5 to 10 million square miles (1.3 to 26 square kilometers). Population densities considered were projected to 1975 from statistical data of all countries having an area greater than one-half million square miles. Nations or geographic regions were classified by an economic grouping based on per capita Gross National Product. For the direct broadcast service, the unit of audience is the television receiver. In the case of the special services, the unit of audience is the primary school, secondary school, university, hospital or terrestrial transmitting station as applicable.

In order to obtain the total size of the potential audience for a given service, the following approach was used: 1) Nations or geographic regions were classified by an economic grouping based on per capital GNP; 2) the audience density (units per capita) was determined as a function of per capital GNP; 3) combining audience density with population density gave units of audience per square mile; and, finally, 4) taking into account a specific coverage area yielded the total audience size characterized by a given economic classification and area size. For the rebroadcast service, the transmitter density (transmitters per thousand square miles) was obtained directly.

Table 3.2-1 gives the results of the audience analysis for the service considered.

Table 3.2-1. Results of Audience Analysis

Economic Classification	Per Capita GNP (dollars)	Direct Service	Special Services					
			Instructional Service			Medical Service	Rebroadcast Service	
		Receivers Per Capita	Primary Schools Per 10^3 People	Secondary Schools Per 10^3 People	Universities Per 10^6 People	Hospitals Per 10^6 People	Transmitters Per 10^3 Sq Mi	Transmitters Per 10^3 Sq km
Emerging	0-160	0.0017	0.78	0.047	3.0	12	0.01	0.004
Developing	161-500	0.017	0.80	0.058	3.7	44	0.27	0.104
Developed	500	0.17	0.94	0.140	8.8	69	1.41	0.545
Range of Audience Size								
Minimum	Not Applicable	8500	3900	235	15	60	5	
Maximum		51,000,000	282,000	42,000	4640	20,700	14,100	

3.3 SERVICE COST EVALUATION CRITERIA

In order to evaluate the specific TVBS systems related to the previously identified missions, it was necessary to compare various components of system costs. Four values of cost were developed for this analysis: 1) TSI (Total system implementation cost), 2) SAOC (satellite annual operating cost), 3) SEDC (satellite engineering development cost), and 4) total ground receiver* investment cost, which is the audience size (N) multiplied by the receiver unit cost ($\Delta\$$). Derivation of these costs are defined in detail in Section 6.1.3.

To provide a basis for developing cost optimization or evaluation criteria, five possible combinations of the above four costs were assumed. These combinations were a function of the identity of the potential developing, operating, and using entities. It was considered that cost factors of importance for decisions regarding system implementation would be dependent upon the financing method. For example, it is possible to postulate a system where a government entity would pay for satellite development, a commercial broadcaster would operate the satellite, and the using public would individually purchase their receiver systems. It is also possible that a single political entity or using group would develop and operate the satellite and purchase and install the ground receiving system, thus bearing the total cost. This approach provided a realistic manner of selecting the specific cost totals to be minimized so that selection of optimum satellite system broadcast parameters could be made.

In order to compare the net worth of a satellite system against a terrestrial distribution system, it was necessary to order the terrestrial system costs in like manner. This data is presented in a later section (Section 7.6). Absolute costs of any projected mission would have to include the costs of the baseline ground receivers, and would have to reflect differences in pricing from the U.S. values used in this study.

*Refers only to the portion of the receiver exclusively required for satellite transmission

SECTION 4

GROUND RECEIVING EQUIPMENT PARAMETRIC ANALYSIS

This section presents the ground equipment cost and performance data compiled for use in the TVBS study. Ground receiving equipment, as defined in this study, is that additional equipment required to accommodate the transmission of a broadcast signal via satellite, as differentiated from a signal transmitted via standard terrestrial broadcasting methods. Thus, components which would be common to both methods, such as the TV receiver, are not included as ground receiving equipment.

Qualitatively, the broadcast satellite signal may differ from the conventional TV signal in frequency, modulation, polarization and power density. Because of these requirements, it is necessary in the general case for the ground receiving equipment to perform the following functions:

1. Intercept the signal (circularly polarized).
2. Discriminate against noise (natural and man-made) by means of directivity.
3. Reject noise outside the signal band.
4. Amplify and convert frequency, as required.
5. Detect.
6. Remodulate.
7. Apply to the TV receiver input.

The first two functions are performed by an antenna. The remaining functions are performed by an electronic device, which is defined for this study as the signal converter.

In the design of a satellite broadcast system to provide a given picture quality at minimum cost, the major performance parameter of the ground receiving equipment is the value of the signal power density it requires to provide the required picture quality. The lower the required power density, the higher the performance. A high quality TV picture with a low RF power density requires a high gain (large aperture) antenna, high quality (mainly low noise figure) electronics, or both. Such equipment is expensive.

In the design of the ground receiving equipment, the general procedure used in the TVBS study was to trade off performance against cost in the following manner:

1. Specify the permitted cost limit, referred to as ground receiver cost in the TVBS study.

2. Determine by an iterative process the combination of antenna and converter which would provide the lowest permissible signal power density or satellite ERP for that cost, for the desired combination of fixed parameters (freq., S/N, ...).

3. If desired, repeat at intervals across a range of permitted costs until sufficient data has been obtained to enable construction of a curve of required signal power density or satellite ERP versus costs.

The cost of the ground receiving equipment was traded off against satellite cost to arrive at the optimum combination of system operational parameters which gave minimum over-all system cost. These relations and the techniques for arriving at ERP vs ground receiver cost are discussed in more detail in the remainder of Section 4. The cost/performance relationships upon which the results depend were estimates based on a survey of manufacturers. A more complete study of the TV ground converter cost/performance problem is presently in progress under NASA LeRC Contract NAS 3-11520. The results of the study are not expected to change the over-all TVBS system designs radically, but will provide more accurate data and more complete verification.

4.1 ANTENNAS

The antennas considered were those required to accommodate the entire range of missions. The major parameters considered were:

1. Aperture, or gain

2. Frequency

3. Number of units manufactured

4. Type

The over-all purpose was to determine the cost per unit as a function of the gain and the number manufactured. For convenience, it was decided to plot curves of cost vs gain. The independent variables for which the cost vs gain curves were determined were:

Frequency = 800 MHz, 2.5 GHz, 8.4 GHz, and 12.2 GHz

Quantity = 10^1, 10^2, 10^3, 10^4, 10^5, 10^6, 10^7, 10^8

Antenna Location = Indoor, Outdoor

Polarization: Circular, Linear

Antenna Type: Tracking, Fixed

The outdoor antenna gain vs cost relationships developed for the four frequency bands of interest are presented in Figures 4.1-1 through 4.1-4. These were derived from cost estimates from three antenna vendors, the data from NASA Contract NASw1305, and GE manufacturing cost estimates. Installation costs are presented separately in Figure 4.1-5 and must be added to antenna cost to get the total antenna cost per receiving unit. The antenna gain vs size relations used for the ground receiving equipment analysis are presented in Figure 4.1-6.

4.2 GROUND CONVERTER

In cases where a signal converter is employed with an outdoor antenna, the converter has been assumed to be mounted at the antenna to avoid noise figure degradation due to transmission line losses.

Basic electronic functions were combined for the following receiving site installation variables: direct or special broadcast services*, AM or FM broadcasting, four specified transmitting frequencies, broadcast frequency conversion to an intermediate frequency or baseband, and indoor or outdoor installation. A matrix was constructed wherein the prices of a range of quantities of units varied with each configuration. The basic functions were preamplification, modulation conversion, and frequency conversion. Quantities of interest for direct services ranged from 10^4 through 10^8; for special services, quantities ranged from 10 through 10^5.

High-production manufacturers of electronic subassemblies were interviewed to assess the expected state of technology in 1971, estimates of circuit components as a function of frequency (in light of the expected technology), and estimates of costs vs quantity.

The ground electronics retail cost per unit will be the average production cost per unit multiplied by a mark-up factor. A value of 1.5 was assumed for the mark-up factor for this study. Production costs for the basic circuitry of the required component types were then estimated for a production quantity of 10^6 units. The resulting basic retail costs used as building blocks are presented in Table 4.2-1.

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* For direct service, it was assumed that the ground converter must demodulate the signal to baseband and then remodulate to AM for reception on a standard VHF or UHF channel for the home receiver. For special service, the only required output is the baseband signal necessary to drive the video monitors in the system; a slight cost decrease is therefore noted for this case.

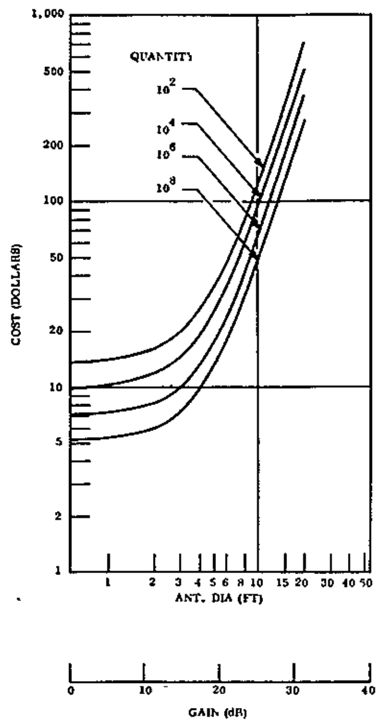

Figure 4.1-1. 0.8 GHz Antenna Cost

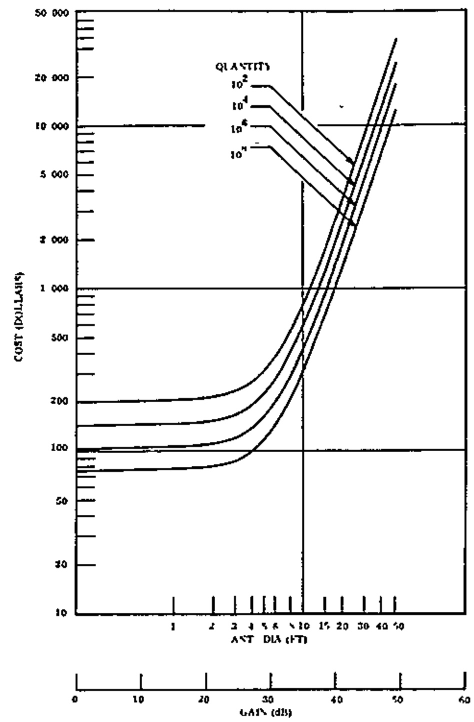

Figure 4.1-2. 2.5 GHz Antenna Cost

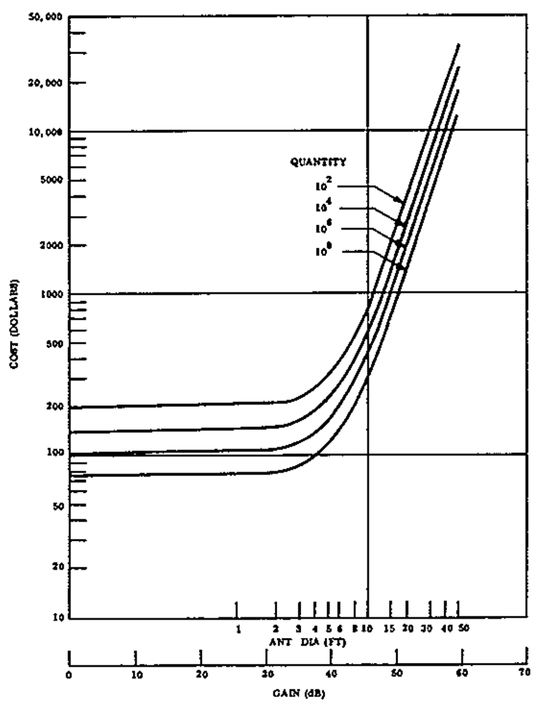

Figure 4.1-3. 8.4 GHz Antenna Cost

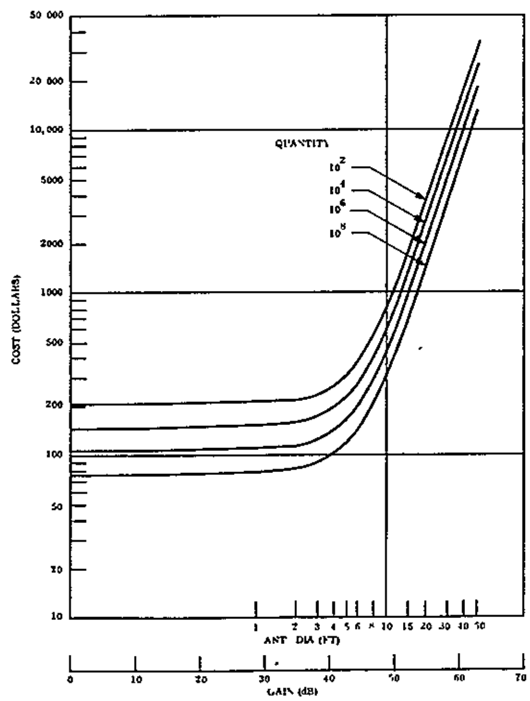

Figure 4.1-4. 12.2 GHz Antenna Cost

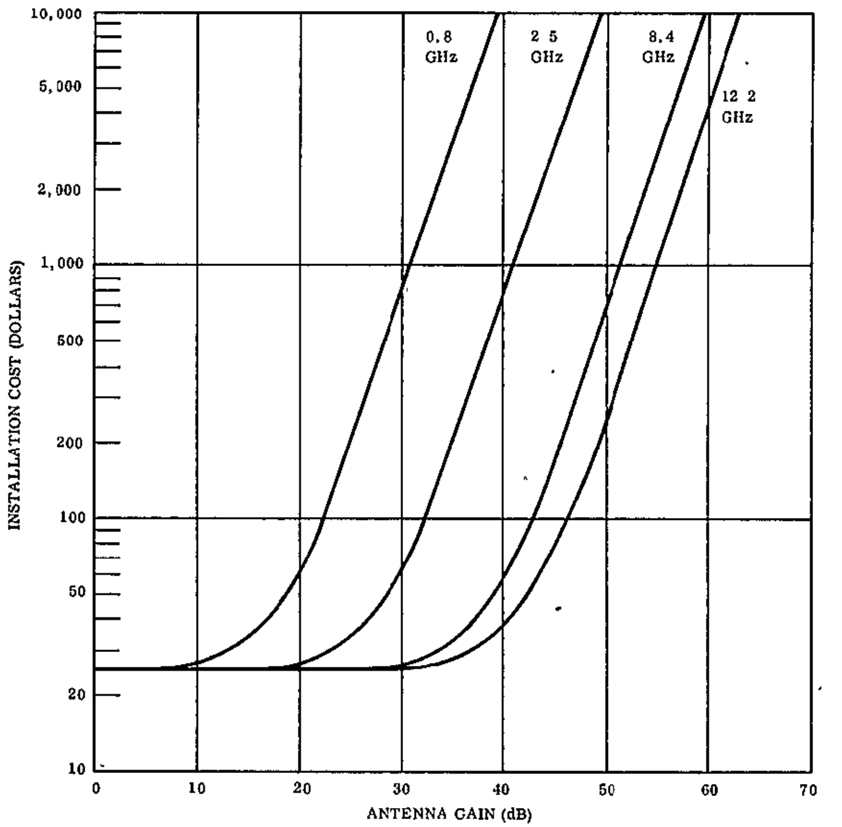

Figure 4.1-5. Antenna Installation Cost

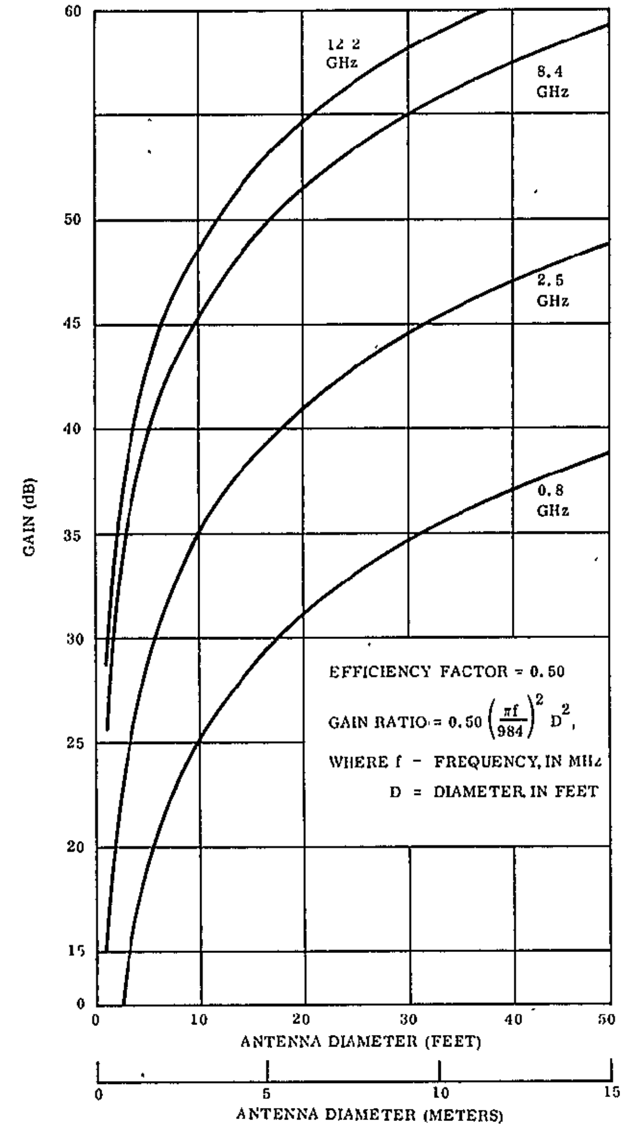

Figure 4.1-6. Antenna Gain-Size Relations

The preamplifiers have been assumed to be transistors, tunnel diodes, or parametric amplifiers. A two stage transistor amplifier of hybrid thin film construction, having a 3-dB noise figure and a gain of 20 dB, has been assumed for 800 MHz and 2.5 GHz. A single stage tunnel diode amplifier having a gain of 17 dB and a noise figure of 4.5 dB has been assumed for 8.4 and 12.2 GHz. An uncooled parametric amplifier of 17-dB gain and 1.0-dB noise figure, and a cooled parametric amplifier of 17-dB gain and 19°K noise temperature, respectively, have been chosen for the configurations using them. A balanced mixer using Schottky barrier diodes and a bulk effect local oscillator has been assumed for frequency conversion. A conversion loss of about 6 dB and a noise figure of 3 dB is assumed. (If the FM noise precludes the use of a bulk effect local oscillator, a crystal-controlled oscillator multiplier chain will be used instead.)

Table 4.2-1. Basic Circuitry Retail Cost per Unit for 10^6 Units

Electronic Circuit	Retail Cost ($)
Preamplifier	1.50
Frequency Converter	1.50
FM Modulation Converter	3.00
FMFB Modulation Converter	3.75
FM/BB Demodulator	2.05
FMFB/BB Demodulator	2.80
AM/BB Demodulator	1.65
Paramplifier	99.00
Cooled Paramplifier	2500.00

The remainder of the converter consists of the IF amplifier, discriminator, remodulator AFC (if used), and the frequency feedback loop in the case of FMFB configurations.

Microwave and UHF circuits could be made of hybrid thin film or microstrip. The IF amplifiers, discriminators, and remodulator circuits are assumed to be integrated circuitry. In those cases in which audio circuits are required, discrete circuits will probably be used because of the large values of inductance and capacitance required.

The cost per total unit (based on a production quantity of 10^6) of a given combination of electronic circuits was calculated from the basic circuitry costs of Table 4.2-1 by means of the following costing formula:

$$\text{Total Cost of Electronics (\$)} = A + B + 0.5\,(C+D) + E + F$$

where

A = Cost of paramplifier or cooled paramplifier if used.

B = Cost of most costly circuit (other than A).

C = Cost of next most costly circuit after B.

D = Cost of next most costly circuit after C.

E = Cost of power supply = \$1.00 per unit for a quantity of 10^6.

F = Cost of installation (if used with outdoor antenna) = \$5.00.

NOTE: In all cases, one power supply is required, but that one unit may provide power to several electronic circuits.

The retail unit costs so calculated are shown in the 10^6 quantity column in Tables 4.2-2 through 4.2-6. Receiver noise figures for the various types of receiver additions are also given. Differences in the noise figures for corresponding "indoor" and "outdoor" installations are attributable to the additional transmission loss suffered with an outdoor antenna-electronics installation.

The cost for the other quantities presented in Tables 4.2-2 through 4.2-6 were determined by using an 85% learning curve, i.e., every time the production quantity is doubled, the cost per unit is reduced to 85% of the original value. Since the quantities of interest were selected to be in multiples of 10 for this study, the cost per unit (exclusive of installation) varies as the ratios presented in the following table:

Item Quantity	10^0	10^1	10^2	10^3	10^4	10^5	10^6	10^7	10^8
Cost per Item	1	0.583	0.34	0.198	0.115	0.067	0.039	0.023	0.013

Table 4.2-2. Receiver Addition Cost vs Production Quantities (at UHF)

Direct Service at 0.8 GHz							
	Electronics Modification	Noise Figure (dB)	Cost per Receiver at Various Quantities ($)				
			10^4	10^5	10^6	10^7	10^8
AM	**Indoor**						
	1. No Electronics	10.0	0	0	0	0	0
	2. Preamp.	3.2	7.40	4.30	2.50	1.45	0.85
	3. Preamp.	1.1	294.45	171.60	100.00	58.30	34.00
	Outdoor						
	4. No Electronics	10.0	0	0	0	0	0
	5. Preamp.	3.3	12.40	9.30	7.50	6.45	5.85
	6 Paramp.	1.1	299.45	176.60	105.00	63.30	39.00
FM	**Indoor**						
	1. FM Mod. Conv.	3.5	11.75	6.85	4.00	2.35	1.35
	2. Preamp. + FM Mod. Conv.	3.0	14.00	8.15	4.75	2.75	1.60
	3 Paramp. + FM Mod. Conv.	1.1	303.30	176.75	103.00	60.05	35.00
	Outdoor						
	4. FM Mod. Conv.	3.5	16.75	11.85	9.00	7.35	6.35
	5. Preamp. + FM Mod Conv.	3.0	19.00	13.15	9.75	7.75	6.60
	6. Paramp. + FM Mod. Conv.	1.1	308.30	181.75	108.00	65.05	40.00
FMFB	**Indoor**						
	1. FMFB Mod. Conv.	3.5	14.00	8.15	4.75	2.75	1.60
	2. Preamp. + FMFB Mod. Conv.	3.0	16.20	9.45	5.50	3.20	1.85
	3 Paramp. + FMFB Mod. Conv.	1.1	305.55	178.05	103.75	60.45	35.25
	Outdoor						
	4. FMFB Mod. Conv.	3.5	19.00	13.15	9.75	7.75	6.60
	5. Preamp. + FMFB Mod. Conv.	3.0	21.20	14.45	10.50	8.20	6.85
	6. Paramp. + FMFB Mod Conv	1.1	310.55	183.05	108.75	65.45	40.25

Table 4.2-3. Receiver Addition Cost vs Production Quantities (at S-Band)

Direct Service at 2.5 GHz							
	Electronics Modification	Noise Figure (dB)	Cost per Receiver at Various Quantities ($)				
			10^4	10^5	10^6	10^7	10^8
AM	**Indoor**						
	1. Freq Conv	11.5	7.40	4.30	2.50	1.45	0.85
	2 Freq Conv. + Preamp.	3.7	9.60	5.60	3.25	1.90	1.10
	3 Freq. Conv. + Paramp	1.4	298.85	174.15	101.50	59.15	34.45
	Outdoor						
	4. Freq Conv.	12.2	12.40	9.30	7.50	6.45	5.85
	5 Freq Conv + Preamp	4.1	14.60	10.60	8.25	6.90	6.10
	6 Freq Conv. + Paramp	1.4	303.85	179.15	106.50	64.15	39.50
FM	**Indoor**						
	1 Freq. Conv. + FM Mod. Conv	8.5	14.00	8.15	4.75	2.75	1.60
	2 Freq Conv + Preamp + FM Mod. Conv	3.2	16.20	9.45	5.50	3.20	1.85
	3 Freq. Conv. + Paramp + FM Mod Conv.	1.4	305.55	178.05	103.75	60.45	35.25
	Outdoor						
	4 Freq. Conv. + FM Mod Conv.	8.5	19.00	13.15	9.75	7.75	6.60
	5 Freq. Conv. + Preamp + FM Mod Conv.	3.2	21.20	14.45	10.50	8.20	6.85
	6. Freq Conv + Paramp + FM Mod. Conv.	1.4	310.55	183.05	108.75	65.45	40.25
FMFB	**Indoor**						
	1 Freq. Conv. + FMFB Mod Conv	8.5	16.20	9.45	5.50	3.20	1.85
	2. Freq. Conv. + Preamp + FMFB Mod Conv.	3.2	18.45	10.75	6.25	3.65	2.15
	3. Freq Conv + Paramp + FMFB Mod Conv	1.4	307.70	179.30	104.50	60.90	35.50
	Outdoor						
	4 Freq Conv. + FMFB Mod Conv.	8.5	21.20	14.45	10.50	8.20	6.85
	5 Freq Conv + Preamp + FMFB Mod Conv	3.2	23.45	15.75	11.25	8.65	7.15
	6 Freq. Conv. + Paramp. + FMFB Mod. Conv	1.4	312.70	184.30	109.50	65.90	40.50

Table 4.2-4. Receiver Addition Cost vs Production Quantities (at X-Band)

Direct Service at 8.4 and 12.2 GHz - OUTDOOR									
	Electronics Modification	Noise Figure (dB) 8.4 GHz	Noise Figure (dB) 12.2 GHz	Cost per Receiver at Various Quantities ($) 10^4	10^5	10^6	10^7	10^8
FM	1. Freq. Conv. + FM Mod. Conv.	8.8	9.0	19.00	13.15	9.75	7.75	6.60
	2. Freq. Conv. + Preamp. + FM Mod. Conv.	4.7	5.2	21.20	14.45	10.50	8.20	6.85
	3. Freq. Conv. + Paramp. + FM Mod. Conv.	1.9	1.9	310.55	183.05	108.75	65.45	40.25
FMFB	1. Freq. Conv. + FMFB Mod. Conv.	8.8	9.0	21.20	14.45	10.50	8.20	6.85
	2. Freq. Conv. + Preamp. + FMFB Mod. Conv.	4.7	5.2	23.45	15.75	11.25	8.65	7.15
	3. Freq. Conv. + Paramp. + FMFB Mod. Conv.	1.9	1.9	312.70	184.30	109.50	65.90	40.50

Table 4.2-5. Receiver Addition Cost vs Production Quantities (Special, at S-Band)

Special Services at 2.5 GHz - OUTDOOR								
	Electronics Modification	Noise Figure (dB)	Cost per Receiver at Various Quantities ($) 10^1	10^2	10^3	10^4	10^5	10^6
AM	1. Freq. Conv. + AM/BB Demod.	8.48	55.80	34.60	22.25	15.05	10.85	8.40
	2. Freq. Conv. + Preamp. + AM/BB Demod.	3.16	66.70	40.95	25.95	17.20	12.10	9.15
	3. Freq. Conv. + Paramp. + AM/BB Demod.	1.4	1,528.40	892.75	522.35	306.50	180.70	107.40
	4. Freq. Conv. + Cooled Paramp. + AM/BB Demod.	0.75	37,901.65	22,089.30	12,874.65	7,504.80	4,375.50	2,551.90
FM	1. Freq. Conv. + FM/BB Demod.	8.48	61.35	37.85	24.15	16.15	11.50	8.80
	2. Freq. Conv. + Preamp. + FM/BB Demod.	3.16	72.70	44.45	28.00	18.40	12.80	9.55
	3. Freq. Conv. + Paramp. + FM/BB Demod.	1.4	1,534.65	896.40	524.45	307.70	181.40	107.80
	4. Freq. Conv. + Cooled Paramp. + FM/BB Demod.	0.75	37,907.30	22,092.60	12,876.55	7,505.90	4,376.15	2,552.30
FMFB	1. Freq. Conv. + FMFB/BB Demod.	8.48	72.70	44.45	28.00	18.40	12.80	9.55
	2. Freq. Conv. + Preamp. + FMFB/BB Demod.	3.16	83.75	50.90	31.75	20.60	14.10	10.30
	3. Freq. Conv. + Paramp. + FMFB/BB Demod.	1.4	1,545.95	903.00	528.30	309.95	182.70	108.55
	4. Freq. Conv. + Cooled Paramp. + FMFB/BB Demod.	0.75	37,918.30	22,099.00	12,880.30	7,508.10	4,377.45	2,553.05

Table 4.2-6. Receiver Addition Cost vs Production Quantities (Special, at X-Band)

Special Services at 8.4 and 12.2 GHz - OUTDOOR										
Electronics Modification		Noise Figure (dB) 8.4 GHz	Noise Figure (dB) 12.2 GHz	Cost per Receiver at Various Quantities ($) 10^1	10^2	10^3	10^4	10^5	10^6
FM	1. Freq. Conv. + FM/BB Demod.	8.8	9.0	61.35	37.85	24.15	16.15	11.50	8.80
	2. Freq. Conv. + Preamp. + FM/BB Demod.	4.7	5.2	72.70	44.45	28.00	18.40	12.80	9.55
	3. Freq. Conv. + Paramp. + FM/BB Demod.	1.9	1.9	1,534.65	896.40	524.45	307.70	181.40	107.80
	4. Freq. Conv. + Cooled Paramp. + FM/BB Demod.	0.9	1.0	37,907.30	22,092.60	12,876.55	7,505.90	4,376.15	2,552.30
FMFB	1. Freq. Conv. + FMFB/BB Demod.	8.8	9.0	72.70	44.45	28.00	18.40	12.80	9.55
	2. Freq. Conv. + Preamp. + FMFB/BB Demod.	4.7	5.2	83.75	50.90	31.75	20.60	14.10	10.30
	3. Freq. Conv. + Paramp. + FMFB/BB Demod.	1.9	1.9	1,545.95	903.00	528.30	309.95	182.70	108.55
	4. Freq. Conv. + Cooled Paramp. + FMFB/BB Demod.	0.9	1.0	37,918.30	22,099.00	12,880.30	7,508.10	4,377.45	2,553.05

SECTION 5

SATELLITE SUBSYSTEM PARAMETRIC ANALYSIS

The purpose of this parametric analysis phase was to develop system cost and weight as a function of performance parameters for each major subsystem. The basic ground rules that were significant to the parametric analysis were:

1. The satellite launch date would be 1973, thereby permitting use of 1971 state-of-the art technology followed by a 2-year design and manufacturing cycle. Hardware of 1971 state of the art is defined to be that for which technical feasibility will have been demonstrated by space use or simulation as of 1971.

2. A minimum satellite lifetime of 2 years.

3. Engineering costs used herein are defined as those costs related to a 2-year design integration cycle using existing (1971) technology; the costs do not include costs associated with the research and development of a device. These engineering costs include the fabrication costs (including tooling) for the necessary breadboard and qualification tests required for the specific design, but do not include first flight units.

4. Fabrication costs are defined as the costs required to manufacture a replacement item of existing design.

The basic approach to generation of the satellite subsystem parametric data desired for system analysis was to determine the system variables which could be used as independent variables critical to determination of the subsystem requirements. Detailed interface considerations not affecting system feasibility were eliminated from consideration by qualitative engineering analysis.

Some subsystems are more amenable to analysis of this nature than others, since they tend to be more independent of other subsystems. In general, the payload components (i.e., receiver, power supply, transmitters and associated thermal control, and antennas) tend to be easier to isolate than the supporting subsystems. The structure tends to be the most configuration dependent, and the associated data is, therefore, inherently less accurate.

The cost, weight, and sizing data of significance for satellite system synthesis and analysis are presented here for the following subsystems:

1. Antenna
2. Transmitter
3. Attitude control
4. Power
5. Thermal control
6. Structure
7. Launch vehicles

The propulsion data are the same as used in the PACES Computer Program and presented in Section 6. The receiver-exciter and TT&C data are presented in Section 7 which discuss the final Phase 3 designs.

5.1 ANTENNA

A parametric analysis was performed on a number of antennas deemed most feasible for application on TV Broadcast Satellite Missions in the 1970-75 time period. These antennas were:

1. Paraboloid antennas
2. Mechanically steerable array antennas
3. Electronically steerable array antennas

To develop the parametric data, analysis in the antenna electrical and structural areas was required. The net result of these investigations was a series of parametric curves with the half power beamwidth as the independent variable related to the following gross antenna parameters:

1. Construction type
2. Performance capability (gain, efficiency, etc.)
3. Size
4. Weight
5. Cost-engineering and fabrication

The antenna size was constrained by the beamwidth range used: 1.6 to 18.8 degrees (2.8 to 32.8 crad).

5.1.1 PARABOLOID ANTENNA

The following paraboloid construction types were considered during the course of these investigations:

1. Rigid
2. Erectable petal
3. Bowstring
4. Inflatable wire grid tube

To determine the antenna weight, the structural design criterion used was primarily a stiffness criterion. Consequently, the structural weight requirement was determined as a function of fundamental natural frequency in the most critical mode. Figure 5.1-1 shows the results of the structural weight analysis for the antenna construction types considered. In this figure the total antenna weight is plotted versus antenna diameter for the frequency bands under consideration. The total antenna weight includes the reflector, feed and support, and a deployment weight for the erectables.

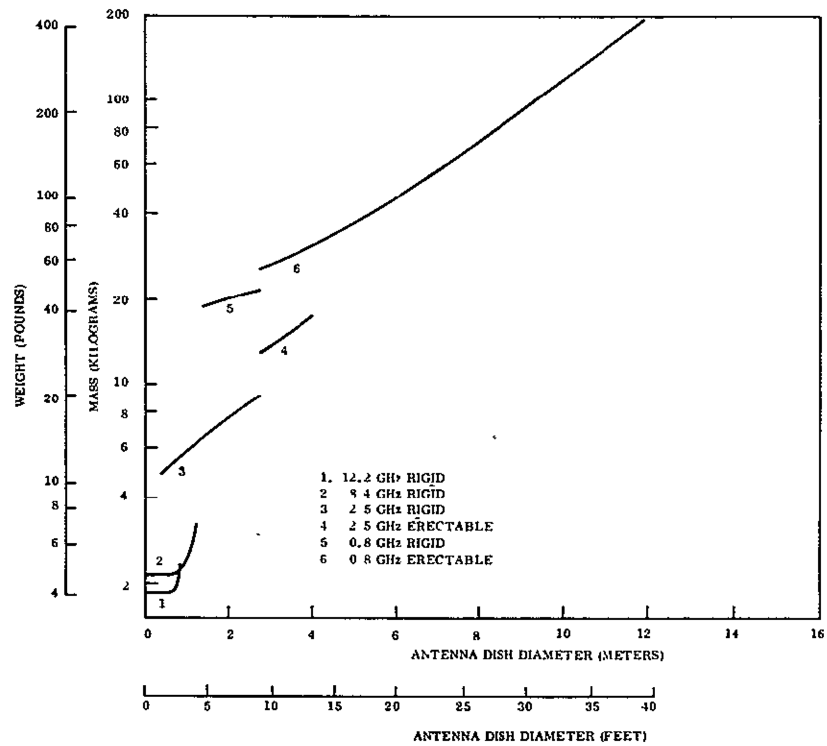

Figure 5.1-1. Paraboloid Weight Versus Diameter

The gain half power beamwidth relationships of paraboloid antennas are influenced by the antenna efficiency. The critical factors determining the antenna efficiency for the cases under consideration are:

1. Antenna surface tolerance

2. Frequency of operation

3. Feed or support blockage

Gain loss due to rms manufacturing surface tolerance is plotted in Figure 5.1-2 for the four frequency bands. Gain loss due to symmetrical edge deflection, such as incurred from uniform heating, is shown in Figure 5.1-3. Figure 5.1-4, showing gain versus half power beamwidth, is plotted with due regard to both the surface tolerances and feed blockage. Antenna efficiencies of 60, 55, and 50 percent are shown, as well as the effect on gain efficiency of a one wavelength fixed feed blockage disk. To assess the efficiency of a particular construction type and frequency, Table 5.1-1 was utilized.

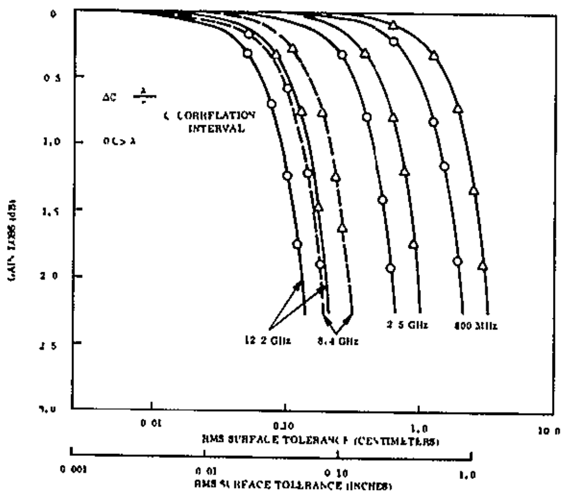

Figure 5.1-2. Gain Loss Versus rms Surface Tolerance (Paraboloid)

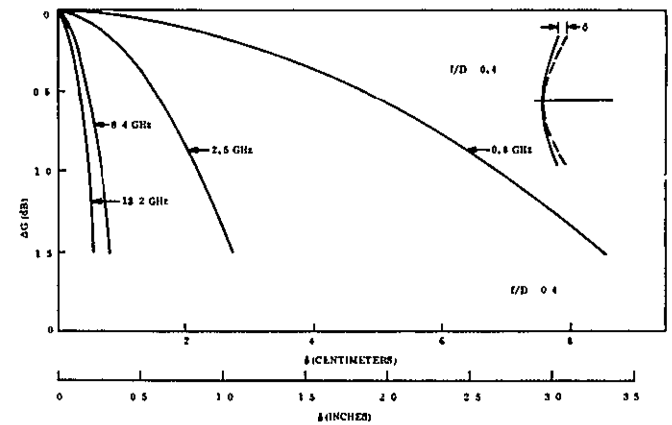

Figure 5.1-3. Gain Degradation Versus Paraboloid Edge Deflection (Symmetrical Heating)

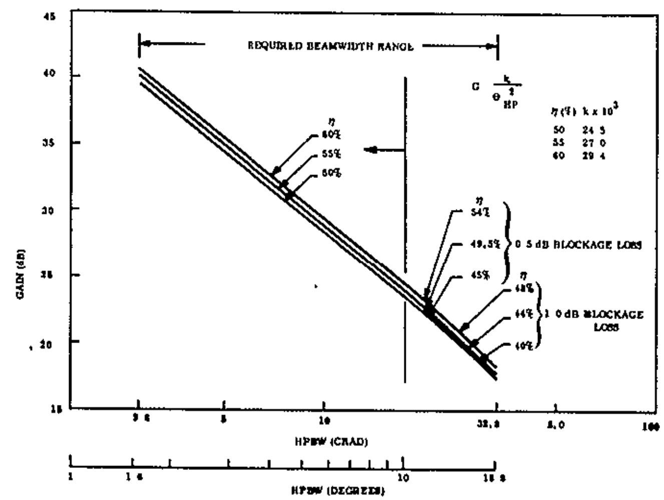

Figure 5.1-4. Gain Versus Half Power Beamwidth (Paraboloid Antenna)

Table 5.1-1. Antenna Efficiency (Percent)

	Frequency (GHz)			
	0.8	2.5	8.4	12.2
Type of Construction				
Rigid	60	60	60	60
Erectable Petal, Bowstring	60	55	--	--
Inflatable Wire Grid Tube	55	50	--	--

This table is for the negligible blockage case. For half power beamwidth ≥ 10 degrees (≥ 17.5 crad) where blockage becomes significant, Figure 5.1-4 must be used to yield the reduced efficiency and antenna gain.

Figure 5.1-5 shows the gain loss incurred when a paraboloid antenna beam is positioned in space by lateral displacement of the primary feed. Figure 5.1-6 shows the amount of feed displacement required to achieve a given scan. The data from these two figures may be used to place upper bounds on allowable gimbal travel and gain loss requirements.

The bandwidth available from a paraboloid antenna system is constrained by the bandwidth of the primary feed and transmission line and hence is closely associated with the RF average power requirement. Waveguide feeds and transmission lines, which would always be used at X-band, limit the system bandwidth to approximately 15 percent.* In the S- and UHF bands, constant beamwidth primary feeds (log-periodic) and coaxial transmission lines could be used to cover the entire frequency bands, provided that the required RF power handling is achievable. If not, a waveguide would be used, hence curtailing bandwidths.

Table 5.1-2 presents catalog data on power handling of coaxial and waveguide transmission lines. Presently this data can be used only as a guide, since space performance at these power levels has not been verified.

Engineering and fabrication costs were developed as a function of half power beamwidth for the four antenna construction types and the four frequencies. These parametric data are shown in Figures 5.1-7 to 5.1-12.

5.1.2 MECHANICALLY STEERABLE ARRAY ANTENNAS

The mechanically steerable arrays proposed have effective aperture area densities approximately 25 percent greater than paraboloid antennas of the same area that are used for the same frequency band. Based on what would be expected of 1971-75 state of art in this antenna area, the inflatable wire grid arrays would have effective aperture weight densities of 0.20 lb/ft^2 (0.978 kg/m^2); the rigid array, 0.375 lb/ft^2 (1.83 kg/m^2). Active devices are not included in these weight estimates.

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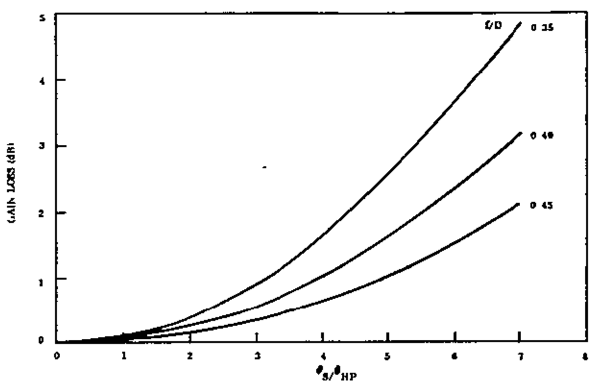
* A rectangular waveguide would likely be used here; however, the restriction applies equally to a circular waveguide.



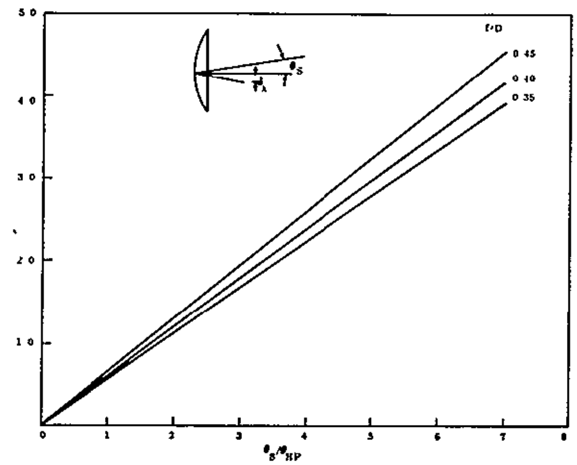


Figure 5.1-5. Gain Reduction Versus Normalized Scan Angle Paraboloid (10 dB Illumination Taper)

Figure 5.1-6. Lateral Feed Displacement Versus Normalized Scan Angle Paraboloid

Table 5.1-2. Transmission Lines and Waveguides Maximum Power and Attenuation Characteristics

Coaxial Line (Andrews)

Frequency (GHz)	Diameter (in.)	Diameter (cm)	Pmax kW	Attenuation dB/100 ft	Attenuation dB/30m	Type
0.8	6-1/8	15.5	45.0	0.2	0.197	Rigid
2.5	1-5/8	4.13	2.5	1.3	1.28	Heliax air dielectric
8.4	1/2	1.27	0.14	15.0	14.8	Heliax foam dielectric
12.2	----	----	----	----	----	----

Rectangular Waveguide (MDL)

Frequency (GHz)	Outside Dimensions A (in.)	A (cm)	B (in.)	B (cm)	Pmax Theoretical (MW)		Attenuation dB/100 ft	Attenuation dB/30m	Type (All Aluminum)
0.75-1.12	10.0	25.4	5.125	13.0	27.0	0.8 GHz	0.137	0.135	WR 975
2.2 -3.3	3.55	9.04	1.86	4.72	3.3	2.5 GHz	0.7	0.69	WR 340
7 05-10.0	1.25	3.18	0.625	1.59	0.40	8.4 GHz	3.1	3.05	WR 112
8.2 -12.4	1.0	2.54	0.50	1.27	0.29	12.2 GHz	3.83	3.77	WR 90

Gain-beamwidth curves were generated for mechanically steerable arrays synthesized of elements with gains of 7, 10, and 13 dB. These elements are assumed to be uniformly distributed over the aperture so that uniform illumination occurs. The aperture is assumed circular, with a gain-beamwidth product of 30,000, i.e., 10 percent loss. This loss is that due to insertion loss of the radiating elements plus phase error losses due to both the structural irregularities and the transmitter/amplifier relative phase alignments. No power division is assumed here, i.e., a transmitter or amplifier per element. These criteria lead to (1) the gain versus beamwidth and gain versus element number relationships of Figure 5.1-13 and (2) the beamwidth versus diameter relations of Figure 5.1-14.

Some typical characteristics of elements that might be utilized for the mechanically steerable array are given in Table 5.1-3a and 5.1-3b.

If the active transmitter/amplifier devices are excluded from consideration, the fundamental limitations on the available bandwidth are then determined by:

1. Element type
2. Element spacing
3. Transmission line/power division
4. Circuitry

The interrelated behavior of these factors is such that a 15 percent bandwidth is available without severe performance degradation in the antenna efficiency area.

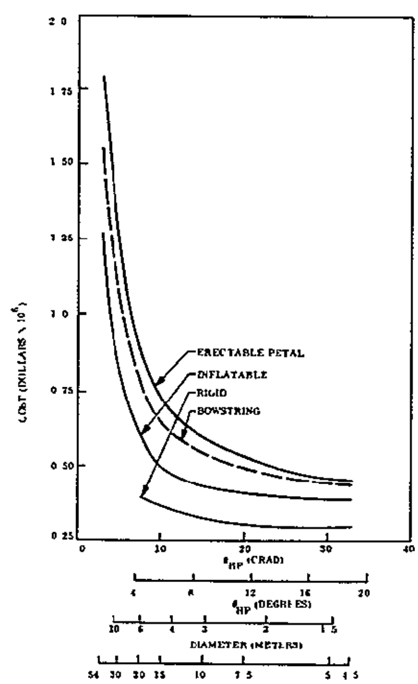


Figure 5.1-7. f = 0.8 GHz Total Engineering Cost Versus Half Power Beamwidth (Paraboloid Antenna)

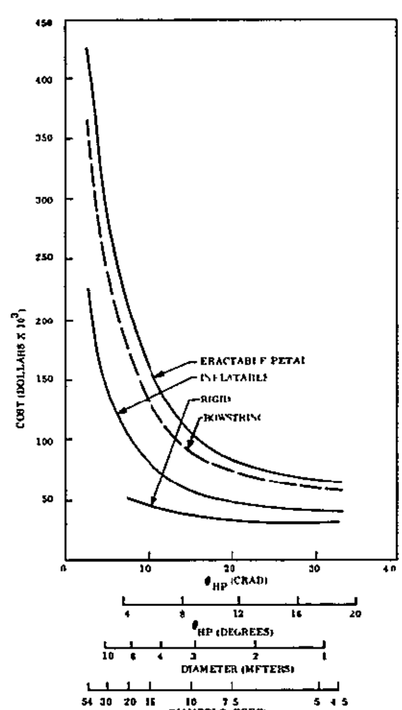
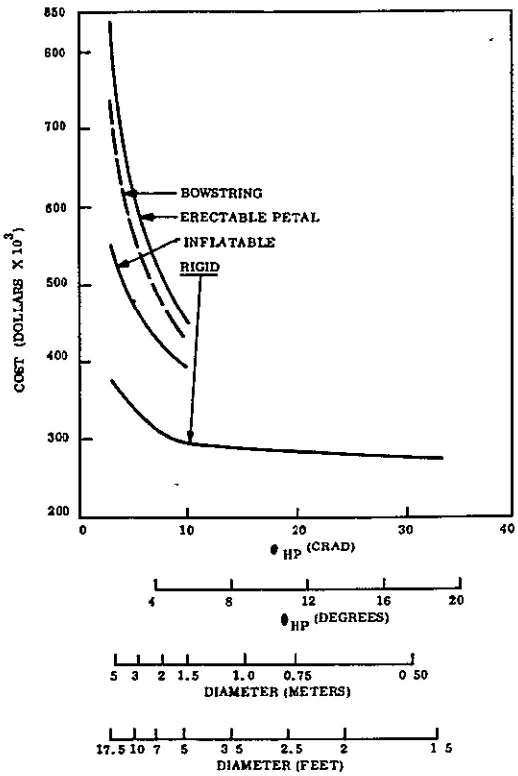
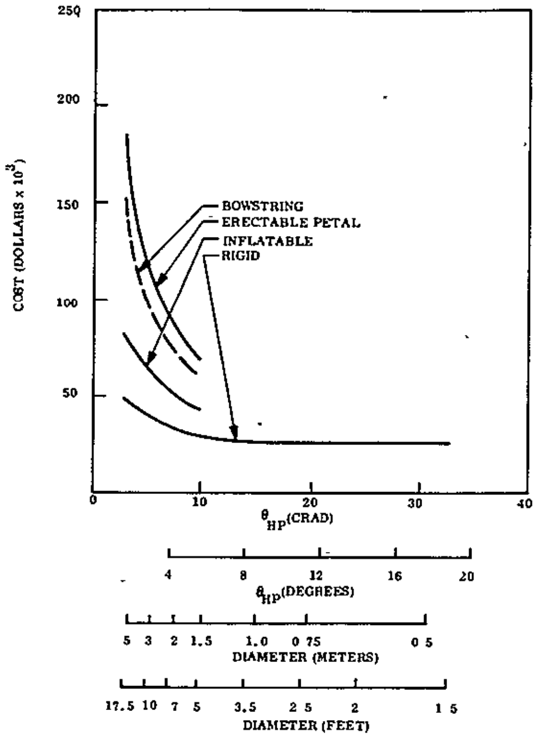


Figure 5.1-8. f = 0.8 GHz Total Fabrication Cost Versus Half Power Beamwidth (Paraboloid Antenna)





gure 5.1-9. f = 2.5 GHz Total Engineering Cost Versus Half Power Beamwidth

Figure 5.1-10. f = 2.5 GHz Total Fabrication Cost Versus Half Power Beamwidth (Paraboloid Antenna)

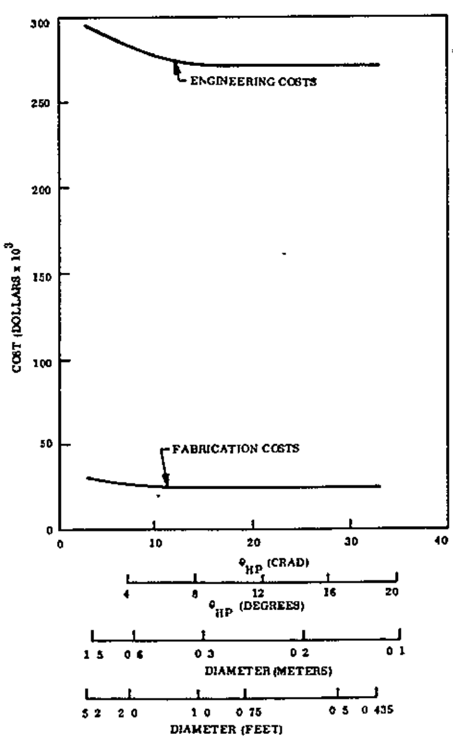


Figure 5.1-11. f = 8.4 GHz Total Engineering and Fabrication Cost Versus Half Power Beamwidth (Paraboloid Antenna-Rigid)

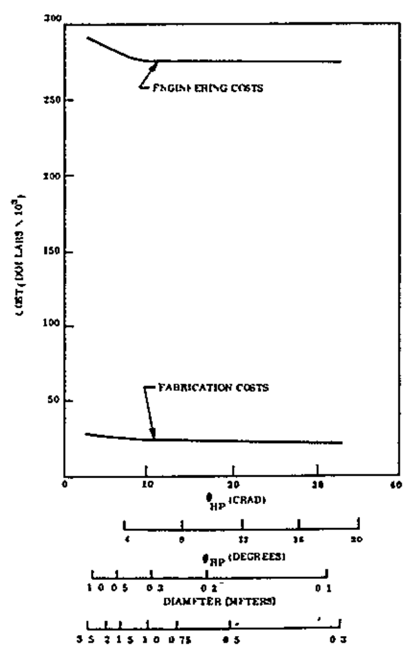


Figure 5.1-12. f = 12.2 GHz Total Engineering and Fabrication Cost Versus Half Power Beamwidth (Paraboloid Antenna-Rigid)

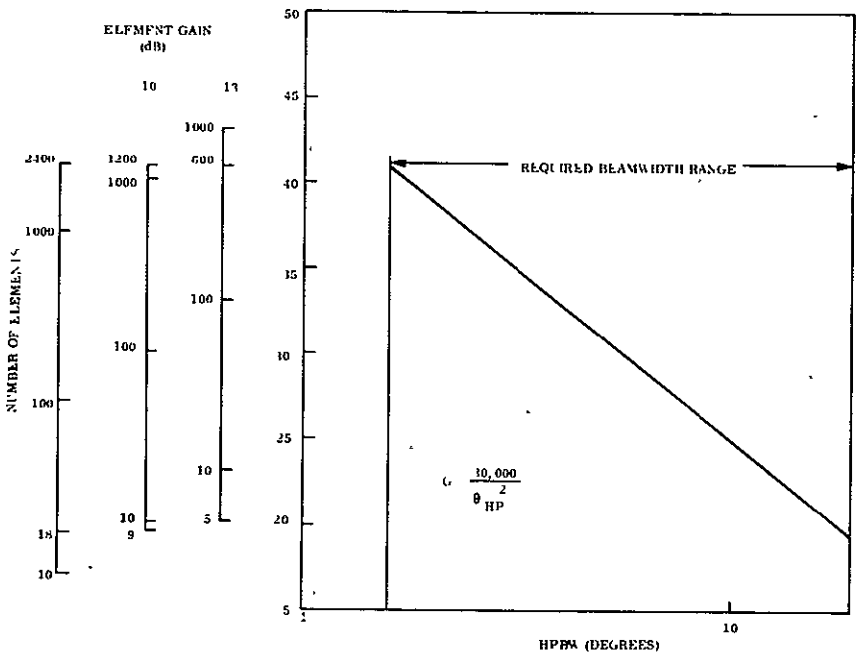


Figure 5.1-13. Gain Versus Half Power Beamwidth (Mechanically Steerable Arrays) and Gain Versus Number of Elements for Element Gains = 7, 10, and 13 dB

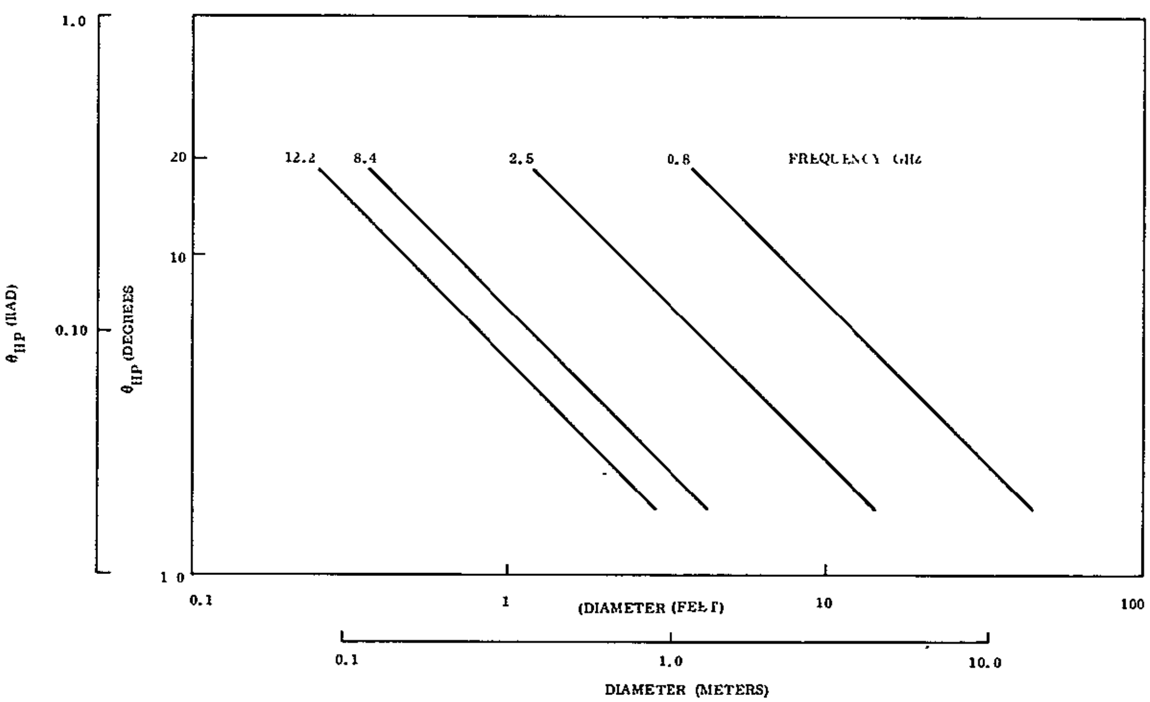


Figure 5.1-14. Half Power Beamwidth Versus Diameter (Mechanically Steerable Arrays)

Table 5.1.3a. Element Characteristics of Mechanically Steerable Arrays (Inches)

Cavity-Backed Spiral Antenna

d = Cavity Depth
D = Cavity Diameter

Frequency (GHz)	D (in.)	d (in.)
0.800	7.4	3.70
2.5	2.4	1.18
8.4	0.70	0.35
12.2	0.48	0.24

G = 7 dB at midband

Helix Antenna

D = Helix Diameter
L = Helix Length

Frequency (GHz)	D (in.)	G_e (Element Gain) 3 dB L (in.)	10 dB L (in.)	7dB L (in.)
0.800	4.7	35.5	17.7	8.9
2.5	1.5	11.3	5.7	2.9
8.4	0.45	3.35	1.68	0.84
12.2	0.31	2.32	1.16	0.58

Horn Antenna (Square Aperture)

H = Vertical Height
L = Aperture Dimension

Frequency (GHz)	G_e Element Gain					
	7 dB		10 dB		13 dB	
	H (in.)	L (in.)	H (in.)	L (in.)	H (in.)	L (in.)
0.8	7.4	10.5	14.8	14.8	29.5	20.8
2.5	2.35	3.35	4.7	4.7	9.4	6.65
8.4	0.70	1.97	1.4	1.4	2.8	1.98
12.2	0.49	0.685	0.97	0.97	1.94	1.37

Table 5.1.3b. Element Characteristics of Mechanically Steerable Arrays (Centimeters)

Cavity-Backed Spiral Antenna

d = Cavity Depth
D = Cavity Diameter

Frequency (GHz)	D (cm)	d (cm)
0.8	18.8	9.4
2.5	6.1	3.0
8.4	1.78	0.89
12.2	1.22	0.61

G = 7 dB at Midband

Helix Antenna

D = Helix Diameter
L = Helix Length

Frequency (GHz)	D (cm)	G_e (Element Gain) 3 dB L (cm)	10 dB L (cm)	7 dB L (cm)
0.8	11.9	90.1	45.0	22.6
2.5	3.81	28.7	14.5	7.36
8.4	1.14	8.5	4.26	2.24
12.2	0.79	5.9	2.95	1.47

Horn Antenna (Square Aperture)

H = Vertical Height
L = Aperture Dimension

Frequency (GHz)	G_e (Element Gain)					
	7 dB		10 dB		13 dB	
	H (cm)	L (cm)	H (cm)	L (cm)	H (cm)	L (cm)
0.8	18.8	26.6	37.6	37.6	75.0	52.9
2.5	5.96	9.03	11.9	11.9	23.8	16.9
8.4	1.78	5.0	3.56	3.56	7.1	5.03
12.2	1.25	1.74	2.12	2.12	4.93	3.48

Potentially, the mechanically steerable array possess greater power handling capability than any single transmission line system. This will be true only if the number of active devices is essentially equal to the number of radiating elements, for then true power dilution would be achieved.

Considerations involving passive power divider networks are such that no real benefit can be achieved in the power handling area, since the problem rapidly diminishes to single transmission line problems, which the mechanically steerable array, in concept, attempts to avoid. In addition, the tremendous bulk of X-band waveguide power dividers makes their extended use impractical. For UHF and S-band, coaxial power divider losses of approximately 0.2 dB per division make impractical the feeding of many elements from one or a few transmitters. Consequently, the real benefit of high power handling capability can be realized only if an amplifier is provided for each or for a small number of elements.

The engineering and fabrication costs developed for the mechanically steerably array for rigid and inflatable structures did not include mechanical design or fabrication estimates, and are therefore not presented. The costs for engineering and fabrication would be high, primarily because of increased testing requirements for large element numbers.

5.1.3 ELECTRONICALLY STEERABLE ARRAY ANTENNAS (PHASED ARRAYS)

A limited investigation of phased array antennas was made. Beam switching systems, as exemplified by the Butler Matrix array, were rejected because of physical bulk and/or dissipative losses in the passive network. Commanded systems which would use ferrite or diode switches for beam pointing were rejected for reasons of weight, insertion loss, drive power, or environmental conditions.

It soon became apparent that the adaptive redirective phased array antenna was the only type of phased array antenna suited in concept to TV Broadcast Satellite missions.

However, the state of the art in the 1970-75 time period is not expected to progress to the point where use of this antenna will be feasible for high-power TV Broadcast Satellites.

5.2 TRANSMITTER SUBSYSTEM PARAMETRIC ANALYSIS

This section presents parametric analysis data on satellite television transmitter parameters of efficiency, weight, and cost and analyzes their interrelationships and their dependence on other transmitter parameters, such as frequency, modulation type, and RF power output. The analysis covers three types of transmitters:

1. Gridded tube
2. Microwave tube (klystrons, traveling wave tubes, and cross-field amplifiers)
3. Solid-state transmitters.

The data was derived from the device survey conducted at the beginning of the program to determine the state of the art for each type of device. The range of parameter values included in the analysis is summarized in Table 5.2-1.

The NASA Lewis Research Center is currently developing klystron, traveling wave tube, and cross-field amplifier devices which show promise of higher efficiencies than the 1971 state-of-the-art devices analyzed in this study. The time period of this study did not permit inclusion of data from these NASA device development programs. However, current efficiency estimates from the NASA development programs are included as a convenience to the reader in Figure 5.2-9. A brief description of these developments is given in Section 8.2.6.

Table 5.2-1. Scope of Parametric Analysis

Frequency	~800 MHz (UHF)		~2.0 to 3.0 GHz (S-Band)		~8.4 GHz & 12.2 GHz (X-Band)	
Modulation/Bandwidth	Modulation	Bandwidth	Modulation	Bandwidth	Modulation	Bandwidth
Video	AM-VSB AM-VSB FM	10 MHz 6 MHz 36 MHz	AM-VSB AM-VSB FM	10 MHz 6 MHz 36 MHz	FM FM	36 MHz 60 MHz
Audio	AM FM		AM FM		FM	
Output Device	Solid state Gridded tube Microwave tube		Solid state Gridded tube Microwave tube		Microwave tube	
Number of Channels	1, 2, & 7		1, 2, & 7		1, 2, & 7	
Audio Carrier Level	-10 dB (relative to sync peak)		-10 dB (relative to sync peak)		-10 dB (relative to sync peak)	
Number of Output Ports	1 to 128		1 to 128		1 to 128	
Power Levels	1 W to 50 kW		1 W to 50 kW		1 W to 50 kW	

Note: Expected 1971 RF performance of solid-state and gridded tube devices above S-band precluded their use in this study.

For this study the word "transmitter" is used to describe the high-power amplifying device, any RF transmission lines, RF power dividers or combiners, filters, and protective and monitoring normally associated with it. The "transmitter" does not include the power supply and power conditioning equipment, heat transfer equipment, nor any part of the antenna or driver hardware and equipment.

A complete television channel is defined to consist of an RF carrier with appropriate video modulation (AM VSB or FM) and one or more aural carriers (with AM or FM audio modulation) at a power level of -10 dB relative to the peak sync level in the case of AM and average power in the case of FM video carrier. The modulation used on the video carrier will determine the overall channel bandwidth in conjunction with the number and type of audio signals used.

Output power levels considered in the analysis were from 1 W to 50 kW. Most calculations were done at decade power levels, such as 100 W, 1 kW, 10 kW, and straight line interpolation used for intermediate power levels.

The analytical approach used involved several basic transmitter "building blocks," or modules. Each module consisted of the appropriate output device which met power, bandwidth, and efficiency requirements for a specific application. The blocks could then be combined, using the proper multiplexing or power combiner/divider circuitry, etc., into a basic transmitter as required. This method afforded considerable flexibility in the use of the data collected and allowed a systematic design procedure as follows:

1. Define RF power output level, bandwidth, modulation mode, and number of channels

2. Select appropriate output device module or building block from the parametric curves derived

3. Determine the efficiency, cost, and weight penalties arising from diplexing, multiplexing, and power divider/combiner parametric curves

4. Assemble the entire transmitter and evaluate the resulting performance (repeat process if necessary to arrive at desired power, efficiency, or other parameters)

5. Determine the performance of alternate configurations, using similar methods

The results of the parametric analysis yielded the efficiencies, weights, and costs for the various trnamitter configurations using the five types of power amplifying devices selected from the device surveys: gridded-tubes, klystrons, TWT's, CFA's, and transistors. These were selected as having merit for those operating modes indicated in Table 5.2-2.

Table 5.2-2. Transmitter Parametric Analysis-Initial Selection

Device	700 to 890 MHz	2 to 3 GHz	8.3 to 8.5 GHz 11.7 to 12.7 GHz
Gridded tubes	AM FM_1	-	-
Klystron	*	FM_1	FM_1, FM_2
TWT	*	FM_1	FM_1, FM_2
CFA	AM FM_1	AM	-
Transistor	AM FM_1	AM FM_1	-
FM_1: m = 2	FM_2: m = 4	(m = modulation index)	

* Klystrons and TWT's for 700 to 890 MHz are too large in size.

For AM-video transmitters, separate amplifier chains were assumed for the aural and visual signals since efficiency for a common channel transmitter would drop to a low value due to the necessity to back off drive level to avoid problems. The two signals were diplexed before being applied to the antenna terminal. Low-level modulation of the video amplifier chain and the use of linear amplifiers at higher levels were assumed. The AM and FM transmitter configurations selected for analysis are shown in Figure 5.2-1. A lower side-band slot filter will be required to remove any spurious color subcarrier image at -3.58 MHz. Also, a harmonic filter will be required in the transmitter outputs. These filter assumptions are reflected in the data.

5.2.1 GRIDDED TUBE TRANSMITTER PARAMETRIC ANALYSIS

For specific data points to be used in representing best parametric performance, several transmitter configurations were considered, using the recommended devices. Overall, five AM-video and four FM-video configurations were evaluated for generating parametric data; three typical circuits are shown in Figures 5.2-2 through 5.2-4. (AM audio was included and will be shown parametrically, but this mode is not considered of great importance for space TV applications.) The tubes considered were primarily the L-64S and L-65S, since these types represent tubes using advanced design techniques. The RCA A-2882 was considered at the higher power levels, but has the problem of being too large for an efficient output cavity; it would be a strong candidate at lower UHF TV channels.

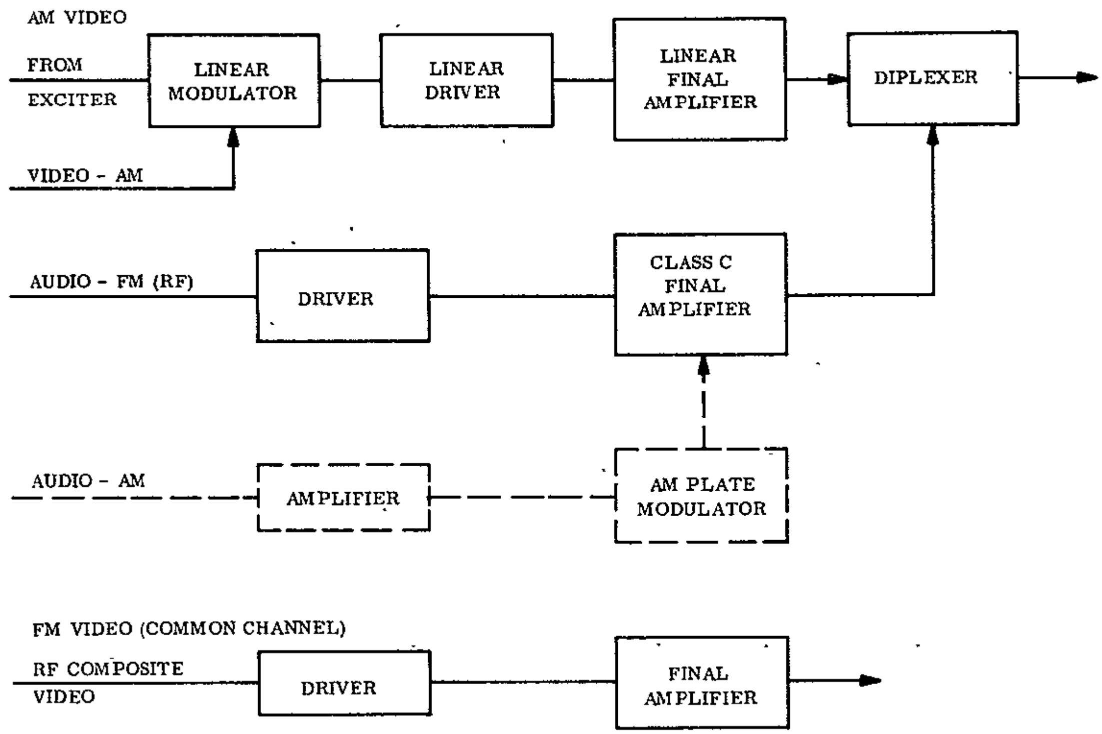


Figure 5.2-1. Transmitter Configurations

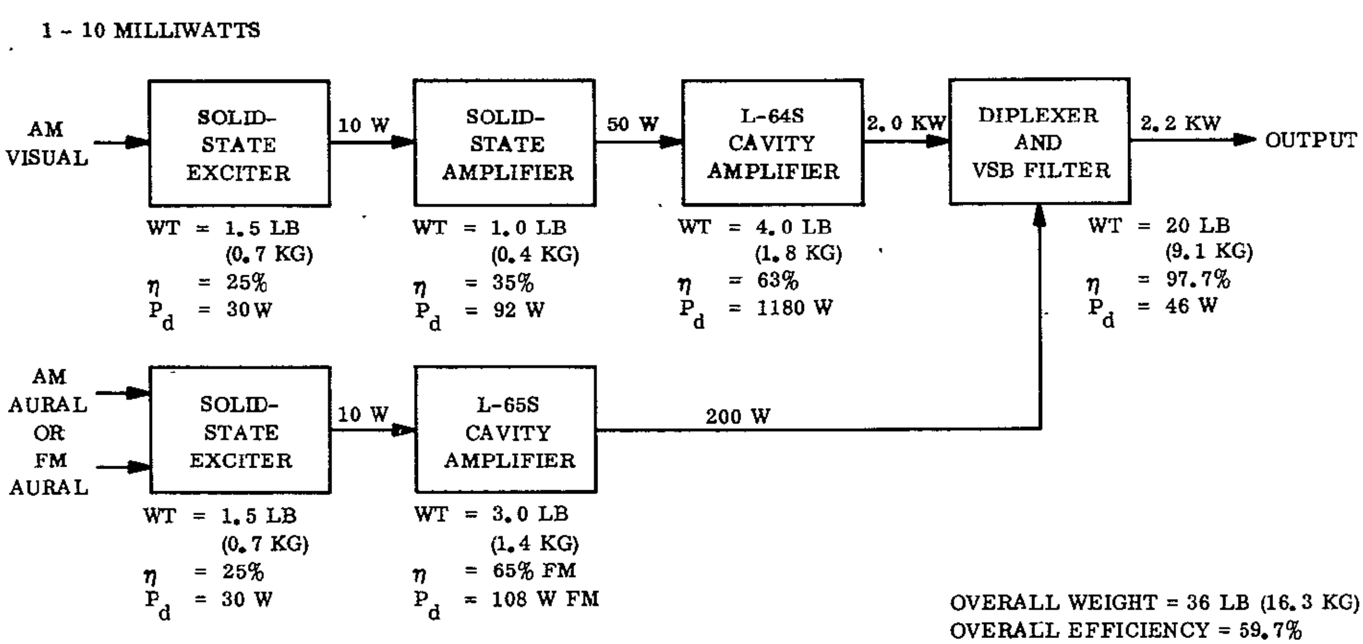


Figure 5.2-2. AM-Video Transmitter Configuration for UHF (800 MHz) with 10-MHz Bandwidth, Using L-65S Triode

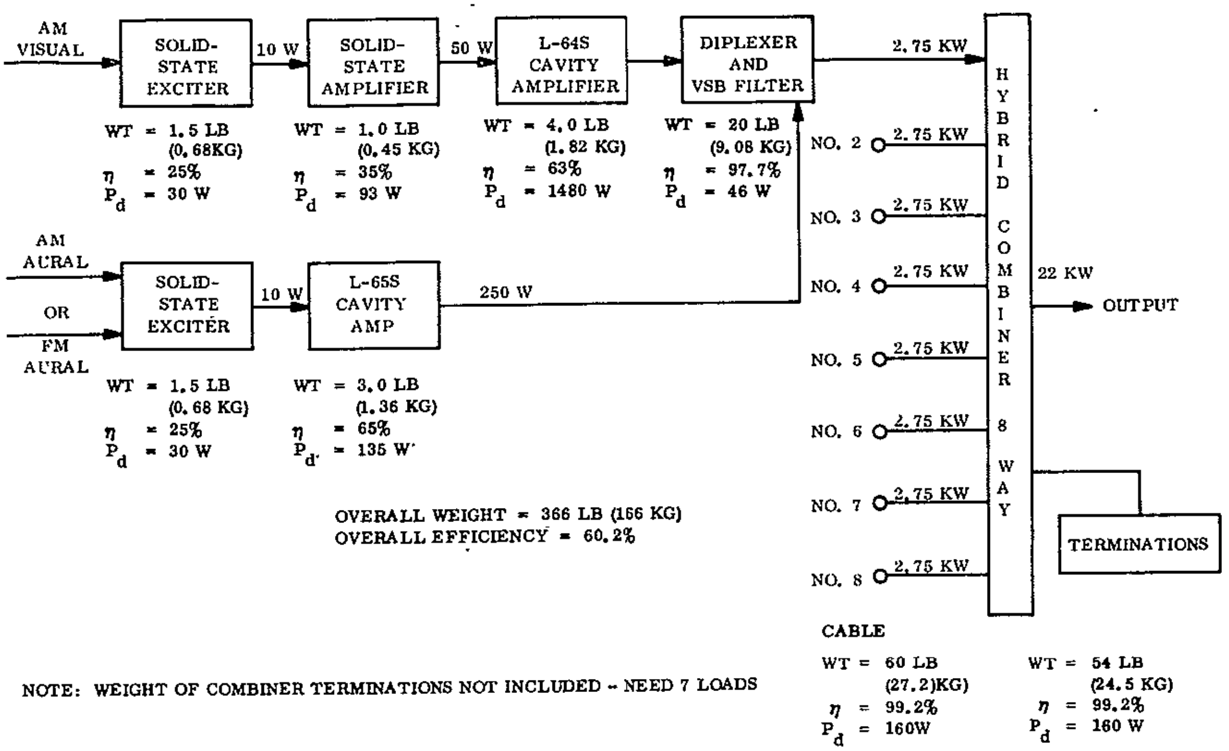


Figure 5.2-3. AM-Video Transmitter Configurations for UHF (800 MHz - 10 MHz Bandwidth, Using L-64S Triodes

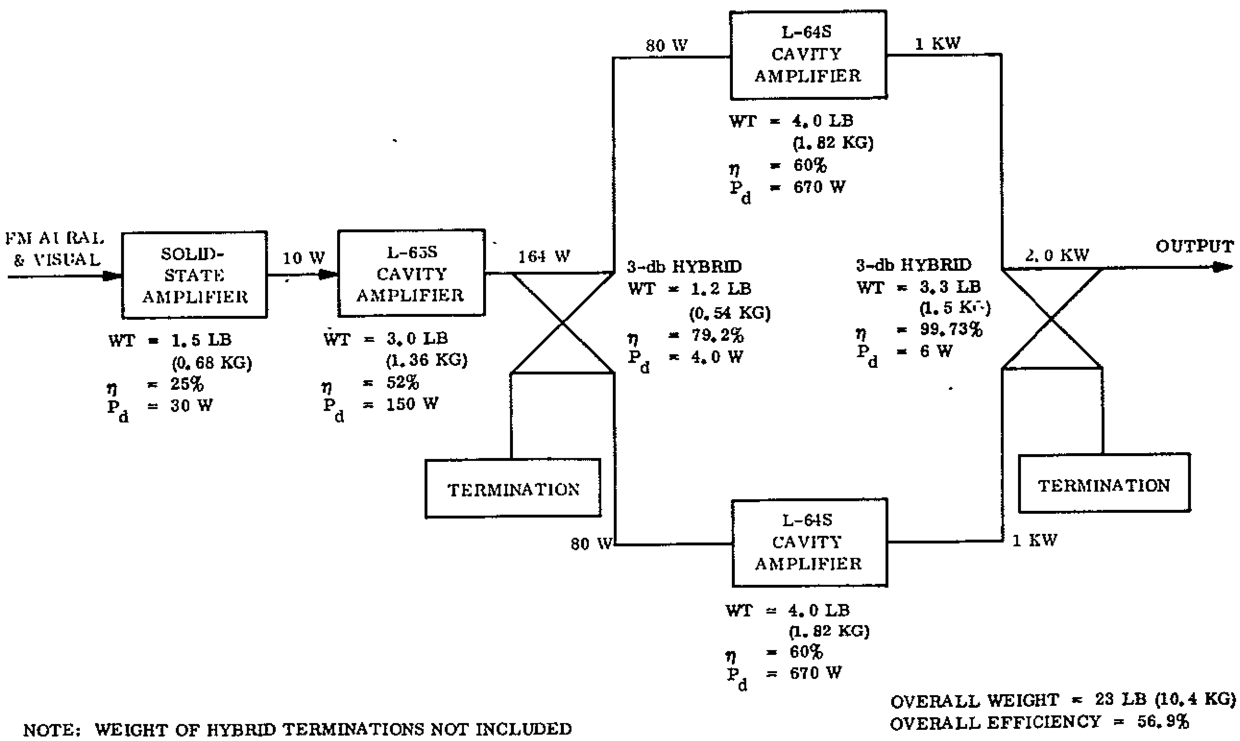


Figure 5.2-4. FM-Video Transmitter Configuration for UHF (800 MHz) - 36-MHz Bandwidth, Using L-64S Triodes

Efficiencies were calculated by determining RF outputs and power inputs to all blocks in the transmitter block diagram and included all output circuit losses. For this analysis, control and protection circuitry were assumed to be external to the transmitter. AM video transmitters include a separate audio RF chain, while FM video circuits have the FM audio in the same common amplifier. Solid-state drivers are utilized to the 50-watt level (from 10 milliwatts input) and gridded tubes are used thereafter, either as final stages for lower power levels or as drivers for higher power levels. The characteristics shown assume that the vestigial sideband filters at the transmitter output will be optimized for minimum weight by proper design.

For the purpose determining the dc power input required for an overall transponder, average power was used. Although average power is not well defined, a nominal average value of TV signal for normal programming has been estimated to be 32 percent of peak sync level. This signal model provides a Class B amplifier efficiency of 63 percent at peak sync. Figure 5.2-5 shows AM peak sync efficiencies for combined video and audio near 45 percent at 100 watts and 60 percent at 10 kw. The average efficiency resulting from the assumed operational duty cycle* is shown for comparison. Usage of high efficiency circuits (Table 5.2-3) would result in very high average efficiencies, as shown by the Doherty circuit example in Figure 5.2-5.

Table 5.2-3. High-Efficiency UHF AM Gridded Tube Amplifiers

Circuit	Approximate Efficiencies Peak Sync (percent)	Approximate Efficiencies Average (percent)
Linear CFA (reference)	70	60
Class B Linear	60	40
Dome Class C Linear (present)	75	53
Terman-Woodyard	73	72
Doherty	65	62
Dome (Transmitter)	60	57
Chireix Outphasing	60	55
Fisher (varies with design)	60	55

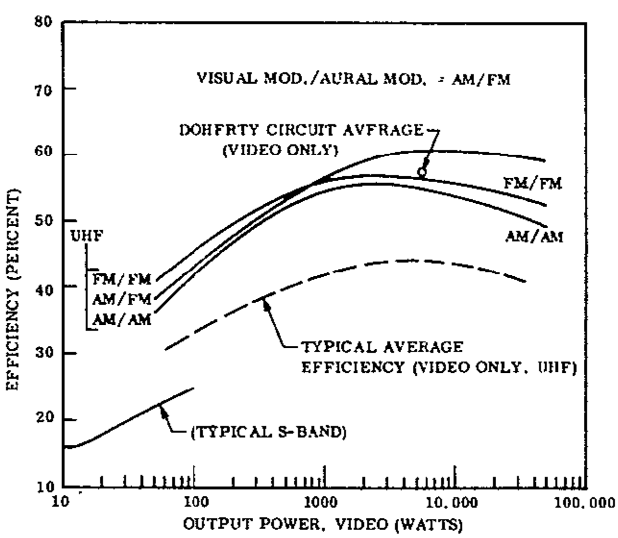


Figure 5.2-5. Efficiency of Gridded Tube Transmitters

* 7.89 percent at peak sync, 15.7 percent at blanking level (56 percent of peak sync), and 76.5 percent at average signal level (20 percent of peak sync).

The FM efficiency was determined to be near the AM peak efficiency. The FM transmitter assumes Class C operation and should be considerably more efficient, especially since the tube operates with a maximum plate voltage swing at all times and has a small angle of plate current flow. However, FM requires a wider bandwidth, 36 MHz as compared to only 10 MHz for AM, and the tube output power and gain are both reduced accordingly due to gain-bandwidth and power-bandwidth limitations. The additional drive required to overcome the larger bandwidth lowers the overall transmitter efficiency, resulting in the data shown in Figure 5.2-5. (The slight dropoff at higher power levels is due to power combiners assumed.)

Due to the relatively low average efficiency of the Class B linear AM amplifier, an investigation was performed on several high-efficiency amplifier circuits which are competitive with the best efficiency devices expected from present studies of CFA and other microwave-type tubes. Table 5.2-3 lists several types of AM RF amplifier circuits that may be used for TV or other wideband transmitters. Comparisons were made for a TV signal, showing peak sync and approximate average efficiencies, with a linear CFA shown as a baseline reference.

The five high-efficiency circuits shown in Table 5.2-3 have been investigated, and all give good average efficiencies on an analytical basis. They are briefly described below:

1. Terman-Woodyard (T-W). Uses a carrier and a peak amplifier (both operating Class C) and uses grid modulation. The efficiency can surpass a Class C plate-modulated amplifier.

2. Doherty. The Doherty is similar to the T-W, but uses a Class B carrier tube with a Class C peak tube. Efficiency is less than the T-W, but is still very good. The circuit accepts a modulated input RF signal so the VSB filter may be placed in a lower level driver stage.

3. Dome. The Dome uses a "modifier" tube which channels part of the instantaneous, untransmitted power back into the power supply, resulting in an improvement in overall transmitter efficiency.

4. Chireix Outphasing Circuit. The Chireix uses an AM output from a PM input. It is quite phase sensitive; full output (100 percent modulation) occurs with only $\pm$ 45 degree ($\pm \pi/4$ rad) phase modulation. Unless phase sensitivity could be decreased, this circuit would probably not be preferred for TV where the tight phase requirements required for good outphasing operation cannot be met.

5. Fisher. This circuit divides the modulation waveform into time segments, which is not a practical technique for a TV signal. In effect, different tubes operate for selected amplitude levels, so that each operates near peak efficiency.

Generally, considerations of efficiency, complexity, and adaptability to a space TV application indicate a preference for the Terman-Woodyard circuit if the high level VSB filter it requires can be designed for a reasonable size, weight, and cost. Otherwise, the Doherty circuit, which is a linear amplifier version of the Terman-Woodyard circuit, would be preferred, since a small input VSB filter can be used to accomplish a major part of the filtering required. The other three circuits are more complex and have features which are not desirable for a TV type of application.

Weights of the various transmitter configurations for different modulations were obtained by adding weights of individual components derived from extrapolations of modules already fabricated (modified as required to account for frequency differences). All cavities, filters, connecting cables, and other components are included; conventional high-level vestigial sideband filters are not used due to their excessive weights. Figure 5.2-6 shows curves based upon the various calculated weights. Weights shown include a supporting structure weight assumed to be equal to 25 percent of all other weights. Support weight depends on some aspects of the satellite design and environmental requirements which are not yet specified.

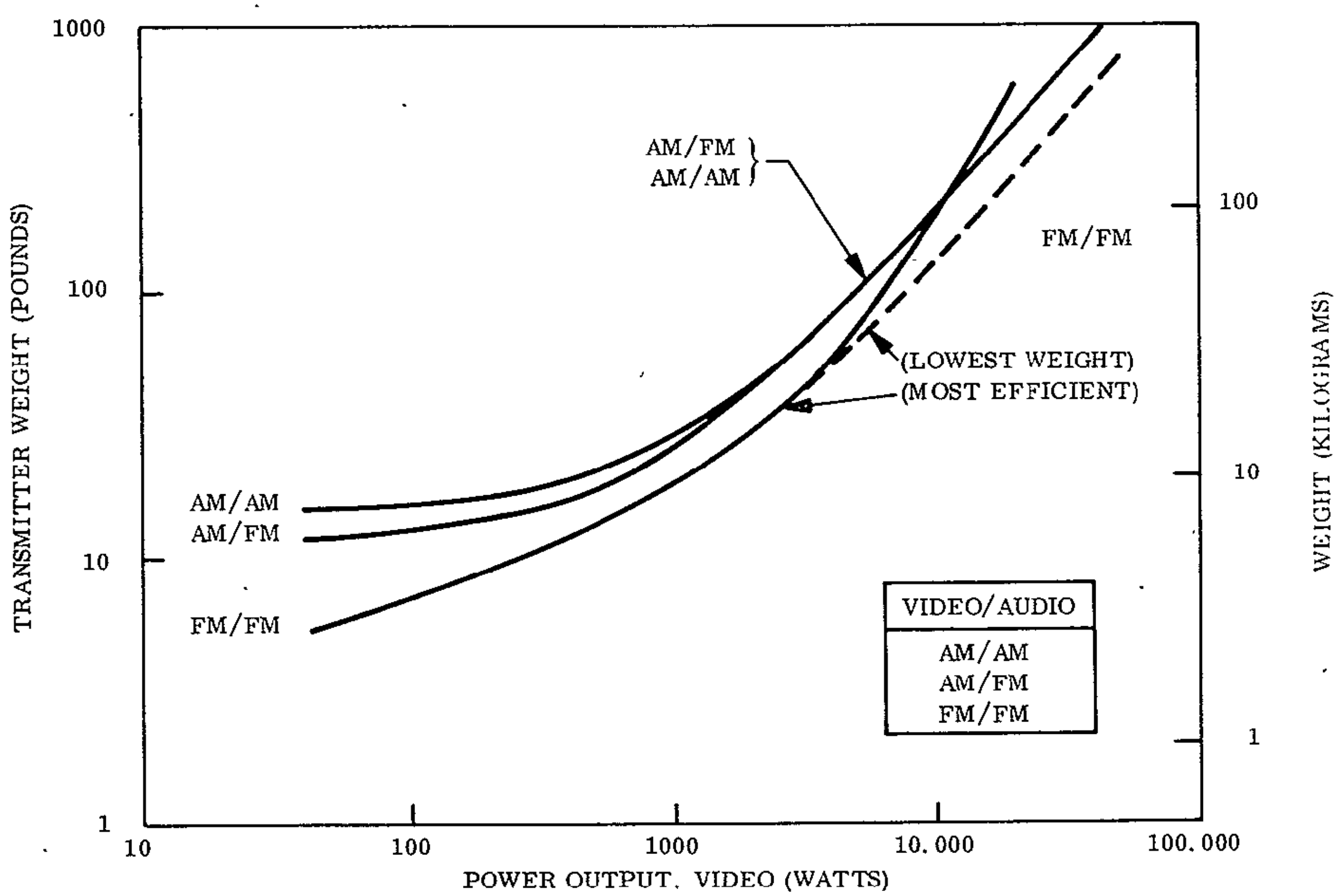


Figure 5.2-6. UHF Gridded Tube Transmitter Weight

Costs are generally expressed in terms of engineering and fabrication costs. Engineering costs include all costs through the qualification of a prototype transmitter. Fabrication costs are those required to make additional copies of the transmitter, using those production techniques suitable for the transmitter type and quantity required. Estimated costs for gridded tube UHF transmitters of output power ratings of up to about 50 kW are based on transmitters using tubes with L-64S capabilities above 2.5 kW (for AM video; 1.0 kW for FM), the L-65S type between 400 watts and 2.5 kW, and undesignated tubes of similar construction at lower powers. These costs are shown in Figure 5.2-7 and are nominal for either AM or FM transmitters. AM requires the additional audio RF channel, but FM requires a much wider bandwidth; this situation tends to create transmitters of about equal costs.

A complete, high-power engineering model of a transmitter is assumed to use only up to four engineering modules (to 10 kW); higher-powered assemblies will utilize final fabricated modules for the additional power requirements. Some additional power combiner cost is included in the engineering costs above 10 kW in Figure 5.2-7.

Fabrication cost represents the cost of fabricating a duplicate of the engineering model transmitter. This includes quality control and all testing prior to installation. This cost is somewhat variable since it will depend on the configuration that the development follows. The two dotted extensions of the fabrication cost indicate limits for multiple-transmitter configurations (upper curve), where several identical chains are paralleled, and a single chain transmitter (lower dotted curve) using a single large tube. The preferred transmitters, on the basis of efficiency, tend to have fabrication costs nearer the upper dotted curve.

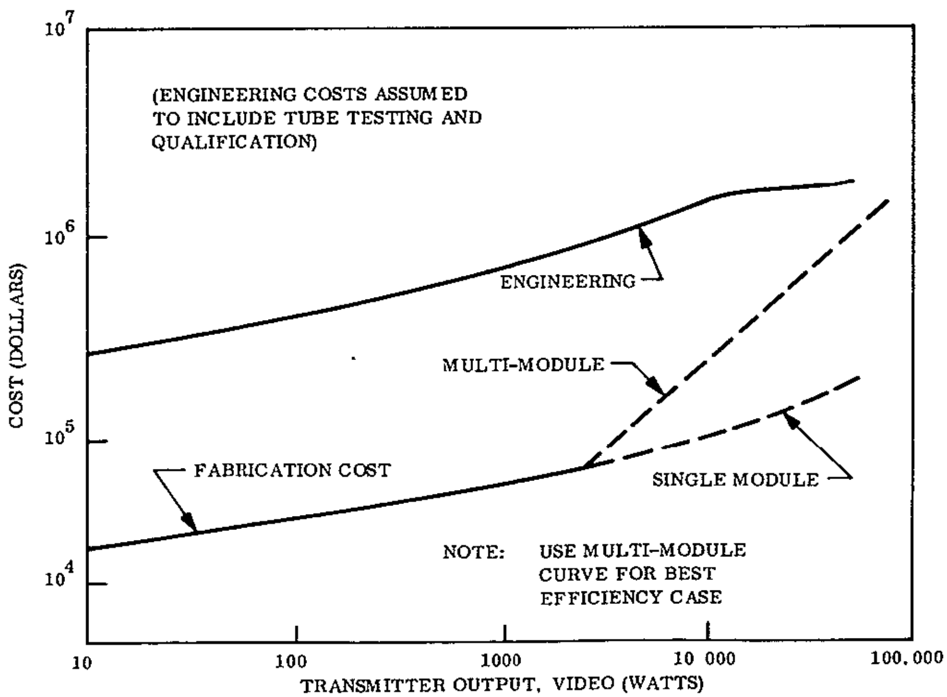


Figure 5.2-7. Gridded Tube UHF Transmitter Cost

5.2.2 MICROWAVE TUBE TRANSMITTER PARAMETRIC ANALYSIS

A somewhat different approach was used in deriving the parametric curves for transmitters using microwave tubes (klystrons, traveling wave tubes, and cross-field amplifiers. In the case of the gridded-tube transmitter, specific existing tube types could be identified for transmitters covering the specified power range. However, no microwave tubes directly suited for space applications were found for power levels above 100 watts. Parametric curves were generated for single-channel transmitters; auxiliary curves and mathematical relations were developed so that desired transmitter configurations could be specified, using characteristics of tubes fitting the previously developed performance curves. Parametric curves were generated for complete transmitters of several representative configurations (as in Figure 5.2-1 or the more general form in Figure 5.2-8). With this approach, performance, weight, and cost were estimated for the transmitter configurations, assuming the particular microwave tube had been developed.

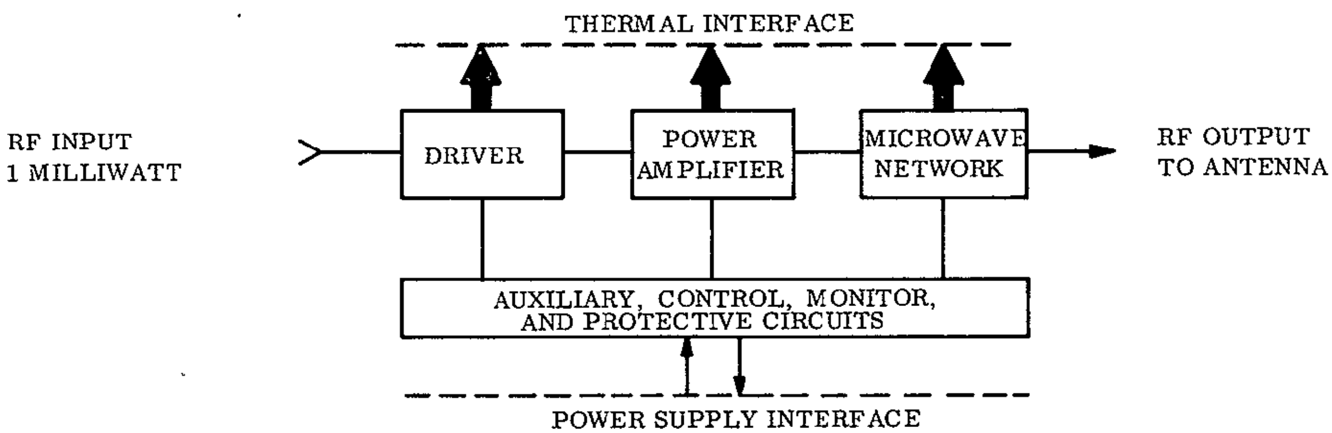


Figure 5.2-8. Block Diagram for Single-Channel Transmitter

The microwave tube transmitter data is given for a unit capable of handling a single TV channel consisting of one visual signal and one aural signal. AM-VSB video transmitters require separate FM aural signal RF amplifiers, while the FM video transmitters amplify the video and audio signals in a common channel. In the latter case, the aural signal is contained on an FM subcarrier which is included in the overall FM spectrum of the transmitter. The approach was to identify requirements for each block in the transmitter block diagram as required for a specified output power and modulation type. Each block was then evaluated in terms of power consumption or loss, inputs and outputs required, and the other parameters of interest. Supporting blocks include the driver, which was described parametrically by referring to the same curves as for the final stage but adjusting to the output power level required in the driver. RF circuitry parameters were determined, and all parameters from the amplifier, driver, and output circuits were combined appropriately.

Efficiency, weight, and cost estimates include the amplifier chain(s) plus auxiliary components and subsystems, such as microwave networks and monitoring and control circuitry. A nominal signal input level from the exciter of 1 milliwatt was assumed. The transmitter must interface with the power supply, heat-rejection subsystem, antenna, and receiver-exciter, but these spacecraft subsystems and their interfaces are not included in transmitter data given in this section. Spare amplifier chains or other major redundancy features were not included at this conceptual design study level.

Since microwave tubes will normally have at least 15 dB (CFA) to 40 dB (linear beam tubes) of signal gain, transmitter characteristics are determined largely by characteristics of the microwave tubes which are attainable for use in the transmitter output stage. Selection of the tube(s) and other transmitter components is dependent primarily upon the requirement for satisfying mission performance parameters listed in Table 5.2-2. Due to the high cost of spaceborne power, maximization of overall transmitter efficiency becomes the most important consideration. Thus, the transmitters are built around the tubes which deliver the most efficient power conversion performance and which meet the mission performance requirements.

Dc to RF conversion efficiencies for microwave tube transmitters are based on the ratio of total RF power output to the antenna to total dc input power to the transmitter. AM-VSB transmitter average efficiencies are based on a video signal model with a gray-level picture content such that the average-to-peak-power ratio for the composite sync/picture video signal is 0.32. Note that this contrasts with most AM-TV ratings where peak sync level efficiency is stated. For AM-VSB transmitters, the efficiency data includes an FM aural transmitter channel with an output power level of 10 percent of video peak sync. Predicted microwave tube transmitter efficiencies are presented in Figure 5.2-9.

Efficiencies of all the microwave-tube type transmitters are less for lower-power units and rise to a maximum level at a higher power, above which efficiency versus transmitter power remains about constant. The power level at which the breakpoint occurs depends, in part, on the relative efficiency of aural and visual channels (for the AM-VSB transmitters), on auxiliary and power requirements, and on tube characteristics. The relatively low efficiency of the S-Band AM-VSB transmitter is due to the anticipated efficiency decrease of the linear amplifier CFA when the higher frequencies are used. This is not a basic limitation in tube capabilities, and anticipated S-band performance will be more nearly that of the UHF tube if development extends past the 1970 period covered in the device survey.

Microwave-tube transmitter weights, -- which include those of the elements shown in Figure 5.2-8 (single-signal channel) for visual channel and, where used, the aural channel and diplexer -- are summarized in Figure 5.2-10. A transition point between the use of coaxial lines and waveguide in the high-level output network occurs at about 10 kW. The waveguide estimated weights are considerably heavier than those of the coaxial line assumed

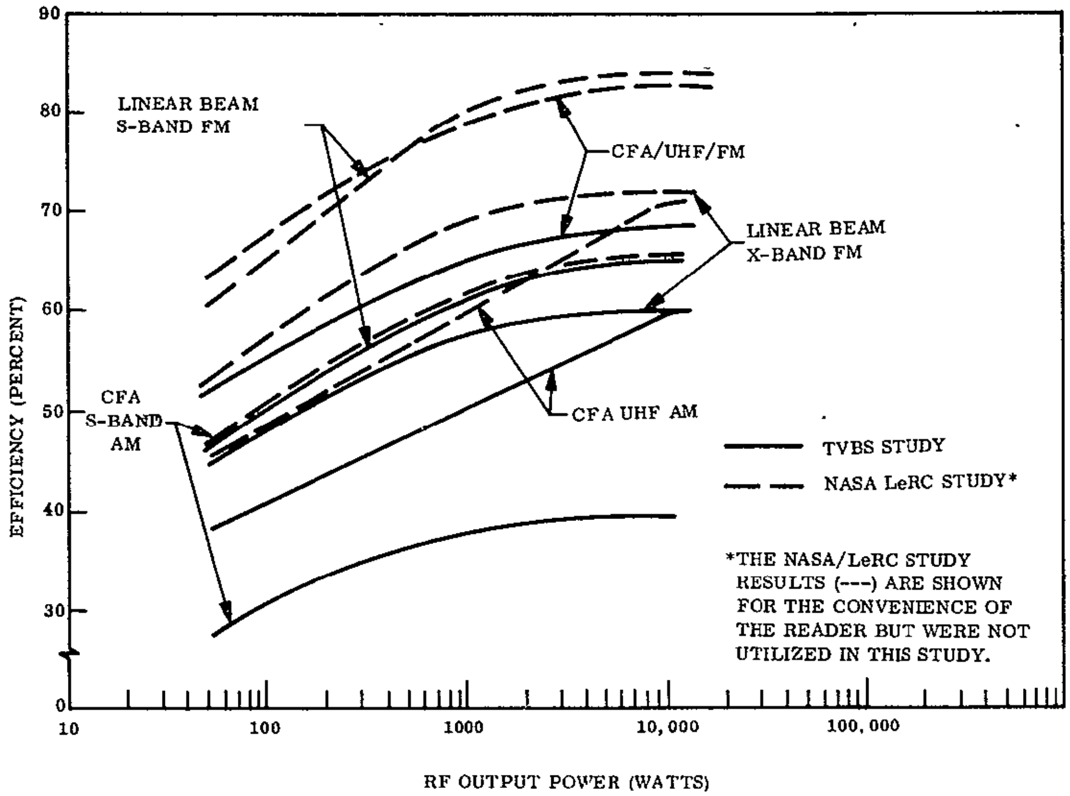


Figure 5.2-9. Microwave Tube Transmitter Efficiencies

for the 100-watt to kW range. Since the choice of the transition point is somewhat arbitrary, a closer determination of the microwave component requirements would be in order if operation near 10 kW is anticipated and if weight determination requirements are critical. This determination would require a more exact definition of the transmitter, including heat sink temperature, cooling method, operating frequency, and detailed transmitter electrical performance specifications.

CFA and linear beam tube transmitter costs for transmitters capable of handling a complete single TV channel (audio plus video) are summarized in Figures 5.2-11 and 5.2-12, respectively.

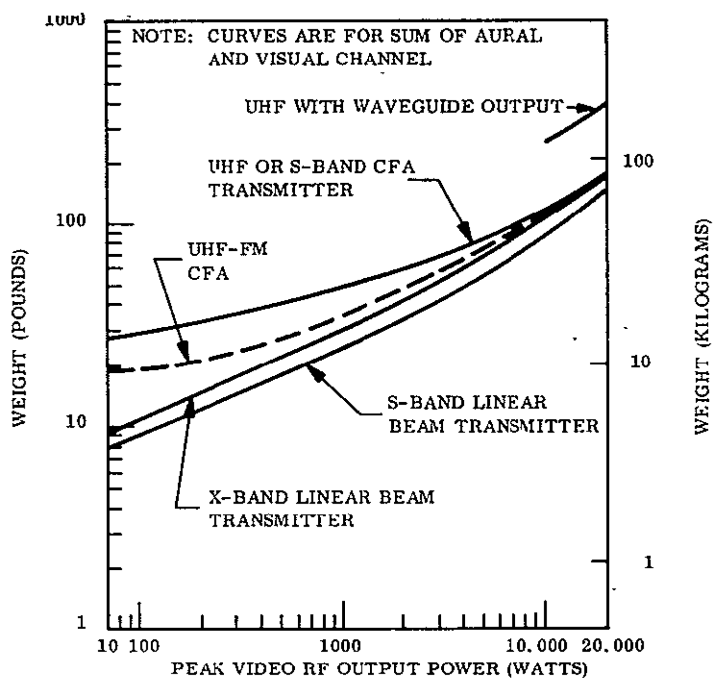


Figure 5.2-10. Microwave Tube Transmitter Weight

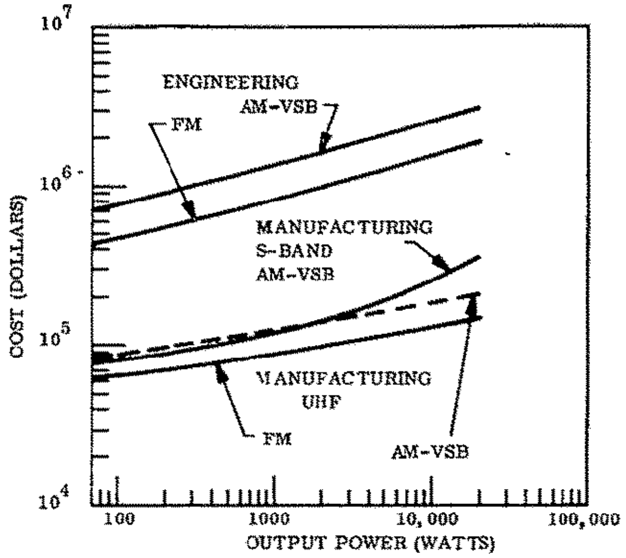


Figure 5.2-11. CFA TV Transmitter Cost

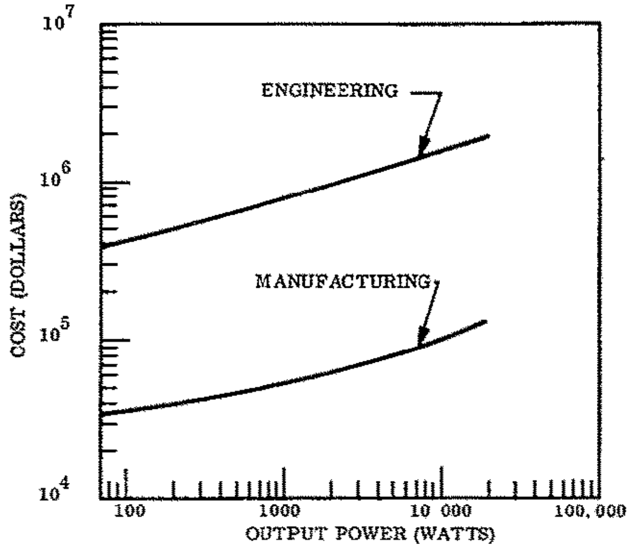


Figure 5.2-12. Linear Beam Tube (Klystron and Traveling Wave Tube) FM TV Transmitter Cost

5.2.3 SOLID-STATE DEVICE TRANSMITTER PARAMETRIC ANALYSIS

In order to obtain the parameters for all power levels, performance was computed at three power levels, spaced about a decade apart, and a smooth curve drawn through the three points (200 watts, 2.0 kW, and 20 kW). The lower power circuits were viewed as being the same circuits as the drivers in higher power transmitters described in the previous two sections. The device survey indicated little variation in device efficiency with power level, so transmitter efficiencies would also vary little with power level.

The RF sections of all transmitters were assumed to be based on standard modules with four output transistors in the final stages. Since one transistor can drive about four others, the choices in output configurations were assumed to be 1, 4, or 16 transistors. A single transistor has too little power for the size of transmitters considered and would require too many modules for even the lowest power levels (near 200 watts). Sixteen transistors would result in too much power for a "universal" module. A four-transistor configuration was therefore considered a reasonable compromise for the purposes of this study. The individual module powers for the frequency/circuit combinations are:

1. UHF
   a. Class B: 119 watts output
   b. Class C: 159 watts output
2. S-band
   a. Class B: 47 watts output
   b. Class C: 59 watts output

Generally, the efficiency effects of combining modules for high-power operation are not greatly influenced by module size. The modules noted were combined to provide near 200 watts, 2 kW, and 20 kW.

Circuit bandwidth for transistor transmitters is greater than required, and 10-MHz AM video can be accommodated with no difficulty. In addition, the 36-MHz FM bandwidth can be attained with the performance indicated for Class C operation.

The AM video transmitter used a separate audio RF channel and combined the video and audio RF signals in a diplexer at the antenna connection. (If AM video and FM audio were in a common channel, the video level could be only 60 percent of that for a single channel having only video. This is the best that can be done with a -10 dB audio level (relative to peak sync) and no saturation distortion. At a 60 percent level, system efficiency would be poor.) For FM video where the audio modulation and its subcarrier are also assumed to be FM, a single-channel transmitter can transmit video and audio simultaneously without requiring a power reduction to avoid saturation distortion. Only a division in total output power results, with 91 percent in the video RF and 9 percent in the audio RF for a -10 dB audio power level. The audio could also be reduced further without loss of audio relative to video.

The vestigial sideband filter for AM video is assumed to be either in a low-level stage, which introduces a final-stage intermodulation problem, or in the antenna system. Conventional output VSB filters as commonly used in ground TV transmitters are too heavy and too large to be acceptable.

The parameters of efficiency, weight, and cost were based on standard modules discussed above and include the effects of power combiners, which are evaluated in Section 5.2.4. Figure 5.2-13 shows transistor transmitter efficiencies. The peak sync powers for the solid-state AM transmitter have to be converted to average in order to permit the power conditioner to be sized. Thus the 35 percent efficiency transmitter may provide only about 20 percent average efficiency for Class B operation. The basic problem with the high-power, solid-state transmitter lies in the low gain and only moderate efficiency of transistors. A large number of transistors are required for the power requirements; a large number are also required for driving the final stages. Consequently, much power is used which is not converted into output RF power, but which must be supplied by the power source, resulting in a low efficiency overall, as indicated in Figure 5.2-13.

Transmitter weights are the sum of the module weights, power combiner weights, and a 25 percent additional factor to cover supporting structures. The latter assumption covers all mechanical requirements for mounting transmitter components in cabinets, which are then available for mounting in the satellite. Figure 5.2-14 shows transmitter weights with and without output power combiners. Weights without output power combiners are representative of transmitters driving array-type antennas having one antenna element per transistor. (The practical factors of interfacing the transmitter with a phased array are not included in the scope of the present parametric analysis.) Multiple-channel operation can be achieved through use of multiple transmitters and a suitable multiplexer. Multiplexer operation is evaluated in Section 5.2.5.

Engineering costs, the largest expense except at highest powers, include the development and qualification of an engineering model of the transmitter (Figure 5.2-15). Also included are the transistor qualification costs, shown as a dotted curve in Figure 5.2-15. At high power, engineering costs are shown to taper off. This assumes that the engineering model will not use more than about 10 engineering modules, and thereafter will use the fabricated production modules (charged to fabrication costs) to demonstrated high-power combiners and other high power components. Fabrication costs show a linear increase in cost above the one -module power level (shown at about 100 to 150 watts in Figure 5.2-15) where a number of identical modules are required. This cost represents that of reproducing identical modules up to the selected power level.

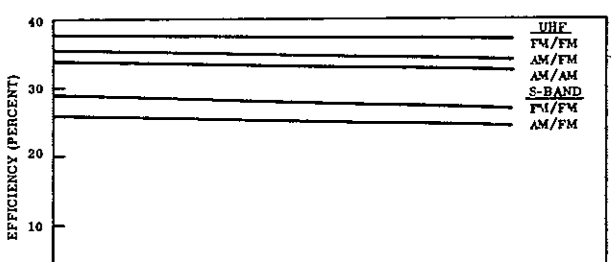


Figure 5.2-13. Transistor Transmitter Efficiency

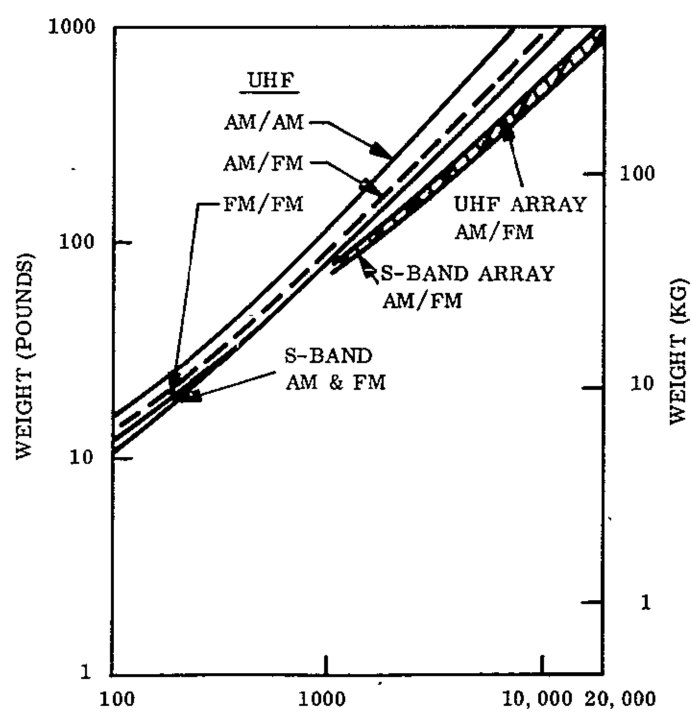


Figure 5.2-14. Transistor Transmitter Weight

5.2.4 POWER COMBINER PARAMETRIC ANALYSIS

Power combiners are waveguide devices (or other transmission line types at lower powers) used for combining identical signals from more than one source. The parametric data is directly applicable to dividers where a multi-port array antenna is to be operated from a single source.

The attainment of high power by summing the outputs of several amplifiers results in some reduction in overall efficiency because of losses in the power-combining network. Figure 5.2-16 shows the estimated nominal insertion loss of these networks versus the number of ports to be summed. Appropriate forms are shown for the power levels and frequencies marked on the curves.

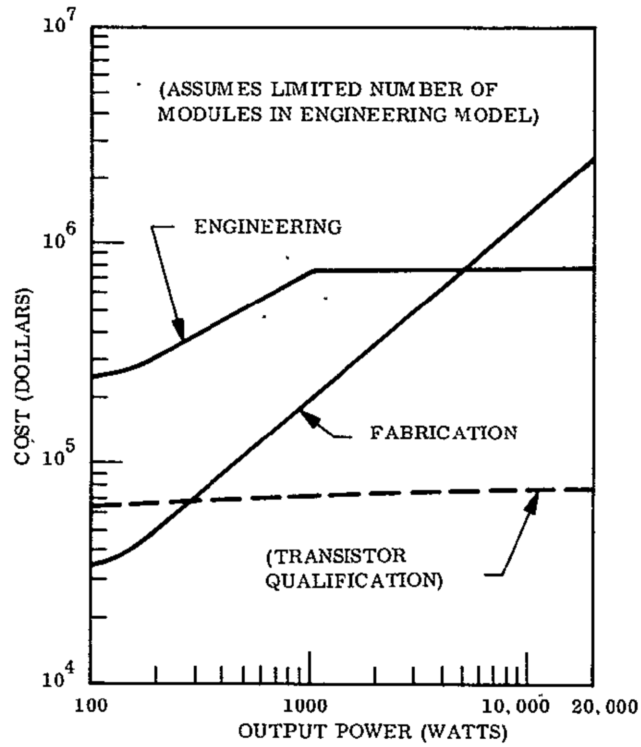


Figure 5.2-15. Transistor Transmitter Costs

For the various types of power combiners (or dividers) considered, weight and cost became excessive for large numbers of ports and lower frequencies. This situation is shown in Figures 5.2-17 and 5.2-18. If a large number of ports should be required, it appears

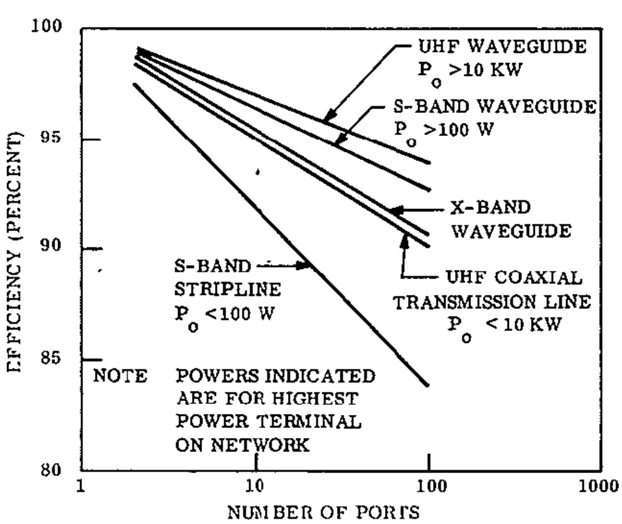


Figure 5.2-16. Power Divider/Combiner Efficiency

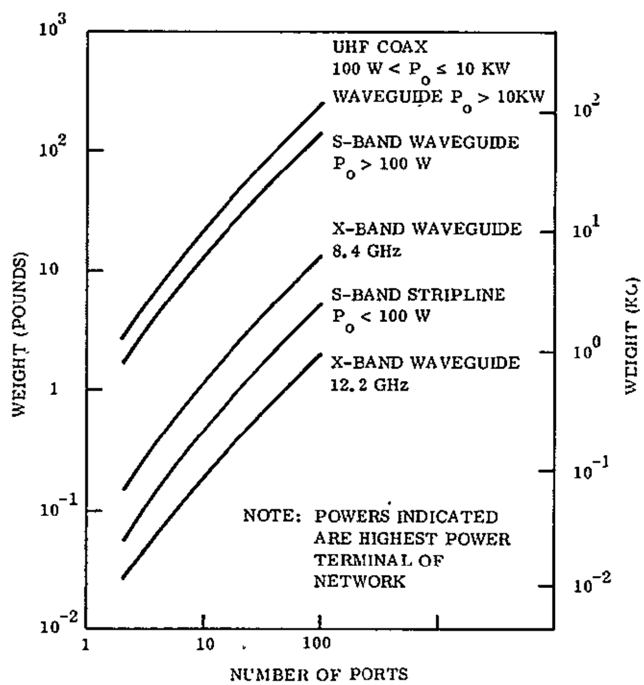


Figure 5.2-17. Power Divider/Combiner Weight Versus Number of Ports

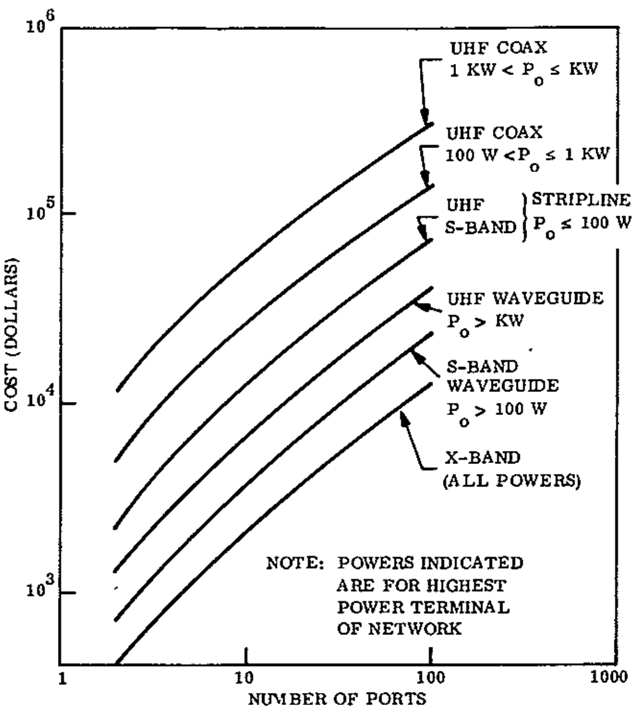


Figure 5.2-18a. Power Divider Network Engineering Cost

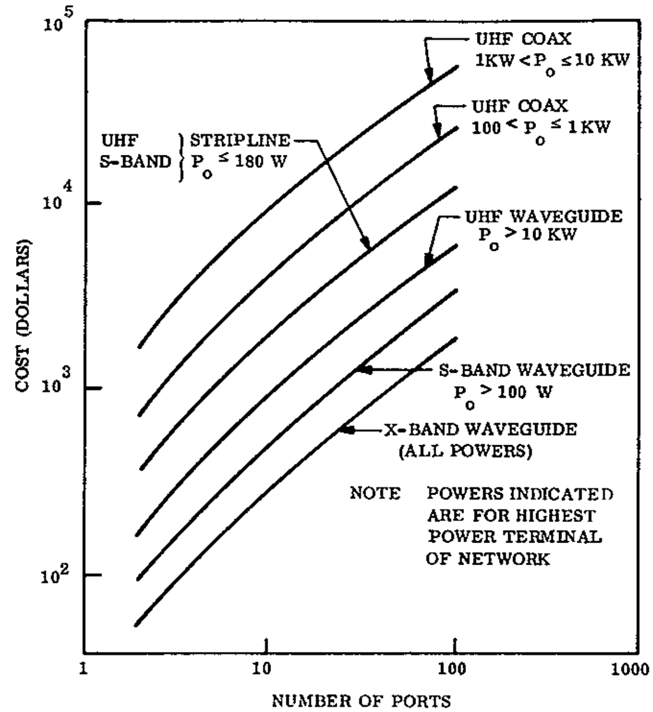


Figure 5.2-18b. Power Divider Network Fabrication Cost

preferable at UHF to consider leaky-guide types rather than the hybrids used here for power dividing. For combining, other approaches, rather than the brute-force hybrid arrangement, may also be considered. Costs are also based on the use of hybrids. This approach is adequate for small numbers of combiners or dividers, while other techniques may be considered for large volume dividing or combining.

5.2.5 MULTIPLEXER PARAMETRIC ANALYSIS

Multiplexers are devices for combining outputs of transmitters on different channels so they can utilize a single antenna. The data presented for multiplexers are generally applicable to any of the transmitter types.

When several channels are to be combined on a single antenna, the estimated efficiency of multiplexers of various constructions at UHF, S-band and X-band frequencies is as given in Figure 5.2-19. Multiple-channel weight and cost effects for the same conditions are given in Figures 5.2-20 and 5.2-21. Multiplexer weight included harmonic filters and visual/aural diplexers, as well as the couplers and filters used to isolate the separate channels.

Stripline costs are basically the lowest, but efficiency and power handling capability generally relegate this form to low-power operation. UHF will use coaxial line types where possible to keep size and weight within reasonable limits; the other bands will use waveguide configurations.

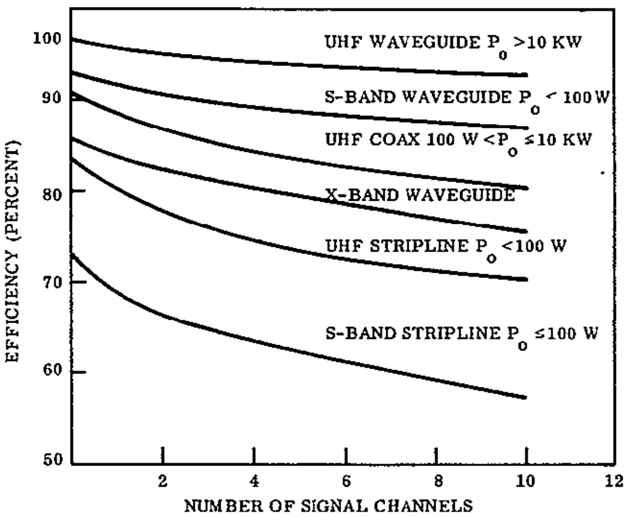


Figure 5.2-19. Efficiency of Multiplexer

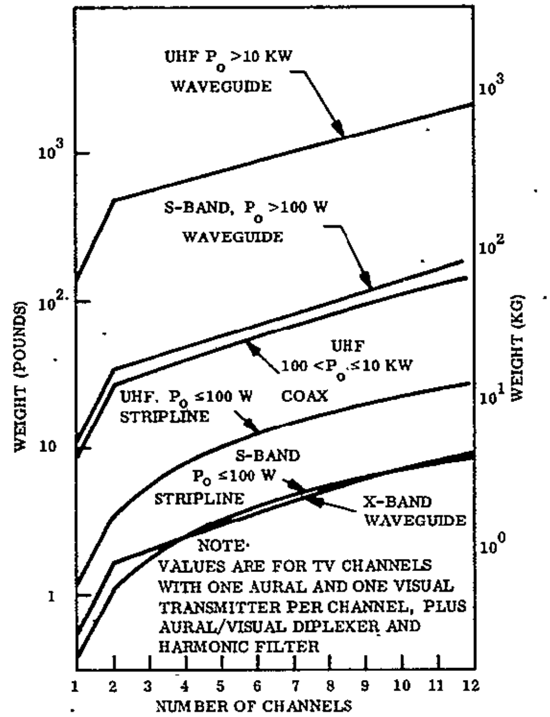


Figure 5.2-20. Weight of Multiplexers

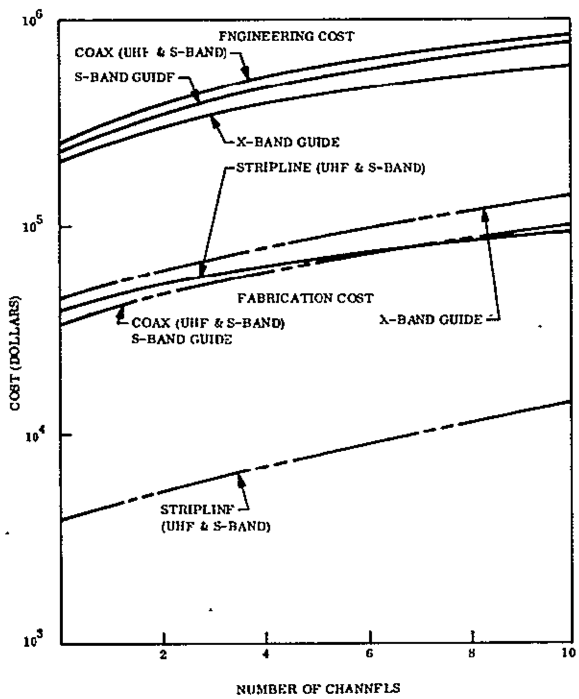


Figure 5.2-21. Cost of Multiplexers

5.3 ATTITUDE CONTROL PARAMETRIC ANALYSIS

Candidate sensors, electronic devices, and control torque actuators were identified for a class of synchronous equatorial satellites having a minimum lifetime of 2 years and performing a range of functions required for television broadcast. Because of the wide ranges of deployed solar array and antenna area, volume, weight, power, costs, configurations and control accuracies involved, a simplified analytical technique was employed. Where practical, the fixed and variable portions of these parameters were analyzed separately, using available data from flight quality hardware programs and manufacturers' extrapolation of advanced hardware. Survey papers were searched and manufacturers were contacted to arrive at a consensus of trends for attitude stabilization methods and components for the 1970-1975 time period. Only those parameter variations that would vary the total broadcast satellite system performance significantly were itemized. For small variations, constant parameter values were specified.

The selection of the form of the controller and the actual design of the subsystem is heavily dependent upon the operational requirements of pointing antennas and solar arrays and upon the configuration interaction with the environment.

A satellite coordinate reference system is established as follows for the configuration discussions of this report: Orbit plane coordinates are used in a standard right-hand rule convention, where roll is "out the nose" in the direction of velocity, pitch is "out the right wing" in the direction of the negative of the orbital angular velocity, and yaw is down.

For broadcast television missions of interest, the controller function is primarily that of a regulator, and the stabilization problem is to provide position regulation in roll and yaw and a velocity regulation in pitch. The three-axis regulator can take on many forms, but each particular design for a given form is sensitive only to the disturbances presented to the regulator.

Within the overall system design of the broadcast satellite are the stabilization system accuracy requirements and the solar array size. Both of these system parameters are power dependent. For a specified coverage, increased pointing accuracy results in reduced solar array area. This reduction has a feedback effect in that the reduced area results in less disturbance force, easing the problem of implementing the high-accuracy pointing or permitting a reduced stabilization subsystem weight.

The accuracy of the particular regulator is determined by the disturbances of the system. Characteristically, the disturbances of importance are the sensor noise and the environmental disturbances. Outside of their commonality of importance, these two disturbance sources are dissimilar in their treatment in the regulator design. Particularly, environmental disturbances tend to "size" the controller. Since the primary environmental disturbance source of concern is solar pressure on the solar array, a reduced solar array area made possible by a more accurate controller results in less environmental disturbance to that particular controller and therefore a reduction size of the controller. Of course, the torque disturbances due to solar pressure on the array can be minimized by a balanced configuration design (which may include solar pressure trim tabs); but once this minimum is reached, further reduction is possible only by reducing the size of the solar array.

It has been assumed that all missions of the TVBS class require some form of operational stationkeeping but that the disturbances due to this operation can be effectively reduced by configuration design to a level an order of magnitude lower than the environmental disturbances on a cumulative basis. On that basis, the stabilization fuel weight requirement is dictated by the ever present solar pressure, rather than by the periodically applied stationkeeping thrust.

The problem of selecting the form of stabilization and performing a regulator design reduces to the investigation of sensors and actuators which are compatible with the mission and configuration, respectively. Consequently, to describe all admissible subsystems parametrically in terms of a range of missions, a sequential process was used to arrive at the final task output: the engineering cost, fabrication cost, power, and weight of attitude stabilization subsystems versus the accuracy of stabilization (antenna pointing accuracy), with vehicle size taken parametrically. An analysis of disturbance torques due to solar radiation pressure was performed in order to determine the control system requirements.

With the requirements of antenna pointing and solar power, a piecewise parametric configuration study was performed on 13 admissible attitude stabilization concepts. These concepts ranged from low-power, body-mounted solar arrays on a spinning body to high-power planar arrays articulated to the sun line. Vehicle size and pointing accuracy were considered in all combinations within the context of each of the stabilization concepts. The concept applicability versus vehicle size and pointing accuracy were plotted with a preferred concept at a particular weight and accuracy was selected by means of a table look-up of preferential concept order. This table had been compiled as a part of the configuration study and reflected factors in addition to cost, weight, and power.

A block diagram of each control concept was prepared as an ordering aid. Types of components applicable to each concept were indicated. The costs, weight, and power for 1971 state-of-the-art hardware from the technical evaluation were used with the appropriate control concept block diagram to produce the final parametric analysis data: subsystem costs, power, and weight versus stabilization accuracy, with vehicle weight as the parameter.

5.3.1 SENSOR PARAMETRIC ANALYSIS

The sources of attitude reference for the television missions are the local vertical established by an earth sensor (horizon sensor, interferometer, etc), the line of sight to the sun establishe by a solar aspect sensor, the equator or orbit plane established by a star tracker or sensor, and the earth's force fields.

RF interferometer or monopulse systems were considered applicable as primary sensors for independent antenna pointing subsystems and as primary or secondary sensors for the spacecraft pitch/roll reference. A ground beacon, either distinct or as part of the television programming uplink, would permit sensing of the antenna pointing error. This technique is particularly attractive if the beacon is located at the coverage area (antenna beam) center and the antenna is grossly pointed by the vehicle stabilization. If the antenna is grossly pointed to the coverage area center (±1 degree, ± 1.75 rad), the field of view requirement is so relaxed that readily implementable interferometer or monopulse sensors are conceivable for any antenna size, type, or mounting location on the satellite. Pointing determination with this technique could achieve accuracies of ± 0.05 degree (0.0872 rad).

Typical performance parameters associated with the sensor types of interest are listed in Table 5.3-1.

5.3.2 ELECTRONICS PARAMETRIC ANALYSIS

Attitude stabilization subsystem electronics is defined as all sensor signal processing, actuator signal generation, and controller logic functions.

The expected configuration for the controller logic implementation is an on-line, spaceborne, programmable digital controller, although it is feasible to perform this function with ground equipment. Potentially this computer function could be a subdivision of a central telemetry, tracking and command (TT&C) computer performing all command and diagnostic operations as well as the stabilization operations. The reason for this approach is its versatility. The alternative is a hard-wire controller, which by its nature requires an early design freeze.

Table 5.3-1. Attitude Reference Sensors

Item	IR Earth Sensor	Solar Aspect Sensor	Star Tracker	RF Interferometer
Null Accuracy (deg)	±0.1	±0.03	±0.005	±0.03
(crad)	±0.175	±0.052	±0.0087	±0.052
Field of View (deg)	10x10	2x2	10x10	--
(crad)	17.5x17.5	3.49x3.49	17.5x17.5	--
Weight (lb)	5	4	8	30
(kg)	2.27	1.82	3.63	13.6
Volume (in.^{3})	100	60	80	60
(cm^3)	1640	984	1311	984
Power (watts)	6	8	8	8
Engineering Costs ($\$ \times 10^3$)	--	--	--	850
Fabrication Costs ($\$ \times 10^3$)	20	20	40	80
Risk	Low	Low	Low	Medium*

* To be flight tested on ATS-F

The on-line, programmable digital computer allows subsystem redesign directly up to the moment of launch and, by command link reprogramming, during the on-station operational mode. This adaptive type of controller logic may be required to handle flexible structures.

A general-purpose, 7.5-microsecond add-time computer is being designed by NASA/GODDARD (Report X562-67-202) to be specifically spaceborne. By using a woven plated wire memory, the weight and power requirements of the memory are very low, giving the needed impetus to design the arithmetic and input/output computer components for reduced weight and, therefore, reduced power.

In addition, vendors have indicated the design feasibility of this implementation approach for the ATS-F on-line digital computer. This vehicle, with its high-accuracy pointing and high-accuracy slew maneuvers, can readily identify the desirability of reprogrammable computer logic because this vehicle is required to perform attitude and orientation functions not previously performed for a system of limited *a priori* definition. These two problems (new and untried operations and poor *a priori* system definition) can best be resolved if the controller is piecewise adaptive in the sense that the control logic is reprogrammable.

The Goddard computer parameters are assumed as characteristic of this class of implementation. The computer weight and power requirements are taken as fixed for the 1970-1975 time period. Conversely, the input/output unit is very much a function of the particular vehicle and is dependent upon sensor type, actuator type, and the controller bandwidth (computational cycle time). It is pessimistically assumed that the input/output unit will be as large as, and require the same power as, the arithmetic unit. A better estimate will become available only when this component is actually designed. The memory component is variable in blocks with units of 8000 words. The memory power unit is specified to handle the full complement within its as yet unspecified range and is considered a fixed parameter. Typical performance characteristics are listed in Table 5.3-2.

Table 5.3-2. Digital Computer Breakdown

Component	Weight		Volume		Power
	(lb)	(kg)	(in^3)	(cm^3)	(watts)
Input/Output	6	2.72	180	2950	3
Arithmetic Unit	6	2.72	180	2950	3
Power Converter	1.5	0.68	40	655	-
Memory 8000 Words of 18 Bits	6	2.72	180	2950	8
Total	19.5	8.85	580	9505	14

The electronics subsystem costs, weights, and volumes are very low compared to those of other satellite subsystems and, as predicted, will remain relatively fixed with variations in total satellite weight.

5.3.3 CONTROL TORQUE ACTUATOR PARAMETRIC ANALYSIS

Sensor and electronics weights and powers are generally a function of the year of flight, with the state-of-the-art generally showing increasing performance for later flight dates. The sensor and electronics are relatively insensitive to system weight.

Actuators, on the other hand, are sensitive to system weight, but relatively insensitive to the year of flight. The actuators represent the muscles and the stored energy of the system, so for larger systems their weight is proportional to both the system weight and mission life. For example, the jet size of a reaction control system (RCS) is dependent upon the vehicle size (environmental disturbance), while the RCS fuel weight is dependent upon the jet size and the total "jet on-time" (mission life).

The most applicable control torque methods at present are momentum exchange and mass expulsion. Gravity gradient and magnetic torques have limited usefulness synchronous altitude. Solar pressure may have some limited applicability for control and, particularly, should be accounted for by striving for a design which is solar pressure stabilized.

5.3.3.1 Momentum Storage Parametric Analysis

External torques act to impart an angular momentum to the vehicle system. With proper logic, this momentum can be transferred to internal moving parts and stored until unloaded by an RCS or until such time as the external torques reverse polarity; in which case, it is recalled by the controller. Such momentum storage devices are electromechanical flywheels, fluid flywheels, and control moment gyros. The latter two have specific utility not justified in the configurations envisioned for television broadcast satellites but are included for completeness. In each class, a small and a large storage capacity machine is hypothesized as indicative. Their characteristics are given in Table 5.3-3. The parameters in the table are interpolations of discrete design points.

5.3.3.2 Mass Expulsion Parametric Analysis

Table 5.3-4 gives parametric data for propulsion systems with 12 nozzles (four sets of three nozzles for three-axis torquing).

5.3.4 SPIN STABILIZATION PARAMETRIC ANALYSIS

A particular approach must be applied to the technical evaluation of so-called spin-stabilized. vehicles. For the 2-year lifetime at the pointing accuracies indicated, a piecewise continuous spin-stabilization system is attractive. Such a system is spin stabilized over intervals of time when no control action is taken. Periodically, the spin axis orientation must be determined and remedial action in the form of active precession maneuver control initiated to re-erect the angular momentum of spin to its proper inertial orientation.

Table 5.3-3. Momentum Storage Devices

Type		Momentum (lb-ft-sec)	Momentum (N-m-sec)	Fabrication Cost per Axis ($ x 10^{-3})	Engineering Cost per Axis ($ x 10^{-3})	Weight per Axis (lb)	Weight per Axis (kg)	Power per Axis (watts)
Electromechanical Flywheel	Low	2	2.71	5	0	4.5	2.04	2
	High	500	677	15	0	45	20.4	200
Fluid Flywheel	Low	0.2	0.271	30	25	2	0.91	2
	High	5	6.77	330	120	1000	454	10,000
Control Moment	Low	5	6.77	48	450	10	4.54	4
	High	500	677	140	450	200	90.9	25
(Data per gyro; 4 gyros for 3-axis).								

Table 5.3-4. Propulsion Systems

Type of Propellant	Thrust		Cost		Power (watts)	Weight of Hardware Plus Propellant					
						Pounds			Kilograms		
						Total Impulse (lb-sec)			Total Impulse (N-sec)		
	lbx10^3	mN	Engineering (x10^{-3}$)	Fabrication (x10^{-3}$)		100	1000	10,000	445	4450	44,500
Freon	2-100	8.9-445	500	25	5-10	42.5	80	410	19.3	36.4	186.4
Subliming Solid	1	4.45	1500	30	20-60	12	34	230	5.45	15.44	104.5
Hydrazine	20-50	89-222	500	35-50	5-10	14	19	86	6.35	8.64	39.1
Ammonia Resistance Jet	1	4.45	750	50	10-30	14.5	19	90	6.6	8.64	40.9
Colloidal Ion Engine	0.3	1.335	1500	60-80	20-35	18.1	21	45	8.22	9.55	20.22
SPET	0.3	1.335	1000	50	15-30	15.1	19	35	6.86	8.64	15.9
C_s or H_g Ion Engine	5	22.2	1500-2000	100-200	1000	24	24.2	26	10.9	11	11.8

The response of a spinning vehicle to external disturbances is reduced by the stiffening of the spin axis by the residual angular momentum. Besides requiring control action only periodically, the configuration is not at all susceptible to cyclic disturbances, and in a sense the spinning is equivalent to a three-axis stabilized vehicle's angular momentum storage system. Comparison of spin to three-axis stabilization is tantamount to comparing the "spin costs" to the costs of momentum storage by flywheels. The flywheel costs have been previously covered, the "spin costs" are the damper needed to ensure nutational stability and, in the case of a "dual spinner," the cost of the internal constant-speed flywhe

Two spinning systems were considered. They are the single spinner and a dual spinner. The components charged to the attitude control system are the damper and, in the case of the dual spinner, a flywheel as the momentum-producing device. Not treated was (due to lack of technical data) the dual-spinner concept in which a portion of the vehicle structure, with or without various subsystem components, is caused to rotate with respect to the remaining vehicle structure.

The spin-up device is not charged to the control system. The damper is assumed to be 1 percent of the vehicle weight. The momentum-producing device for a dual spinner is a flywheel driven by an ac motor. Solar cells are assumed to be body mounted. Spin axis is normal to the orbit plane.

Table 5.3-5 is a summary of the weight of combined damper and flywheel for two typical antenna sizes. The power required by the flywheel is practically constant at 5 watts.

For a single spinner, the only component to be considered is the damper. For a 300-pound (136.1 kilogram) vehicle, the damper weight is 3 pounds (1.36 kilograms)

Table 5.3-6 is an estimate of the development and fabrication costs for the dual spinner flywheel and damper in the range of vehicle weights and accuracies being considered for TVBS.

An advantage accrues in the case of liquid propulsion systems when all or part of the vehicle is spinning. On the spinning part a mechanical force field exists due to centripetal force. The gradient of the force field with distance from the spin axis guarantees separation of the liquid propellant and its pressurant, usually N_2; and by placing the feed valves on the tanks at their furthest point from the spin axis, fuel is always present at the engine valves. Conversely, a three-axis stabilized vehicle would require bladders in the fuel tanks.

Several disadvantages are present also. For a single spinner, the solar array power is limited to the half cylinder area and its poor angle of incidence. For high-power satellites this is a very expensive and heavy way to obtain solar power. With shroud constraints and the requirement that the spin axis of inertia be greater than the transverse inertia for nutational stability, the typical power limit is 200 watts. For a dual spinner, nutational stability is, of course, guaranteed, but the dead weight of the constant speed internal flywheel approaches the weight of a three-axis momentum storage system. In addition, as more of the vehicle is "despun," the form of the solar pressure disturbance torque goes from one of all cyclic components to one of all cumulative components. This nullifies the most desirable feature of spin stabilization, which is the time separation between the required control action. The typical power limit for a dual spinner is therefore nominally 500 watts. This value corresponds to the largest despun array which can be handled without its cumulative solar pressure torque adversely affecting the time interval between corrections of the spin axis orientation.

5.3.5 ATTITUDE CONTROL SUBSYSTEM PARAMETRIC ANALYSIS

Figure 5.3-1 identifies the preferred type of attitude stabilization subsystem versus the desired attitude accuracy and the vehicle weight. This figure was constructed as a result of a sequential analytical process, which involved: disturbance torque analysis, control concept applicability study with block diagrams, preferential ordering of concepts, control torque study, bus power versus vehicle weight factor, and 1971 technology evaluation factors.

In this study task, the subsystem types selected for potentially flexible-body vehicles were based on the following definition: A rigid body is any vehicle with an operating attitude stabilization system which reaches an equilibrium condition wherein the amplitudes of any of the structure's normal modes of vibration are of such limited magnitude that they do not at any time degrade the mission performance. A joint analytical and design effort is, therefore, presumed that will result in dictating (1) the placement of sensors and actuators and (2) the

Table 5.3-5a. Subsystem Weight for Antenna Diameters 20/40 Feet

Pointing Accuracy (deg)	Vehicle Size (Weight)		
	300 lb	1000 lb	2000 lb
0.15	54/83	61/90	71/100
0.5	43/72	50/79	60/89
1.0	28/56	35/63	45/73

Table 5.3-5b. Subsystem Weight for Antenna Diameters 20/40 Feet

Pointing Accuracy (crad)	Vehicle Size (Weight)		
	300 kg	1000 kg	2000 kg
0.262	24.5/37.7	27.7/40.9	32.2/45.4
0.872	19.5/32.7	22.7/35.9	27.2/40.5
1.74	12.7/25.4	15.9/28.6	20.4/33.2

Table 5.3-6. Estimated Development and Fabrication Costs of Attitude Control Subsystems (The table gives development costs over fabrication costs for each item in thousands of dollars.)

					Costs		
Vehicle Type	Attitude Accuracy		Antenna Diameter		Damper	Flywheel	Total
	deg	crad	ft	m			
Single Spinner	1	1.74	--	---	8/7	0/0	8/7
Dual Spinner	0.15	0.262	1	0.45	8/7	0/22	8/29
			20	9.1	8/7	0/41	8/48
			40	18.2	8/7	0/75	8/82
Dual Spinner	1	1.74	1	0.45	8/7	0/22	8/29
			20	9.1	8/7	0/23	8/30
			40	18.2	8/7	0/43	8/50

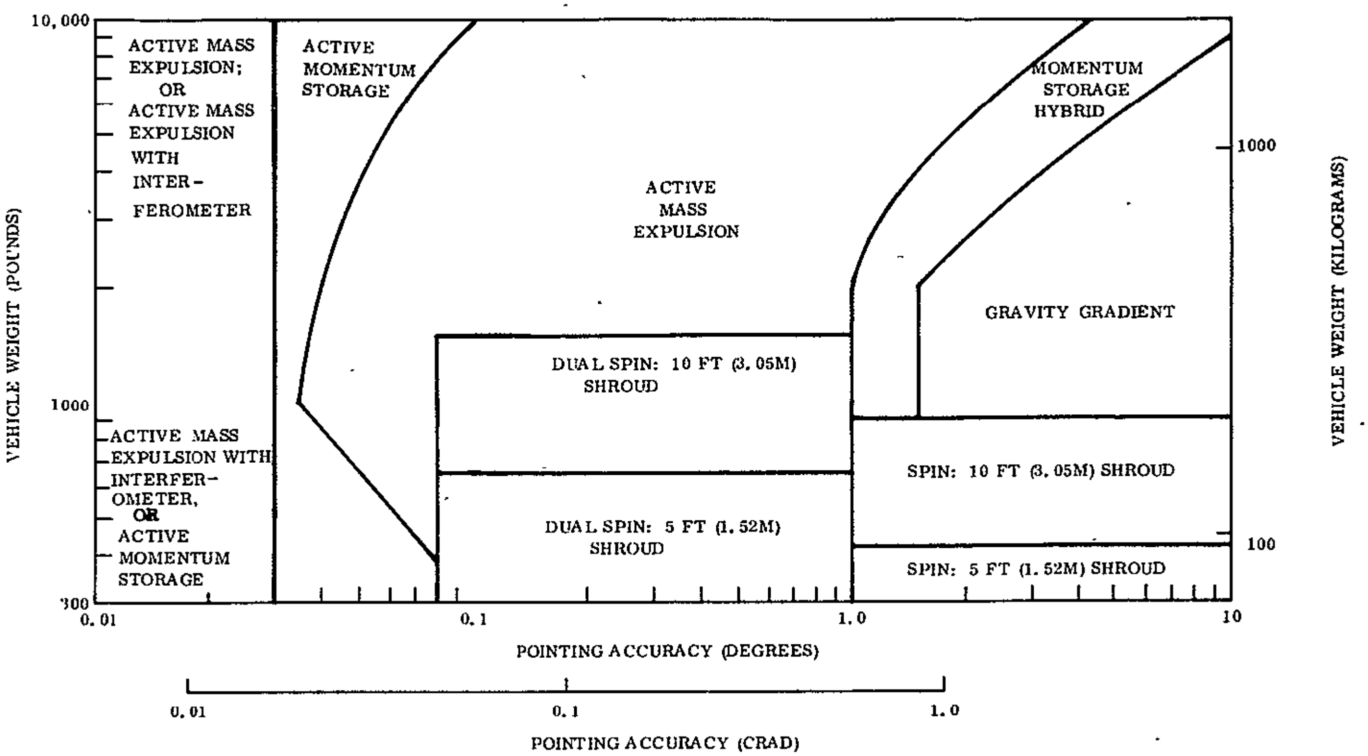


Figure 5.3-1. Preferential Configuration Selection for TVBS Mission

requirements for multiple controllers and actuators being interconnected to attitude reference sensors and structural motion sensors through an on-board computer, which will serve to uncouple sensor outputs and permit this type of multiple control. Schemes are currently under development to add active damping to various parts of structures.

The parameters of the attitude control subsystem are summarized in curve form for five of the subsystem types considered. These five types encompass nearly the full range of accuracy and vehicle weight as Figure 5.3-1, omitting only those accuracies below 0.03 degree (0.017 crad) and combinations of weight less than 900 pounds (409 kilograms) and accuracies greater than 1 degree (1.75 crad). In Figures 5.3-2 through 5.3-4, subsystem weight is plotted versus vehicle weight for three different sizes of antenna diameter: 1 foot (0.3 meters), 20 feet (6.1 meters), and 40 feet (12.2 meters). The varying antenna sizes were examined to provide a nominal range of satellite size.

The attitude control subsystem cost estimates are presented in Figure 5.3-5.

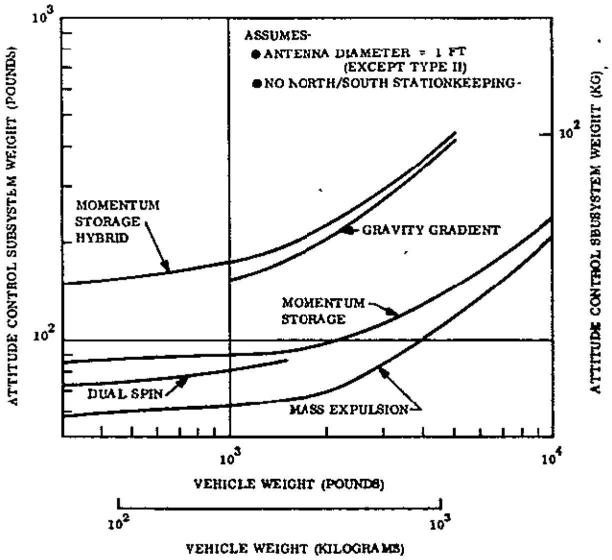


Figure 5.3-2. Attitude Control Subsystem Weight Versus Vehicle Weight (Antenna Diameter = 1 Foot)

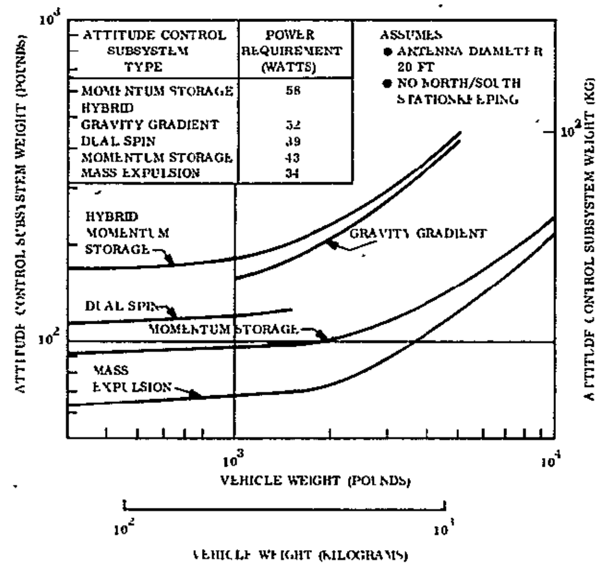


Figure 5.3-3. Attitude Control Subsystem Weight Versus Vehicle Weight (Antenna Diameter = 20 Feet)

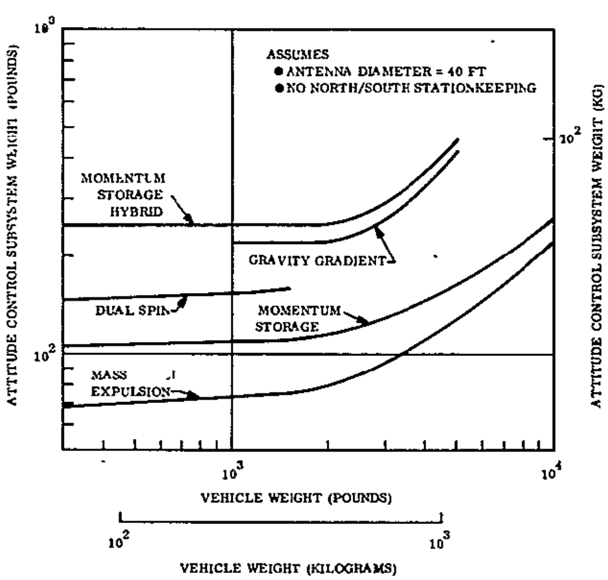


Figure 5.3-4. Attitude Control Subsystem Weight Versus Vehicle Weight (Antenna Diameter = 40 Feet)

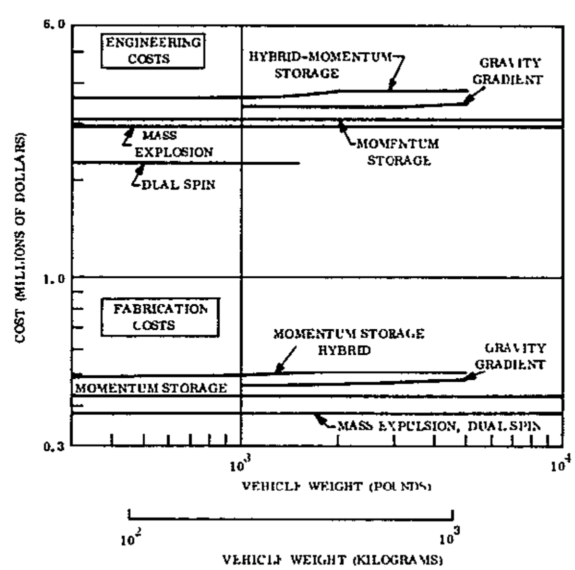


Figure 5.3-5. Attitude Control Subsystem Costs Versus Vehicle Weight

5.4 POWER SUBSYSTEM PARAMETRIC ANALYSIS

Several alternative power subsystems were considered for this application. These types are summarized in Table 5.4-1. It is apparent from this tabulation that none of the nuclear-powered systems will reach the development status required for a 1973 launch date. In addition, it is doubtful that any dynamic power source will have the demonstrated 2-year life capability before the late 1970's.

The solar array/battery power subsystem is the only candidate which meets the requirements of 2-year design life and 1971 state of the art. Boron doped silicon N/P, lithium doped silicon P/N, cadmium sulfide thin film, and cadmium telluride thin film solar cells were investigated with respect to the growth potential from 1970 to 1975. The parameters studied were costs, weight-to-power ratio, weight-to-area ratio, cell thickness, cover glass thickness, efficiency, and radiation degradation.

Table 5.4-1. Candidate Power Subsystems

Type	Best Range of Application	Earliest Availability Date
Solar Array/Battery		
Rigid Substrate Silicon Cells	Up to 50 kW(e)	Now
Lightweight, Rigid Silicon Cells	Up to 50 kW(e)	1969
Roll-up Silicon Cells	Up to 50 kW(e)	1970
Roll-up CdS Cells	Up to 50 kW(e)	Dependent on R&D
Roll-up CdTe Cells	Up to 50 kW(e)	Dependent on R&D
Solar-Brayton	5 to 15 kW(e)	1975
Isotope-Brayton	5 to 15 kW(e)	1975
Isotope-Rankine	Up to 10 kW(e)	1975
Mercury		
Organic		
Reactor-Thermoelectric	10 to 20 kW(e)	
Direct Radiating Type		1975
Compact Converter Type		1977
Reactor-Brayton	10 to 30 kW(e)	1977
Reactor-Rankine	25 kW(e) and higher	1978
Mercury		
Organic		

The 8-mil, 1 to 3 ohm-centimeter N/P silicon cell with a 3-mil cover glass was selected as the best combination, based on cost, weight, and area considerations. A 2 centimeter x 2 centimeter cell size has been used in this analysis, although a larger 2 centimeter x 6 centimeter cell might be established as the preferred cell configuration by 1971.

The following constraints were imposed on this analysis by the mission and system requirements

1. 2-year satellite mission in geostationary orbit.

2. Duty cycle of 24 hours per day for housekeeping and 10 to 24 hours per day for broadcasting.

3. The 11-year solar radiation cycle cannot be precisely forecasted; therefore, the maximum radiation damage model was employed.

The following assumptions were made, based upon system analysis or the desire to simplify the parametric plots:

1. The housekeeping input power load is between 10 and 400 watts.

2. The broadcast transmitter input power load is between 100 and 50,000 watts.

3. Transmitter input voltages selected as representative for transistors, gridded tubes, cross-field amplifiers, traveling wave tubes, and klystrons are 45, 600, 3000, and 20,000 volts dc.

4. Body-mounted solar cells were selected as representative of the current technology for low-power (less than 1000 watts), spinning cylindrical spacecraft configurations of the ATS-I type. Fixed-panel arrays of the ATS F configuration (normal panels-cells on both sides on the pitch axis) were selected to be representative of nonoriented rigid-array structures. Lightweight foldout panels (Boeing design for JPL - beryllium framework with fiberglass tape substrate) and roll-up arrays (GE design for JPL, Contract No. 951969) were selected to represent lightweight approaches; the technolog for these approaches should be developed by 1971. These structures may require the use of special attitude control techniques to orient the flexible appendages.

5. The plots of the power subsystem parameters have been held to within $\pm$ 10 percent variation of the summation of the subsystem parameters. This close tolerance (for a conceptual design study) was necessary since for high-powered satellites the power subsystem is a significant percentage of the total satellite weight and cost.

5.4.1 PARAMETRIC ANALYSIS OF COMPONENTS USED IN THE POWER SUBSYSTEM

This section contains the parametric analysis of the principal building blocks in the power subsystem.

Body-mounted cells, fixed-panel arrays, lightweight foldout arrays, and roll-up arrays were analyzed. The foldout and roll-up arrays have the potential to significantly improve the power-to-weight ratio over that attainable with fixed-panel arrays.

The estimated 1971 performance parameters for the selected 8-mil silicon solar cells are summarized in Table 5.4-2 for the four types of array construction studied.

Table 5.4-2. Performance Parameters for Solar Cells

	Spinning Cylindrical Body-Mounted Cells	Fixed-Panel Array	Foldout Array	Roll-up Array
Watts/Square Meter	20.4	102	89.2	92.5
Watts/Square Foot	1.90	9.47	8.31	8.60
Watts/Kilogram	4.10	11.9	34.4	40.4
Watts/Pound	1.86	5.42	15.6	18.3
$/Watt-Fabrication	2230	428	473	457
$/Watt-Engineering	1860	930	930	930
Cover Glass (mils)	6	6	3	3
(millimeter)	0.152	0.152	0.076	0.076
Percent of Power at End of 2 Years of Radiation	87%	87%	76%	79%

Nickel-cadmium and silver-zinc batteries were analyzed for use in supplying housekeeping power during eclipse. Nickel-cadmium batteries were selected for this application because of proven performance. Pertinent performance parameters of this type of battery are given below.

1. Watt-hour charge-discharge efficiency: 73 percent
2. Specific weight:
    a. 0.245 pound/watt hour
    b. 0.540 kilogram/watt hour
3. Specific volume:
    a. 3.10 cubic inches/watt hour
    b. 50.7 cubic centimeters/watt hour

Battery charge regulators and partial shunt array regulators represent an insignificant design factor when compared to the remainder of the power subsystem. Off-the-shelf equipment was selected with the following 1971 performance factors:

1. Specific weight:

   a. 15.0 kilogram/kilowatt

   b. 33.1 pound/kilowatt

2. Specific volume:

   a. 10 cubic centimeters/watt

   b. 0.35 cubic feet/kilowatt

3. Efficiency: 90 percent

Inductance-capacitance filters selected for AM modulation power averaging were based upon modifying current ground equipment designs for space use. This is not considered an R&D problem; however, the design of these equipments should be initiated early so that flight-qualified hardware would be available prior to the start of the satellite design cycle. The specific weight of filters decreases from 60 kilograms/kilowatt (134 pounds/kilowatt) at 40 watts of power to 20 kilograms/kilowatt (45 pounds/kilowatt) at 20,000 watts of power. The specific volume decreases from 41 cubic centimeters/watt (2.5 cubic inches/watt) at 40 watts of power to 18 cubic centimeters/watt (1.1 cubic inches/watt) at 50,000 watts of power.

The converter/regulator equipments selected were based upon modifying current ground equipment designs for space use for output voltages up to 20,000 volts. The largest single module will be rated at 5 kilowatts. Modules will be interconnected for higher powers. Figure 5.4-1 shows the variation in specific weight of a converter/regulator (pulse width regulation of ± 1 percent) as a function of input and output voltages. The transmitter types being evaluated for the program have input voltage requirements in the 45-, 600-, 3000-, and 20,000-volt dc regimes. For the transistor-type transmitters, a 45-vdc solar array and a low-voltage converter-regulator output will be used. For the other transmitters, a 300-vdc array with either a 600-, 3000-, or 20,000-vdc output will be used to conserve weight.

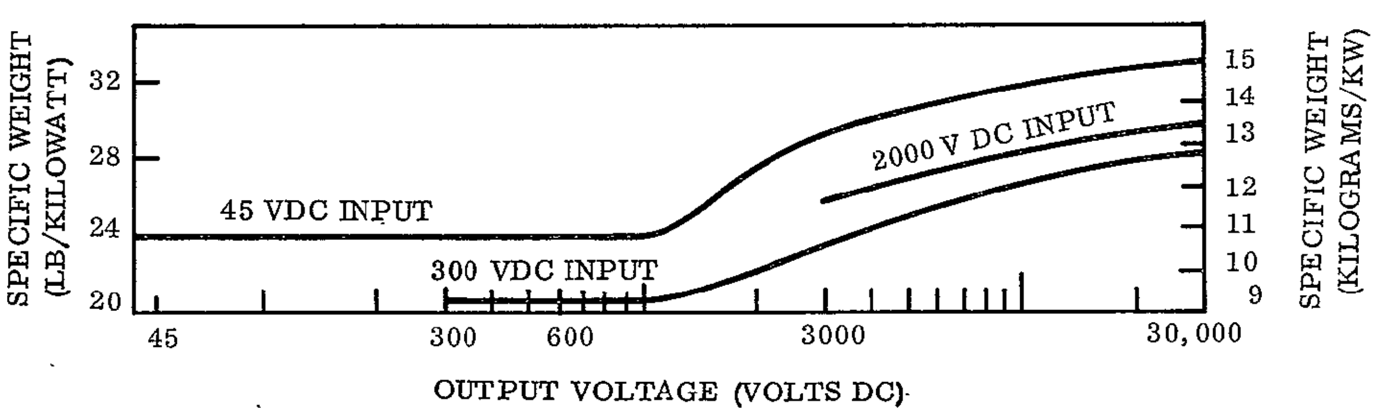


Figure 5.4-1. Converter/Regulator Specific Weight Versus Input and Output Voltage

Figure 5.4-2 shows the variation of the specific volume of a converter/regulator as a function of output voltage.

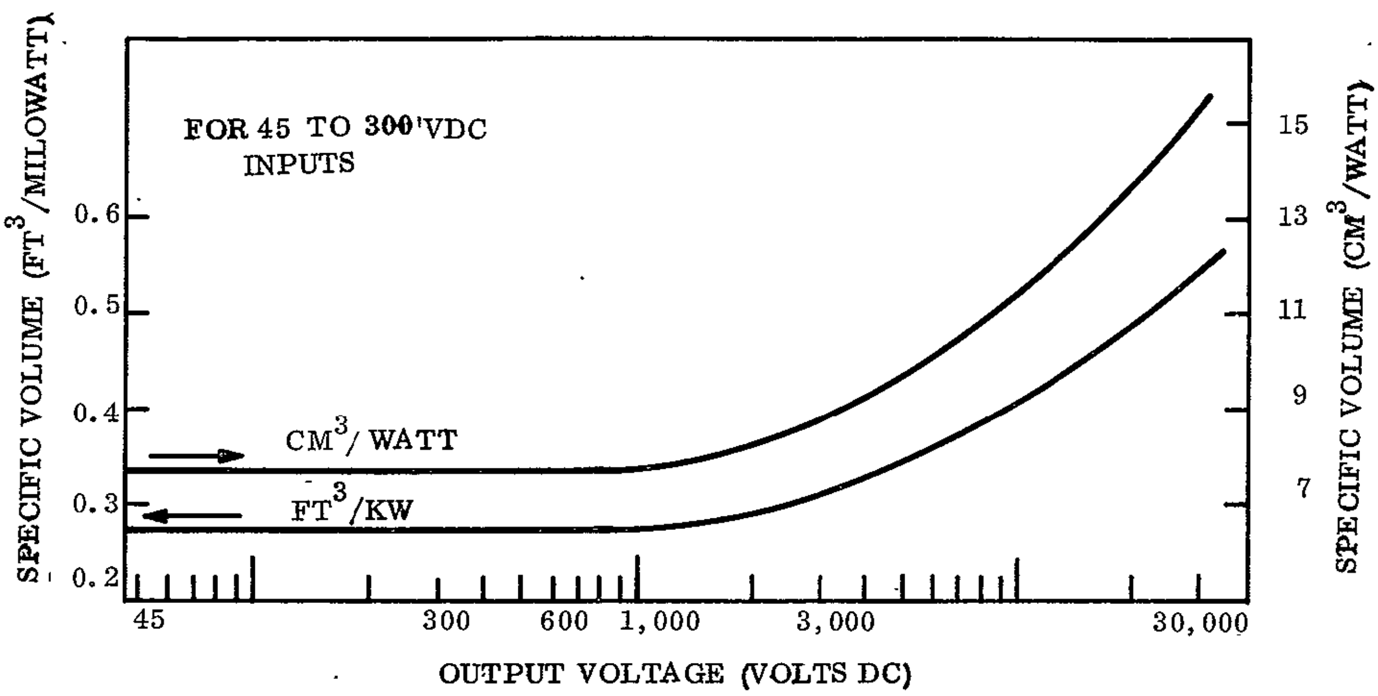


Figure 5.4-2. Converter/Regulator Specific Volume Versus Output Voltage

Figure 5.4-3 shows the efficiency of the converter/regulator as a function of output power. The step at 5 kW(e) is caused by interconnecting 5 kW(e) modules for higher power. An efficiency of 85 percent was selected as representative for parametric analysis calculations.

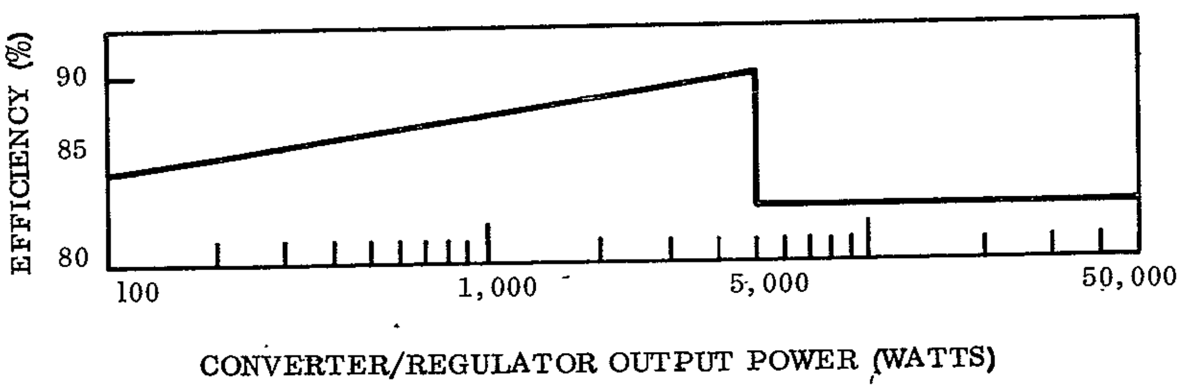


Figure 5.4-3. Converter/Regulator Efficiency Versus Output Power

5.4.2 SELECTED POWER SUBSYSTEM

The basic power subsystem has been divided into two parts to supply the requirements of the missions considered. The housekeeping power system supplies the loads associated with the basic spacecraft exclusive of the transmitter functions. The housekeeping bus voltage will be a commonly used value (+28 vdc or -24.5 vdc) to be compatible with existing equipment. The transmitter loads will be supplied by the transmitter power system. This portion of the power subsystem operates directly into the transmitter through a converter/regulator and filter (if required). The solar array bus, in this case, will be a higher voltage (300 vdc) to reduce losses. The same array structure will supply both array bus voltage requirements. Some array solar cell strings will be interconnected to supply the housekeeping power system at a low voltage (e.g., +45 vdc for a +28 vdc regulated bus), and the remaining array strings will be configured to supply the higher voltage, which is desirable for the converter/regulator input.

5.4.2.1 Power Subsystem Parametric Analysis for Housekeeping Loads

Figure 5.4-4 is a block diagram of the housekeeping portion of the total power subsystem.

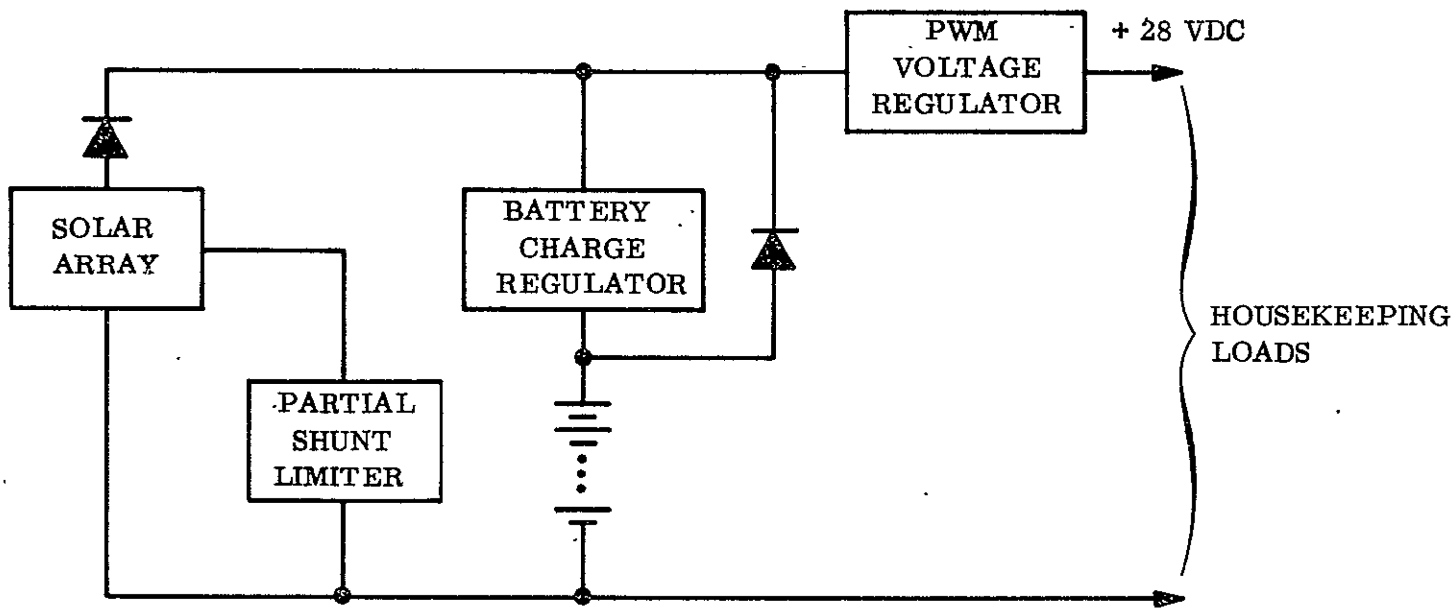


Figure 5.4-4. Block Diagram of Housekeeping Portion of Power Subsystem

Figures 5.4-5 through 5.4-10 give the engineering cost, fabrication cost, weight, array area, packaged volume, and array power, respectively, for a continuous housekeeping power requirement which varies from 10 to 400 watts. One curve for a combination of array types is employed where the parameter varies less than $\pm$ 10 percent. These curves are a summation of the parameters given for the components in Section 5.4.1.

5.4.2.2 Power Subsystem Parametric Analysis for Transmitter Loads

Figure 5.4-11 is a block diagram of the portion of the total system supplying power into an FM modulated transmitter. Figure 5.4-12 is the block diagram for an AM modulated transmitter employing a filter to average the power demand during a single TV picture frame. Both block diagrams are for continuous broadcasting during satellite day and no eclipse operation.

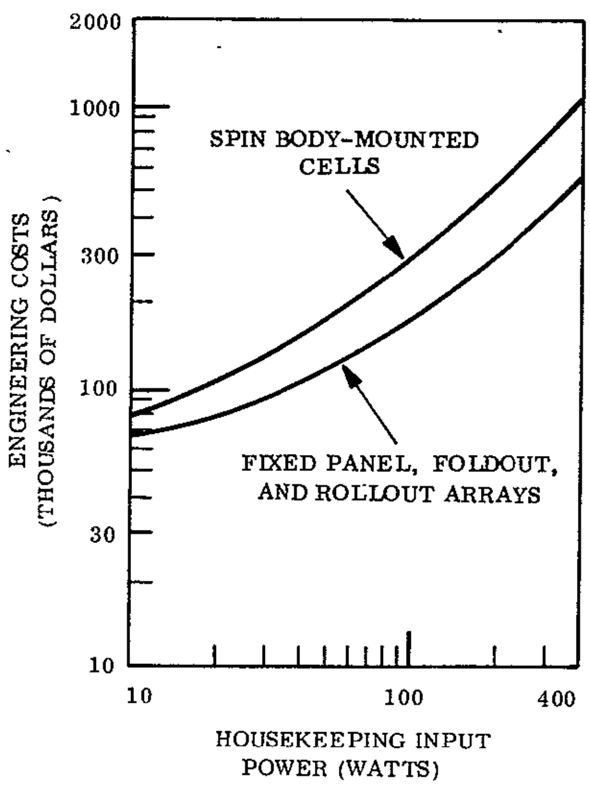


Figure 5.4-5. Housekeeping Power System Engineering Costs Versus Input Power

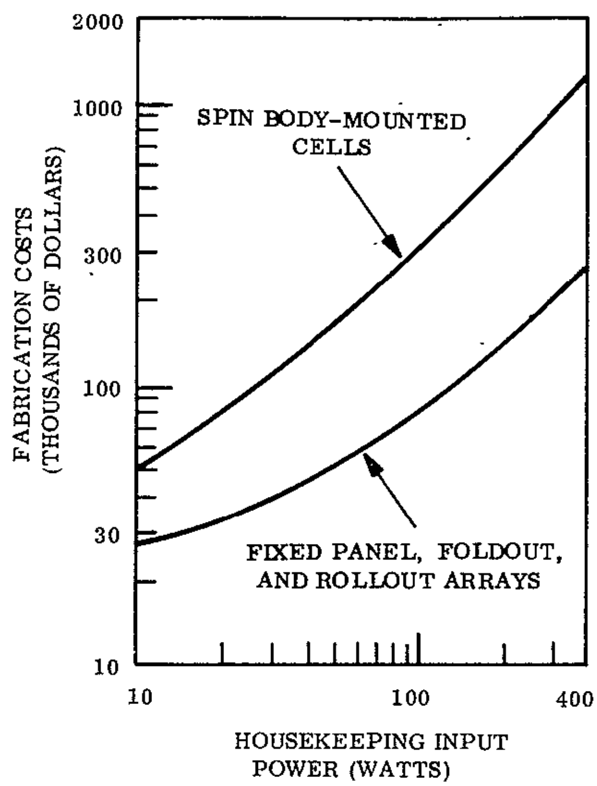


Figure 5.4-6. Housekeeping Power System Fabrication Costs Versus Input Power

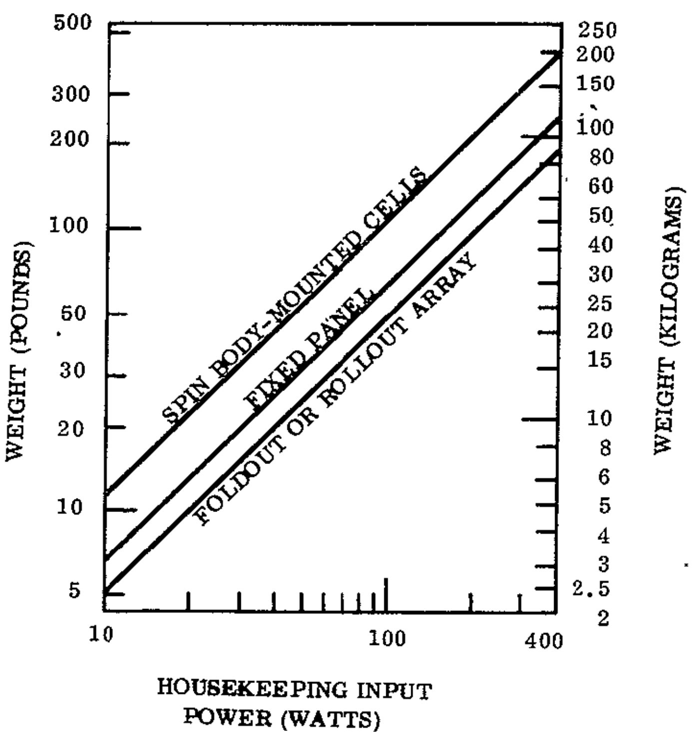


Figure 5.4-7. Housekeeping Power System Weight Versus Input Power

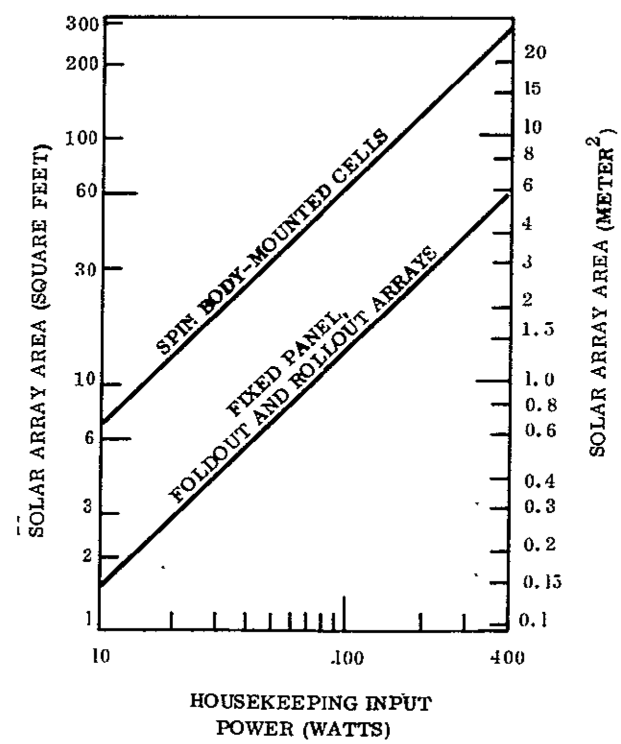


Figure 5.4-8. Housekeeping Power System Solar Array Area Versus Input Power

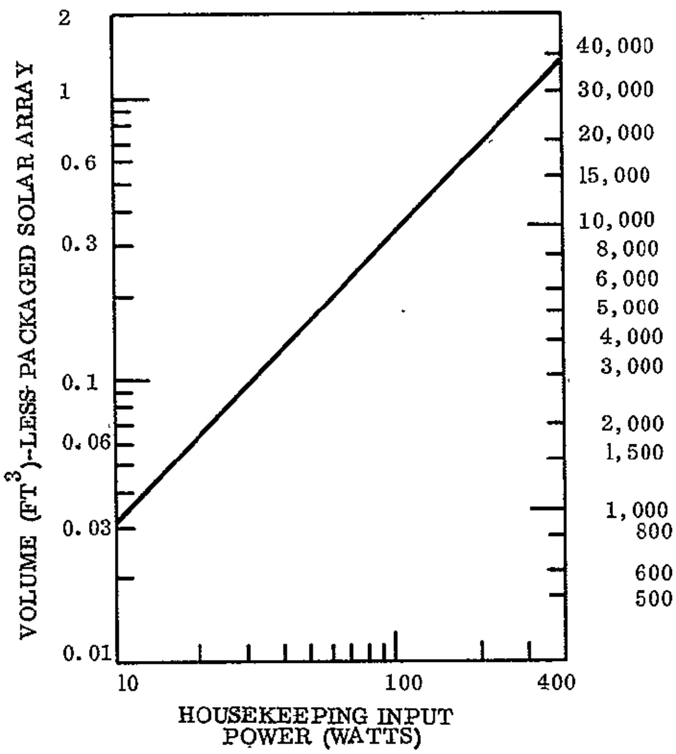


Figure 5.4-9. Housekeeping Power System Volume Versus Input Power

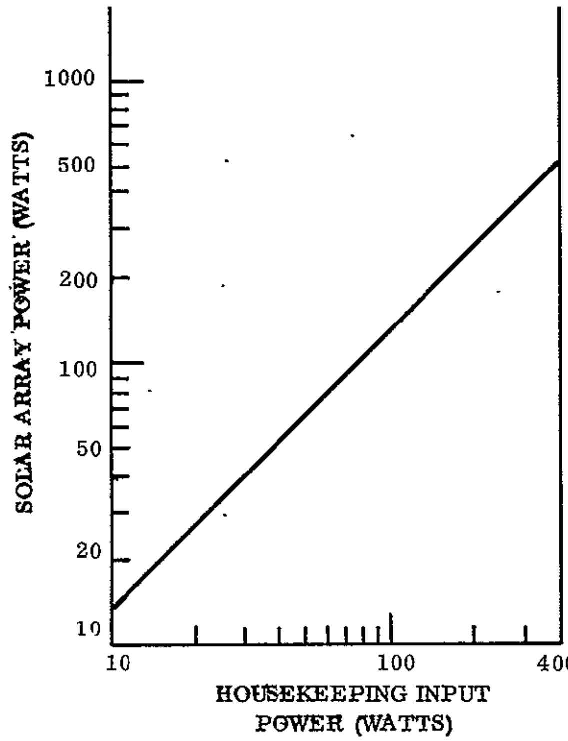


Figure 5.4-10. Housekeeping Power System Solar Array Power Versus Housekeeping Input Power

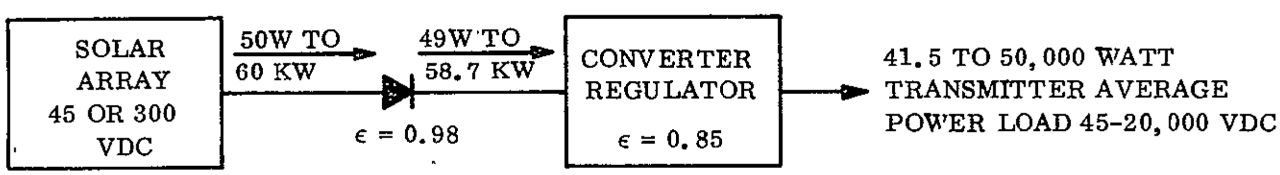


Figure 5.4-11. Block Diagram for FM Video and Audio Transmitter Power System

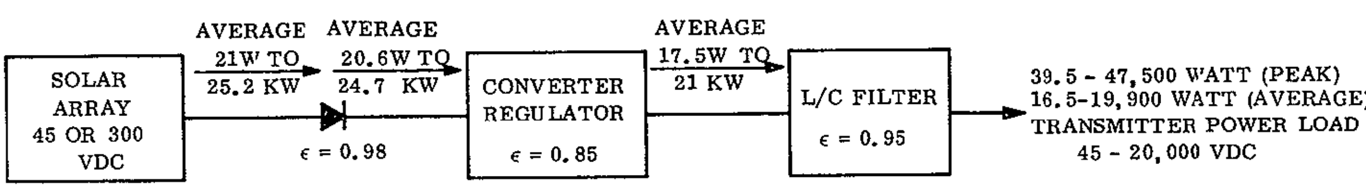


Figure 5.4-12. Block Diagram for AM Video Transmitter Power System

The following plots of cost, weight, volume and area distinguish choices of array type, input voltage, and output voltage for both the FM and AM modulated transmitter. One curve is given for combinations of array types and voltages where the parameter varies less than ± 10 percent. These plots are a summation of the parameters given for the components in Section 5.4.1.

The power subsystem parameters are plotted for spinning, cylindrical body-mounted solar cells and for fixed-panel, foldout, and roll-up arrays at power levels deemed appropriate for each array type. Body-mounted cell arrays were selected for low-power systems because, in these cases, solar cell cost and weight do not significantly affect total satellite cost and weight. On the other hand, foldout and roll-up arrays were selected for the medium- and high-power systems, where array cost and weight are a significant portion of the total satellite cost and weight. Fixed-panel arrays were selected to overlap the low- and medium-power regimes in order to permit a selection to be made for a more rigid structure.

Figures 5.4-13 through 5.4-18 give the engineering cost, fabrication cost, weight, array area, volume, and array power, as a function of transmitter input power from 100 to 50,000 watts, for 45- and 300-volt arrays, and for transmitter input voltages of 45 to 300, 3000, and 20,000 volts.

The maximum value of engineering cost shown in Figure 5.4-13 is based on the approach that the largest solar array panel to be designed, fabricated, and qualification tested is 2.4 kilowatts. The additional cost of fabricating a prototype of the multipanel array was assumed to be insignificant. The cost of ground support equipment and of deployment testing the multipanel prototype is included in system cost factors, which are added after all subsystem costs have been summed up.

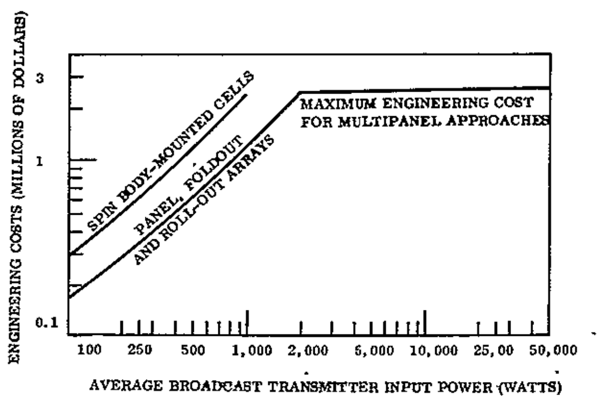


Figure 5.4-13. Broadcast Power System Engineering Costs Versus Input Power

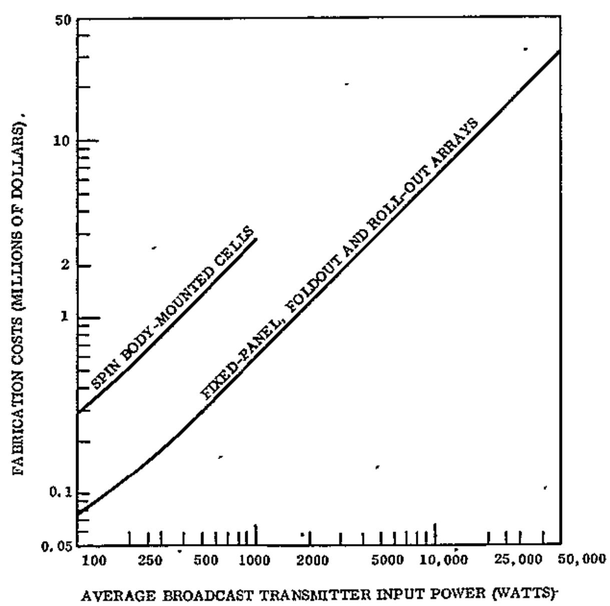


Figure 5.4-14. Broadcast Power System Fabrication Costs Versus Input Power

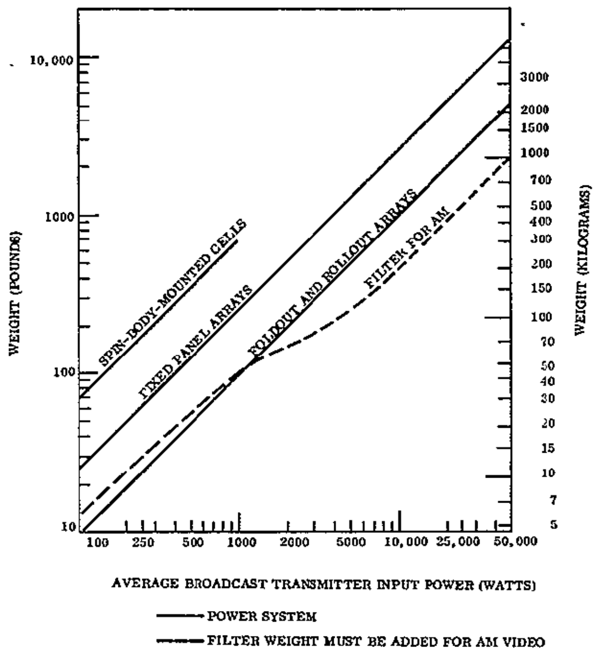


Figure 5.4-15. Broadcast Power System Weight Versus Input Power

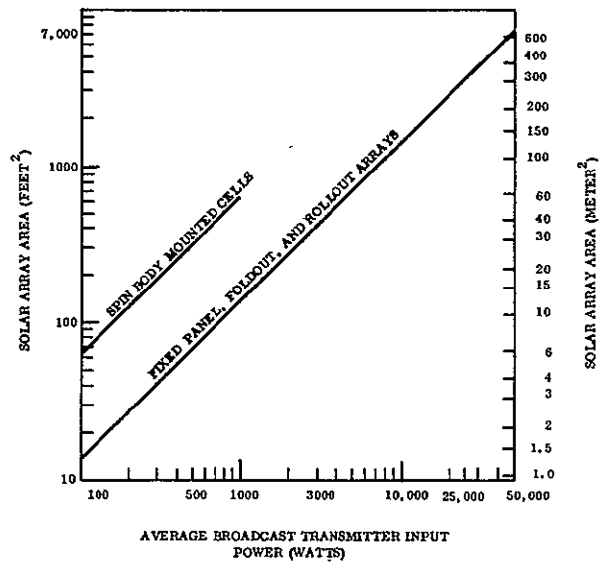


Figure 5.4-16. Broadcast Power System Solar Array Area Versus Input Power

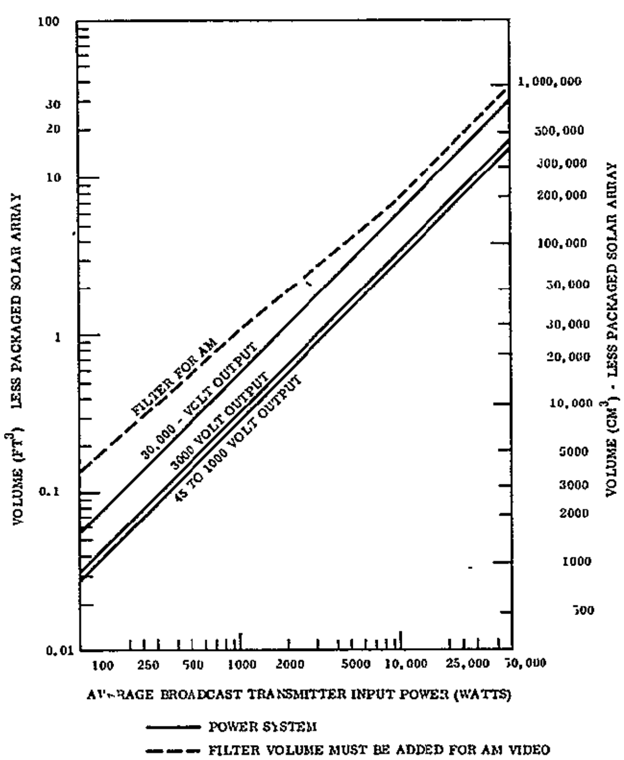


Figure 5.4-17. Broadcast Power System Volume Versus Input Power and Voltage

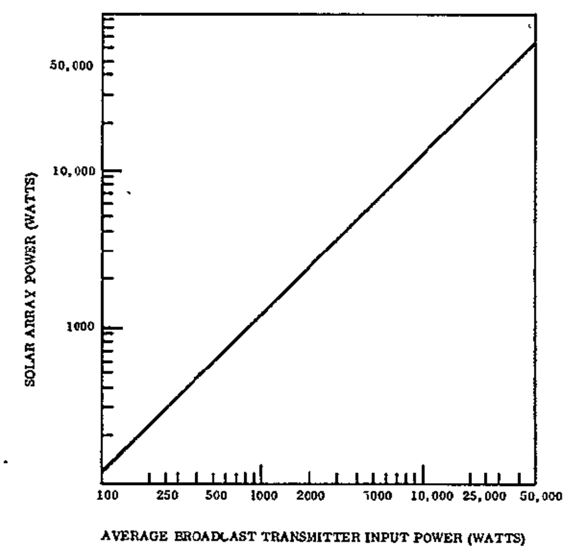


Figure 5.4-18. Broadcast Power System Solar Array Power Versus Broadcast Input Power

The major penalty associated with broadcasting during the eclipse period is due to the batteries required. Table 5.4-3 gives the multiplying factors to be used to increase the broadcast power subsystem parameter given in Figures 5.4-13 through 5.4-18 to account for the added eclipse broadcasting capability.

For example, Table 5.4-3 indicates that a weight multiplication factor of 4.9 must be used for an FM roll-up array system. Figure 5.4-15 indicates that a 50 kW(e) FM roll-up array system would weigh approximately 5000 pounds (2270 kilograms) for satellite daytime broadcasting. To broadcast during satellite eclipse, the power system would weight 4.9 times 5000 pounds, or 24,500 pounds (11,100 kilograms). This example illustrates the infeasibility of broadcasting during the eclipse for high-power satellites. The applicability of adding batteries for a specific case will depend upon the satellite power, the excess booster capability available for a specific satellite, and the premium which can be afforded for a specific mission.

Table 5.4-3. Multiplication Factors to Account for Eclipse Broadcasting

Parameter	Multiplication Factor
Weight: AM - Spinning Body Mounted	1.5
Weight: FM - Spinning Body Mounted	1.6
Engineering Cost: AM or FM	1.1
Fabrication Cost: AM or FM	1.1
Array Area: AM or FM	1.1
Array Power: AM or FM	1.1
Weight: AM - Fixed Panel	2.1
Weight: FM - Fixed Panel	2.5
Weight: AM - Foldout or Roll-up	3.0
Volume: AM - 45 to 20,000 volts	3.2
Weight: FM - Foldout or Roll-up	4.9
Volume: FM - 30,000 volts	6.0
Volume: FM - 3000 volts	9.7
Volume: FM - 45 to 1000 volts	11.0

Further investigations of the effects of solar array flexibility on the dynamics of the vehicle is required. Solar array flexibility is a function of array weight and, if flexible arrays cannot be accommodated by the stabilization system, an additional constraint that can have a significant influence on weight is imposed on the array design. This interaction problem is a complex one and is a long lead-time item because there are a number of disciplines and subsystems involved.

5.5 THERMAL CONTROL PARAMETRIC ANALYSIS

A description and parametric analysis of thermal control systems and devices potentially applicable to the TVBS vehicle and its subsystems are presented herein. Data are presented which compare these systems on a size, weight, and cost basis.

The components requiring thermal control considered in this evaluation included satellite housekeeping components and candidate transmitter devices (i.e., solid state, gridded tubes, TWT's, Klystrons, and CFA's). Trade-off information data presented cover thermal dissipation ranges from 10 watts to 20 kilowatts, and source temperature ranges from 300^{o}K to 800^{o}K for a minimum 2-year mission.

5.5.1 CANDIDATE THERMAL CONTROL SYSTEMS

The following thermal control systems were analyzed for cooling the TVBS housekeeping and transmitter components.

5.5.1.1 Passive Systems

Passive temperature control methods are the simplest and most reliable. A pure passive system requires no moving parts or fluid loops and no electrical power for its operation. Systems of this type have been utilized either wholly or in part in all spacecraft flown to date. The key to the design of a passive temperature control system lies in coupling an adequate heat rejection area with an equivalent sink temperature such that the heat generated within the vehicle is rejected to space at temperature levels which are within the allowable limits of vehicle components. Equivalent sink temperatures are determined by the incident external fluxes on the vehicle and the solar absorptivity and hemispherical emissivity of the external surface coatings. Proper selection of surface coatings is an important task in the design of a passive temperature control system. Super-insulating materials are also used extensively in passive systems, particularly in vehicles which have relatively low power dissipation or where desired equivalent sink temperatures cannot be achieved by application of surface coatings.

In relation to the vehicle under study, pure passive thermal control systems can be most successfully utilized in conjunction with transmitting devices which operate at high temperatures and have low total power dissipation. Area and weight requirements become very large, and are probably prohibitive, as device temperatures decrease and total power dissipation increases. All of the systems described in this study utilize passive control methods for the space radiators which are described in Section 5.5.2.

5.5.1.2 Heat Pipe Systems

Heat pipe systems are a combination of a fluid system in a closed volume (the volume being the heat pipe) with a passive radiator. The heat is rejected by being transported through the two-phase fluid in the pipe, conducted into the radiator and ultimately radiated to space. The major advantage of a heat pipe system is its capability of transporting large amounts of heat over long distance with very little change in temperature. This results in a drastic reduction in the system radiator area and weight requirements. Heat pipe systems are operable over a wide range of temperatures and powers, and require no electrical power for operation. Their reliability is high due to an absence of moving parts. This was the system employed to cool the transmitter heat loads as described in Sections 5.5.3 and 5.5.5.

5.5.1.3 Liquid-Loop Systems

The liquid-loop system carries with it the inherent disadvantages of requiring electrical power to operate a pump and being heavier due to additional component requirements. The reliability is also reduced by the need to include a pump in the system. The weight and power requirements of this type of system are heavily dependent on a specific vehicle configuration; radiator requirements are somewhat higher than those for a heat pipe system since the lack of redundancy in the fluid lines increases the requirements for micrometeoroid armor. These active systems were rejected for the above reasons.

5.5.1.4 Thermal Shutter Systems

Thermal shutter systems were employed for housekeeping loads where the vehicle heat dissipation varies significantly over the orbital period. Shutters provide proportional or on-off control of heat rejection as a function of temperature at some spacecraft location. They can be designed to operate at any temperature level considered for a vehicle and have been very successfully flown on Mariner, Pegasus, and Nimbus satellites. The addition of a louver system to a passive radiating baseplate reduces the effective emissivity and increases effective solar absorptivity of the baseplate and thus increases the radiation area necessary to dissipate the generated heat. However, they provide a simple, self-contained means of maintaining temperature control over a wide range of duty cycles.

5.5.2 SPACE RADIATORS

In a space environment, the only mode by which an electronic component can reject heat directly to space is by radiation. In the case of a component with a low thermal dissipation, it may be possible to reject the heat by radiation from the component baseplate while maintaining the component below some fixed upper temperature limit. The component baseplate acts as a radiator and the amount of heat rejected can be controlled, to a certain extent, through the use of coating materials. However, as component dissipations increase and/or the size of component baseplates decreases, a point is reached where it is no longer possible to reject a sufficient amount of heat from the baseplate to keep the component temperature from exceeding its specified upper limit. Hence, in order to maintain the component temperature below the upper limit, it is necessary to increase the heat rejection capability of the baseplate. One method of accomplishing this is to attach an extended surface or fin to the baseplate which increases the effective area for radiation. The fin can be of a completely passive nature or it can have heat pipes attached in order to bring it closer to the isothermal condition.

This section contains a comparison between weight-optimized passive fins and heat pipe fins over a wide range of power dissipations and for various source temperatures. In order to make a meaningful comparison between the two types of fins the following simplifying assumptions were made:

1. The baseplate of the electronic device is isothermal.

2. Temperature drop between the baseplate and the fin is negligible.

3. All power is dissipated through the baseplate.

4. Fin material is aluminum:

   a. Thermal Conductivity = 80 btu/hr-ft-^{o}F (138 J/m-sec-^{o}K)

   b. Density = 0.1 lb/in^{3} (2.767 kg/cm^{3})

   c. Specific Heat = 0.2 btu/lb-^{o}F (857 J/k -^{o}C)

5. Fin surface emissivity = 0.85.

6. Fin radiates from one side to a 0^{o}R sink only.

7. View factor to space is 1.0.

The results of this fin analysis are shown on Figures 5.5-1 through 5.5-4. Figures 5.5-1 and 5.5-2 compare passive fins with heat pipe fins on a heat rejection versus weight basis and on a heat rejection versus area basis, respectively, for a source radius of 1.0 in. It can be seen from Figure 5.5-1 that at any source temperature there is a definite advantage to heat pipe fins over passive fins except in the region near the origin. Examining Figure 5.5-2 discloses that heat pipe fins offer a definite area advantage over passive fins for all source temperatures and at all heat rejection levels. It is known that a minimum area heat rejection surface is one that is at a uniform temperature (isothermal). This type of surface would have a fin effectiveness value of 1.0 and is an idealized case. However, since the addition of heat pipes makes a fin approach the isothermal surface, it is obvious that it will require less area to reject a given amount of heat at a specified source temperature.

It is noticed that the curves on Figures 5.5-1 and 5.5-2 do not start exactly at the origin. The reason for this is that the baseplate itself has a certain heat rejection capability, depending on its temperature. The requirement for fins starts after this baseplate capability has been exceeded.

Since both the radius ratio and the radius difference were involved, it is necessary to pick a value of the source radius. Two cases are analyzed, one with R_o = 1 in. and one with R_o = 5 in. These are selected because a 1 in. radius device size approximately corresponds to the size of gridded tubes, traveling wave tubes, klystron collectors and solid-state devices. A 5 in. radius device size approximately corresponds to the size of cross field amplifiers. From Figures 5.5-3 and 5.5-4, it can be see that, in general, the results for a source radius of 5.0 in. show the same trends as do the results for a source radius of 1.0 in. As a result, the preceding discussion is applicable to the results for both source sizes.

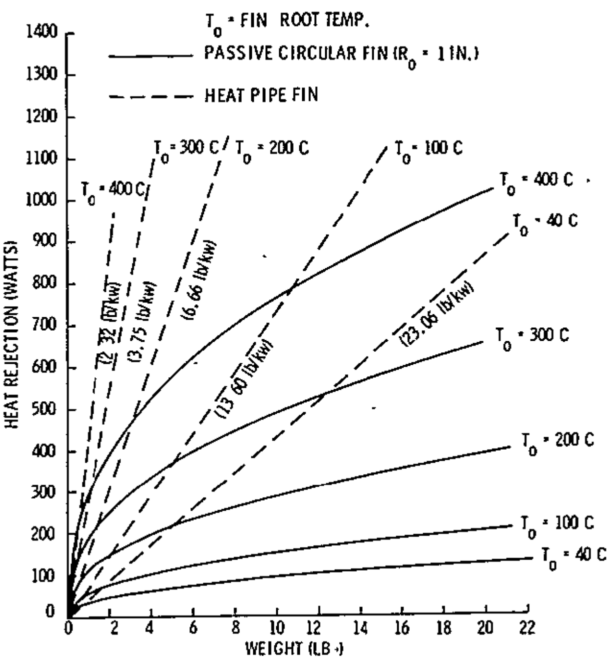


Figure 5.5-1. Radiator Weight Characteristics ($R_0 = 1$ in.)

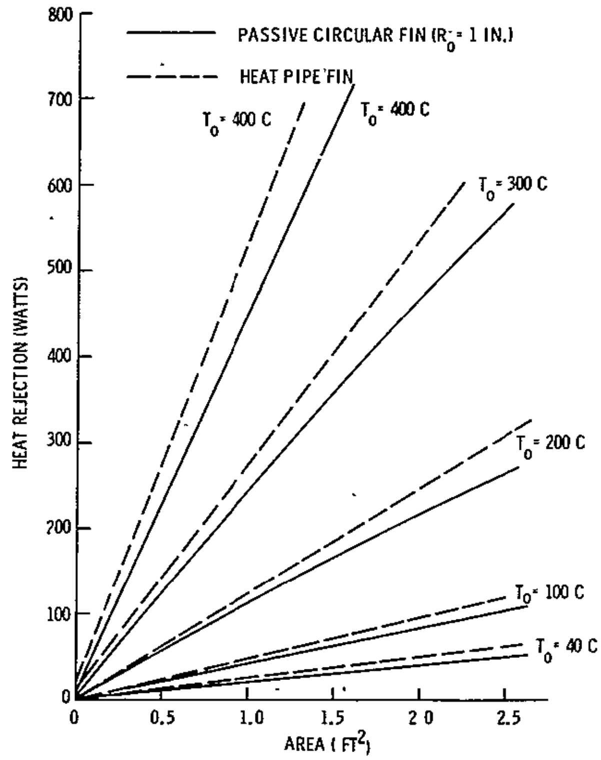


Figure 5.5-2. Radiator Area Characteristics ($R_0 = 1$ in.)

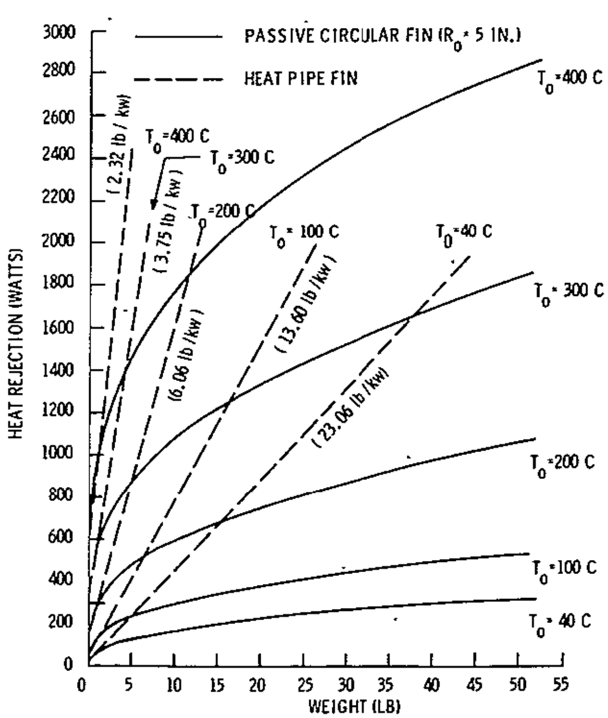


Figure 5.5-3. Radiator Weight Characteristics ($R_0 = 5$ in.)

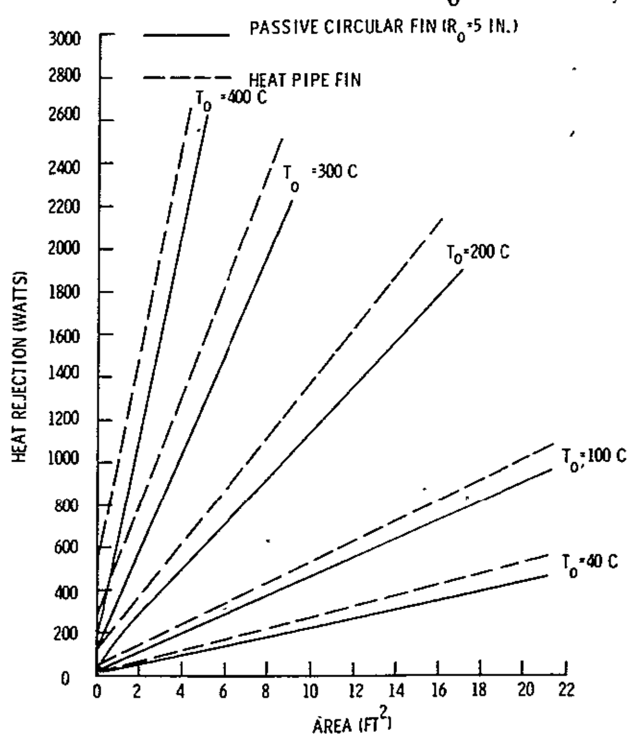


Figure 5.5-4. Radiator Area Characteristics ($R_0 = 5$ in.)

Figures 5.5-5 and 5.5-6 present area and weight requirements, per kilowatt of vehicle power dissipation, as a function of source (device) temperature for minimum weight heat pipe radiators; curves for equivalent sink temperatures ranging from -460 F to +30 F are included. Inspection of the resultant curves shows the radiator requirements are less dependent upon sink temperature as the source temperature increases.

Figures 5.5-7 and 5.5-8 are the area and weight requirements for minimum area radiators. These curves assume a radiator effectiveness of 100%,which can only be achieved physically by utilizing a radiator which is completely made up of heat pipes. The weight of a continuous heat pipe surface was assumed to be 6 pounds per square foot; this is considered to be a reasonable value for a radiator of this type which is fabricated of stainless steel. This value will vary as a function of source temperature and radiator material, but can probably not be reduced by more than 50%. It is important to note that the minimum area (isothermal) radiators are no more than 40 to 50 percent smaller than the minimum weight radiators. The weight increases are on the order of 200 to 500 percent. Development and fabrication costs of a passive radiator are compared to those of a heat pipe radiator in Section 5.5.6.

5.5.3 HEAT PIPES

A heat pipe is basically a closed system containing a two-phase fluid. If one portion of the system boundary in contact with the fluid is heated to a temperature above the saturation temperature of the fluid, a vapor is formed which decreases the specific volume of the vapor portion of the system. This vapor, however, will condense on any portion of the boundary whose temperature is below the fluid saturation temperature. The result is a transfer of the latent heat of vaporization from the hot surface to the cold surface. The vapor is moved by the pressure differential created by the vaporizing and condensing fluid. Since the heat transfer coefficients between a surface and a fluid changing phase are very high, large quantities of heat can be transferred with little temperature change. If a means is provided to return the condensed fluid to the hot portion of the boundary, a continuous cycle can be maintained.

In an orbital or zero "g" environment, some means of pumping the condensate back to the evaporator must be provided. A mechanical pump could be used, but the addition of an active component to an otherwise passive system would reduce the inherent reliability of the passive system. A capillary return network provides extremely high reliability and simplicity of design. Since test results have shown that capillary networks have sufficient flow rates to operate the heat pipe, this type of pump is the logical choice for space application.

A heat pipe flight experiment has flown "piggyback" on an ATS Agena Vehicle; a GEOS/B experiment has also flown successfully. Evaluation of flight data shows that the heat pipe system is compatible with a space environment.

The purpose of the heat pipe is to move heat with almost no temperature drop. Applied to a physical system related to this study, it is used to remove heat from a high power dissipation component or group of components and carry the heat to a radiator where it can be rejected to space. The heat pipe is put to its most efficient use in a practical spacecraft design where it is evenly spaced and attached to a radiator in a parallel configuration. The spacing and fin

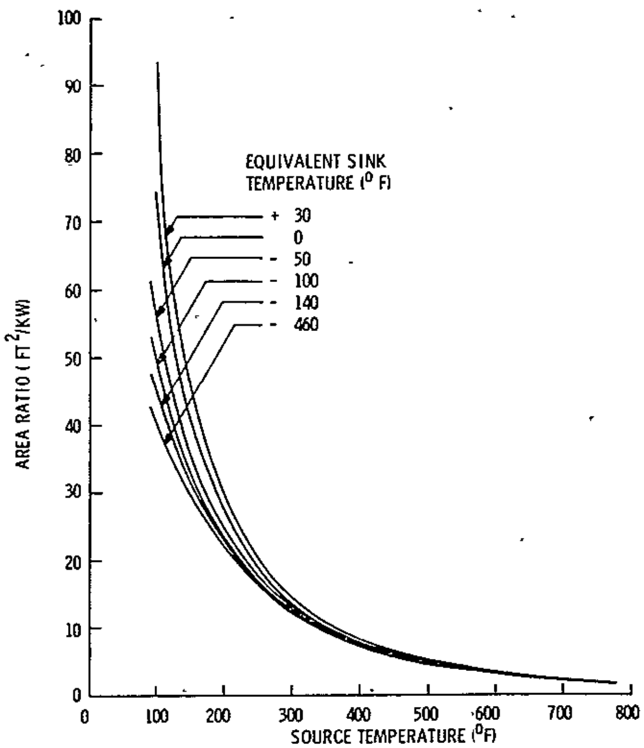


Figure 5.5-5. Weight-Optimized Heat Pipe Radiator, Area to Power Ratio vs Source Temperature

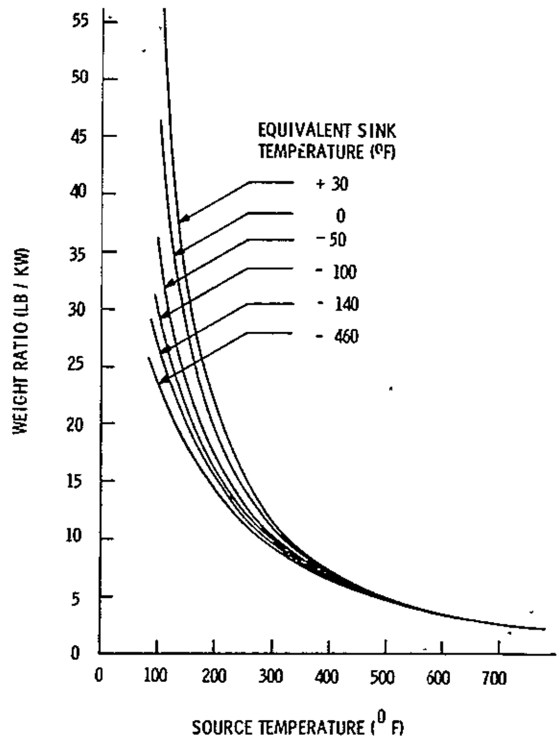


Figure 5.5-6. Weight-Optimized Heat Pipe Radiator, Weight to Power Ratio vs Source Temperature

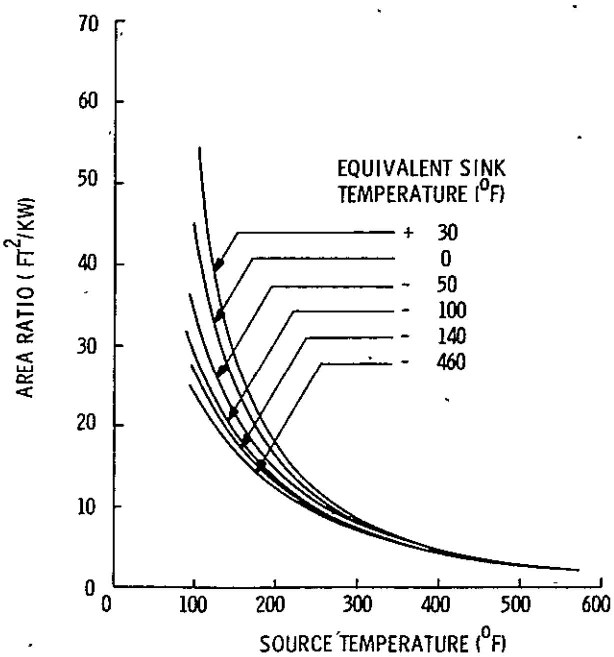


Figure 5.5-7. Minimum Area Fins - Isothermal Radiator Area to Power Ratio vs Source Temperature

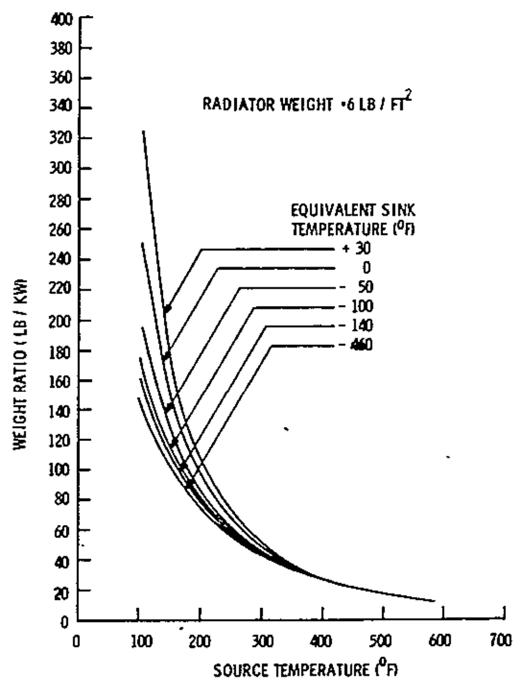


Figure 5.5-8. Minimum Area Fins - Isothermal Radiator Weight to Power Ratio vs Source Temperature

dimensions and materials determine the overall performance. The radiator and heat pipes can be flat or curved to conform with the spacecraft requirements. Radiators can take the shape of cylinders, cones, parallelepipeds, or almost any reasonable shapes as required by vehicle constraints.

The four basic areas of design of a heat pipe are the vapor flow passage, the capillary structure, the evaporator area, and the condenser area. Since all depend on the properties of the working fluid, the fluid selection must be made before the heat pipe can be designed. The selection of a working fluid for use in a heat pipe is extremely important when attempting to utilize the heat flow capability of this device to its fullest extent. The property requirements for a heat pipe working fluid are determined by the application, operating temperature, and heat flow capacity. The main characteristics of interest are as follows:

1. Melting Point. Since the material must flow through a capillary structure as it moves from the condensing section to the evaporator of the pipe, it must be in liquid form. Thus, the operating temperature must be above the melting point of the working fluid.

2. Vapor Pressure. The vapor pressure of the working fluid should be low enough at the operating temperature so that it can be easily contained. On the other hand, it must be high enough that the vapor will be sufficiently dense to carry the heat load without reaching choke velocity.

3. Latent Heat of Vaporization. A high latent heat of vaporization is important for a large heat flow capacity because it reduces the mass flow requirement. This reduces the required vapor flow cross section as well as the capillary cross section.

4. Liquid Viscosity. Since the liquid must flow through the capillary structure, the viscosity of the liquid phase of the working fluid should be as low as possible to minimize the pressure drop in the capillary.

5. Surface Tension. The return of the liquid phase of the working fluid from the condensing section to the evaporator of the heat pipe is accomplished entirely by capillary action. Since the force available for the movement of the fluid is proportional to the surface tension, it should be as high as possible.

6. Wetting. The liquid phase of the working fluid must wet the surface of the capillary structure in order to pump the working fluid to the evaporator.

7. Corrosive Properties. No chemical interaction between any parts of the system can be tolerated. Not only would this endanger the mechanical integrity of the heat pipe, but solid contaminants could be deposited in the capillaries of the evaporator section and stop the flow of the working fluid. Non-condensible gases formed by corrosion reduce the efficiency of the heat pipe.

8. Density. The density of the liquid phase of the working fluid should be high to minimize the flow rate of the liquid through the capillary structure.

9. Stability. The fluid must be chemically stable at the operating temperature and pressure.

10. Thermal Conductivity. Where large quantities of heat are conducted radially through the fluid-filled wick at the condensing section of the heat pipe, large temperature differentials can occur. Since this differential is almost a direct function of the thermal conductivity of the liquid, this property should be as high as possible.

11. Critical Heat Flux. The critical heat flux is the maximum heat flux which can be carried from a surface by a boiling fluid. While it depends, in part, on surface conditions, it is primarily a function of material and pressure. Its importance as a property of a heat pipe working fluid is that it determines the minimum area of the evaporator.

As an aid in determining the best working fluid for the particular heat pipe system under investigation, it is helpful to examine the theoretical maximum heat flux as a function of temperature. By examining these values for the pertinent system parameters (such as component operating temperature, and maximum heat transport demands) the choice can be narrowed to those fluids whose useful temperature range coincides with the system demands. In order to establish a general means of fluid evaluation, a system of curves for various fluids is presented in Figure 5.5-9.

Another fluid property that must be considered is the vapor pressure at the heat pipe system operating temperature. This property has a direct effect on the system weight and reliability, since to operate at high internal heat pipe pressures additional wall thickness and structural members will be required. Vapor pressure as a function of temperature for various working fluids is presented in Figure 5.5-10.

The estimated costs of heat pipe systems are presented in Figure 5.5-11. Costs are broken down as development cost which includes design, feasibility testing and life testing and unit cost which is the cost to develop each flight unit. Heat pipes using water as the working fluid have been extensively tested and therefore result in the highest development cost. The liquid metal system will cost less than the organic fluid system to develop, since a great deal of work has been done in this area; but, unit costs are higher due to handling problems.

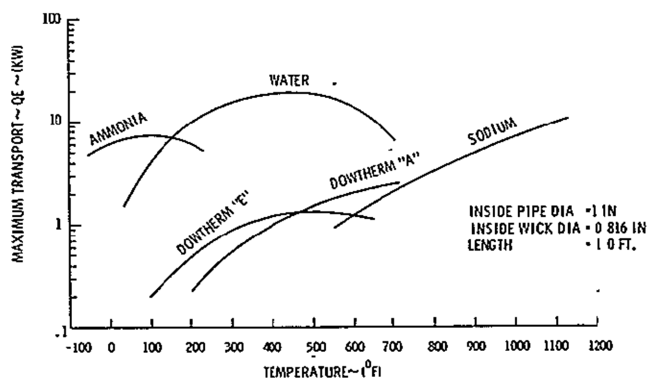


Figure 5.5-9. Transport Capacity for Various Heat Pipe Fluids

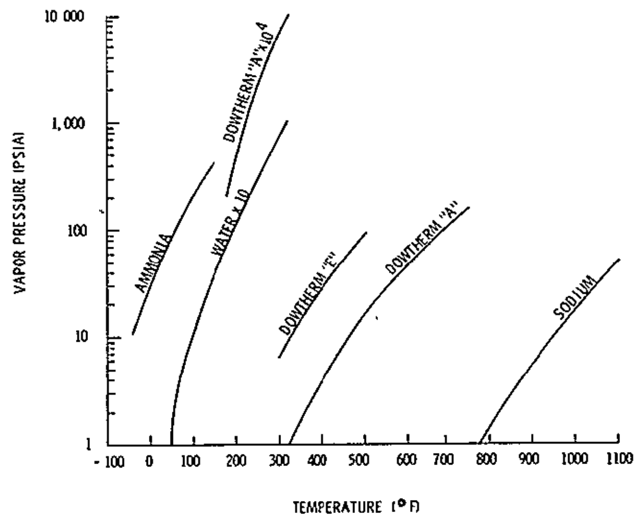


Figure 5.5-10. Vapor Pressure for Various Heat Pipe Fluids

5.5.4 THERMAL CONTROL SHUTTER SYSTEMS

The most common thermal control system presently used on spacecraft which have non-continuously operating components is the thermal shutter or louver system. These systems employ temperature sensing elements which control the opening and closing of light-weight blades placed on the space-facing side of a passive baseplate radiator. The effective radiation properties of the baseplate are changed and the louvers are, thus, heat valves which inhibit heat flow to space as vehicle temperature decreases. Louver systems have been successfully flown on Mariner, Pegasus, and Nimbus satellites. For high dissipation devices which are either on at full power or off at zero power, it may be desirable to provide on-off control of the shutter blades (corresponding to fully open-fully closed positions). To do so, however, would probably necessitate the use of electrical power.

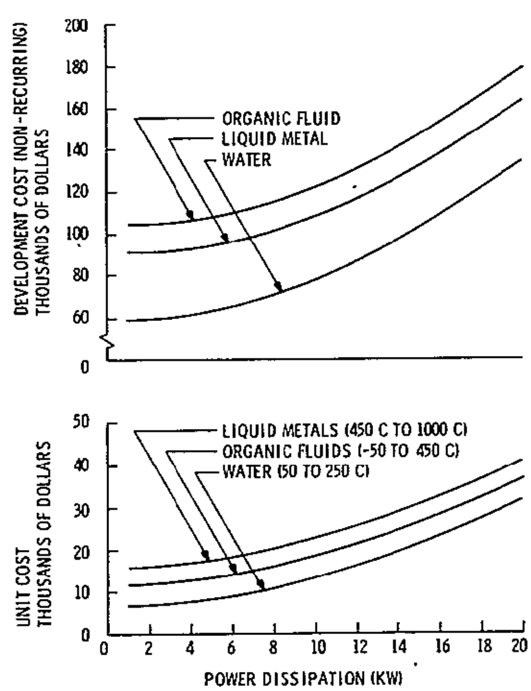


Figure 5.5-11. Heat Pipe Radiator Cost

All shutter systems exhibit some heat leak in the closed position. This leak takes place mainly around the edges of the blades, rather than through them. Because the leak is significant, it is sometimes necessary to provide "compensation" heaters that are activated when a component is off. These heaters dissipate a minimal amount of heat to overcome the leakage and maintain component temperature at some specified lower limit.

The addition of a louver system to a passive radiator increases the area required to reject a given quantity of heat. This is because, even in the fully open position, the effective emissivity and absorptivity of the integrated system cannot equal the properties of the baseplate coating. The effective emissivity is decreased by thermal interactions between the baseplate the the blades, and the absorptivity is increased due to the effect of the created "cavities" on incident solar flux. Consequently, area and weight penalties are incurred whenever shutter systems are used.

Louver systems must always be designed to dissipate the maximum component heat. Area and weight are independent of duty cycle, since it is assumed that the louvers will close and limit heat rejection whenever the component is off. The weight of a louver system (not including baseplate) is a function of the area covered. The use of 0.7 lb/sq ft as a reasonable obtainable value was used.

Costs for shutter (louver) thermal control hardware are shown in Figure 5.5-12. Costs include design, drafting, manufacturing, and quality control of all parts of the thermal control systems. Development costs (as given) do not include system analyses. This will be about equal to the hardware cost and, thus, the cost for the total thermal development effort will be approximately double that shown in Figure 5.5-12.

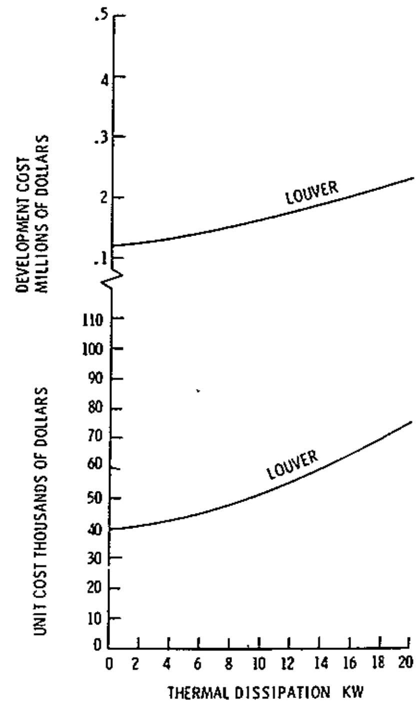


Figure 5.5-12. Estimated Costs of Thermal Shutter System

5.5.5 ELECTRO-MECHANICAL INTERFACES

Attaching the heat transfer system to the heat source must be done in such a way that temperature drop at the interface is minimized. This problem is complicated in some cases by a high electrical potential on the heat transfer surface, requiring the use of insulators and in others by assembly requirements.

Figure 5.5-13 shows a comparison between a clamped and a brazed interface as a function of power density. The brazed interface, as the figure shows, reduces by almost two orders of magnitude the temperature drop at an interface where clamps are used.

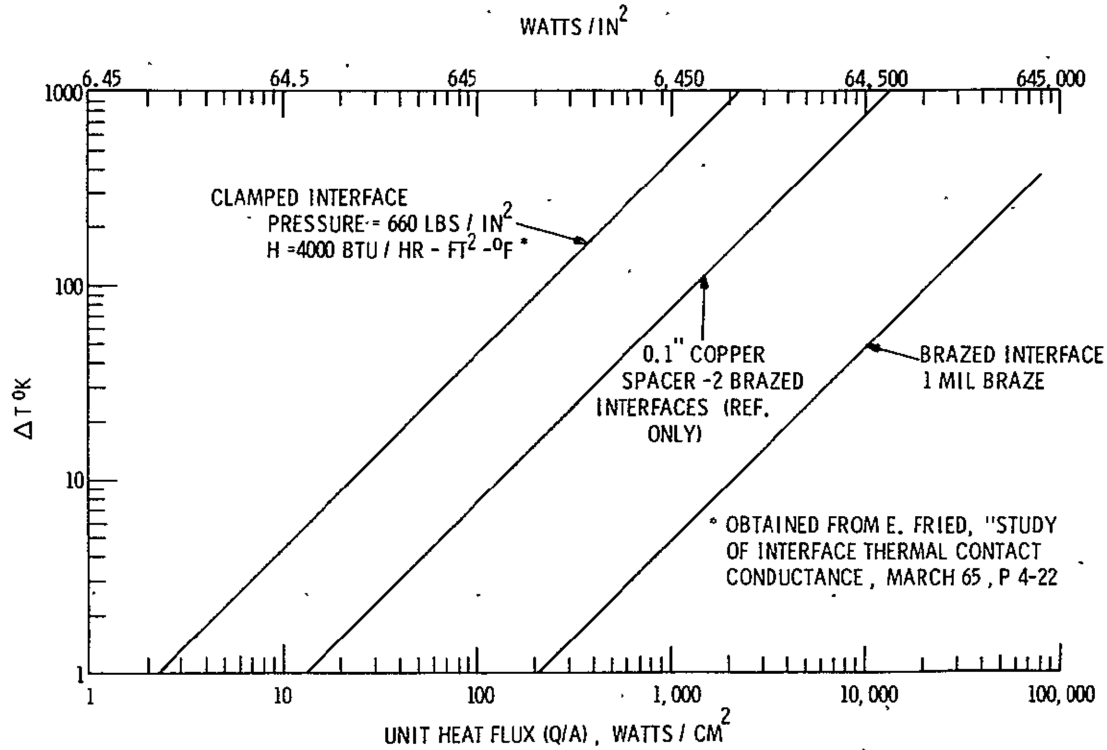


Figure 5.5-13. Thermal Interface Characteristics, No Electrical Isolation

Where electrical isolation is required at the heat transfer interface, a ceramic insulator with a high thermal conductivity is brazed to the interface. Figures 5.5-14, 5.5-15 and 5.5-16 show the temperature differentials resulting from heat flow through insulation sufficient to withstand 3, 6 and 9 kv. On each figure, the drop across boron nitride and beryllium oxide insulators is shown. Beryllium oxide is shown for two temperatures sin its thermal conductivity is a strong function of temperature. Aluminum oxide insulators fall between the data shown for boron nitride and beryllium oxide.

A vital approach to temperature control of electronic devices is an integrated thermal design. The differences between requirements for ground and space operation, particularly where heat pipes are to be applied, necessitates this approach to avoid excessive internal temperature differentials which lower the temperature at which heat can be radiated. Reduced radiator temperature significantly increases weight and area requirements.

The most critical component in a high power dissipating satellite is the RF output device. A discussion of the thermal requirements and control of several types of electronic devices are given in this section.

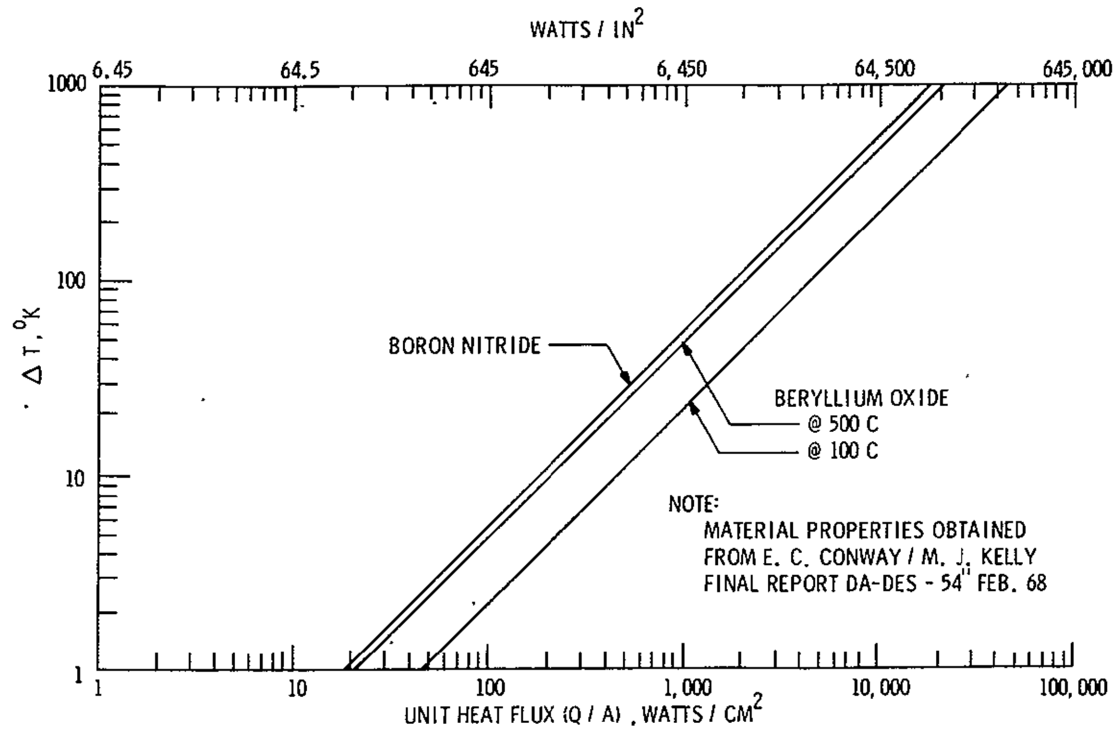


Figure 5.5-14. Thermal Interface Characteristics, 3 kv Electrical Isolation

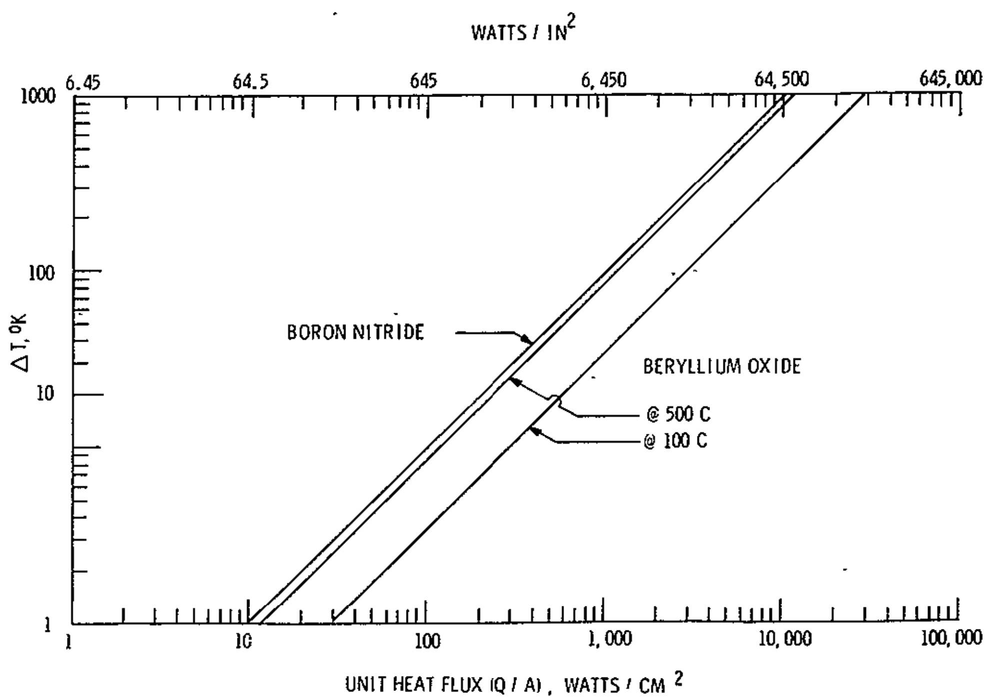


Figure 5.5-15. Thermal Interface Characteristics, 6 kv Electrical Isolation

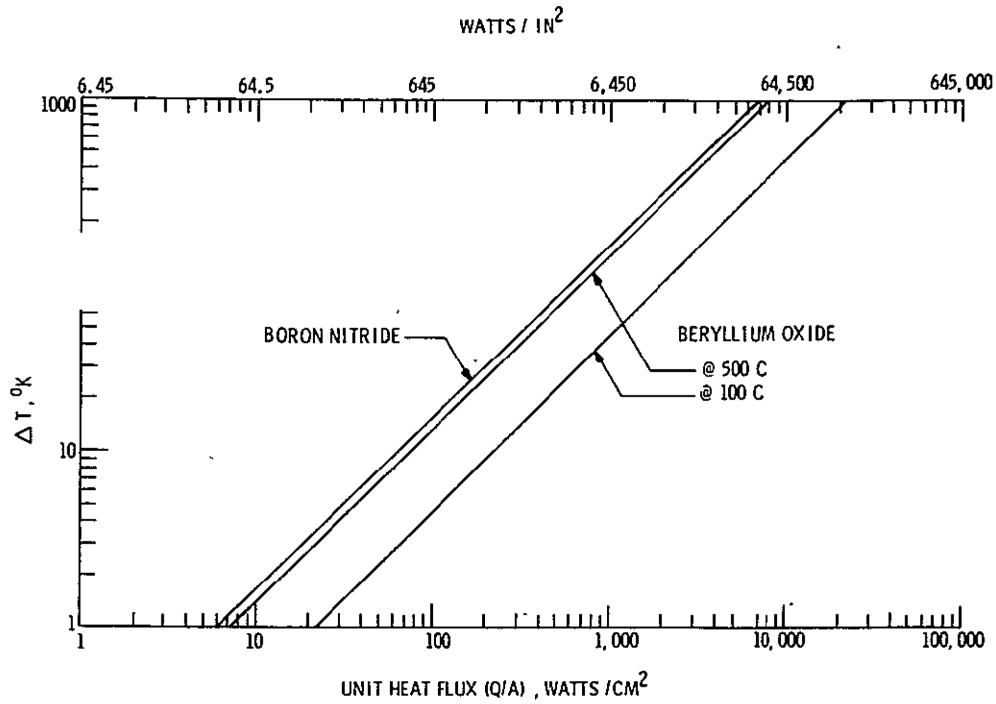


Figure 5.5-16. Thermal Interface Characteristics, 9 kv Electrical Isolation

5.5.5.1 Gridded Tubes

Thermal control of gridded tubes covers a very broad range of powers and temperatures. A thermal control system was designed, built and successfully tested for the triode shown in Figure 5.5-17. The maximum temperature requirements of the system are:

Anode:	500 C
Power Dissipation:	2.5 kw
Grid:	150 C
Electrical Insulation:	3 kw

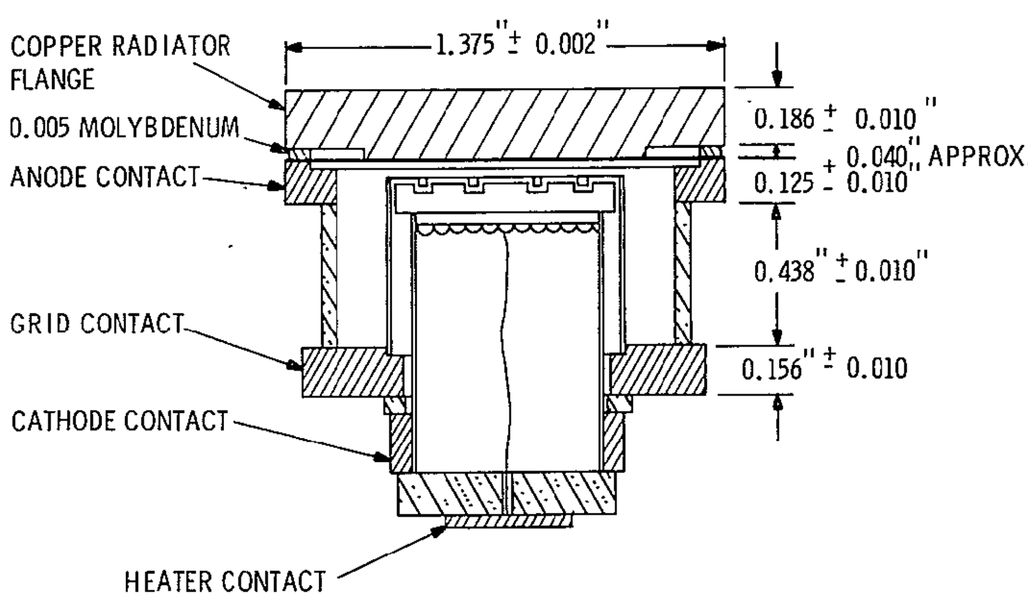


Figure 5.5-17. Illustrative Thermal Design for L64SA Triode

The primary problem areas with this type of device are the extremely high power densities (in excess of 200 w/in^2) encountered at the anode, and the high electrical potentials encountered on exposed surfaces. Where heat pipes are used, high power densities must be reduced to a value below the critical heat flux of the heat pipe evaporator through the use of a heat flow path with an increasing area.

5.5.5.2 Klystrons

Thermal requirements for a klystron are dictated by several limitations. Maximum temperature limits of 400 to 450 C are imposed on internal cavities to avoid excessive copper "boil off." Collectors can be fabricated from refractory metals and insulators of high temperature ceramics, but metal to ceramic seals are temperature limited and differential thermal expansion is a serious problem. Solenoid power must be traded off against radiator size in magnetically focused klystrons since resistivity increases with temperature thus increasing power requirements. Further problems are introduced due to variation in the length of the klystron body with wave length. In general, the collector dissipates 60 to 80 percent of the heat generated in the klystron while the remainder is dissipated in the cavities along the body of the tube. This is fortunate, since the collector can operate at a higher temperature than the body, thus reducing radiator area and weight requirements. Some recent klystron designs for up to 15 kw RF output have the following thermal characteristics:

Collector:	1500 to 2000 W	600 C
Cavities:	15 to 30 W	200 to 300 C
Output Cavity:	350 to 700 W	150 to 250 C
Solenoid:	200 to 600 W	100 to 140 C

5.5.5.3 Traveling Wave Tubes

The thermal considerations for the TWT are very close to those of the klystron. Heat is generated at two surfaces and, in general, must be removed either at two different temperatures or all of the heat can be removed at the lowest temperature limit. The highest temperature limit is on the collector and the lower on the body of the TWT. Since most of the heat is generated at the collector, it is advantageous, from the standpoint of radiator area and weight, to use two fin systems at different temperatures to cool the TWT.

5.5.5.4 Crossed Field Amplifiers

Thermal control of a crossed field amplifier (CFA) requires cooling of 3 internal elements, the sole, the anode/slow wave structure, and the collector. In addition, magnets must be maintained well below their curie temperature and penetrations through the magnetic shield must be minimized.

5.5.5.5 Solid State Devices

The use of solid state devices in high power application requires combining the outputs of many devices, each of which operates at relatively low power. The primary problem with these devices is the low operating temperature required which results in extremely large radiators. The general approach to cooling of solid state devices is to integrate heat pipes into the heat sinks to which the transistors are attached. Since each device outputs a relatively low power, the evaporators of the heat pipes can easily be designed to maintain the power density below 200 to 300 w/in^2.

5.5.6 COSTS

The development and fabrication costs of the passive and heat pipe radiator systems are given in Figure 5.5-18. Figure 5.5-19 gives the incremental costs to be added if a shutter (louver) system is added to either the passive or heat pipe radiator.

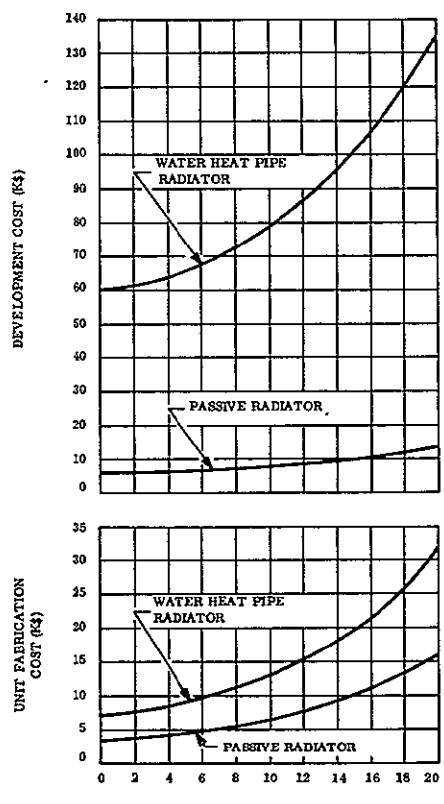


Figure 5.5-18. Baseplate Costs

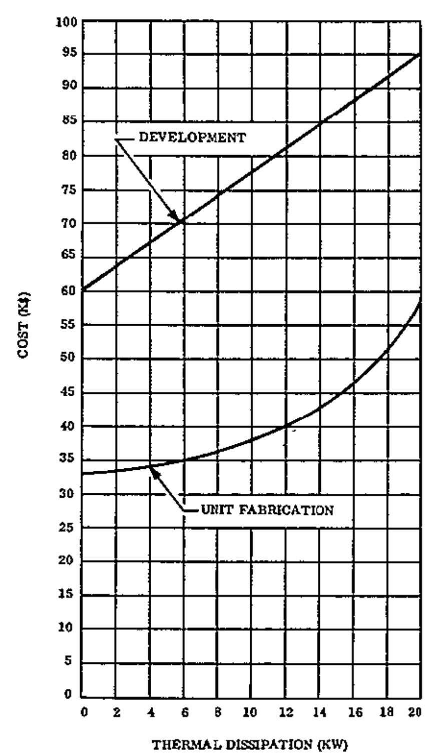


Figure 5.5-19. Incremental Louver Costs

5.6 STRUCTURAL SUBSYSTEM PARAMETRIC ANALYSIS

The purpose of the structural parametric analysis was to provide the subsystem weight and cost data required for system analysis.

Satellite weights up to 10,000 lbs (4540 kg), antennas up to 40 ft (12.2 m) diameter, and solar arrays up to 20,000 ft^2 (1858 m^2) were analyzed. The structure was examined as two separate parts: 1) the primary structure required to accommodate the launch load acceleration and vibration environment, and 2) the additional structure necessary to provide the required structural dynamic characteristics of the orbital configuration. The approach selected was to rely on historical data for the basic structural weight, and develop a simplified structural dynamic model to estimate the stiffening weight.

State-of-the-art structure was assumed to be made of conventional light metal alloy with no usage of beryllium alloys, whisker reinforcements or filament-wound structures, etc. The geometry was assumed determined by a two panel solar array separated by a distance equal to the maximum antenna dimension.

The primary structural weight, including launch vehicle adapters is estimated (from historical data) to vary from approximately 30% of the total satellite weight for small satellites to 10% for large satellites. The higher values for small satellites results from certain fixed adapter weights, minimum gauge materials and the like.

The resultant plot of primary structural weight vs the summation of subsystem weight is given in Figure 5.6-1. The summation includes all subsystems except the orbit maintenance and orbit trim systems, and, therefore, includes the antenna, transmitter, receiver-exciter, power, attitude control, thermal control, and TT&C.

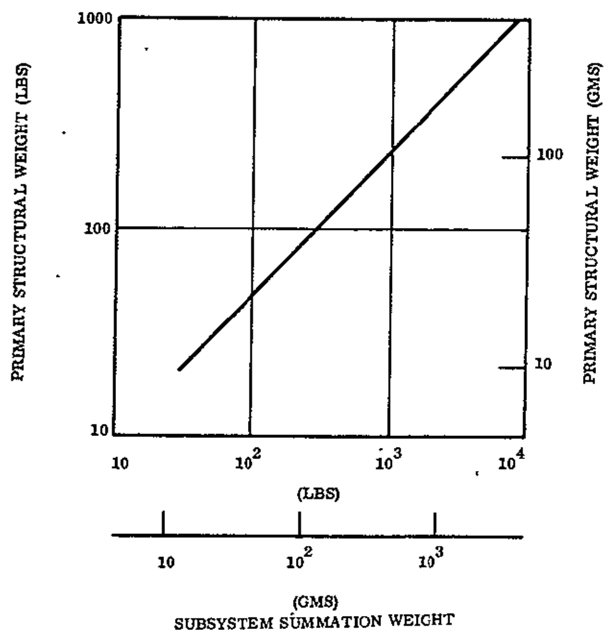
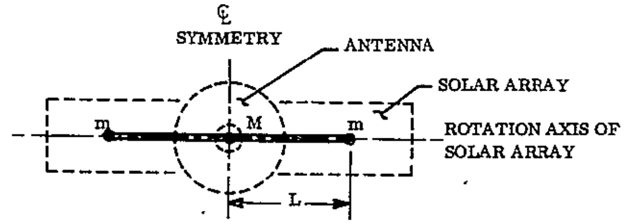


Figure 5.6-1. Structural Weight Requirements

The spacecraft configuration postulated for purposes of assessing the in-orbit stiffness weight is shown in the sketch. This assumes two solar array areas symmetrically distributed along the spacecraft nominal pitch axis and spaced far enough out to clear the antenna during the daily and seasonal articulations.



This configuration then results in a simplified dynamic model which neglects the flexibility of the solar array or the antenna itself, but includes their inertia as rigid elements. The primary element of the stiffness matrix is the structure connecting the masses, which is assumed to be a tubular aluminum structure.

The simple 3-mass model is then described as follows:

Aspect ratio of panels, $a/b = 2$

$R/t = 300$ = radius of tubular member/wall thickness of tubular member

Aluminum modulus and density

M = mass of the spacecraft less solar arrays

m = 1/2 of the total solar array mass

The conversion to weight thus resulted in the following relation for stiffening weight as a function of natural frequency.

$$W_S = 0.0048\, L^{2.5} \left(\frac{M}{1 + \frac{n}{2}} \right)^{1/2} f_n$$

where

f_n = fundamental frequency requirement

L = distance described on sketch (ft)

$n = M/m$, mass ratio

Cost data for the structural subsystem was estimated (on the basis of historical program costs) as a function of structural weight, and the resultant data is shown in Figure 5.6-2. The curves show engineering cost (including development and test models) and fabrication costs per unit.

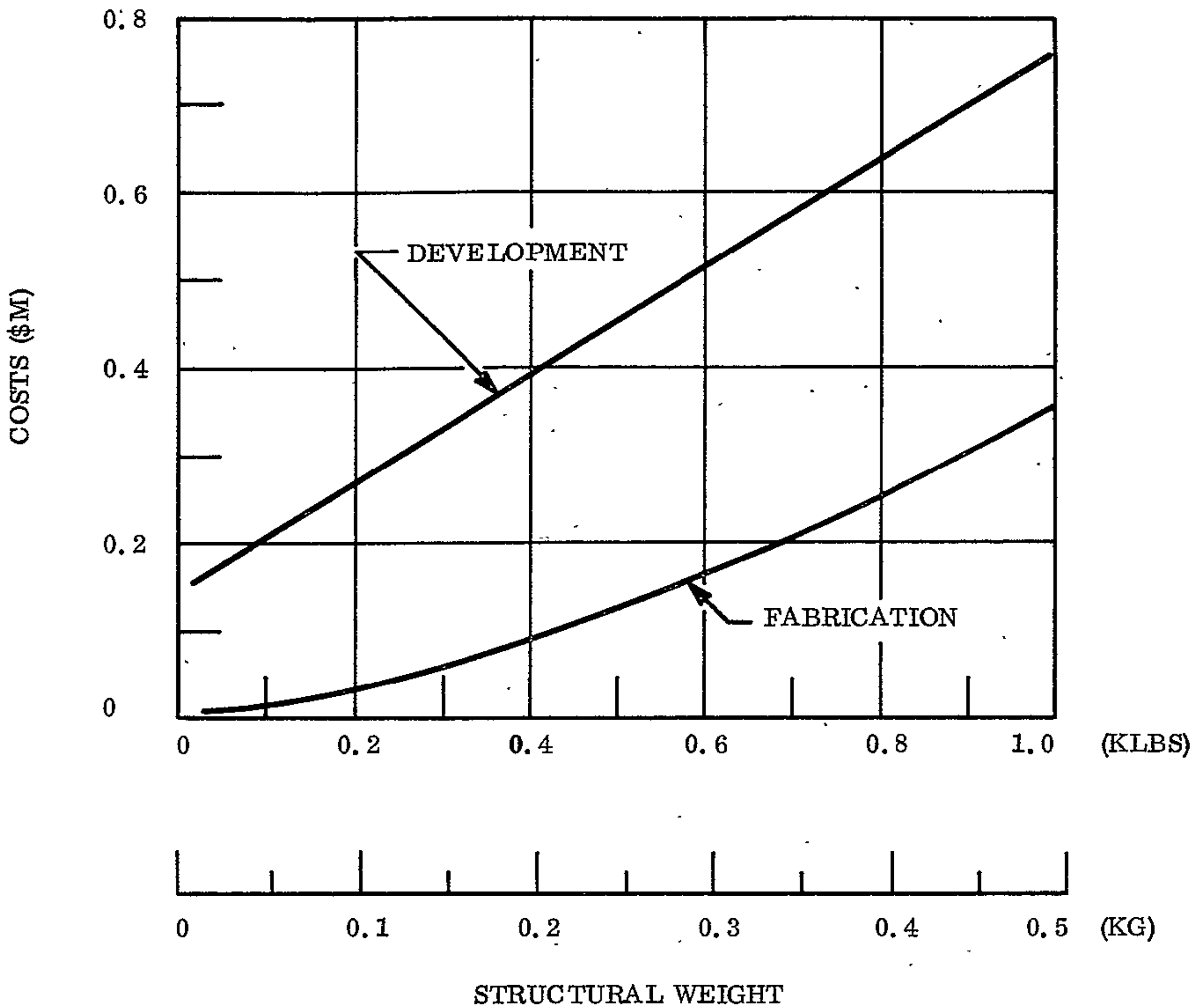


Figure 5.6-2. Structural Subsystem Costs

5.7 LAUNCH VEHICLE PARAMETRIC ANALYSIS

Existing and planned launch vehicle performance and costs were analyzed. Eleven boosters with nominal hardware and launch costs were selected to give a synchronous orbit payload range from 540 pounds (245 kg) to 10,100 pounds (4580 kg). This data, shown in Figure 5.7-1, was used as an input to the Computerized System Analysis (PACES model, Section 6.1.2) and was used for all subsequent Phase 2 system analysis described in Section 6.

Launch vehicles are continually being added to and removed from the government inventory. Launch service costs as estimated by various government agencies are subject to rather wide variations (as high as two to one) depending upon the current estimated launch rates over a period of years, the resulting amortization of launch facilities, and differing methods of bookkeeping. For these reasons, an updating of launch service availability and costs was accomplished for the boosters of interest during the Phase 3 conceptual designs. This information is given in Section 7.4.

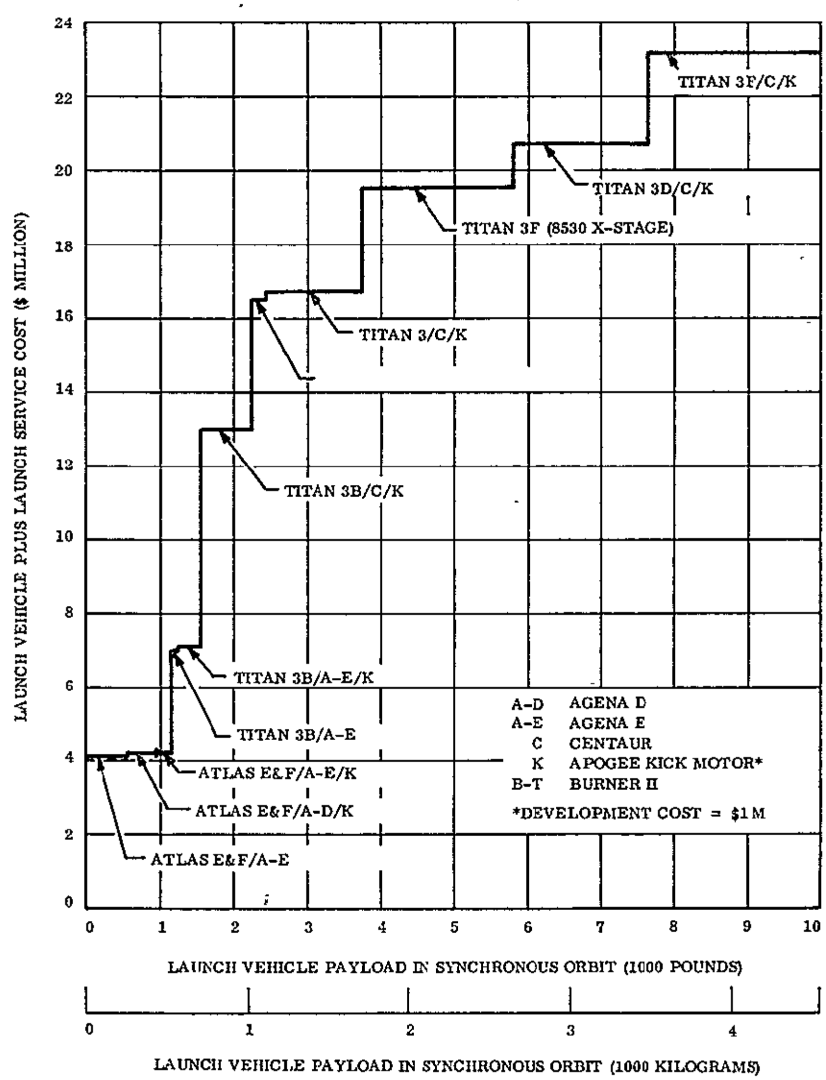


Figure 5.7-1. Launch Vehicle Payload vs Cost

SECTION 6

SYSTEM ANALYSIS

This section describes the tools employed and presents the data generated during the System Technical Analysis (Phase 1 of the study) and during the System Protoconcept Designs (Phase 2 of the study).

Section 6.1 describes a Computer Synthesis Model developed by General Electric prior to start of the TVBS study. This computer model was employed to synthesize the thousands of possible ground and satellite systems, which resulted from the broad parameter ranges imposed by the scope of the study. The computer output related system costs to performance parameters, and determined the lowest cost system for a specific set of parameters.

Section 6.2 describes the system trade-off curves generated by the Computer Synthesis Model. The curves were cross plots of various performance parameters versus system costs. These trade-off curves were used to systematically explore the effects of variations of the mission, system, and subsystem parameters on system cost. This permitted the selection of the optimum system for a specific television service from a group of candidate lowest cost systems, all of which had sets of parameter values to meet the requirements of that specific television service.

Section 6.3 describes 13 of the System Prototype Designs conceived. These were based upon the mission analysis described in Section 3 and the outputs of the Computer Synthesis Model for those optimum sets of performance parameters determined from the trade-off curves.

6.1 COMPUTER SYNTHESIS MODEL

The General Electric Computer Synthesis Model used in this study is shown in Figure 6.1-1. The model consists of three subroutines: 1) The Receiver Synthesis Model accepts a set of mission parameters as an input, searches for the maximum performance ground receiving electronics and antenna within the input constraints, and calculates the minimum ERP required in the satellite, 2) The Satellite Synthesis Model accepts the minimum ERP from the receiver model plus several additional mission parameters as inputs, selects various combinations of nine satellite subsystems which are feasible for the inputs, calculates the performance parameters and costs for a satellite with each subsystem combination, and outputs the lowest cost satellite, 3) The System Cost Model then calculates various system costs for this lowest cost satellite, the ground equipment, system integration and test, support system investment, operation and program management.

The output of the Computer Synthesis Model is a description of the lowest cost system which meets the requirements of a single set of input mission parameters. This description (in computer printout format) specifies the input mission parameters, gives the ground equipment and satellite performance parameters for the subsystem types selected, and gives the system costs for this minimum cost system.

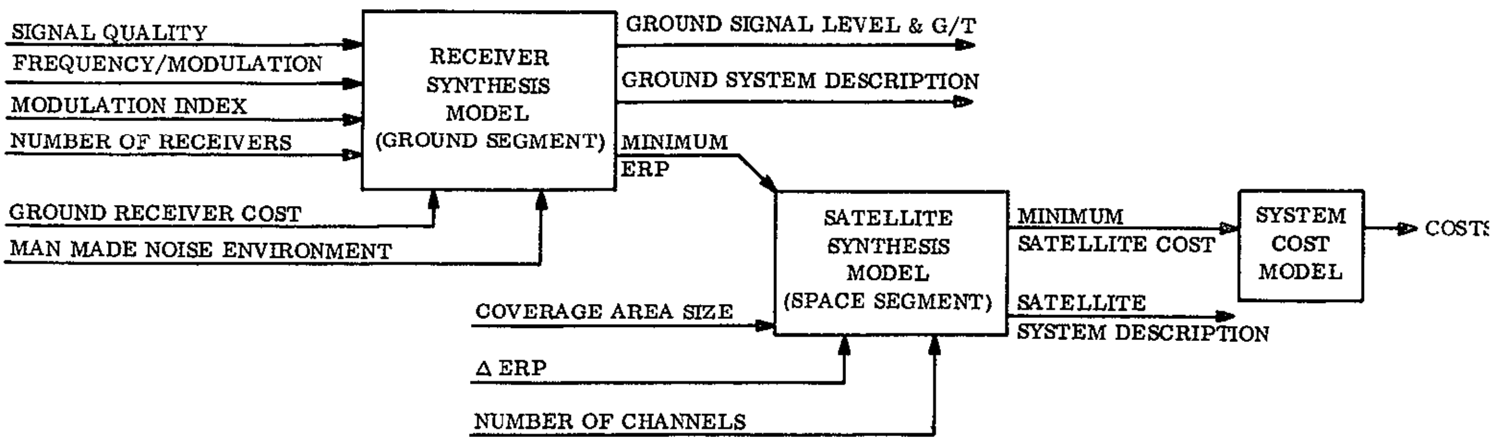


Figure 6.1-1. Computer Synthesis Model

The Computer Synthesis Model can handle, as a set, the hundreds of thousands of combinations of the nine variable mission input parameters and synthesizes up to sixteen possible satellites for each possible set. It was necessary to fix the number of sets of input parameters considered to approximately 600 cases to limit the data to a manageable amount. This resulted in the synthesis of approximately 10,000 satellites and the plotting of 2500 plots on 160 trade-off curves. These curves are described in Section 6.2

The Computer Synthesis Model which was developed by General Electric prior to this TVBS study was updated during the study from the parametric analysis data previously described in Sections 4 and 5. A detailed description of the Computer Synthesis Model is given in Sections 6.1.1, 6.1.2 and 6.1.3. Table 6.1-1 lists the 16 input mission parameters which define a television service and which were used as the input to the computer program. The first nine parameters were treated as variables, with specific values used to input the computer within the variable range. The other seven parameters were treated by the computer as constants (the four marked with an asterisk were handled as a continuous variable (ΔERP).

6.1.1 RECEIVER SYNTHESIS MODEL (ERP MODEL)

The purpose of the ERP model is to determine the minimum value of ERP required for a given receiving system performance and cost, consistent with the specific TV service broadcast parameter. The scope, as related to the input broadcast service parameters, was

Table 6.1-1. TVBS Broadcast Mission Parameters

Constraint Parameter	Value	Comments
Coverage Area Size Million sq mi (Million km^2)	1/2, 1, 3, 10 (1.29, 2.59, 7.76, 25.9)	Four coverage area sizes were selected to cover the range from 1/2 to 10 million square miles. These are referenced to the subsatellite point, for which the four values represent minimum satellite transmitting antenna beamwidths of 2.1, 2.9, 5.5, and 8.8° respectively.
Audience - Number of Receivers	$10-10^8$	The audience size value range as shown with five specific values investigated for each service type as was previously presented in the audience analysis model ($10-10^5$ for Special Service and 10^4-10^8 for Direct Service).
Signal Quality	TASO Grades 1, 2, & 3 and CCIR Relay Quality	Signal quality was investigated for TASO grades 1, 2, and 3 for Direct Service and for 2 values for Special Service: TASO grade 1 and CCIR relay quality (specified as Picutre Grade 0). Corresponding AM input S/N ratios for grades 0, 1, 2, and 3 were 50.0, 44.5, 33.5, and 27.0, respectively.
Transmission Frequencies	0.8, 2.5, 8.4, and 12.2 GH_z	Representative transmission frequencies were selected as shown respectively. The following four bands of interest: (0.47-0.89, 2-3, 8.3-8.5, and 11.7-12.7 GHz)
Man-made Noise Levels	Urban, suburban, and rural	Man-made noise levels were separated into three different categories for study as shown which result in the noise temperature/frequency functions used in the model.
Ground Receiver Cost	Direct -$0 to $150 Special - $1K to $50K	Allowable cost ranges for ground receiver modifications are shown here for the two service types. These were established on the basis of the service definition analysis previously presented.
Signal Modulation	AM and FM	FM modulation index = 2 for 800 MH_z and 2.5 GH_z; = 4 for 8.4 and 12.2 GH_z
Satellite Orbit	24 hr, circular, equatorial	The satellite orbit was specified to be the geostationary orbit, which made practicable development of the desired system analysis tools.
Operating time	24 hours/day	The operating (broadcast) time was established to be full-time which is about 23 hrs minimum (due to maximum eclipse at the equinox). The satellite synthesis model is capable of analyzing systems other than full-time duty cycles, but the most cost-effective satellite would take maximum advantage of the power generation period, and there is little (if any) advantage to the satellite configuration by designing for lower duty cycle.
Number of TV Channels	One*	General system trends were developed for one channel; however, the model can treat up to 18 channels.
Coverage Area Location	Equatorial*	
Coverage Satellite Transmitter	Single Target Area only*	Satellite transmitter coverage is limited to one area only for the generation of the system trade data. This associates with one channel and negligible effect of beam repositioning. The model, however, has a capability for three areas covered simultaneously.
Satellite Implementation	Single Satellite only Single Mission only	Multiple satellite launches and multi-purpose satellite payloads are not considered, due to the expectation that the effect on system results would not warrant the introduction of the added complexity.
Propagation Effects	Zero*	
System Life	Satellite - 2 years Ground Equipment - 10 yrs	The system operating lifetimes have been selected as shown here for amortization purposes. The 2-year assumption for the satellite system is considered to be conservative, as it is not unlikely that satellite lifetimes of from 5-10 years could be achieved. This assumption tends to lend strong validity to the conclusions that satellite broadcasting is more cost-effective than existing terrestrial methods. The 10-year life of ground system is average for electronic components, although, again, this is conservative when applied to ground antennas.
Technology Base	1971 State of the Art	All technology performance estimates are based on predicted 1971 state of the art.

*Variations in these parameters were accounted for by addition of a ΔERP to that determined from the ERP model, to compensate for additional channels, increased slant range, and all propagation effects.

previously described in Table 6.1-1. The receiving equipment performance parameter ranges were established from allowable cost, quantity to be purchased,. operating frequency, and advanced 1971 state-of-the-art manufacturing technology (see Section 4).

This model solves the link equation associated with RF transmission from synchronous altitude for all possible combinations of input service variables and electronic component performance characteristics. It was convenient to set this up for solution on a digital computer to examine the large number of input cost values desired, and to iterate through the variety of electronics components and antenna data, for all of the combinations of frequency, modulation, audience size, noise location, and picture quality.

The equation for satellite ERP requirements which was programmed for solution on the digital computer is

$$ERP = \frac{(S/N)_o \, 4\pi R^2 K \; B_{RF} \left[T_A (1-L_L) + L_L \, T_{RA} + T_{RN}\right] L_B}{A_R (1-L_L) \; (1-L_P) \, M} \qquad (6\text{-}1)$$

where

ERP = effective radiated power (watts).

$(S/N)_o$ = receiver output signal to noise ratio.

R = distance from satellite to receiver.

k = Boltzman's Constant = 1.38×10^{-23} watt sec/^oK.

B_{RF} = system noise bandwidth, Hertz.

L_B = building attenuation factor.

T_A = effective antenna temperature (^oK).

L_L = fraction of the energy passing through the feeder line which is absorbed by the feeder line.

T_{RA} = ambient temperature of the receiver RF components (290^o).

T_{RN} = receiver noise temperature (F-1) (290^oK).

F = receiver noise figure expressed as a power ratio.

L_P = mismatch of the satellite antenna and receiving antenna caused b Faraday rotation occurring in the atmosphere.

A_R = effective antenna area.

M = modulation improvement factor.

This equation has been derived subject to the following assumptions:

1. The equivalent brightness temperatures over the solid angles through which the antenna faces the sky, earth, and man-made noise, are constant throughout these angles.

2. Ionosphere brightness temperatures and ionospheric absorption can be neglected with respect to cosmic brightness temperature and atmospheric absorption.

3. No point source noise is considered since it would be a function of the specific location which is not considered.

4. Rain absorption is negligible.

5. Atmospheric noise and atmospheric absorption can be neglected with respect to receiving system noise parameters and cosmic noise.

6. The angle above the horizon through which the antenna receives indigenous (man-made) noise is assumed to be 10^{o}.

7. All ambient temperatures are assumed to be 290^{o}K.

8. Due to the existence of different baseband bandwidth requirements throughout the world an average value of 6 MHz was assumed.

9. An average transmitter-receiver line of sight distance was assumed to be 19,500 nautical miles, representing transmission from satellite to latitude $\pm 30^{o}$.

10. The satellite broadcast antenna is circularly polarized.

A complete derivation of this equation is given in Section 6.1.1(I).

The ERP is to be minimized, subject to a receiving system modification cost constraint. The assumed receiving system is given in Figure 6.1-2. For direct broadcasting to home receivers, the cost constraint applies only to the receiving system modification; for special services, the cost constraint applies to the entire receiving system.

A flow chart of the digital computer program is shown in Figure 6.1-3. Each of the program elements will be described in the following sections.

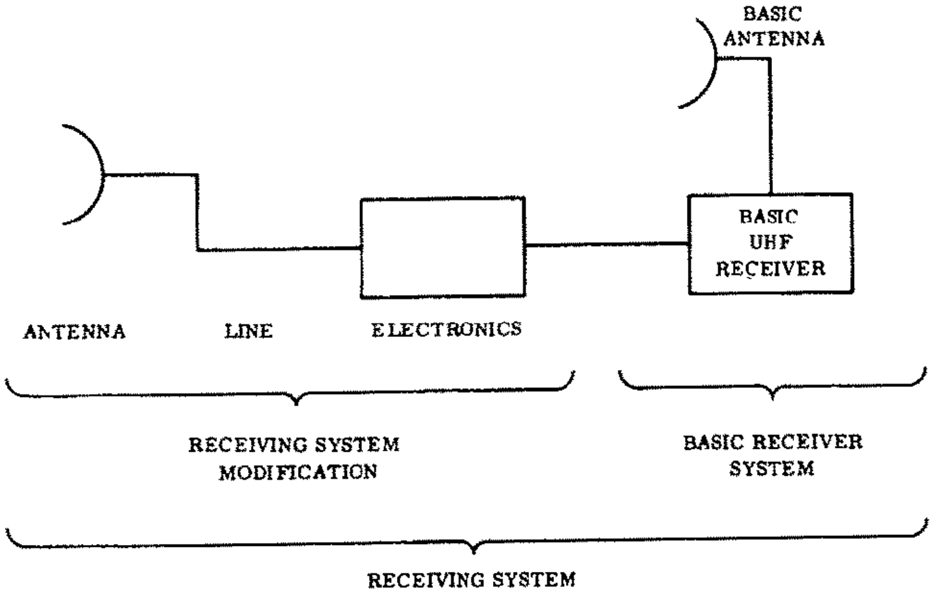


Figure 6.1-2. Receiving System Components

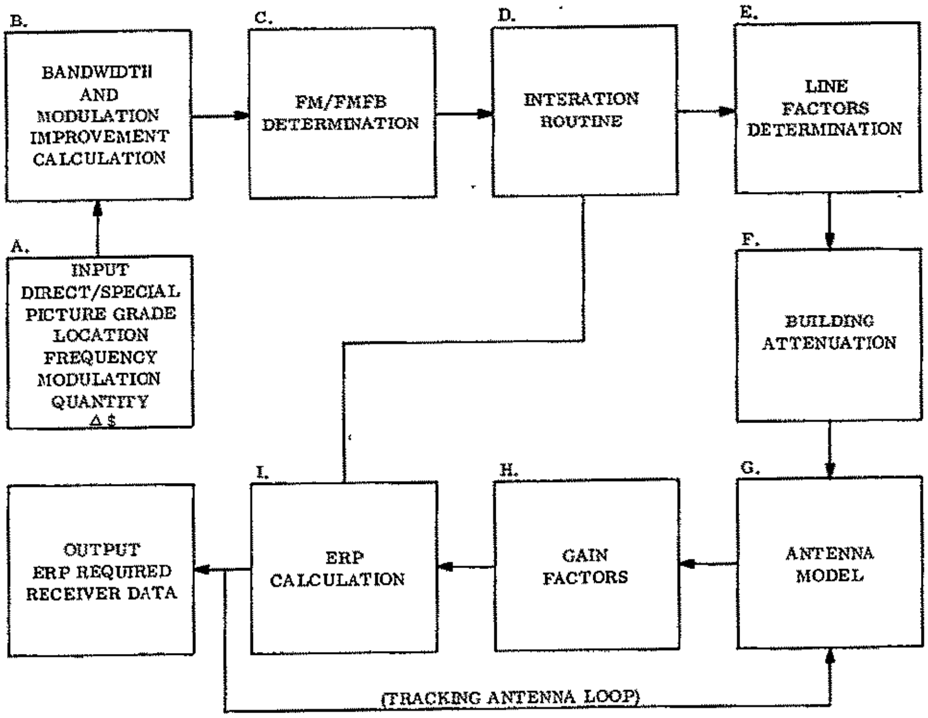


Figure 6.1-3. Receiver Synthesis Model Flow Chart

A. Input Parameters

The necessary input parameters are the service type (direct or special), picture grade, noise location of the receiving system, broadcast frequency and modulation, the quantity of receivers, and the receiving system modification cost. The range of input parameter values was previously described in Table 6.1-1. A given TV service is therefore defined by specification of the above input parameters.

B. Bandwidth and Modulation Improvement Calculation

The RF bandwidth factor is given by

$$B_{RF} = 2\,(1 + m)b$$

where

m = modulation index

b = baseband (Hertz)

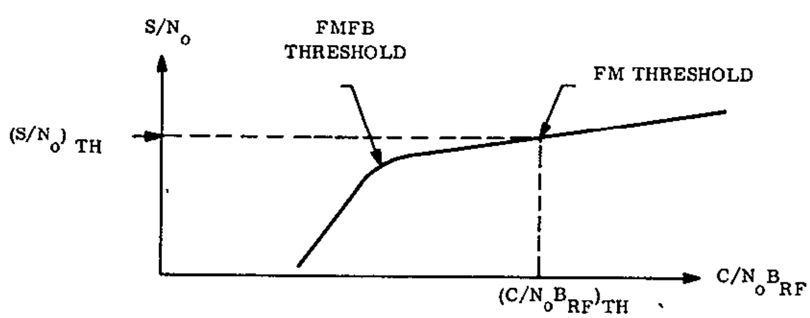
B_{RF} = RF bandwidth (Hertz)

Originally, for this study, it was assumed that only two modulation indices would be used: two for FM/FMFB reception at frequencies of 800 MHz, and 2.5 GHz, and four at frequencies of 8.4 and 12.2 GHz. The baseband b, has been assumed to be 6 MHz. The RF bandwidth for AM transmission is assumed to be 6 MHz.

The modulation improvement factor is a function of frequency and modulation with no improvement for the AM system, 22-dB improvement for FM/FMFB reception at 0.8 or 2.5 GHz, and a 30-dB improvement for FM/FMFB reception at 8.4 and 12.2 GHz.

C. FM/FMFB Determination

The program-selects on FM or on FMFB receiving system depending on frequency, picture grade, and the specific modulation index used. The usage of feedback circuitry in the receiver is dependent upon the relationship of the desired output signal-to-noise ratio (S/N_o) and the signal-to-noise ratio at Standard FM threshold (S/N_{TH}) for the specific modulation index. This can be explained in conjunction with the sketch below, which shows S/N_o plotted vs RF carrier-to-noise ($C/N_o\,B_{RF}$), for a specific modulation index.



It can be seen that if the desired S/N_0 is less than S/N_{TH}, $C/N\ B_{RF}$ could be reduced from $(C/N_0 B_{RF})_{TH}$ by feedback circuitry. It could be reduced to the value of $C/N_0 B_{RF}$, which is threshold operation of the FMFB system in the qualitative example shown. (Further reduction below the FMFB threshold would not be advantageous due to the steep slope encountered.) The potential maximum power savings is then a function of the spread between the threshold values of $C/N_0 B_{RF}$ for FM and FMFB and could be as much as 6 dB. Conversely, if the required S/N_0 is greater than $(S/N_0)_{TH}$, the value of $C/N_0 B_{RF}$ must increase above $(C/N_0 B_{RF})_{TH}$ and employment of feedback circuitry would be a penalty.

The selection chart shown in Table 6.1-2 resulted from these considerations. The no system label implies that threshold operation automatically results in the next higher picture grade. These FM improvements do not include additional improvements possible due to noise weighting factor and pre-emphasis.

D. Interation Routine

The program has stored information in a data bank on the type of receiving system modification electronics package, its noise figure, and its cost as a function of quantity. The electronics packages are identified by the parameters of the service for which they are to be used, i.e., service type, frequency, modulation, quantity of receivers, and by the package number, which is the iteration parameter.

Once the service has been defined by the basic input, the program identifies how many packages it has available to fulfill the services; it then begins with the first one to carry out the ERP calculations. This procedure is repeated until all potential packages have been evaluated.

E. Line Factors Determination

The electronics package is assumed to be attached at the antenna and hence, only one line type need be considered; i.e., all frequency conversion is done at the antenna and the transmission to the set from the antenna is, thus, independent of the broadcast frequency. For this model, if an electronics package is used, line losses are included in the noise figure of the electronics package. The line factors used in the program are presented in Table 6.1-3.

F. Building Attenuation

If an indoor antenna is utilized, the ERP requirement increases due to building attenuation. (See Table 6.1-4.) This model was derived, and higher frequency results extrapolated, from FCC studies.

G. Antenna Model

Having determined the electronics package cost, line cost, and the input cost constraint, the amount of money available to be spent on the antenna can now be calculated. It has been assumed that outdoor antennas are circularly polarized.

Table 6.1-2. FM Modulation Type and Indix

Model	Picture Grade 0	1	2	3	Modulation Index
0.8 GHz	FM	FM	FMFB	*	2
2.5	FM	FM	FMFB	*	2
8.4	FM	FMFB	*	*	4
12.2	FM	FMFB	*	*	4

*No system

Table 6.1-3. Line Factors

Frequency	Antenna/Electronics	Loss	Cost ($)
0.8 GHz	Indoor antenna	0	0
0.8 GHz	Outdoor antenna and no electronics	0.33	2.50
0.8 GHz	Outdoor antenna and electronics	0	2.50
2.5, 8.4, and 12.2 GHz	Indoor antenna and electronics	0	0
2.5, 8.4, and 12.2 GHz	Outdoor antenna and electronics	0	2.50

Table 6.1-4. Building Attenuation

Location	Antenna Location: Indoor	Outdoor
Urban	$L_B = \frac{0.555 \times Freq}{10^6}$	$L_B = 1$
Suburban	$L_B = \frac{0.216 \times Freq}{10^6}$	$L_B = 1$
Rural	$L_B = \frac{0.055 \times Freq}{10^6}$	$L_B = 1$

Table 6.1-5. Galactic Noise

Frequency	Temperature T_{CK}
0.8 GHz	$90^\circ K$
2.5 GHz	$50^\circ K$
8.4 GHz	$2^\circ K$
12.2 GHz	$18^\circ K$

H. Gain Factors

In the ERP calculation, the effective antenna temperature is calculated by using the following equation:

$$T_A = \frac{T_{CK} \times G_S + 0.174\, G_I \times T_{IP}}{2\, L_B} + \left[\frac{G_E \times 290^\circ}{2}\right] + \sigma T_{RF} + T_W \qquad (6\text{-}2)$$

where

T_{CK} = cosmic noise temperature ($^\circ$K).

T_{IP} = indigenous noise temperature ($^\circ$K).

σ = antenna radiation loss (0.1)

G_S = average gain factor over the front half of the antenna, which is the region that accepts sky noise.

G_E = average gain factor over the back half of the antenna which is the region that accepts thermal earth noise.

G_I = average antenna gain factor over the sector near the horizon that accept man-made noise.

T_W = $(L_B-1)\, 290/L_B$ = equivalent building-wall temperature.

The other terms have been previously defined in Equation 6-1 for the satellite ERP.

The values of galactic noise shown in Table 6.1-5 are the averages between the minimum and maximum noise of the galaxy from studies at the Paris Observatory and the book, Radio Astronomy, by Steinberg.

It is assumed that average indigenous noise shown in Table 6.1-6 consists primarily of that noise generated by the ignition systems of internal combustion engines in automobiles and other motor vehicles. The values in the table give equivalent noise temperature for the average RMS noise. Measurements taken at NASA LeRC have indicated that, if a more conservative 90% percentile is used, the noise values should be increased by a factor of approximately three.

I. ERP Derivation

The required Effective Radiated Power (ERP) is a function of the power density required by the ground receiver, the distance from the satellite transmitter to the ground receiver, and the losses encountered by the radio wave in transit. The power density required is in turn a function of the external noise (natural and man-made) with which the signal must compete, the effective antenna signal intercept area, the losses in the receiver and the receiver internal noise.

The required ERP is given explicitly in Equation 6-1. However, this expression is somewhat complicated. Therefore, it appears useful and convenient to present a derivation of this equation. Essentially this same derivation will be found in most standard texts on television, radio, and radar systems.

This link calculation model is based on the simple expression for signal-to-noise ratio at the output of a receiver which is receiving signals from the satellite:

$$(S/N)_o = \frac{P_t G_t A_R M (1-L)}{4\pi R^2 N_R} \qquad (6-3)$$

Table 6.1-6. Indigenous (Man Made) Noise

Frequency	Temperature (°K)		
	Urban	Suburban	Rural
0.8 GHz	6500	916	0
2.5 GHz	290	0	0
8.4 GHz	0	0	0
12.2 GHz	0	0	0

where

P_t = transmitter power (W).

G_t = transmitter antenna gain (power ratio).

A_R = receiver antenna effective area (M^2).

M = signal processing improvement in the receiver (power ratio).

L = fraction of energy lost in transmission.

R = distance from transmitter to receiver (meters).

N_r = receiver noise power (W).

The transmission loss (L) can be considered to be in two parts: L_p, for polarization mismatch due to ellipticity of nominally circularly polarized antennas, and L_L, for line attenuation from the antenna terminals to the receiver input terminals. Therefore, we can write the loss as $(1-L_p)(1-L_L)$ rather than (1-L).

N_R may be expressed as follows:

$$N_R = k T_S B_{RF}$$

where

T_s = system noise temperature (^oK), and the other factors previously defined.

Since, by definition:

$$ERP = P_T = P_t \; G_t$$

Where P_T = ERP in watts, we may now write Equation 6-3 as follows, solving for ERP in the process:

$$ERP = \frac{(S/N)_o \; 4\pi R^2 \; k \; B_{RF} \left[T_A \; (1-L_L) + L_L \; T_{RA} + T_{RN}\right] L_B}{A_R \; (1-L_L) \; (1-1_p) \; M} \qquad (6-4)$$

where the total system noise temperature is given by

$T_S = T_A \; (1-L_L) + L_L \; T_{RA} + T_A$, and T_A is as defined in Section 6.1.1(H), and L_B is the building attenuation factor added to account for indoor receiver installations.

6.1.2 SATELLITE SYNTHESIS MODEL (PACES)

The purpose of the Parametric Analysis and Concept Evaluation System (PACES) model is to determine that spacecraft system which satisfies the necessary broadcast service requirements and minimizes the satellite annual operating cost. Resulting subsystem data is necessary for development of conceptual designs.

The specific subsystems used for synthesis of a broadcast satellite were:

1. Antenna
2. Transmitter
3. Electrical Power
4. Thermal Control
5. Attitude Control
6. Telemetry, Tracking and Command
7. Station Keeping subsystem (both North-South and East-West)
8. Orbit trim
9. Structure

The general flow diagram of the calculations through PACES are shown in Figure 6.1-4.

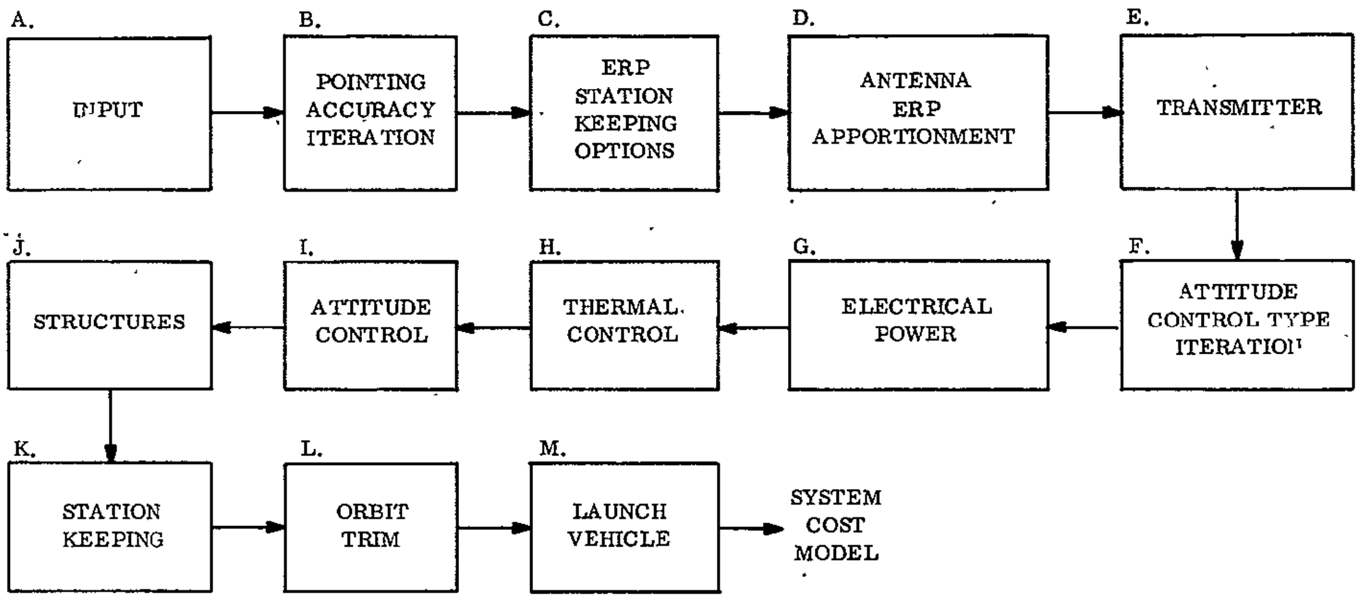


Figure 6.1-4. TVBS Satellite Synthesis Model

A. Input

The input required for PACES is derived as output from the ERP program when the two programs are connected, the procedure is automatic. The specific data needed is as follows:

1. Service Type.

2. Frequency.

3. Modulation.

4. Quantity of receivers*.

5. Receiving system costs

6. Fixed ground antenna gain

*Required for the Cost Summation section only

7. Effective Radiated Power (two values---one for a fixed ground antenna and one for a tracking ground antenna)

8. Minimum half-power beamwidth (HPBW) required of the satellite transmitting antenna.

B. Pointing Accuracy Iteration

Since each of the attitude control subsystems are capable of providing accuracies above some lower limit, the choice of a pointing accuracy limits the number of candidate attitude control systems. Hence, an iteration of accuracies over the range of capabilities of the candidate attitude control systems must be performed to insure that all candidate subsystems are compared. For the subsystems stored in this program (active, passive, hybrid) the following accuracies were chosen:

Accuracy	Type of Subsystem
0.05 deg	active and hybrid
0.5 deg	active only
5.0 deg	passive only

C. ERP - Station Keeping Options

The satellite orbital position, both in longitude and latitude, may significantly affect the total broadcast system performance. In all cases, it was deemed desirable to accommodate longitudinal drift by providing an E-W station keeping system in the satellite. Ground antennas would be aligned to a specific longitudinal position. The E-W station keeping system imposes minimal cost and weight requirements to the satellite.

The North-South station keeping presents a considerably different situation, however, due to the weight and/or power requirements of a N-S station keeping system. For the direct services, it was felt that the receiving system modification cost limitations ruled out the consideration of a tracking ground antenna, and that the selected fixed ground antenna beamwidth would be wide enough to eliminate consideration of N-S stationkeeping. For the special services, however, this was not the case; hence, the following three options were evaluated:

1. Fixed ground antenna with satellite stationkeeping - uses on-axis ground antenna gain.

2. Fixed ground antenna with no satellite N-S stationkeeping subsystem - uses ground antenna gain degradation due to off-axis.

3. Tracking ground antenna with no satellite N-S stationkeeping - uses ground antenna on-axis gain.

Two values of required ERP are calculable: 1) ERP 1 is identified as the value resulting from use of a non-tracking ground antenna, and 2) ERP 2 is the value associated with use of a tracking ground antenna.

The trade study between using a tracking antenna on the ground or using a fixed ground antenna in conjunction with satellite orbit inclination control was resolved in favor of the latter, where feasible, for this TVBS study. This results from an a priori estimate made of the point at which the number of ground receivers becomes large enough to make it more cost-effective to implement satellite orbital maintenance in place of ground antenna tracking mechanisms. The cross-over point was estimated to be in the vicinity of 40 ground receivers, which is below the minimum projected audience for any of the potential TVBS special service missions under consideration. Tracking ground antennas were then considered only for those satellites using attitude control subsystems which could not tolerate an orbital inclination subsystem on-board.

The significant parameter affecting performance is the half-power beamwidth (HPBW) of the ground antenna. This will basically determine if the specific system must implement either a tracking ground antenna or a satellite orbit inclination control, or if it can do without either.

The selection criteria used for N/S stationkeeping and type of ground antenna is given in Table 6.1-7.

Table 6.1-7. North-South Station Keeping Option Chart

	Fixed Ground Antenna Gain		
Pointing Accuracy (deg)	Gain > 39 dB HPBW < 1.8 deg.	24 dB < gain < 39 dB 10.4 deg > HPBW > 1.8 deg	Gain < 24 dB HPBW > 10.4 deg
0.05	ERP = ERP 1 N-S Station Keeping	ERP = ERP 1 N-S Station Keeping	ERP = ERP 1 No N-S Station Keeping
0.5	ERP = ERP 1 N-S Station Keeping	ERP = ERP 1 N-S Station Keeping	ERP = ERP 1 No N-S Station Keeping
0.5	ERP = ERP 2 No N-S Station Keeping	ERP = ERP 1 + ERP No N-S Station Keeping or ERP = ERP 2 No N-S Station Keeping	ERP = ERP 1 No N-S Station Keeping

D. Antenna

After careful consideration of the broadcast requirements, basic assumptions given in Table 6.1-1, and investigation of candidate antenna types, it was decided that, based on weight, cost, performance, and desired state-of-the-art technology, a paraboloid type antenna should be selected. The basic antenna assumptions, program module input/output requirements, and the model are discussed below.

1. A paraboloid type antenna is used with the construction type dependent on RF frequency as shown below:

RF Frequency	Construction Type
0.8 GHz	Wire Grid
2.5 GHz	Erectable Petal
8.4 GHz	Rigid
12.2 GHz	Rigid

2. Antenna efficiency is 55%

3. Weight equations are based on the following densities for the reflector dishes

Wire Grid	0.15 lb/ft^2 (0.73 kg/m^2)
Erectable Petal	0.3 lb/ft^2 (1.46 kg/m^2)
Rigid	0.3 lb/ft^2 (1.46 kg/m^2)

4. The spacecraft antenna is circularly polarized.

5. The antenna parameters of gain and diameter were determined as a function of HPBW with the following equations:

$$\phi = \phi_1 + \phi_2$$

$$G_1 = 27000/\phi_2$$

$$G = 10 \log_{10} G_1$$

$$D = \left[G_1/0.55 \ (C/\pi f)^2\right]^{1/2}$$

$$A = \pi D^2/4$$

where

ϕ = Required half power beamwidth (deg)

G = Gain (db)

D = Diameter (ft)

A = Area (ft^2)

ϕ_1 = Minimum half power beamwidth (deg)

ϕ_2 = Pointing error accuracy (deg)

G_1 = Gain (power ratio)

c = Speed of light (ft/sec)

f = Frequency (Hz)

Analytical expressions were derived for curve matching of plots of cost and weight of the antennas as a function of gain for the different frequencies desired.

E. Transmitter

Based upon required RF power levels, frequencies, modulations, efficiencies, and state-of-the-art technology, certain transmitter tube types are definitely superior in certain regimes of operation. The selected types were stored in the program and the type used depended upon the service requirements. The selections and their regimes of operation are given in Table 6.1-8. The assumptions used to derive the parametric and the computer model are given as follows:

Table 6.1-8. Transmitter Selection

Frequency	Modulation	Power, watts	Selection
0.8 GHz	AM	<100	Solid State
0.8 GHz	AM	>100	CFA Gridded Tube
0.8 GHz	FM	<100	Solid State
0.8 GHz	FM	>100	Gridded Tube
2.5 GHz	AM	<100	Gridded Tube
2.5 GHz	AM	>100	CFA

1. Power output of the aural transmitter is 10% of the peak synchronizing signal RF level in an AM-VSB video transmitter, or 10% of the RF carrier level for a FM video transmitter.

2. Power amplifying devices and their characteristics to be considered are:

Type	Maximum RF Power Output per device	Operating Temp	DC to RF Conversion Efficiency
Solid State	50 W	75° 9348°K)	UHF/AM = 35% at peak sync level UHF/FM - 40 to 50%
Gridded Tube	2.5 KW	300°C (573°K)	UHF/FM & AM - 60% at peak sync level S-Band/AM - 33% at peak sync. level
CFA	25 KW for UHF, AM 10 KW for S-Band/AM	200°C (473°K)	UHF & S-Band/AM - 60%
Linear Beam (TWT, Klystron)	10 KW	200°C (473°K)	S-Band - 40 to 60% X-Band - 40 to 60%

3. Microwave circuit losses are considered in calculating overall transmitter efficiency, with a loss of 5% assumed for the aural/video diplexer and a 3.5% loss assumed for each stage of combining. The number of combining stages is determined by the total RF power output and the allowable maximum power per device.

4. A space amplifier is assumed for redundancy at power levels below 10 kw.

5. DC power demand mode for AM-VSB transmitters is as follows:

TV Signal Level	Relative Power Level	Duty Factor	Average Power Level
Peak Synchronizing Level	1.0	0.078	0.078
Blanking Level	0.56	0.157	0.088
Average Grey Signal	0.2	0.763	0.153
			0.319

6. The computer program selects the tube type on the basis of Table 6.1-5. The maximum RF power output per device and operating temperature are stored in the computer as a function of tube type; hence, when the tube type has been selected, that information is available for determining the number of devices. With this information, the heat to be dissipated per device and the operating temperatures which are needed in the thermal control calculations can also be determined. The transmitter weight and costs were expressed as a function of the tube type, frequency, and RF power required.

F. Attitude Control Type Iteration

The pointing accuracy model was described in Section 6.1.2(B). It was necessary to select attitude control subsystem options such that those attitude control types could fulfill the selected accuracy requirements. The choices are listed below:

Pointing Accuracy (deg)	Attitude Control Type
0.05	Active
0.05	Hybrid
0.5	Active
5.0	Passive

G. Electrical Power

A photovoltaic/battery conversion system, as well as various nuclear power subsystems were considered. Nuclear powered subsystems will not be available in the specified time period. Also, when available, they will have specific weight and cost which are significantly higher than the photovoltaic battery system. Hence, the photovoltaic/battery system was chosen for the parametric studies. The assumptions and model are as follows:

Only two-axis oriented arrays were considered.

Lightweight designs 0.40 lb/ft^2, (1.95 kg/m^2) were used for the arrays.

Silicon cells, 11% air mass zero, AMO, 8 mils (0.203 mm), 3 mil (0.076 mm) covers were utilized.

Allowable battery depth of discharge was 50%.

Battery watt-hour charge-discharge was 70%.

The housekeeping power requirements are defined by the needs of the attitude control system, the TV exciter and the TT&C and are given by:

Pointing Accuracy (deg)	Housekeeping Power (watts)		
	Active	Hybrid	Passive
0.05	133	80	--
0.5	100	80	--
5.0	-	-	15

where the exciter requires 5 W and TT&C requires 10 W.

7. The subsystem components and their efficiencies are shown on Figure 6.1-5. This block diagram represents the components required for an AM transmitter. For an FM system, the L-C filter is removed and the net efficiency adjusted accordingly.

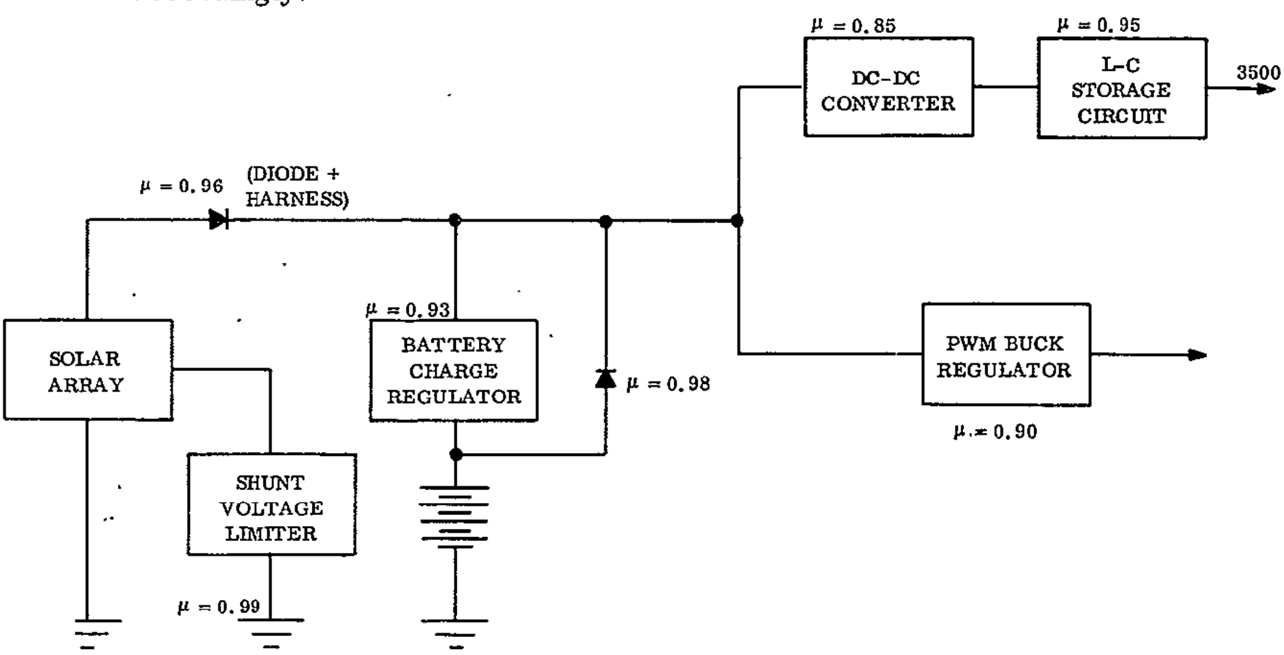


Figure 6.1-5. Photovoltaic/Battery Power Subsystem Block Diagram

H. Thermal Control

The thermal control subsystem is required to dissipate the power supplied to the transmitter by the electrical subsystem which is not broadcast due to the transmitter efficiency and the housekeeping power needs of the other subsystems. This control is obtained through the use of a radiator to dissipate housekeeping power and finned radiators or direct coupled heat pipes to dissipate the heat rejected by the transmitter. The assumptions and model are as follows:

a. Capability - 12 watts/ft^2 (129 w/m^2).

b. Radiating surface temperature - 80°F (300°K).

c. Weight - 0.5 lb/ft^2 (2.44 kg/m^2).

d. Since the radiator will form a part of the basic vehicle structure its cost is included there.

2. α = 0.25

3. The radiators do not see the sun.

4. Heat of fusion for the change of phase material - 100 Btu/pound.

5. Fin efficiency - 0.9.

6. The radiator does not have shutters.

7. No heater power is available.

I. Attitude Control

As previously mentioned, certain pointing accuracies and the candidate attitude control subsystems were selected to accommodate these accuracies. The assumptions, input/output, and model are described below:

1. The possible types are active, hybrid, and passive: The active implies three axis control, passive implies control with a gravity gradient rod, and hybrid utilizes the passive subsystem with the addition of flywheels and an interferometer system.

2. The weights and costs can be expressed as a function of accuracy and total vehicle weight for each type.

3. The fixed weights consist of sensors, electronics, etc., and are independent of vehicle weight.

4. The variable weights such as control torque producing devices, thrusting devices, force couple devices, and inertia management devices vary with vehicle weight.

5. For the hybrid system, the interferometer and antenna feed gimbal system parameters are:

   a. Weight - 45 lbs (20.2 kg)

   b. Fabrication Cost - $ 80,000

   c. Engineering Development Cost - $546,000

6. The lowest structural mode of oscillation is to be kept one decade above the frequency at the "crossover point" of the control system. The following values of structural frequency were selected for this program:

   a. Active - 0.0159 Hz
   b. Hybrid - 0.00159 Hz
   c. Passive - 0.000159 Hz

7. Curves of fixed and variable weight and costs vs accuracy as a function of attitude control subsystem type were developed; mathematical expressions were derived for the weights and costs as a function of accuracy and type and were used in the program.

J. Structure

The data presented in Section 5.6 was programmed on the computer for the calculatio of the structural subsystem parameters.

K. Station Keeping

East-West station keeping is mandatory and is supplied by a separate engine than that used for North-South station keeping. Cesium ion engine parameters are used for the data, with cost data assumed constant (i.e., fabrication cost = $50,000 and developı cost = $800,000. North-South station keeping is optional, and is dependent upon the fixed ground antenna gain, the pointing accuracy, and the attitude control system type

Orbit inclination may be controlled by propulsion systems operating with the minimun number of thrust cycles (as required by allowable inclination limits) to systems thrus as often as twice a day. The thrust values required can vary through a wide range, dependent upon the burn time associated with each thrust cycle. In general, the orbit inclination control system employing the minimum number of thrust cycles and minimum burn times (e.g., the hydrazine system) is more desirable for the TVBS operational requirements. This can be seen in the listing of advantages and disadvantages of each type of station keeping engine in Table 6.1-9.

Table 6.1-9. Station Keeping Engine Considerations

Type of Engine	Advantages	Disadvantages
High Thrust/Short Burn Time (Minimum number of cycles allowable is about 1.5/maximum orbit inclination angle) [Maximum ΔV (ft/sec) $\cong$ 200 x (maximum orbit inclination angle)*] per thrust cycle *Angle in degrees	1. Ample tracking time for precise determination of orbital node and subsequent selection of nodes least disturbing to broadcast operation. 2. May require one nozzle only by permitting thrusting on one node only. 3. Short burn time permits minimal disturbance time. 4. High thrust systems are well developed. 5 Commonality of propellant with other functions. 6 Electrical power requirements very low.	1. Larger disturbance requires larger control torque available 2. Lower I_{sp} of system requires more fuel. weight is dominant factor in considering implementation of electric thrusters
Low Thrust/Long Duty Cycles (Twice a day thrusting for V = 0 20 fps/period = 0 061 m/sec)	1 Lower fuel weight with high I_{sp} of electrical thrust, balances out inefficiency and becomes dominant factor in selection 2. Broadcast duty cycle could be such that power would be available for thrusting mode although this is basically contrary to a profit-oriented commercial operation which would attempt to maximize usage of satellite broadcast transmission capability. 3 Low thrust minimizes control torque requirements for potential disturbances.	1. Orbit node position less determine due to limited tracking permitted, result in less efficient thrusting 2 More frequency thrusting requires operation that is perhaps simultaneous with prime broadcast time. 3 May require thrusting at each node ± some period of time 4. High electric power consumption incompatible with broadcast Associated cost of arrays for thrusting purpose only makes system very non-cost-effective 5. Increased length of thrusting mode requires longer duty cycle control system

Candidate engines for the North-South station keeping subsystem are the SPET, ion, and hydrazine. The engine type selection is made on the basis of a cost/power versus weight tradeoff. In general, the type of system selected is a hydrazine system, which is lower in cost and power requirements. The selection of a higher-cost electric engine system would not be justified unless the added weight of a hydrazine engine was enough to require a larger booster which would result in a large step increment of cost.

The candidate launch vehicle table shown in Section 6.1.2(M) shows that there are only four large incremental steps in booster costs which might justify selection of a station keeping system other than hydrazine. These steps occurred in going from:

1. Thor/Delta to the Atlas/Agena.
2. Atlas/Agena to the Atlas/Centaur.
3. Titan 3/Agena to the Titan 3/Centaur
4. Titan 3/156-inch solids to the Titan 3F/Centaur

The payload at which the hydrazine N-S station keeping engine would jump the booster cost (as noted above) was then determined and a payload range which would thus justify the selection of the electric engine system was established. The station keeping model is shown in Table 6.1-10.

Table 6.1-10. Station Keeping Model

East-West Motor	
Weight = $7.6 + 0.0014 \times (W_{SYS} - 1000)$	
North-South Motors	
SPET	
W_{SK}	$3 + 0.009\ W_{SYS}$
Fabrication Cost	\$100 000
Engineering Development Cost	\$800,000
Ion	
W_{SK}	$20.0 + 0.0074\ W_{SYS}$
Fabrication Cost	\$200,000
Engineering Development Cost	\$2,000,000
Hydrazine	
W_{SK}	$10.0 + 0.046\ W_{SYS}$
Fabrication Cost	\$42,000
Engineering Development Cost	\$500,000
Selection Criteria	
$0 < W_{SYS} < 385$	Hydrazine
$385 < W_{SYS} < 405$	SPET
$405 < W_{SYS} < 1510$	Hydrazine
$1510 < W_{SYS} < 1585$	ION
$1585 < W_{SYS} < 4200$	Hydrazine
$4200 < W_{SYS} < 4380$	ION
$4380 < W_{SYS} < 7480$	Hydrazine
$7400 < W_{SYS} < 7800$	ION
$7800 < W_{SYS} < 10100$	Hydrazine
$10100 < W_{SYS} < 10800$	ION

L. Orbit Trim

The orbit trim system must be capable of supplying a 100 fps velocity correction to the spacecraft. A hydrazine propulsion device is used with $I_{SP} = 220$ sec, and propellant mass fraction (weight of usable propellant/total propulsion system weight) = 0.9. The orbit trim model is as follows:

1. $W_{orbit\ trim} = 10 + 0.019 \times$ system weight (lbs)

2. Fabrication cost = $0.035 \times 10^6 + 1.5 \times$ orbit trim weight

3. Engineering cost = \$500,000

M. Launch Vehicle

All of the potential boosters are expected to be available in the 1970-1975 time period. Apogee kick motors are assumed to have $I_{SP} = 200$ sec, mass fraction = 0.9. Shroud geometry constraints are not considered for this phase of the study. Payload margin is defined as the difference between spacecraft weight and the maximum payload of the selected booster. The booster model is given in Table 6.1-11.

Table 6.1-11. Booster Model

Launch Vehicle	Payload Capacity (kg)	Payload Capacity (lbs)	Unit Cost (\$M)	Development Cost (\$M)
Atlas E&F/Agena E	245	540	4 1	None
Atlas E&F/Agena D/AKM	413	910	4 2	1 0
Atlas E&F/Agena E/AKM	521	1150	4.2	1 0
Titan 3B/Agena E	565	1247	7 0	None
Titan 3B/Agena E/AKM	695	1535	7 1	1.0
Titan 3B (No Agena) Centaur/AKM	1025	2260	13.0	1.0
Titan 3C (Impp x-stage)	1110	2450	16 5	None
Titan 3C/AKM	1757	3875	16 7	1.0
Titan 3F (BELL 8533 x-stage)	2630	5800	19.5	None
Titan 3D/Centaur/AKM	3470	7650	20.7	1 0
Titan 3F/Centaur/AKM	4580	10,100	23 2	1 0

6.1.3 SYSTEM COST MODEL

The system cost model supplements the subsystem cost data generated in the PACES Model to account for satellite system integration and test, program management, and supporting system investment and operation. The costs are combined into the forms required for the satellite optimization trade-off and the Top Level Trade (TLT) curves. The following cost definitions apply to the model:

1. Development Costs. Those costs associated with a normal two-year engineering design integration cycle, including model fabrication and testing.

2. Investment Costs. Defined as the program-peculiar primary facility and supporting equipment costs that are considered replaceable on a long term basis.

3. Operating Costs. Defined as those costs associated with direct operation and replacement of the satellite system.

The satellite system includes the launch vehicle. The amortization periods used are two years for the satellite system and 10 years for the investment and development costs. Probability of achieving successful orbit injection and satellite activation is assumed to be 1.0, since the amortization period above inherently considers this.

The following cost outputs were generated:

1. Satellite development costs.
2. Total satellite costs.
3. Satellite annual operating cost.
4. Total system implementation cost.
5. Satellite manufacturing costs.
6. Total ground investment cost.

A schematic block diagram of the calculations of the various cost combinations is shown in Figure 6.1-6. A verbal description is given in the following sections.

6.1.3.1 Satellite System

The total of subsystem costs were increased by multiplier factors $K_{1/2}$, K_2, and K_3 to account, respectively, for Production Revision, Systems Integration and Test, and Program Management. The values used for K_1, K_2, and K_3 used for this study were 1.2, 1.42, and 1.18 respectively, based upon historical data of past programs.

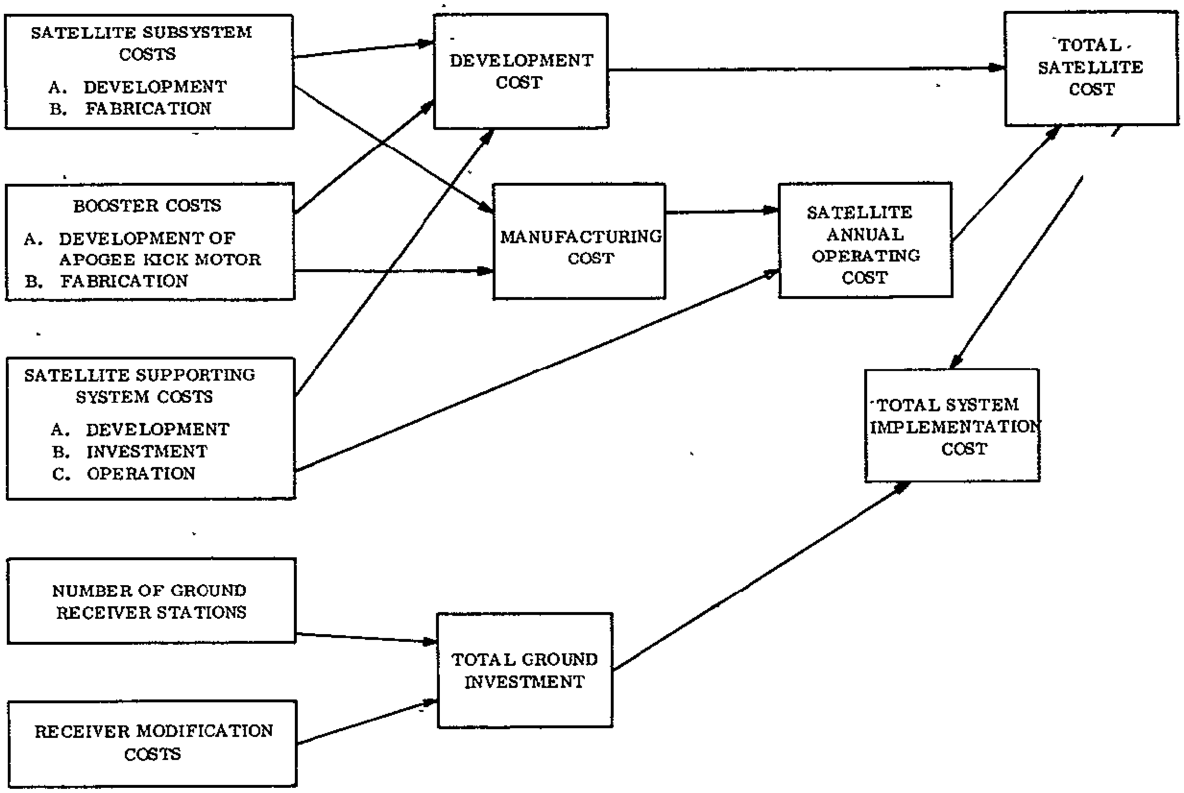


Figure 6.1-6. System Cost Model

The K_1 factor for production revision exists mainly because of the limited numbers of satellites (five) used as the basis for costing and for the following conclusion that the engineering liaison, manufacturing tool revisions, and other costs associated with setting up an assembly line for a new product are not insignificant when amortized over a very few vehicles. The existence of the K_2 and K_3 factors is due to the normal methods of cost estimation breakdown by subsystem and the subsequent interface definition and total system integration being handled as tasks separate from the subsystem design and development. The necessary systems integration and overall program management are thus considered estimable as a percentage of the subsystem total costs.

1. Satellite Manufacturing Cost = $K_1 K_2 K_3 \Sigma$ [Subsystem manufacturing costs (excluding launch vehicle)] + the launch vehicle cost.

2. Satellite Flight Hardware Development Costs = $K_2 K_3 \Sigma$ (subsystem development costs) + development cost of launch vehicle apogee kick motor.

6.1.3.2 Satellite Supporting Systems

The supporting systems include: 1) the uplink station, 2) the Aerospace Ground Equipment (AGE), 3) Manufacturing/Test Fixture, and 4) Tracking/Telemetry/Command Costs.

The results and references are presented in Table 6.1-12. The values of C_{AGE} and $C_{M/T}$ are those obtained from Figure 6.1-7.

6.1.3.3 Satellite Cost Summations

The satellite cost items required are obtained in the following manner:

1. Satellite Development Cost = satellite flight hardware development cost + Σ (satellite supporting system development cost).

2. Satellite Investment Cost = Σ (satellite supporting system investment cost).

3. Satellite Annual Operating Cost = 1/2 (satellite manufacturing and launch vehicle) + Σ (satellite supporting system annual operation costs)+ 1/10 satellite investment cost.

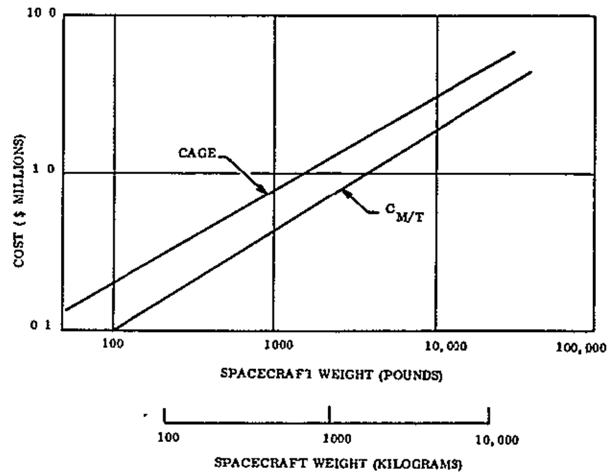


Figure 6.1-7. AGE and Manufacturing/ Test Fixture Costs

6.1.3.4 Ground Receiver Costs

1. Total ground investment is equal to the number of ground receivers, N, multiplied by receiver unit modification costs, $\Delta\$$, or N x $\Delta\$$.

2. Ground Annual Cost = 1/10 (N x $\Delta\$$)

6.1.3.5 Total System Costs

1. Total System Implementation Cost = satellite development cost + 10 (satellite annual operation cost) + ground investment cost.

Table 6.1-12. Supporting System Costs

Item	Development Costs	Investment Costs	Annual Operational
Uplink	None	\$0.8M	\$0.5M
AGE	$0.67\ C_{AGE}$	$0.33\ C_{AGE}$	$0.33\ C_{AGE}$
Manufacturing	$0.20\ C_{M/T}$	$0.80\ C_{M/T}$	$0.04\ C_{M/T}$
Tracking/Command	None	None	\$0.3M

6.2 SYSTEM TRADEOFF ANALYSIS

The Computer Synthesis Model described in Section 6.1 was employed to generate system and subsystem tradeoff curves and printouts which were used for cost-effectiveness analysis of broadcast service and equipment performance parameters. Over 4000 tradeoff curves were plotted directly by the computer. These curves were analyzed to select the optimum satellite system for each television broadcast service. These optimum service parameters (signal quality, frequency, modulation, number of ground receivers, cost of ground receivers, man-made noise environment, coverage area size and location, number of channels, and propagation attenuation) were fed to the computer for a printout of the performance, type, weight and cost of the major ground and satellite subsystems making up the system. This information was used in the Phase 2 protoconcept designs described in Section 6.3.

The computer models described in Section 6.1 (i.e., the ERP, PACES, and cost models) were combined in such manner as to provide output-data options as follows:

1. System Tradeoff Curves. The program first developed was a combination of all three elements to obtain overall system data to be used for cost-effectiveness analysis of broadcast service parameters. The output was system tradeoff curves in the form of system cost data versus the ground receiving modification costs for varying coverage area size for each desired combination of the following broadcast service parameters:

   a. Type of service
   b. Picture grade
   c. Noise location
   d. Frequency
   e. Modulation
   f. Audience size

2. Ground Tradeoff Curves. The second option was then a plot to determine required ERP versus delta dollars* for varying picture grade for the combinations of five of the six service parameters listed above (coverage area drops out and picture grade is the third plot variable). These plots are called ground tradeoff curves.

3. Satellite Tradeoff Curves. The third program develops plots of satellite costs versus required ERP for varying coverage area for each desired combination of service type, frequency, and modulation. These plots are called satellite tradeoff curves.

4. Subsystem Data Printout. The fourth program calculates the detailed subsystem data required for further engineering feasibility and performance evaluation. It consists of performances, cost, and weight data for each subsystem and its components.

*The ground receiver modification costs are called delta dollars (Δ \$)

6.2.1 SYSTEM TRADEOFF CURVES

The system tradeoff curves consisted of system cost data plotted versus delta dollars. The specific combinations of Broadcast System parameters for which curves were developed are shown in Table 6.2-1. The sets of data consisted of four cost plots for all the combinations listed in the table.

The curves shown in Figure 6.2-1 are typical of those generated for the 200 sets of specific cases which were run to encompass the total scope of the TVBS study. These cases resulted in the generation of 5600 four-point curves.

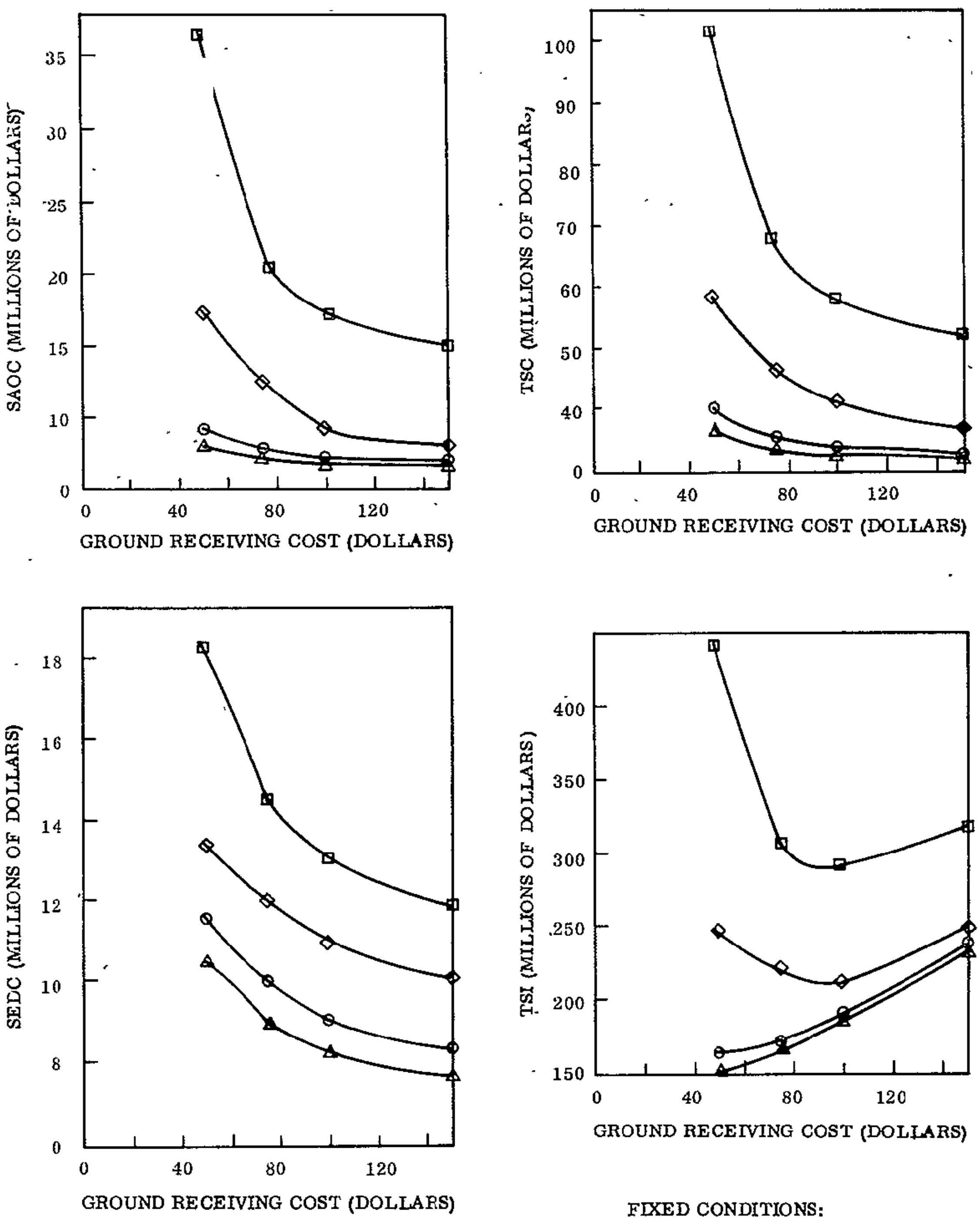
The independent variable on the abscissa is ground receiving cost, which is the cost allocated to modify existing ground receiver systems. The following data is plotted along the ordinates: (1) satellite annual operating cost (SAOC); (2) satellite engineering development cost (SEDC); (3) total satellite cost (TSC), which is the cost required to implement one 2-year life broadcast satellite; and (4) total system implementation (TSI), which is the cost required to implement a 10-year TVBS system, including the ground receiver modification. The additional independent variable plotted is coverage area, with the centroid at the subsatellite point.

These curves provide a useful tool for system optimization minima analysis by (1) inspection by cross-plotting for system trends as a function of the significant variables and (2) by direct comparison with terrestrial cost systems.

Table 6.2-1. Parameter Combinations for System Tradeoff Curves

Frequency	Modulation	Noise Location	Signal Quality					Audience (No. of Receivers)										No. of Plots
			Direct			Special		Direct					Special					
			1	2	3	0	1	10^4	10^5	10^6	10^7	10^8	10	10^2	10^3	10^4	10^5	
0.8	AM	R	X	X	X			X	X	X	X	X						15
0.8	AM	S	X	X	X			X	X	X	X	X						15
0.8	AM	U	X	X	X			X	X	X	X	X						15
0.8	FM	R	X	X				X	X	X	X	X						10
0.8	FM	S	X	X				X	X	X	X	X						10
0.8	FM	U	X	X				X	X	X	X	X						10
2.5	AM	R	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	25
2.5	AM	S	X	X	X			X	X	X	X	X						15
2.5	AM	U	X	X	X			X	X	X	X	X						15
2.5	FM	R	X	X		X	X	X	X	X	X	X	X	X	X	X	X	20
2.5	FM	S	X	X				X	X	X	X	X	X	X	X	X	X	10
2.5	FM	U	X	X				X	X	X	X	X	X	X	X	X	X	10
8.4	FM	R	X			X	X	X	X	X	X	X	X	X	X	X	X	15
12.2	FM	R	X			X	X	X	X	X	X	X	X	X	X	X	X	15
																	Total	200

For each of the 200 sets of parameter combinations, the four types of system costs were plotted versus four coverage area sizes and versus four values of Δ$ (ground equipment costs) for a total of 12,800 plotted points.



AREA
□ = 10×10^6 MILES (25.9×10^6 KM^2)
◇ = 3×10^6 MILES (7.76×10^6 KM^2)
○ = 1×10^6 MILES (2.59×10^6 KM^2)
△ = 0.5×10^6 MILES (1.29×10^6 KM^2)

FIXED CONDITIONS:

DIRECT SERVICE
PICTURE GRADE 2
URBAN LOCATION
FREQUENCY ≈ 0.8 GHz, AM
AUDIENCE ≈ 10^6 RECEIVERS

Figure 6.2-1. TVBS System Tradeoff Curves

6.2.2 GROUND TRADEOFF CURVES

A typical plot of an intermediate level tradeoff curve is presented in Figure 6.2-2. This is a plot of ERP required versus ground receiver modification costs for varying picture grades. The ERP value is the minimum value required from all the combinations of subsystems available for the specific amount of expenditure on receiver system modifications.

Curves were generated for all the combinations of parameters, as was done previously for the system tradeoff curves. In addition, two values of ERP were calculated for the special service cases, one for a fixed ground antenna and another for a tracking ground antenna. This resulted in a total of 70 sets of plots for the direct service cases and 40 sets of plots for the special service cases.

6.2.3 SATELLITE TRADEOFF CURVES

Additional system analysis data developed was the variation of satellite costs as a function of the satellite ERP. This resulted in a set of plots as shown in Figure 6.2-3, in which the four system costs (as defined previously) are plotted versus ERP for varying subsatellite areas (or transmitting antenna beamwidths). In these plots the ERP value is that required at the beam edge. These plots were generated for all possible combinations of frequency, modulation, area, and service type, resulting in 24 sets of plots for the direct service and 16 sets of plots for the special service cases.

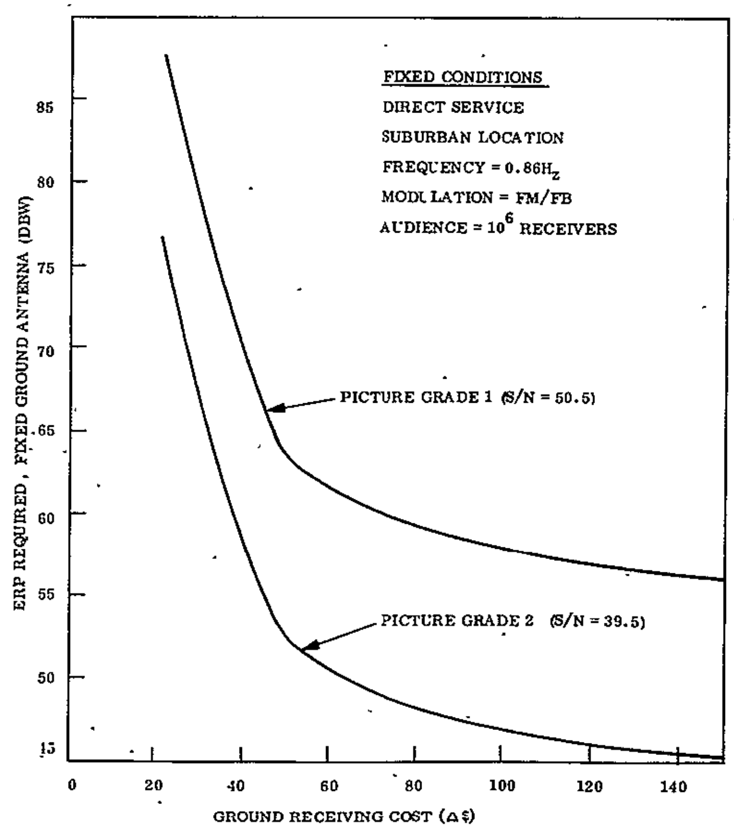


Figure 6.2-2. Ground Tradeoff Curves

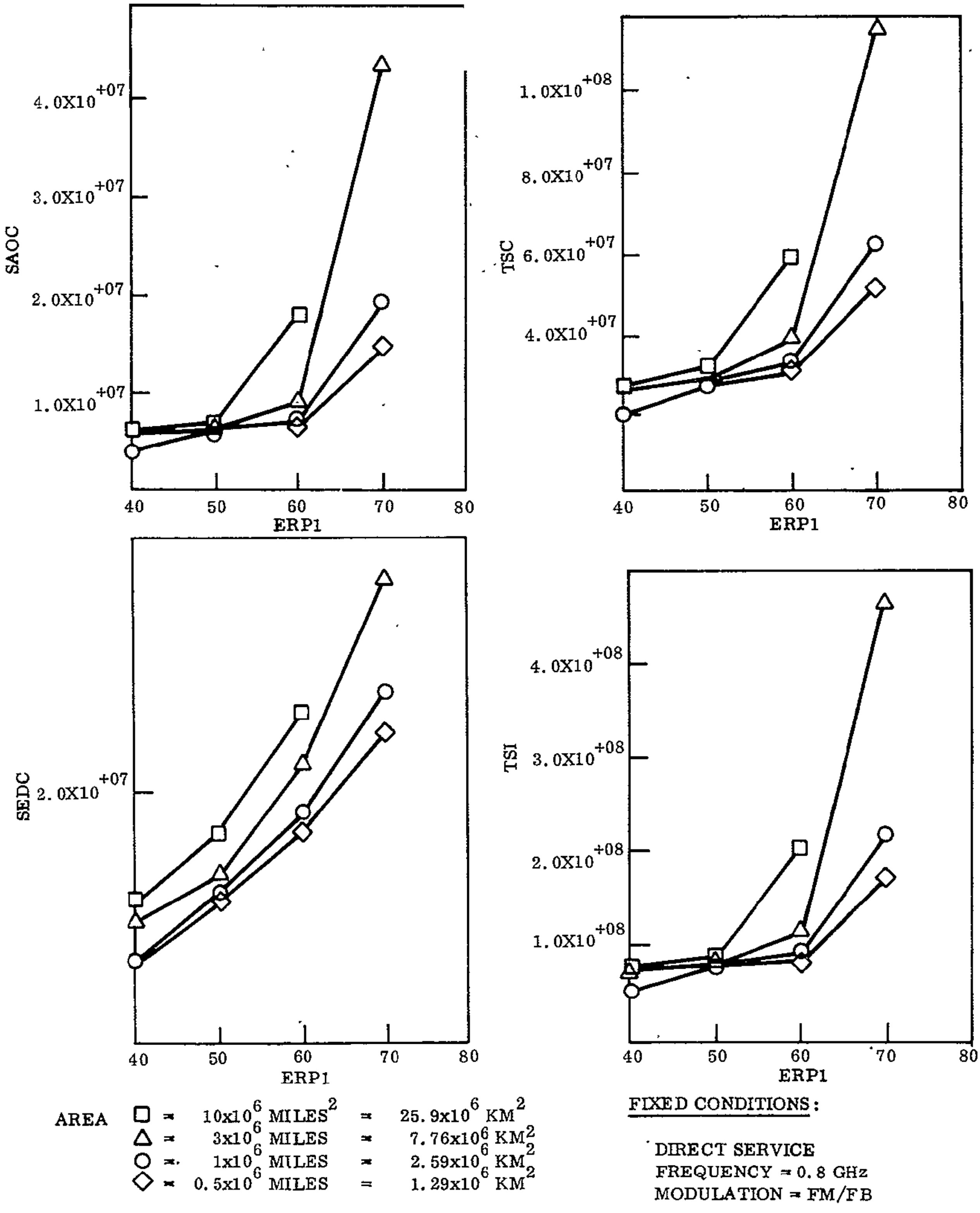


Figure 6.2-3. Satellite Tradeoff Curves - Cost (Dollars) Versus ERP (dBW) Versus Coverage Area Size

6.2.4 SUBSYSTEM DATA PRINTOUT

This program provides detailed subsystem performance, weight, and cost data in addition to basic system cost data and was used to provide the baseline characteristics required for the protoconcept and phase 3 designs. Sample output data is given in Table 6.2-2.

Table 6.2-2. Cost and Subsystem Data Output

```
DIRECT SERVICE      PICTURE GRADE 3      RURAL LOC      FREQ   .8 GHZ
                     AUDIENCE 10**6

   INPUT DELTA DOLLARS =      50.00

 CASE 1

     ELECTRONICS            OUTDOOR            CIRCULAR

         AM

   POWER DENSITY 1 =  5.43247608E-11
   FIELD STRENGTH 1 =  1.42919941E 02
   POWER DENSITY 2 =  1.37576507E-10
   FIELD STRENGTH 2 =  2.27439589E 02

   GAIN 1 =      15.38 DB          GAIN 2 =       0.   DB
ECEIVER TYPE 1 =   5            RECEIVER TYPE 2 =   0

   ACTUAL DELTA DOLLARS =      50.00

   ERP1 =     59.57           ERP2 =

   DELTA ERP =       1.04

   BEAMWIDTH =        5.00

   FINAL MINIMIZED VALUES

   ANTENNA

   WEIGHT =  4.60821571E 01(lb)        FAB. COST =  5.05659087E 04
   ENGINEERING DEVELOPMENT COST =  4.68738113E 05

   GAIN =  2.53543824E 01            DANT =   9.7468915E 00

   TRANSMITTER

   WEIGHT =  1.05667441E 02(lb)        FAB. COST =  3.15545227E 05
   ENGINEERING DEVELOPMENT COST =  6.54798820E 05

   RF POWER =   4.61918300E 03          TRANSMITTER TYPE =   3
   DC POWER =   5.91050826E 03
   BPU =   3.13780649E 03
   NO. OF DEVICES =   1

   ELECTRICAL POWER

   WEIGHT =  9.48371010E 02(lb)        FAB. COST =  4.48574558E 06
   ENGINEERING DEVELOPMENT COST =  7.75818968E 06

   PSA =   7.8499727E 00          HOUSEKEEPING =   7.9999999E-02
   AREA =   1.40176008E 03

                             WEIGHT                  COST
                              (lb)
   ARRAY                  5.6071233E 02          4.2053424E 06
   FILTER                 1.2801702E 02          3.8405106E 04
   BATTERY                2.7200000E 01          8.7039998E 03
   CONVERTER              1.1222108E 02          1.6833162E 05
   CHARGE REGULATOR       2.6293333E-01          1.3146666E 02
   REGULATOR              1.6000000E 00          1.6000000E 03
   VOLTAGE LIMITER        1.8204965E 02          3.0614894E 04
   DRIVE                  1.6308013E 01          3.2616027E 04
   HARNESS                1.0040654E 02

THERMAL CONTROL

   WEIGHT =  1.64491339E 02(lb)        FAB. COST =  3.45497700E 0
   ENGINEERING DEVELOPMENT COST =  3.54956367E 05

   HOUSEKEEPING =   3.3279999E 00
   CHANGE OF PHASE =   1.1923917E 02AREA =   1.3692822E 01 (ft^2)
   TYPE =   2

ATTITUDE CONTROL

   WEIGHT =  2.46691798E 02(lb)        FAB. COST =  4.77561188E 0
   ENGINEERING DEVELOPMENT COST =  1.07731752E 06

   TYPE =   2

STRUCTURES

   WEIGHT =  2.82441753E 02(lb)        FAB. COST =  5.83289316E 04
   ENGINEERING DEVELOPMENT COST =  3.19465051E 05

   STIFFENING WEIGHT =   8.5641598E-02(lb)
   EL =   2.4739831E 01            EN =   7.1085924E 00

STATION KEEPING

   WEIGHT =  0.                        FAB. COST =  0.
   ENGINEERING DEVELOPMENT COST =  0.

EAST WEST =   8.9931600E 00          TYPE =   0

ORBIT TRIM

   WEIGHT =  4.65397964E 01(lb)        FAB. COST =  3.79660420E 04
   ENGINEERING DEVELOPMENT COST =  5.00000000E 05

SYSTEM

   WEIGHT =   1.9696870E 03

LAUNCH VEHICLE

   TYPE =   9            COST 1 =   1.5800000E 07
   COST 2 =   0.

   MARGIN =   1.8031302E 02
   SAOC =   1.4282584E 07
   SEDC =   2.1581296E 07
   TSC =   5.0146464E 07
   TSI =   2.1363759E 08
   SCE =   2.1697705E 01
   SYSC1 =   1.7844358E 01
   SYSC2 =   2.8853864E 01
```

6.3 OPERATIONAL PROTOCONCEPT DESIGNS

The mission analysis described in Section 3 identified the 22 potential television broadcast services and their parameter ranges, shown in Table 6.3-1. The Space Broadcast Advisory Board recommended the use of those services as a basis for protoconcept designs.

Table 6.3-1. Protoconcept Service Requirements

Service Name	Example Target Area	Area $X 10^6$	Audience	Number Channels V-A	Signal Grade	Loc.	$Δ	Freq GHz	Modulation	ΔERP
DIRECT SERVICE										
*UN	- Africa	10	10^6	1-4	3	U	50	0.8	AM	1.38
Cultural	- USA	3	10^6	1-1	2	U	150	2.5	FM	0.83
*Cultural	- USA	3	10^6	1-1	2	U	150	0.8	AM	0.80
Cultural	- USA	3	10^6	1-1	1	U	150	12.2	FM	2.11
*Cultural	- USA	3	10^6	1-1	1	U	100	12.2	FM	2.11
Americas	- Cent. & So. America	3	10^6	1-2	3	S	50	0.8	AM	1.04
Rural/Suburban	- Australia	3	10^6	1-1	3	S	50	0.8	AM	0.34
*Rural/Suburban	- Australia	3	10^6	3-1 ea	3	S	50	0.8	AM	5.66
*Gen. Purpose (Community)	- India	1	10^6	1-4	2	U	50	0.8	AM	1 38
*Urban	- W. Europe	1	10^8	1-4	1	U	100	0.8	AM	2.48
*Urban	- W. Europe	1	10^8	2-4 ea	1	U	100	0 8	AM	5.64
Urban	- W. Europe	1	10^8	1-4	1	U	100	12.2	FM	3.64
*Urban	- W. Europe	1	10^8	1-4	1	U	65	12.2	FM	3 64
Urban	- W. Europe	1	10^8	1-4	2	U	50	0.8	AM	2 48
*Community	- India	1	10^6	1-4	2	U	50	0.8	FM	1.38
SPECIAL SERVICE										
*Instructional	- All USA	$2\text{-}10^6$	10^4	(6-1 ea)/Area	1	R	1K	2.5	AM	12.95
Instructional	- All USA	$2\text{-}10^6$	10^4	(6-1 ea)/Area	1	U	1K	12.2	FM	14.86
*Professional (Medical)	- USA	1/2	10^3	1-1	0	U	5K	12.2	FM	2.11
*TV Distribution	- All USA	3-1/2	10^3	(6-1 ea)/Area	0	U	5K	8.4	FM	16.07
TV Distribution	- USA	3-1/2	10^3	(6-1 ea)/Area	0	U	2K/3.5K	8.4	FM	14.1
*Americas	- Cent. & So. America	10	10^3	1-2		R	5K	2.5	FM	1.07
Americas	- Cent. & So. America	10	10^3	1-2	0	U	1K	8.4	FM	1 48

NOTE: V = Video Channel

A = Audio Channel

* = Selected for Protoconcept Design

Daily broadcasting time was eliminated as a variable parameter (2 to 23 hours per day), since later analysis indicated (1) that the satellite would be essentially identical for any duty cycle from 4 to 23 hours per day and (2) that low duty cycles (less than 4 hours per day) would not be a cost-effective method of using satellites. Also, several short-duty-cycle missions could be combined in a single, multimission, long-duty-cycle satellite. Duty cycles for the protoconcept designs were held constant at 23 hours per day (no broadcasting during eclipse).

Further examination of the potential combinations of parameters in Table 6.3-1 indicated that specific sets of satellite design parameter combinations would satisfy more than one desired mission, and this "commonality" principle then permitted reduction of the 22 combinations to 13 final concepts. The final set of selected parameters and applicable missions is shown in Table 6.3-2.

The protoconcept design phase then resulted in the evolution of conceptual designs compatible with the requirements. The basic objective of the protoconcept design was to assess the feasibility of attaining practical satellite launch stowage and orbital configurations.

This design phase refined the baseline designs as generated by the satellite synthesis computer models by application of the results of the subsystem parametric analysis phase (Sections 4 and 5). This general approach is shown by the subsystem interaction flow diagram in Figure 6.3-1.

The 13 satellite orbital configurations are shown pictorially in Figures 6.3-2 through 6.3-14. Based upon the design results of these 13 protoconcept configurations, the characteristics of the four systems configured in the third and final phase of the study were selected.

Table 6.3-2. Broadcast Service Parameters

	Unit of Meas	A	B	C	D	E	F	G	H	I	J	K	L	M
Service Type		Prof-Med	Community	Americas	TV Dist	Cultural	G. P. Com	Rural/Sub	Urban	UN	Cultural	Urban	Instruc	Urban
Example of Target Area		USA	India	C&S Amer	All USA	USA	India	Australia	W. Europe	Africa	USA	W. Europe	All USA	W. Europe
Area of Coverage	10^6 mi^2 10^6 km^2	0.5 1.29	1.0 2.59	10 25.9	3(0.5) (1.29)	3.0 7.76	1.0 2.59	3.0 7.76	1.0 2.59	10 25.9	3.0 7.76	1.0 2.59	2(1.0) (2.59)	1.0 2.59
Audience		10^3	10^6	10^3	10^3	10^6	10^6	10^6	10^8	10^6	10^6	10^8	10^4	10^8
Number of Channels (V/A)		1/1	1/4	1/2	3(6/6)	1/1	1/4	3/3	1/4	1/4	1/1	1/4	2(6/6)	2/8
Signal Grade		0	2	0	0	2	2	3	1	3	1	1	1	1
Location		Urban	Urban	Rural	Urban	Urban	Urban	Suburban	Urban	Urban	Urban	Urban	Rural	Urban
Frequency	GHz	12.2	0.8	2.5	8.4	0.8	0.8	0.8	12.2	0.8	12.2	0.8	2.5	0.8
Video Modulation		FM	FM	FM	FM	AM	AM	AM	FM	AM	FM	AM	AM	AM
Δ ERP	dB	2.11	1.38	1.07	16.07	0.80	1.38	5.66	3.64	1.38	2.11	2.48	12.95	5.64
Ground Receiver Subsystem														
Δ$	$	5000	50	5000	5000	150	50	50	65	50	100	100	1000	100
Antenna														
Type		Parabola	Parabola*	Parabola	Parabola	Parabola	Parabola*	Parabola*	Parabola	Parabola*	Parabola	Parabola	Parabola	Parabola
Size	ft m	17.0 5.19	2.8 0.855	20.0 6.1	17.7 5.4	7.5 2.28	3.6 1.1	3.6 1.1	2.2 0.67	3.6 1.1	2.2 0.67	7.1 2.16	9.0 2.72	7.1 2.16
Gain	dB	53.9	14.6	41.5	50.9	21.9	15.4	15.4	36.2	15.4	36.1	21.2	34.5	21.2
HPBW	deg crad	0.33 0.576	30.5 53.2	1.92 3.35	0.46 0.804	13.1 22.8	27.5 48	27.5 48	2.52 4.4	27.4 47.8	2.55 4.45	14.0 24.4	3.10 5.41	14.0 24.4
Electronics														
Type		Par+conv	Pre+conv	Par+conv	Par+conv	Preamp	Preamp	Preamp	Pre+conv	Preamp	Pre+conv	Preamp	Par+conv	Preamp
Noise Figure	dB	1.9	3.0	1.4	1.9	3.3	3.3	3.3	4.7	3.3	5.2	3.3	1.4	3.3

*May be helix

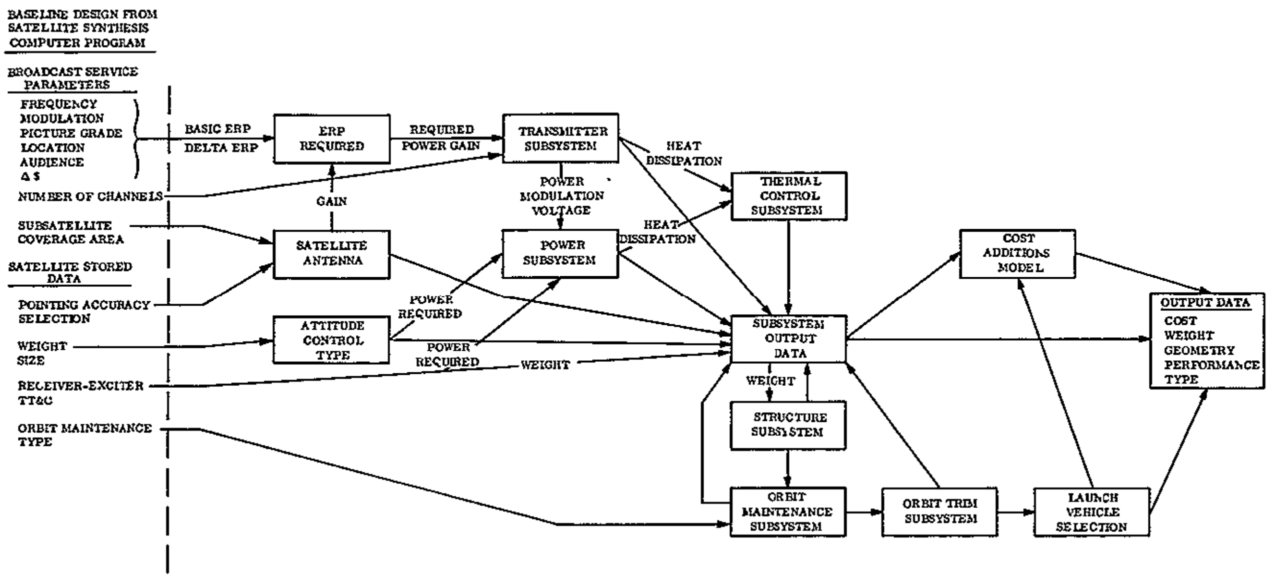
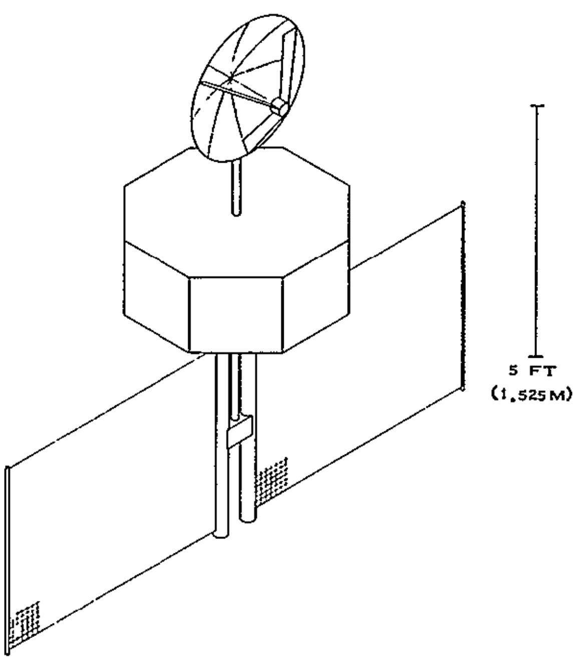


Figure 6.3-1. System Interaction Flow Diagram

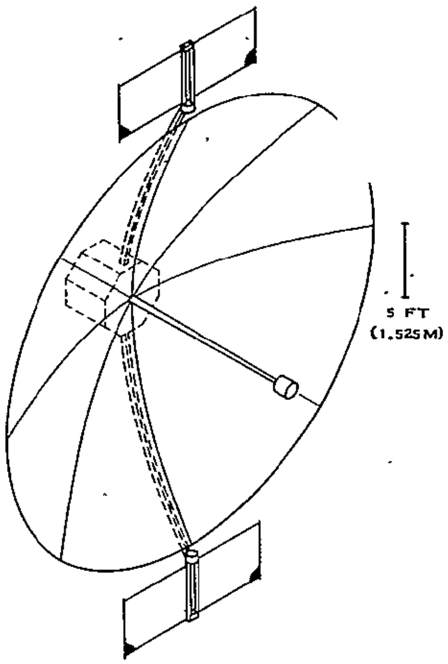


(SPECIAL SERVICE) PROFESSIONAL TELEVISION

THE PROFESSIONAL TELEVISION SERVICE IS INTENDED TO PROVIDE SPECIALIZED EDUCATIONAL PROGRAMS TO THE VARIOUS PROFESSIONS. THESE WOULD BE IN THE NATURE OF FORMAL LECTURES, AS TO MEDICAL GROUPS; SPECIAL EVENTS, AS THE TEST FIRING OF A NEW ROCKET; OR THE EVENTS AT A PROFESSIONAL SOCIETY MEETING.

SCHEDULE OF USE AND OF COVERAGE AREA WOULD BE ARRANGED AMONG THE PARTICIPATING SOCIETIES, THE INTENT BEING TO KEEP THE SATELLITE PROGRAMMING AS NEAR CONTINUOUS AS IS REASONABLE. UPLINK FACILITIES WOULD BE LOCATED AT THE HEADQUARTERS OF MAJOR SOCIETIES, WITH SOME USE BEING MADE OF PRERECORDED PROGRAMMING AND OF TRANSPORTABLE TERMINALS.

Figure 6.3-2. TVBS Protoconcept: Configuration A



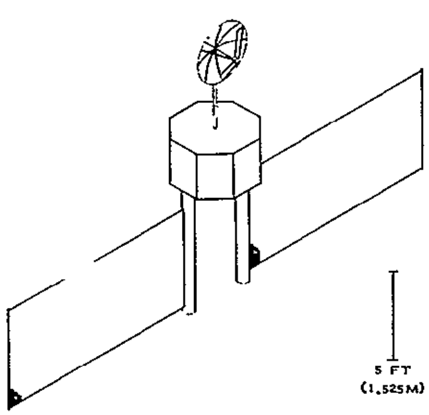
(BROADCASTING SERVICE) COMMUNITY TELEVISION

A COMMUNITY TELEVISION SERVICE IS INTENDED PRIMARILY FOR USE IN EMERGING COUNTRIES WHICH COULD NOT HAVE A NATIONAL TELEVISION SERVICE BY OTHER MEANS. EXTENSIVE USE OF RECEIVERS LOCATED AT COMMUNITY CENTERS, RATHER THAN IN HOMES, WOULD BE MADE. BECAUSE OF THE SPECIALIZED AUDIENCE, COMPATIBILITY WITH EXISTING TELEVISION IS LESS IMPORTANT THAN COST.

THE SERVICE IS A COUNTRYWIDE EXTENSION OF THE "TELECLUBS" WIDELY USED WHEN TELEVISION IS FIRST BEING INTRODUCED, AND IS ALSO AN EXTENSION OF THE INFORMAL COMMUNITY VIEWING COMMON WHERE TELECLUBS ARE NOT FORMALLY ORGANIZED.

PROGRAMMING CHARACTERISTICS WOULD BE IDENTICAL TO THOSE FOR GENERAL TELEVISION.

Figure 6.3-3. TVBS Protoconcept: Configuration B

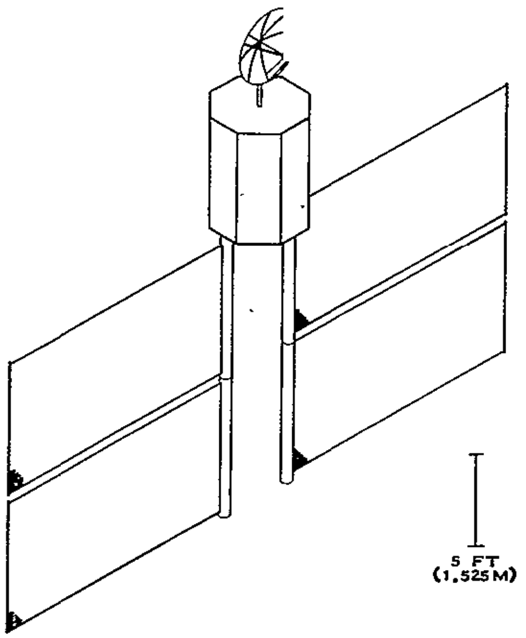


(SPECIAL SERVICE) DISTRIBUTION FOR THE AMERICAS

THE AMERICAS' DISTRIBUTION SERVICE IS INTENDED TO PROVIDE FOR BASIC DISTRIBUTION OF A TELEVISION PROGRAM TO EXISTING AND FUTURE TERRESTRIAL STATIONS IN THOSE AREAS OF THE WORLD WHERE GROUND FACILITIES ARE INADEQUATE OR LACKING, USUALLY ON A REGIONAL BASIS.

THE SERVICE WOULD BE IDENTICAL IN FORM TO THAT OF COUNTRIES HAVING EXISTING DISTRIBUTION NETWORKS AND WOULD RESEMBLE CLOSELY THE OPERATION OF EUROVISION. USUALLY THE AMERICAS' SERVICE WOULD PICK UP A PROGRAM ALREADY IN EXISTENCE AT SOME POINT IN THE COVERAGE AREA AND DISTRIBUTE IT TO OTHER STATIONS. NORMALLY PROGRAMS WOULD BE IN REAL TIME. UPLINK TERMINALS IN MAJOR TELEVISION CENTERS WOULD BE USED, WITH RECEIVING TERMINALS EITHER AT NATIONAL DISTRIBUTION POINTS OR AT INDIVIDUAL STATIONS, ACCORDING TO AVAILABILITY OF OTHER MODES OF TERRESTRIAL TRANSMISSION. THE PATTERN OF EUROVISION AND INTERVISION REGARDING CONTROL, PROGRAMMING, HANDLING OF LANGUAGE, ETC., WOULD BE FOLLOWED.

Figure 6.3-4. TVBS Protoconcept: Configuration C



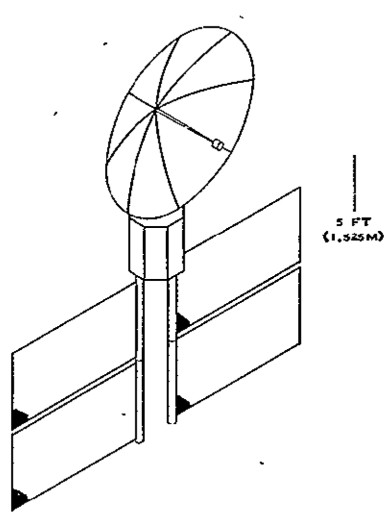
(SPECIAL SERVICE) TV DISTRIBUTION

THE TV DISTRIBUTION SERVICE IS INTENDED TO PROVIDE A LOW-COST METHOD OF DISTRIBUTING TELEVISION PROGRAMS FROM THE ORIGINATING STUDIOS TO CONVENTIONAL BROADCAST TRANSMITTERS.

THE SERVICE IS CURRENTLY ACCOMPLISHED BY MICROWAVE RELAY OR, IN A FEW CASES, BY COAXIAL CABLE.

OPERATION OF THE SERVICE WOULD BE IDENTICAL TO THAT OF THE EXISTING TELEVISION NETWORK OPERATION OF THE US AND OVERSEAS. IN MULTILINGUAL AREAS, THE SOUND CHANNELS WOULD BE ARRANGED TO PROVIDE "PROGRAM INTRINSIC SOUND" ON ONE CHANNEL, WITH SEPARATE CHANNELS FOR COMMENTARY OR INTERPRETATION IN EACH LANGUAGE. THE SERVICE MAY EVENTUALLY BECOME WORLD-WIDE.

Figure 6.3-5. TVBS Protoconcept: Configuration D



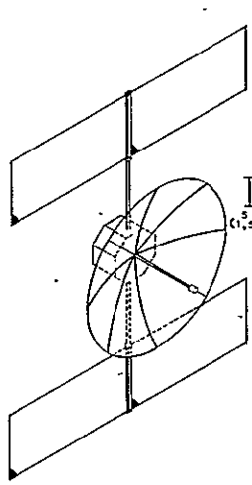
(BROADCAST SERVICE) CULTURAL TELEVISION (CTV)

CULTURAL TELEVISION IS A HIGH-QUALITY SERVICE INTENDED TO SUPPLEMENT THE GENERAL BROADCASTING SERVICE OF DEVELOPED AREAS BY PROVIDING PROGRAMS OF HIGH CULTURAL INTEREST, AND THEREFORE TO A LIMITED FRACTION OF THE TOTAL TELEVISION AUDIENCE. HIGH-QUALITY PERFORMANCE IS CONSIDERED MANDATORY FOR THIS SERVICE, ALTHOUGH INSTALLATION COST CONSIDERATIONS ARE MINIMAL.

THIS SERVICE CORRESPONDS APPROXIMATELY TO THE EXISTING "EDUCATIONAL TELEVISION" OF THE USA. HOWEVER, IT IS NOT VISUALIZED THAT IT WOULD BE USED EXTENSIVELY FOR FORMAL TYPES OF EDUCATIONAL PROGRAMS, ALTHOUGH SUCH USE WOULD BE DETERMINED BY THE PROGRAM CONTENT.

IN VIEW OF THE RELATIVELY SMALL FRACTION OF THE TOTAL AUDIENCE, THE SATELLITE IS VISUALIZED AS PROVIDING CONTINUOUS SINGLE-CHANNEL COVERAGE TO A SIZEABLE AREA. PROGRAMS OF THE PERFORMING ARTS WOULD BE CARRIED IN REAL TIME, USING UPLINK TERMINALS AT THE MAJOR CITIES IN THE COVERAGE AREA. PROGRAMS GENERATED OUTSIDE THE COVERAGE AREA WOULD NORMALLY BE BROUGHT TO ONE OF THE UPLINK STATIONS VIA MICROWAVE RELAY OR SATELLITE RELAY. WITH TIME, MULTIPLE-SATELLITE NETWORKS WOULD BE ESTABLISHED.

Figure 6.3-6. TVBS Protoconcept: Configuration E



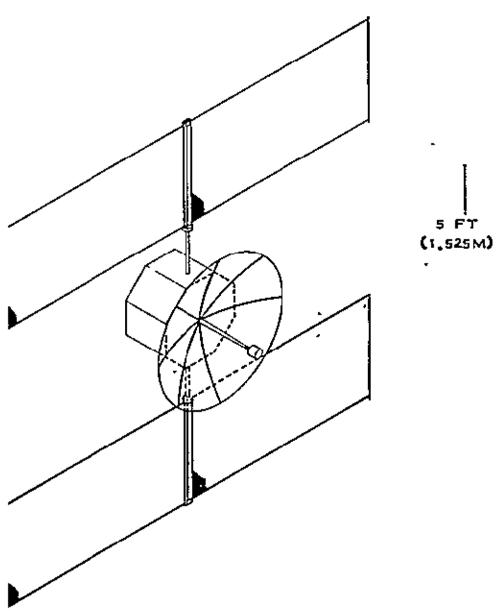
(BROADCAST SERVICE) GENERAL AND COMMUNITY TELEVISION - DEVELOPING AND EMERGING COUNTRIES (GTV)

GENERAL TELEVISION IS VISUALIZED AS APPLYING TO THOSE DEVELOPING AND EMERGING AREAS IN WHICH ECONOMIC PROGRESS IS SUCH THAT COMMUNITY LISTENING IS NOT EXPECTED TO BE AN IMPORTANT FUTURE ELEMENT IN RECEPTION. IN OTHER WORDS, THE GENERAL TELEVISION IS INTENDED TO PROVIDE, AS A MINIMUM, THE INITIAL STATE OF NATIONAL PROGRAMMING COVERAGE; THEREAFTER THE SERVICE MAY CONTINUE, OR IT MAY BE OPERATED AS A RURAL SERVICE. AS A RESULT, COMPATIBILITY WITH A NATIONAL OR REGIONAL TELEVISION PLAN IS MANDATORY FOR THIS SERVICE.

THIS SERVICE CORRESPONDS TO THE FIRST USE OF NETWORK TELEVISION IN A COUNTRY OR AREA.

WHERE A SINGLE COUNTRY IS COVERED, THE UPLINK TERMINAL WOULD BE LOCATED AT THE MAJOR FUTURE TELEVISION CENTERS OF THE COUNTRY, USUALLY AT THE CAPITAL. FOR MOST COUNTRIES, A SINGLE PROGRAM CARRIED NATIONALLY AND LIMITED TO THE EVENING HOURS FOR ENTERTAINMENT WOULD BE REQUIRED. FULL USE OF A SATELLITE WOULD INDICATE THAT IT SHOULD ALSO BE USED FOR FORMAL EDUCATION DURING THE DAYTIME SCHOOL HOURS AND FOR INFORMAL EDUCATION DURING THE EARLY EVENING HOURS. WHERE SEVERAL COUNTRIES ARE COVERED, PROGRAMS WOULD TYPICALLY BE COORDINATED, WITH THE VARIOUS COUNTRIES CREATING PROGRAMS FOR COMPLETE USE; FOR THESE CASES, UPLINKS IN EACH OF THE COUNTRIES INVOLVED WOULD BE NEEDED.

Figure 6.3-7. TVBS Protoconcept: Configuration F



(BROADCASTING SERVICE) RURAL TELEVISION (RTV)

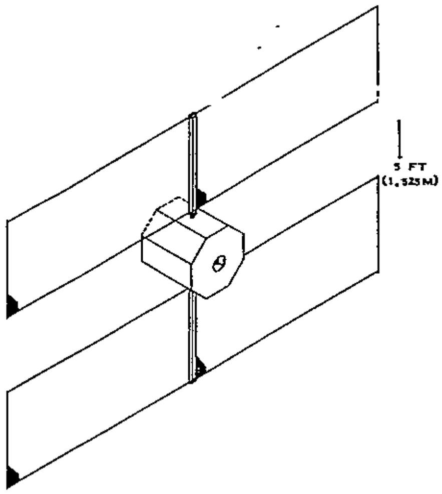
THE RURAL TELEVISION SERVICE IS INTENDED TO BE A SUPPLEMENT TO EXISTING SERVICES, PROVIDING NATIONALLY GENERATED PROGRAMS TO THE RESIDUAL FRACTION OF THE TOTAL AUDIENCE NOT SERVED BY TERRESTRIAL STATIONS. THE SERVICE IS NATIONAL RATHER THAN REGIONAL IN NATURE.

THE SERVICE CORRESPONDS CLOSELY TO THE EXISTING "REPEATER RE-BROADCAST" AND TO CABLE EXTENSION FOR OUTLYING AREAS.

AS A SUPPLEMENTAL SERVICE HAVING A RELATIVELY SMALL AUDIENCE WHICH IS WIDELY DISPERSED, SINGLE-CHANNEL COVERAGE IS CONSIDERED ADEQUATE. PROGRAMS WOULD NORMALLY BE THOSE

ARRIED BY THE NATIONAL NET OR NETS- ORKS. USUALLY A SINGLE UPLINK OCATED AT A CONVENIENT AND LOW- OST POINT WOULD BE USED. SEVERAL GEOGRAPHICALLY SEPARATED COUNTRIES MIGHT COOPERATE, USING THE SATELLITE ON A TIME-SCHEDULED BASIS.

Figure 6.3-8. TVBS Protoconcept: Configuration G

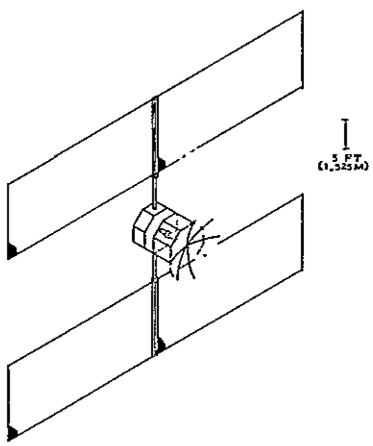


(BROADCASTING SERVICE) URBAN TELEVISION

URBAN TELEVISION IS INTENDED FOR THE INDUSTRIALLY DEVELOPED AREAS. IT IS INTENDED TO PROVIDE HIGH-QUALITY SIGNALS TO 100 PERCENT OF THE POTENTIAL AUDIENCE WITHIN ITS COVERAGE AREAS. THE SERVICE CORRESPONDS ALMOST EXACTLY TO NETWORK TELEVISION IN THE MORE DEVELOPED AREAS OF THE WORLD.

THE SERVICE WOULD BE A FULL-TIME SERVICE TO THE COVERAGE ZONE. PROGRAM INPUTS AT MAJOR TELEVISION CENTERS WOULD BE USED, TOGETHER WITH REMOTE PICKUPS AND TRANSPORTABLE UPLINKS. PROGRAMMING PRACTICES AND PATTERNS WOULD BE ESSENTIALLY IDENTICAL WITH THOSE OF THIS EXISTING NETWORK TELEVISION IN THE USA AND OVERSEAS. INITIALLY THE SERVICE WOULD BE SINGLE CHANNEL, WITH ADDED CHANNELS BEING USED AS THE AUDIENCE SIZE INCREASES.

Figure 6.3-9. TVBS Protoconcept: Configuration H



(BROADCAST SERVICE) UN-TV

IN ITS FULLY DEVELOPED FORM THE UN-TV SERVICE IS AN INTERNATIONAL TELEVISION BROADCASTING SERVICE OF WORLD WIDE CAPABILITY. THIS CAPABILITY WOULD BE PROVIDED BY 3 OR 4 SATELLITES, PROPERLY LOCATED WITH RESPECT TO THE MAJOR LAND MASSES. AS PRESENTLY VISUALIZED, COVERAGE WOULD BE RESTRICTED TO APPROXIMATELY 10 MILLION SQUARE MILES FOR A SINGLE PROGRAM; ANTENNA POSITIONING WOULD BE USED TO CHANGE THE COVERAGE AREAS, IN ACCORDANCE WITH A PRE-ESTABLISHED SCHEDULE. COVERAGE WOULD NORMALLY BEGIN AT AN EASTERNMOST PART OF THE VISIBLE EARTH, PROGRESSING WESTWARD WITH TIME TO TAKE MAXIMUM ADVANTAGE OF THE TIME SPAN IN THE COVERAGE AREA.

SATELLITES OF THIS CLASS WOULD TYPICALLY BE USED BY THE UN, AS A MEANS OF BRINGING UN GENERAL ASSEMBLY AND SPECIAL MEETINGS, UNESCO MEETINGS, SPECIAL EDUCATIONAL PROGRAMS, AND SO FORTH, TO THE VARIOUS AREAS OF THE WORLD. SATELLITES COULD ALSO BE USED FOR OTHER TYPES OF INTERNATIONAL BROADCASTING, INCLUDING THE RE-BROADCAST OF NATIONAL PROGRAMS TO OVERSEAS AREAS WHERE DESIRED.

IN TYPICAL OPERATIONS, PROGRAMS WOULD ORIGINATE AT A SINGLE POINT ON EARTH, BEING DISTRIBUTED TO THE BROADCAST SATELLITE UPLINK TERMINAL BY VARIOUS COMBINATIONS OF MICROWAVE RELAYS, COMMUNICATION SATELLITE RELAYS, AND/OR "OFF-THE-AIR-PICKUP." SECOND-GENERATION SATELLITES MIGHT INCORPORATE INTERSATELLITE RELAY FACILITIES. ADDITIONAL UPLINKS MIGHT BE ESTABLISHED IN VARIOUS MAJOR CAPITALS, AND TRANSPORTABLE UPLINKS MIGHT BE USED.

THIS SERVICE DOES NOT EXIST AT PRESENT FOR TELEVISION, ALTHOUGH MANY COUNTRIES OPERATE VOICE-HF EQUIVALENTS.

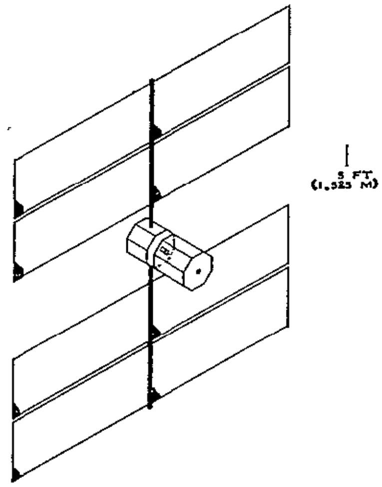
THIS PROTOCONCEPT DESIGN WILL ALSO SATISFY THE REQUIREMENTS FOR AN AMERICAS SERVICE, AS DESCRIBED BELOW.

THE AMERICAS' TV SERVICE IS INTENDED TO BE A SUPPLEMENT TO EXISTING TELEVISION SERVICE, WHERE THE EXISTING SERVICE IS CONFINED TO CITIES, AND WHERE A REGIONAL "COMMUNITY OF INTEREST" EXISTS. SINCE IT IS A SUPPLEMENTAL SERVICE, IT IS NOT INTENDED TO REACH URBAN AUDIENCES.

THE SERVICE IS SIMILAR TO THAT PROVIDED BY THE SO-CALLED SATELLITE REPEATERS, AND BY CABLE RECEPTION IN THE OUTLYING AREAS.

AS A REGIONAL SERVICE, IT IS VISUALIZED THAT A RELATIVELY LIMITED NUMBER OF CHANNELS WOULD BE AVAILABLE, ONE INITIALLY. PROGRAMS WOULD COVER THE ENTIRE ZONE. PROGRAMS WOULD NORMALLY BE IDENTICAL TO THOSE IN ONE OR MORE OF THE AREAS HAVING EXISTING TELEVISION; GROUND STATIONS IN MAJOR CITIES AND CAPITALS WOULD PROVIDE UPLINK SERVICES.

Figure 6.3-10. TVBS Protoconcept: Configuration I



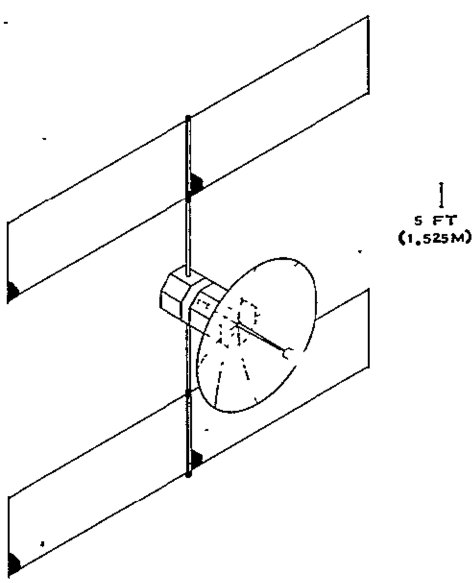
(BROADCASTING SERVICE) CULTURAL TELEVISION (CTV)

CULTURAL TELEVISION IS A HIGH-QUALITY SERVICE INTENDED TO SUPPLEMENT THE GENERAL BROADCASTING SERVICE OF DEVELOPED AREAS BY PROVIDING PROGRAMS OF HIGH CULTURAL INTEREST, AND THEREFORE TO A LIMITED FRACTION OF THE TOTAL TELEVISION AUDIENCE. HIGH-QUALITY PERFORMANCE IS CONSIDERED MANDATORY FOR THIS SERVICE, ALTHOUGH INSTALLATION COST CONSIDERATIONS ARE MINIMAL.

THIS SERVICE CORRESPONDS APPROXIMATELY TO THE EXISTING "EDUCATIONAL TELEVISION" OF THE USA. HOWEVER, IT IS NOT VISUALIZED THAT IT WOULD BE USED EXTENSIVELY FOR FORMAL TYPES OF EDUCATIONAL PROGRAMS, ALTHOUGH SUCH USE WOULD BE DETERMINED BY THE PROGRAM CONTENT.

IN VIEW OF THE RELATIVELY SMALL FRACTION OF THE TOTAL AUDIENCE, THE SATELLITE IS VISUALIZED AS PROVIDING CONTINUOUS SINGLE-CHANNEL COVERAGE TO A SIZEABLE AREA. PROGRAMS OF THE PERFORMING ARTS WOULD BE CARRIED IN REAL TIME, USING UPLINK TERMINALS AT THE MAJOR CITIES IN THE COVERAGE AREA. PROGRAMS GENERATED OUTSIDE THE COVERAGE AREA WOULD NORMALLY BE BROUGHT TO ONE OF THE UPLINK STATIONS VIA MICROWAVE RELAY OR SATELLITE RELAY. WITH TIME, MULTIPLE SATELLITE NETWORKS WOULD BE ESTABLISHED.

Figure 6.3-11. TVBS Protoconcept: Configuration J

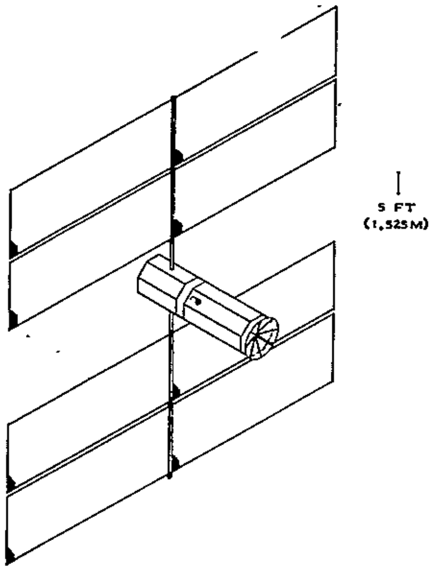


(BROADCASTING SERVICE) URBAN TELEVISION

URBAN TELEVISION IS INTENDED FOR THE INDUSTRIALLY DEVELOPED AREAS. IT IS INTENDED TO PROVIDE HIGH QUALITY SIGNALS TO 100% OF THE POTENTIAL AUDIENCE WITHIN ITS COVERAGE AREA. THE SERVICE CORRESPONDS ALMOST EXACTLY TO NETWORK TELEVISION IN THE MORE DEVELOPED AREAS OF THE WORLD.

THE SERVICE WOULD BE A FULL TIME SERVICE TO THE COVERAGE ZONE. PROGRAM INPUTS AT MAJOR TELEVISION CENTERS WOULD BE USED, TOGETHER WITH REMOTE PICKUPS AND TRANSPORTABLE UPLINKS. PROGRAMMING PRACTICES AND PATTERNS WOULD BE ESSENTIALLY IDENTICAL WITH THOSE OF THIS EXISTING NETWORK TELEVISION IN THE USA AND OVERSEAS. INITIALLY THE SERVICE WOULD BE SINGLE CHANNEL, WITH ADDED CHANNELS BEING USED AS THE AUDIENCE SIZE INCREASES.

Figure 6.3-12. TVBS Protoconcept: Configuration K



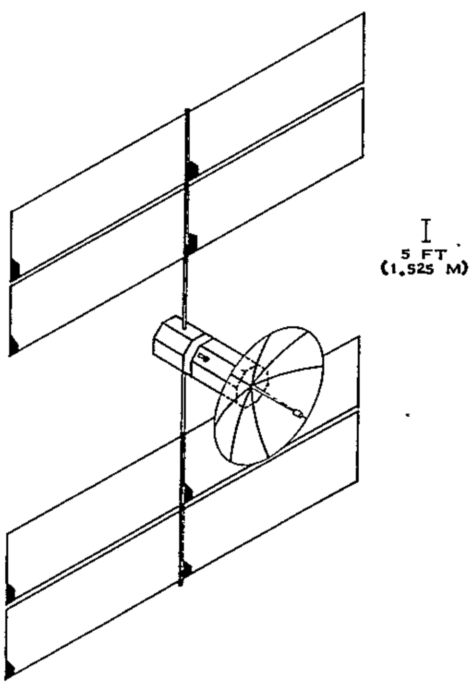
(SPÉCIAL SERVICE) INSTRUCTIONAL TELEVISION

INSTRUCTIONAL TELEVISION IS INTENDED TO PROVIDE FORMAL EDUCATIONAL PROGRAMS FOR INTEGRATION IN SCHOOL CURRICULA. ALTHOUGH PRIMARILY INTENDED FOR PRIMARY AND SECONDARY EDUCATION, IT MIGHT ALSO BE USED FOR COLLEGE-LEVEL AND POST-GRADUATE ADULT EDUCATION IN THE FORMAL SENSE. THE SERVICE IS AN EXTENSION OF THE MPATI SERVICE TO A WIDER AREA.

OPERATIONALLY THE SERVICE WOULD BE SCHEDULED TO TAKE MAXIMUM ADVANTAGE OF THE DEGREES OF FREEDOM ALLOWED BY THE NUMBER OF CHANNELS, THE PARTIAL COVERAGE AREA, AND TIME ZONE DIFFERENCES: MULTIPLE CHANNELS ARE NEEDED TO COVER THE VARIOUS SUBJECTS OF THE CURRICULUM.

PROGRAMS WOULD GENERALLY BE RECORDED AND OPERATED TO A WELL-PUBLICIZED ADVANCE SCHEDULE, TO ALLOW MAXIMUM USE OF THE MATERIAL WITHIN THE CLASS SCHEDULE. CURRENT EVENTS WOULD PROBABLY BE CONFINED TO ONE CHANNEL. RECORDED PROGRAMS COULD ORIGINATE AT A SINGLE AREA, WITH CURRENT EVENTS RELAYD THROUGH THIS AREA OR SENT TO THE SATELLITE BY UP-TERMINALS AT MAJOR CITIES.

Figure 6.3-13. TVBS Protoconcept: Configuration L



(BROADCASTING SERVICE) URBAN TELEVISION

URBAN TELEVISION IS INTENDED FOR THE INDUSTRIALLY DEVELOPED AREAS. IT IS INTENDED TO PROVIDE HIGH QUALITY SIGNALS TO 100% OF THE POTENTIAL AUDIENCE WITHIN ITS COVERAGE AREA. THE SERVICE CORRESPONDS ALMOST EXACTLY TO NETWORK TELEVISION IN THI MORE DEVELOPED AREAS OF THE WORLD.

THE SERVICE WOULD BE A FULL TIME SERVICE TO THE COVERAGE ZONE. PROGRAM INPUTS AT MAJOR TELEVISION CENTERS WOULD BE USED, TOGETHER WITH REMOTE PICKUPS AND TRANSPORTABLE UPLINKS. PROGRAMMING PRACTICES AND PATTERNS WOULD BE ESSENTIALLY IDENTICAL WITH THOSE OF THIS EXISTING NETWORK TELEVISION IN THE USA AND OVERSEAS. INITIALLY THE SERVICE WOULD BE SINGLE CHANNEL, WITH ADDED CHANNELS BEING USED AS THE AUDIENCE SIZE INCREASES.

Figure 6.3-14. TVBS Protoconcept: Configuration M

SECTION 7

SYSTEM CONCEPTUAL DESIGN (PHASE 3)

Four representative TVBS systems were examined to sufficient depth to establish feasibility, estimate cost, and compare costs to alternative terrestrial systems. Three of the systems were considered representative of operational TVBS systems. These were selected as a result of the evaluation of Phase 2 protoconcept designs. The fourth system (demonstration mission) was defined to encompass a wide range of mission requirements that would demonstrate a corresponding range of subsystem performance parameters.

The selection of Broadcast Satellite Concepts for further study required that a choice be made of a service for a potential user (nation, agency or company), a target area, and a frequency. There was no determination upon which to base the choice of a service to a user, and there has been no decision made which would allocate a portion of the frequency spectrum in a specific geographical location for a Broadcast Satellite. These aspects were beyond the scope of the TVBS Study. The concepts selected were chosen primarily as best representing a broad spectrum of services, potential users, and frequencies.

The three satellite systems selected as representative of operational TV space broadcasting were: (1) a direct community TV service to India with an added distribution service; (2) a direct rural/suburban TV service to Alaska and; (3) a special instructional TV service to the continental United States. The demonstration satellite system is to provide a TV signal to interested technical and user audiences in the United States. The baseline requirements for the four systems are shown in Table 7-1. The design description of the resulting systems is summarized in Table 7-2. Descriptions of the example services and the key results of the design analyses follow.

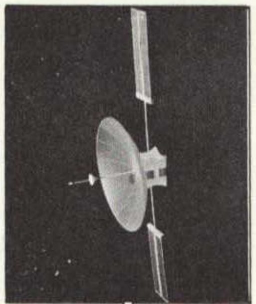
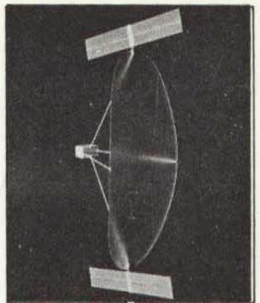
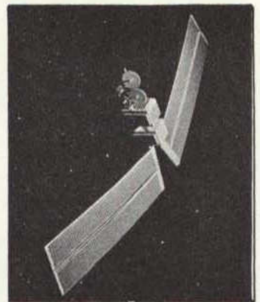
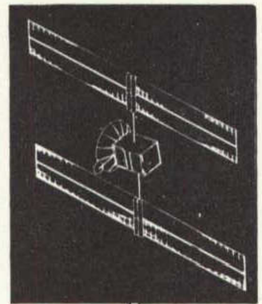
This section is organized to present in each subsection the same type of information for each of the four conceptual satellite designs. This method of organization reduces repetition and permits easy comparison between the four systems.

Table 7-1. TVBS Phase 3 Baseline Requirements

Service Description	Frequency (GHz)	Modulation	Coverage Area	Signal Quality	Receiver Cost ($)	Number of Channels
Community-Direct	0.8	FM	India	2	<50	1V/4A
Rebroadcast-Special	8.4	FM		CCIR Relay	1000-5000	1V/4A
Rural/Suburban-Direct	0.8	AM	Alaska	2	< 100	3
Instruction-Special	12.2	FM	USA	1	1000	6 Ea to 2 Areas
Demonstration Satellite	2.5	FM	45^{o}N-10^{o}S	0/1	5000/150	2
	2.5	AM		0	1000	1
	12.2	FM		0/1	5000/1000	2

V = Video
A = Audio

Table 7-2. Baseline Requirements for Four Possible Systems

	CASE I COMMUNITY/DISTRIBUTION SERVICE TO INDIA		CASE II DIRECT SERVICE TO ALASKA	CASE III INSTRUCTIONAL SERVICE TO U.S.	CASE IV DEMONSTRATION MISSION TO US
SATELLITE WEIGHT, LBS.	752		2043	983	2036
BOOSTER (CAPABILITY, LBS.)	ATLAS E/AGENA D/KICK (910)		TITAN 3B/CENTAUR/KICK (2260)	ATLAS E/AGENA E/KICK (910)	ATLAS (SLV-3C)/CENTAUR/KICK (2267)
SATELLITE DESCRIPTION	FIG. 7		FIG. 9	FIG. 11	
Si SOLAR CELL PANELS	2 AT 72 FT^2		4 AT 171 FT^2	2 AT 145 FT^2	4 AT 2.00 FT^2
TOTAL CELL AREA (FT^2):	124		621	259	779
POWER LEVEL AFTER 2 YRS (KW):	1.1		5.5	2.3	7.0
ANTENNA TYPE & SIZE	2 CONCENTRIC PARABOLAS 21 FT (0.8 GHz), 2 FT (8.4 GHz)		ELLIPTICAL SEGMENT OF PARABOLOID 29 FT x 80 FT	4 PARABOLAS 2 AT 1.4 FT; 2 AT 2.25 FT	2 PARABOLAS 9.0 FT (2.5 GHZ); 1.4 FT (12.2 GHZ
CONSTRUCTION:	DEPLOYABLE (UMBRELLA) AND RIGID		INFLATABLE WIRE GRID	RIGID	RIGID
GAIN & HPBW:	BOTH 4.1° CIRCULAR/32 DB		1.1° x 3.1°/39 DB	4.1° CIRC./32 DB; 2.5° CIRC./36.3 DB	3.0° CIRC./34.5 DB; 4.1° CIRC./32 DB
BEAM POINTING (.05° ACCURACY):	ANTENNA ELECTRICAL AXIS USING RF INTERFEROMETER		FEED TRANSLATION USING RF INTERFEROMETER	ORBIT INCLINATION FOR ELEVATION CONTROL, RF INTERFEROMETER FOR AZIMUTH POSITIONING	ORBIT INCLINATION FOR ELEVATION CONTROL, RF INTERFEROMETER FOR AZIMUTH POSITIONING
TRANSMITTER TYPE	CFA	TWT	CFA (SEPARATE VIDEO AND AUDIO)	TWT	CFA (S-BAND AM)(SEP. VID.& AUD.)
AVG RF POWER OUTPUT CH (W):	416	20	505	70 (MAX)	1830
OVERALL EFFICIENCY OF TRANSMITTER SYSTEM (%):	58	35	42	34	37
ATTITUDE CONTROL TYPE	3 AXIS ACTIVE-MOMENTUM WHEEL		3 AXIS-MOMENTUM WHEEL (FLYWHEEL AUGMENTED)	3 AXIS ACTIVE-REACTION CONTROL SYSTEM AUGMENTED WITH PITCH FLYWHEEL	3 AXIS ACTIVE-REACTION CONTROL SYSTEM AUGMENTED WITH PITCH FLYWHEEL
PERFORMANCE					
SATELLITE ERP/CH. (DBW):	58	45	71	50 (MAX)	71
FIELD STRENGTH ($\mu V/M$):	122	18	420	24	437
(REQ'D/ACT.) COVERAGE AREA, 10^6 MI^2:	1.1/2.3		0.6/≈1.2	3/≈7.6	-1≈3.0
PICTURE QUALITY (TASO GRADE/S/N):	2/39.5 DB	CCIR RELAY/56.5 DB	2/39.5 DB	1/50.5 DB	1
AUDIENCE SIZE:	0.5×10^6	100	10^5	10^5	
GROUND STATION COST ($):	50	2885	100	1100	2110
COST COMPARISON - TOTAL 10 YEAR PROGRAM					NOT APPLICABLE
SATELLITE ($ M):	87		155	95	
TERRESTRIAL ($ M):	151		325	1284	
TERR. TO SAT. RATIO:	1.7		2.1	13.5	

7.1 MISSION DESCRIPTION

The three satellite systems selected as representative of operational television space broadcasting were: (1) a direct community TV service to the villages of India with an added distribution service for the cities; (2) a direct rural/suburban TV service to Alaska; and (3) a special instructional TV service to the continental United States. The demonstration satellite system would provide a TV signal to interested technical and user audiences in the United States. Further descriptions of the four services are presented below.

7.1.1 TELEVISION TO INDIA

7.1.1.1 Community Direct Broadcast TV

A community direct broadcast TV service would provide a greatly needed instructional service aimed at the general inhabitants of developing nations. India is an example of these, with relatively large coverage area, many small villages (500,000 villages of under 5000 population), and the added complexity of multilingual broadcast requirements. This type of mission is ideal for satellites in that, being aimed at developing areas, the broadcast missio should be able to utilize optimum approaches; i.e., the broadcast parameters should be assumed to be sufficiently flexible to arrive at optimum values. Also, the broadcast parameters are selected on the basis of minimizing the total system implementation cost, which would likely to borne by a single governmental entity.

7.1.1.2 Distribution TV

This additional service would be aimed at demonstrating a TV distribution system for the major metropolitan areas of a newly developed nation which would be desirous of providing TV to individual residences with no receiver modification cost. This service, in conjunction with the previous community service, would provide the flexible service mix necessary for the developing nations.

7.1.2 DIRECT SERVICE TO ALASKA

This television service is representative of a system providing general-purpose television to remote areas of relatively sparse population. Standard television sets representative of current state of the art are assumed, and existing AM modulation practice is used. Reception of the satellite signal requires only the addition of an outdoor antenna and preamplifier. Three channels are deemed sufficient to provide a variety of programming, with the potential of reducing the number for specific cases.

The development and installation of this type of satellite system is likely to be borne by the U.S. government, the ground system installation cost borne by the user, and the operation conducted by a broadcasting company. This implies that either the satellite annual operating cost and/or the receiver cost be the governing cost for minimization. For this service, it was decided to restrict operation to the current UHF/AM standards of terrestrial broadcast.

The basic advantages of this service would be provision of television to isolated geographical areas, which are extremely costly to serve under present terrestrial methods, and the utilization of existing equipment and current frequency allocations.

7.1.3 INSTRUCTIONAL SERVICE TO USA

The instructional service satellite is aimed at a developed nation which has a need for supplementing present educational methods at all education levels and for establishing cultural/educational adult community programs. This service requires establishment of sophisticated ground receiving stations at discrete centralized locations (schools, libraries, etc.).

Frequency selection is made on the basis of being an authorized service and FM modulation is used for optimization considerations with respect to satellite power requirements.

Optimum ground station receiver modification cost was based on total system implementation cost, since the project would likely be federally financed. Minimum system costs occur with frequency modulation of either X- of S-band. However, since the cost differences are small between operation at 2.5, 8.4, and 12.2 GHz, operation at 12.2 GHz was chosen since allocation of spectrum appears more probable in this frequency band.

7.1.4 DEMONSTRATION SATELLITE - USA

This satellite is postulated as being typical of a satellite which would demonstrate the major unique characteristics and technologies associated with television broadcasting from space. The two carrier frequencies (2.5 GHz and 12.2 GHz) were selected to be representative of low and high values of the range under consideration without going to the extreme antenna size associated with UHF. Both AM and FM modulation are included with a required (S/N) ratio established at the receiver for a TASO Grade 1 picture and for CCIR Relay quality pictures.

It is desirable to demonstrate feasibililty of critical technology items, and the following items are included: (1) multiple channel/feed, (2) deployment of large solar arrays, (3) high dc power rotary joints, (4) high-voltage power conditioners, (5) antenna pointing (movable feeds and/or gimbals,), (6) thermal control technology associated with heat pipe transmitter integration, and (7) high-power operation of broadcasting transmitter components.

7.2 SYSTEM DESIGN REQUIREMENTS

The baseline requirements established for these four selected system designs were presented in Table 7-1. These had to be expanded to provide the necessary criteria for the additional satellite design analysis.

The TVBS satellite design requirements must include: (1) selection of the broadcast service parameters (i.e., frequency, modulation, picture grade, etc.); (2) definition of the ground receiving system; and (3) corresponding definition of the satellite performance requirements and the associated subsystem design requirements.

7.2.1 DESCRIPTION OF SELECTED APPROACH

The approach to establishing final system design requirements consisted of sufficient iterations of variable broadcast performance requirements (namely, modulation index for FM systems and ground receiving antenna gain and beamwidth) to arrive at a cost-optimum selection of requirements.

Once the general design requirements were established, the final, detailed calculations associated with signal propagation were completed to determine RF power levels required from the satellite.

The steps listed below outline the analysis made in arriving at specific values of design requirements.

1. Selection of frequency, modulation, picture quality, coverage area, number of channels, number of beams, and ground receiver modification costs were made from overall recommendations of the Space Broadcast Advisory Board and from results of system tradeoff analyses.

2. Television Broadcast standards were then established based on assumed receiver equipment for the geographical region under consideration and CCIR standards. S/N_o and video bandwidths were thus established.

3. Broadcast coverage geometric parameters were then derived. This included establishment of satellite location and required beamwidths and time of day of broadcast. The transmission slant range was then established for: (a) propagation path length, (b) ground elevation angle, (c) earth central angle from subsatellite point to ground stations, (d) beam centerline location, (e) coverage area on the ground, and (f) satellite beam offset angle (from local vertical).

4. The ground receiving system performance was then established within constraints of the cost goals. This resulted in establishment of the receiver, cable, and antenna noise temperatures. The receiver noise temperatures in these cases include the effects of the preamplifier, converters, and basic unmodified receiver and their relative placement. The antenna noise temperatures include effects of sky, cosmic, and indigenous (man-made) noise with respect to ground elevation

angle. The effects of clouds and precipitation were then imposed on the system noise temperature derived from considerations outlined in the previous paragraph to arrive at the total system noise temperature. Ground receiving antenna net gain, including effects of polarization mismatch and antenna pointing/alignment, was then determined.

5. Propagation factors were determined for the following effects where applicable: (a) ionospheric absorption, (b) tropospheric absorption, (c) Faraday rotation, (d) refraction loss, (e) fading, (f) cloud attenuation, (g) precipitation loss, and (h) free space loss.

6. With the above data established, ERP requirements were established for the broadcast transmitters. Since the power required is the basic design criteria for broadcast satellites (once the antenna size is fixed) and since the broadcast payloads are the primary power users, this then established the satellite primary design requirements.

7.2.2 SYSTEM PERFORMANCE REQUIREMENTS

The basic system design requirements resulting from the previous steps are presented in Table 7.2-1. Pertinent discussion concerning the specific values is given where applicable in the following text.

7.2.2.1 Operating Requirements

The frequency, modulation, number of channels, and picture grade presented in rows 1, 2, 3, and 14 of Table 7.2-1 were selected from the Phase 2 protoconcept design results.

7.2.2.2 Coverage Areas

The coverage area and TV standard in rows 4 and 13 were derived directly from the coverage areas selected: (1) India, (2) Alaska, and (3) continental United States, Alaska, Hawaii and their respective existing standards for terrestrial operation. The demonstration satellite coverage area is the continental United States.

The TV standards are those considered applicable for the region: System M for the United States and System B for India.

7.2.2.3 Broadcast Coverage

The broadcast coverage parameters are presented in rows 5 through 12. Minimum coverage angles, subsatellite locations, and beam centerline locations were derived from the geometry of each situation. The selection of values with supporting rationale is given below for the four satellites.

Row	Item	Unit	Community Service to India (Rebroadcast)		Direct Service to Alaska	Instructional Service to US				Demonstration Service to USA		
1	Frequency	GHz	0.8	8.4	0.8	12.2		12.2		2.5	2.5	12.2
2	Modulation		FM	FMFB	AMVSB	FMFB		FMFB		AM	FMFB	FMFB
3	No. Channels		1V/4A	1V/4A	3V/3A	6V/6A	6V/6A	6V/6A	6V/6A	1V/1A	2V/2A	2V/2A
4	Coverage Area Required	MI^2	$2.3x10^6$	$2.3x10^6$	$0.6x10^6$	East US ($1.5x10^6$)	Alaska ($0.6x10^6$)	Hawaii	West US ($1.5x10^6$)			
4a	Coverage Area Required	km^2	$5.45x10^6$	$5.95x10^6$	$1.555x10^6$	$3.88x10^6$	$1.555x10^6$		$3.88x10^6$			
5	Min Coverage Angle		4.1°	4.1°	1.1°x3.1°Ellipse	4.0	2.4	2.4	4.0	3.0°	3.0°	4.1°
6	Subsatellite Long		76°E	76°E	135°W	120°W	120°W	120°W	120°W	107°W	107°W	107°W
7	Beam Location Long		79°E	79°E	145°W	90°	145°W	162°W	109°W	82°W	98°W	112°W
	Lat		20.5°N	20.5°N	60°N	32°N	60°N	22°N	42°N	35°N or	38°N or	40°N
8	Most Distant Rcvr		AMRITSAR	AMRITSAR	Pt Barrow	Maine	Pt Barrow	Nihoa	Michigan	Maine	Maine	Maine
	Long		74°E	74°E	156°W	68°W	156°W	163°W	86°W	68°W	68°W	68°W
	Lat		32°N	32°N	72°N	47°N	72°N	23°N	47°N	47°N	47°N	47°N
9	Max Earth Cen Ang	degrees	32°	32°	73.2°	65.2	75.5	47.7	54.7	58.4°	58.4°	58.4°
10	Max Slant Range	NM	20,000	20,000	22,000	21,550	22,200	20,600	20,950	21,200	21,200	21,200
10a	Max Slant Range	km	53° 78°	53° 78°	7.7° 26.4°	39900	41100	38150	38800	39250	39250	39250
11	Ground Elevation Angle	degrees	37,000	37,000	40,700	18°-46°	5.9°-23.9°	49.5	29°-52°	24° 57.5°	24° 57.5°	24° 57.5°
12	Satellite Beam Offset Angle	degrees	3.6°	3.6°	3.04° 3.14°(0.8°inc)	6.6°	8.2		6.6	6.5°/6.2°/6.3°	6.5°/6.2°/6.3°	6.5°/6.2°/6.3°
13	TV Standard		Sys B	Sys B	Sys M		System M			Sys M	Sys M	Sys M
14	Picture Grade		TASO GD2+*	CCIR Relay Qual	TASO GD 2		TASO Grade 1+*			TASO GD 1	TASO GD 1+*	GASO GD 1+*
15	Video Bandwidth	MHz	5	5	4.2		4.2			4.2	4.2	4.2
16	Composite Baseband	MHz	7	7	-		5.0			-	5	5
17	Modulation Index		1.5	6.26	-	5.1	5.1	5.1	5.1	-	5.15	5.15
18	IF Noise Bandwidth MHz		35	101.5	6	61.5	61.5	61.5	61.6	6	61.5	61.5
19	Output S/N (Weighted)	dB	39.5	56.0	35.9	50.5	50.5	50.5	50.5	46.9	50.5	50.5
20	De-emphasis and Weighting	dB	-16.40	-16.4	-6.0	-12.5	-12.5	-12.5	-12.5	-6.0	-12.5	-12.5
21	Mod Improvement	dB	-15.6	-34.3	-	-32.9	-32.9	-32.9	-32.9	-	-32.9	-32.9
22	Required IF C/N Ratio	dB	7.5	4.3	29.9	5.1	5.1	5.1	5.1	40.9	5.1	5.1
23	Margin	dB	1.5	1.6	1.5	1.5	2.7	8.5	1.5	1.5	1.5	1.5
24	Threshold	dB	8.8	4.3	-	5.1	5.1	5.1	5.1	-	5.1	5.1
25	Actual IF C/N Ratio	dB	9.0	6.3	35.0	6.6	7.8	13.6	6.6	46.0	6.6	6.6
26	Ground Receiver Δ$	$	50.00	2945	100.00	1100.00	1100.00	1100.00	1100.00	2111.00	453.50	1100.00
27	Type		Preamp + Mod Conv	Paramp + Mod Conv	Preamp	Paramp + Mod Conv	Paramp + Mod Conv	Paramp + Mod Conv	Paramp + Mod Conv	Paramp + Freq Conv	Paramp + Freq Conv	Paramp + Mod Conv
28	Cost	$	11.50	903.00	12.50	475.00	475	475	475.00	1528.00	41.00	475.00
29	Noise Figure	dB	3.0	1.9	3.3	1.9	1.9	1.9	1.9	1.4	3.2	1.9
30	Noise Temperature	°K	290	159	330	159	159	159	159	110	316	159
31	Line Loss	dB	0	0.2	0	0.2	0.2	0.2	0.2	0.05	0.05	0.2
32	Receiver and Cable Noise, Antenna Terminal	°K	290	175	330	175	175	175	175	114	322	175
33	Antenna Characteristics											
34	Cost	$	37.00	2040.00	85.00	620.00	620.00	620.00	620.00	580.00	420.00	620.00
35	Gain	dB	10.0	48.3	19.5	47.7	47.7	47.7	47.7	33.0	30.0	47.7
36	Size (Equiv Dia)	ft	1.75	13.7	5.2	8.8	8.8	8.8	8.8	7.8	5.5	8.8
36a	Size (Equiv Dia)	m	0.535	4.25	1.59	2.68	2.68	2.68	2.68	2.38	1.67	2.68
37	HPBW		49°	0.59°	16.5°	0.64	0.64	0.64	0.64	3.5°	5°	0.64
38	Sky Temperature	°K	2 35	152	45	202	204	138	158	22	22	177
39	Indigenous (Man-Made)	°K	0	0	29	0	0	0	0	4	6	0
40	Earth	°K	87	3	87	3	3	3	3	17	32	3
41	Ohmic Loss	°K	29	29	29	29	29	29	29	29	29	29
42	Main Lobe Noise	°K	-	-	263	-	-	-	-	-	-	-
43	Total System Noise Temperature	°K	441	369	772	409	411	340	365	186	411	390
44	System Noise Power	dBW	-128.9	-128.0	-131.9	-124.6	-124.6	-125.4	-125.0	-135.1	-124.6	-124.8
45	Carrier Power (Antenna Terminal)	dBW	-117.7	-118.7	-96.9	-118.0	-116.8	-111.8	-118.4	-92.2	-118.0	-118.2
46	Antenna Pointing Loss	dB	0	0.5	0.10(0.8°incl'n)	0.7	0.7	0.7	0.7	0.10	0.10	0.7
47	Polarization Mismatch	dB	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
48	Net Receiving Antenna Gain	dB	-9.5	-47.1 -46.9	-18.9	-46.5	-46.5	-46.5	-46.5	-32.4	-29.4	-46.5
49	Total Propagation Loss	dB	182.5	206.0	183.8	211.8	211.6	208.6	209.5	192.5	192.5	210.8
50	Ionospheric Absorption	dB	-	-	0.1	-	-	-	-	-	-	-
51	Tropospheric Absorption	dB	-	0.1	-	0.4	0.6	0.1	0.3	0.1	0.1	0.3
52	Refraction Loss	dB	1	1	0.1	-	-	-	-	-	-	-
53	Fading	dB	-	-	0.0	-	-	-	-	-	-	-
54	Cloud Loss	dB	-	3.0	-	0.9	2.8	2.0	0.6	0.1	0.1	0.7
55	Precipitation Loss	dB	-	0.4	-	4.3	2.0	0.7	2.7	-	-	3.3
56	Free Space Loss	dB	182.5	202.5	182.7	206.2	206.4	205.8	205.9	192.3	192.3	206.0
57	Beam Edge Erp/V. CH.	dBW	55.3	42.2	68.0	47.3	48.3	50.3	44.6	67.9	45.1	45.6
58	On-Axis ERP/V. CH.	dBW	58.3	45.2	71.0	50.3	51.3	51.3	47.6	70.9	48.1	48.6
59	Satellite Antenna Gain	dB	32.1	32.1	39.0	32.1	36.3	36.3	32.1	34.5	34.5	32.1
60	Power Gain/V. CH.	dBW	26.2	13.1	32.0	18.2	15.0	15.0	15.5	36.4	13.6	16.5
61	RF Power Output/V. CH.	W	417.0	20.4	1583.0	66	32	32	36	4370	23	45

* With respect to row 14, that sign indicates picture quality slightly better than grade shown.

A FOLDOUT FRAME #1

B FOLDOUT FRAME #2

7.2.2.3.1 Television to India

The subsatellite location, minimum coverage angle, and beam centerline locations were derived from the following considerations.

"Optimum" location of a satellite to India from the coverage standpoint is 79 to 80°E, although there is wide latitude with respect to the placement. Since there is a stable point at ≈ 77°E, it was selected to minimize E-W stationkeeping considerations. The minimum coverage angle to cover all of India, including Assam (the area between East Pakistan and Burma), would be 5 degrees, but if Assam is excluded India can essentially be completely covered by a 4 degree beam as shown in Figure 7.2-1. Since the population

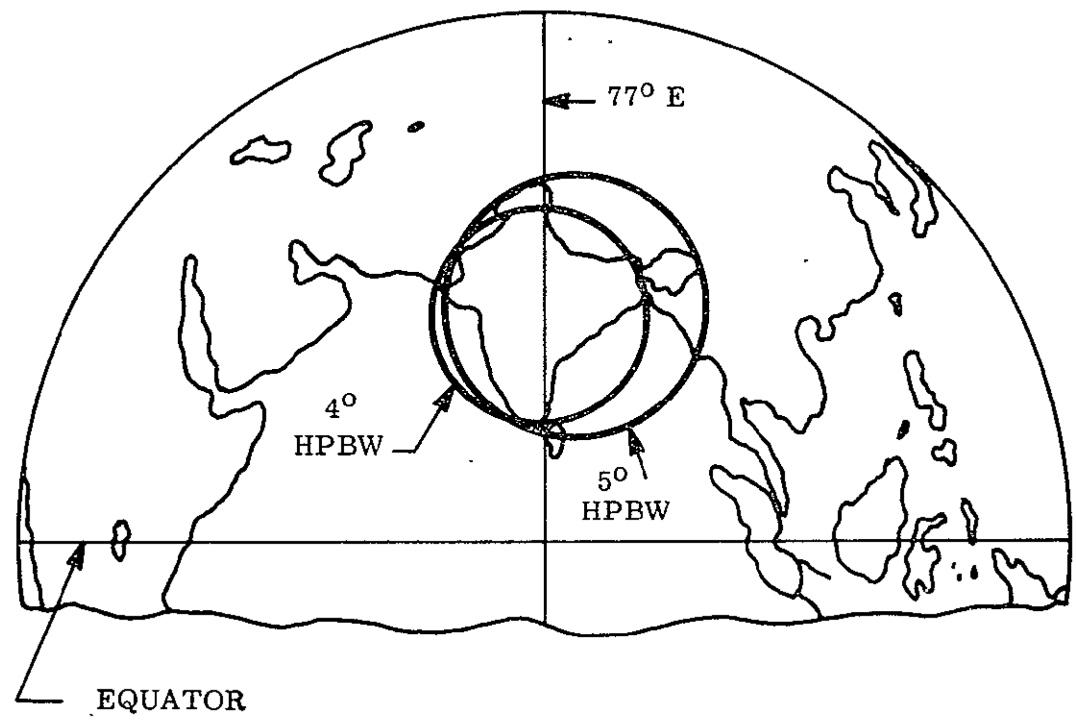


Figure 7.2-1. Community Service to India Beam Coverage

is small in the sector mentioned above, and the price to the satellite would be about 2 dB of additional power an economic tradeoff results in the selection of a 4-degree HPBW antenna and more sensitive ground receiver equipment in Assam. The signal level at this region would be down an additional 4 to 5 dB from that at the HPBW point, but this differential can readily be achieved at UHF frequency for approximately a $10 increase in antenna cost (see Section 4).

The beam centerline location was taken directly from Figure 7.2-1. The data in rows 8 through 12 are based on an extreme coverage location such as Amritsar near Lahore at the Pakistan border.

7.2.2.3.2 Direct Service to Alaska

The satellite must be positioned so that it can see the western United States for the uplink and transmit to any area of Alaska, excluding the Aleutian chain. It would have been desirable to permit location of the uplink in the eastern United States region, but the following considerations precluded this. Positioning the satellite at 120°W would permit good coverage of Alaska with a reasonable ground elevation angle from New York (25°). However, this would result in the satellite eclipse coming at about 9:30 p.m. local time to Alaska, which would be basically undesirable. Therefore, the satellite was positioned at 135°W, resulting in eclipse at 10:30 local time. The RF radiation pattern for the Alaska case was initially assumed to be circular in shape, but the excess spillover and inefficiency led to the decision to consider a shaped beam. The E-W distance from Ketchikan to the Alaskan peninsula governs the maximum beam dimension, which is 3 degrees (5.24 crad). A 1-degree (1.75 crad) width can cover Alaska from N-S as shown in Figure 7.2-2. Therefore, with an antenna pointing error of 0.05 degree (.0874 crad) rms, we have a requirement of a 1.1 x 3.1 degree (1.92 x 5.4 crad) elliptical beam. The beam centerline location is 145°W, 60°N.

The resultant broadcast geometric propagation factors presented in rows 8 through 12 are derived using Point Barrow as the extreme fringe target.

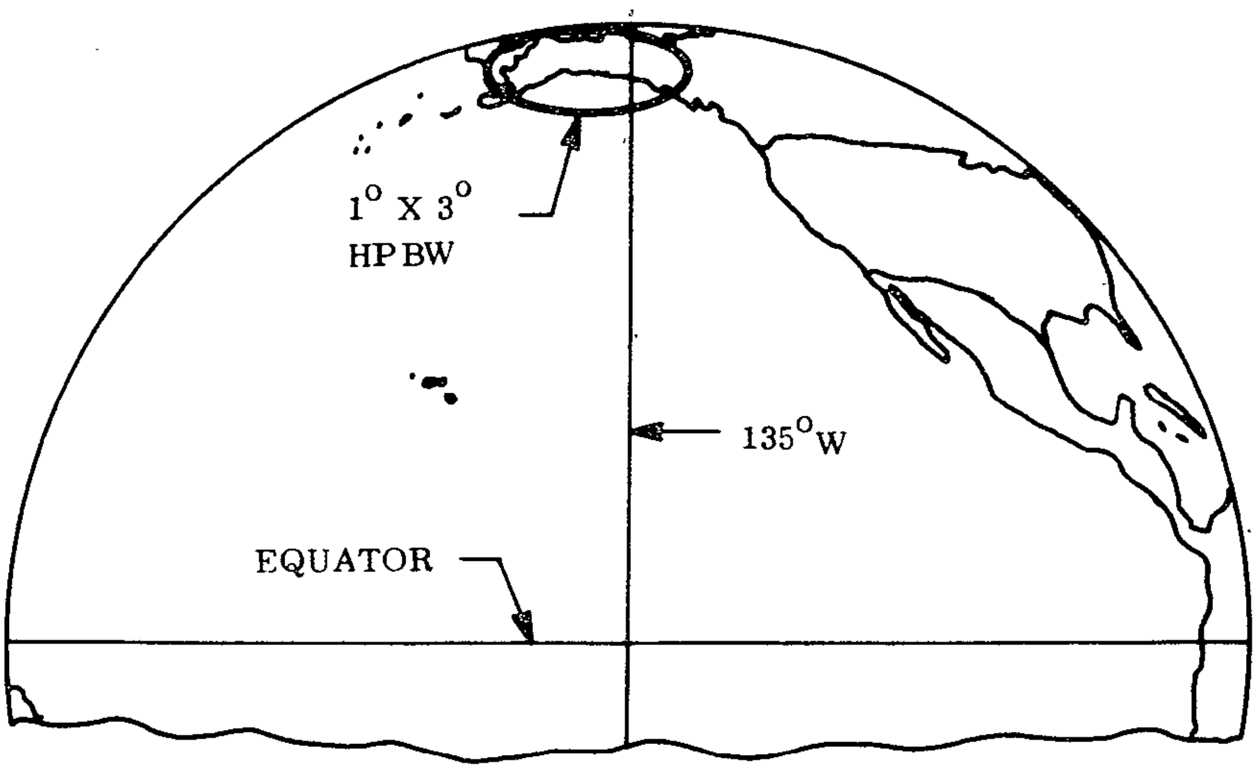


Figure 7.2-2. Direct Service to Alaska Beam Coverage

7.2.2.3.3 Instructional TV to U. S.

The primary mission of this satellite system is to provide coverage of the continental United States with two beams. In order to minimize the beamwidth and use circular beams, it is desirable to locate the satellite off to the side of the target area (in an east/west direction) and thus gain effective beam shaping by the elliptical intersection of the radiation pattern and the earth's surface. The natural direction to shift a satellite would be west of a target area in order to prevent eclipse at an early evening local time, and since this satellite must also provide a secondary service by shifting to cover Alaska and Hawaii, the subsatellite longitude is then selected to be near the western edge of the United States. A location of 120°W is selected in order to achieve satisfactory parameters for Alaska, Hawaii, and Maine.

The satellite can then achieve coverage of the United States with two beams of HPBW = 4 degrees (6.99 crad) as shown in Figure 7.2-3. The remainder of the data is related to the extreme locations for each beam position. The beam centerline coordinates are listed in Table 7.2-2.

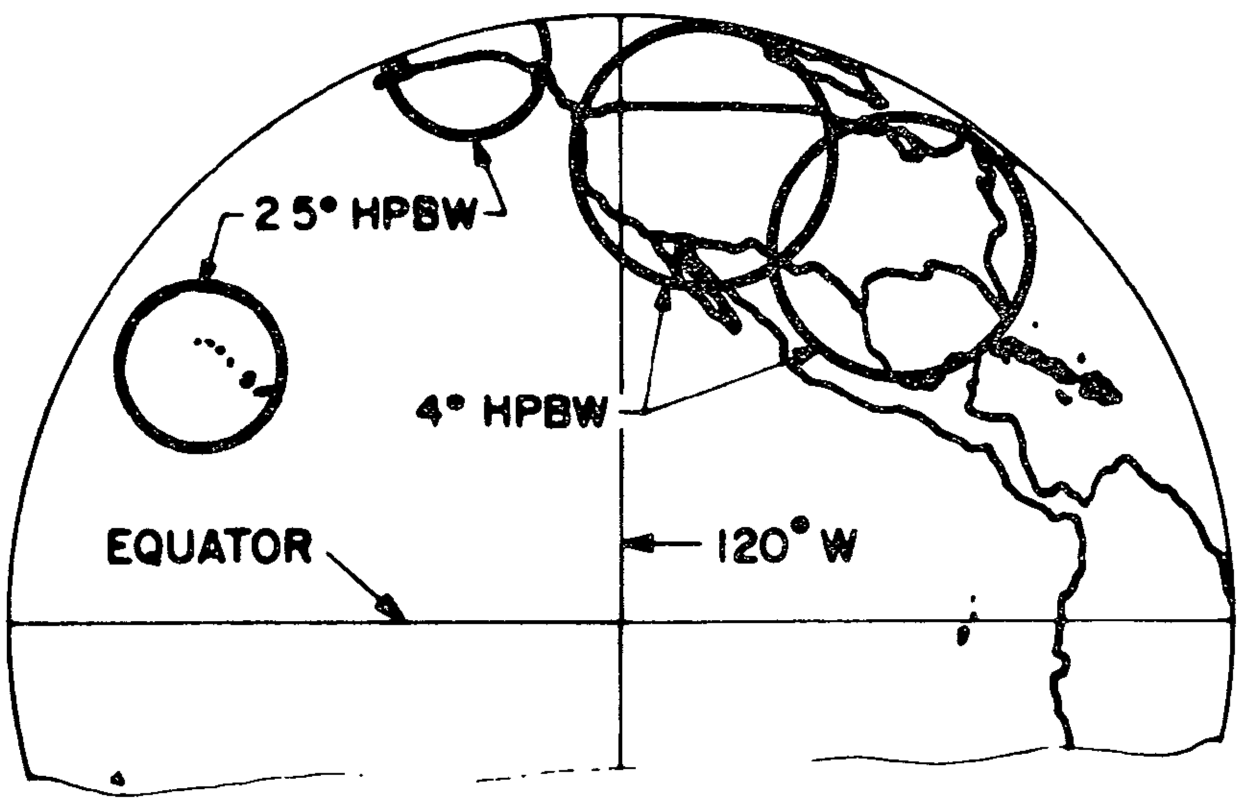


Figure 7.2-3. Instructional Service Beam Coverage

Table 7.2-2. Beam Axis Coordinates (Instructional Service)

Service	Latitude	Longitude
Eastern U. S.	47^{o}N	68^{o}W
Western U. S.	47^{o}N	88^{o}W
Alaska	72^{o}N	156^{o}W
Hawaii	22^{o}N	162^{o}W

The selected method of operation is to provide two beams of 4 degrees (6.99 crad) HPBW to the continental United States, one providing full time coverage to the western United States and one to the eastern United States during morning and early afternoon hours. When the eastern region daytime programming is completed, the power for this service is switched and divided between two previously inactive antennas aimed at Alaska and Hawaii. Daytime instruction for Alaska and Hawaii would be possible for 5 to 6 hours, and the power could then be switched back to the east for evening cultural/educational programming.

The operational system requirements then result in four sets of propagation parameters to consider. The requirements for the eastern United States (Northern Maine) are considered the critical design condition for the transmitter which also provides the Alaska and Hawaii service, and the ground receiver system in the latter regions would have to accommodate the available power level. Northern Michigan provides the critical design condition for the payload providing coverage to the western United States.

7.2.2.3.4 Demonstration Satellite to the USA

The demonstration satellite is selected to be centrally located with respect to the United States and the specific location is at the west stable point (about 107^{o}W). This causes Maine to be the critical target area and the three payloads onboard were all based on the HPBW coverage extremity being in Maine. The possibility of positioning the satellite farther east exists since it may be easier to inject at around 92^{o}W; however, total propagation factors would not change appreciably. Beam centerline locations were derived from the coverage plots shown in Figure 7.2-4, and resultant requirements based on the Maine target area.

7.2.2.4 Bandwidth Considerations (Rows 15, 16, and 18)

The video baseband bandwidths are taken to be those specified by the CCIR (Reference 7.2-1). These are 5 MHz for System B and 4.2 MHz for System M.

The nominal RF noise bandwidths for the standard AM/VSB transmission are also given by the CCIR (Reference 7.2-2), and for System M this bandwidth is 6 MHz. This is shown in row 18.

For the FM cases, the bandwidth of the audio channels is added to the video bandwidth to arrive at the composite bandwidth values shown in row 16. The exact choice of audio subcarrier frequencies and bandwidths for the multiple aural case depends on many factors

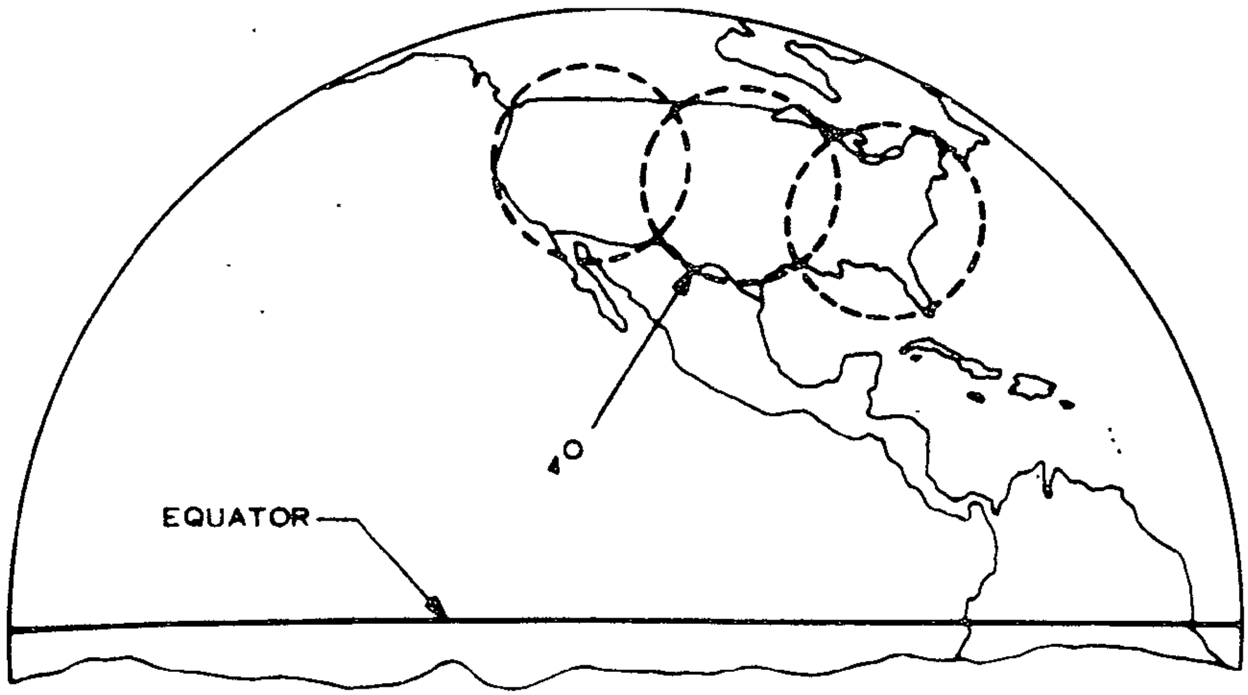


Figure 7.2-4. TVBS Demonstration Satellite Coverage

and the desired objectives. The criterion for selection of audio subcarrier parameters will usually be minimization of RF power and/or bandwidth. However, system nonlinearities, for example, could be the controlling factor (Reference 7.2-2) in the placement of the subcarrier frequencies. Pending a detailed investigation of these factors, it was felt that 0.5 MHz per audio channel, including guardbands, should give a reasonably close estimate of the required bandwidth. This led to the 7 MHz figure for System B with four audio subcarriers. The same audio subcarrier bandwidth of 0.5 MHz for System M would have resulted in 4.75 MHz baseband with the subcarrier frequency at the standard 4.5 MHz. The slightly more conservative value of 5 MHz was chosen for the link calculation.

The IF noise bandwidths for the FM cases shown in row 18 were calculated by using Carson's rule and the modulation indices in row 17. The choice of these modulation indices is discussed below.

7.2.2.5 Required Signal-to-Noise Ratios (Rows 14 and 19)

The required signal-to-noise ratios (SNR) are specified in terms of two different (but related) measures. The more fundamental description is the signal-to-weighted noise ratio shown in row 19. The "signal" in this definition is the white-to-blanking level, as specified by the CCIR (Reference 7.2-3). The noise is measured at the output of a noise-weighting filter which simulates the "filtering" done by the psychophysical system of a human observer. The characteristics of this filter are given by the CCIR, which also gives the noise-weighting "improvement" (ratio of noise power at output to that at input of the filter). This improvement is a function of bandwidth and noise spectral density and hence, as expected, depends on the TV system used and on the modulation method. For System B using FM, the improvement is given (Reference 7.2-3) as 16.3 dB; the corresponding number for System M using FM is 10.2 dB and for System M using AM, it is 6.1 dB (rounded off to 6 dB). If preemphasis and deemphasis filters are used, following the recommended CCIR relay characteristics (Reference 7.2-4), the combined effect of noise-weighting and deemphasis can be thought of as arising from two cascaded filters. The overall transfer characteristic for the cascade was obtained, and applied to the detector output noise spectrum. By means of graphical integration, the output noise power was obtained, from which a combined improvement for noise-weighting and deemphasis was calculated. This improvement (which applies here only to FM) was calculated for System B as 16.4 dB and for System M as 12.5 dB. These numbers appear in row 20.

In row 14, a description in terms of "Grade," corresponding to the weighted SNR, is given. The Grade descriptions are not inherently quantitative and thus serve, rather, to give a measure of user satisfaction.

7.2.2.6 Modulation Index Selection for FM (Row 17)

The weighted SNR can be written as the sum (in dB) of three terms: (1) the carrier-to-noise ratio (C/N); (2) noise-weighting and deemphasis improvement; and (3) the modulation improvement factor. The latter factor is a function of the modulation index. The weighted SNR for System B and System M is plotted in Figures 7.2-5 and 7.2-6, respectively, as a function of C/N with modulation index as a parameter. The line connecting the threshold points for normal FM reception is shown dashed on the right side of the graphs. Data for threshold was obtained from Enloe (Reference 7.2-5). On the left side of the graphs, a solid line connects the threshold points for FMFB reception. This was obtained from Heitzman, (Reference 7.2-6) using the data for the FMFB system using a single RC low pass filter.

The operating value of modulation index, β, was selected such that the required output SNR corresponds to threshold operation* for that value of β. This is the optimum condition (excluding bandwidth limitations) in the sense that power is minimized for FM

* This applies to all but the broadcast payload for the Community Service to India. Figure 7.2-5 shows that threshold operation would occur for values of $\beta = 1.15$ and ≈ 1.05 for FM with feedback or standard FM, respectively, for the Grade 2 picture with System B specifications. These particular values were deemed to be too small to achieve FM benefits, and the value of $\beta = 1.5$ was selected for this case.

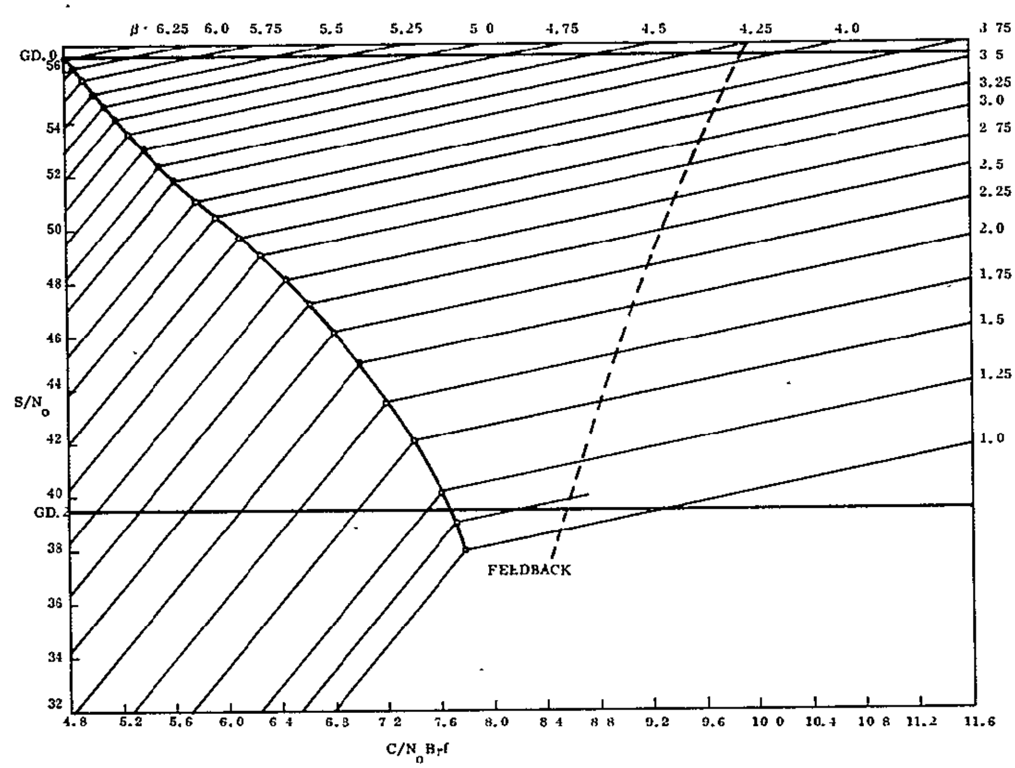


Figure 7.2-5. System B S/N_o Versus C/N_oB_{rf}

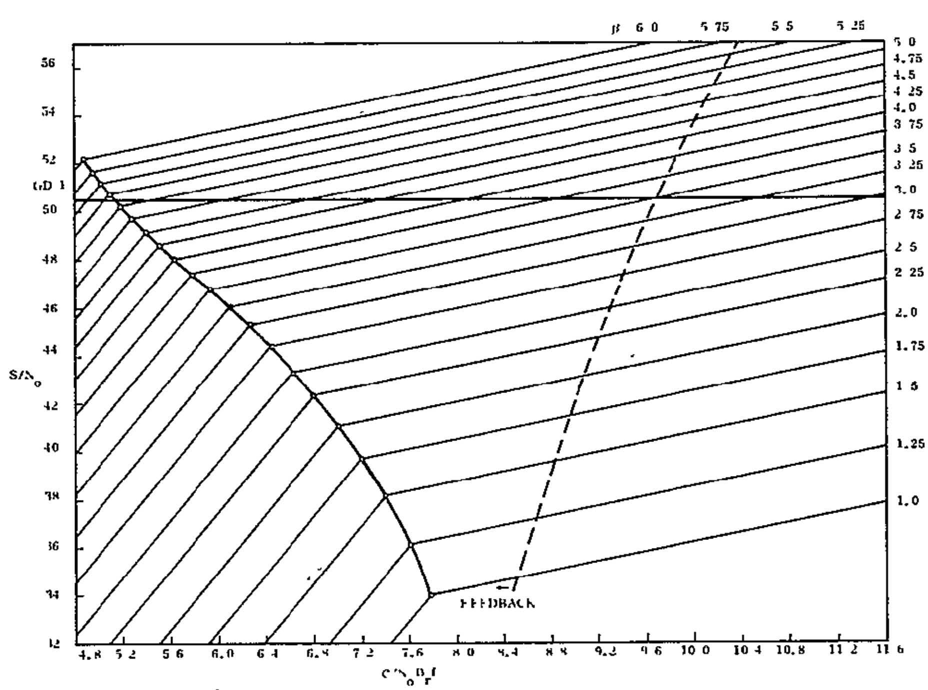


Figure 7.2-6. System M S/N_o Versus C/N_oB_{rf}

reception. This can be easily seen by plotting SNR versus $C/N_o f_m$, where f_m is baseband bandwidth, rather than against $C/N_o B_{rf}$. Such plots have previously been published (Reference 7.2-7). The above statement is not quite true for the lower values of β (<2) but the minimum power required, for given SNR, lies below threshold for some β and is negligibly less than that required for the β which yields threshold operation.

For FMFB reception, the threshold curve has a different slope than that for FM reception. Consequently, the minimum power point, for given SNR, is not at that β which gives threshold operation. However, as before, the minimum power point requires only slightly less power and has the considerable dual disadvantage of lying below threshold for some β, and requiring greater bandwidth. Thus, for FMFB reception, the modulation index was also chosen such that, for the required SNR, it resulted in operation at threshold.

Another point needs clarification. Figures 7.2-5 and 7.2-6 apply, strictly speaking, to a single modulating signal. When two signals (as a video and an audio) simultaneously FM modulate a carrier, the relationship between the SNR (for each of the signals) and C/N is no longer straightforward and the meaning of β becomes vague at best. What has been assumed, in essence, is that the audio subcarrier energy is sufficiently smaller than the video energy that the latter signal essentially determines the frequency deviation, Δf. Then, a meaningful $\beta = \Delta f/f_m$ can be defined. It remains to say, however, what is meant by f_m. To be perfectly consistent, f_m should be the video baseband; however, to recognize the fact that an aural subcarrier does in fact exist, f_m is taken as the composite baseband bandwidth. This method, to be sure, is approximate. However, it gives a very good estimate (which tends to be conservative) and is adequate for the purpose of estimating power budgets until a more detailed design determines the exact audio channel parameters to be used.

7.2.2.7 Required Carrier-to-Noise Ratios (Rows 22 and 25)

The required carrier-to-noise ratio (C/N) together with required IF bandwidth and operating margin determines the required transmitted power. For this study, a system margin on the overall link calculations of 1.5 dB was used, to compensate for the tolerances on propagation factors, equipment installation variation, and potential equipment degradation due to weathering and usage.

Omitting margin, the required C/N is obtained by subtracting from the weighted SNR the noise-weighting and deemphasis improvement and the modulation improvement factor, as discussed above.

In the AM cases, the modulation improvement factor is unity (0 dB). Thus the required carrier power is easily computed, given the system noise temperature. Row 22 shows required C/N. It should be noted, from the definition of SNR, that the corresponding carrier power is (approximately) the average power on sync peaks.

In the FM cases, the modulation improvement factor is computed using the selected values of modulation index. As noted above, the modulation index defined does not, strictly speaking, apply to the video wave-form itself. However, its use introduces negligible error in computation of the modulation improvement. Having computed the latter, the resulting required value of C/N is shown in row 22 and in row 25, with margin added.

7.2.2.8 Ground Receiving Systems

The values of receiving system modification costs were derived from analysis of system trade data by determining trends and minima for specific optimization criteria within the established mission cost constraints and then performing a more detailed trade study to establish the "optimum" design value.

7.2.2.8.1 Direct Service to Alaska

The development and installation of this type of satellite system is likely to be borne by the U.S. government, the ground system installation cost borne by the user, and the operation conducted by a broadcasting company. This implies that either the satellite annual operating cost and/or the receiver cost be the governing cost for minimization. For this service, it was decided to restrict operation to the current UHF/AM standards of terrestrial broadcast.

In this case, the cost factor evaluated was the sum of the amortized costs of the ground receiving equipment (using a ten year amortization) and the satellite annual operating cost. As shown in Figure 7.2-7, the annual operating cost decreases rapidly with increasing ground receiver cost up to about $100. The ground cost of $100 was chosen for this system since increases do not significantly reduce the total cost and would tend to make the service considerably less attractive to the user.

A general system curve applicable to this type of service is shown in Figure 7.2-8, which verifies the above conclusion. This plot shows Total System Implementation cost for a 10 year program plotted versus receiver cost, for varying coverage areas. It can be seen that the larger coverage areas are more sensitive to ground receiver costs (as would be expected), but in all cases the TSI costs decrease as receiver cost increases over the range studies. Since this type of service is essentially geared to provide signals to large remote areas, the decision to select the highest cost receiver within established limits is sound.

7.2.2.8.2 Community TV-to-India

This service, operating at UHF-FM with an audience of 500,000 receivers and a rural environment was to be optimized for minimum Total System Implementation (TSI) cost because it was assumed that a single entity would be sustaining the system costs.

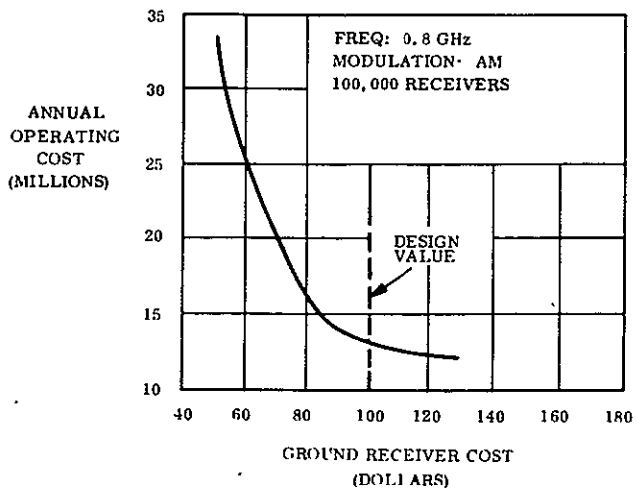


Figure 7.2-7. System Operation Cost - Direct Service to Alaska

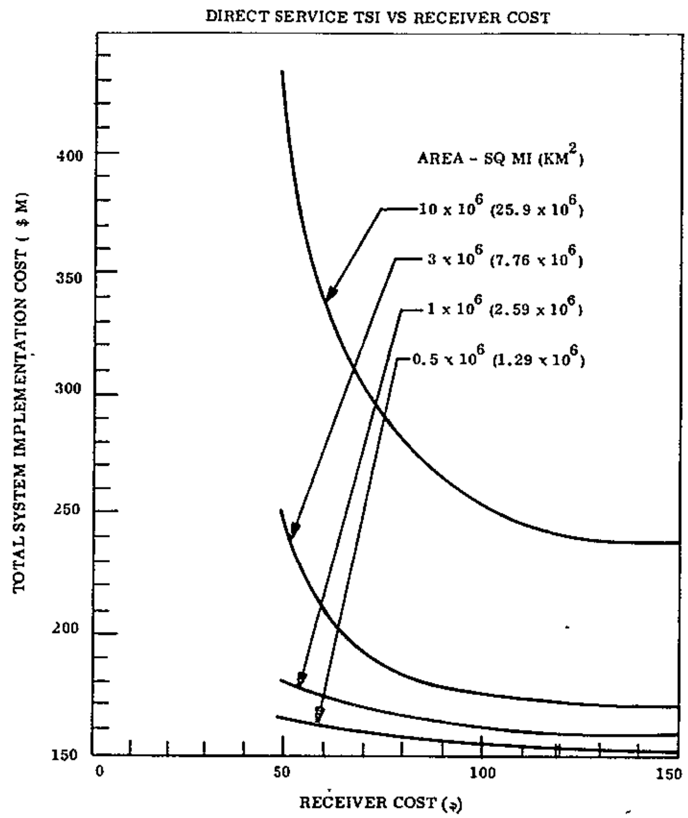


Figure 7.2-8. Direct Service TSI Versus Receiver Cost

The plot of TSI versus ground receiver costs is shown in Figure 7.2-9 for the community service operating at 0.8 GHz/FM. This shows the TSI to be minimized at approximately $50 expenditure on the ground, which was the design value selected. It should be noted that this particular value is based upon U.S. costs. Adjustments may be needed for India, or other countries, but the shape of the curve should be similar with the major effect being slight shifting of the ordinates.

7.2.2.8.3 Distribution-to-India

The ground antenna gain versus HPBW as a function of pointing error is shown in Figure 7.2-10, where it can be noted that maximum values of attainable gain exist, dependent on pointing alignment.

The cost data used for both this case and the Instructional TV to USA case following is shown in Figure 7.2-11, derived from the data of Section 4. The resultant plot of total antenna and satellite power annual cost is then presented as Figure 7.2-12, based upon a quantity of 100 receiving stations.

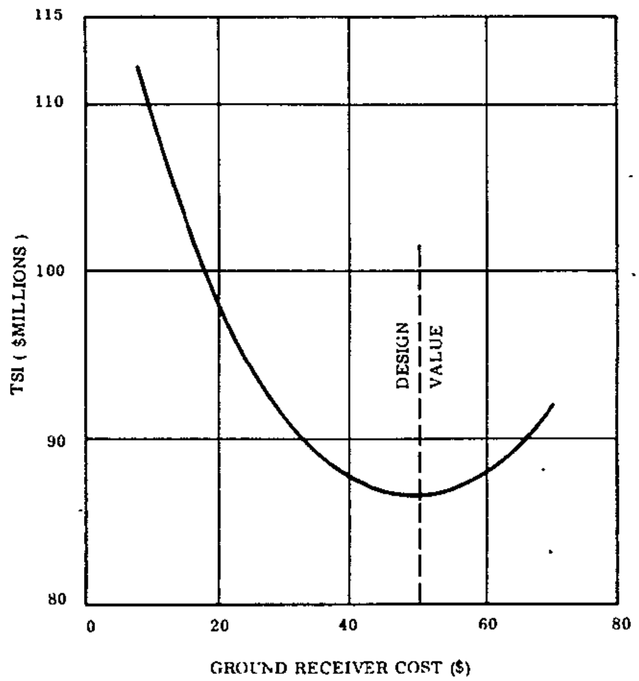


Figure 7.2-9. Community Service to India - TSI Versus Receiver Cost

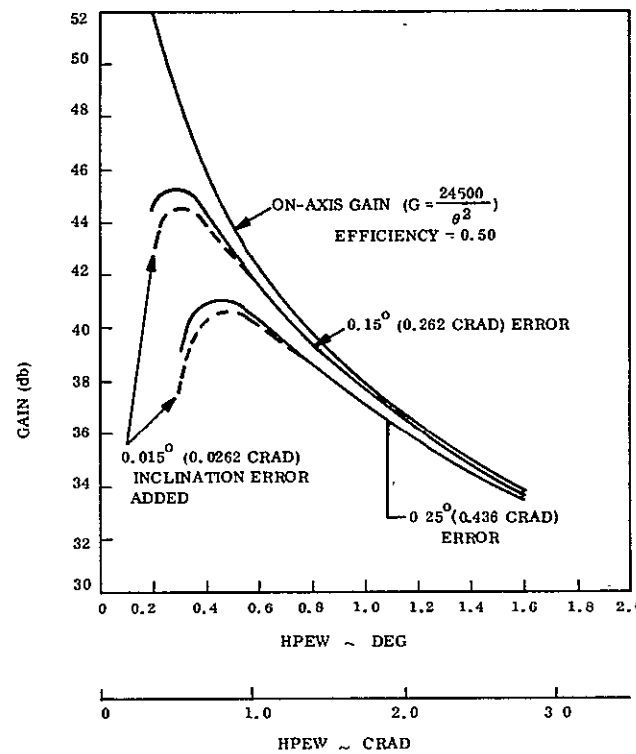


Figure 7.2-10. Antenna Gain Versus HPBW for Varying Pointing Error

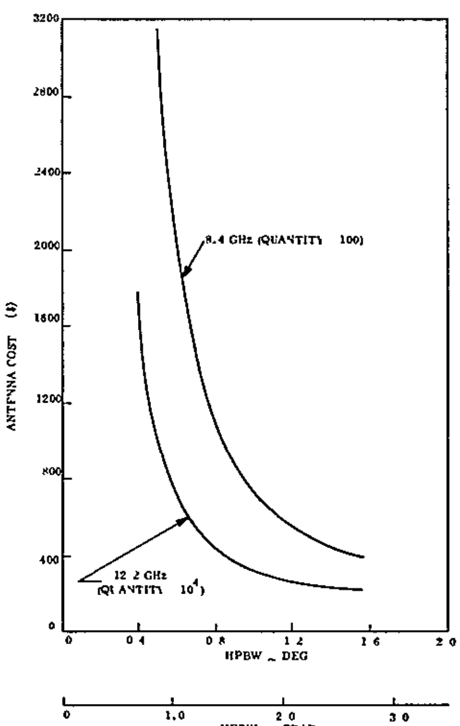


Figure 7.2-11. Antenna Cost Versus HPBW for Varying Frequency

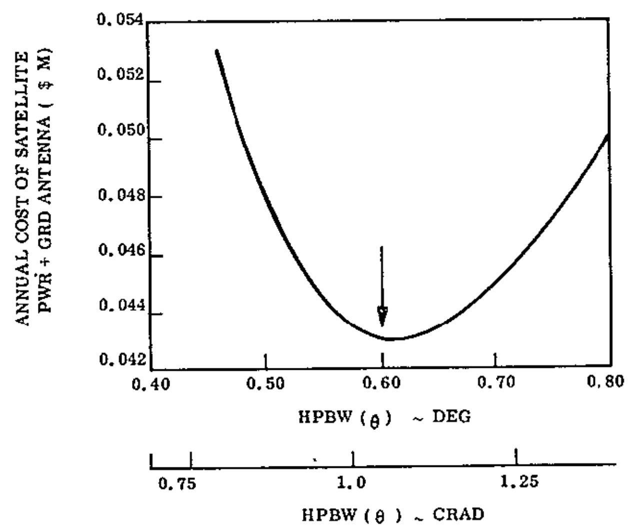


Figure 7.2-12. Distribution to India Total Annual Cost Versus HPBW Ground Antenna

If the effect of pointing error is not included, the antenna cost at 8.4 to 12 GHz is dependent on the area only. The effect of the pointing error is to decrease the effective area or collecting efficiency of the antenna at a given cost.

Examination of Figure 7.2-12 shows that there is very little effect over the range of antennas under consideration in the absolute sense due to the scale of the ordinate, and thus the selection could be made for considerations other than cost, if any. If all other things are basically equal, then the "optimum" cost point does occur at the design value of HPBW = 0.60 degree (1.05 crad).

The ground receiver data for the distribution system to India is obtained directly from Section 4 based on a quantity of 100. The audience figure of 100 was derived from a count of the Indian cities over 100,000 population which came to about 101*.

7.2.2.8.4 Instructional TV to USA

Optimization of ground receiver cost for this service was based on minimizing Total System Implementation cost (TSI), since the system was assumed to be federally financed. In order to obtain a plot of TSI versus receiver cost, the modification in antenna gain due to pointing misalignment had to be taken into account. The resultant plot of TSI versus receiver cost is shown in Figure 7.2-13, and it can be seen that the selected design value of $1100 is optimum.

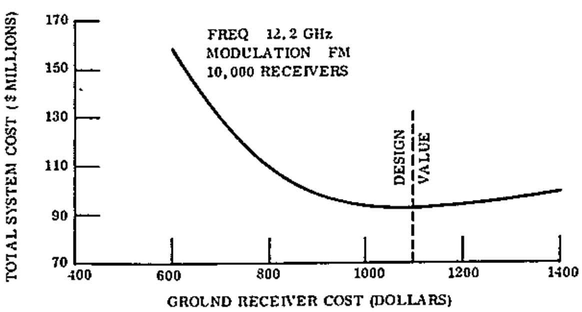


Figure 7.2-13. TSI Versus Receiver Cost

The ground receiver for the Instructional TV to USA must accommodate 6 channels. This design assumed two preamplifiers for the six-channel system. Cost estimates were made based on assumed learning curve and multiple unit integration factors, which resulted in a unit cost of $475 for the frequency converter + preamp + FMFB demodulation converter, with a noise figure of 1.9 dB.

7.2.2.8.5 Miscellaneous Receiving System Data

The remainder of the data presented in rows 26 through 37 is derived directly from considerations just mentioned, and the following criteria.

1. Receiver line loss is assumed to result from a line length equivalent to the focal distance of a parabolic receiving link of equivalent gain.

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* Metropolitan areas with population over 100,000. Total population reached is about 40 million.

2. Receiver and cable noise temperature are then referred to the antenna feed terminals as a reference.

3. Antenna HPBW and size are based on an antenna efficiency of 50 percent.

7.2.2.9 Total System Noise Temperature

The total system noise temperature (row 43) is made up of the receiver noise temperature (row 32) and noise temperature due to external sources. The latter noise contributions are listed in rows 38-42.

The sky temperature, under clear sky conditions with no rain is normally fairly low. The noise temperature for these conditions, denoted T_e*, is available from CCIR data (Reference 7.2-8). Under conditions of cloud, rain, and other attenuation effects, an additional contribution to the noise temperature exists. Let A represent the total attenuation and let ρ be the associated transmissivity, i.e., $A = -10 \log \rho$. Let $T_o = 273^oK$ be the average temperature of the atmosphere, including cloud and rain. Then the total sky temperature is:

$$T_{sky} = (1 - \rho)\, T_o + \rho T_e \tag{7.2-1}$$

The portion of Equation 7.2-1 which is picked up by the antenna is porportional to the average gain of the antenna over the solid angle which the noise source illuminates (Reference 7.2-9). This factor depends upon whether the noise source illuminates primarily the main lobe or side lobes, and is a function of the nominal on-axis gain. Applying this factor to Equation 7.2-1 results in the final value of T_{sky} shown in row 38.

The indigenous (or man-made) noise contribution to the system temperature was computed using the average gain for indigenous noise, as per Reference 7.2-9, and the curves of noise temperature as a function of frequency given in Section 6.1. The result is shown in row 39.

The contribution to noise temperature by pickup from antenna back lobes was again calculated using the procedure of Reference 7.2-9. The resulting number in row 40 was computed assuming a constant earth temperature of 290^oK.

The noise contribution due to the antenna's ohmic loss is shown in row 41. This assumed an antenna radiation efficiency of 0.90 (Reference 7.2-9).

The item (row 42) referred to as "main lobe noise" is indigenous radiation picked up by the main lobe of the antenna. This occurs only in the case of direct service to Alaska and is due to the combination of a very low elevation angle and a relatively wide antenna

*The values of T_e, in ^oK, used for the particular payloads are 53 and 70, respectively, for the UHF cases to India and Alaska, 11^o for the S-band, 2 for the 8.4 GHz case, and 18 for the 12.2 GHz case.

beam. The number shown was computed by assuming that half the main lobe receives indigenous noise, and the temperature contribution was determined by integrating this over the appropriate portion of the antenna pattern.

7.2.2.10 System Noise Power

The system noise power is calculated directly from $N_R = K\, T_S B$, where

N_R = Receiver noise power (watts)

K = Boltzman's constant = 1.38×10^{-23} joule/^oK/Hz

T_S = System noise temperature (^oK)

B = System (IF) noise bandwidth (Hz)

The resulting N_R values are converted into dBW and presented in row 44.

7.2.2.11 Required Carrier Power

These values presented in row 45 are simply the summation of the N_R values in row 44 and the required S/N presented in row 25.

7.2.2.12 Ground Antenna Gain

The ground antenna gain factors are presented in rows 46, 47, and 48. The antenna pointing loss values of row 46 are based on assumption of the ability to maintain a precise alignment of axis to within ± 0.15 degree and an associated orbital inclination angle of 0.8 degree (1.4 crad) for the Direct to Alaska Service case and 0.015 degree (0.0262 crad) for the remainder, which have N-S stationkeeping.

A constant value of polarization mismatch value is assumed and shown in row 47.

The net values of gain shown in row 48 are derived by subtracting the loss values of row 46 and 47 from the gain of row 35.

7.2.2.13 Propagation Losses

The atmospheric propagation loss factors are listed in rows 50 through 55, although in many cases the values become negligible.

The transmission loss, in addition to free space, may be due to absorption in the ionosphere or scattering in either region. In the ionosphere, the expected absorption is usually given by contour plots of attenuation as a function of latitude and time of day. At frequencies above a few hundred MHz, however, the absorption is normally negligible. A possible exception occurs at polar latitudes under conditions of polar cap absorption events for which absorption is about 1 dB at 100 MHz for vertical incidence. For these worst case events, then, absorption in dB is given by

$$(10^4/f^2) \sec \theta \qquad (7.2\text{-}2)$$

where f is in MHz and θ is the angle of incidence.

Tropospheric absorption losses are due to absorption as the water vapor and oxygen resonance lines are approached. The expected losses for vertical propagation through the atmosphere are shown in Figures 7.2-14 and 7.2-15. The absorption increases with the angle from the zenith as shown in Figure 7.2-16. The atmosphere, in addition, exhibits refractive effects on nonvertical ray paths. This induces a change in apparent elevation angle and an associated defocusing, or energy-spreading loss. This is shown in Figure 7.2-17.

Scattering in the ionosphere gives rise to amplitude scintillations, or fading. This effect, for the frequencies considered, is largely negligible except at the highest latitudes and lowest elevation angles. The computation of fading depth has been well documented in previous work (Reference 7.2-10).

Another ionospheric effect, Faraday rotation, does not influence the present systems configurations since the antennas are all circularly polarized.

Atmospheric, or tropospheric scattering loss is usually due to scattering from condensed water in the form of rain, snow, or fog. The attendant attenuations were computed, using Reference 7.2-11 as a basis. For the UHF cases, the rainfall and cloud losses are negligible. The following table gives the assumed parameters used in calculating the precipitation and cloud attenuation factors.

Broadcast Service	Freq (GHz)	Model Type	Rate of Rainfall mm/hr (exceeded 0.1%)	Ground Elevation Angle		Cloud Density (gm/m^3)
				deg	rad	
Rebroadcast to India	8.4	Tropical	23	53	0.925	5
Instructional Service to U.S.						
Eastern U.S.	12.2	Temperate	13	18	0.314	0.3
Alaska	12.2	Temperate	2	5.9	0.103	0.3
Western U.S.	12.2	Temperate	13	29	0.506	0.3
Hawaii	12.2	*	13	49.5	0.864	3.9
Demonstration-U.S.	12.2	Temperate	13	24	0.419	0.3

* Hawaii fits neither the tropical nor temperate model. For the calculations, cloud thickness of 2.1 km was assumed and rain depth of 1 km.

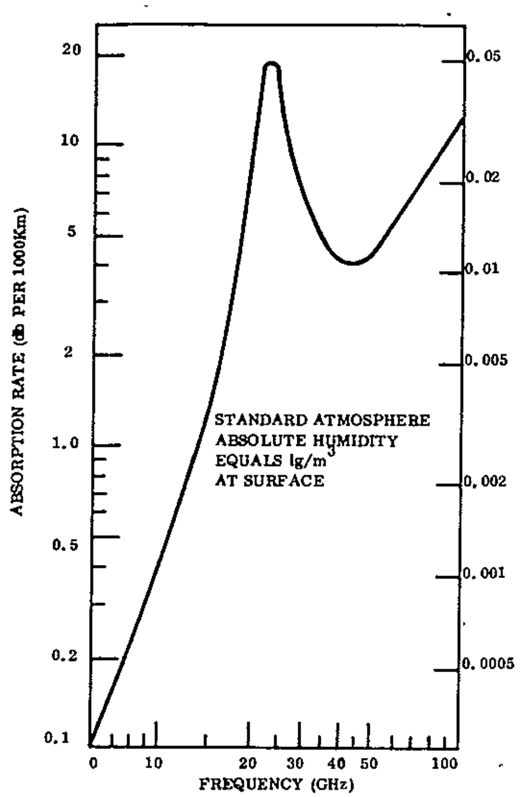

Figure 7.2-14. Water Vapor Absorption Versus Frequency

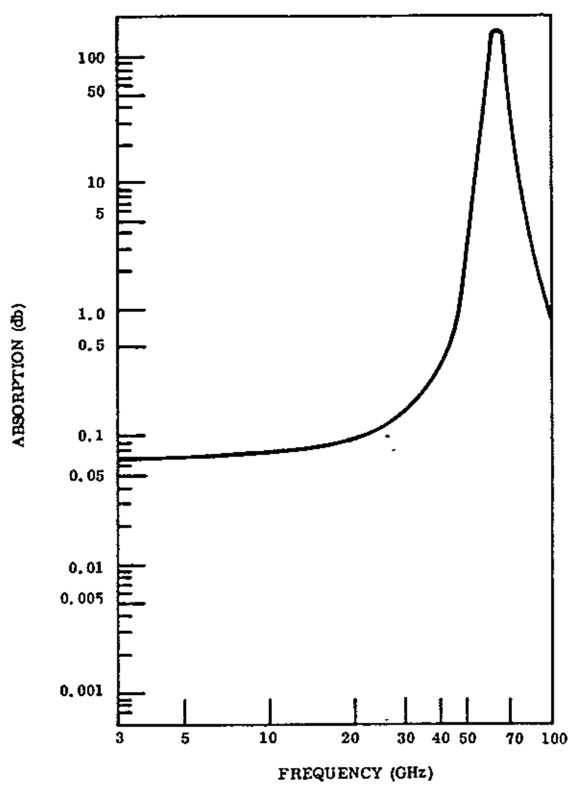

Figure 7.2-15. Earth-to-Space Absorption by Oxygen Along a Vertical Path Between Discrete Resonant Frequencies

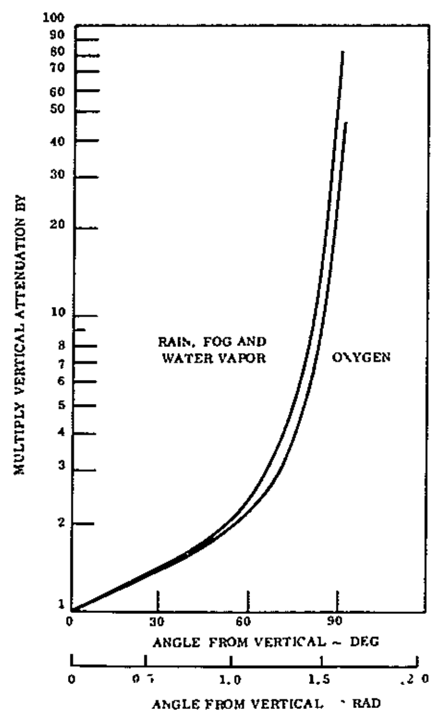

Figure 7.2-16. Path Angle Correction Atmospheric Absorption

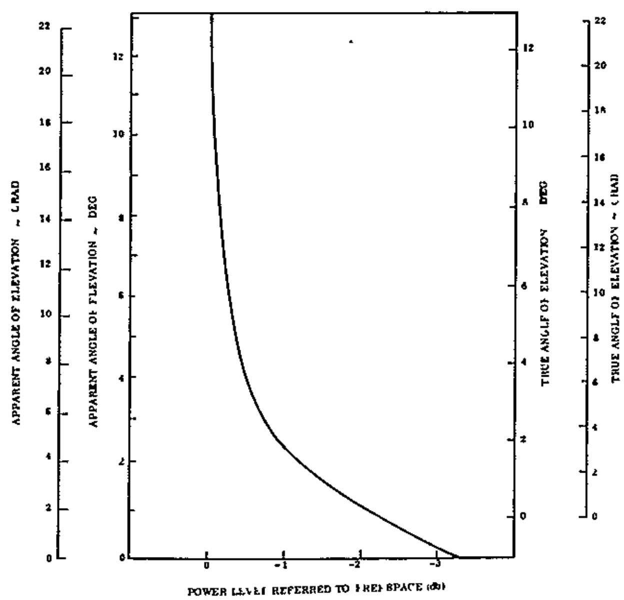

Figure 7.2-17. Attenuation Due to Angular Deviation and Refraction in Passing

Free space loss values in row 56 were derived from the term $(\lambda/4fd)^2$ contained in the link calculation equation for resultant S/No, at the receiver. In this term, λ is the wavelength and d is the distance from transmitter to receiver, both in the same units.

The conventional decibel form for this is

$$\text{free space loss} = 37.8 + 20 \log f + 20 \log d \qquad (7.2\text{-}3)$$

where f = frequency in MHz
d = distance in nautical miles
The d values used here were those of row 10.

The total propagation loss presented in row 49 is the summation of those factors in rows 50 through 56.

7.2.2.14 Satellite ERP Required

The satellite ERP required to achieve the desired signal-to-noise ratio at the receiver is then obtained from the summation of the required carrier power (row 45) net receiving antenna gain (row 48) and the propagation loss (row 49). The resulting values are presented in row 57, and are labeled beam edge ERP because of the system requirement to provide this signal as a minimum over the entire broadcast coverage area.

The total satellite ERP required per video channel (and also assumed to be pertinent for the multiple audio cases) listed in row 58 is simply the value in row 57 plus 3 dB, to account for describing satellite antenna gain in terms of the on-axis gain, and the corresponding requirement to use the HPBW at the edge of the coverage area. An exception is Hawaii, for which the gain at the edge of the coverage area is 1 dB down.

The transmitting antenna gain is then listed in row 59, and the required power gain in dBW and W are listed in rows 60 and 61.

7.2.3 REFERENCES

7.2-1. CCIR: Documents of the XIth Plenary Assembly, Oslo, 1966: Volume V, Report 308-1.

7.2-2. CCIR: Documents of the XIth Plenary Assembly, Oslo, 1966: Volume V, Reports 289, 290.

7.2-3. CCIR: Documents of the XIth Plenary Assembly, Oslo, 1966: Volume V, Recommendation 421-1.

7.2-4. CCIR: Documents of the XIth Plenary Assembly, Oslo, 1966: Volume IV, Recommendation 405.

7.2-5. L. H. Enloe, "Decreasing the Threshold in FM by Frequency Feedback," Proc. IRE, Vol. 50, pp. 18-30, January 1962.

7.2-6. R. E. Hertzman, "A Study of the Threshold Power Requirements of FMFB Receivers,: IRE Trans. Space Electronics and Telemetry, December 1962.

7.2-7. H. Akima, "Theoretical Studies on Signal-to-Noise Characteristics of an FM System," IEEE Trans. Space Electronics and Telemetry, December 1963

7.2-8. CCIR: Documents of the XIth Plenary Assembly, Oslo, 1966; Volume IV, Report 205-1.

7.2-9. Report TR-PL-9037, "Technical and Cost Factors that Affect Television Reception from a Synchronous Satellite," by Jansky and Bailey Systems Engineering Department, under contract NASW-1035, dated 30 June 1966.

7.2-10. Document No. 67SD4330, "Final Report - Voice Broadcast Mission Study - Volume II - Study Report," by General Electric Co., under contract NASW-1475, dated 14 July 1967.

7.2-11. W. Holzer, "Atmospheric Attenuation in Satellite Communications," Microwave Journal, March 1965.

7.3 CONCEPTUAL SATELLITE DESIGNS

This section describes the conceptual designs generated for the satellites and satellite subsystems for the four TVBS systems analyzed during Phase 3 of the study. These designs meet the system requirements specified in Section 7.2 which, in turn, resulted from the mission goals described in Section 7.1.

The four satellites are representative of the low-to-medium power (1 to 7 kilowatt) class of satellites analyzed during the study. The size of the antennas vary from very small (a parabola 1.4 feet in diameter) to very large (a 28 by 80 foot elliptical paraboloid). A unique requirement of these satellites is the necessity to point a high-gain, narrow-beam antenna at the earth while continuously orienting a large array of solar cells toward the sun. This dictates a two-body satellite where the two bodies rotate with respect to each other at a rate of one revolution per day.

The narrow beam antenna pattern must be pointed at the earth coverage area with great precision to prevent RF power loss and interference due to spillover into areas adjacent to the coverage area. However, the solar array can be oriented to the sun with considerable less accuracy for a comparable loss of dc power caused by the solar cell angle offset to the sun line. As an example, three of the four satellites have half power beamwidths of 4.1 degrees and a pointing requirement of ± 0.05 degrees. This results in approximately 0.5% (0.2 dB) power loss. A comparable 5% power loss from solar array misalignment would occur with a pointing accuracy of ± 18 degrees. Therefore, the attitude control system must point the antenna with 360 times the precision that it could point the solar array.

Employment of aperture antennas in the four satellite concepts implies an antenna module which is rotated mechanically with respect to the solar array module. This rotation makes possible several concepts for transferring power from the solar array to the antenna. The satellite is considered to be composed of the following four major payload elements: 1) the transmitting antenna subsystem, 2), the transmitter subsystem, 3) the power conditioning subsystem, and 4) the solar array subsystem. The basic difference in configuration is the manner of combining the four elements into the two modules and the mechanical and electrical characteristics of the joint between the modules. These alternative concepts are shown schematically in Table 7.3-1 with the characteristics of the joint defined.

All concepts use a flexible cable to transfer power through the $\pm 23\ 1/2$ degree motion caused by the seasonal variation of the sun line to the orbital plane. The dc rotary joint (concepts II and III) was selected for all four conceptual designs. The satellite yaw flip required for concepts IV and V would impart large disturbances. The RF joint required by concept I has higher power losses and is more complex than a dc rotary joint.

Each satellite design discussed below shows the launch stowage configuration, the deployed orbital configuration, and the interface considerations associated with going from the launch to the orbital configuration.

Table 7.3-1. Schematic Configuration Concepts

Concept Number	Schematic of Elements	Definition
I	$\boxed{A}\ \underset{RF}{/}\ \boxed{T}\boxed{PC}\boxed{SA}$	Single axis, full rotation RF joint between antenna and transmitter.
II	$\boxed{A}\boxed{T}\ \underset{DC}{/}\ \boxed{PC}\boxed{SA}$	Single-axis, full rotation dc joint between transmitter and power conditioner. Requires high voltage transfer at slip-rings.
III	$\boxed{A}\boxed{T}\boxed{PC}\ \underset{DC}{/}\ \boxed{SA}$	Single-axis, full rotation dc joint between power conditioner and prime power. Permits low voltage transfer at slip rings.
IV	$\boxed{A}\boxed{T}\ \underset{360^o}{/}\ \boxed{PC}\boxed{SA}$	Same as II except the joint rotation is limited to $\lesssim 360^o$, coupled with a reversal of satellite yaw motion at one period in the orbit. Uses a flexible cable in place of slip rings to transfer power.
V	$\boxed{A}\boxed{T}\boxed{PC}\ \underset{360^o}{/}\ \boxed{SA}$	Same as III but with the joint described in IV above.

A - Antenna PC - Power Conditioner
T - Transmitter SA - Solar Array

7.3.1 SATELLITE DESIGNS

The four TVBS phase 3 designs are presented in this section, with a brief discussion of the pertinent characteristics associated with each.

7.3.1.1 Community/Rebroadcast Service to India

The satellite concept for this service to India employs a sun orbit-normal reference system to fully orient the solar array to the sun, and a cooperative ground beacon for pointing the antennas to the desired location on the earth. This requires a full 360^o (2π rad) per day rotation of the solar array assembly with respect to the antenna/body module. The power is transferred using low voltage, dc slip rings. Seasonal inclination of the solar array to track the sun would be accomplished by a $\pm$ 23-1/2^o (0.41 rad) motion.

The satellite antenna package consists of a deployable 21 ft (6.4 m) diameter UHF antenna with a concentric X-band antenna (8.4 GHz) mounted on the back of the prime focus feed. Highly accurate pointing of the antennas is accomplished by error signal detection from an RF interferometer system. CFA and TWT power amplifiers are used for the UHF and X-band systems, respectively. Alternate power amplifiers are the gridded tube for UHF and the Klystron for X-band.

The satellite configuration is shown in Figure 7.3-1.

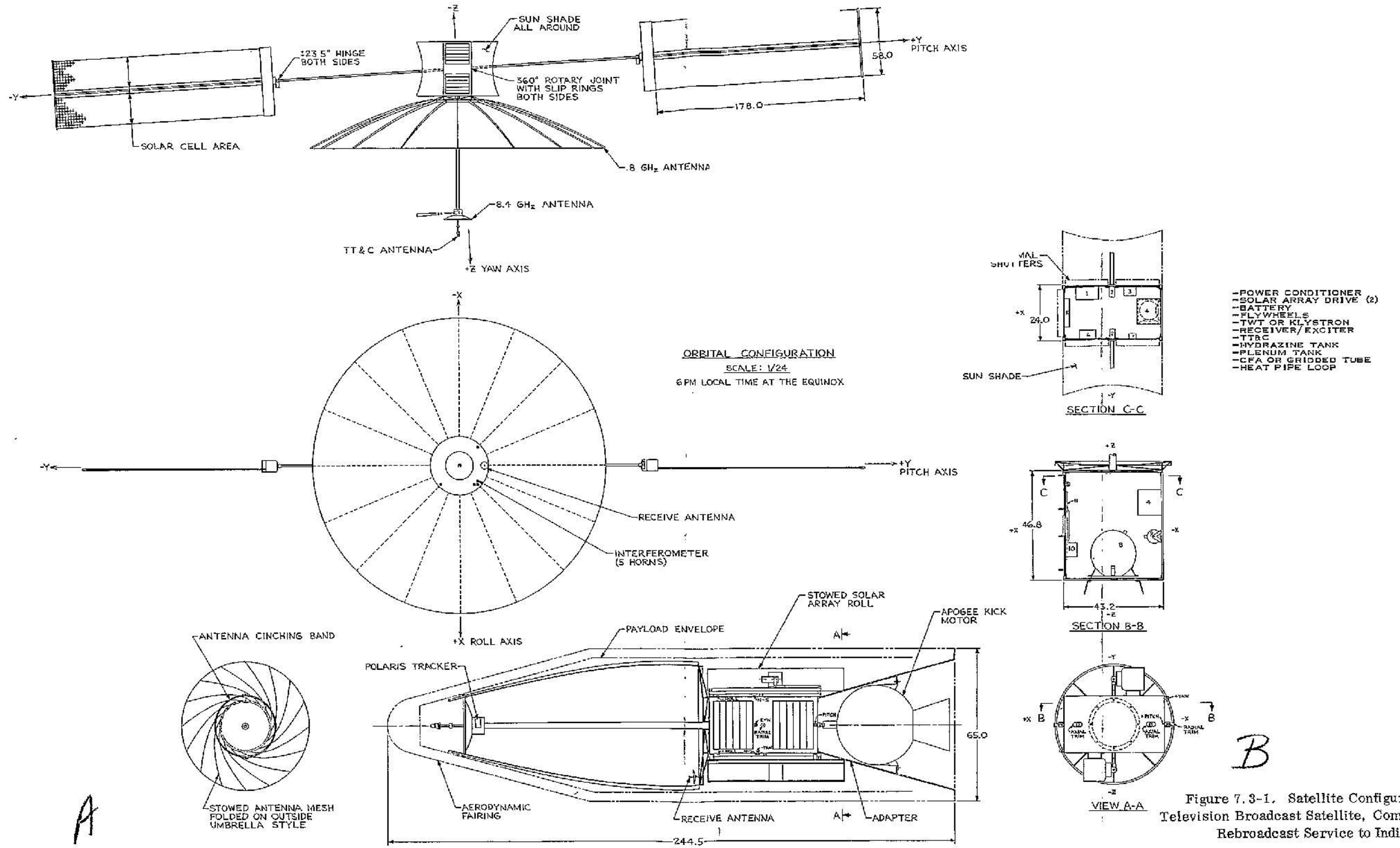

Figure 7.3-1. Satellite Configuration, Television Broadcast Satellite, Community/ Rebroadcast Service to India

FOLDOUT FRAME #1

FOLDOUT FRAME #2

Total orbital weight of the satellite is 752 lbs (341.9 kg). Since the booster selected (Atlas E (or F)/Agena D/AKM*) has a payload capacity of 910 lbs (413 kg), there is a weight margin of 21%. The AKM was assumed to be nominal design of the Surveyor type employing a mass fraction of 0.9 and an I_{sp} of 290 seconds.

7.3.1.2 Direct Service to Alaska

Direct Service to Alaska would require a significant increase in performance from present-day satellites. Broadcasting is done with existing standards, using AM modulation, which requires high power levels ($\approx$ 5.5 kw). Restriction to UHF as the carrier frequency, causes the squinted narrow-beam antenna to be extremely large (29 x 80 ft) (8.85 x 24.4 m) although it may be possible to somewhat reduce the size of the antenna without incurring a significant system penalty. A large elliptical dish to track the earth is, therefore, specified, with the long axis approximately parallel to the satellite pitch axis. The high power level requires fully-oriented solar arrays that rotate about the pitch axis one revolution per day with respect to the antenna.

The size, orientation, and rotation requirements impose a serious constraint on the satellite configuration, since existing and proposed shroud dimensions mandate a deployable antenna and deployment of the solar array to a position beyond the antenna extremities. The configuration (shown in Figure 7.3-2) includes an inflatable antenna reflector and two symmetrical solar arrays deployed with four telescoping tube assemblies. The satellite body is located in the vicinity of the antenna focal point, so that the feed location can be controlled from a sensor platform which is not separated from the feed by a "soft" structural link.

The solar array assemblies are articulated and rotated by independent drive assemblies at the junction of the array with the antenna. In addition, separate propulsion units are located at this junction to provide for balancing of torque during thrusting modes.

The satellite accomplishes attitude control with a constant-speed, pitch fly-wheel to provide orbit normal stabilization, a modulation flywheel for pitch control, sun sensors at the solar array for full orientation, and an RF interferometer for pointing of the antenna in a "closed-loop" mode.

Satellite weight totals 2043 lbs (927.4 kg) as shown in Table 7.3-1. The booster selected (for minimum cost) was a Titan 3B/Centaur/AKM (Ref. Sec. 7.4) which provides an in-orbit payload of 2260 lbs (1025 kg). This provides a 217-lb (97.6 kg) weight margin (about 11%).

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*Apogee Kick Motor

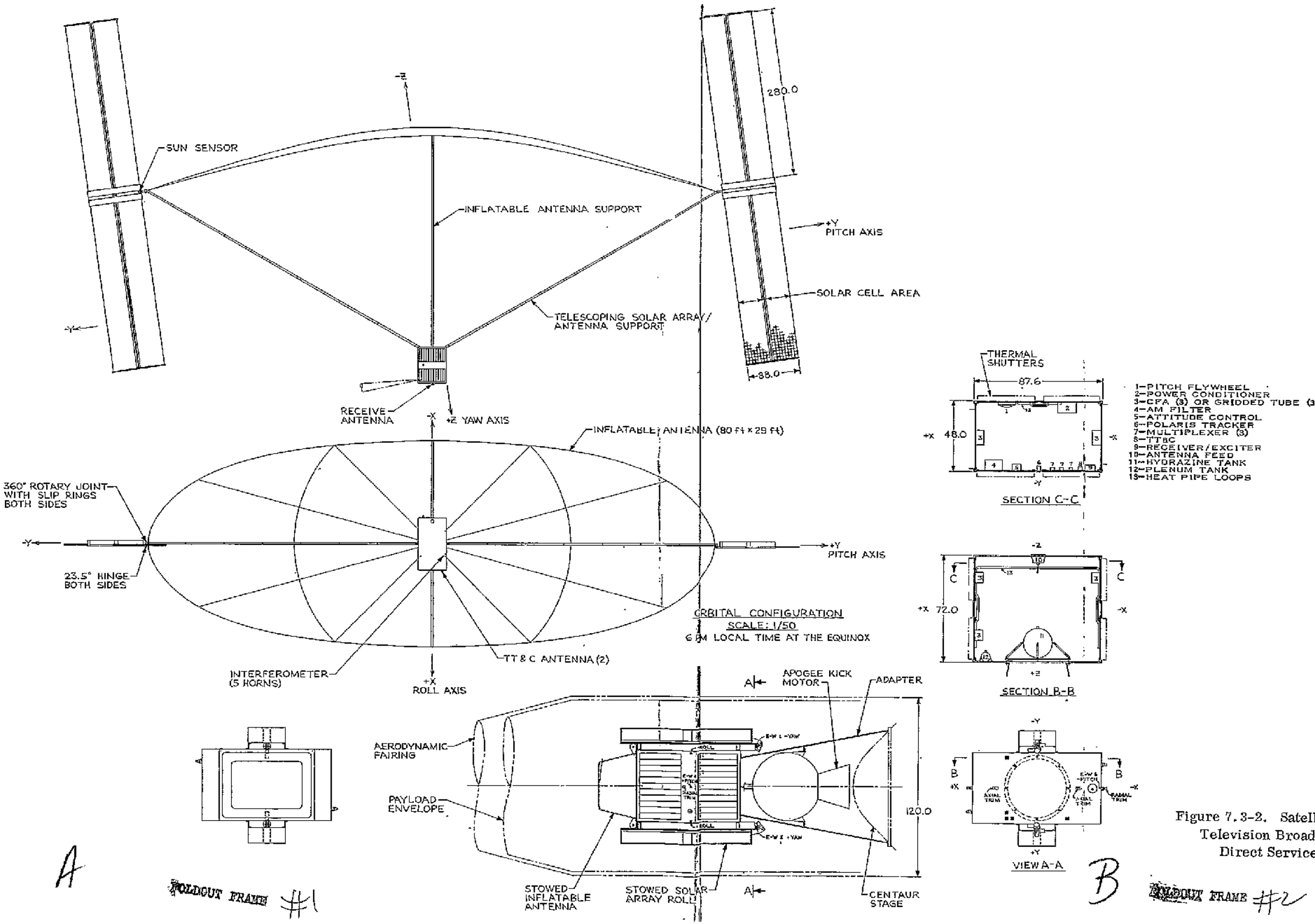


Figure 7.3-2. Satellite Configuration, Television Broadcast Satellite, Direct Service to Alaska

7.3.1.2.1 An Alternate Approach for Direct Service to Alaska

The above design requirements for the satellite providing Direct Television Broadcast to Alaska (namely amplitude modulation, frequency, coverage area location, and picture grade) represent extreme conditions. The use of amplitude modulation (to minimize ground receiver cost and RF bandwidth) requires a very high signal strength to achieve reasonable picture quality. This brings about a requirement for high satellite power levels. Minimizing this power level requires beam shaping to derive a beam that would provide desired coverage to Alaska without excessive spillover. This requirement plus the selection of UHF frequency dictates the use of an elliptical antenna with reflector dimensions of 80 x 29 ft to provide a 1.1^{o} beam in the North-South direction, and a 3.1^{o} beam in the East-West direction. A lower power and smaller satellite, such as for the Community Service to India (see Section 7.3.1.1), would be directly applicable to Alaska. This alternate satellite would be trading off the present usage of existing receivers without converters for the lower power requirements associated with frequency modulation. The India satellite, which has a prime power capability of 1.1 kw, could provide the desired 3-channel service to Alaska, but would sacrifice RF bandwidth and would require a modulation converter at each receiver.

7.3.1.3 Instructional Service to the U.S.A.

This satellite uses a sun/orbit-normal reference system with an RF interferometer system to achieve antenna pointing accuracy of 0.05^{o} (0.0872 crad). Two fully oriented roll-out solar arrays produce a prime power of 2.3 kw. A power conditioning compartment (or module) is fixed relative to the solar array and joined to the earth-tracking transmitting module through a high-voltage dc-slip ring bearing to provide the daily 360^{o} (2π rad) rotation. Seasonal tracking of the solar array is accompished by a pivot on the power supply side of the slip ring. The use of dc rather than RF joints means much smaller losses than would be associated with RF joints at the X-band frequencies. The transmitting module contains the reference sensors and tracking electronics, broadcast transmitters, TT&C equipment, and a pitch flywheel to "stiffen" the roll and yaw stabilization. Figure 7.3-3 shows the satellite configuration. The broadcast transmitting antennas are fixed relative to one another, and the power amplifier output will be switched by means of a mechanical RF switch/divider assembly in the waveguide feed system.

An alternate concept for the orbital configuration, which may be more desirable, is shown in Figure 7.3-4. The major change is the positioning of the solar array with respect to the body so that the resultant solar pressure force vector will be close to the satellite center of mass, thus minimizing the roll/yaw disturbance torque. This will decrease the expendable propellant requirement and eliminate the initial solar array deployment required of the original configuration. The only disadvantage would be a higher aspect ratio solar array, increased thermal radiation blockage for the transmitting module, and a requirement for a different size structure for the upper module as compared to the lower module.

An additional feature is sweeping of the arrays to provide a solar pressure neutrally stable condition by moving the solar pressure center of pressure aft of the center of mass.

Modifications to the stowed configuration would be minimal, as shown in the Figure 7.3-4.

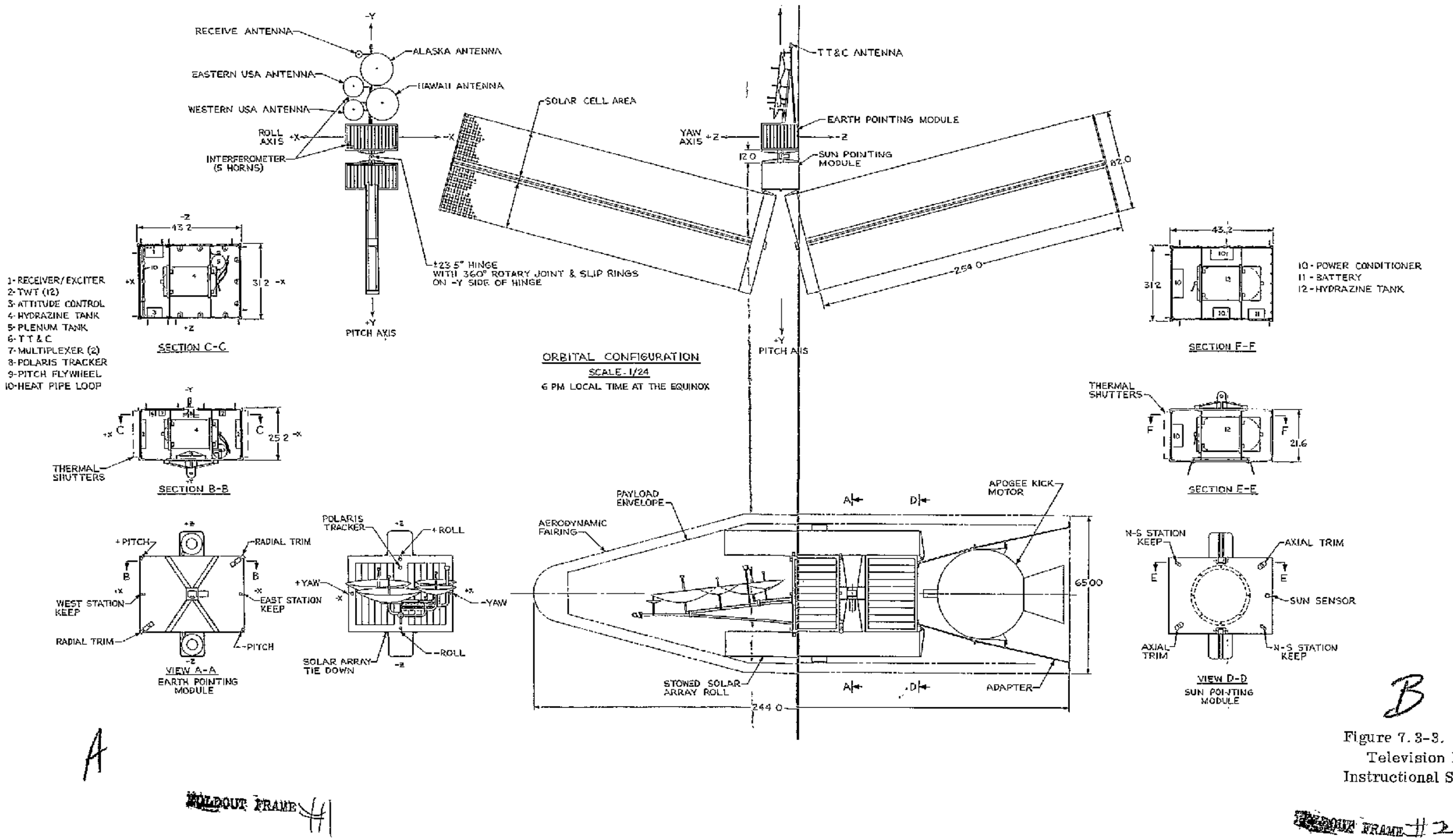


Figure 7.3-3. Satellite Configuration Television Broadcast Satellite, Instructional Service to the U.S.A.

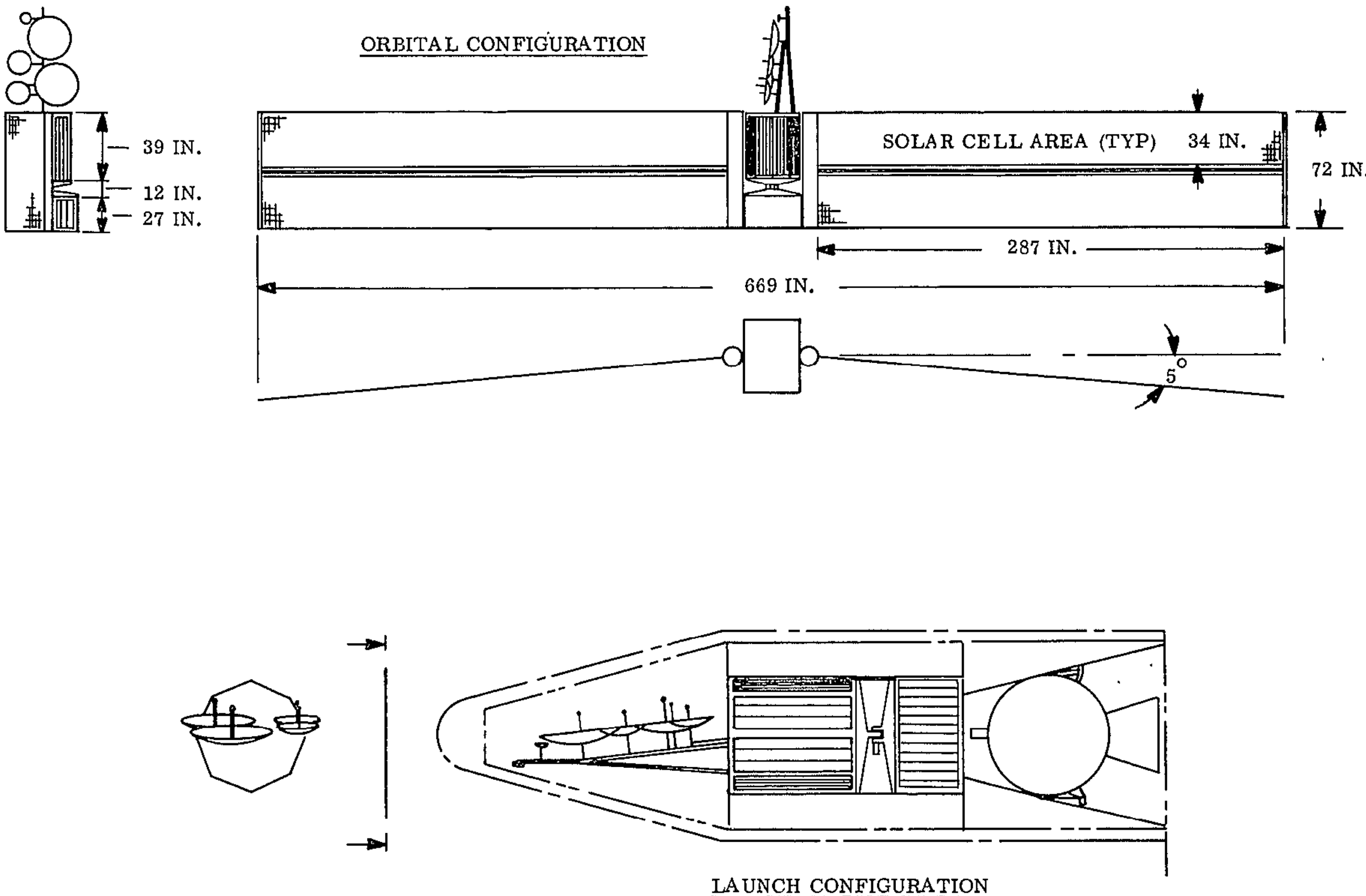


Figure 7.3-4. Alternate Satellite Configuration, Television Broadcast Satellite, Instructional Service to the U. S. A.

7.3.1.4 Demonstration Satellite to the U.S.A.

Figure 7.3-5 shows the Demonstration Satellite to the U.S.A. There are two RF carrier frequencies required: 2.5 GHz and 12.2 GHz. The relative sizes of the antennas would induce unacceptable blockage to the S-band antenna if the X-band antenna were concentric to it, and, therefore, they are positioned side-by-side. The large solar array also would resist motion of the entire satellite to achieve antenna pointing. This pointing is thus accomplished with a gimbal which provides a 2-degree of freedom translational motion.

The attitude control and stabilization is accomplished by an earth/orbit normal reference system using a large pitch angular momentum to stabilize the vehicle frame to the orbit normal. The angular positioning required in pitch is derived from an error signal generated by the RF interferometer beacon from the ground target area.

The precise antenna pointing required is then accomplished by means of the gimbal system mentioned previously in conjunction with a "closed-loop" control electronics employing the interferometer.

The large solar arrays are shown to be four roll-out panels, each with almost 200 sq ft (18.6 m^2) of area, with a total solar cell area of 779 sq ft (72.3 m^2). These arrays would be nominally oriented normal to the sun line with seasonal motion requirements accomplished by means of a $\pm 23\text{-}1/2^{\circ}$ (0.41 rad) hinge.

Thermal control requirements are satisfied by employing four of the six sides for radiating surfaces, as shown in Figure 7.3-5, and internal heat pipe loops to compensate for sun travel around the vehicle in a nominal X-Y plane.

The launch stowage configuration shows the vehicle within a modified OAO shroud for usage with the Atlas/Centaur booster system selected. The weight margin resulting from the selected set of design requirements was only 34 lbs (15.4 kg) or less than 2%.

7.3.1.5 Weight Summary

Table 7.3-2 is a weight summary for the four TVBS designs. All subsystems, exclusive of structure and propulsion, were subtotaled to provide a weight base for estimation of the structural weight. A second subtotal, including structure, was then used for determining the propulsion subsystem weight. The total weight was then used for each launch vehicle selection described in Section 7.4.

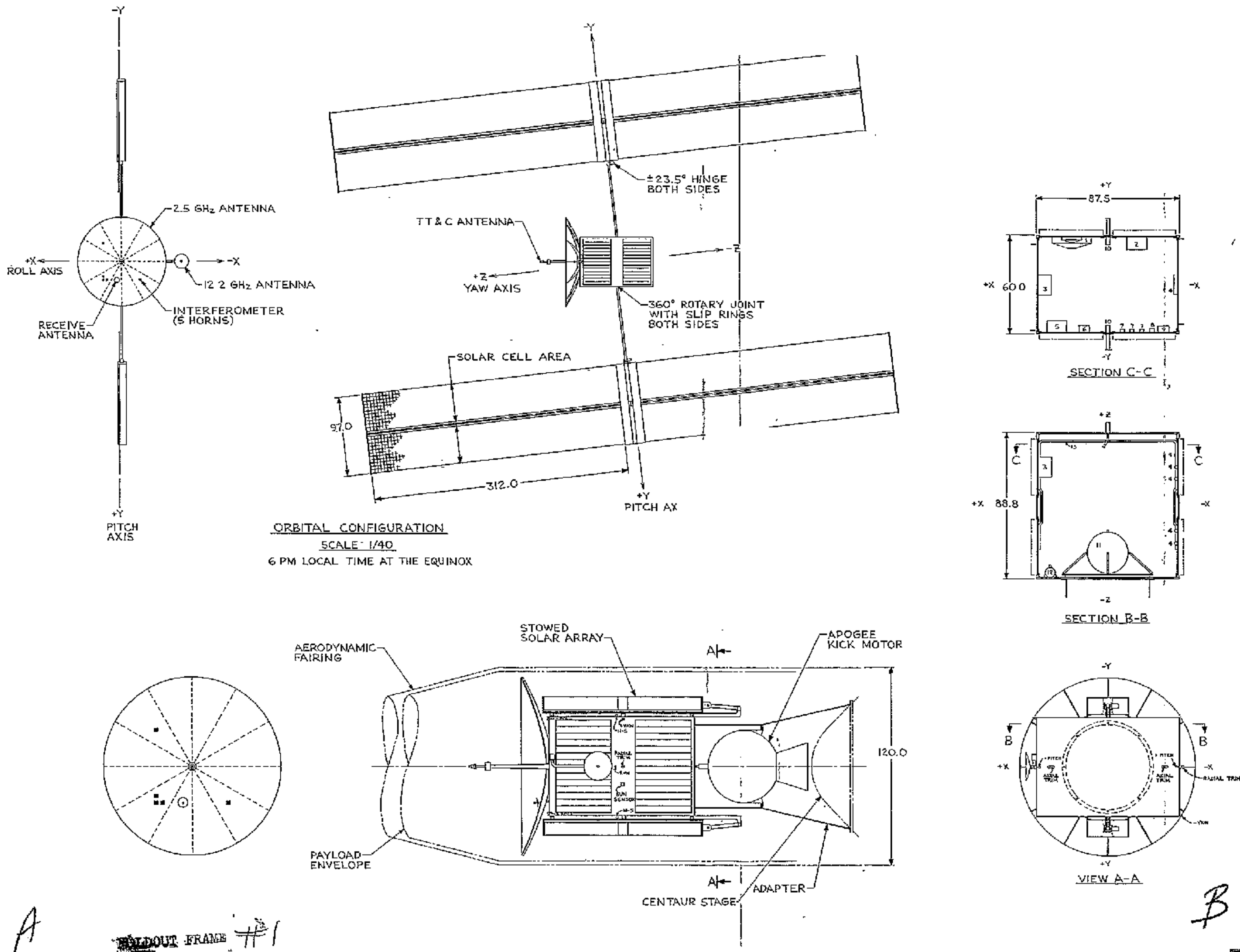


Figure 7.3-5. Satellite Configuration, Television Broadcast Satellite, Demonstration to U. S. A.

Table 7.3-2. TVBS Configuration Weight Summary

Weight in Pounds

Subsystem	TVBS Service			
	Community Service to India	Direct Service to Alaska	Instructional TV to the U.S.	Demonstration to U.S.
Antenna	120	312	21	33
Receiver/Exciter	28	14	52	42
Transmitter	33	232	160	158
Power	150	708	248	868
Thermal Control	43	168	64	240
Attitude Control	86	102	97	109
TT&C	20	20	20	20
Subtotal	(480)	(1556)	(662)	(1480)
Structure	137	360	172	300
Subtotal	(617)	(1916)	(834)	(1780)
Propulsion	135	127	149	256
Total	752	2043	983	2036

Weight in Kilograms

Subsystem	TVBS System			
	Community Service to India	Direct Service to Alaska	Instructional TV to the U S.	Demonstration to U.S.
Antenna	54.5	141.5	9.5	15.0
Receiver/Exciter	12.7	6.4	23.6	19.1
Transmitter	15.0	105.1	72.6	71.6
Power	68.0	321.5	112.5	394.0
Thermal Control	19.5	76.2	30.0	109.0
Attitude Control	39.0	46.3	44.0	49.5
TT&C	9.7	9.7	9.7	9.7
Subtotal	(218.4)	(706.7)	(301.9)	666 9
Structure	62.2	163.1	78.0	136.0
Subtotal	(280.6)	(869.8)	(379.9)	(802.9)
Propulsion	61.3	57.6	67.6	116.0
Total	341.9	927.4	447.5	918.9

7.3.2 ANTENNA DESIGN

This section describes the antenna electrical design for the four satellites. The following system parameters and characteristics were investigated:

1. Electrical Performance Parameters.
2. Antenna Type, Number, and Size.
3. Stowed Volume and Weight.
4. Feed and Transmission Line.
5. Development and Fabrication Cost.

Table 7.3-3 lists the Phase 3 design requirements for the four satellites. These nominal requirements are such that paraboloid antennas were chosen for all configurations. The results from the TVBS Antenna Parametric Analysis performed in Phase I of this study (Section 5.1) were utilized wherever applicable.

Table 7.3-3. TVBS Phase III Antenna Design Requirements

<table>
<tr><th rowspan="2">Parameter</th><th colspan="10">Service</th></tr>
<tr><th>Direct to Alaska</th><th colspan="2">Community to India</th><th colspan="4">Instructional to U S A.</th><th colspan="3">Demonstration to U S A</th></tr>
<tr><td>Number of Antennas</td><td>1</td><td colspan="2">2</td><td colspan="2">2</td><td colspan="2">2</td><td colspan="3">2</td></tr>
<tr><td>Frequency - GHz</td><td>0 80</td><td>0.80</td><td>8.4</td><td colspan="2">12.2</td><td colspan="2">12 2</td><td colspan="2">2 5</td><td>12.2</td></tr>
<tr><td>Half-Power Beamwidths (Deg)</td><td>1.1 x 3.1</td><td>4.1</td><td>4.1</td><td colspan="2">4 1</td><td colspan="2">2.5</td><td colspan="2">3 0</td><td>4.1</td></tr>
<tr><td>" " " (crad)</td><td>1.92 x 5.4</td><td>7.15</td><td>7.15</td><td colspan="2">7.15</td><td colspan="2">4 36</td><td colspan="2">5.24</td><td>7.15</td></tr>
<tr><td>Number of Channel/Feed</td><td>3V/3A</td><td>1V/4A</td><td>1V/4A</td><td colspan="2">6</td><td colspan="2">6</td><td>1 (AM)</td><td>2 (FM)</td><td>2</td></tr>
<tr><td>Number of Feeds/Antenna</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Avg RF Power/Chan (kw)</td><td>0.667</td><td>0.417</td><td>0.0195</td><td>0.066</td><td>0.0355</td><td>0.033</td><td>0 033</td><td>1 826</td><td>0.0225</td><td>0 0445</td></tr>
<tr><td>Avg RF Power/Feed (kw)</td><td>2</td><td>0.417</td><td>0.0195</td><td>0.396</td><td>0.213</td><td>0 198</td><td>0 198</td><td>1 826</td><td>0.045</td><td>0 089</td></tr>
<tr><td>Polarization</td><td>Circular</td><td>Circular</td><td>Circular</td><td colspan="2">Circular</td><td colspan="2">Circular</td><td>Circular</td><td>Circular</td><td>Circular</td></tr>
<tr><td>Bandwidth (MHz)</td><td>6</td><td>35</td><td>101.5</td><td colspan="2">61.5</td><td colspan="2">61 5</td><td>6</td><td>61 5</td><td>61 5</td></tr>
</table>

V = Video
A = Audio

7.3.2.1 Antenna for the Alaska Satellite

Table 7.3-4 lists the antenna system parameters that were developed to satisfy the design requirements.

The shaped beam of 1.1 degrees by 3.1 degrees (1.92 x 5.4 crad), plus the operating frequency of 0.8 GHz, leads to a reflector antenna size that can most readily be configured by using the Inflatable Wire Grid Tube approach. The aperture of this antenna is elliptical; hence, the primary feed warrants special consideration in providing proper edge illumination of the reflector aperture. Because the secondary pattern principal plane beamwidths are in

Table 7.3-4. Antenna System Parameters and Characteristics, Direct Service to Alaska

Number of Antennas	One
Frequency	0.8 GHz
Beamwidths	1.1 x 3.1 deg (1.92 x 5.4 crad)
Type of Antenna	Inflatable Wire Grid Paraboloid; Elliptical Aperture
Aperture Dimensions	Major Diameter = 80 ft (24 4 m) Minor Diameter = 29 ft (8.85 m)
Major f/D Ratio	0.465
Focal Length	37 ft (11.3 m)
Feed Type	Three Element Helix Array
Polarization	Circular
Gain	39.0 dB (η = 55%)
Bandwidth (Available)	20%
Surface Tolerance	±0.5 in (0.3 dB loss)
Sidelobe Levels	Major Axis - 22 dB Minor Axis - 18 dB
Weight	312 lb (141.8 kg), Incl 20-lb (9.08 kg) feed, power divider
Power	2 kw
Stowed Volume	36 ft^3 (1.02 m^3)
Engineering Cost	1.2 million
Fabrication Cost	210 K
Transmission Line	None

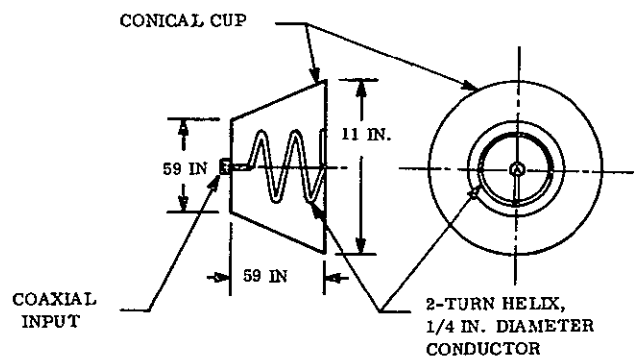


Figure 7.3-6. 800 MHz Helix Element

a ratio of approximately 3:1, the primary pattern beamwidth ratio must also be close to this ratio. Box horns were rejected for the primary feed because of the circular polarization requirement. Arrays of waveguide horns were rejected because of bulk. An array of three helices was finally chosen, and a sketch of a typical element is shown in Figure 7.3-6.

The normally utilized flat ground plane has been replaced by a conical type. Work performed by GE during the Sidelobe Suppression Study (NAS 3-9717) indicates that this conical cup immensely improves the primary pattern of a helix in two ways: First, it symmetrizes the pattern (i.e., minimizes beam squint). Second, the sidelobe levels are decreased and the front-back ratio increased, thus providing a more efficient illumination pattern.

The major and minor axes of the elliptical aperture are 80 ft (24.4 m) and 29 ft (8.85 m), respectively. The three element helix array provides an edge illumination of -10 dB in the major axis plane and -14 dB in the minor axis plane. Typically, in shaped beam antennas of this type, higher sidelobes occur in the plane of the minor axis. This is also the case for this configuration where the sidelobes are estimated to be -18 dB in the minor axis plane and -22 dB in the major axis plane. The focal length of this reflector is 37 ft (11.3 m).

Transmission line considerations for this configuration are not severe since the output devices themselves are located at the focal point of the reflector. The three element feed would nominally be fed from a 3-port coaxial power divider. Since the power requirement is 2 kw, a severe design problem does not exist here.

To point the beam of this antenna in two independent planes, a means of providing lateral feed displacement in orthogonal planes relative to the focal point would be provided. The amount of repositioning required would be a function of the attitude control error and is anticipated as small (<< 1 deg) (1.75 crad). This feed movement would be simple to implement if the active output devices were attached to the feed proper, i.e., no flexible transmission line between the transmitter and feeds.

7.3.2.2 Antennas for the India Satellite

Table 7.3-5 lists the antenna system parameters that were developed to satisfy the design requirements for this service. Two different frequencies of transmission, 0.8 GHz and 8.4 GHz, with equal half power beamwidth requirements of 4.1 degrees (7.15 crad) necessitate the use of two separate parabolical reflectors. The diameters required for this beamwidth are 21 ft (6.4 m) for 0.8 GHz and 2 ft (0.61 m) for 8.4 GHz. Figure 7.3-7 shows the chosen antenna configuration for this service. The focal axes of the reflectors are coincident, and the blockage ratio of approximately 1/10 causes no severe problems.

An erectable petal approach is chosen for the 0.8 GHz frequency band. The primary feed is a helix identical to Figure 7.3-6. The transmission line chosen is 1-5/8 in. (4.13 cm) rigid coax which is coincident with the focal axis. This relatively large size is chosen not to satisfy the relatively low power requirement of 0.417 kw, but to permit the rigid inner conductor to be utilized for the X-band frequency.

Table 7.3-5. Antenna System Parameters and Characteristics, Instructional Service to U.S.A.

Number of Antennas	Two	
Number of Frequencies	0.8 GHz	8.4 GHz
Beamwidths (Circular)	4.1 deg (7.15 crad)	4.1 deg (7.15 crad)
Type of Antennas	Erectable Petal Dish	Non-Erectable Rigid Dish
Deployed Configuration (Figure 7.3-7)	Common Axis	
Aperture Diameters	21 ft (6.4 m)	2 ft (0.61 m)
f/D Ratios	0.375	0.375
Focal Length	7.9 ft (2.41 m)	0.75 ft (0.229 m)
Feed Type	Single Helix	Waveguide Horn
Transmission Line	1-5/8 in. (4.13 cm) Rigid Coax	WR90 Waveguide-Coaxial Waveguide
Polarization	Circular	Circular
Gain	32 dB (η=55%)	32 dB (η = 55%)
RMS Surface Tolerances	0.10 in. (0.254 cm)	0.025 in. (0 0635 cm)
Sidelobe Levels	-23 dB	-25 dB
Weight	115 lb (52.1 kg) [15 lb (6.8 kg) feed, line]	5 lb (2.27 kg) [1.5 lb (0.68 kg) feed, line]
Power	0.417 kw	19 5 Watts
Stowed Volume-Cylindrical:	4 ft diameter x 9 ft length (1.81 m x 4 08 m)	
Eng Cost	900 K	280 K
Fab Cost	220 K	25 K
Bandwidth (Available)	20%	15%

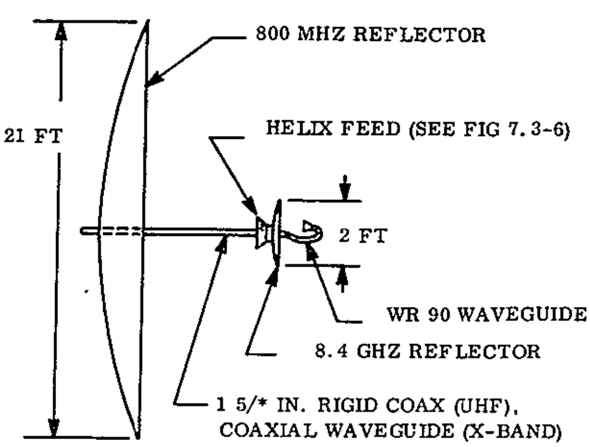


Figure 7.3-7. Deployed Configuration, Community to India

The aperture blockage incurred because of the 2-ft (0.61 m) X-band dish causes a negligible gain decrease. The side lobe level, due to this blockage disc, is -34 dB, and i: hence, not severe. The secondary pattern side lobes are consequently estimated to be -23 dB for the 0.8 GHz frequency.

The 2-ft (0.61 m) rigid 8.4 GHz dish is fed by a 0.9 in. (2.28 cm) square waveguide feed equipped with a polarizer for circular polarization. WR 90 waveguide serves as the trans mission line-feed support in a "quotation mark" configuration. A transition from the TE_1 mode in the WR 90 to the TE_{11} mode in coaxial waveguide is made so that the transmissio line can be symmetric about the focal axis. The coaxial waveguide transmission line utili the inner conductor of the 1-5/8 in. (4.13 cm) rigid coaxial UHF line as its outer conduct plus its own inner conductor. The inner conductor is required to decrease the cutoff frequency of the transmission line. The dimensions of this transmission line are 0.588 in. (1.49 cm) O.D. and 0.392 in. (0.995 cm) I.D. The attenuation which results for this line at 8.4 GHz has been calculated as 4.3 dB per 100 ft (4.23 dB per 30 m). Hence, the line loss is only 0.34 dB. No particular problems are anticipated insofar as power handling is concerned because of the relatively small amounts of power involved in each frequency band.

7.3.2.3 Antennas for the U.S.A. Instructional Satellite

For the antenna design requirements the antenna system parameters of Table 7.3-6 have been developed. Four individual beams at 12.2 GHz are required. Four parabolic reflectors are chosen to produce half-power beamwidths of 4.1 (7.15 crad) and 2.5 (4.36 cr degrees. Two of these reflectors of diameter 1.4 ft (0.426 m), illuminate the east and we coasts. The two additional reflectors of diameter 2.25 ft (0.685 m) are utilized for servi to Alaska and Hawaii. These beams are not generated simultaneously. To provide servic to Alaska and Hawaii, the 396-watt east coast source is switched into a power divider that splits the power equally between the feeds of the 2.25-ft (0.685 m) reflectors. The switch can be accomplished using either a 3-port switching circulator or an electro-mechanical switch. The former may be a latching ferrite type, the latter solenoid actuated. In any event, no holding power is required. The insertion loss of the ferrite circulator is typica 0.4 -0.5 dB; the loss of the electro-mechanical switch is typically 0.2 dB. Both devices are suitable for performing the switching function.

Power division can easily be accomplished by utilizing either a matched E or H plane Tee, or a Magic Tee. Either would be fabricated in WR 62 waveguide. The transmission line i all WR 62 waveguide, and power handling is not anticipated as a problem area. The feeds for all four paraboloids are square waveguide (0.651 in.) (1.65 cm) with polarizers for circular polarization.

7.3.2.4 Antennas for the U.S.A. Demonstration Satellite

Table 7.3-7 lists the antenna system parameters that have been developed for the design requirements. There are two frequencies of transmission: 2.5 GHz and 12.2 GHz. The half power beamwidth requirements are 3.0 deg (5.24 crad) and 4.1 deg (7.15 crad) respectively. These beamwidths require paraboloids with diameters of 9.3 ft (2.84 m) and 1.4 ft (0.426 m) respectively.

Table 7.3-6. Antenna System Parameters and Characteristics, Instructional Service to U.S.A.

Number of Antennas (4)	Two	Two
Number of Frequencies	Two (both 12.2 GHz)	Two (both 12.2 GHz)
Beamwidth (Circular)	4.1 deg (7.15 crad)	2.5 deg (4.36 m)
Type of Antennas	Rigid Non-Erectable	Rigid Non-Erectable
Aperture Diameters	1.4 ft (0.427 m)	2.25 ft (0.686 m)
f/D Ratio	0.375	0 375
Focal Length	0.525 ft (0 16 m)	0.845 ft (0.258 m)
Feed Type	Waveguide Horn	Waveguide horn
Transmission Line	WR 62 Waveguide	WR 62 waveguide
Polarization	Circular	Circular
Gain	32 dB (η= 55%)	36.3 dB (η = 55%)
RMS Surface Tolerances	0.025" (0.635 cm)	0.025" (0.0635 cm)
Sidelobe Levels	-25 dB	-25 dB
Weight	4 5 lb (2.04 kg) (each)	5.5 lb (2 5 kg) (each)
Power	396 watts; 213 watts	198 watts (each)
Engineering Cost	275K each, 550K total	285 K each; 570 K Total
Fabrication Cost	25 K each, 50 K total	27 K each, 54 K Total
Bandwidth available	15%	15%

Table 7.3-7. Antenna System Parameters and Characteristics

Number of Antennas	Two	
Number of Frequencies	2.5 GHz	12.2 GHz
Beamwidth (circular)	3.0 deg (5 24)	4.1 deg (7.15 crad)
Type of Antennas	Rigid	
Aperture Diameters	9.3 ft (2.84 m)	1 4 ft (0.426 m)
f/D Ratios	0.375	
Focal Length	3.5 ft (1.07 m)	0.525 ft (0 16 m)
Feed Type	Single Helix	Waveguide Horn
Transmission Line	1-5/8 in. (4.13 cm) Rigid Coax	WR 62 Waveguide
Polarization	Circular	Circular
Gain	34.5 dB	32 dB
RMS Surface Tolerance	0.10" (0.254 cm)	0.025 in. (0.0635 cm)
Sidelobe Levels	-25 dB	-25 dB
Weight	28 lb (12 7 kg)	4.5 lb (2.04 kg)
Power	1.88 KW (3 channels)	0.089 kw
Engineering Cost	340 K Total: 677 K (10% integ)	275 K Total: 677K (10% integ)
Fabrication Cost	40 K Total: 65 K	25K Total: 65 K
Bandwidth Achievable	20%	15%

The deployed configuration has these antennas positioned side-by-side. A concentric arrangement was rejected here because of the blockage that would be caused by the smaller dish. This blockage would, in addition to causing a 1-dB gain loss, increase the secondary pattern side lobes to approximately -15 dB at S-band. This performance compromise is considered unnecessary.

The primary feed for the 2.5 GHz band is a single helix of the type shown in Figure 7.3-6 scaled by the proper frequency ratio. Rigid coaxial transmission line with a diameter of 1-5/8 in. (4.13 cm) is used to satisfy the power requirement of 1.83 kw. The transmission line for the 12.2 GHz band is WR 62 waveguide. The horn feed aperture is square with dimensions 0.65 x 0.65 inches (1.98 cm x 1.98 cm).

There may be some antenna and/or feed articulation required for this configuration. Limited repositioning requirements in two planes enables flexible transmission lines to be utilized.

7.3.3 RECEIVER-EXCITER DESIGN

The satellite receiver-exciter is designed to minimize the cost of the uplink subsystem. The major externally imposed constraints are:

1. Frequency: 8.0 to 8.5 GHz
2. Receiver Antenna Gain: 18 dB (corresponding to full earth coverage)
3. Required receiver (S/N): 10 dB above that required at the ground receiver

The antenna noise is dictated by the earth coverage requirement and by the noise temperature of the earth. At the frequencies specified, a preamplifier was selected which incorporated either a tunnel diode or an uncooled parametric amplifier. Further analysis indicated that an uncooled parametric amplifier available by 1971 will permit reduction in the uplink ERP by a factor of approximately 3; therefore, an uncooled parametric amplifier is selected.

The type of modulation determines whether the receiver-exciter is a linear repeater or a modulation converter. The number of channels determines the detailed signal processing requirements. In the interests of efficient use of power and spectrum, each visual and aural channel will be transmitted on a separate carrier. Representative block diagrams of the receiver-exciter for each type of service are shown in Figures 7.3-8 and 7.3-9. The power, weight, and costs of the receiver-exciters for the various services are shown in Table 7.3-8.

Table 7.3-8. Power, Weight, and Cost of Receiver-Exciters

Service	No. of Channels Visual	Aural	Visual Modulation	Power (Watts)	Weight (lbs)	kg	Fabrication Cost Quantity ($)	Engineering Cost ($)
Direct to Alaska	3	3	AM/VSB	10	14	6.35	1 @ 45,000	245.000
Community to India	1	4	FM	10	14	6.35	2 @ 40,000	410,000
Instructional to USA	6	6	FM	20	26	11.80	2 @ 85.000	560,000
Demonstration to USA	1	1	AM	10	14	6.35	1 @ 45 000	450,000
Demonstration to USA	2	2	FM	10	14	6.35	1 @ 40 000	

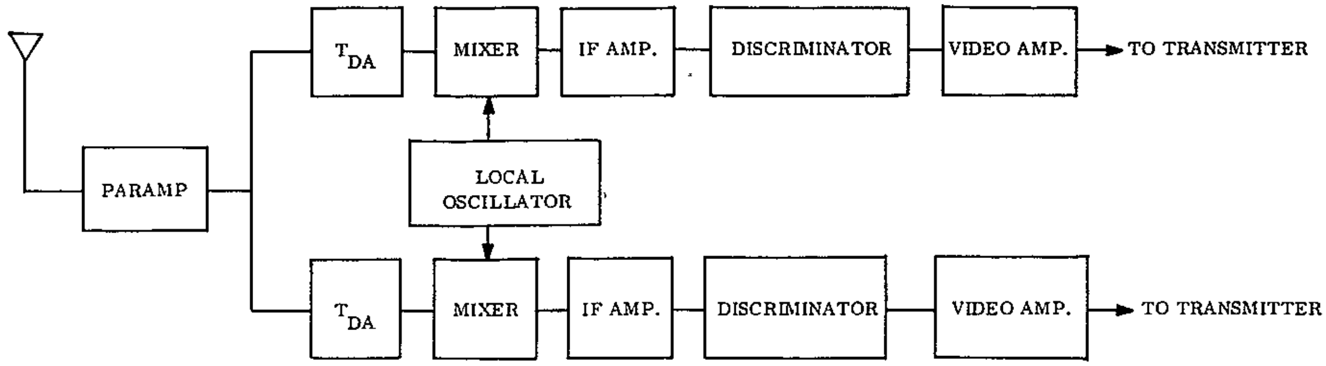


Figure 7.3-8. Receiver-Exciter for Multi-Channel AM/VSB System

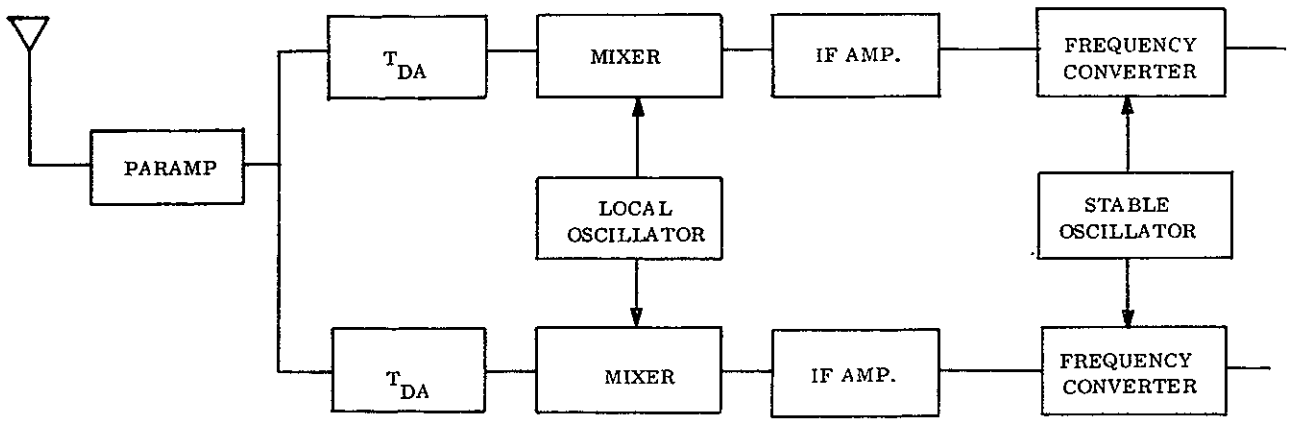


Figure 7.3-9. Receiver-Exciter for Multi-Channel FM System

7.3.4 TRANSMITTER DESIGN

This section describes the transmitter designs that will meet the requirements outlined in Table 7.3-9.

Table 7.3-9. Selected TVBS Mission Requirements

Requirement	Direct Service Alaska	Community Service India		Instructional Service U.S.A		Demonstration to U.S.A		
Frequency (GHz)	0.8	0.8	8.4	12.2	12.2	2.5	2.5	12.2
Modulation (Vid/Aud)	AM/FM	FM/FM	FM/FM	FM/FM	FM/FM	AM/FM	FM/FM	FM/FM
No. of Channels (Vid/Aud)	3/3	1/4	1/4	6/6	6/6	1/1	2/2	2/2
Signal Grade	2	2	0	1	1	1	1	1
Required Power Output/Channel at Antenna (Watts)	1584	416	19.5	66.0	35.5	4360	22.9	44.6

The general approach to establishing the transmitter design was to utilize the results of the parametric analyses (Section 5.2) in a systematic building block approach. The parameters considered in selecting the appropriate output device were frequency, modulation/bandwidth, and output power. Once an appropriate device was selected, design of the specific transmitter was started using the techniques of multiplexing and power dividing/combining to achieve the required output power and performance. Once the design was completed, system parameters such as weight, cost, efficiency, and voltage requirements were then calculated:

Several assumptions and constraints were employed to simplify the design. These included:

1. Where AM-VSB video modulation was used efficiency and intermodulation considerations dictated the use of a separate video and audio amplifier. The composite video signal was then obtained after final amplification by using multiplexing techniques.

2. For the purpose of these designs, the word "transmitter" is used to describe the power amplifying device, any RF transmission lines, RF power dividers or combines, filters and protective and monitoring devices normally associated with it. The transmitter does not include the power supply and power conditioning equipment, heat transfer equipment, or any part of the antenna or driver hardware or equipment.

3. The power output level of the aural signal was assumed to be -10 dB relative to the peak sync output level of the video. Average video power was taken to be 0.32 of the peak sync level.

4. Each transmitter was designed to have some degree of standby redundancy. Instead of providing for spare output devices, however, a completely redundant channel was used. In the case of all transmitters (except for the

two 6-channel USA Instructional Satellite) one spare channel was provided. For the 6-channel transmitters in the Instructional Satellite, each one was provided with two spare channels.

The results of the transmitter design task for the four missions specified (Direct Service to Alaska; Community Service and Rebroadcast to India; Instructional service to the USA; and Demonstrational Service to the USA) are summarized in Table 7.3-10. The table contains the mission requirements listed in Table 7.3-9 plus the design parameters.

Table 7.3-10. Summary of Transmitter Design Parameters

Transmitter Design Parameter	(Unit)	Direct Service Alaska	Community Service India		Instructional Service U.S A.		Demonstration Service U S A		
Frequency	(GHz)	0.8	0.8	8.4	12 2	12 2	2.5	2 5	12 2
Modulation	(V/A)	AM/FM	FM/FM	FM/FM	FM/FM	FM/FM	AM/FM	FM/FM	FM/FM
No. of Channels	(V/A)	3/3	14	1/4	6/6	6/6	1/1	2/2	2/2
Signal Grade	(TASO)	2	2	0	1	1	1	1	1
Video Pwr Output/Chan at Antenna	(DBW)	32 0	26.2	12.9	18.2	15.5	36.4	13 6	16 5
Peak Video Pwr Output/Chan at Ant.	(W)	15841	416	19.5	66.0	35.5	4360	22 9	44 6
Avg. Video Pwr Output/Chan at Ant.	(W)	505	416	19.5	66.0	35 5	1392	22 9	44 6
Avg. Audio Pwr Output/Chan at Ant.	(W)	158	-	-		-	436	-	-
Feed/Mission Line Effic	(%)	93.3	93.3	93 3	93 3	93 3	93 3	93 3	93 3
Avg Video Pwr/Chan to Ant.	(W)	542	446	20.9	70 8	38 1	1494	24 6	47 9
Avg Audio Pwr/Chan to Ant.	(W)	170	-	-	-	-	468	-	-
Diplexer &/or Multiplexer Type		Coax	-	-	WG	WG	WG	SL	WG
Dpx &/or Mtpx. Effic	(%)	80.5	-	-	80 3	80 3	93	73 2	85 7
Avg Video Pwr/Chan to Dpx &/or Mtpx	(W)	673	-	-	88 2	47 5	1574	33 6	55.9
Avg Audio Pwr Chan to Dpx &/or Mtpx	(W)	211	-	-	-	-	492	-	-
Tube Type	V/A	CFA/CFA	CFA	TWT	TWT	TWT	CFA/TWT	TWT	TWT
Tube Efficiency	(% V/A)	55 5/58.1	61 9	37.7	47.2	43.2	38 0/58 8	44 1	44 3
Avg Video Pwr/Chan to Tube	W	1210	721	55.4	187	110	4145	76.1	126
Avg Audio Pwr/Chan to Tube	W	363	-	-	-	-	838	-	-
Avg Video Pwr/Feed to Tube	W	3630	721	55 4	1122	660	4145	152	252
Avg Audio Pwr/Feed to Tube	W	1089	-	-	-	-	838	-	-
Avg Video & Audio Pwr/Feed to Tube	W	4619	721	55 4	1122	660	4983	152	252
Voltage Req'd. for Video Tube	KV	2 1	1 6	2.5	4 0	3.3	2 7	2.9	3.4
Transmitter Weight	LBS	271	40	13 6	93 3	77 7	189	22.7	30 2
	kg	123	18.1	6.17	42.3	35 2	85 7	10.3	13 7
Transmitter Eng Cost	$	$3\ 28 \times 10^6$	$8\ 5 \times 10^5$	4.0×10^5	$2\ 08 \times 10^6$	$1\ 88 \times 10^6$	2.59×10^6	$4\ 0 \times 10^5$	$8\ 5 \times 10^5$
Transmitter Fabrication Cost	$	5.39×10^5	1.04×10^5	5.2×10^5	$3\ 75 \times 10^5$	3.43×10^5	2.74×10^5	$1\ 29 \times 10^5$	1.57×10^5
Overall Transmitter Effic.	%	42.1	57.8	35 3	35.3	32.2	35.3	30.1	35 4

The power requirements were translated back through the antenna feed and any required multiplexers and/or diplexers to the output of the amplifying device to arrive at a required transmitter output power. In the case of an AM signal, this power is expressed in terms of both its peak sync and average value. For FM video/FM audio channels, powers expressed represent the combined video and audio signal power. Next, the tube type was specified, its efficiency listed and the required input power was calculated. Finally, all required inputs were summed (according to the number of channels). The transmitter weight was calculated from the weights of the individual components (such as amplifying device and multiplexer and/or diplexer) then multiplied by the number of channels (plus the appropriate number of redundant channels). Transmitter costs were calculated from the costs derived in the Transmitter Parametric Analysis (Section 5.2).

7.3.4.1 Transmitter for Alaska Satellite

The direct service mission to Alaska requires a 3-channel transmitter operating at a nominal frequency of 800 MHz. Each complete channel consists of an AM-VSB modulated video signal with an FM aural signal. Signal grade requirements and link calculations require that the output power per channel at the antenna be 1584 watts. A block diagram of the transmitter appears in Figure 7.3-10.

7.3.4.2 Transmitter for the India Satellite

The block diagram of one of the proposed transmitters for the Community Service mission to India is shown in Figure 7.3-11. This transmitter is a one channel, FM video (with 4 FM audio signals in the baseband) configuration at a frequency of 800 MHz. The required output power at the antenna terminal was 416 watts (composite video and audio). Figure 7.3-12 is a block diagram of the second transmitter for this mission, which operates at 8.4 GHz. The configuration of this transmitter is basically exactly the same as the 800 MHz transmitter, except that signal grade requirements have dictated a required output power of 19.5 watts for the composite video and audio signal at the antenna terminal.

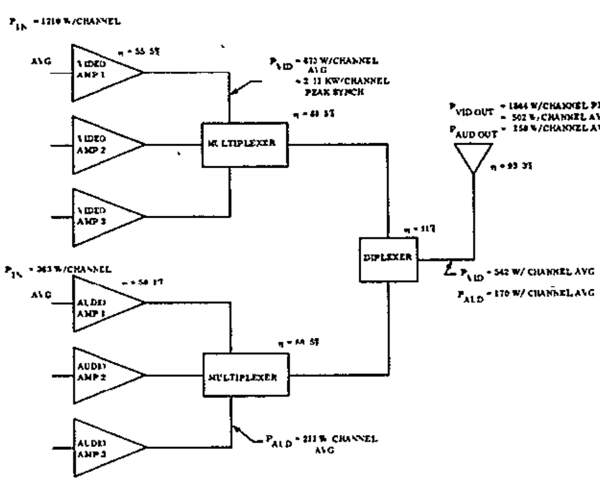


Figure 7.3-10. Block Diagram of 800 MHz Transmitter for Direct Service to Alaska

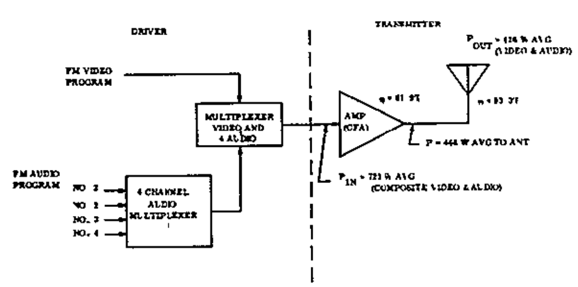


Figure 7.3-11. Block Diagram of 800 MHz Transmitter for Community Service to India

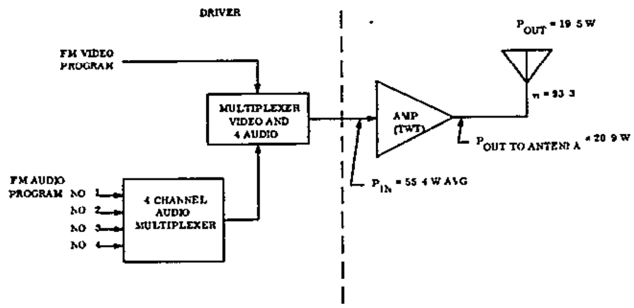


Figure 7.3-12. Block Diagram of 8.4 GHz Transmitter for Community Service to India

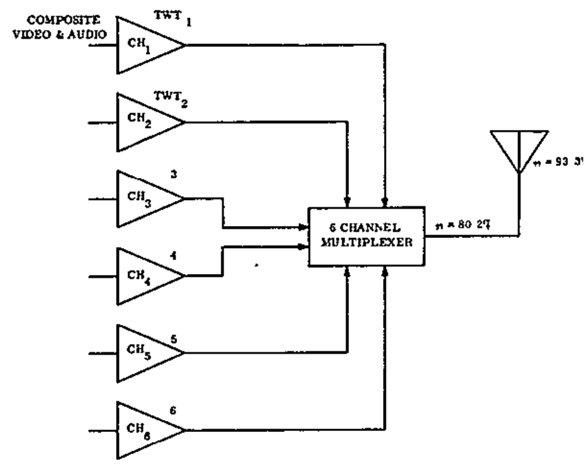


Figure 7.3-13. Block Diagram of Basic Transmitter for Instructional Service to U.S.A.

7.3.4.3 Transmitter for the U.S.A. Instructional Satellite

The two transmitters proposed for this mission have almost identical system configurations. Both are 6-channel (FM video/FM audio) transmitters which will operate in the 12.2 GHz band. In one case, output power at the antenna is to be 66.2 watts (composite video and audio) per channel; in the second case, the output power is 35.5 watts. Figure 7.3-13 shows the transmitter block diagram.

7.3.4.4 Transmitter for the U.S.A. Demonstration Satellite

Figure 7.3-14 is a block diagram of the 1-channel (AM-VSB video/FM audio) S-band transmitter for a Demonstration Service mission to the U.S.A. The transmitter consists of a CFA or gridded tube amplifier for the video signal, and a TWT or klystron for the aural. The two signals are then combined and fed to the antenna.

The block diagram of the 2-channel (FM video/FM audio) transmitter for S-band in this mission is illustrated in Figure 7.3-15. The required power output (composite video and audio) is 22.9 watts per channel.

The X-band, 12.2 GHz, 2-channel (FM video/FM audio) transmitter has the same basic configuration as that shown in Figure 7.3-15. The required output power per channel is 44.6 watts.

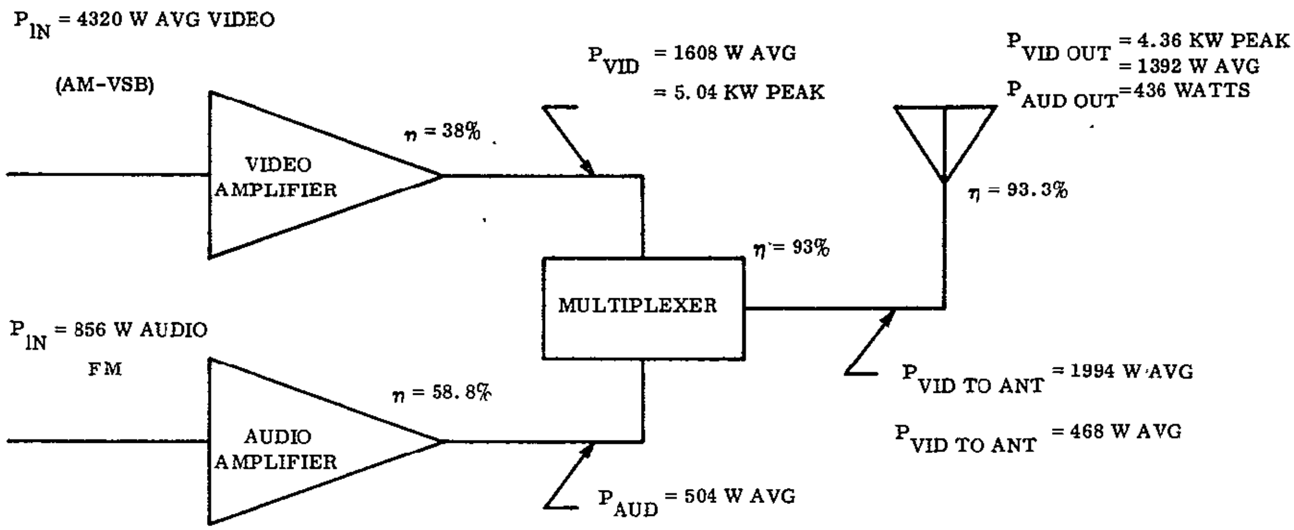


Figure 7. 3-14. Block Diagram of S-band Transmitter for Demonstration Service to U. S. A.

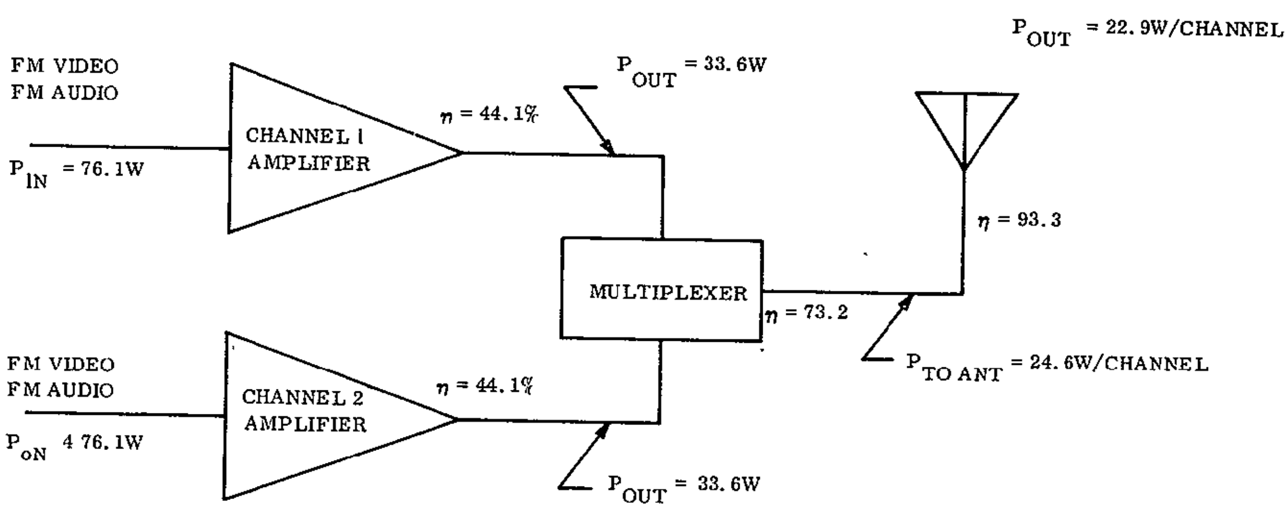


Figure 7. 3-15. Block Diagram of S-band, 2-Channel, FM Transmitter for Service to U. S. A.

7.3.5 ATTITUDE CONTROL DESIGN

The antenna pointing accuracy for each satellite was set at ±0.05 degree (0.087 crad). This was done to minimize the RF power loss and interference due to spillover into areas adjacent to the earth coverage areas.

The following sections describe the attitude control conceptual designs for each of the four satellites, along with the major constraints imposed on each control system by the satellite.

The solar array pointing accuracy was not estimated since the structural analysis required for such an error analysis was beyond the scope of the TVBS study. This problem of controlling a satellite with flexible structures is one of the major technology problems uncovered during the study. This problem is defined in Sections 8.2.1 and 8.2.13.

7.3.5.1 Attitude Control Design for the Alaska Satellite

The earth-tracking antenna is a 29 x 80 ft (8.8 m x 24.6 m) elliptical reflector with the 80-ft dimension along the pitch (N-S) axis; the solar array area required is approximately 684 square feet (63.5 m^2).

Because of the large dimensions of the antenna, continuous sun line sensing cannot be achieved. This is due to the fact that only the control module will demonstrate adequate rigidity, other vehicle sections being erectable. Thus, no sensor location on the control module was possible that would not be subject to sun sensor interference by the reflector.

The accuracy requirements precluded the use of an earth sensor exclusively, due to target anomalies. Sensors applicable to establish adequate references were sun and star trackers, high quality gyros and RF interferometers. As a result, two approaches were investigated. In the first approach, the vehicle frame would be controlled to the ultimate accuracy.

In the second (the selected approach), the vehicle frame would be controlled less accurately while beam pointing accuracy will be achieved by the use of a beam steering system. The steering system will employ an RF interferometer on the satellite in conjunction with a ground beacon. Pointing error detection will occur on the ground (by use of signal strength measuring devices) and beam steering will be accomplished with commands from ground equipment.

An orbit plane coordinate system is established by an earth sensor and a Polaris tracker. This gross orientation control provides a platform for solar array articulation, station-keeping thrust, and beam pointing by means of an RF interferometer. A large internal flywheel is used to stabilize the vehicle pitch axis to the orbit normal. This approach results in minimum control operations in roll and yaw even in the presence of the solar pressure disturbances inherent with doubly articulated arrays not perfectly balanced to the vehicle center of mass. Doubly articulated arrays compensate for the daily sun motion and the seasonal sun motion.

Precession control is used in roll and yaw and is obtained by using a reaction control system (RCS). In pitch, a modulated flywheel is employed, with unloading provided by the RCS.

For this satellite (without balancing solar vanes), the solar pressure configuration will achieve maximum unbalance when the satellite antenna axis is approximately normal to the sun line (6:00 a.m. or 6:00 p.m.). This c.p./c.m. offset will produce a pitch torque which must be accommodated. The moment arm of the individual arrays in roll/yaw is 42 feet (12.8 m), and imbalance of force on the two opposing arrays would cause a significant torque. However, this particular torque is capable of being minimized by trimming during orbital configuration establishment (the solar array area can be easily adjusted).

Because the nature of the disturbance torque and the goal of minimizing stabilization control operations, a constant speed pitch flywheel is used to reduce the vehicle response to the overturning torque. This torque exists alternately in roll and yaw due to variations in surface characteristics.

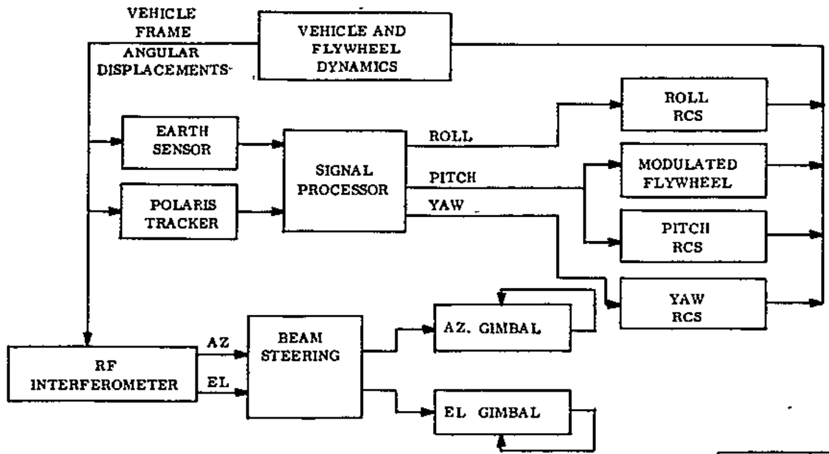
Pitch disturbance torques arise primarily from the c.p./c.m. offset due to the unbalanced configuration; they also arise from the sun-tracking angular rotation requirements of the solar array with respect to the rest of the satellite. To stabilize this axis, it is proposed that a modulated flywheel be employed to provide the necessary bandwidth to compensate for the solar array drive disturbances. Reaction jets would be used to establish the relative rates and keep the modulated flywheel running near the middle of its speed range. (Modulation of flywheel speed about some nominal speed eliminates the static friction non-linearities at stall of the array drive.)

Station-keeping could be constrained to non-broadcast times in which case larger errors in orientation may be allowable. Alternately, close control of station-keeping thrust offset from the vehicle center of mass could be employed to minimize station-keeping disturbances. At any rate, the effect of control during station-keeping would be on the required thrust level of the reaction control thrusters used for stabilization.

The reference axes are those of the Earth sensor and Polaris tracker. The Polaris tracker would be used periodically to correct roll and yaw errors by precessing the angular momentum of the pitch axis constant speed flywheel. The earth sensor would be used to establish the local vertical during initial acquisition. Only one axis information would be required during operation. The Earth sensor would drive the modulated pitch flywheel to maintain the nominal rate of 15 degrees (2.6 crad) per hour of the synchronous satellite, while stabilizing the solar array to a "fixed" sun line.

The beam steering could be implemented by feed drive. Errors in the orientation of the mechanical axis of the antenna would be determined by an RF interferometer located on the Earth side of the feed or on the reflector frame. This implenentation is considered as part of the stabilization subsystem to facilitate comparison with open-loop pointing.

The block diagram of the stabilization system and the closed-loop pointing system is shown in Figure 7.3-16. Weight and power estimates are also shown in the figure.



	WEIGHT		POWER, AVG
	16	Kg	W
EARTH SENSOR	6	2.7	4
POLARIS TRACKER	12	5 4	5
SIGNAL PROCESSOR	18	8 2	10
FLYWHEEL	18	8 2	2
MOD FLYWHEEL	12	5 4	2
RCS	*	*	
RF INTERFEROMETER	8	3.6	-
BEAM STEERING	10	4.5	5
GIMBALS (EQ)	4	1 8	

* RCS WEIGHT INCLUDED IN PROPULSION SYSTEM

Figure 7.3-16. Block Diagram for the Attitude Control Subsystem - Direct Service to Alaska

7.3.5.2 Attitude Control Design for the India Satellite

This satellite requires two transmitting antennas of 4.1° (7.2 crad) circular beamwidth with diameters of 21 feet (6.4 m) and 2 feet (0.61 m), respectively, for operation at UHF (0.8 GHz) and X-band (8.4 GHz). The sun-oriented solar array area of 144 sq feet (13.4 m^2) is divided between two panels symmetrically arranged along the pitch axis.

The reflector dimension precludes the use of a sun reference continuously. This is because only the reflector base and feed support will demonstrate adequate rigidity for the mounting of sensors, and these locations would have sun sensor interference by the rotating reflector.

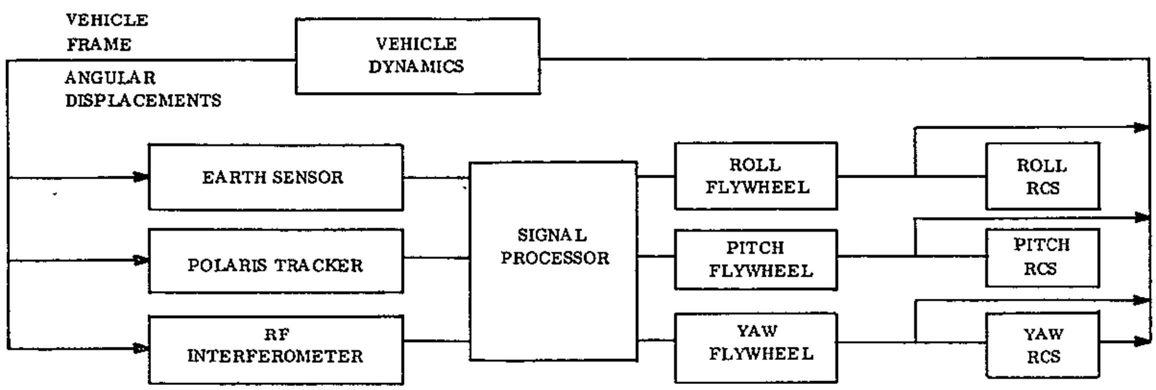
The two antennas are arranged coaxially and fixed with respect to the transmitter module. Therefore, the entire satellite, exclusive of the solar arrays, will be held to the 0.05 degree (0.087 crad) accuracy in roll and pitch in a closed loop mode of the RF interferometer and ground beacon system. Yaw may be held to the desired accuracy by means of the Polaris tracker.

Since India is near the equator, the satellite at synchronous altitude requires only an elevation of a few degrees from the equator in order to point the double antenna to the coverage area. A roll angle of four degrees would be adequate. Neither the solar array articulation nor a Polaris tracker is adversely affected if the vehicle orientation has a steady roll bias of this magnitude.

Initially, an earth sensor is used to establish the local vertical. Polaris is found and tracked for pitch control; then, a beacon in the coverage area is acquired. Subsequently, control in roll and yaw is switched to an interferometer with pitch control remaining with Polaris.

Angular momentum management by means of three flywheels is the preferred control. This method was selected because the necessity to move the entire satellite for pointing precludes the use of spin stabilized approaches; also, pure mass expulsion systems result in weight penalties due to fuel consumption.

The block diagram of the controller is shown in Figure 7.3-17. Component weight and power estimates are listed.



	WEIGHT		POWER, AVG
	LB	Kg	W
EARTH SENSOR	6	2.7	10
POLARIS TRACKER	15	6.8	5
RF INTERFEROMETER	15	6.8	10
SIGNAL PROCESSOR	20	9.1	10
FLYWHEELS (3)	30	13.6	6
RCS	*	*	--
	86	39.0	41

* RCS WEIGHT INCLUDED IN PROPULSION SYSTEM

Figure 7.3-17. Block Diagram for the Attitude Control Subsystem - India Satellite

7.3.5.3 Attitude Control Design for the U. S. A. Instructional Satellite

This satellite transmits at 12.2 GHz via four small, earth-tracking antennas arranged on the top (north side) of a transmitter module. Two solar array panels of 145 ft^2 (13.5 m^2) each are attached on either side of the power conditioner module. The panels are arranged so that their longitudinal axis of symmetry lies in the roll-yaw plane.

The small antenna sizes allow the use of 360° (2π rad) azimuth control. Elevation control about the coverage tilt angle is also achievable.

The approach selected for this satellite will orient the solar array longitudinal axis normal to the pitch axis, and will use an earth/orbit normal reference system for the antenna/transmitter module as the basic reference system. The main reason for the solar array orientation was the ability to achieve simple packaging of the roll-out arrays for launch and later deployment.

The control reference selection was made on the basis that it is inherently desirable to place the reference platform as close as possible to the critical alignment object (in this case, the antennas) and, thus, minimize structural deformation influence. This is particularly true with the very stringent pointing accuracy requirements of this mission.

The United States, as the user, has adequate tracking facilities to implement N-S station-keeping to a high degree of accuracy. As such, the orbit plane and the Earth's equator are assumed coincident to a fraction of one degree during all operations.

A Polaris tracker is used to establish the orbit normal on the basis that the orbit plane is equatorial. A sun sensor is used to control one axis of the vehicle frame so that the sun-line projection in the orbit plane is tracked continuously. An internal flywheel is systematically precessed to maintain the orbit normal in the presence of solar pressure disturbance. Only periodic precession operations are required so that Polaris tracker information is adequately monitored and filtered.

The RF interferometer is required only for the azimuth gimbal drive system since the N-S station-keeping negates the need for elevation control.

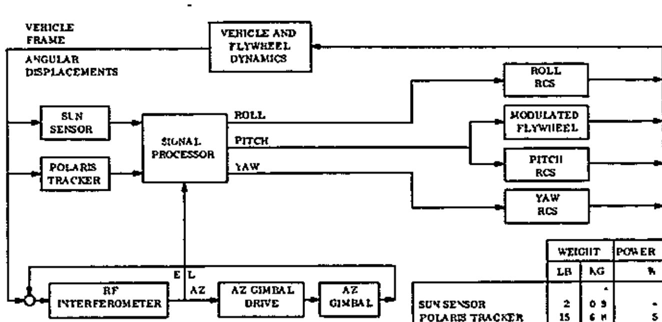
The block diagram for the attitude control subsystem is shown in Figure 7.3-18 along with the component weights and power.

This satellite would employ a large, internal, angular momentum for precise control of the orbit normal axis. This internal angular momentum will be generated by a high speed motor whose axis is the vehicle pitch axis. The antenna azimuth drive would also be parallel to pitch. The azimuth drive disturbances would be isolated from the vehicle frame by a modulated pitch flywheel.

Periodic torques will be applied to "precess" the system and remove roll/yaw pointing errors, aligning the flywheel to the orbit normal. The attitude determination in roll/yaw will use digital sun sensing and Polaris tracking, respectively.

7.3.5.4 Attitude Control Design for the U.S.A. Demonstration Satellite

The solar array is a four panel roll-out requiring full sun orientation. The large antenna and high-power transmitter result in a configuration which requires the vehicle frame to be Earth-pointing. A doubly articulated solar array is, therefore, mandatory with the solar array drive occurring between the vehicle frame and the roll out arrays.



	WEIGHT		POWER AVG
	LB	KG	W
SUN SENSOR	2	0.9	-
POLARIS TRACKER	15	6.8	5
SIGNAL PROCESSOR	12	5.4	4
FLYWHEEL	18	8.2	2
MOD FLYWHEEL	12	5.4	2
RF INTERFEROMETER	15	6.8	10
AZ GIMBAL & DRIVE	15	6.8	5
RCS	*	*	-
	89	40.3	28

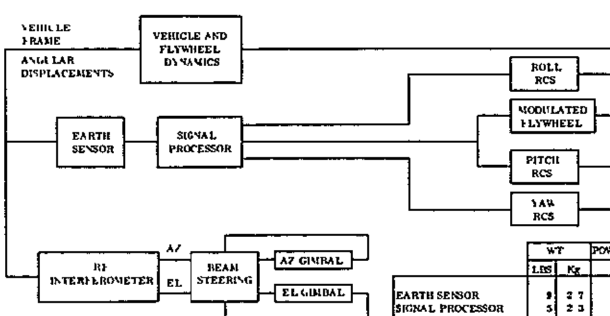
*RCS WEIGHT INCLUDED IN PROPULSION SYSTEM

Figure 7.3-18. Block Diagram for the Attitude Control Subsystem - U.S.A. Instructional Satellite

Alternative approaches to subsystem selection were in the area of controller design. Two approaches were considered. The first control considered employs a three axis angular momentum management system. The second controller implementation uses an internal rotor or flywheel which is aligned to the pitch axis, the axis of the solar array articulation. A reaction jet precession system controls roll/yaw to maintain an orbit normal system while a modulated pitch wheel isolates the vehicle frame from the solar array drive disturbances.

The controller system selected was the second approach, which uses the large pitch angular momentum to stabilize the vehicle frame to the orbit normal. An antenna-mounted interferometer system is used to track the earth. This system provides a pitch error signal which results in a nominal vehicle (and antenna) pitch rate of 15 degrees (2.6 crad) per hour at synchronism implemented by modulation of a separate pitch flywheel. A "roll" error from the interferometer is used to steer the antenna/body module in elevation to compensate for station errors. The yaw positioning sensor required for maintaining the momentum vector parallel to the orbit normal is the sun sensor shown on the vehicle body.

The controller block diagram is shown in Figure 7.3-19 along with a list of component weight and power estimates.



	WT		POWER (AVE)
	LBS	Kg	W
EARTH SENSOR	9	2.7	10
SIGNAL PROCESSOR	5	2.3	2
FLYWHEEL	60	27.2	10
MOD FLYWHEEL	20	9.1	15
RCS	*	*	--
RF INTERFEROMETER	8	3.6	--
BEAM STEERING	10	4.5	5
	109	49.4	42

* RCS WEIGHT INCLUDED IN PROPULSION SYSTEM

Figure 7.3-19. Block Diagram for the Attitude Control Subsystem - U.S.A. Demonstration Satellite

7.3.6 POWER SUBSYSTEM DESIGN

The power subsystems for these selected missions are similar except for the magnitude of the power required. The power subsystem type used for these specific designs is the same as that given in the parametric investigations described in Section 5.4 and are repeated in Table 7.3-11. In each case, it is assumed that there is no broadcast power requirement during a satellite eclipse.

Table 7.3-11. Power Subsystem Characteristics

Array Type	Rollup array
Solar Cell Type	Silicon, N/P, 1-3 ohm-centimeter, 8-mil, 2x2 cm, 11% AMO at 28°C
Coverglass	3-mil, microsheet
Orientation Mechanism	Single axis, brushless, dc motors
Battery Type	Nickel-Cadmium
Maximum Depth-of-Discharge	40%

A roll-up solar array design has been identified as the power source for each vehicle configuration. This array is similar to the GE design for JPL under contract 951970. Phase II of this array development program will yield prototype hardware for a 2500-watt array by early 1970.

The summary of the pertinent power subsystem design parameters is shown in Table 7.3-12 for each of the four satellites. The block diagrams of the power subsystems are given in Section 5.4. The solar array and power conditioning was separated into a housekeeping and a broadcast subassembly, with the parameter values obtained from the parameter curves in Section 5.4.

Table 7.3-12. Summary of Power Subsystem Parameters

Power Subsystem Parameter	Unit of Measure	Direct Service to Alaska	Community Service to India	Instructional Service to USA	Demonstration Satellite USA
Housekeeping Power					
Output Power Requirement	(W)	150.0	150.0	150.0	200.0
Array Power Required	(W)	213.0	213.0	213.0	282.0
Battery Energy	(W-hr)	505.0	505.0	505.0	672.0
Array Area	(ft^2)	24.8	24.8	24.8	32.8
	(m^2)	2.3	2.3	2.3	2.3
Battery Weight	(lb)	61.0	61.0	61.0	82.0
	(kg)	27.7	27.7	27.7	37.2
Power Conditioning Equip. Weight	(lb)	6.0	6.0	6.0	8.0
	(kg)	2.7	2.7	2.7	3.6
Broadcast Transmitter Power					
Output Power Requirement	(W)	4472.0	776.0	1782.0	5602.0
Array Power Required	(W)	5370.0	931.0	2140.0	6730.0
Array Area	(ft^2)	625.0	108.0	249.0	783.0
	(m^2)	58.0	10.0	23.0	73.0
Converter/Regulator Weight	(lb)	98.0	17.0	41.0	129.0
	(kg)	44.5	7.7	18.6	58.5
Filter Weight	(lb)	230.0	---	---	250.0
	(kg)	104.2	---	---	113.5
Total Power Subsystem					
Array Area	(ft^2)	650.0	133.0	274.0	816.0
	(m^2)	60.4	12.3	25.0	75.8
Array Weight	(lb)	312.0	62.0	128.0	382.0
	(kg)	141.0	28.2	58.0	173.0
Total Weight	(lb)	707.0	146.0	236.0	851.0
	(kg)	321.0	66.0	107.0	386.0
Engineering Cost	(M$)	2.74	1.20	2.39	2.80
Fabrication Cost	(M$)	2.76	0.58	1.19	3.44

7.3.7 THERMAL CONTROL DESIGN

This section describes the designs of the thermal control systems for each of the four broadcast satellites.

The total thermal dissipation for each satellite is presented as the sum of the dissipations of the electronic components comprising the satellite systems at their operating temperatures. Temperature differentials were calculated for all interfaces and the rejection temperatures were determined. The required parameters (area, weight, and cost) were obtained by using this temperature, the dissipation value, and the characteristics of the selected system from the parametric analysis given in Section 5.5.

All satellites were in synchronous orbit with both shaded and unshaded surfaces available for heat dissipation. Thermal control systems for all broadcast transmitter tubes were positioned on unshaded surfaces to take maximum advantage of their high allowable operating temperature. Incident external flux on the radiative areas was assumed at a maximum value of solar flux. Thus, unshaded surfaces received a solar flux of 1.39 kw/m^2 (440 btu/hr-ft^2) and shaded plates receiving a maximum of 23-1/2° (0.41 rad) solar impingement were designed to accommodate 0.55 kw/m^2 (1.39 x sin 23-1/2°) of solar flux. Louvers were assumed completely open at this condition.

All components were oriented within the spacecraft to permit the necessary thermal connection with their radiating systems. TWT, klystron, and gridded tube heat was considered generated entirely at a 1 in. (2.54 cm) diameter collector. Body heat of these tubes (approximately 10% of the total) is small so that tube orientation can be arranged to dissipate this heat adequately.

The CFA tube was assumed to be a 7 in. (17.8 cm) diameter by 1 in. (2.54 cm) thick disc with heat generation around the cylindrical surface. Diplexers, multiplexers, AM filters, and power conditioners were considered black boxes, each with a heat rejection baseplate. Housekeeping elements were assumed sufficiently spread to enable dissipation at a radiator efficiency of 80%.

Certain system properties were constant in all designs (as described in Section 5.5) and are repeated below:

1. All radiative surfaces are aluminum: $\rho = 170 \frac{\text{lb}}{\text{ft}^3}$ $(272 \frac{\text{kg}}{\text{m}^3})$, $k = 80 \frac{\text{btu}}{\text{hr-ft-}^\circ\text{F}}$

   Coatings on these plates have an $\alpha_s/\epsilon = 0.3/0.9$. Radiation to space is from one side only.

2. Louvers reduce the effective emittance of a radiator to 0.7 and raise the solar absorptivity to 0.33.

3. The additional weight of louver systems was taken as $0.7 \frac{lb}{ft^2}$ $(3.42 \frac{kg}{m^2})$.

4. All heat pipe systems use water as the working fluid. Water is suitable for use at temperatures between $50^{o}C$ and $250^{o}C$ and, consequently, can be employed in all cases under consideration.

5. Special evaporator weights are not included in the weights given for heat pipe systems in Tables 7.3-13 through 7.3-16. These evaporators will only be necessary in a few instances, and their weights will be small [1-3 lbs (0.45 - 1.4 kg)] where employed.

All of the thermal control systems described in Section 5.5 were considered for application in this task. Based on power dissipation and operating temperature, one of the following two methods was selected for each component.

1. Passive Radiator. The source is either bolted or brazed directly to an aluminum radiator plate. Heat is dissipated by conduction through the radiator and radiation from the fin to space.

2. Heat Pipe Finned Radiator. The heat source is attached to the evaporator of a heat pipe system. A network of small heat pipes extend into a flat plate radiator, thereby making it more thermally efficient than the passive system.

Wherever practical, passive radiators were employed. Where passive plates led to excessive weight and area requirements, a heat pipe finned radiator was used. All active temperature control was accomplished with louver systems.

System analyses indicated the need for active temperature control on all radiative surfaces. During the solar eclipse, the spacecraft receives no thermal input (either solar or component) and its temperature decreases at a rate determined by its thermal capacity and rejection characteristics. At the end of a 70-minute eclipse, the thin radiator plates employed for heat dissipation will reach a temperature of approximately $158^{o}K$ $(-115^{o}C)$. Because of the direct thermal contact between electronic components and their radiator plates provided in the system design, the component temperatures will become excessively low during eclipse. For this reason, louver systems are employed on all radiating surfaces.

The system consists of distribution and fin heat pipes forming a network which is brazed or clamped onto a 1/16 in. (0.159 cm) aluminum plate. Fin heat pipes are spaced on 9 in. (22.8 cm) centers; distribution pipes are provided to transport the heat from its source to the fin heat pipes. The overall efficiency of this radiator is calculated to be 78 percent. Heat pipe walls are 20 mils (0.509 mm) thick, and wicking is provided to direct the heat in the desired manner. Weight was calculated on the basis of 1.10 $\frac{lb}{ft^2}$ (5.38 $\frac{kg}{m^2}$) of which 0.9 $\frac{lb}{ft^2}$ (4.4 $\frac{kg}{m^2}$) is allowed for the radiator plate and a nominal value of 0.2 $\frac{lb}{ft^2}$ (0.98 $\frac{kg}{m^2}$) is assigned to the heat pipe network.

Tables 7.3-13 through 7.3-14 describe the thermal control systems proposed for the four satellites. The following information clarifies the data given in these tables:

1. Feed/Transmission Line. It is necessary to expose only a portion of the line to space to radiate the generated heat away.

2. CFA. Because of the tube configuration, it was necessary to provide additional heat pipes for the Demonstration Satellite to transport heat from the disc circumference to the main evaporator of the distribution heat pipe. The number of such transport heat pipes is given in Table 7.3-16. Interface areas were adjusted to maintain a heat flux below the critical value of 300 W/in.^{2} (46.5 W/cm^2).

3. Power Conditioner and Housekeeping. Low operating temperatures and high dissipations necessitated the large rejection systems specified for these components. In view of these large system requirements, the possibility of shading a radiator plate entirely from the incident solar flux was analyzed. In this case, sun screens would be provided to block the 23-1/2^{o} (0.41 rad) impingement on a rejection surface. However, these screens will also decrease the view factor from the surface to space, thereby limiting the dissipation from the plate. Based on an approximate configuration it was found that these screens are beneficial only if the radiating surface is at a temperature below 55^{o}C. Thus, the shading technique will reduce system requirements (by about one-half) only in the housekeeping case.

4. Hardware development costs shown in Tables 7.3-13 through 7.3-16 reflect only baseplate development cost. The total shown is adjusted to include the development of either one- or two-louver systems. The development of a second louver system for a given satellite is necessary only in those cases which have a significantly large range of component area requirements.

Table 7.3-13. Satellite Thermal Control System Characteristics - Direct Servie to Alaska

Item	No. of Items	Total Power Dissipation (Watts)	Item/(Rej) Temp (^oC)	Interface A (in^2)	Interface Type*	Type of System**	Radiator Area (ft^2)	Radiator Area (M^2)	System Weight (lbs)	System Weight (kg)	Hardware Cost Dev. (K$)	Hardware Cost Unit (K$)
Feed/XMission line		144	100 (90)			(Expose Wire)	(3.30)	(.307)				
Diplexer and/or Multiplexer	4	273 B	100 (90)	4.0	CL	HP, L	7.80	0.725	13.9	6.3	60	40
CFA	3	1896 A	200 (170)	2.2	BR	HP, L	30.90	2.870	55.4	25.2	61	41
AM Filter	1	170 B	100 (88)	7.0	CL	HP, L	4.80	0.447	8.6	3.9	60	40
Power Conditioner	1	878 B	120 (80)	5.0	BR	HP, L	29.60	2.750	53.3	24.2	60	40
Housekeeping		150 B	30 (25)	6.0	CL	Pa, L	23.10	2.150	37.0	16.8	6	37
Total		3511					96.2	8.950	168.2	76.4	372#	198

* BR-Brazed
CL-Clamped or Bolted

** HP, L-Heat pipe finned radiator with louvers
Pa, L-Passive radiator plate with louvers

\# Includes 60 K$ for development of 7.8 ft^2 (0.73 m^2) louver system
+65 K$ for development of 30.9 ft^2 (2.9 m^2) louver system

A Full Solar Load
B 23.5° Max. Solar Incidence
C Full Solar Shading with Baffles
D Full Solar Shading

Table 7.3-14. Satellite Thermal Control System Characteristics - Community Service to India

Item	No. of Items	Total Power Dissipation (Watts)	Item/(Rej) Temp (^oC)	Interface A (in^2)	Interface Type*	Type of System**	Radiator Area (ft^2)	Radiator Area (M^2)	System Weight (lbs)	System Weight (kg)	Hardware Cost Dev. (K$)	Hardware Cost Unit (K$)
Feed/XMission line	2	31	100 (90)			(Expose Wire)	(0.70)	(0.65)				
TWT	1	32 A	200 (192)	0.78	CL	Pa, L	0.31	0.029	0.5	0.2	6	37
CFA	1	275 A	200 (170)	1.0	BR	HP, L	4.20	0.391	7.5	3.4	60	40
Power Conditioner	1	189 C	120 (80)	2.0	BR	HP, L	8.15	0.758	14.6	6.6	60	40
Housekeeping		150 C	30 (25)	6.0	CL	Pa, L	12.82	1.193	20.6	9.4	6	37
Total		677					25.48	2.371	43.2	19.6	192#	154

* BR - Brazed
CL - Clamped or bolted

** HP, L - Heat pipe finned radiator with louvers
Pa, L - Passive radiator plate with louvers

\# Includes 60 K$ for development of 8.15 ft^2 (0.76 m^2) louver system

A Full Solar Load
C Full Solar Shading with Baffles

Table 7.3-15. Satellite Thermal Control System Characteristics - Instructional Service to U.S.A.

Item	No. of Items	Total Power Dissipation (Watts)	Item/ (Rej) Temp (^{o}C)	Interface		Type of System**	Radiator Area		System Weight		Hardware Cost	
				A (in^2)	Type*		(ft^2)	(M^2)	(lbs)	(kg)	Dev. (K$)	Unit (K$)
Feed/XMission line	2	44	100 (90)			(Expose Wire)	(0.93)	(.086)				
Diplexer and/or Multiplexer	2	161 B	100 (90)	4.0	CL	HP, L	4.60	0.428	8.2	3.7	60	40
TWT	12	968 A	200 (163)	0.78	CL	HP, L	17.04	1.586	30.7	14.0	60	40
TT&C	1	20 B	100 (90)	1.0	CL	Pa, L	0.57	0.053	1.0	0.5	6	10
Power Conditioner	1	378 D	120 (80)	4.0	BR	HP, L	8.1	0.753	14.5	6.6	60	40
Housekeeping		68 D	45 (40)	3.0	CL	Pa, L	2.40	0.223	3.9	1.8	6	37
Total		1478					32.71	3.043	58.4	26.6	309#	154

* BR - Brazed
CL - Clamped or Bolted

** HP, L - Heat pipe finned radiator with louvers
Pa, L - Passive radiator plate with louvers

\# Includes 60 K$ for development of 4.6 ft^2 louver system + 63 K$ for development of 17.04 ft^2 louver system

A Full Solar Load
B 23.5° Max. Solar Incidence
D Full Solar Shading

Table 7.3-16. Satellite Thermal Control System Characteristics Demonstration to U.S.A.

Item	No. of Items	Total Power Dissipation (Watts)	Item (Rej) Temp (^{o}C)	Interface		Type of System **	Radiator Area		System Weight		Hardware Cost	
				A (in^2)	Type*		(ft^2)	(M^2)	(lbs)	(kg)	Dev. (K$)	Unit (K$)
Feed/XMission line	3	144	100 (90)			(Expose Wire)	(3.30)	(0.307)				
Diplexer and/or Multiplexer	2 1	120 B 18 B	100 100 (91)	2.0 1.0	CL CL	HP, L Pa, L	3.66 0.50	0.341 0.046	6.6 0.8	3.0 0.4	60 6	37 10
TWT	5	571 A	200 (180)	0.78	BR	HP, L	8.15	0.758	14.8	6.7	60	40
CFA	1	2571 A	200 (165)	10.0	BR (4 transport heat pipes)	HP, L	44.20	4.120	87.5	39.8	62	42
AM Filter	1	215 B	100 (88)	8.0	CL	HP, L	6.06	0.564	10.9	4.9	60	40
Power Condition	1	1163 B	120 (80)	5.0	BR	HP, L	39.10	3.640	70.4	32.0	60	40
Housekeeping		200 B	30 (25)	8.0	CL	Pa, L	30.80	2.86	49.3	22.4	6	37
Total		5002					132.40	12.32	240.3	109.2	441#	246

* BR - Brazed
CL - Clamped or Bolted

** HP, L - Heat pipe finned radiator with louvers
Pa, L - Passive radiator plate with louvers

\# Includes 60 K$ for development of 8.15 ft^2 (0.76 M^2) louver system + 67 K$ for development of 44.2 ft^2 louver system

A Full Solar Load
B 23.5° Max. Solar Incidence

7.3.8 STATION KEEPING PROPULSION DESIGN

This section defines the East/West and North/South station keeping requirements for each of the four satellites for a two-year period. A selection is made of a thrust level which is compatible with the stabilization system. Propulsion schematics, component weights, trade-offs, and schedule and cost estimate are provided.

All four satellites will require East/West station keeping, and only the Alaska satellite does not require North/South station keeping. The location of the satellite, satellite weight, velocity, and impulse required for two years were shown in Table 7.3-17.

The East/West station keeping requirements for the India and Demonstration satellites are theoretically zero since the satellites are located at longitudinal stable points. A nominal one foot per second of energy is allocated to this function for these two satellites since injection and positioning will not be precise.

Thrust levels for East/West station keeping were selected on the basis of a daily input of energy that would be of the order of 40 minutes or less. In this way misalignment torque effects could be quite low and, in turn, the pitch, roll, yaw thrusters would be compatible for mass unloading of the reaction wheels used in stabilization and control. The North/South station keeping is currently planned to be performed on a weekly basis; thrust levels were also sized to be compatible with the pitch, roll, and yaw thrust capability. Thrust levels selected and projected firing times for both types of station keeping were shown in Table 7.3-18.

Three thrusters will be used for East/West station keeping for the Alaska satellite. Three are required because of the large antenna and because the center of mass and center of gravity will be above the equipment container. The thrusts will be 0.381 mlb (1.69 mN), 0.106 mlb (0.471 mN), and 0.013 mlb (0.058 mN) which adds to a net of 0.5 mlb (2.23 mN) as shown in the table. Coupled plus and minus yaw nozzles will be on the equipment container. The East/West nozzles of 0.38 mlb (1.69 mN) will also be used for plus-minus pitch unloading.

7.3.8.1 Five Millipound (5 mlb) Thrusters

Five millipound (22.3 mN) thrusters are used for pitch, roll, and yaw control and mass unloading on the India, Instructional, and Demonstration satellites. These thrusters will provide 1800-3700 lb sec (8,000-16,450 N-sec) over the two-year period, depending upon the satellite. This thrust level could be provided by "hot" (I_{sp} = 200 sec) or warm ammonia jets (I_{sp} = 100 sec), a hydrazine plenum system (I_{sp} = 100-115 sec), ion engines (I_{sp} = 5000 sec), or cold gas (freon or nitrogen) (I_{sp} = 40-60 sec). The thrust level is too high for colloidal engines (I_{sp} = 1000 sec), solid propellant electric thrusters (I_{sp} = 1000 sec) or subliming solid thrusters (I_{sp} = 60-80 sec).

The high power requirement for ion engines, 150-200 watts per mlb (350-450 W/mN), makes these unusable, although the thrust level is present state of the part. Cold gas freon or nitrogen) has low performance, would require an additional system, and is too heavy.

Table 7.3-17. Station Keeping and Mass Unloading Requirements

Satellite	Wt (lbs)	Longitude	E/W, 2 Yr (fps)	E/W, 2 Yr (lb sec)	N/S, 2 Yr (fps)	N/S, 2 Yr (lb sec)	Attitude Control Unloading (lb sec)
Alaska	2043	135°W	13	850	----	-------	1,885
India	752	77°E	1	25	300	7,500	2,600
Instructional	983	120°W	10.4	332	300	9,540	1,800
Demonstration	2036	105°W	1	63	300	19,000	3,680

Satellite	Wt (kg)	Longitude	E/W, 2 Yr (m/sec)	E/W, 2 Yr (N-sec)	N/S, 2 Yr (m/sec)	N/S, 2 Yr (N-sec)	Attitude Control Unloading (N-sec)
Alaska	927	135°W	3.96	3,780	----	------	8,370
India	342	77°E	0.305	111	91.5	33,400	11,550
Instructional	446	120°W	3.17	1,475	91.5	42,400	8,000
Demonstration	924	105°W	0.305	280	91.5	84,500	16,400

Table 7.3-18. Thrust Levels and Firing Times

Satellite	E/W (Daily) Thrust (mlb)	E/W (Daily) On Time (min)	N/S (Weekly) Thrust (mlb)	N/S (Weekly) On Time (min)	P, R, Y Thrust (mlb)
Alaska	0.5	39	--	--	0.5
India	0.5	*	50	26	5.0
Instructional	0.5	17	50	30	5.0
Demonstration	0.5	*	50	60	5.0

Satellite	E/W (Daily) Thrust (mN)	E/W (Daily) On Time (min)	N/S (Weekly) Thrust (mN)	N/S (Weekly) On Time (min)	P, R, Y Thrust (mN)
Alaska	2.23	39	223	-	2.23
India	2.23	*	223	26	22.3
Instructional	2.23	17	223	30	22.3
Demonstration	2.23	*	223	60	22.3

* Time to achieve orbit.

The heated or "hot" ammonia resistance jets use 10 watts per millipound (44.5 W/mN) or about 50 watts per thruster. This is 10 times that required for a hydrazine plenum or warm ammonia jet. Both the hydrazine plenum system and the warm ammonia jets are fairly well developed, and will be of equal technical stature by 1971. Since there is hydrazine on board for the injection correction and station change functions, it was decided to select the hydrazine plenum system approach for the 5-millipound (22.3 mN) thrusters.

The hydrazine plenum system operates by decomposing hydrazine to largely hydrogen and nitrogen with a minimum amount of ammonia. The gas mixture is stored in a low pressure tank and distributed to the thrusters, which are controlled by series solenoid valves. A pressure switch on the plenum tank is used to control the feed of hydrazine to the gas generator. The ΔP on the pressure switch can be set at a desirable range to perform its controlling functions. Measured performance is in the range of 100-115 sec for a thrust range of 2-50 mlb (8.9-22.3 mN).

7.3.8.2 Half Millipound (0.5 mlb) Thrusters

East/West station keeping for three satellites will be accomplished with 0.5 mlb (2.23 mN) thrusters. This size of thrust is also used for roll and yaw control and mass unloading for the Alaska satellite. The East/West energy requirements are 25 to 850 lb sec (111 to 3780 N sec) for two years. The pitch, roll, and yaw energy requirements for the Alaska satellite is 1885 lb sec (8400 N-sec).

The hydrazine plenum system was selected for the 0.5 mlb (2.23 mN) thrusters primarily for the same reasons this system was selected for the 5 mlb (22.3 mN) thrusters (see Section 7.3.8.1).

7.3.8.3 Micropound Thrusters

The thrust levels for the Alaska spacecraft East/West station keeping thrusters located near the two ends of the antenna are 0.106 (0.471 mN) and 0.013 mlb (0.058 mN). The energy to be expended during two years is only 181 lb sec (805 N-sec) by the 0.106 mlb (0.471 mN) thruster and 22 lb sec (98 N-sec) by the 0.013 mlb (0.058 mN) thruster. The space at these locations is limited. Cold gas, ammonia resistance jets and hydrazine plenum systems are all more complex, occupy more volume and are heavier than a Solid Propellant Electric Thruster (SPET). The specific impulse of SPET is 1000 sec. Power requirement would be about 20 watts for the 0.106 mlb (0.471 mN) unit and about 5 watts for the 0.013 mlb (0.058 mN) unit. Nominal on time would be about 39 minutes per day. Total pulses required over two years, at five pulses per second, would be 8.5×10^6. This pulse requirement is within the present state of the art as quite a few thrusters have been operated for well over 5×10^6 pulses, each without degradation.

7.3.8.4 Secondary Propulsion Subsystem Designs

Schematics for the secondary propulsion subsystem for the four satellites are shown in Figures 7.3-20 and 7.3-21. The hardware components and weights are listed in Tables 7.3-19, 7.3-20, 7.3-21 and 7.3-22. The gross diameter of the hydrazine tanks is listed which gives a rough volume estimate for the systems. Power required is about 5 watts per solenoid valve and 5 and 20 watts for the two SPET units used on the Alaska spacecraft.

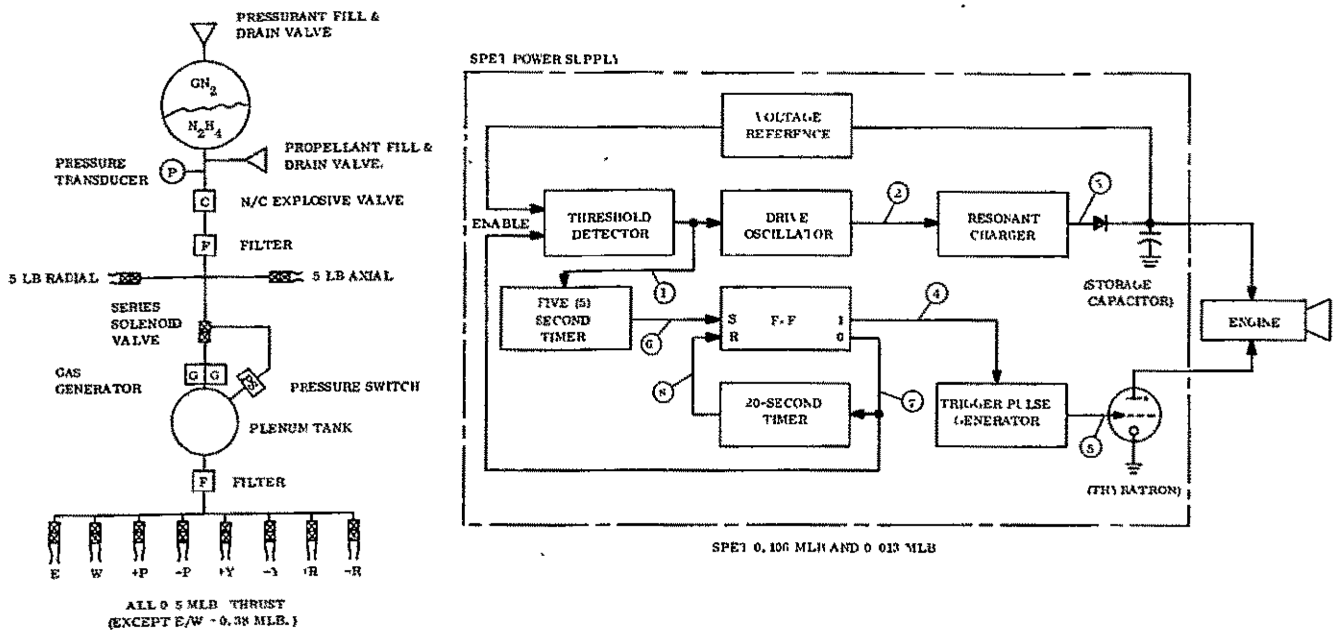


Figure 7.3-20. Schematic Diagram of Secondary Propulsion Subsystem for Alaska Satellite

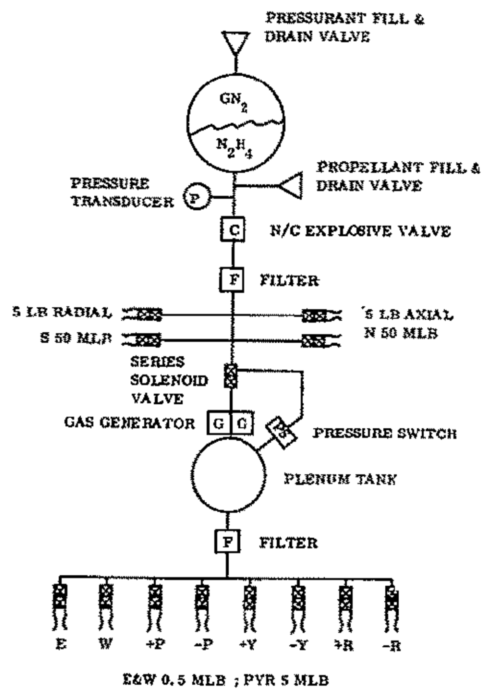


Figure 7.3-21. Schematic Diagram of Secondary Propulsion Subsystem for India Satellite and U.S. Instructional and Demonstration Satellite

Table 7.3-19. Alaska Secondary Propulsion Hardware Weight

Component	No.	Wt (lb)	Wt (kg)
Tank & Bladder (19.8 dia)	1	12.5	5.67
Fill & Drain Valves	2	0.6	0.27
Pressure Transducer	1	0.3	0.14
N/C Explosive Valve	1	0.4	0.18
Filter	2	0.8	0.36
Series Solenoid Valve	1	0.5	0.23
Gas Generator	1	1.0	0.45
Pressure Switch	1	0.8	0.36
Plenum Tank	1	3.00	1.36
5-lb TCA's	2	2.50	1.13
0.5-mlb TCA's	8	6.00	2.72
Miscellaneous	AR	5.00	2.27
	Total Dry wt	33.4	15.15
	Hydrazine	92.2	41.90
	Nitrogen	1.7	0.77
	Net Weight	127.3	57.92

SPET	Lbs	kg
Fuel	0.5	0.23
Engine Assembly	0.5	0.24
Capacitors	1.0	0.45
Power Conditioning	0.8	0.36
Packaging	0.7 (4 x4"x1)	0.32
	3.5	15 9

Table 7.3-20. India Secondary Propulsion Hardware Weight

Component	No.	Wt (lbs)	Wt (kg)
Tank and Bladder (20.2" dia)	1	13.5	6.13
Fill & Drain Valves	2	0.6	0.27
Pressure Transducer	1	0.3	0.14
N/C Explosive Valve	1	0.4	0.18
Filter	2	0.8	0.36
Series Solenoid Valve	1	0.5	0.23
Gas Generator	1	1.0	0.45
Pressure Switch	1	0.8	0.36
Plenum Tank	1	3.00	1.36
5-lb TCA's	2	2.50	1.13
50-mlb TCA's	2	1.5	0.68
5-mlb TCA's	6	4.50	2.04
0.5-mlb TCA's	2	1.50	0.68
Miscellaneous	AR	5.00	2.27
		35.9	16.30
	Hydrazine	97.8	44.40
	Nitrogen	1.7	0.77
		135.4	61.47

Table 7.3-21. Instructional Secondary Propulsion Weight Hardware

Component	No	Wt (lbs)	Wt (kg)
Tank and Bladder (21.0" dia)	1	15.0	6.81
Fill & Drain Valves	2	0.6	0.27
Pressure Transducer	1	0.3	0.14
N/C Explosive Valve	1	0.4	0.18
Filter	2	0.8	0.36
Series Solenoid Valve	1	0.5	0.23
Gas Generator	1	1.0	0.45
Pressure Switch	1	0.8	0.36
Plenum Tank	1	3.00	1.36
5-lb TCA's	2	2.50	1.13
50-mlb TCA's	2	1.50	0.68
5-mlb TCA's	6	4.50	2.04
0.5-mlb TCA's	2	1.50	0.68
Miscellaneous	AR	5.00	2.27
		37.4	17.00
	Hydrazine	110.5	50.20
	Nitrogen	1.8	0.82
		149.7	68.02

Table 7.3-22. Demonstration Secondary Propulsion Weight Hardware

Component	No.	Wt (lbs)	Wt (kg)
Tank and Bladder (25.9" dia)	1	23.0	10.43
Fill & Drain Valves	2	0.6	0.27
Pressure Transducer	1	0.3	0.14
N/C Explosive Valve	1	0.4	0.18
Filter	2	0.8	0.36
Series Solenoid Valve	1	0.5	0.23
Gas Generator	1	1.3	0.59
Pressure Switch	1	0.8	0.36
Plenum Tank	1	3.00	1.36
5-lb TCA's	2	2.50	1.13
50 mlb TCA's	2	1.70	0.77
5-mlb TCA's	6	4.50	2.04
0.5-mlb TCA's	2	1.50	0.68
Miscellaneous	AR	5.00	2.27
		46.0	20.88
	Hydrazine	207.6	94.1
	Nitrogen	2.5	1.14
		256.1	116.12

Development and qualification of the hydrazine propulsion subsystem can be accomplished within 18 months from go ahead. Most of the components are already developed or need little additional development before final qualification. The major task will be development and qualification of the complete system. This latter task will include experimental verification of the "blow down" performance of the 5-lb (22.3 N) thrusters. Thus, as the pressure in the system decreases, ready reference to calibration tables of thrust versus system pressur can enable the ground controller to command the proper on time versus total impulse needed.

A budgetary estimate of development and qualification cost is about $1,500,000. One prime subsystem should cost between $50,000 to $75,000. The SPET development will cost an additional $900,000, with prime units delivering at about $25,000 each.

7.3.9 TELEMETRY, TRACKING, AND COMMAND (TT&C)

The TT&C requirements and equipment will be almost identical in all TVBS configurations. The functions of the TT&C subsystem in the TVBS are conventional. They are to support operation, evaluation, diagnosis and correction of malfunctions, and tracking of the satellite. The TT&C subsystem will be compatible with the NASA Space Tracking and Data Acquisition System.

The telementry format will include satellite identification, word and frame synchronization, and 8-bit NRZ-C data words. Subcommutation will be used for low data rate channels and super-commutation (cross-strapping) for high data rate channels. Modulation will be PCM-PSK-PM and FM/FM for digital and analog data, respectively.

The command data format will include vehicle identification, address code, data bits, and parity bit. It will also include bit, word, and frame synchronization. The data will be PCM-NRZ-C. Command words will be frequency shift keyed onto subcarriers, which will then amplitude modulate the S-band carrier.

Spacecraft tracking will be performed by the NASA Space Tracking and Data Acquisition System. For this purpose, a CW beacon compatible with the Minitrack system and a transponder compatible with the NASA Range and Range Rate System will be required.

Estimated characteristics of the TT&C subsystem for each of the four satellites are:

1. Weight. . . . . 20 lbs (9.08 kg)
2. Power requirements . . . . 10 Watts
3. Engineering costs $380,000
4. Fabrication costs $160,000

7.4 LAUNCH VEHICLE AND INJECTION SELECTION

This section defines the launch-injection-stationing sequence for each of the four satellites. The design objectives were to maximize pay load, minimize booster cost, and minimize transfer time, allowing for a maximum of thirty days to get on station. Described herein are the booster/upper stage and apogee kick motor size for injection, the orbit trim (injection correction) subsystem and the orbit change (positioning) subsystem. Weight, volume, and power requirements of these subsystems are given.

7.4.1 LAUNCH-INJECTION-STATIONING SEQUENCE

Table 7.4-1 shows the longitudinal location and weight of the four geocentric satellites.

Table 7.4-1. Orbit Location and Weight of Satellites

Satellite	Longitude	Weight (lbs)	Weight (kg)
Alaska	135°W	2043	929
India	77°E	752	342
Instructional (U.S.)	120°W	983	446
Demonstration (U.S.)	105-107°W	2036	924

With the exception of Titan IIIC, none of the boosters can place the desired payloads close to desired final longitudes within one to one-half revolutions in the transfer orbit. Therefore, the selected approach to maximize payload at minimum cost was to select an optimum coast period in the 100 nm (185 km) parking orbit and, then, make the second firing of the upper stage. Table 7.4-2 lists orbit crossing longitudes at perigee for the transfer orbit, and shows longitude for first and second apogees at synchronous altitude.

Table 7.4-2. Perigee of Transfer Orbit at Equatorial Crossings
(90° Azimuth ETR Launch)

	Crossings											
	1	2	3	4	5	6	7	8	9	10	11	12
Longitude of Perigee	4.0E	171.5E	21.0W	146.5E	46.0W	121.5E	71.0W	96.5E	96.0W	71.5E	121.0W	46.5E
Longitude 1st Apogee	105.0E	85.5W	82.0E	110.5W	57.0E	135.5W	32.0E	160.5W	7.0E	176.5E	18.0W	151.5E
Longitude 2nd Apogee	53.0W	116.5E	76.0W	91.5E	91.0W	66.5E	116.0W	41.5E	141.0W	16.5E	166.0W	8.5W

The time between crossings (half orbit) is about 44 minutes. The perigee-apogee firing points selected will place the satellite closest to its desired longitude location and, thus, minimize the on-board propellant required to effect the station change.

The apogee firings are all scheduled for the second apogee of the transfer ellipse. Present day tracking capability requires more time to obtain accurate position data than is available if it is attempted to fire the apogee kick motor for circularization at the first apogee. The Titan 3C transtage is capable of first apogee firing of the transtage, but the guidance and control package is limited to about six and one-half hours life. The transtage is thus limited to first or second perigee and to first apogee longitude placement. This cannot be used for the presently desired locations without large vernier (station change) energy requirements on the satellite's station change propulsion subsystem.

The launch sequence of events is similar for all four satellites regardless of the booster selected. Launch will be from ETR at an azimuth of 90°. Soon after separation of the 1st stage, the first firing of the second stage to place the vehicle into an 100 nm (185 km) orbit will occur. The second firing, to place the spacecraft into the transfer ellipse will be made at the appropriate equatorial crossing for the particular satellite. The time in parking orbit, number of equatorial crossings, longitude of perigee and second apogee are shown in Table 7.4-3.

Table 7.4-3. Perigee-Apogee Longitude

Satellite	Time in Parking Orbit	Longitude Location		No. of Crossings
		Perigee	2nd Apogee	
Alaska	377 min.	96°W	141°W	9
India	245 min.	121.5°E	66.5°E	6
Instructional	289 min.	71°W	116°W	7
Demonstration	289 min.	71°W	116°W	7

After perigee firing of the second booster stage, there will be separation of the spacecraft and spin-up for stabilization. Coning and precession will be controlled by an on-board thruster system.

At second apogee, the spacecraft will be oriented and an apogee kick motor fired to circularize the orbit of the spacecraft. Subsequent to apogee kick motor firing, the axial and radial engines will be used to trim the orbit (correct for accumulated booster and apogee kick errors). The same thrusters will be used to initiate drift and stop the spacecraft at its desired station longitude.

7.4.2 BOOSTER SELECTION

The booster selections were made from those listed in Section 5.7 wherein payload and launch cost are compared. The boosters chosen for the four spacecraft are as follows:

Alaska:	Titan 3B/Centaur/AKM
India:	Atlas E-F/Agena D/AKM
Instructional:	Atlas E-F/Agena E/AKM
Demonstration:	SLV 3C/Centaur/AKM

7.4.2.1 Booster for the Alaska Satellite

The weight of the Alaska Satellite is 2247 lb (2043 + 10% margin) (1020 kg). The most likely boosters are listed below along with their payload capabilities and launch costs:

Booster	Payload (lbs)	Cost	Payload (kg)
SLV 3C/Centaur/AKM	2010	\$12-13.5 M + \$1 M for AKM	914
Titan 3C	2050	\$16.5-17 M	931
Titan 3B/Centaur/AKM	2220-2260	\$13 M + \$1 M for AKM	1010-1040

The SLV 3C/Centaur/AKM has no margin on maximum gross weight of the satellite and will cost about the same as a Titan 3B/Centaur/AKM combination. The Titan 3C has a 70 lb (31.8 kg) weight margin on the maximum expected satellite weight, but would cost several million dollars more than either of the other two boosters. There appears to be a fairly good likelihood that a Titan 3B/Centaur will become operational about 1972. On this basis, the Titan 3B/Centaur with an apogee kick motor (AKM) was selected. Second choice would be the SLV 3C/Centaur. By 1971, the roll down radiation control curtain for Centaur should be available so that coast in the 100 nm (185 km) parking orbit for seven or more hours will be possible with little or no hydrogen boil-off loss.

7.4.2.2 Booster for the India Satellite

The weight of the India satellite is 827 lb (752 + 10% margin) (376 kg). The most likely boosters with payload capability and launch costs are listed below.

Booster	Payload (lbs)	Cost	Payload (kg)
SLV 3A/Agena D/BII	831	\$6.5-8.5 M	378
Titan 3B/Agena D	837	\$6-8 M	380
SLV 3A/Agena E	890	\$6-8 M	404
Atlas E-F/Agena D/AKM	910	\$4.2 M + \$1 M AKM	413

The Atlas E-F/Agena D/AKM is the most cost effective booster. Its total cost estimate, including an optimized apogee kick motor, is \$5.2 million. An Atlas SLV 3A/Agena E or Titan 3B/Agena D are both estimated at \$6-8 million. The Atlas E-F/Agena D/AKM also offers a payload weight margin of about 150-lb (68 kg) over the present maximum estimated weight for the India satellite.

7.4.2.3 Booster for the U. S. A. Instructional Satellite

The weight of the Instructional Satellite is 1081 lb (983 + 10% margin) (491 kg). The most likely boosters with payload capability and cost are listed below.

Booster	Payload (lbs)	Cost	Payload (kg)
SLV 3A/Agena E/BII	1082	\$6.5-8.5 M	491
Atlas E-F/Agena E/AKM	1150	\$4.2 M + \$1 M for AKM	522
SLV 3C/Centaur/BII	1500	\$14 M	680

The Atlas E-F/Agena E/AKM is the most cost effective booster. Its total cost estimate including an optimized apogee motor is $5.2 million whereas the SLV 3A/Agena E/BII is estimated at $6.5-$8.5 million and has only a 60 lb (27.2 kg) payload margin over maximum estimated weight of the satellite. The Atlas E-F/Agena E/AKM has a 130 lb (59 kg) payload margin over the present maximum estimated weight for the satellite.

7.4.2.4 Booster for the U.S.A. Demonstration Satellite

The weight of the Demonstration Satellite is 2239 lb (2036 + 10% margin) (1014 kg). The most likely boosters are listed below along with their payload capabilities and costs.

	Payload (lbs)	Cost	Payload (kg)
SLV 3C/Centaur/AKM	2050	$12-13.5 M + $1 M for AKM	914
Titan 3B/Centaur/AKM	2220-2260	$13 M + $1 M for AKM	1010-1030
Titan 3C/Impr. Transtage	2450	$16-17 M	1110

Because of the desire to utilize the SLV 3C/Centaur, this booster plus an optimized apogee kick motor is selected. It is the least expensive of the three suggested boosters. However, the weight control monitoring will have to be tightly managed in order not to exceed the capability of this combination.

7.4.3 FINAL INJECTION-STATIONING

The satellite is spun-up after separation from the booster second stage. Two small solid propellant motors will accomplish the spin up. During the approximately 15-hour coast in the transfer orbit, coning and precession control will be effected by use of 5-lb (22.3 n) thrust radial and axial hydrazine engines. At second apogee, the spacecraft is oriented and the solid propellant apogee kick motor is fired to circularize the orbit. Subsequent to the AKM firing, the 5-lb (22.3 n) thrust engines will be used to remove the cumulative injection errors and to place the spacecraft on station within a minimum of thirty days.

7.4.3.1 Apogee Kick Motors

Apogee kick motors (AKM) will be used to provide the circularization energy for the four satellites. Table 7.4-4 lists the total motor weight, propellant weight, and dry motor weight for the four motors. A specific impulse of 290 sec and mass loading fraction of 0.9 was assumed in sizing the motors.

Table 7.4-4. Apogee Kick Motors

Satellite	Motor Wt	Propellant Wt	Base Wt
Alaska	2541 lb (1155 kg)	2287 lb (1040 kg)	254 lb (115 kg)
India	988 lb (449 kg)	889 lb (403 kg)	99 lb (45 kg)
Instructional	1250 lb (567 kg)	1125 lb (511 kg)	125 lb (58 kg)
Demonstration	2240 lb (1015 kg)	1016 lb (461 kg)	224 lb (102 kg)

Development costs are estimated at about one million dollars ($1 M) and development time of one year and one-half years for each motor. None of the motors are off the shelf motors.

7.4.3.2 Correction-Stationing Propulsion

The energy requirements for the various satellites are listed in Table 7.4-5.

Table 7.4-5. Orbit Trim and Stationing Energy

		fps	m/sec	lb/sec	N/sec	lb (N_2H_4)	kg
Alaska	Injection Correction	210	64	13,055	58,000	59.3	26.9
	Stationing (141°W to 135°W)	4	1.22	250	1,110	1.1	0.5
India	Injection Correction	230	70	5,326	23,700	24.3	11.0
	Stationing (66.5°E to 77°E)	7	2.12	162	720	0.75	0.34
Instructional	Injection Correction	230	70	7,314	32,600	33.3	15.1
	Stationing (116°W to 120°W)	3	0.91	85	378	0.4	0.18
Demonstration	Injection Correction	210	64	13,108	58,000	59.6	27.1
	Stationing (116°W to 105°W)	7.3	2.22	458	2,020	2.1	0.95

For the station change (stationing) and injection correction (orbit trim) 5-lb thrust axial and radial hydrazine engines were selected. The propulsion subsystem schematics including station keeping and mass unloading were shown previously in Figures 7.3-20 and 7.3-21; the hardware list and weights in Tables 7.3-19 through 7.3-22.

7.4.3.3 Propulsion Tradeoffs

A few pounds of weight could be saved by using a liquid bipropellant system for the injection correction and stationing functions as contrasted to the use of hydrazine. However, the maturity of technology at the five-pound thrust level is slightly in favor of hydrazine versus a nitrogen tetroxide (N_2O_4) - hydrazine fuel subsystem. Steady state specific impulse of the hydrazine engines is 230 sec versus about 260 sec for the bipropellant engines. However, performance degrades somewhat faster in pulse mode operation of the bipropellant engines. In addition, there are 5-lb (22.3 N) thrust hydrazine engines now in orbit on ATS-C and a classified program, and both systems are operating quite well.

The system will operate in the "blow down" mode which reduces the number of components required and, thus, increases the reliability of the hydrazine system. A high pressure gas regulator, in particular, is not required.

Hydrogen Peroxide could be used for the injection correction and stationing function. However, the specific impulse, steady state, is only 160 sec in contrast to 230 sec for hydrazine. This is thirty percent lower and, thus, would involve considerable weight penalty. Another drawback with hydrogen peroxide is the occasional requirement to "valve off" gas due to the slow decomposition of the propellant to oxygen and water. Since all satellites are to be three-axis stabilized once they are on station, the use of hydrogen peroxide is precluded.

7.5 PROGRAM PLANS AND COSTS

This section presents the estimated schedules and costs associated with the four TVBS systems investigated during Phase 3 of the study.

7.5.1 PROGRAM PLANS

In order to display the several parallel and interrelated events on a time scale of the program summary schedule and a project schedule are presented for each configuration. The NASA Phased Project Planning approach was used as a basis for these schedules, as is noted by the general grouping of tasks on the summary schedules presented. Schedules are assumed to start from the award of a Phase B contract.

In general, an eleven month period is allowed for Phase B, a twenty-four month period for Phase C/D through Qualification Test, and about twelve months are allotted for Phase D flight hardware fabrication, test, prelaunch, and launch. The overall schedule for the space segment of the program encompasses 47 months for the Direct Service to Alaska case (Figures 7.5-1 and 7.5-2), and 41 months for the other three cases (Figures 7.5-3 and 7.5-4). This reduction of six months results, mainly, from overlapping of flight hardware fabrication with final design and qualification test. Justification for this would be the greater confidence level associated with the smaller size and more straight forward design of these three satellites as compared to the Alaska satellite.

Note that a schedule block to account for post-launch operation is included on the Summary Schedules. This would extend 48 months from flight date and would include all of the tracking, command, and maintenance activities associated with satellite operation.

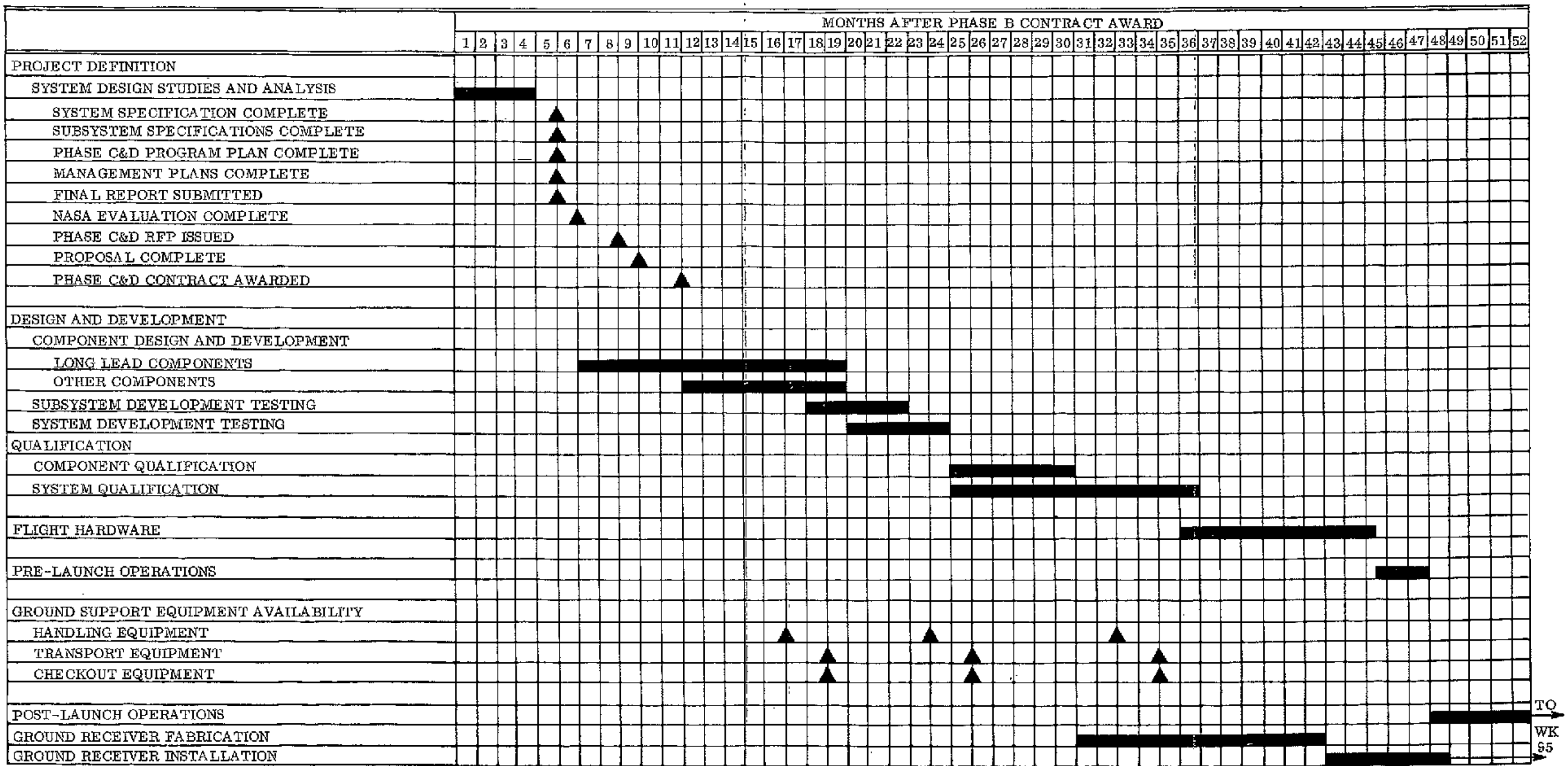
A separate block for ground receiver fabrication and installation is shown as a lead item prior to flight date. This is an estimate based upon the desired quantities, and is made on the assumption that manufacturing facilities are in place to provide the necessary output.

The NASA Phased Project Planning schedules described above are more extended than those which would result from competitive commercial business after the technology had been developed by NASA. To arrive at schedules for operational systems, Phase B would be eliminated and the Phase C and D tasks would be overlapped. Using these assumptions, the time between contract go-ahead and launch for the operational systems would be as follows:

1. Community Service to India: 24 months
2. Educational TV Service to the U.S.: 24 months
3. Direct Service to Alaska: 30 months

7.5.2 PROGRAM COSTS

The approach used for the computerized costing of the four TVBS systems was previously described in Section 6.1.3. Costs of specific subsystems were determined from the parametric performance/cost data presented in Section 5 (or from other required sources) to



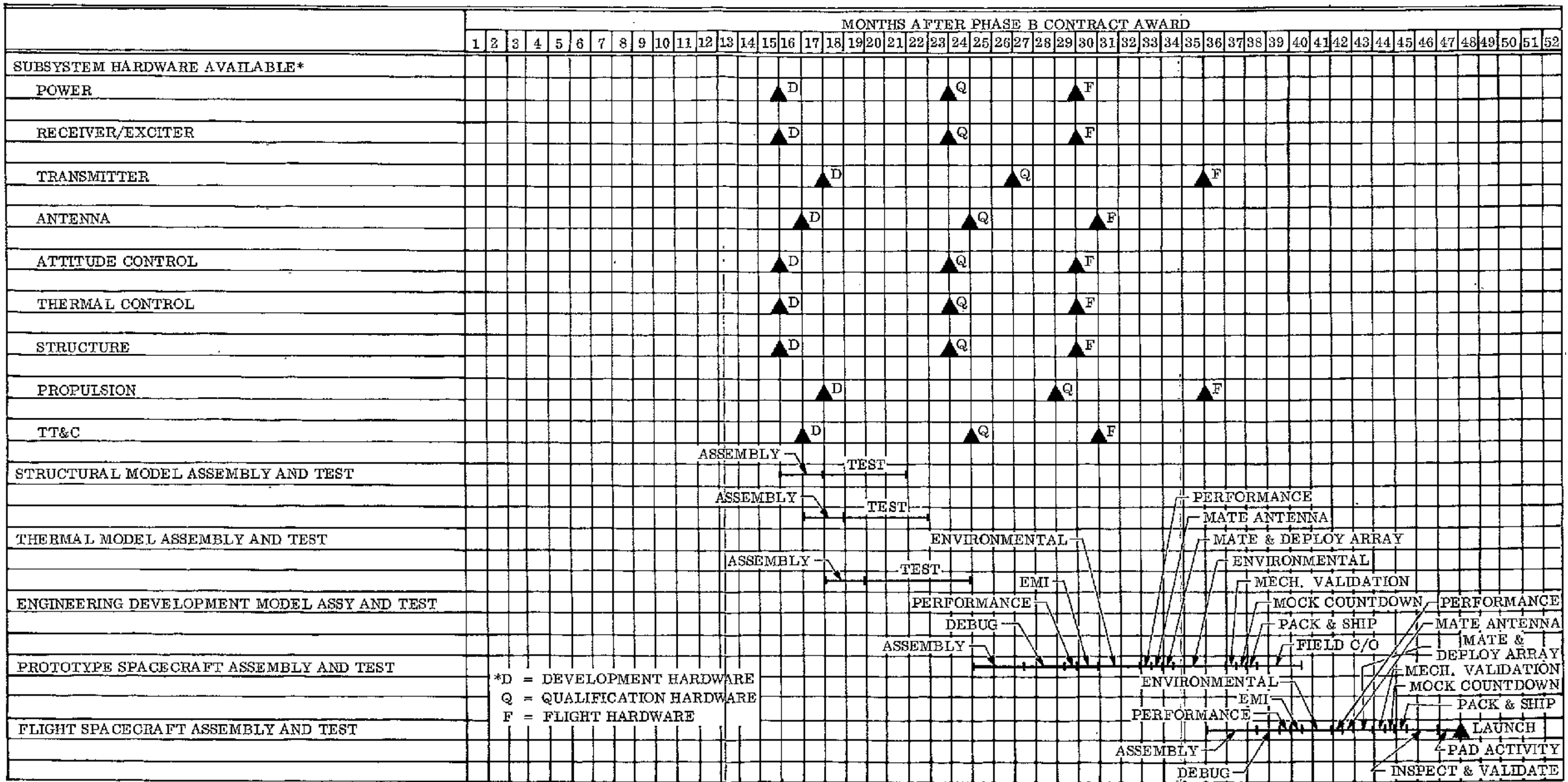
A

FOLDOUT FRAME #1

B

Figure 7.5-1. Summary Program Schedule, Direct Service to Alaska System

FOLDOUT FRAME #2



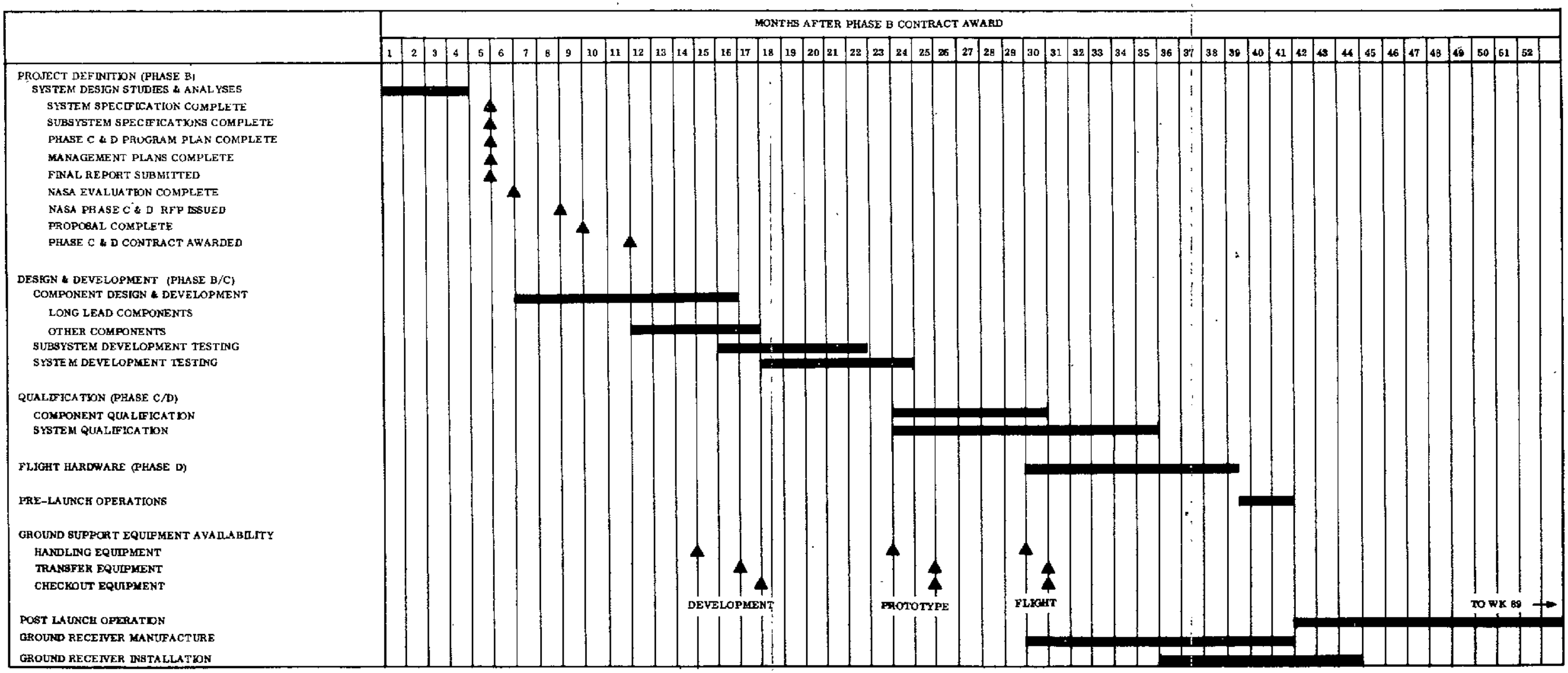
A

FOLDOUT FRAME #1

B

Figure 7.5-2. Project Schedule, Direct Service to Alaska System

FOLDOUT FRAME #2



A

B

Figure 7.5-3. Summary Program Schedule for: 1) Community Service to India, 2) Instructional Service to U.S.A., 3) Demonstration Service to U.S.A.

FOLDOUT FRAME #1

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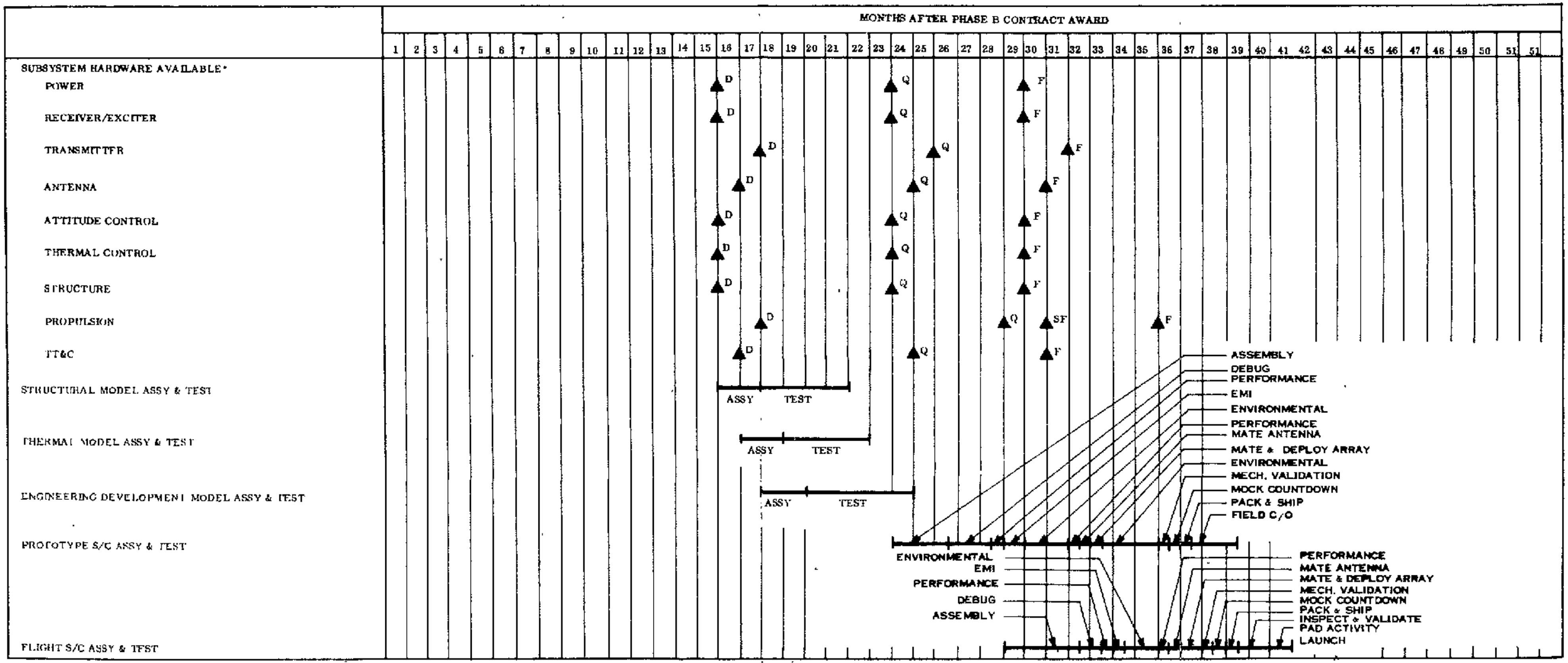

D DEVELOPMENT HARDWARE
Q QUALIFICATION HARDWARE
F = FLIGHT HARDWARE
SF = SIMULATED FLIGHT HARDWARE

Figure 7.5-4. Project Schedule for:
1) Community Service to India
2) Instructional Service to U.S.A.
3) Demonstration Service to U.S.A.

A

FOLDOUT FRAME #1

B

FOLDOUT FRAME #2

serve as the baseline for costing estimating. The summation of these subsystem costs were then modified by appropriate factors (integration, liaison, and management) and combined with ground receiver costs to develop the total costs.

A summary of the development, investment, and operation cost estimates for the four TVBS systems are presented in Table 7.5-1. More detailed cost breakdowns for the four TVBS systems are presented in Tables 7.5-2 through 7.5-5.

Table 7.5-1. TVBS System Cost Summary

Configuration	Satellite Development	10-Year Satellite Operation(2)	Ground Receiver Investment	Total 10-Year Program(1)
Community/Rebroadcast Service to India	14.8	47.0	25.3	87.1
Direct Broadcast to Alaska	22.7	122.0	10.0	154.7
Instructional TV to U.S.	23.6	60.0	11.0	94.6
Demonstration TV to U.S.	23.3	27.8(1)	Not Applicable	51.1(1)

(1) In the case of the demonstration satellite, the totals are based on a 2-year period.

(2) This allows for 5 launches in the 10 year period.

Table 7.5-2. System Costs, Community/Rebroadcast TV to India Service

Item	Categorized Data Cost ($ Millions)		
	Development Costs	Operational Costs	Investment Costs
Satellite System			
Subsystem			
Power-Supply	1.20	0.58	--
Receiver/Exciter	0.41	0.08	--
Transmitter	1.25	0.16	--
Antenna	1.18	0.25	--
Attitude Control	1.47	0.34	--
Thermal Control	0.30	0.08	--
Structures	0 23	0 02	--
Propulsion	1.50	0 05	--
TT&C	0.38	0.16	--
Subtotal	7.92	1.72	--
Production Revisions	--	0.34	--
Systems Integration and Test	3 33	0.86	--
Program Management	2.02	0 53	--
Satellite Totals	13 27	3 45	--
Launch Vehicle	1.0	4.2	--
Supporting Systems			
AGE	0.42	0.02	0.21
Manufacturing & Test Fixtures	0 07	0 01	0.29
Uplink	--	0.50	0.80
Tracking/Command	--	0.30	--
Supporting System Totals	0.49	0.83	1.30
Ground Receiving System	--	--	25.3

$$SAOC = \frac{1}{2}(3\ 4 + 4.2) + 0.8 + \frac{1}{10}(1.3) = 4.7$$

$$SEDC = 13\ 3 + 1.0 + 0.5 = 14.8$$

$$TSI = 10(4.7) + 14\ 8 + 25.3 = 87.1$$

Table 7.5-3. System Costs, Direct TV to Alaska Service

Item	Categorized Data Cost ($ Millions) Development Costs	Operational Costs	Investment Costs
Satellite System			
Subsystem			
Power Supply	2.74	2.76	--
Receiver/Exciter	0.25	0.05	--
Transmitter	3.30	0.54	--
Antenna	1.20	0.21	--
Attitude Control	1.77	0.46	--
Thermal Control	0.90	0.22	--
Structures	0.37	0.08	--
Propulsion	1.50	0.10	--
TT&C	0.38	0.16	--
Subtotal	12.41	4.58	--
Production Revisions	--	0.91	--
Systems Integration & Test	5.21	2.30	--
Program Management	3.17	1.40	--
Satellite Totals	20.79	9.19	--
Launch Vehicle	1.0	13.0	--
Supporting Systems			
AGE	0.78	0.04	0.39
Manufacturing & Test Fixtures	0.13	0.03	0.54
Uplink	--	0.50	0.80
Tracking/Command	--	0.30	--
Supporting System Totals	0.91	0.87	1.73
Ground Receiving System	--	--	10.0

$$SAOC = \frac{1}{2}(9.2 + 13.0) + 0.9 + \frac{1}{10}(1.7) = 12.2$$

$$SEDC = 20.8 + 1.0 + 0.9 = 22.7$$

$$TSI = 10(12.2) + 22.7 + 10.0 = 154.7$$

Table 7.5-4. System Costs, Instructional TV to U.S. Service

Item	Categorized Data Cost ($ Millions) Development Costs	Operational Costs	Investment Costs
Satellite System			
Subsystems			
Power Supply	2.39	1.19	--
Receiver/Exciter	0.56	0.17	--
Transmitter	3.96	0.72	--
Antenna	1.12	0.10	--
Attitude Control	1.74	0.36	--
Thermal Control	0.63	0.14	--
Structures	0.25	0.03	--
Propulsion	1.50	0.06	--
TT&C	0.38	0.16	--
Subtotal	12.51	2.93	--
Production Revisions	--	0.59	--
Systems Integration & Test	5.25	1.48	--
Program Management	3.19	0.90	--
Satellite Totals	20.95	5.90	--
Launch Vehicle	1.0	4.2	--
Supporting Systems			
AGE	0.50	0.03	0.25
Manufacturing & Test Fixtures	0.08	0.02	0.34
Uplink	--	0.50	0.80
Tracking/Command	--	0.30	--
Supporting System Totals	0.58	0.85	1.39
Ground Receiving System	--	--	11.0

$$SAOC = \frac{1}{2}(5.9 + 4.2) + 0.85 + \frac{1}{10}(1.4) = 6.0$$

$$SEDC = 22.0 + 1.0 + 0.6 = 23.6$$

$$TSI = 10(6.0) + 23.6 + 11.0 = 94.6$$

Table 7.5-5. System Costs TV Demonstration to U.S. Service

Item	Categorized Data Cost ($ Millions) Development Costs	Operational Costs	Investment Costs
Satellite System			
Subsystems			
Power Supply	2.80	3.44	--
Receiver/Exciter	0.45	0.09	--
Transmitter	3.84	0.56	--
Antenna	0.68	0.07	--
Attitude Control	1.67	0.42	--
Thermal Control	1.14	0.31	--
Structures	0.33	0.06	--
Propulsion	1.50	0.08	--
TT&C	0.38	0.16	--
Subtotals	12.79	5.19	--
Production Revisions	--	1.04	--
Systems Integration & Test	5.35	2.62	--
Program Management	3.26	1.59	--
Satellite Totals	21.40	10.44	--
Launch Vehicle	1.0	13.7	--
Supporting Systems			
AGE	0.8	0.04	0.39
Manufacturing & Test Fixtures	0.1	0.03	0.54
Uplink	--	0.50	0.80
Tracking Command	--	0.30	--
Supporting System Totals	0.9	0.87	1.73

$$SAOC = \frac{1}{2}(10.4 + 13.7) + 0.9 + \frac{1}{2}(1.73)^* = 13.9$$

$$SEDC = 21.4 + 1.0 + 0.9 = 23.3$$

$$TSC = 23.3 + 2(13.9)^* = 51.1$$

*Based on 2-year program

7.6 TERRESTRIAL TRANSMISSION COSTS

This section discusses a method of determining system costs associated with terrestrial methods of transmitting a television signal from the originating source to the user. This will enable a determination to be made of the cost-effectiveness of satellites as compared to present terrestrial methods. The satellite cost-effectiveness is a prime factor in determining its usefullness to a potential user.

The terrestrial television transmission system was assumed to consist of television broadcast stations interconnected with microwave links. The initial investment and annual operating costs were determined as a function of the number of transmitters and the separation distance between transmitters.

Five models were defined relating four types of ownership and three types service. Section 7.6.1 describes the following four types of ownership:

1. Commercial networks with independently owned facilities.
2. Commercial networks with jointly owned facilities.
3. Government owned network.
4. Government owned network and microwave link.

In all except the last case, the microwave interconnections are rented from a common carrier. Sections 7.6-1 and 7.6-2 explain how the different ownership arrangements affect the investment and operating costs.

The three types of service involved are distribution, direct broadcast and educational TV. Unlike satellite systems, the distribution and direct broadcast services of terrestrial systems have the same transmission costs. The educational TV system differs in costs primarily because of lower microwave interconnection rental rates. The lower rental rates are due to the lower interconnection reliability guaranteed.

Four classes of ownership and three types of service result in twelve combinations of costs. However, as illustrated in Table 7.6-1, some of these combinations produce identical costs which can be handled with only five models. In the table, the models are designated by the Roman numerals I, II, III, IV, and V. This major reduction in the number of expected models results from the fact that "distribution" and "broadcast" services of terrestrial networks are identical.

The cost results are calculated from the five sets of equations given in Table 7.6-2 below. These equations give the total investment and annual operating costs for a terrestrial broadcast system as a function of the number of transmitters required and transmitter separation distance.

Table 7.6-3 summarizes the broadcast station and the microwave link cost parameters used for each model.

Table 7.6-1. Application of Models Developed for the Analysis

Ownership	Rebroadcast	Service Broadcast	Educational
Commercial network, independent facilities	I	I	None
Commercial network, joint facilities	V	V	None
Government network, fully owned	II	II	II
Government network, rented interconnection	III	III	IV

Table 7.6-2. Terrestrial Cost Models

MODEL NUMBER	INVESTMENT COST	OPERATING COST
I	$N C_2$	$N (D K_8+K_3+K_2)$
II	$N (D C_3+C_1)$	$N (D K_4+K_1)$
III	$N C_1$	$N (D K_7+K_1)$
IV	$N C_1$	$N (D K_6+K_1)$
V	$N C_1$	$N (D K_8+K_3+K_1)$

Where

N is the number of broadcast stations required for a system

D is the distance between adjacent transmitters for the specific transmitter, receiving antenna

C is an investment cost associated with the type of ownership and the service of the system

K is an annual operating cost associated with ownership and service of the system

Table 7.6-3. Summary of Basic Cost Coefficients

	PARAMETER	NUMBER OF CHANNELS 1	2	3	4	5
INVESTMENT COSTS						
BROADCAST STATIONS ($\$10^3$)						
GOVERNMENT OWNED	C_1	549	1021	1481	1941	2871
COMMERCIALLY OWNED	C_2	549	1098		2196	3294
MICROWAVE LINK ($/MILE)						
GOVERNMENT OWNED	C_3	1500	2010		2950	4320
COMMERCIALLY OWNED(1)	C_4	1500	2010		2950	4320
ANNUAL OPERATING COSTS						
BROADCAST STATIONS ($\$10^3$)						
GOVERNMENT DIRECT COSTS	K_1	42	82	113	142	212
COMMERCIAL DIRECT COSTS	K_2	42	85		171	256
INDIRECT COST	K_3	52	99		193	288
MICROWAVE LINK ($/MILE)						
OWNED FACILITIES						
DIRECT COSTS	K_4	150	210		330	450
INDIRECT COSTS(1)	K_5	150	201		295	432
RENTED FACILITIES						
EDUCATIONAL TV	K_6	300	435		680	900
GOVERNMENT	K_7	480	700		1090	1440
COMMERCIAL	K_8	480	960	1440	1920	2880

Section 7.6-2 gives examples of the use of these equations for determining the costs of a terrestrial transmission system in Alaska, a community system in India, and an educational system in the U.S.; Section 7.6.1.5.3 provides some costs of receivers and their antennas for the school systems. If required, these items are added to the total investment costs.

7.6.1 COST MODELS

This section develops the five cost models and describes the elements of each model. Table 7.6-4 defines the terms and symbols used in the following sections.

7.6.1.1 Network Coverage Area

A network of broadcasting stations must accommodate the topographic and demographic pecularities of the region it covers. However, for this generic model, it is assumed that there are no topographic peculiarities and that the population distribution is homogenous. The system layout is a uniform network of stations spaced at equal intervals. The basic module of the network is a hexagonal area containing a broadcast station at its center. The network of stations was laid out by nesting rows and columns of these areas. Figure 7.6-1 shows that 100% signal coverage is obtained for a separation distance between transmitters of $\sqrt{3}\ R_H$, where R_H is the distance from the transmitter to the radio horizon.

Table 7.6-4. Definitions and Symbols

Coverage Area (A_r)	Area encompassed by circle having a radius equal to the distance from the transmitter to the radio horizon.
Station Separation (D)	Distance between adjacent stations.
Percent Coverage (P_c)	The percent of the total area receiving a signal
Radius of Coverage	The maximum distance at which a signal is received.
A Broadcast Station	UHF repeater station that broadcasts programs received from a programming center. For this cost analysis, the only personnel associated with a repeater station, are those required for maintenance. There are none of the personnel or equipment normally associated with a local commercial broadcast station for purposes of originating programs. No management or administrative personnel are included. The station automatically broadcasts whatever is received from its microwave interconnection.
Government Ownership	Facilities are fully owned by the government. Equipment is procured by an initial appropriation; there are no amortization or insurance costs involved
Partial Government Ownership	Government ownership of the broadcast station facilities and rental of the microwave linkage facilities.
Commercial Ownership	Ownership by private enterprise.

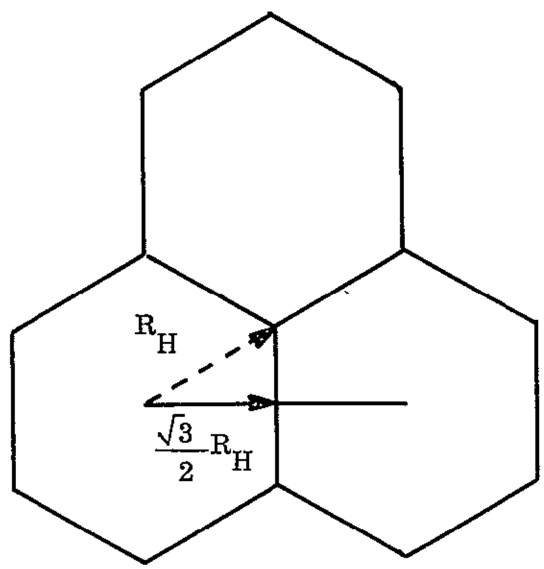

Figure 7.6-1. Network Coverage Area

7.6.1.2 Station Separation

The station separation is the key factor in determining terrestrial system costs. From Figure 7.6-2, for a transmitting antenna height of 1000-ft and receiving antenna height of 30-ft, the distance to the radio horizon is 52.5 miles. The transmitter separation distance which will provide 100% coverage is then 52.3 x$\sqrt{3}$, or 91 miles.

The minimum separation distance between transmitters which will provide 100% coverage is 91 miles. A receiving antenna having the appropriate gain will provide the desired picture quality. For transmitter separation distances greater than 91 miles less than 100% coverage is obtained. The separation distance required for a given percent coverage is given in Figure 7.6-3. The direct service assumes a 30-ft receiving antenna height; the special service assumes a 50-ft height.

Figure 7.6-3 was obtained in the following manner. The area of a hexagon having a perpendicular distance from the center to a side equal to D/2 is given as $\sqrt{3}/2\ D^2$. The area of a circle having a radius equal to the radio horizon distance R_H is πR_H^2. The percent coverage of the hexagon by the circle is the ratio of their areas. Thus,

$$\text{Percent Coverage} = 100 \text{ x circle area/hexagonal area} = 2\pi R_H^2 / 3 D^2 \times 100.$$

This is plotted in Figure 7.6-3 to obtain D, the transmitter separation distance, as a function of percent coverage for the two assumed values of receiving antenna height.

7.6.1.3 Number of Transmitters

The number of transmitters is required to determine total system costs. The number of transmitters required for a broadcast system is a function of the transmitter station separation (obtained from Figure 7.6-3) and the total area A_n. Thus

$$N = An/Ahex = An/\sqrt{3}/2 \quad D^2$$

This is plotted in Figure 7.6-4 for an area of one million square miles.

7.6.1.4 Description of the Five Models

Model I is for commercially owned systems providing distribution or direct broadcast services; because there is no distinction between the two services supplied by terrestrial TV systems, the costs are the same. The investment cost is, therefore, the number of stations times the cost to build a single commercial station: N C_2. The microwave linkage is rented, so there is no microwave investment cost. The annual operating cost per station consists of the sum of three parts; the cost of renting the microwave link, the direct costs of operating the station, and the indirect (primarily amortization of investment) costs: N (D K_8 + K_3 + K_2).

Model II is for fully government owned systems. Ownership is of both the stations and the microwave link. The initial investment cost, which can be considered as an initial government appropriation, is the cost of building the microwave link plus the stations: N (D C_3 + C_1).

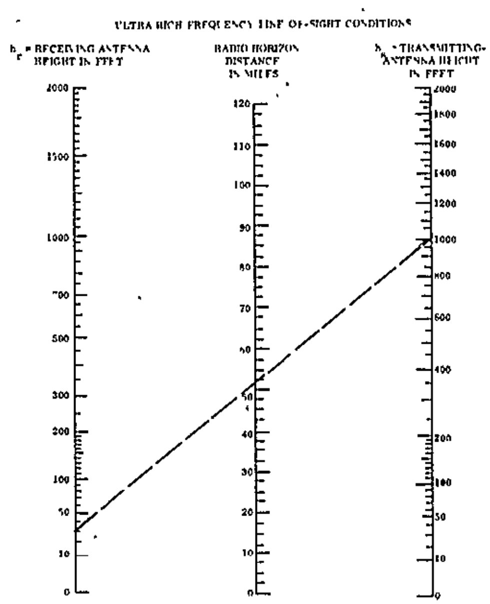

Figure 7.6-2. Nomogram Giving Radio-Horizon Distance in Miles When h_r and h_s are known

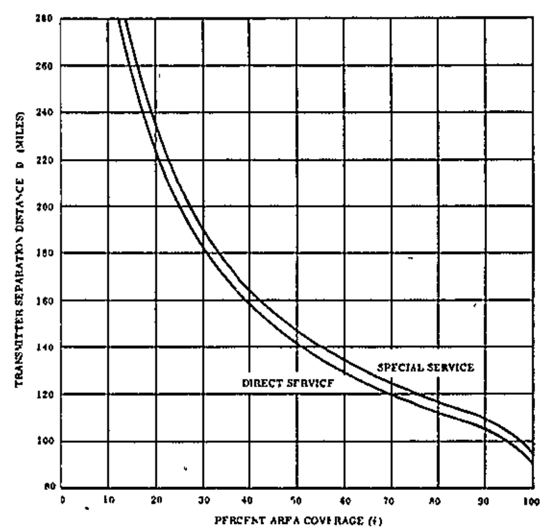

Figure 7.6-3. Transmitter Separation Distance vs Percent Area Coverage

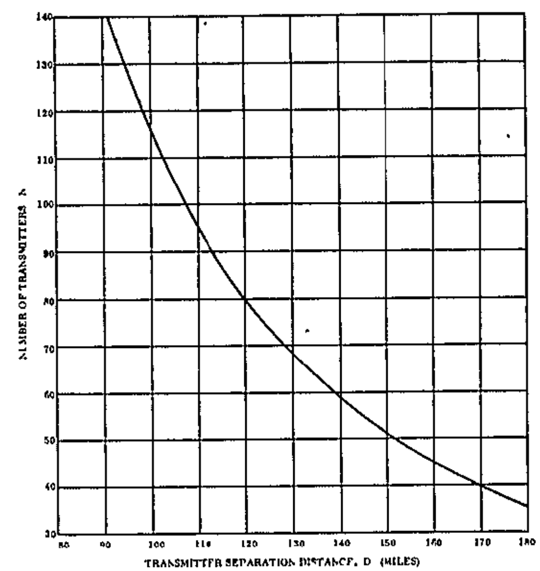

Figure 7.6-4. Number of Broadcast Transmitters Required per Million Square Miles vs Transmitter Separation Distance

The operating costs cover only the direct operating costs, because it is assumed that government accounting procedures do not depreciate an initial appropriation as commercial enterprises must. Consequently, annual government operating costs appear less than commercial ones: $N (D K_4 + K_1)$.

Models III and IV, partially government owned, assume the government owns the station, but rents the microwave link. This investment cost is, therefore, only the cost of the stations: $N C_1$. The operating costs differ in the two models because common carriers quote a lower microwave rental rate for carrying educational programs. For Model III, distribution and broadcast, the annual operating cost is $N (D K_7 + K_1)$; for Model IV, educational service, the annual operating cost is $N (D K_6 + K_1)$.

Other models can be developed from the basic cost data if different combinations of investment and accounting procedures are defined. As an example, direct service to Alaska was considered to be a modified commercial enterprise, whereby the individual channels would cooperate by jointly using the same building, land, and towers, as would a government system. However, in this case the operating costs would be amortized as in regular commercial enterprises. In this case, Model V, the investment cost is $N C_1$ and the annual operating cost is $N (D K_8 + K_3 + K_1)$.

7.6.1.5 Development of Basic Costs

The basic costs of broadcast stations and the connecting microwave links were determined. These costs were the initial investment costs and the annual operating costs. The initial investment costs for broadcast stations cover the costs of the facilities required for a basic station having an effective radiated power level of 1000 kw and 1, 2, 4, or 6 operating channels. The station was assumed to be a repeater station in that it did not originate any programs, but merely rebroadcast programs transmitted to it over the micrwave linkage. The investment costs for the microwave links cover the facility costs for links approximately 30 miles (48.2 km) long, and were found on the basis of cost per mile.

The annual operating costs were determined for broadcast stations and microwave links. These were the costs to run a station or microwave link on a yearly basis for single and multiple channels. These costs were broken down into the direct and indirect costs as well as rental costs. The direct costs included the costs of operation, maintenance parts, and maintenance personnel. The indirect costs include depreciation of facilities. The costs of borrowing money was not considered in the determination of the indirect costs. The annual operating costs were broken down into direct and indirect costs so that the costs to governments could be distinguished from commercial costs. The cost to government would be different than commercial costs since the methods of finance differ. Also, commercial ownership requires, for example, certain duplications of equipment for multiple channel operation. The basic period of operation was assumed to be approximately 16 hours a day, every day of the year. In addition, the annual costs for the rental of microwave equipment was determined for ETV, government, and commerical service.

7.6.1.5.1 Investment Costs

The investment cost of broadcast stations was determined for both government owned and commercially owned stations having 1, 2, 4, and 6 channels of service. The difference in cost between government and commercial ownership occurs for multiple channels, the cost of a single channel being identical for both cases of ownership. The reason for this cost difference for multiple channels stems from the fact that in government ownership, additional channels can utilize the basic facilities of the station with only small additional costs for the extra channels. In commercial ownership, additional channels require complete duplication of facilities since each channel is owned by a different commercial company.

The transmitter is assumed to have 1000 kw effective radiated power with a 1000-foot tower. Investment costs include the following items: the transmitter itself, control console, input and monitoring equipment, antenna, transmission line, line pressurization, miscellaneous equipment, etc., land, site improvement, legal, engineering, and installation costs.

Table 7.6-5 shows the costs for government and commercially owned stations.

Table 7.6-5. Comparison of Investment Costs for Commercially Owned and Government Owned Broadcast Station

	Government Owned No. of Channels					Commercially Owned No. of Channels			
	1	2	3	4	6	1	2	4	6
Broadcast Station ($\$10^3$)	Parameter C_1					Parameter C_2			
Transmitter and Equipment	431.0	862.0	1293.0	1724.0	2486.0	431.0	862.0	1724.0	2586.0
Tower and Building	118.0	159.0	188.5	217.5	285.5	118.0	236.0	472.0	708.0
Total	549.0	1021.5	1481.5	1941.5	2871.5	549.0	1098.0	2196.0	3294.0
Microwave Link ($/mile)	Parameter C_3					Parameter C_4			
Equipment	1500	2010		2950	4320	1500	2010	2950	4320

The microwave link connects broadcast stations. It was assumed that the link consisted of three portions, each approximately 30 miles (48.2 km) long. Each portion consisted of a relay station capable of receiving microwave signals and retransmitting them along the link. Of the three relay stations, one was considered to be at the broadcast station. The investment costs for both governmental and commercial ownership were identical. The microwave link was assumed to include the following equipment: TV relay equipment, fault alarm, audio channel, antennas, waveguides, battery power, tower buildings, multiplexer-filters, land, site improvement, engineering, installation, etc. The cost of a single channel was found to be $1500 per mile ($935/km). Table 7.6-5 gives equipment costs for either government owned or commercially owned microwave links.

7.6.1.5.2 Annual Operating Costs

The annual direct operating costs for broadcast stations cover the direct costs of station operation. Since the broadcast station was assumed not to produce any programs, either live or taped, but to rebroadcast to its service area the programs it received over the microwave link, no programming costs were included. The costs that were considered were basically those for operation and maintenance (engineering maintenance personnel, tubes, spare parts, power, etc.). Sixteen hours (two shifts) of operation daily throughout the entire year was assumed. Table 7.6-6 shows a tabulation of the cost breakdown for the annual direct operating costs for government owned stations.

Table 7.6-6.. Annual Operating Costs - Broadcast Stations

	Government Owned - Parameter K_1					Commercially Owned - Parameter K_2			
	No. of Channels					No. of Channels			
	1	2	3	4	6	1	2	4	6
Broadcast Station ($\$10^3$/year)									
Direct Costs									
Tower Maintenance and Misc	2	2	2	2	2	2	4	8	12
Building Maintenance and Misc	2	3	4	5	6	2	4	7	12
Tubes and Parts	18	26	54	72	108	18	36	72	108
Power	11	22	33	44	66	11	22	44	66
Engineering Technicians	10	20	20	20	30	10	20	40	60
Total	43	83	113	143	212	43	86	171	257
Indirect Costs	Not Applicable					Parameter K			
Transmitter @ 10 yrs						43	86	172	259
Tower and Bldg. @ 30 yrs						4	5	7	9
Insurance						6	8	14	20
Total						52	99	193	288

(Ref 1 pg. 194, ref 2 pg 63)

The annual indirect operating costs for broadcast stations cover the direct costs of commercially owned station operation. Basically, these costs cover those associated with maintenance and power. Table 7.6-6 shows a breakdown of the annual direct operating costs for commercially owned stations.

The annual indirect operating costs for broadcast stations cover the indirect charges attributed to station operation. Basically, these are the depreciation charges on equipment and facilities, and insurance costs. Generally, equipment was depreciated at 10% per year for a period of 10 years; the tower and building were depreciated over a period of 30 years. Table 7.6-6 tabulates the annual indirect operating costs for broadcast stations.

The direct annual operating costs for the microwave link for owned rather than leased facilities cover the yearly direct costs of operation and maintenance. Specifically, these costs include technicians, power and parts, and repair. Operation was assumed to be 16 hours a day, every day of the year. Table 7.6-7 is a cost breakdown of the annual direct operating costs.

Table 7.6-7. Annual Operating Costs - Microwave Link

	No. of Channels				
	1	2	4	6	
	Parameter K_4				
Owned Facilities ($\$10^3$/year)					
Direct Costs					
Technicians	60	72	96	120	
Power	36	60	108	156	
Parts and Repairs	54	78	126	174	
Total	150	210	330	450	
Indirect Costs	Parameter K_5				
($\$10^3$/yr)	150	201	295	432	
	No. of Channels				
Rented Facilities ($/mile/year)	1	2	3	4	6
	Parameter K_6				
Educational TV	100	435		680	900
	Parameter K_7				
Government Usage	480	700		1090	1440
	Parameter K_8				
Commercial Usage	490	960	1440	1920	2880

The indirect annual operating costs for owned microwave link facilities represent depreciation on equipment, buildings, tower, etc. The depreciation on equipment was taken over a 10-year period, while the depreciation of building and tower was taken over 30 years. The basic indirect costs for one channel were taken at $150 per mile ($93/km) per year. For multiple channels, the cost ratios were used.

As an alternative to owning microwave link facilities, they can be rented from the "common carrier." Rental charges are based on daily rates for 24 hours service; additional channels after the first can be rented at decreasing incremental costs. Table 7.6-7 provides the cost of rental ETV microwave links.

More reliable service than is required for ETV usage can be obtained at somewhat higher rates. More reliable service would be required for continuous or public reception. The service would also be available from the "common carrier." Multichannel service would be met with proportionately lower costs. The costs are given in Table 7.6-7.

Commercial usage would require the more reliable service and would be comparable to government service. However, since it is commercial service, additional channels would not be obtained at proportionately lower costs. The costs are shown in Table 7.6-7.

7.6.1.5.3 School Reception and Distribution Costs

The costs for the reception and distribution of educational television programs from broadcast stations were established for school districts. The costs were based on the following: receiving equipment, incremental costs for 20-dB and 30-dB antennas, room wiring and monitor costs. Receiving equipment, included the following items: 10-dB antenna, amplifying booster, splitter and cabling.

It was assumed that in the United States there are 100,000 schools located in 10,000 school districts. It was further assumed that each school district consists of 1 high school, 2 junior highs, and 7 elementary schools each having 50, 30, and 10 rooms each, respectively. Monitors are provided on the basis of one monitor for each 10 high school and junior high rooms, and one for each 3 elementary school rooms.

Table 7.6-8 is a breakdown of the required room wiring and monitors required for each school district. Table 7.6-9 is a tabulation of the costs for receiving and distribution facilities for each school district. Total costs of receiving and distribution facilities are also given in Table 7.6-9. These costs are tabulated per school district and also for the entire United States, assuming there are 10,000 school districts in the country.

7.6.1.6 Reliability and Outage Constraints

The reliability of terrestrial broadcast systems is very high, a typical broadcast company (GE Broadcasting Co.) reports total outage time as approximately four hours per year for its VHF station. UHF outage time could be slightly longer. Although the FCC does not specify allowable outages, the direct loss of revenue caused by outages is of concern to commercial stations.

Table 7.6-8. School Requirements for TV Reception

School	Schools per District	Rooms Wired per School	Total Rooms Wired	Number of Monitors
High	1	50	50	5
Junior High	2	30	60	6
Elementary	7	10	70	23
Totals	10		180	34

Table 7.6-9. School TV Reception Costs

	High School (1 per district)			Junior High (2 per district)			Elementary (7 per district)		
Antenna Gain	10 dB	20 dB	30 dB	10 dB	20 dB	30 dB	10 dB	20 dB	30 dB
Receiving Equipment	500	500	500	1000	1000	1000	3500	3500	3500
Additional Antenna Costs	0	68	1082	0	136	2164	0	476	7574
Room Wiring @ $40	2000	2000	2000	2400	2400	2400	2800	2800	2800
Monitors @ $100	500	500	500	600	600	600	2300	2300	2300
Total	$3000	$3068	$4082	$4000	$4136	$6064	$8600	$13376	$16174

Total Cost Per School District	Total Cost for U. S. (10,000 school districts)
$15,600 with 10 dB antenna	$156.0 million with 10 dB antenna
$20,580 with 20 dB antenna	$205.8 million with 20 dB antenna
$26,320 with 30 dB antenna	$263.2 million with 30 dB antenna

There are three major sources of outage. These are failures in the microwave link, station, or power. The microwave link contributes less than one hour of outage per year while the station accounts for three hours per year. Outage due to power failure is highly variable, depending upon local conditions and the availability of automatically controlled auxiliary power supplies.

Because of the extremely high reliability of terrestrial systems, the cost to improve such systems was not considered in the cost analysis. The addition of supplementary standby equipment and maintenance personnel was felt to have only a negligible effect on the continuity of service.

7.6.2 TERRESTRIAL COSTS FOR THE PHASE 3 SERVICES

The following sections present the terrestrial costs for a direct broadcast system for Alaska, a community system to India, and an educational (special) service to the United States. These are the services for which satellite system conceptual designs were accomplished during Phase 3 of the TVBS study.

7.6.2.1 Direct Service to Alaska

The Alaska system specifies three channel coverage of 85% of its 600,000 square mile region. Station transmitters with a 1000 kw effective radiated power and 1000-ft antenna height are assumed. The receiving antenna height is assumed to be 30 feet. Model V is applicable here:

1. From Figure 7.6-2, the transmitter separation distance is 108 miles for 85% coverage.

2. From Figure 7.6-3, 99 transmitters per million square miles are required. For Alaska, the number of transmitters is 99 x 0.6 or 60 transmitters.

3. From Model V, the investment cost is NC_1. (The values for these constants are given in Table 7.6-2).

$$NC_1 = 60 \times 1.48 \times 10^6 = \$88,800,000$$

The annual operating cost is $N (D K_8 + K_3 + K_1)$.

$$N (D K_8 + K_3 + K_1) = 60 (108 \times 1440 + 146,000 + 113,000)$$

$$= \$24,800,000$$

7.6.2.2 Community Service to India

The system for India has specifications which are similar to those of the Alaska system. Exceptions are that the India system is fully government owned and requires 85% coverage of its 1.1 million square miles by a single channel. Model II applies here:

1. Steps 1 and 2 are the same as for Alaska, resulting in a separation distance of 108 miles and a requirement for 99 transmitters per million square miles. For India, the total number of transmitters is 99 x 1.1 or 110.

2. From Model II (Table 7.6-4), the investment costs are $N (DC_3 + C_1) = 110 (108 \times 1500 + 549,000) = \$78,200,000$.
   The annual operating costs are $N (D K_4 + K_1)$
   $N (D K_4 + K_1) = 110 \quad (108 \times 150 + 42,000) = \$6,670,000$

7.6.2.3 Educational TV Service to the United States

The educational TV service specified covering 65% of the country's 3.02 million square miles with six channels. Model IV is applicable here:

1. From Figure 7.6-3, 65% coverage for a special service requires a transmitter separation of 129 miles.

2. From Figure 7.6-4, 69.5 transmitters per million square miles result in a total of 210 transmitters.

3. The investment cost is NC_1. $NC_1 = 210 \times 2.87 \times 10^6$ or \$603,000,000. The annual operating cost is $N (DK_6 + K_1)$. $N (DK_6 + K_1) = 210 (129 \times 900 + 212,000) =$ \$68,900,000.

These three applications are summarized in Table 7.6-10.

Table 7.6-10. Specifications, Requirements and Transmission Cost for Terrestrial Systems

	Direct Service for Alaska	Community Broadcast for India	Instructional TV Service to U.S.
SPECIFICATIONS			
Ownership	Commercial, modified	Fully Government	Partially Government
Service Class	Direct Broadcast	Direct Broadcast	Education
TASO Picture Quality	Grade 2, or better, for 84.5% of area	Grade 2, or better for 84.5% of area	Grade 1 for 65% of area
No. of Channels	3	1	6
Area Covered (Sq mi x 10^6)	0.6	1.1	3.0
Receiver Antenna Ht, ft (m)	30 (9.15)	30 (9.15)	7.77 as required
Daily Operation	16 hours	16 hours	16 hours
REQUIREMENTS			
No. of Stations	60	110	210
Station Separation (miles)	108	108	129
TRANSMISSION COSTS (Millions of dollars)			
Investment Costs	90	78	603
Annual Operating Cost	24.8	6.7	69

7.7 COST EFFECTIVENESS COMPARISONS

The following sections compare the costs of implementing television services by satellite and terrestrial means.

7.7.1 DIRECT TV SERVICE TO ALASKA

The comparison of the costs for a direct broadcast service to Alaska is given in Figure 7.7-1. As shown, the satellite system is almost twice as cost-effective as the terrestrial system. The requirements and characteristics of the two systems are alike, except for coverage and ground receiving equipment. The satellite system provides 100% area coverage while the terrestrial costs are calculated on the basis of 85% coverage. Since population is not uniformly distributed, 85% area coverage will encompass essentially all the population. Reducing the coverage area for a terrestrial system reduces the system cost in the same proportion.

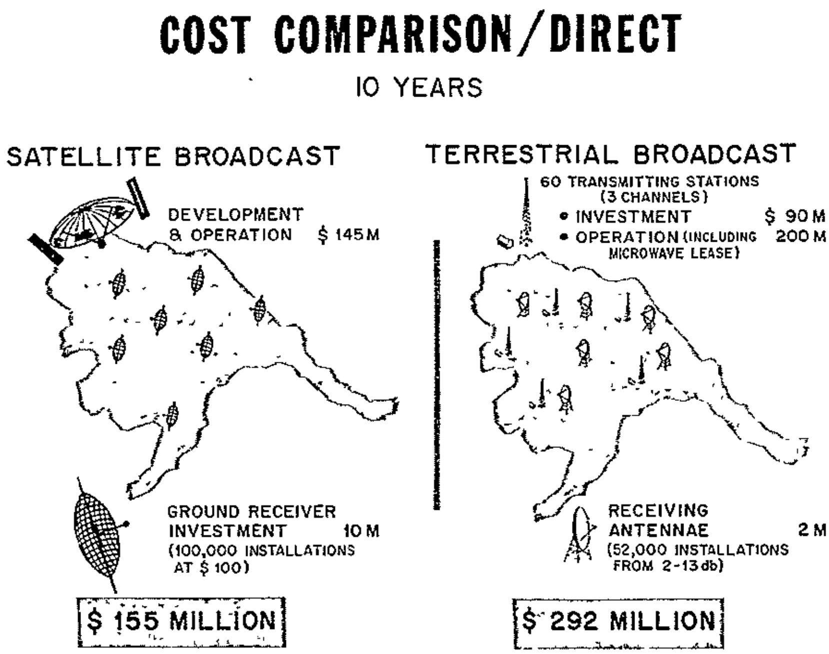

Figure 7.7-1. Cost Comparison - Direct Service to Alaska

Optimum design of the satellite system resulted in a ground receiving equipment cost of \$100 per ground receiver. This cost is included in the total satellite system costs. Because of the varying distances between receivers and the terrestrial transmitters, antennas having gains up to 13 dB will be required to obtain a TASO Grade 2 picture. The installed cost of a 13 dB, linearly polarized antenna is \$42. For the assumed 52,000 receivers the maximum costs for antennas would be 2 million dollars. This cost is not included in the terrestrial system costs; however, it is insignificant in comparison with the total system cost of 292 million dollars.

7.7.2 COMMUNITY BROADCAST FOR INDIA

The cost comparisons for a community broadcast service to India are shown in Figure 7.7-2. As shown, the satellite system is almost twice as cost-effective as the terrestrial system. The satellite system implementation costs are minimum for a ground equipment cost of $50 per receiver. This cost is included in the total satellite system costs. For the terrestrial system, the specified Grade 2 signal quality requires antenna gains up to 13 dB. For the assumption that 260,000 of the 500,000 receivers require antenna gains varying from 2 to 13 dB, an additional 10 million dollars for receiving antennas is required.

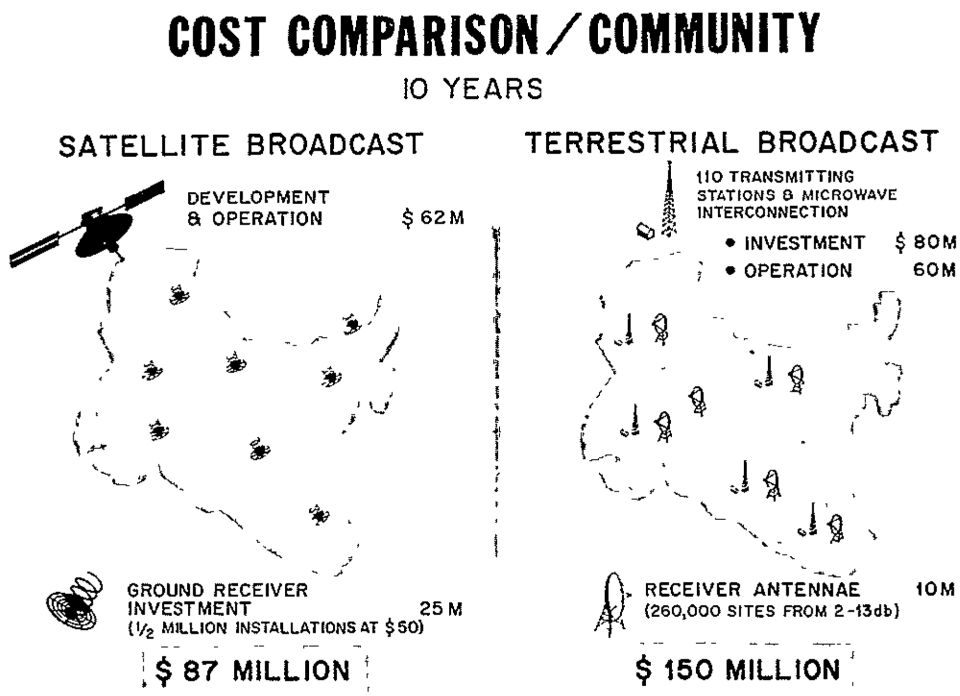

Figure 7.7-2. Cost Comparison - Community Service to India

7.7.3 EDUCATIONAL TV SERVICE TO THE UNITED STATES

The comparison of the system costs for an educational TV service to the United States is shown in Figure 7.7-3. As shown, the satellite system is more than 13 times as cost-effective as the terrestrial system. The terrestrial model assumes only 65% area coverage of the 3 million square miles of the continental United States. The satellite system provides for 100% coverage of the continental U. S. and includes Hawaii and Alaska.

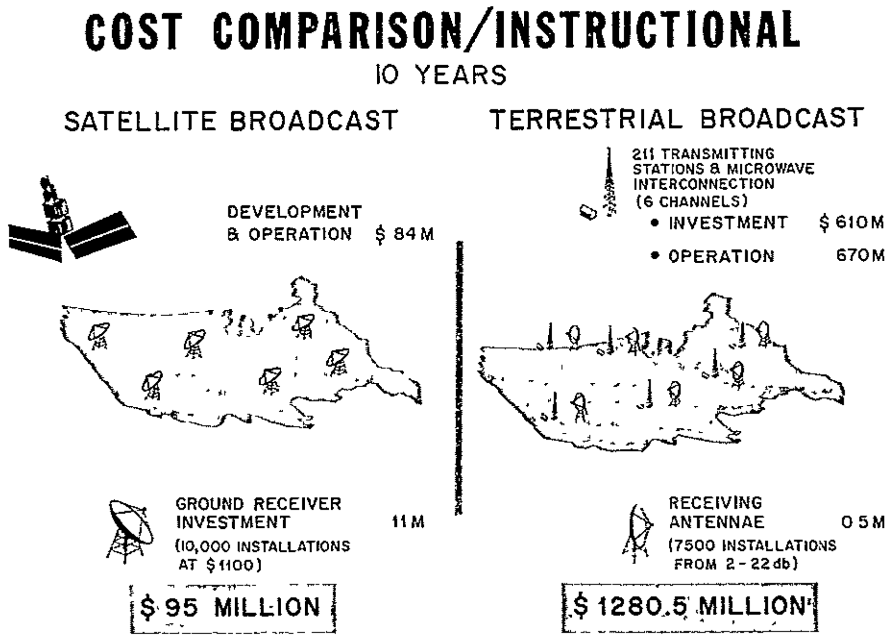

Figure 7.7-3. Cost Comparison - Instructional Service to U.S.A.

The receiving equipment costs included in the satellite system are 11 million dollars ($1100 for each of 10,000 school districts). For the terrestrial system, antenna gains from 2 to 22 dB are required to obtain the specified TASO Grade 1 signal quality. Installed costs of these antennas are approximately 0.5 million dollars; this amount is insignificant in relation to the 1.28 billion dollar system cost.

If the system were designed to reach all the 100,000 schools in the U.S. instead of the 10,000 school districts assumed, the satellite system cost would increase by 100 million dollars compared to a 5 million dollar increase for the terrestrial system. However, the cost ratio would still be about 7 to 1 in favor of the satellite system. In addition, a full 100% area coverage is obtained with the satellite system.

7.8 SCHEDULE COMPARISONS

Another significant advantage of the satellite broadcast system over the terrestrial broadcast system is the significantly shorter time required to establish communication signal coverage to a majority of the population of large geographical areas (areas larger than $\frac{1}{2}$ million square miles - roughly equivalent to one U.S. time zone).

In the United States the first terrestrial television channel coverage was obtained in six years for 90% of the population. Sixteen years elapsed before 95% of the population had coverage. For developing and emerging nations, the time period for coverage will be extended considerably since they must industrialize before they can install and maintain a terrestrial system.

In contrast, television by satellite offers full national coverage from the beginning of services. The schedule (see Section 7.5.1) for establishing a television satellite ranges from two years for an operational satellite to four years from the start of development.

In the United States it took $5\frac{1}{2}$ years to produce television receivers for 50% of the population. It took 12 years before 90% of the population had receivers, and it was 9 years later before 95% of the population had receivers.

The above time factors lead to the following conclusions:

1. An additional TV channel can be established for 100% of the population of a developed nation via satellite in 1/4 to 1/8 of the time required to install an additional terrestrial system for 90 to 95% of the population.

2. A new satellite TV service can be established for 100% of the population of developing and emerging nations many decades before a terrestrial system could be installed and maintained. The time period for the satellite system will be determined by the time needed for production, distribution, and maintenance of the television receivers. This time period can be shortened significantly by designing the sytem for the simplest of television recievers and by having these receivers produced in a developed nation.

Broadcast television has been conducted as an experimental service since the late 1920's but the modern electronic television receiver did not become operational until just prior to WWII. It was developed simultaneously in several countries, the United States being one of them.

Figure 7.8-1 summarizes the early time history of the introduction of television coverage and receiver usage for the United States. Neglecting the war years as shown by the dashed curves, signal coverage reached 20 percent of the population within approximately 3 years, 50 percent in about $4\frac{1}{2}$ years, and 90 percent in 6 years. Ninety-five percent coverage was not attained until another 10 years had passed, and even today, after 30 years, the coverage has not yet reached 100 percent.

Second program availability showed about the same initial rate, but growth slowed markedly after 50 percent coverage had been reached. In part this was due to a re-examination of policy.

SOURCE: BELSON, THE IMPACT OF TV

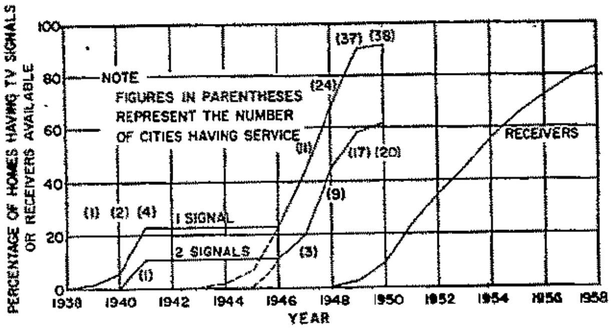

Figure 7.8-1. Time History of Television in the Unitied States

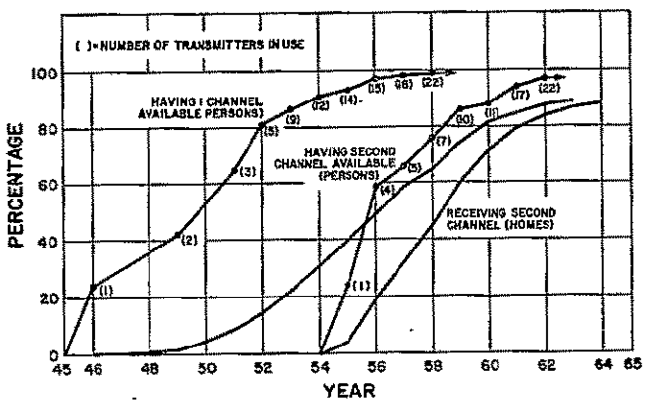

Figure 7.8-2. Growth of Television in the United Kingdom

Wide use of the television signal, however, was delayed, showing a lower growth rate. Sets did not reach 20 percent of the homes until approximately 13 years after the actual beginning of service, or approximately 8 years after its effective start. During this period there was extensive informal community viewing at neighbor's homes, stores, and in taverns. Growth continued, reaching 50 percent of the homes within 10-1/2 years (effective) and 80 percent in 15 years. Today, sets are used in approximately 92.5 percent of the homes, with 22 percent of the homes having two or more sets.

Except for the availability of additional broadcasting frequencies (usually delayed for 20 or so years), the pattern in other developed countries has been similar. This is true even where television is a national service rather than a commercial enterprise. Figure 7.8-2 shows a similiar but slightly slower pattern of events for the United Kingdom.

In lesser developed areas, however, the pattern is somewhat different. This is illustrated by the growth of television in Brazil, which began televising in 1953. Less than 15 percent of the households have receivers, and they only have 45 transmitters for a country larger than the United States. Twenty-one of these stations are in five of the more important cities.

In still lesser developed areas, it is common for service to be available only in the largest city, and even they have low receiver density. An exception to this is the United Arab Republic, where television transmitters have been installed to provide signals to some 80 percent of the population. But this is part of a program of education and national unity.

From the above data, it appears clear that attainment of complete large-area national coverage is a very difficult and time consuming process. Even the United States has not achieved it after 30 years. Reasonable coverage (90 to 95 percent) is easier, but still may require six to eight years in a country with ample resources, or longer if resources are limited.

In contrast, television by satellites offers full national coverage from the beginning of service. The duration of the necessary design and construction program would depend on the system parameters chosen. A program of 2 to 4 years duration (See Section 7.5.1) would be sufficient to produce and launch the satellite. In view of this, it seems clear that satellites are the fastest means for attaining national coverage.

SECTION 8

RESEARCH AND TECHNOLOGY IMPLICATIONS

8.1 INTRODUCTION

This Research and Technology Implications Section (R&TI) presents results obtained during the Television Broadcast Satellite (TVBS) study. The TVBS study phases are shown in Figure 8-1 with the technology tasks enclosed in a heavy border.

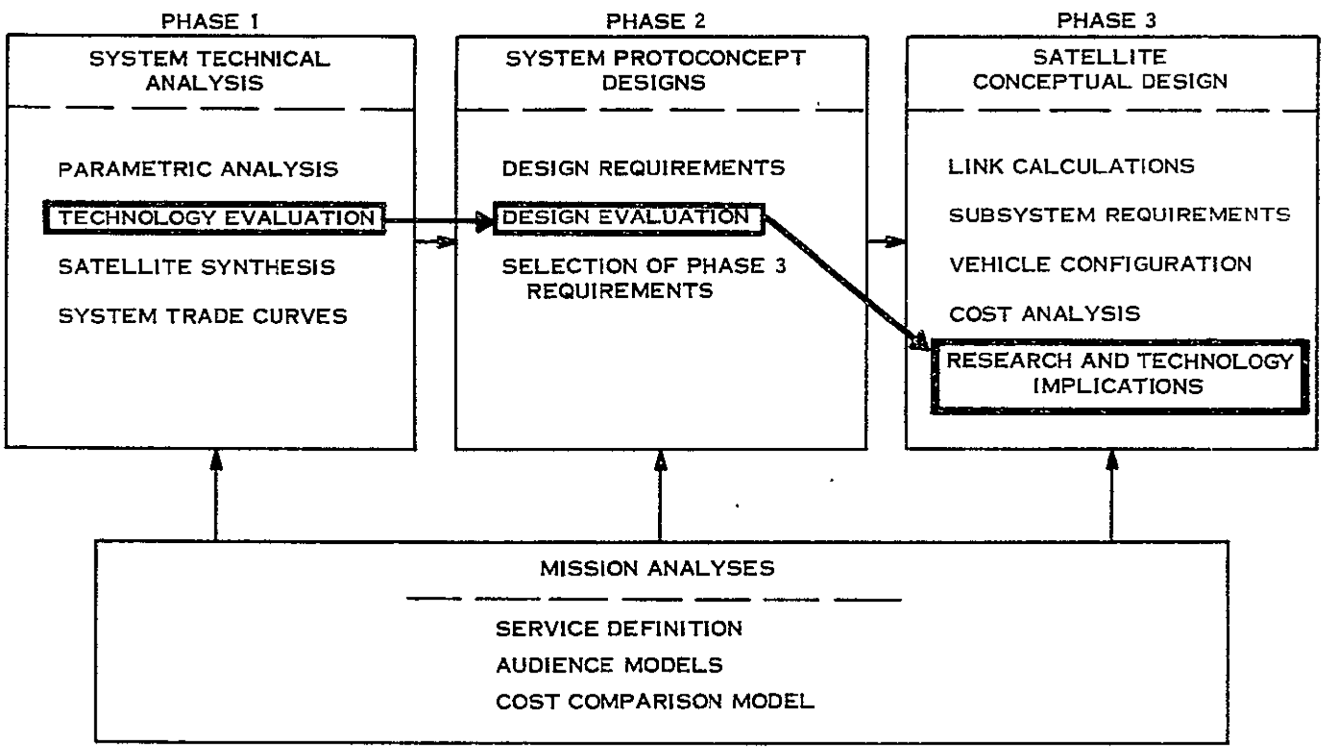

Figure 8-1. TVBS Program Plan

During Phase I, state-of-the-art and performance characteristics available in the early 1970's were estimated for satellite and ground system components and subsystems. This data permitted feasibility evaluation of synthesized systems and provided a basis for establishing research and technology implications and development program recommendations during Phases 2 and 3.

The technology evaluation was concerned with the evaluation of technologies underlying the TV Broadcast Satellite system requirements. This was done to determine those programs required to develop or advance the state of the art. Pertinent technologies were identified, their parameter improvements with time predicted, and their impact on significant system parameters evaluated. Ranking criteria were established to permit listing the finally selected technologies in order of recommended priority for allocating development funding.

A logical basis for selection of any particular technology is the magnitude of its impact upon one or more significant system parameters such as weight, size, cost, life, or performance. Candidate technologies were ranked to provide a basis for selecting the sequence in which additional development funds should be applied. Not only was the impact of the specific technology upon the TVBS system considered, but also the estimated cost, time, and risk associated with each technology development program. Also considered were the lead times needed for developing each required technology as compared to others.

8.2 STATE OF THE ART

The following paragraphs present the state of the art for various broadcast satellite subsystems and components including the solar array, power conditioner, dc and RF rotary joints, transmitter circuits and output tubes, high power RF components, antennas, flexible structures effects, thermal control, attitude control, and ground receiver installations. In each case, the discussion covers the general capability available today throughout the aerospace industry and the major problems which still need solving. Also identified are currently funded efforts as well as those efforts required but not adequately funded.

8.2.1 SOLAR ARRAY PRIME POWER

8.2.1.1 General Capability

The solar array generates primary power for all the satellite subsystems by converting sunlight into electrical energy. The performance of a large area solar array is an important factor in the design of broadcast satellites for several reasons. First, the array is the major portion of the satellite cost and weight for medium and high power broadcast satellites. Secondly, since the solar array may consist of a large flexible structure requiring solar orientation, its possible interaction with the attitude control system becomes a significant consideration. Lastly, the array cannot be tested in its operating configuration in a reasonable ground simulation of the zero "G" environment.

Deployment of large structures and long life operation of solar tracking mechanisms on past space programs attest to the feasibility and potential performance of large solar arrays. The successful deployment of the large area (1344 square feet) micrometeoroid detection panels on Pegasus and the operation of the 356 square feet of solar array on one Agena military satellite configuration provide a basis of flight-proven experience for the feasibility of large area solar arrays. The approximately 9 watts per pound (and per square foot) capability exhibited by the Mariner 4 solar panels and the successful operation of the Nimbus solar array tracking mechanism for over two years provide proven performance baselines for power density and long life operation. Recent large-area design for flight applications includes the 1.5 watt SERT II panels which weigh nearly 2.5 pounds per square foot (4 watts per pound for a nominal output of 10 watts per square foot).

For the past several years it has been recognized that solar arrays would have to be used to provide the large power requirements until at least the mid-1970's because nuclear systems will probably not be available, cost-effective, or weight-effective in the sizes required until then. Thus, there are in progress several solar array development activities that will provide technology of benefit to broadcast satellites.

The anticipated state of the art in solar arrays may be described in terms of expected power capability and power per pound. Examples of advanced concepts are as follows. A Boeing/JPL development program includes the construction of a 12.5 kW foldout array subsystem (part of a 50 kW array design) which is designed to produce 20 watts/lb. General Electric is performing for JPL a design for a 2.5 kW roll-up array subsystem (part of a 10 kW array) which would provide 30 watts/lb. (A photograph of a full-scale demonstration model of this array is shown in Figure 8-2). On the basis of these programs, a 10 to 15 kW array with a specific performance of at least 30 watts/lb (or 33 lbs/kW) appears reasonable for a vehicle design start in 1971.

Table 8-1 indicates the present and anticipated state-of-the-art capability of solar arrays by listing parameters for several flight hardware and development programs.

8.2.1.2 Major Problems

Critical technology problems are discussed in the following paragraphs. It should be noted that the problems associated with large solar arrays involve improved performance rather than a fundamental breakthrough into a new technology area. With unlimited weight and the lack of other system constraints, very large areas of solar arrays could be deployed in space.

The cost of the solar array fabrication is a large, identifiable, discrete item in a broadcast satellite program. Estimates during the TVBS study ranged from $400 to $500 per watt. Significant cost elements include the solar cell and cover glass costs, and the labor associated with assembling the very large number of piece parts in a solar array.

The solar array can be a large contributor to the over-all weight of a high power broadcast satellite system. Increasing the performance from 4 watts per pound (typical for the SERT II array) to 30 watts per pound (a goal for one of the current array development programs) reduces the weight of the array by 217 pounds for each kilowatt of electrical power. Most of the improvement is achieved by reducing the weight of the array structural elements rather than by increasing the solar cell performance.

Orientation of the array may be a problem because the equipment to orient the solar array is electromechanical. This type of hardware has historically presented a long life reliability design challenge.

The interaction between the attitude control system and the array when it is re-oriented may be a problem. A large solar array is inherently a large appendage on the vehicle and is likely to contribute a major portion of the moments of inertia. In order to be lightweight, the array will be unavoidably flexible so that its dynamic characteristics will interact with the orientation system.

The use of a high voltage solar array may be desirable if it reduces the requirements for the power conditioner. However, testing a high voltage array is a major problem because of personnel hazards. Electrical breakdown in orbit is another problem when dealing with

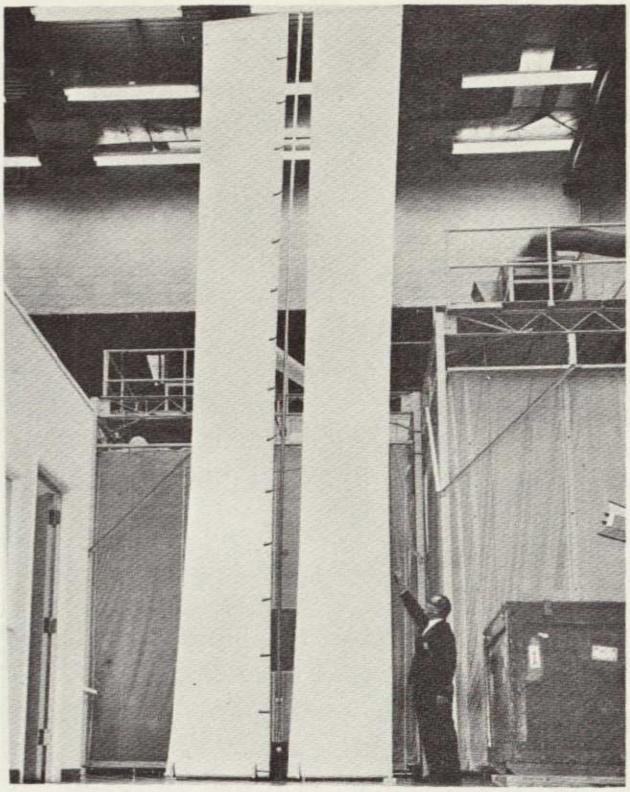

Figure 8-2. Demonstration Model of 30-Foot Boom Deployment Using Simulated Roll-up Solar Array

Table 8-1. Solar Array Design Parameter Values

Major Parameters	Nimbus 2	Mariner 4	SERT 2	Apollo Telescope Mount	Boeing Foldout Solar Array	GE Rollup Array	Hughes FISCA(1)	EOS Lightweight Rigid Solar Panel
Status as of September 1969	Has been flown	Has been flown	Flight Hdwr Delivered	Flight Hdwr Delivered	R&D Phase Completed	In R&D phase	R&D Completed	In Advanced Development
Total Array Area (ft^2)	50	70	188	1,509	4,924	1,000	93	1,239
Total Array Weight (lbs)	74	75	416	3,720	2,101	306	21	285
No. of Cells (2 cm x 2 cm, or equivalent)	10,944	14,112	33,300	246,264	1,026,368	220,704	21,080	241,920
Initial Power (watts, based on 45.7 mW/cell)	500	645	1,520	11,250	46,900	10,090	965	10,400(2)
Power Developed per Unit Weight (watts/lb)	6.8	8.6	3.7	3.0	22.3	30	22	27
Power Developed per Unit Area (watts/sq ft)	10	9.2	8.1	7.4	9.5	10.1	10.4	8.4
Weight per Unit Power (lbs/kW)	148	116	270	333	45	33	46.5	36.5

Notes: (1) Flight demonstration program now called LRSCA (Large Retractable Solar Cell Array)
(2) Based on 44.2 mV/cell for 4 mil thick cell
FISCA = Flexible, Integrated Solar Cell Array
SERT = Space Electric Rocket Test
EOS = Electro-Optical Systems, Inc.

high voltage levels. Possible failure of an entire high-voltage series string of solar cells due to an open or short circuit in (or between) one or more cells may conceivably be alleviated by using bypass diodes. This would permit a 30-volt potential to cause a cell to act as a diode. The problem could also be alleviated by employing appropriate series-parallel arrangements designed for high voltages. The deleterious effects of leakage currents caused by the electrical interaction of a high-voltage solar array with any plasma, charged particles, or outgassing products existing in the space environment, have yet to be investigated.

8.2.1.3 Currently Funded Efforts

Since the solar array is an item common to most long life spacecraft, there are a number of programs under way. Those of most interest to broadcast satellites are listed in Table 8-2.

8.2.1.4 Additional Effort Required

The selection of the design concepts and the implementation of the design will be important aspects of the broadcast satellite program. As described in the previous sections, there are numerous technology developments under way which can be applied to a broadcast satellite. However, it is important to realize that these developments are not likely to carry the technology to the state required by broadcast satellites. There remains useful work to be done to achieve the necessary confidence level for long life success for a 1973 launch. For example, the Boeing 20-watt per pound foldout solar array program has been very successful and has reached the point where its sponsor, NASA-OART, is evaluating whether or not the technology has matured sufficiently to achieve the goal of technology readiness. The GE 30-watt per pound roll-up array design is being developed under the sponsorship of JPL. Both systems are near the point where either could be selected for a flight program with confidence of technical and schedule success, although full-scale system fabrication and testing remain. The Hughes/AF LRSCA array program flight demonstration should take place in the 1970-71 time period. It is important, therefore, for the broadcast satellite program to identify areas of prime interest and insure that programs are under way in these areas.

The general aspects of reducing weight and improving solar cell performance are proceeding at a pace governed by the total Government space program; it is not necessary for the broadcast satellite program to do more than lend its support to this type of activity and provide inputs with respect to its general needs.

Due to the high labor costs associated with the manufacture of large solar arrays, a development effort to create an automated cell laydown technique could reduce the cost of array manufacture.

High voltage solar arrays should be investigated in order to determine the problems. limitations, and areas where work is needed. This work needs to be related to the tradeoffs of producing high voltage power at the solar array rather than stepping up the voltage with power conditioning equipment. High voltage arrays could permit cost and weight reductions and eliminate problems in the power conditioner.

Table 8-2. Currently Funded Efforts

Program	Contract No.	Sponsor	Contractor	Amount	Remarks
1. Advanced Solar Arrays a. Feasibility study of 30-watt-per-pound roll-up solar array	Phase 1 951969 951970 951971 Phase 2 952314	JPL JPL	General Electric Ryan Aircraft Fairchild Hiller General Electric	$167K $167K $167K $ 811K	Phase 1 feasibility studies of 10 kW solar array system for interplanetary mission completed in July 1968. Phase 2 program to assemble an engineering prototype and subject it to a vigorous environmental test program is expected to be completed in early 1970. A full size demonstration of one element (of four) of the General Electric system is shown in Figure 2-1
b. Large-area solar array program	951653 951934	JPL	Boeing Aircraft	$5.6M	Design of a 50 kW system comprised of four 12.5 kW subsystems for an interplanetary mission. Selected design concept utilizes thin silicon solar cells, beryllium frames, and stretched fiberglass substrates. Manufacturing methods have been investigated and environmental tests of elements of the system have been completed.
c. Development of lightweight rigid solar panels	NAS 7-428	OART	EOS	$463K	Performance goal is 25 lb/kW. Design concept uses electroformed aluminum substrate, beryllium frames, and thin silicon solar cells Prototype models being designed and constructed.
d Large retractable solar array	F33615-68C-1676	AF-APL	Hughes Aircraft	$1M	Design concepts for rollup solar arrays for power levels of 0.5 to 20 kW 2-axis solar orientation system to be provided A 1 5 kilowatt flight experiment is to be ready for flight by October 1970. Goal is 35 lbs/kW (array only). Laboratory testing to demonstrate 3 to 5 year component lifetime.
e. Cadmium-sulfide thin film solar array development	NAS 3-11821 NAS 3-10605	NASA-Lewis	General Electric	$54.5K	Initial contract was to develop methods of interconnecting CdS solar cells into, 25 cell modules that could be rolled on 2-inch diameter roll. Second contract was to fabricate three 100-cell sub-panels.
2. Solar Cell Development a. Improved CdTe solar cell and array environmental effects' investigation	F33615-67-C-1485	AF-APL	General Electric	$341K	The objectives of this program are to produce a stable cell with an efficiency of 8% and cell weight of 0 02 pound per square foot.
b. Improved solar cell contacts	NAS 5-11595	NASA-Goddard	Litton Industries	$ 56K	Research on the degradation of solderless Te-Ag contact silicon solar cells.
c. Photovoltaic radiation program	----	NASA	JPL	$224K	Determination of the radiation characteristics of lithium-doped solar cells.
d. Development of improved solar cell contacting techniques	952144	JPL	High Voltage Engineering Corporation	$44K	Analysis and development of a superior type of solar cell contact - interconnection combination
e. Cadmium-sulfide thin film photovoltaic cell development	NAS 3-9434	NASA	Clevite Corporation	$514K	Effort directed toward improving CdS film quality, cell efficiency, and stability.
3. Auxiliaries a. Brushless, direct drive solar array re-orientation system	NAS 5-10459	NASA-Goddard	Westinghouse Electric Co.	$49.8K	Development of control and logic circuits for use in the design of a brushless, direct drive solar array re-orientation system.
b. Orientation linkage of a solar array	F33615-67-C-1785	Air Force APL	Hughes Aircraft Co.	$283K	Development of the technology for actively orienting solar cell arrays with power requirements in the 0.5 to 20 kW power range for 3 to 5 years of mission life at altitudes ranging from 200 n m. to synchronous altitude.

Deployment and orientation of arrays larger than 5 kilowatts present a spacecraft system design problem. It is important to investigate further the effects of solar array structural flexibility on the dynamics of the vehicle. Solar array flexibility is a function of array weight and, if flexible arrays cannot be accommodated by the stabilization system, an additional constraint is imposed on the array design that can have significant influence on weight. This interaction problem is a complex one and is a long lead-time item because a number of disciplines and subsystems are involved.

The two-axis drive subsystem should be investigated as a potential long-life reliability problem. The Nimbus 2 single-axis drive subsystem for a 500 watt array has been flying successfully for over two years. Despite the success of the array drive subsystem on this one satellite, there still remains a degree of uncertainty about the long-life reliability of such electromechanical drive devices. Furthermore, no large-panel, two-axis drive subsystem for arrays delivering powers over 5 kilowatts has ever been flown in space.

A continuing review of the projected requirements of broadcast satellites, coupled hopefully with a focusing on specific configurations with respect to solar array technology, is required. The long lead times associated with establishing a high confidence on the long life reliability of a design should provide an incentive for early design selections.

8.2.2 HIGH POWER DC ROTARY JOINT

Transfer of direct current electrical power across continuously rotatable mechanical joints requires the use of rolling, sliding or liquid metal electrical contacts. The most widely used and highly developed power transfer device is the slip ring-brush combination. A rotary transformer concept for power conditioning might be employed to eliminate the need for a dc rotary joint for high voltage applications.

A typical spacecraft power slip-ring assembly is shown schematically in Figure 8-3. A round, conductive metal ring rotates with its supporting shaft. One or more conductive brushes mounted on the nonrotating member of the rotary joint slides against the surface of the ring to provide the electrical contact. The electrical circuit passes from the array through an insulated conductor to the inner surface of the ring; it then travels from the brush, which contacts the ring continuously, through another conductor to the load. The return path is identical except that a separate brush and slip ring are utilized to complete the circuit back to the power source.

8.2.2.1 General Capability

Low-power and medium-power slip rings have been tested in vacuum and successfully flown on operational spacecraft. These include the Nimbus, OSO, and classified space vehicles. A more frequent application of sliding electrical contacts in space has been the use of brushes for motor power commutation. Devices of this type have operated at low or medium power levels in a number of space applications. The achieved current levels, however, are far below the projected requirements of a broadcast satellite rotary joint.

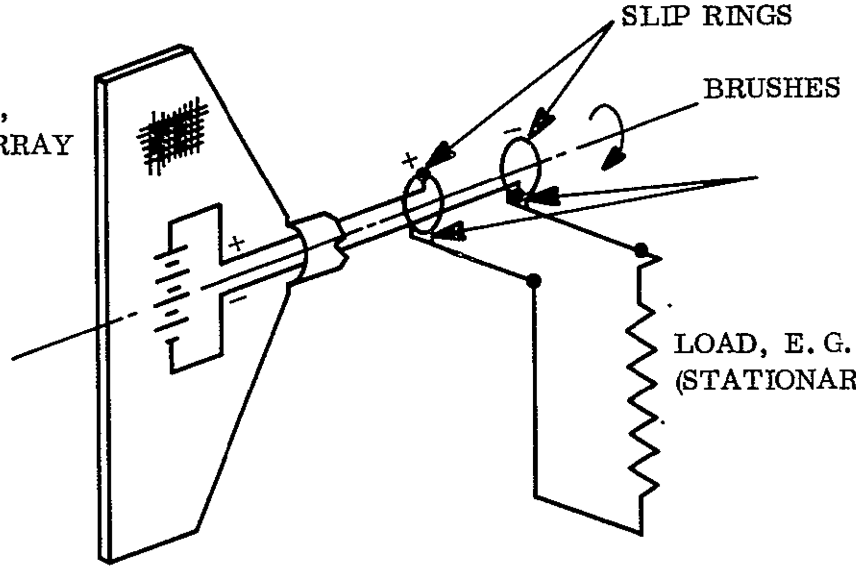

Figure 8-3. Typical Power Slip Ring Schematic

Results of reported applications or tests to date are as follows: Nimbus power slip-ring contacts carrying 10 amperes of current have accumulated approximately 10^4 feet of sliding wear during approximately 2-1/2 years of space operation. OSO slip rings, rated at 3.5 amperes, have operated for approximately 2.5×10^6 feet of ring-surface travel for approximately 8800 hours during one year in space.

In vacuum tests for ground based equipment, Clauss has operated power slip rings for 1.8×10^6 feet of surface travel, while conducting currents on the order of 4 amperes. (Current density peak was approximately 300 amp/in^2.) In these tests, the characteristic brush wear quoted is on the order of 10 mils of brush height reduction per 10^6 feet of lineal ring-surface travel.

The power transfer applications cited above all involve conventional voltage levels for space applications, i.e., in the range of 28 to 32 vdc. Thus, the added problems associated with high inter-ring voltages were not present in these evaluations.

8.2.2.2 Major Problems

Rotary joints for various broadcast satellite applications under consideration have a broad range of potential operating conditions and requirements. For a 20 kW design power level, inter-ring voltages could range from 50 to 20,000 vdc, while corresponding series currents range from 400 amp. down to 1 amp. Rotational speeds also vary with possible vehicle designs, i.e., basic rotational speeds are either one revolution per day (non-spinning vehicles) or 60 to 100 revolutions per minute (spin-stabilized vehicles). For purposes of comparison, a brush operating against a slip ring turning at 100 rpm will slide 1.44×10^5 times as far as the same brush would travel in the same time interval if the ring were turning at one revolution per day.

The major problems associated with the possible sets of operating conditions vary significantly.

Brush wear is proportional to surface sliding distance after run-in has been achieved. Therefore, brush life and wear-debris accumulation are vastly more severe problems (other conditions being equal) in the 60 to 100 rpm operating mode than at one revolution per day.

Brush heating is a function of contact resistance, current and current density, friction, lubrication technique, brush thermal conductivity and mass, ring thermal conductivity and mass, and a number of other factors. Brush temperature in turn affects the wear rate of both ring and brush, the mechanical durability of each, the bond strength and method of attachment of the brush to its mechanical support, the thermal compatibility of the ring with its insulating support and with the electrical conductor material, and the chemical stability and evaporation rate of the lubricating medium provided.

High voltage configurations of the rotary joint present other significant problems. The convoluted insulating surface which must be provided to prevent arc-over between slip rings adds significantly to the weight of the basic elements of the rotary joint. Another severe problem is the prevention of surface tracking due to insulator surface breakdown at high voltage due to contamination caused by brush debris.

Electron bombardment of insulator surfaces, which may result from arcing at the brushes, can cause the release and ionization of surface-adsorbed gas films which, in turn, can also bring about surface tracking under high voltage conditions. Both the gas production and the breakdown probability increase directly with inter-ring voltage levels.

Bearing lubrication presents significant problems, particularly at the higher rotational rates under consideration. In addition to intrinsic lubricant life problems, there may be considerations relating to the compatibility between brush and bearing lubricants, as well as thermal problems resulting from the brush heating noted above. Another significant problem may result from bearing contamination with brush wear debris. Minor contamination may degrade lubricant performance, while higher levels of contamination may result in excessive driving torque and, ultimately, in jamming of the bearings.

Material selection can be a problem area not only due to requirements for high dielectric strength or other special electrical or mechanical properties, but also due to the necessity to minimize the degree of outgassing and sublimation from material surfaces. Outgassing of adsorbed surface gases which occurs under vacuum conditions is a function of the type of material and the temperature. The partial gas pressures created could cause high-voltage breakdown at voltage levels lower than otherwise expected. Very little data is currently available on outgassing and sublimation phenomena for the types of needed materials at the high voltages, high temperatures, radiation environment and vacuum conditions encountered in broadcast satellite applications.

8.2.2.3 Currently Funded Efforts

Current efforts in the development and evaluation of dc rotary joints are rather limited. Tests of narrow scope are being performed or are planned at TRW, LMSC, and Hughes for medium-power slip rings for use in future spacecraft. Evaluation of two brush-commutator material combinations was recently (1966-1967) performed at NASA Marshall Space Flight Center for an Apollo Telescope Mount torque-motor application. The program conducted at MSFC has involved sliding with conduction on motor commutators, and sliding without conduction on simulated commutators.

The only recently reported work (1965) directly applicable to the TVBS system is the self-lubricating, high-current, bursh material development program conducted by Clauss and others for Arnold Air Development Center. In this program, intended for a ground-based radiation simulator, a sintered brush of 82.5% Ag, 2.5% Cu, and 15% MoS_2 was found to be superior in low-noise characteristics and wear resistance to several other material combinations evaluated.

The only known tests currently being conducted are for various spin-stabilized spacecraft applications. No data is available, but significant failures are known to have occurred recently in simulation tests. In these tests, desired sliding wear life and power levels were <u>less</u> than those sought for broadcast satellite applications.

8.2.2.4 Additional Effort Required

Review of broadcast satellite dc rotary joint requirements has resulted in the identification of several significant and necessary development areas shown in Table 8-3.

Table 8-3. Recommended Rotary Joint Technologies

• Materials selection - Brush - Ring - Lubricant (brush and bearing) - Insulation	• Thermal design
• High voltage design	• Operational considerations - Brush debris collection - Pre-operation bake-out - Programmed multiple brush use for wear compensation
	• New rotary power transfer device concepts

New concepts such as rotary transformers, rolling ring (non-sliding) and liquid metal rotary joints should be studied as a means of eliminating wear and heating problems, and reducing noise associated with sliding power-transfer devices.

8.2.3 HIGH VOLTAGE POWER CONDITIONING

8.2.3.1 General Capability

The power conditioner is the spacecraft subsystem which accepts the dc electrical power generated at comparatively low voltage by the primary power source (e.g., solar array), and converts it to the several regulated voltages and/or currents required to operate the various spacecraft electrical loads. Some of the major functions performed by the power conditioner could include line filtering, inversion from dc to ac, transformation of voltage amplitudes, filtering of ac ripple regulation, and overload and short circuit protection.

High level power conditioning refers to that portion of the power conditioner subsystem which is employed primarily to provide the high voltages and currents essential for the operation of the high power stages of the broadcast satellite transmitter, such as the final output amplifier. Typical inputs to the high level power conditioner from the solar array might be 28 to 300 vdc (depending on array design); typical outputs might range from 1,000 to 16,000 volts dc with regulation percentages between $\pm 0.05\%$ and 3%, depending on output tube requirements.

The technology for long-life, space-borne power conditioning equipment is well-known up to dc levels of approximately 1000 watts. However, no unclassified power conditioning hardware operating at power levels above 650 watts has yet been placed in orbit. The power conditioning system for SERT II, which is to be flown in the latter part of 1969, and has requirements for 1 kW at 3 kV (unregulated), contains some new concepts which may be used for the higher voltage levels.

These include open transformer and component packaging instead of potting (thus using the vacuum of space for insulation), and thermal control by bonding heat sinks to the integrated circuit boards and having oversized holes in the sink for leads. This subsystem weighs approximately 30 lbs/kW.

An operational spacecraft with a power level in the 500 watt range still in orbit is Nimbus II. Other examples of space hardware programs using powers up to this level are shown in Table 8-4.

A recent study by NASA/GSFC of over 70 satellite high-voltage failures concluded that almost 80% of the failures were due to poor design. Table 8-5 lists typical failures and the resulting design changes. Corona and arc breakdown were caused by improper selection of materials and components, by inadequate geometric orientation of piece parts, and by poor techniques for potting, foaming, encapsulation and conformal coating. These failures occurred at low power. High power plus high voltage is a potential for catastrophic failure in a satellite. The technical feasibility of high-power, high-voltage conditioners in the hard vacuum of space over periods of more than 2 years has yet to be shown.

Table 8-4. Typical Satellite Power Levels

Satellites Flown	Max. Input Power	Highest DC Voltage Used
Nimbus II	500 W	1300 Vdc
OAO	250 W, continuous 500 W, 10 minutes	1000 Vdc
ATS-D	175 W initially	600 Vdc (800 Vac) 3000 Vdc (ion engine)
Syncom	< 100 W	1000 Vdc
Early Bird	< 100 W	1500 Vdc

Table 8-5. Typical Satellite High Voltage/Low Power Levels

Probes or Satellites Flown	DC Voltage At Low Power	Failure	Design Fix
Nimbus	1000 Vdc	Arc in harness and connectors due to entrapped gas	Separate high voltage cables, used new connector insulation.
Mariner IV	1200 Vdc	Arc punctured insulation in TWT terminals	Changed geometry and improved encapsulation
Mariner IV	2800 Vdc	Arc due to trapped gas in power supply	Used stycast in place of foam
Explorer	5000 Vdc	Arc in connector due to entrapped gas	Improved potting techniques
Agena	1650 Vdc	Arc in radar transmitter caused by outgassing of silicone grease	Pressurized the transmitter
SERT I	5000 Vdc	Corona in connector caused treeing, resulting in an arc	Use vented connectors with out potting
Javelin	15000 Vdc	Corona caused by trapped outgassing in plasma detector	Changed potting material and vented detector case

General industrial capability mirrors that shown in Tables 8-4 and 8-5 quite closely. The equipments which most nearly approximate the broadcast satellite requirements are power conditioning apparatus for aircraft (in particular, the high power systems used for radar modulators in high performance, high altitude aircraft). Here, the power and voltage levels may be closer to broadcast satellite requirements than present spacecraft designs; however, satellite environmental requirements will not have been considered in designing for aircraft applications.

8.2.3.2 Major Problems

The feasibility, performance, and long-life reliability would be improved by the application of additional R&D effort. The technologies leading to high-voltage design which minimizes the probability of electrical breakdown are technologies for which feasibility is yet to be established. A separate discussion of the critical technology associated with the handling of high dc and ac voltages may be found in Section 8.4.

Determination of the maximum modular size of the power transformer in such a power conditioner and the generation of multiple high voltages for transmitter output devices are also considerations involved in solving the feasibility, performance (e.g., efficiency), and reliability problems. Special load requirements may have to be considered in determining the maximum size for power conditioner modules. For example, a multi-collector, high-power transmitter tube which requires a number of steps of high voltage for proper operation may well determine the quantity, power output, and size of the conditioner modules.

High voltage power conditioning is an important technology because a large percentage of the weight of the broadcast satellite is in the power subsystem. To get the best combination of power conditioner and solar array, a tradeoff between solar array weight and power conditioner weight must be made. System analyses should be performed to determine whether it is better to build a highly efficient but heavy power conditioner (and thus reduce the solar array size) or to accept higher power-conditioner losses and/or a larger solar array in favor of reduced power conditioner weight.

8.2.3.3 Currently Funded Effort

A survey of currently funded efforts uncovered only items designed primarily for low-power and low-voltage applications. Very few studies are in progress which might be applicable to the high-power, high-voltage, and long-life requirements of a broadcast satellite.

Representative examples of recent or current contract efforts are:

1. Design of a Multi-kilowatt Photovoltaic Power System for Manned Space Stations (NAS 9-5266).

2. Power Conditioner for Experimental Model, SERT II Ion Thruster (NAS 3-7939).

3. Analysis of Aerospace Power Conditioning Component Limitations, Solar and Chemical Power Systems (NAS 7-546).

Current effort fails to provide the required power conditioner information in two respects; first, the power and voltage do not approach the levels required for a TVBS system; second, the simultaneous combination of high power and high voltage has not been investigated.

8.2.3.4 Additional Effort Required

More study and experimentation are required to determine the effects of outgassing, hydrolysis, and thermal degradation on voltage breakdown of materials at low gas pressures. An extensive report containing technical papers on the voltage breakdown problem can be found in JPL Technical Memorandum 33-280, "Proceedings of the Workshop on Voltage Breakdown in Electronic Equipment at Low Air Pressures," dated December 15, 1966. High voltage breakdown is a very critical problem in components and devices. Voltages from 327V to 50,000V can cause failure by corona; they can also cause breakdown through gases, as predicted by Paschen's Law. These problems are covered in Section 8.2.4 on High Voltage Handling.

Determination of the maximum hot-spot temperature for long-life operation and optimum materials to be used in magnetic devices both need considerable attention. (Standard transformers generally operate at maximum hot-spot temperatures between 105°C and 220°C). It is necessary to determine the best thermal-radiating fin size, shape, weight, and temperature versus the best power conditioning size, shape, weight, temperature, and efficiency. This study is extremely complex due to the large number of variables. Some of the interactions between variables are inadequately known at this time, although much is known about most of these variables. Thus, with some reasonable assumptions, a parametric analysis should result in optimum configurations for both the thermal radiating fin and the power conditioning equipment.

Trade-off studies are needed to obtain the best combination of designs for the power conditioner components, thermal control, solar array and dc rotary joint. Thus, additional development effort could have an impact on the broadcast satellite system in terms of improving system performance, reducing weight and proving the technical feasibility of large, high-power, high-voltage power conditioning subsystems in the vacuum of space.

8.2.4 HIGH VOLTAGE HANDLING

8.2.4.1 General Capability

Various subsystems of the broadcast satellite systems will have to be designed to generate, conduct, or otherwise handle high voltages, either dc or ac (up to RF). For some foreseeable applications, voltage levels may go as high as 20,000 volts. The primary areas of the system where high voltages may be present include the solar array (in cases where no separate power conditioner is used), the dc rotary joint, the power conditioner, possibly an RF rotary joint, and the final output stage of the transmitter.

Many types of voltage breakdown phenomena (glow, corona, arcing, tracking, treeing, etc.) are known to exist. Generally, breakdown is a function of factors such as the nature and geometry of the materials present, the voltage level, the frequency of the voltage, the temperature, the pressure of any gases present (either through intentional use or as the result of outgassing), the condition of the surface of the material, and the distance between conducting electrodes or surfaces. The importance of material selection to avoid breakdown is immediately evident from this series of factors.

Most materials suitable for ground-based systems cannot be used, a priori, in space-borne systems because the effects of hard vacuum seriously alter material performance. Outgassing and sublimation phenomena under vacuum conditions lead to such problems as arc-over and corona which, in turn, can short out electrical systems and, in addition, can cause reduction in attained performance levels of materials. These problems are aggravated in high-power systems because of the elevated operating temperatures of various components which tend to cause more rapid deterioration of the insulating and dielectric materials and the production of large volumes of outgassing and sublimation species.

Some empirical work has been accomplished regarding the outgassing of dielectric materials, but direct application of the available data to broadcast satellites cannot be made. The two major drawbacks in applying this data are: (1) experiments have been conducted at relatively low temperatures, generally below 150°F, and (2) no system analyses have been conducted to establish the exact magnitude of the problem in terms of various system operating parameters and geometries.

8.2.4.2 Major Problems

The outgassing of materials in vacuum poses other electrical problems besides the change in properties of the insulation materials. These problems are related to high-voltage, electrical breakdown phenomena. For example, the impaired performance of the OSO I and II satellites was attributed to high voltage breakdown because of inadequacies in insulation and improper venting, degassing and materials selection.

Because of the outgassing phenomenon under vacuum conditions, a small partial gas pressure may build up which could cause a breakdown in a high-voltage system. In general, as the pressure between a given pair of electrodes decreases, the voltage necessary to initiate a discharge decreases to the minimum predicted by Paschen's Law. At pressures below this Paschen minimum, the voltage required to cause an electrical discharge increases as pressure decreases further. Thus, when operating in a hard vacuum condition, outgassing can raise the gas pressure and cause breakdown as the pressure adjacent to piece parts approaches the Paschen minimum voltage point.

There are special cases where strict adherence to Paschen's Law predictions for air may give unexpected results. Ordinarily, the minimum sparking or breakdown potential in air (for parallel plate electrodes at, say, a 1 mm spacing and a pressure of 5 torr) is 330 volts. However, this voltage varies considerably for gases other than air and for different electrode shapes. Also, where electrodes are near surfaces of potting compounds or other types of material prone to outgassing and development of surface charges, the minimum breakdown voltage will generally be reduced. The proximity of surfaces with polar molecules can provide lower energy paths of conduction than would be predicted by Paschen's Law calculations for parallel plate separation and gas pressure factors.

Since a broadcast satellite will not be required to operate in the critical altitude region (60,000 to 310,000 feet), measures should be taken to prevent the high voltage equipment from being energized until a hard vacuum has been attained inside the vehicle. The hard vacuum of space has a very high dielectric strength; thus, open type (unencapsulated) construction becomes a promising technique provided that outgassing, multipacting and sublimation effects can be avoided, and adequate thermal dissipation can be effected.

Equipment must be designed to avoid high voltage stress areas which could produce corona. Corona can jam or block the very sensitive electron devices necessary for broadcast operation. Equipment must also be designed to avoid dielectric discontinuities, prevent voids in encapsulants, use non-tracking insulations, prevent condensation, avoid pointed electrodes, use low dielectric-constant insulators, use proper air gap length, dampen inductive switching surges, and prevent sublimation or evaporation of conductive materials.

Multipacting failure does not occur in power conditioning equipment. However, in the RF sections of the broadcast satellite system (e.g., circuits, connectors, coaxial lines, microwave components, waveguides, antennas, etc.) the proper combination of conditions may exist which will support a multipacting discharge. Much information is already available on the interaction of RF voltage amplitude, electrode spacing and applied frequency, and on combinations of these conditions with electrode configurations and materials which will produce a multipacting discharge. Much of the work to date is on parallel plate electrodes or is based on experimental data, because electron trajectories and electron distributions between complex electrode configurations (with non-uniform fields) do not lend themselves easily to rigorous analysis. Much work is still needed to predict possible multipacting breakdown with real hardware configurations and materials. Also, effort is needed to further investigate the degree and nature of the various deleterious effects due to multipacting (e.g., deterioration of the emitting surface, change in circuit impedance, detuning, noise content, non-linear effects), and the effectiveness and implementation of various techniques for eliminating multipacting.

8.2.4.3 Currently Funded Effort

A review of high voltage handling technology is being performed at GE under the Multi-kilowatt Transmitter Study for NASA/MSFC (NAS 8-21886). Program task objectives are to identify and characterize materials for specific pertinent areas of application in high-power, satellite-borne transmitters and associated power conditioners. The results of the program will be an identification of critical problem areas and suggested solutions.

The SERT II program has requirements for a 1 kW, 3 kV (unregulated) power conditioner for energizing an ion engine. In addition, Hughes Aircraft has been developing a 3 kW, 2 kV power conditioner for JPL for operation from a solar array. This conditioner is also to be used to operate an ion engine in space.

8.2.4.4 Additional Effort Required

Both system and subsystem analyses are needed to establish the magnitude of the problems described here. In addition, basic empirical data concerning sublimation and outgassing rates for typical materials used at nominal operating parameters in these systems is required. Numerous methods have been employed to determine the effect of outgassing materials condensing on other surfaces. Some have attempted to simulate hardware geometry, while others have used a direct line-of-sight criterion. Data obtained in this fashion cannot be generalized to other cases because of the possibility of reflection of outgassing particles from other surfaces. The recently developed "distribution box" technique for acquisition of condensation data would make it possible to analyze the condensation phenomenon for any geometry.

The distribution box technique is a material test method in which outgassing products from a material sample heated by radiation from the inside walls of an electrically heated cylindrical box are directed through two holes in the bottom of the box. After passing through the holes, the outgassing products are collected as condensate on two cooler mirrors; the weight gain of the mirrors is measured as a function of time so that the degree of outgassing can be assessed for this sample and deduced for other geometric configurations.

Concurrently with material selection, testing, and evaluation; the basic design philosophy must be analyzed and resolved. Several possible design approaches should be assessed. These include: the use of a system hermetically sealed with dielectric gas, liquid or solid; the enclosure of all high voltage parts or components in vacuum cast encapsulations; designing the system for operation only in hard vacuum, with provisions to control sublimation, limit outgassing and prevent energizing of the high voltage unless hard vacuum exists.

8.2.5 GRIDDED TUBE TRANSMITTER

There are several requirements which may dictate the use of UHF for certain broadcast satellite systems. For these applications, the high-power gridded tube is a simpler device which is several years ahead in development than high power microwave tubes. Several high efficiency circuits are available which make gridded tube transmitter efficiencies competitive with microwave tube transmitters.

8.2.5.1 General Capability

Present gridded-tube transmitters with capabilities for transmitting TV type video-modulated signals employ Class B linear amplifiers. Unfortunately, this type of final amplifier is relatively low in efficiency (e.g., 43%) when used for TV type transmission. Until now, there has been little demand for higher efficiency, high-power gridded tubes in space-environment applications.

Available tubes can provide good efficiencies either at low RF power levels (under a kilowatt) or at low frequencies (under 700 MHz). For space missions requiring multi-kilowatts of power at 800 to 900 MHz new tubes like the GE L-64S presently under development are needed.

Weights and costs of gridded tube transmitters are substantially less than for solid state transmitters due to the high output power and small size of a typical gridded tube. The 2.5 kW L-64S gridded tube shown in Figure 8-4 is approximately 1 inch in diameter and 1-1/4 inches long, exclusive of any cavity.* From the standpoint of best efficiency, modular construction is recommended only at power levels above 2.5 kW.

Based on recent life tests in cathode fabrication techniques, the cathode life of a gridded tube is expected to be five years. Reliability will also be substantially enhanced by a bonded grid technique in which the grid is physically joined to the cathode through an insulator, thereby eliminating the possibility of grid-to-cathode electrical breakdowns.

8.2.5.2 Major Problems

A major problem in gridded tube design has been grid-cathode shorting. However, new techniques have been developed which improve the tube operation by a substantial margin. The most significant of these techniques involves the bonding of the grid to the cathode structure which will eliminate grid-cathode shorting problems, and should provide a very high transconductance of the order of one mho. This will result in higher gains and efficiencies.

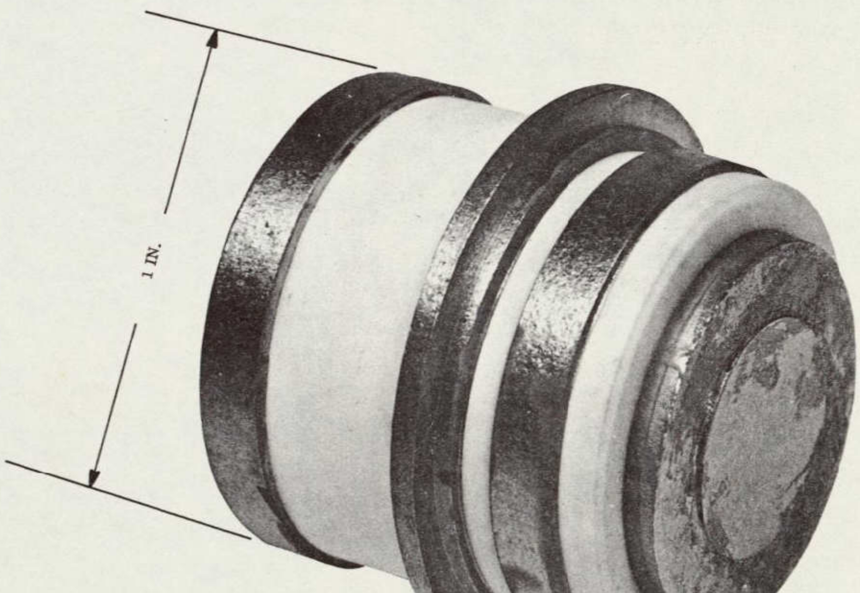

Figure 8-4. 2.5 to 5 Kilowatt GE L-64S Gridded Tube

*Including a UHF output cavity, the over-all size might typically be 6 inches in diameter by 2 inches long. An input cavity is also required.

A second problem area is material selection for the external cavity required by the gridded tube. Materials effects are of primary concern since they influence electrical breakdown characteristics in the very high vacuum of space. Multipacting is probably the most serious cause of breakdown in the RF cavity. Gridded tubes should be used in a high efficiency configuration rather than in a Class B linear amplifier. For AM modulation, peak efficiency would not be greatly improved, but average efficiency would be substantially increased by using the gridded tube in a high efficiency circuit. The comparison presented in Table 8-6 indicates the efficiency values for the higher efficiency configurations.

Table 8-6. Efficiency Comparison for Gridded Tube Amplifier (AM Modulation)

Circuit	Peak Efficiency	Average Efficiency*
Class B Linear	60%	43%
Doherty Type	65%	62%

*Average efficiency is based on an average signal power level of 32% of peak sync power in a TV AM modulated signal.

Thus, a high efficiency circuit, probably a Doherty type as in Figure 8-5, should be investigated further for a TVBS application at UHF.

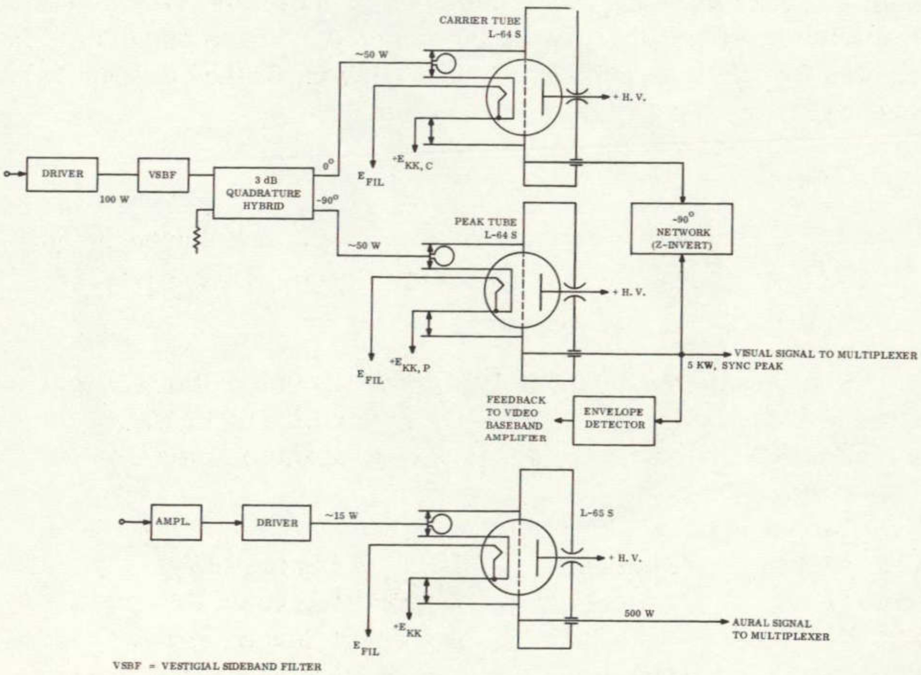

Figure 8-5. 5 kW UHF TV Transmitter Channel Using a Doherty Circuit for the Final Video Stage

8.2.5.3 Currently Funded Effort

The L-64S tube has been developed with GE funds between 1965 and 1969, and is presently undergoing a final test. Assistance in the development is being derived from parallel contracts with the Signal Corps, Contract DA-28-AMC-02483 (E).

Under the Multikilowatt Transmitter Study (NASA MSFC Contract NAS 8-21886) a breadboard version of the Doherty type UHF amplifier for AM-TV application is being constructed and tested. The purpose of this effort is primarily to show feasibility, but additional requirements not included in this effort must be considered ultimately.

8.2.5.4 Additional Effort Required

Additional efforts are required to extend the L-64S tube development to include the advanced concept of the bonded grid. This will result in a gridded tube equal or superior to any other UHF tube in terms of stability and performance for UHF-AM applications.

Effort in evaluating and developing components specifically for space would consider the various materials effects on electrical operation, and also weights, sizes, and costs where unusual situations exist, such as for vestigial sideband filters.

Developing and evaluating high efficiency circuits is a requirement for the application of gridded tubes to high-power operation of the circuitry, linearization (if required), and integration of thermal control techniques with the electrical and mechanical design.

8.2.6 MICROWAVE TUBE TRANSMITTER

For those broadcast satellite mission requirements which dictate frequencies higher than UHF, the microwave tube transmitters would be selected. Three candidate microwave devices are candidates for the transmitter: 1) the klystron; 2) the crossed field amplifier (CFA); 3) the traveling wave tube (TWT).

8.2.6.1 General Capability

At the present time, there is one traveling wave tube (Watkins Johnson TWT type WJ395) in the 100-watt range which is qualified for space operation. Otherwise, only low-power space tubes are available.

Several NASA tube study contracts represent the most advanced status of microwave devices, and will dictate the nature of future transmitters. The initial studies are complete, and follow-on contracts will provide laboratory confirmation of study results. The contracts are as follows:

NAS 3-9719	Hughes	Design of Space TWT
NAS 3-11513	Litton	Design of Space CFA
NAS 3-11514	GE	Design of Space Klystron
NAS 3-11515	Litton	Design of Space ESF Klystron
NAS 3-11516	SFD	Design of Space CFA

There is no firm indication of any effort being expended on development of space-qualified, high power RF circuitry, which represents another major problem area. Thus, the above studies in conjunction with certain related thermal control studies appear to represent the present state of microwave transmitter development for high-power space applications.

Table 8-7 lists the predicted efficiencies for some of the tube types being studied. If development of these tubes is continued, they could be available and qualified for space transmitters in about 3 to 5 years.

Table 8-7. Predicted Efficiencies of Microwave Tubes

Tube Type	Type of Operation	Predicted Efficiency
CFA	UHF FM	80%
	UHF AM	70% (average)
	S-Band AM	60% (average)
TWT	S-Band FM	80%
	X-Band FM	75%
Klystron	S-Band FM	
	• Electromagnetic Focus	80%
	• Electrostatic Focus	75%
	X-Band FM	75%

8.2.6.2 Major Problems

The major problem is the development of a high frequency tube to provide a high-power signal with high efficiency. Tube studies are progressing, but results cannot be well assessed until some experimental test data is forthcoming. In considering the tubes themselves, a significant problem with the large UHF TWT and klystron types concerns mechanical fabrication to insure compatibility with launch and orbit environment requirements. High frequency tubes encounter problems resulting from constrained beam sizes.

The attainment of the high efficiencies predicted is dependent upon the performance of multistage depressed collectors (4 to 20) and upon the use of voltage jumps in the case of the TWT. Efficiencies without depressed collectors range from 55 to 70 percent at saturation. Where many collector rings are postulated, the weight, size, and complexity of the power conditioner would increase significantly.

With each tube type, there is the problem of thermal dissipation. All the tubes under development have mechanical configurations dictating the use of heat pipes, which are not only custom-designed for the particular tube but which are also an integral part of the tube design.

It should also be noted that the operational standards already established for distribution satellite services are not necessarily applicable; therefore, new circuits, concepts, and propagation and operating phenomena peculiar to broadcast satellite applications will need to be investigated to determine standards and circuit specifications.

In the realm of circuitry for microwave transmitters, the circuitry will be an assembly of components which must retain a low overall VSWR and phase distortion characteristic to insure TV performance within distortion standards (such as EIA RS-240). The problems are more serious and not as well understood for FM transmission, where wide bandwidths of 30 to 60 MHz are required, especially since TV picture phase and amplitude linearities must still be maintained. To determine circuit performance in practice, a monitor subsystem including sensors for VSWR, power flow, and electrical breakdowns is required as an integral part of the circuitry. The circuitry to include these devices, with techniques to correct for faults, is sufficiently undefined to constitute a major area of effort in implementing a space TV transmitter.

8.2.6.3 Currently Funded Effort

The major effort in direct contracts for microwave transmitters are the five NASA contracts noted previously, each of which is described below. In addition, the Multikilowatt Transmitter Study (contract NAS 8-21886) includes applications of these tubes to transmitter configurations, and will also include a study of the high-power RF component problem.

8.2.6.3.1 Space-Borne Axial Injection Crossed Field Amplifier (NASA Contract NAS 3-11516; Report CR 72393)

An analytic study program to produce an optimum design of an axial injection crossed field amplifier to be used as the output stage aboard a broadcast satellite has been carried out by SFD Laboratories. The design was optimized with respect to highest efficiency, minimum weight, and minimum size while insuring the required lifetime and the meeting of other requirements such as the bandwidth, signal-to-noise ratio, linear dynamic range, and phase linearity specifications. The designs are for AM modulated tubes capable of providing peak sync output powers of 7.5 kW and 5.0 kW at 890 MHz and 2 GHz, respectively.

A trade-off analysis was performed to find an optimum combination of design parameters. Several concepts for a multi-stage collector were evaluated and a design with inherent field suppression of secondaries has been made.

The expected efficiencies are 80 to 85 percent at saturation and 60 to 70 percent at the average signal level. The multi-stage collector assumes a great importance in preserving high efficiency at the reduced drive levels encountered under AM operation. This is particularly true since the concept of RF control of the input current was not found to be of practical importance in this application. The collector will have 10 to 15 stages, the potential at some of the stages being below that of the cathode. The latter stages will require special power conditioning. Tube cooling is to be accomplished by the use of heat pipes.

This tube utilizes new approaches for the injection gun and the collector. However, since the slow wave structure parameters were not obtained by direct measurement, the direct experimental verification of the predicted performance is viewed mandatory. Of particular importance are demonstrations of high efficiency at reduced drive levels and a linear dynamic range of 20 dB.

8.2.6.3.2 Space-Borne Linear Injected Beam Crossed Field Amplifier (NASA Contract NAS 3-11513; Report CR 72392)

This study by Litton Industries involved an analytic program to produce an optimum design for a linear injected beam CFA to be used as a broadcast satellite output stage. The size, weight and efficiency of the design were optimized while meeting other performance specifications. The design is for a 2.0 GHz FM modulated tube with a power output of 5 kW.

A large, signal computer simulation of the interaction was employed to evaluate various efficiency enhancement techniques and the tube performance. A computer analysis was used to optimize the design of a multi-stage collector which includes field suppression techniques for secondaries. An over-all efficiency, in excess of 80 percent, was obtained by the combination of a moderate electronic efficiency, in the 50 to 60 percent range, and a 16-stage depressed collector. The four stages with potentials below that of the cathode will require special power conditioning. Tube cooling is to be accomplished by the use of heat pipes.

Although a number of efficiency enhancement techniques, such as phase focusing by field shaping, pre-bunching and potential limiting, have been evaluated and found to be favorable, the design does not rely on these techniques. Moreover, the slow wave structure parameters are based on direct experimental measurements. Consequently, while experimental verification of the predicted tube performance is still required, a relatively high degree of confidence is associated with this design. Direct experimental verification of the predicted performance with multi-stage collectors, however, is viewed mandatory.

8.2.6.3.3 Space-Borne Electrostatically Focused Klystron Amplifiers (NASA Contract NAS 3-11515; Report CR 72449)

Litton industries has recently completed a seven-month study program to develop the theoretical designs of space-borne, electrostatically focused klystron (ESFK) amplifiers. These tubes were required to transmit AM and FM television signals. The peak sync power for the AM tubes was to be 7.5 and 5.0 kW (at 0.85 and 2.0 GHz, respectively). The saturated output power for the FM tubes was to be 5.0 kW (at 2, 8 and 11 GHz).

At the inception of this contract, the state of the art for ESFK's was represented by two Litton ESFK's. The L5101 provides 1 kW CW at 2.3 GHz with an efficiency of 49% and the L5182 provides 1.2 kW CW at 4.4 GHz with an efficiency of 44%. These klystrons operate without collector depression.

Primary emphasis was placed on the problems of obtaining high efficiency and adequate heat transfer while maintaining long operating life, small size and low weight. The contractor investigated velocity jumps, extended interaction resonators, low perveance electron beams (0.5×10^{-6} perv), and multistage collectors. Mechanical and thermal studies were also performed. A combination of the above components and parameters was selected in an attempt to maximize over-all efficiency. This combination was translated into complete electrical and mechanical designs for tubes at 0.85, 2.0, and 11.0 GHz. Designs at other frequencies and power levels could be obtained by scaling techniques. These tubes were deliberately designed with a relatively low electronic efficiency (30%) to reduce the velocity spread of electrons in the spent beam. This was done to facilitate the use of depressed collectors.

A transverse magnetic field collector promises a better solution to the efficiency problem than previous designs by recovering a larger portion of the unused beam power. It is now estimated that ESFK's could be built with efficiencies* from 81% for the 0.85 GHz case to 74% for the 11 GHz case, utilizing the transverse collector scheme.

Direct experimentation to verify certain critical areas of the design is yet to be performed.

8.2.6.3.4 Space-Borne Traveling Wave Tubes (NASA Contract NAS 3-9719; Report CR 72450)

An analytical study program to develop the theoretical design of traveling wave tubes has recently been concluded by Hughes Aircraft. AM and FM applications were considered in a frequency range from UHF to 11 GHz. The program was primarily directed to explore concepts and techniques for advanced design and performance. Such an approach was necessary, since the intended application for a broadcast satellite transmitter becomes feasible only when such advanced performance can be achieved at the time of a launching (e.g., in 1975). A number of concepts and design approaches have been evaluated for the tube design. With these new methods, it appears feasible that the tube performance can be very substantially improved compared to the present state of the art.

A major part of these advanced features is concerned with improving the efficiency. This is one of the most important factors (in addition to reliability and long life) in deciding whether such a system can be developed. The studies have shown that tube efficiencies in the range of 70 to 80% are possible. This compares to 50 to 60% efficiencies demonstrated on experimental traveling wave tubes, and 30 to 40% efficiencies on commercially available tubes.

Dielectric loading is being recommended for weight and size reduction of the UHF and S-band designs.

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*Based on average picture power

However, some of these new concepts have not yet been used in traveling wave tubes. Before these methods are incorporated into a traveling wave tube design, they have to be evaluated experimentally to determine their limitations and to establish design procedures for them. Among the concepts, the following are considered the most important and critical:

1. Multi-voltage jump taper. This efficiency enhancement method has been derived and evaluated with a large signal computer program for traveling wave tubes. The computer program is well proven and has provided useful and accurate analysis for similar methods in the past. However, this scheme has not yet been demonstrated experimentally.

2. Multi-stage collector depression. The multi-stage collector design incorporates several new concepts:

   a. Magnetic refocusing of the spent beam to improve the velocity sorting efficiency.

   b. Transverse magnetic beam deflection also to improve the velocity sorting efficiency.

   c. Electrostatic potential barrier on collector electrodes for improved suppression of secondaries.

3. Traveling wave tube modulator. The essential components and devices of the traveling wave tube modulator are within the present state of the art. However, the design concept requires experimental evaluation to determine its limitations.

8.2.6.3.5 Space-Borne Magnetically Focused Klystron Amplifiers (NASA Contract NAS 3-11514; Report CR 72461)

An analytic study of magnetically focused, space-borne, klystron amplifiers for potential use as output stages aboard broadcast satellites has been performed by General Electric. The study covers a frequency range from UHF to 12 GHz in AM and FM applications. The study stresses high efficiency designs while maintaining long-life capabilities, low weight and size, and employing heat pipe cooling. An accurate and detailed large signal computer simulation of the interaction was employed to develop designs having electronic conversion efficiencies in excess of 60% before collector depression. The designs also met other requirements for gain, phase linearity and bandwidth.

A collector design was proposed which effectively suppresses secondaries and indicates high efficiencies of recovering the unspent energies of the beam. Over-all tube efficiencies in excess of 80% for FM and 60% for AM in television service are estimated. The tubes are designed for an optimum perveance of 0.5×10^{-6} and employ confined-flow solenoid focusing of 2 to 3 times the Brouillon value to secure low interception under large signal conditions and to provide a good entry into the depressed collector. The amplifiers are cooled by heat pipes and are of rugged construction.

Although the designs are based on a sound foundation, none of the concepts have been evaluated experimentally and a verification of the interaction process, focusing schemes, collector operation and later of heat pipe cooling is viewed mandatory.

8.2.6.4 Additional Effort Required

The tube studies should be continued into the prototype stage to better determine the characteristics that will be realized in practice. Linearity and power supply requirements for AM operation and efficiency for all tubes in all applicable frequency bands are of major significance.

High power RF technology should be expanded. This will frequently be concerned with the design of custom components for specific tubes to obtain the proper impedances, operating power levels, bandwidth characteristics and such other factors as the system and mission studies indicate.

Supporting techniques which are vitally related to the transmitter development and also need further development effort include those in the power conditioner area, particularly for the multiple-collector type tubes. Thermal control is also of concern especially where efforts are leaning toward a heat pipe designed as an integral part of the tube, both for initial heat transfer and for interfacing with the external heat sink.

Microwave transmitter circuits need to be developed further for low VSWR, amplitude distortion and phase distortion across wide bandwidths, and for required fault monitoring and automatic correction.

8.2.7 HIGH POWER RF COMPONENTS

8.2.7.1 General Capability

Radio frequency components used in a high-power braodcast satellite transmitter include devices such as multiplexers, vestigial sideband filters, power combiners, circulators, RF filters, tuned circuits and similar items. Little has been published on the problems and solutions for high power RF components for use in space transmitters. Presently, most RF components in space applications operate either at low voltages (under 300 volts) or under pressurized conditions so that the materials effects which occur at high voltages in space do not appear. The potential breakdown conditions in space include the phenomena of outgassing, multipacting, dielectric breakdown and sublimation, any of which can cause operational failure unless eliminated.

Related problem areas include the adequate design of monitor and protection circuitry to indicate abnormal operating conditions and to prevent damage from RF breakdown.

8.2.7.2 Major Problems

Electrical breakdown is characterized by arcing, corona, and dielectric deterioration. These effects, in turn, are determined by the action of materials in a high vacuum. Thus, the problem involves an evaluation of materials, the effects of these materials when acted upon by electrical fields, and the integrated effects of materials and fields upon RF components.

Large size and weight normally dictated by the high power levels at which the components must operate represent another problem for power combiners, frequency multiplexers, and vestigial sideband filters (required for AM-TV operation). The larger size and weight are generally due to the need for greater power handling capability without breakdown and for the addition of thermal radiating fins to dissipate heat more effectively. The size and weight of ground based RF components of these types are generally unacceptable for space operation. Consequently, a component selection or design approach which provides the necessary performance while minimizing undesirable mechanical features is required.

Thermal control of RF components has generally been ignored. On the earth, convection provides some cooling effects. In space, the power absorbed in the RF lines and components can only be dissipated by conduction to a heat sink radiator or by direct radiation to space.

8.2.7.3 Currently Funded Effort

The only known funded effort on the specific problem of high-power RF components in space is the Phase II Program of the MKTS contract (NAS 8-21886). Those aspects of the high RF power problem (up to 1 kilowatt per channel) involving the antenna system are being studied under NASA contracts NAS 3-11524 and NAS 3-11525 which were started early in 1969.

8.2.7.4 Additional Effort Required

Efforts are required in several areas to ensure the satisfactory performance of the RF section of a space transmitter. The initial area requiring better definition is an extended study of how materials are affected at high temperatures in the presence of high intensity RF fields. An identification and evaluation of the best materials, processing techniques, and supplementary techniques to minimize the possibilities of an RF voltage breakdown are needed.

Following the identification of optimum materials, a subsequent area for additional effort should be the design of RF components with minimum size and weight. This should be considered when the transmitter RF circuit requirements are reasonably well established so that the feasibility of developing new components specifically for space systems can be determined.

Other areas requiring additional effort include component design using integrated thermal control techniques. In general, this can be performed initially as an RF component study, and then integrated with a transmitter system study in future programs.

8.2.8 RF ROTARY JOINT

8.2.8.1 General Capability

The general performance capability of high-power RF rotary joints operating in the hard vacuum of space (required for anticipated TV Satellite missions) is not known. At present, the only barometer that can be used to attempt to assess the capability is the data that exists from ground tests. Table 8-8 lists typical rotary joint types that might be utilized at a given power level and frequency band.

Table 8-8. Typical Types of Rotary Joints

Average Power (kW)	UHF	Frequency Range S-Band	X-Band
0.5	In-line coax	In-line coax	W.G.
5.0	In-line coax	W.G.	W.G. (TM_{01})
25	In-line coax	W.G. (TM_{01})	-----

Here, W.G. means that the input and output ports are rectangular waveguides and the rotating section is coaxial; W.G. (TM_{01}) means that the input and output ports are rectangular waveguides but the rotating section is circular waveguide. If data from ground-based tests could be used to predict correctly the performance of rotary joints in the hard vacuum of space, then one could assume from the information given in Table 8-8 that there is no problem in the power-handling area. However, because the mechanisms of breakdown differ considerably under the two different environments, little correlation may exist. It is consequently impossible to state the general power-handling capability of rotary joints in space with any degree of confidence. As is usual in circumstances such as this, design data from ground applications is utilized for conceptual designs until simulated test or actual flight data becomes available.

8.2.8.2 Major Problems

The major problem area relating to the utilization of RF rotary joints in broadcast satellite missions is the general lack of design data necessary to cope with the high-power breakdown problems that occur in hard vacuum. The information available from ground tests of rotary joints under controlled environments may be of limited value in predicting power handling in space. In ground-based systems, the breakdown phenomenon is usually associated with gas discharge where ionization of the gas molecules provides the conducting path required for arcing or voltage breakdown.

In the hard vacuum of space, the breakdown phenomenon is characterized as a multipactor breakdown. This breakdown is triggered primarily by secondary electron emission. For multipacting to occur, an electrical-mechanical resonance must exist between the magnitude of the RF field, the frequency, and the physical dimensions of the component under consideration. The multipactor effect can, however, persist over a considerable range of variation of these three parameters. More importantly, the multipactor effect may induce side effects that can trigger arcing which is similar to that observed in a gas discharge breakdown. These side effects may be those associated with localized heating and changes in the conductor work function, or with outgassing of the material itself and the resulting plasma.

There is also cause for concern in the rotary joint conductor temperature rise due to dissipative heating. Thermal design should be sufficiently effective so that temperature equilibrium would be reached by heat radiation before thermionic emission would ensue. However, the work function of the conductors in question would undoubtedly decrease and, therefore, make secondary emission more of a problem, even outside the multipactor region. It is important to realize that, although precautionary measures will be taken against multipacting, there is still a possibility that a high-altitude breakdown environment will be created due to all other complex side effects. The amount of experimental data available is inadequate and, therefore, a high degree of confidence in theoretical or conceptual designs does not exist.

Potential problem areas are identifiable and to some extent can be addressed during rotary joint design. The rotary joint dimensions should be chosen such that the resonance condition required for multipacting at a given power level and frequency will not occur. Outgassing from the rotary joint conductors, choke bearings or lubricants due to dissipative heating should be minimized. Material outgassing from the spacecraft itself should be minimized so that entry through an open feed radiator is curtailed. Allowable conductor temperature rise may be controlled in concept by heat radiation devices.

8.2.8.3 Currently Funded Effort

Current programs for a study of Antenna Pattern Shaping, Sensing and Steering (NAS 3-11524 and NAS 3-11525) include a study of RF rotary joint design for multi-channel space transmission at power levels of approximately 1 kW per channel.

8.2.8.4 Additional Effort Required

Experimental work is required to establish performance criteria in terms of RF power for the UHF, S- and X-bands in order to predict power-handling capability.

A theoretical investigation of breakdown problems in a high vacuum should be conducted. Off-the-shelf RF rotary joints should then be tested under high-power conditions in a high vacuum for frequencies in the UHF, S- and X-bands. After these tests, the rotary joint designs should be modified as necessary to ensure high power-handling capability without breakdown in a high vacuum. Finally, the maximum power capability of the modified designs should be established.

8.2.9 PARABOLOIDAL ANTENNA

8.2.9.1 General Capability

The capability of paraboloidal reflector antennas for broadcast satellites is best evaluated by assessing the technology state of the art of:

- Paraboloidal reflectors
- Paraboloidal feed systems

The general state of the art of reflector type antennas with diameters less than 30 feet is being developed. For example, the Apollo and Lunar Excursion Module tracking and communications antennas (flown in 1969) possess parabolic reflectors with diameters of approximately 2.5 feet that are suitable for S- and X-band operation as far as surface tolerance is concerned. The ATS-F/G 30-foot reflector, designed with an rms surface tolerance of approximately 0.050 inch, gives a capability of operation from the UHF through the X-band frequency range for this relatively large, erectable antenna. The ATS reflector has already been successfully erected in ground test, and surface tolerance measurements and launch vibration tests have been performed.

The antenna feed system for use in a space environment has not been adequately developed with respect to feed interaction, control of side lobes, and high power operation. The antenna feed system is composed of the primary feed, transmission line, rotary or flexible joints and polarizers. Many problems can be anticipated in the feed system area for power levels over a kilowatt.

In addition to problems of the feed system, there are several areas relating to the paraboloid antenna performance capability where a requirement for high power broadcast operation introduces additional complexities and problems not generally encountered in low power systems. These additional problems affect the areas of beam pointing, beam shaping, and generation of multi-beam patterns.

8.2.9.2 Major Problems

The major problem in the paraboloid antenna area is the general lack of knowledge necessary for the design of antenna feed systems (single and composite feeds) capable of high-power operation in the hard vacuum of space. The solution to the high-power handling problem will be achieved only when the breakdown problems caused by factors such as sublimation, condensation, multipacting, outgassing, plasma, photoelectric effect, and allowable conductor temperature rise are fully understood and controllable. At present, this is not the situation, therefore, design uncertainties still exist for high-power antenna feed systems build to operate in a space environment.

Additional problems relating to high power transmission using a paraboloid antenna were mentioned in the previous section. The first of these is beam pointing. For low-power systems, the technology available from ground-based systems is sufficient to cope with the design problems. For high power systems, where flexible transmission lines and/or rotary joints would have to be significantly larger in size to adequately handle the large amounts of power without breakdown and with adequate thermal dissipation, considerable interface complications with the gimballing system can be anticipated.

A second area of consideration relates to the changes required and difficulties introduced in the reflector and feed system if there is a requirement for high-power beam shaping. Elliptical beam shapes would utilize power more optimally for irregular shaped coverage areas. Shaped beam systems are widely used in many commercial ground applications, so that the design techniques are well established. However, without additional effort for development of high-power feed systems for space applications and some structural and packaging design investigations, it is questionable whether shaped-beam, high-power reflector antennas will be available by the mid-1970's.

A third area relates to multi-beam antennas. The power-handling problems for these antennas are multiplied by complex feed interaction. The increased side-lobe and coma-lobe levels resulting from multiple feeds and feed displacement from the focal point may be unacceptable.

Thermal dissipation from waveguide is a problem for high-power broadcast satellites. At X-band frequencies, the waveguide loss (e.g., for rectangular waveguide type WR90 at a frequency of 12.2 GHz) in an earth-based system is about 0.38 dB per 10 feet: at S-band (e.g., type WR340 at 2.5 GHz), the loss is only about 0.07 dB per 10 feet. However, these ratings are for a ground environment where convection, conduction, and radiation from the waveguide are all possible means of cooling, and where forced air cooling might even be employed. In a space environment, however, cooling of the waveguide must depend upon radiation only, or some combination of conduction and radiation. Thus, the magnitude of the losses stated above may not be correct for waveguide operation in a space application, and therefore further investigation is needed.

8.2.9.3 Currently Funded Effort

In the paraboloidal reflector antenna area, the 30-foot ATS-F/G reflector model development is currently being funded by NASA and internally by Goodyear Aerospace.

Under NASA Contracts NAS-W-1438, NAS 8-11818, and currently under NAS 8-21460, General Dynamics has performed an erectable antenna development study resulting in a deep truss antenna design for a rigid paraboloid up to 300 feet in diameter. Radio frequency tests have been performed on a 6-foot operating model of this design at 15 GHz.

Additional studies will be performed under NASA contracts NAS 3-11524 and NAS 3-11525.

Effort in the antenna feed system area for high-powered broadcast satellite systems is almost nonexistent. Companies and government organizations that have been involved in planetary or interplanetary satellite missions and have observed RF breakdown problems in hardware have devoted some research toward the general solution of these problems. These organizations are NASA, GE, Hughes, JPL, MIT and SRI. Multipacting has been one of the major sources of breakdown in these missions. Moreover, the power levels involved have been several orders of magnitude lower than what is anticipated for broadcast satellite missions. Thus, the probability of multipacting type of breakdown occurring in the latter application will be greatly increased.

The beam-shaping problem was assessed by Goodyear Aerospace when an inflatable wire-grid tube version of a reflector with an elliptical aperture was built. Effort along these lines appears to have diminished, and the present state of development of shaped-beam antennas for high-power broadcast satellites is rather low. Current programs for a study of Antenna Pattern Shaping, Sensing, and Steering (NASA NAS 3-11524 and 11525) have as their major objective the design study of a multibeam space antenna system with multi-channel capability. Included in the study will be the ability to re-orient the beams in space. Maximum power outputs of 1 kW per channel and of 4 kW for all channels combined are requirements.

8.2.9.4 Additional Effort Required

Additional theoretical and experimental work is required to assess the performance and power-handling capability of single and multiple antenna feed systems under the conditions of hard vacuum. This effort should not be restricted to the testing of only a particular component of the feed system (e.g., a rotary joint), but should include individual testing of each component as well as subsystem testing of the entire integrated feed assembly. In the past, practically no effort has been applied to the design problems associated with primary feeds for kilowatt-level antennas in space. However, it is in the primary feed area where intense electromagnetic fields exist. In combination with phenomena such as solar radiation, outgassing and plasmas, these strong fields can result in high-power breakdown. Unlike the rotary joint or transmitter line, which are generally closed or shielded, the high-power primary feed is open and exposed to the hazards of space such as solar radiation and plasma which may form around or be intercepted by the satellite vehicle. Therefore, the primary feed may be the weakest link in the feed system chain, with respect to high-power breakdown, and an area requiring the majority of theoretical and experimental efforts. A theoretical investigation of potential high-power breakdown problems in the RF feed should be conducted for UHF, S- and X-bands.

It is important that the RF rotary joint, transmission line, and RF feed be investigated on an individual component basis so that design data on high power conditions is available for each component. It is also important that the entire feed system be tested and evaluated under high-power, high-vacuum conditions. As a result of the tests, design criteria for high-power feed system design should be established for all the pertinent frequency bands.

For the beam-pointing problem, the design limitation for prime-focus scan in high power paraboloid systems should be assessed and performance bounds should be established.

For multibeam antenna problems, the high power design criteria for single RF feed systems should be reviewed and evaluated to assess the potential multibeam transmission problems. High-power testing of primary feed clusters under high vacuum should be performed if results from prior single-feed tests indicate a possible problem area.

For beam-shaping problems, the previously developed high-power feed system design criteria should be assessed and then performance limitations for shaped beam primary feed designs established.

If reflector antennas present insurmountable problems at higher power levels, mechanically steerable arrays could be the next step because high-power can then be distributed over many elements. Redirective electronically-steerable phased arrays offer additional advantages in satellite beam steering and attitude control requirements for the future; however, these latter advantages are offset by cost, weight, and efficiency penalties.

8.2.10 MECHANICALLY STEERABLE ANTENNA ARRAY

8.2.10.1 General Capability

One example of a mechanically steerable array which has been flown is the S-band waveguide-slot, Surveyor antenna built by Hughes. This planar array antenna has an aperture 38 inches x 38 inches, a gain of 27 dB, and an aperture efficiency of 70 percent. The North American Rockwell Company is studying a mechanically steerable phased array utilizing endfire elements and sinuous waveguide feed lines.

The chief advantages of a mechanically steerable array over a paraboloid type antenna are the distribution of power over the entire radiating aperture and the use of (many) low power transmitter power amplifiers. The disadvantages of packaging and higher weight, however, are usually of such magnitude that paraboloids are preferred. The mechanically steerable array which would have application for broadcast satellite missions, that is, one with distributed amplifier output devices, is not now being investigated. On the other hand, various redirective phased array studies currently in progress should precipitate knowledge also useful for mechanically steerable designs.

In general, the state of the art for mechanically steerable arrays must be considered relatively low in so far as adaptability of any present designs to high power broadcast satellites is concerned.

8.2.10.2 Major Problems

The problems existing in the implementation of mechanically steerable arrays are two-fold. The first problem area relates to the difficulty in mechanically packaging and deploying the array, regardless of the mechanism chosen to excite the array elements. The design of the antenna for packaging within the shroud and for subsequent erection in space is considerably more difficult than for a parabolic reflector antenna.

The second problem involves the method chosen to feed the array elements. Possible passive feed techniques are: a) to use a series-fed transmission line or waveguide, or b) to utilize corporate feed networks, such as the Butler matrix scheme. As an alternate scheme, each individual element or element group (i.e., subarray) may be associated with its own output device or amplifier.

The passive network feed technique is bulky, heavy, difficult to package and deploy, and considerably limited in bandwidth capability. Extending the bandwidth capability, and hence the number of channels, increases design problems by at least an order of magnitude. The passive network feed technique is, therefore, not as flexible in performance capability as is the mechanically steerable array with individually fed array elements.

However, the problems created in distributing RF signals from individual output devices to each element are not minor. The major problem area lies in the required phase stability for the output amplifiers in order to produce a tolerable rms phase error over the entire array aperture. This problem area has not been addressed until now primarily because a real need for a mechanically steerable array has not yet been established. If high-power primary feed system problems can be solved for a reflector type antenna within a reasonable time period, distributed amplifier array antenna problems may be studied not in connection with mechanically steered arrays but rather as part of the more advanced, redirective phased array antenna systems. Consequently, the mechanically steerable array should receive only a limited level of investigative effort unless something unexpected occurs in the reflector antenna design area which prohibits its general usage for high-power broadcast satellite missions, or reliability of high power transmitters is too low, forcing the use of multiple low power amplifiers.

8.2.10.3 Currently Funded Effort

The efforts of Hughes and North American Rockwell have been discussed in paragraph 2.10.1. Other companies, including General Electric, are pursuing various electronically-steerable phased array activities from which some results could be adapted to mechanically-steerable array requirements. For example, for the past 2 years redirective antenna arrays have been investigated by GE. During the course of these investigations, a 79-element, randomly spaced, S-band phased array antenna (Figure 8-6) was built. To assess the performance of the antenna, a 79-port, stripline power divider was built, and the antenna pattern characteristics and gain were measured. This antenna system, which possessed a gain in excess of 30 dB, is representative of the antenna and corporate feed structure required for a mechanically steerable array. Although the stripline power divider is not suitable as a high-power device, the applicability of results to the mechanically steerable array antenna design is evident.

8.2.10.4 Additional Effort Required

Additional investigations may be required for the mechanically steerable array antenna depending upon the high-power capability available from reflector antenna systems. If major problems develop in the high-power feed system design for reflector type antennas, and if these problems severely limit the broadcast satellite effective radiated power, then the logical progression would seem to lead next to a mechanically steerable array system.

Any additional effort for advancing the state of the art of mechanically-steerable, high-power arrays should include both structural and electrical considerations. The deployment and erection techniques used for large arrays should be investigated and engineering models built to justify design approaches for these techniques. In addition, the behavior of the distributed amplifier output device in the mechanically-steerable system should be studied and a partial array built and evaluated in terms of high power and efficiency.

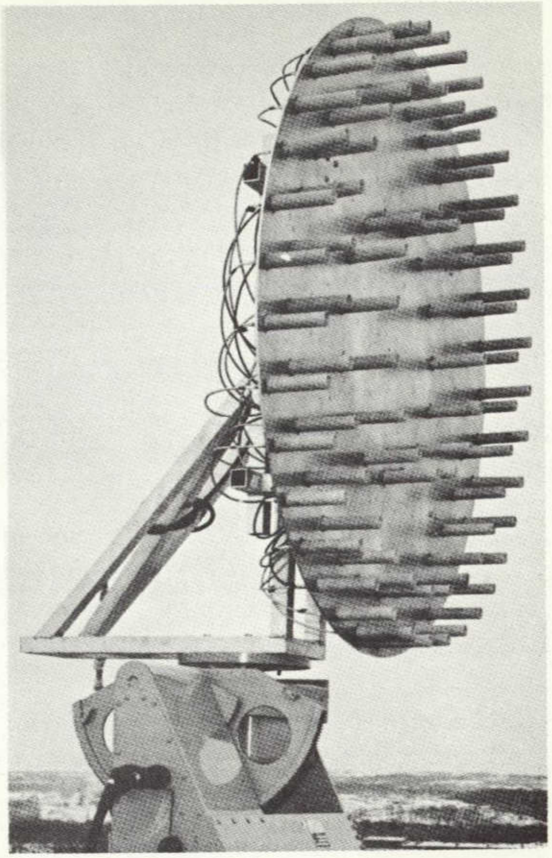

Figure 8-6. A 79-Helical Element Phased Array —Transmit Portion

8.2.11 ELECTRONICALLY STEERABLE PHASED ARRAY

8.2.11.1 General Capability

Only the redirective self-adaptive type of electronically steerable antenna array will be considered in this discussion. Other types of phased arrays, such as the commanded systems utilizing phase shifters or beam switching networks (having extensive ground application capabilities) are generally part of a radar system and are not readily adaptable to broadcast satellite applications.

As applied to space-borne systems, a redirective antenna system is a cooperative ground-to-satellite system using directive beams for receiving and/or transmitting, and having provisions for keeping the beams pointed in the proper direction. In this system, phased array antennas are employed in the satellite for receiving and transmitting functions.

An originating ground station transmits to the satellite the information to be relayed in combination with a pilot signal. By heterodyne action, the satellite antenna electronics processes the signal received by each array element so that all of the received signals are then in phase. A user ground station desiring to receive the information from the satellite emits a proper pilot signal. This is received at the satellite and heterodyned with the previously processed signal in such a way as to produce a conjugate phase in each array element. The transmitted satellite beam is thus automatically steered back in the direction of the user station.

The redirective type of phased array with its self-phasing, inherently inertialess, beam-pointing capability is in concept perfectly suited for broadcast satellite missions. While despun phased array antenna systems have been flown, no truly redirective antenna system has been launched. The Data Relay Satellite System (DRSS) presently being considered by the NASA Goddard Space Flight Center will probably constitute one of the first generations of satellites equipped with a redirective antenna system. Redirective antenna sizes up to 40 feet in diameter are being considered for the S-band range. The half-power beamwidth for this proposed DRSS antenna is approximately 1 to 2 degrees.

At the present time, the general capability of redirective phased array antennas systems for broadcast satellites must be classed as low and noncompetitive with reflector antennas.

Packaging and deployment of these antenna types is only in the conceptual stage. The weight of a redirective antenna system including amplifiers is estimated at the present time as approximately two to four times as large as a reflector antenna plus transmitter on a comparable basis.

The antenna system efficiency is presently low because of the limitations of the output amplifier devices and the way they are utilized in the system. A design of an X-band redirective antenna analyzed for ATS-F/G had a system efficiency of less than one percent. A General Electric design for an S-band redirective system that was developed during a 1967 company funded effort had an efficiency of a few percent.

Because of the increased complexity of these systems in both the number of radiating and amplifying elements plus the associated circuitry, (phase shifters, diode switches, power dividers, couplers, etc.) the cost of the redirective phased array antenna system is estimated at present to be 2 to 4 times the cost of a reflector antenna system with comparable performance. In addition to the increased cost of the antenna system itself, the presently available low efficiency would result in increased solar array costs for any system requiring substantial power levels.

It is, therefore, concluded that the present state of the art for redirective phased array antennas is inadequate for the majority of anticipated broadcast satellite missions, and the general capability is consequently classed as low.

8.2.11.2 Major Problems

Certain problems exist at the present time in the implementation of the redirective phased array antenna for broadcast satellite missions. The mechanical packaging and deployment of this array is considerably more difficult than for the reflector antenna. Approaches at present are largely conceptual and, hence, unproven.

The antenna system efficiency is constrained by the available output device efficiency for the particular frequency band under consideration. This device efficiency is indicative of the component state of the art at any given time but, in general, is constantly increasing. However, the output device efficiency is sometimes deceiving. For example, a transistor amplifier at UHF may have an efficiency of 35 percent, but the gain of this device may be only 5 to 6 dB. Thus, if a gain of 20 dB is required for the output device, a cascaded amplifier chain is required. In this case, the required drive power becomes a significant consideration and the over-all amplifier efficiency may decrease to 10 percent or less.

In addition to the behavior of the output device itself, the associated circuitry required to perform the heterodyning function (for the redirective capability) is complex and difficult to implement at a reasonable weight even when microminiaturization techniques are used.

8.2.11.3 Currently Funded Effort

In spite of the existing problems associated with the redirective phased array approach, the potential performance capability is so great that many companies have invested their own funds for the development of these systems. The most prominent among those firms who are participating in the development of these systems are the General Electric Company, AIL, Hughes, Sylvania, RCA, Texas Instruments and Lockheed.

The Orbiting Data Relay Network Study, recently performed by Lockheed and RCA, involved the conceptual design of S-band redirective antenna systems. The Data Relay Satellite System study by AIL, just getting under way for NASA Goddard SFC, involves similar requirements for a redirective phased array for S-band. For the Air Force MERA program (AF33(615)-1933), Texas Instruments has developed a laboratory prototype of an X-band, redirective, solid-state phased array antenna.

Figures 8-6, 8-7, and 8-8 are photographs of antennas and antenna elements which have been investigated by GE (under internal company funding) for various phased array antenna requirements. The planar array of endfire helical elements (Figures 8-5 and 8-6) was built to demonstrate the feasibility of randomly thinning a planar aperture, then recovering with the use of endfire elements the majority of gain lost by thinning. There are a total of 158 elements in this array, 79 transmit elements at 4 GHz and 79 receive elements at 6 GHz. The thinned transmitting portion (shown in Figure 8-6) was pattern-tested and the measured gain was in excess of 30 dB. The corresponding aperture efficiency was nearly 50 percent so that, in essence, much of the gain lost by thinning was recovered by the increased element gain.

A 7-element sub-array of cavity-backed spiral antennas is shown in Figure 8-8. The measured element gain of this sub-array ranged from 14 to 16 dB depending on the frequency and spiral spacing. Such a sub-array element is ideal where considerable element gains and yet a thin element profile are required.

8.2.11.4 Additional Effort

The redirective phased array antenna approach is not likely to displace the paraboloid antenna in the first generation broadcast satellite regardless of the magnitude of funding which might be applied toward this goal. Many companies are gradually advancing the state of the art in this area, but the fundamental problems to be solved relating to output device efficiency and power output require time as well as money. In addition, the solutions to problems involving weight reduction through the use of fully integrated or hybrid circuitry should be

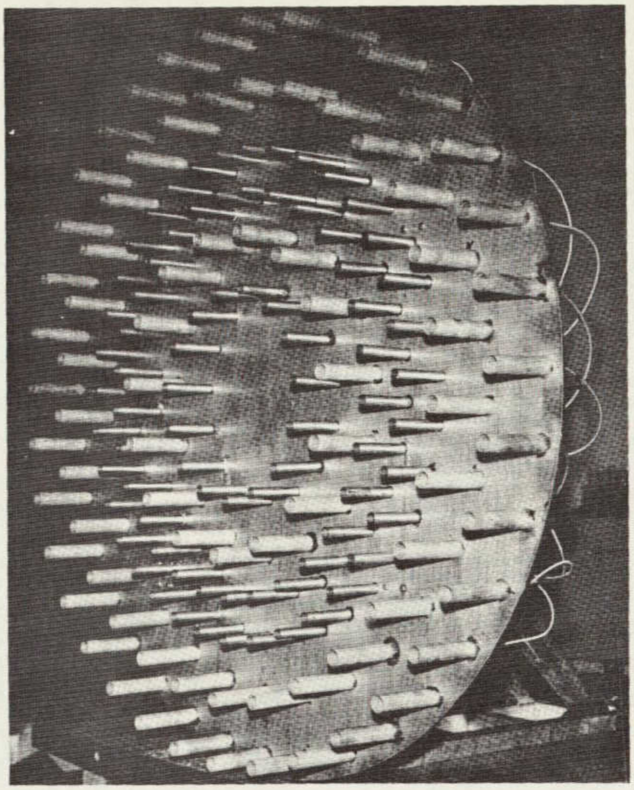

Figure 8-7. A 158-Helical Element Phased Array - Transmit and Receive

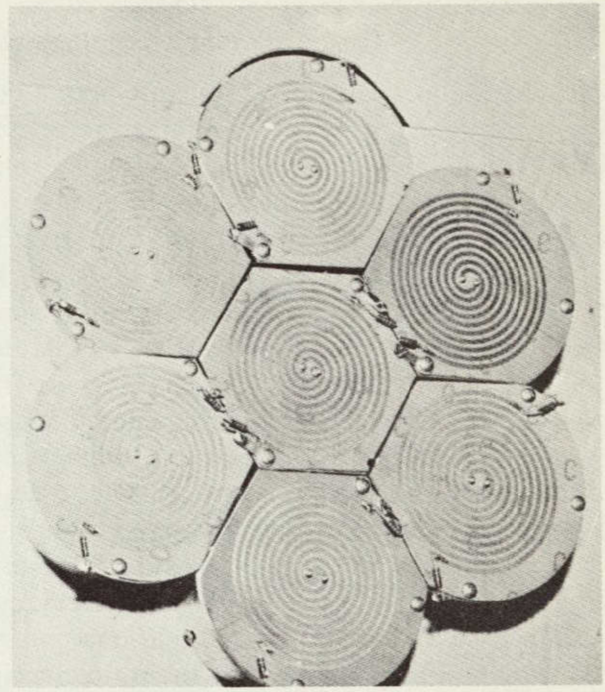

Figure 8-8. A 7-Element Sub-Array of Cavity-Backed Spiral Antennas

such that the performance is not compromised by the reduction in weight and size. Consequently, technology contracts in the redirective phased array antenna area would serve to expedite the eventual utilization of these systems for TV Broadcast Satellite missions.

Two main areas of additional effort are required, structural and electrical. Large antenna deployment and erection techniques need to be investigated and engineering models need to be built to justify the approaches. Efficiency limitations of the presently available output devices and the effect on antenna system efficiency should be established. Suitable redirective array circuitry, using current miniaturization techniques, should be designed. Partial arrays with the best state-of-the-art components should be built and the system performance then evaluated.

One major impact of the redirective electronically-steerable phased array upon satellite cost and weight is by way of its effect on the attitude control system requirements. By using such a phased array, it is possible that the attitude control subsystem accuracy requirement might be relaxed, for example, from ±0.5 degree to ±5 degrees. The electronically steerable array may improve the performance of the satellite system because of its inertialess beam-steering. Thus, with a phased array, there would be a minimum interaction between the antenna subsystem and the attitude control subsystem, and overall system performance could be enhanced.

8.2.12 FLEXIBLE BODY AND ATTITUDE CONTROL INTERACTION

8.2.12.1 General Capability

Mission requirements for larger, more complex spacecraft (which are representative of medium and high power broadcast satellites) have already introduced many new structural concepts and unusual vehicle configurations. Inflatable and erectable structures are being developed. All of these large flexible structures have little of their total mass allotted for structural stiffness which is not required in the relatively mild space environment.

The complete analytical description of space vehicle motion involves the highly nonlinear coupling of rigid body motions with flexible spacecraft deflections. The motion of any vehicle in flight is best described by nonlinear equations; however, the linear approximations to these equations have been adequate for design purposes in the past. Linear approximations are valid as long as: a) the structure behaves in a linear manner, and b) the Euler cross-coupling terms are negligible. However, for very large, very flexible spacecraft, these nonlinear (i.e., Euler cross-coupling) terms are not negligible and, in fact, sometimes predominate over the first-order terms. Flexible appendages, such as long rods and hinged members which are usually erected in space, generally exhibit low natural frequencies which may lie within the attitude control filter bandwidth, resulting in command errors to the controller. Therefore, in any dynamic analysis of flexible spacecraft, the interaction of the structure and the attitude control system is of paramount importance in both the structural and control system designs.

The fact that the equations of motion cannot always be linearized and that the control-structural interaction problem becomes very important precludes exclusive use of the highly-developed frequency domain solutions used so successfully in the past in control design and in the solution of control-structural interaction problems. The application of time domain solutions appears to be the only feasible alternative at the present time. It has been the primary goal of both the current in-house projects at GE and the GE contract with NASA MSFC (NAS 8-21043) on flexible vehicle dynamics to obtain solutions in the time domain. A secondary purpose is to establish criteria for determining where frequency domain solutions can be employed advantageously.

The nature of this broad-based attack on the dynamics of spacecraft dictates that it cannot be done from the parochial view of only a control dynamicist, structural dynamicist, or trajectory analyst; but it must be performed at the systems level where every discipline must contribute and interact to solve the engineering problems associated with the total space vehicle system.

Work at General Electric, over a period of about three years, has led to the formulation of equations of motion of a collection of bodies related to a rotating space frame, coupled through structural constraints, and capable of being forced or monitored at any coordinate.

Computing systems to perform the evaluation of system performance have been developed for use on the IBM 7094 and have been used in analysis of control system/structure studies on the ATS-4, a flight experiment study for NASA MSFC, some cable studies, and an analysis performed for ATS-2.

Programming of computing capability suitable for the UNIVAC is presently under way under contract to NASA MSFC (addendum to contract NAS 8-21043).

8.2.12.2 Major Problems

The major problem is the application of the available analytical tools to a total spacecraft design, such as a broadcast satellite system, and then the verification of the analysis with a test program.

Although both the analytical and computational tools are available, experience in application to given mission requirements is lacking; therefore, the procedures cannot be considered operational. To achieve this status requires application to specific real problems and verification by test.

8.2.12.3 Currently Funded Effort

The General Electric Company is currently funding programs to evaluate the effects of flexibility on spin-stabilized motion, and the parametric evaluation of the cross-product coupling effects of vehicle parameters.

A programming effort to develop a system, comparable or superior to the IBM 7049 system in use at GE, for computation of the motion response using UNIVAC is in progress under contract to NASA MSFC.

Most aerospace companies are expending some level of effort on the problem of flexible structure/attitude control interaction. However, the above programming effort represents the only known contractual effort on the general analysis of the problem.

8.2.12.4 Additional Effort Required

Most of the effort to date has been directed to the manipulation of structural analysis into a form in which it is compatible with control system analysis so that the flexible motion of the coordinates can be monitored. Figure 8-9 illustrates the nature of the problem. The purpose of a control system is to maintain the orientation of the vehicle constant with respect to inertial space or some other reference frame. This is ordinarily accomplished by sensing the position of the body axis with attitude sensors at point "a" and by firing thrusters at points "b" and "c." The magnitude of the thrust at each point is T. Due to deformation of the connecting member (shown between the larger and smaller bodies) when the thrusters are energized, the attitude sensor indicates a pointing error of ϵ even though the body axis has a true pointing error of β. This would result in an incorrect error signal being fed back to the control system unless the sensor coordinate relative to the body axis were to be monitored and used to correct the error feedback signal.

A form of analysis which allows evaluation and selection of overall spacecraft candidate configurations on the basis of controllability and flexibility has been developed. This is in addition to tools for detailed performance analysis.

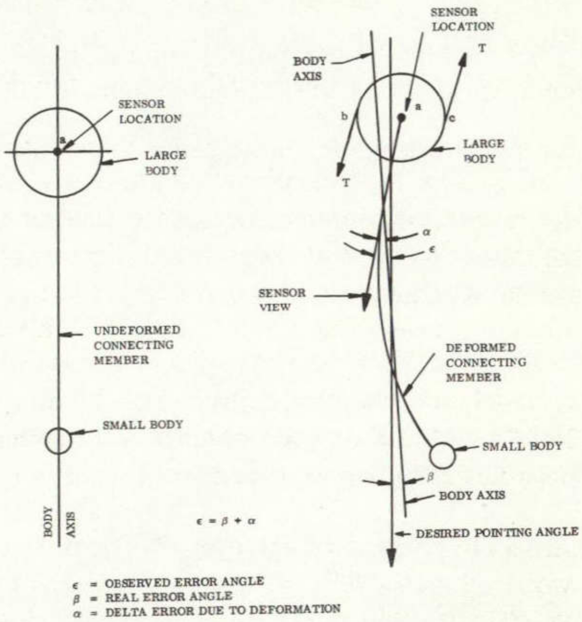

Figure 8-9. Effects of Flexible Body Motion on Pointing Error Signals

Various analytical and computational tools for detailed performance analysis are available. To achieve an engineering design capability, an effort is needed primarily to select and evaluate specific useful applications and then to exercise the system and bring the tools to an operational status. Flexible structure modes of vibration must be studied and the structure must be defined to adequately assess problems arising in solar array deployment, articulation and manufacture, antenna beam shaping, beam pointing, deployment and erection, and in attitude control and station keeping. Interactions of large flexible structure with its space environment and with an active attitude control system should be further investigated to avoid degradation of control accuracy and functional performance. A small number of configurations representative of deformation mode shapes should be analyzed over suitable ranges of sizes and frequencies in order to facilitate the selection of flight vehicle configurations, evolve design criteria, and evaluate the feasibility of actual final designs.

The steps to be taken as an initial effort should be the selection of a vehicle configuration for a typical broadcast satellite mission. Station-keeping requirements (representative of the largest disturbance) should then be defined. A structural synthesis, which would permit parametric variations, should be performed for the broadcast satellite chosen. From an evaluation of the parametric variations, the location, the size and the on-time of the thruster engine should be determined. The open loop responses of the vehicle due to the propulsion jets or other internal (e.g., articulation of an array) or external (e.g., solar pressure, meteorite impact) excitations should also be examined. Tradeoff criteria should be developed for acceptable antenna beam shape and beam pointing using closed-loop attitude control analysis. Finally, through parametric variations of attitude control and structure, fixes for obtaining satisfactory performance should be specified.

The scope of a follow-on verification test program and whether a ground or space experiment is warranted will depend upon the complexity and flexibility of the system configuration selected and the success of the analytical program.

8.2.13 THERMAL CONTROL

8.2.13.1 General Capability

The thermal control systems considered for cooling high-power transmitter tubes are heat pipes and active fluid loops. Heat pipes have been selected as the better approach due to their inherently higher reliability and operation without electrical power.

Heat pipes have been flight proven thus far on two occasions. An experiment of short duration was orbited on the Agena booster used for the ATS/A launch. This heat pipe was made from stainless steel and used water as a working fluid. Two heat pipes have been operating aboard the GEOS/B satellite for several months with no apparent degradation. They are made of aluminum and use freon for the working fluid. Two more heat pipes are to be used to cool a traveling wave tube (TWT) aboard the 1969 Mariner launch.

Ground-operated heat pipes have been used over a broad range of temperatures and power levels. One heat pipe test in conjunction with a heater simulating a GE L-64SA triode has demonstrated cooling to 500°C at dissipated power levels in excess of 2.5 kW.

In another test, a heat pipe radiator has been employed to cool first a simulated traveling wave tube to 280°C at a dissipated power level of 1.5 kW, and then the TWT itself to below 200°C with 960 watts dissipated. Both systems were built and tested at General Electric.

A simplified schematic diagram illustrating the basic principle of operation of a heat pipe is shown in Figure 8-10.

8.2.13.2 Major Problems

The major problems identified in the design of a heat-pipe thermal control system for broadcast satellites involve a lack of specific information on evaporator capability and the potential problems associated with the electrical and mechanical interfaces between the heat pipe and the heat dissipating elements of klystrons, traveling wave tubes, crossed field amplifiers, and gridded tubes. If the devices to be cooled have extremely high heat fluxes, more detailed data will be required concerning evaporator capacity and design. This data is currently available only for pool boiling and a few specific wicking configurations. More information is also required to identify possible problem areas at the electro-mechanical interface between the heat pipe and the device or tube to be cooled. These problem areas may include the effect of launch load environment on the heat

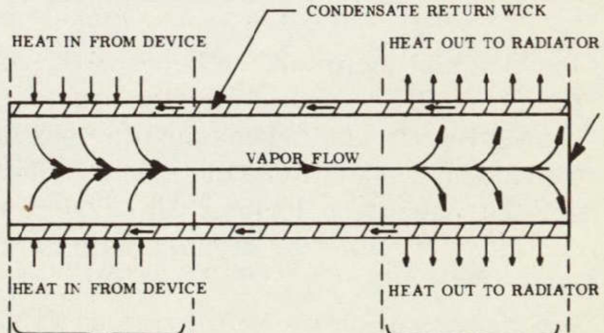

Figure 8-10. Heat Pipe Operation Schematic

pipe/device interface, and the possible problem of electrical isolation. Two plausible approaches to the latter problem are the use of insulating heat pipes, and the use of ceramic insulators inside or outside the device. Another possible approach (which may not always be achievable because of tube design limitations) is to operate the high thermal-dissipating tube elements at voltages close to ground potential wherever possible.

8.2.13.3 Currently Funded Effort

The major funded efforts in the area of thermal design for microwave tubes are being performed as parts of several microwave tube development contracts funded by NASA (NAS 1-7497, Varian; NAS 3-9719, Hughes; NAS 3-11513, Litton; NAS 3-11514, GE; NAS 3-11515, Litton; NAS 3-11516, SFD; and NAS 13-565, GE). Most of these contracts are primarily output-device design studies, but all have taken thermal control into consideration and all have used heat pipes as the primary means of heat transport. The NASA, ERC contract (NAS 12-565) has resulted in the successful cooling of a TWT by means of a heat-pipe radiator and the investigation of cooling techniques for other tubes. The final reports of all of these studies are due to be published early in 1969.

8.2.13.4 Additional Effort Required

Future work in the area of heat-pipe design should be directed toward optimization of the evaporator. Present designs have evaporators capable of up to 300 $W/in.^2$. Above this power density (at a level referred to as the critical or burn-out heat flux), the wick dries out, and heat transfer through the heat pipe drops abruptly, causing a sudden drastic rise in evaporator temperature. In a tube where the power density is well below 300 $W/in.^2$, there is no problem. In many devices, however, power density can be several times this maximum, requiring thermal conduction paths to spread out the dissipated heat to an acceptable density. Since it is proportional to the power density, the temperature drop through these conduction paths is high, resulting in a reduced radiator temperature which requires more radiator area and weight.

By developing an evaporator with a burn-out heat flux considerably above presently used levels, the heat pipe can be brought much nearer the heat source, thus increasing the temperature at which the radiator can be allowed to operate. The higher the operating temperature of the radiator, the more effective its cooling ability.

Problems at the interface between the output device and the thermal control system are encountered due to several design requirements. Mechanical alignment may require flexible connections to avoid damaging the tube during either installation, launch vibration or thermal expansion. In addition, electrical isolation of high potentials is required by some high-power transmitter devices. A ceramic material, such as beryllia, has a high thermal conductivity (of the order of aluminum) as well as good electrical insulation properties.

8.2.14 GROUND RECEIVING SYSTEMS

8.2.14.1 General Capability

The TV ground installation considered for the broadcast satellite's missions consists of equipment which must be added to the conventional TV receiver to permit it to receive a signal from a broadcast satellite. This installation will normally consist of an antenna and a converter (frequency or modulation or both). The ground installations constitute a critical technology area because future improvements could permit:

1. Reduction in required satellite transmitted (and hence prime) power by:

    a. Use of wideband (e.g., FM) modulation techniques.

    b. Operation at frequencies where low ambient noise is attainable.

    c. Use of relatively large ground antenna apertures.

2. Improved spectral availability by permitting operation in spectral regions where more frequency bandwidth is available.

3. Low total system implementation costs where the ground equipments can be fabricated and installed at very low costs.

Both antennas and converters exist or can readily be designed which will easily meet all broadcast satellite performance requirements. However, these are high quality commercial and military equipments which cost much more than can be considered for home installations. In addition, low-cost commercial UHF TV antennas with gains of up to 20 dB can be bought quite cheaply; however, these are linearly (rather than circularly) polarized, and there are no low-cost antennas available at the higher (S-band and X-band) frequencies.

By 1971, it is anticipated that advances in the state of the art in components and circuits will have made the production of low-cost converters and antennas somewhat less difficult. However, studies aimed specifically at the broadcast satellite requirements are required to attain this anticipated state of the art since the electronics industry presently has no strong motivation to design such equipment.

8.2.14.2 Major Problems

TV signal converters are devices which convert a satellite signal from some different frequency and/or modulation to an AM vestigial sideband signal frequency suitable for a conventional TV receiver.

The major problem in TV converter technology is economic, i.e., the question of whether a converter can be built at an acceptable cost. The converter cost is an important consideration in most broadcast satellite services. However, for those services where the audience size is extremely large, the total cost of adding converters may be so high as to become the predominant economic factor in the system. No such converters have been built because of lack of demand, and for the same reason the problem has been given relatively little attention by the industry. The cost of the ground antenna also promises to be quite important where large audiences are involved.

8.2.14.3 Currently Funded Effort

An investigation of the ground converter has been initiated by NASA, LeRC under Contract NAS 3-11520 to GE. This is a study in two phases, with the purpose of determining the feasibility and cost of representative TV converters. The first phase will investigate all appropriate techniques, screen them to obtain the most promising, with respect to performance and cost, and provide designs and cost estimates for representative converters. During the second phase the selected types of converters will be designed, fabricated, demonstrated and delivered. Specific converters, illustrative of the configurations most likely to be preferred, were selected by NASA for this investigation. These are:

1. 2.25 GHz - AM

2. 2.25 GHz - FM, modulation index of 2

3. 12.00 GHz - FM, modulation index of 3

An antenna investigation was conducted at GE (as part of this broadcast satellite study) which involved designing and building a 10 foot paraboloid (Figure 8-11) with a gain of approximately 24 dB at 860 MHz, and preparing estimates of the cost of such an antenna if manufactored in quantity. This study indicated factory costs of the order of $50 per antenna in quantities of 5,000. So far as is known, this is the only investigation of the ground antenna problem which has been conducted to date.

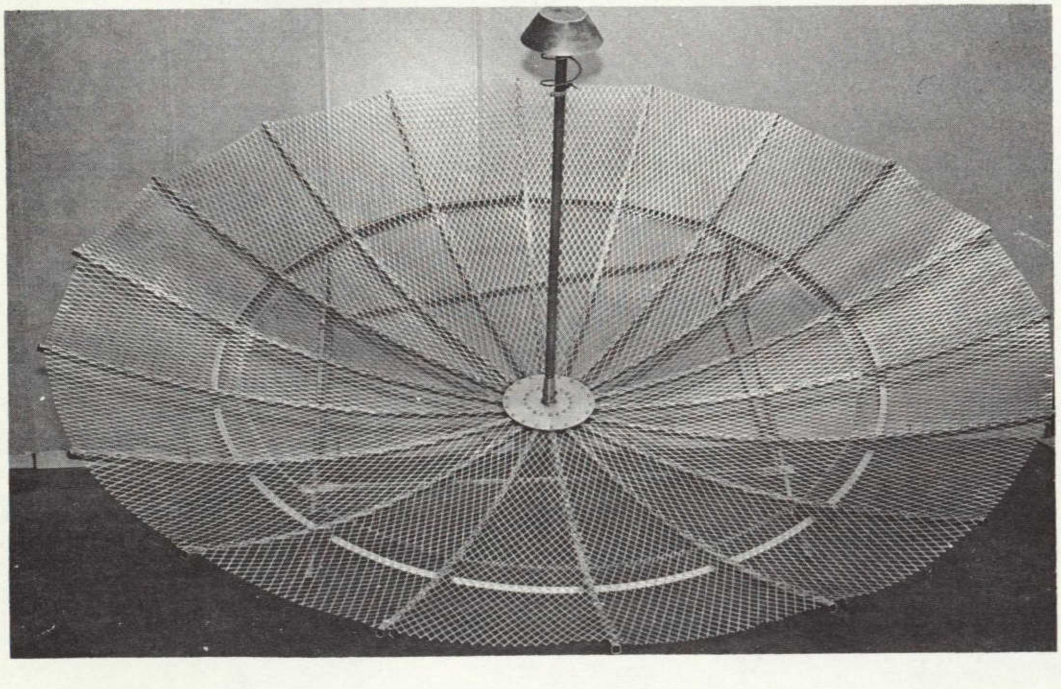

Figure 8-11. Ten-Foot Paraboloid Antenna for Ground Reception of UHF Television from a Broadcast Satellite or the ATS-G Satellite

8.2.14.4 Additional Effort Required

The present converter program (NAS 3-11520) is an appropriate response to the needs of the converter technology area. However, certain additional efforts are desirable. These are:

1. Investigation of low cost threshold reduction techniques

2. Consideration of ultra-high frequencies in the 700 to 900 MHz range

3. Cost sensitivity to antenna performance improvements

It is recommended that consideration be given to a study of low cost antenna design across the 1 to 12 GHz frequency range and for gains of 20 to 35 dB. This study should include examination of alternate design approaches in terms of performance and cost parameters, design and test of developmental prototype antennas across the range of frequency and gain, and examination of the compatibility of the antenna with the ground converter.

Some consideration should also be given to the question of the convenience of high-gain antennas for home installation. A 25-dB paraboloidal antenna at 1 GHz, for example, is almost 10 feet in diameter, a size which might be unacceptable to the homeowner for a home installation in an urban or suburban area. Alternate approaches to the problem of obtaining equivalent apertures with physically smaller antenna configurations should, therefore, be considered.

If the need for very narrow receiving beamwidths becomes established for certain broadcast satellite services, electronically self-steerable array antennas may offer a more economical solution than mechanically steerable arrays and, therefore, warrant additional R&D effort.

8.3 SUBSYSTEM TECHNOLOGY PRIORITY LISTING

One of the objectives of the broadcast satellite technology evaluation was to examine the candidate technology development programs previously described and to recommend some order of priority for additional effort required. The purpose of this section is to describe the criteria and the rationale used to rank the technologies discussed in Section 8.2 and to present the results of this evaluation.

8.3.1 RANKING CRITERIA EMPLOYED

The primary criteria used to rank the technologies were the estimated impacts that the particular candidate technology would have upon each of the following factors:

1. System cost
2. System weight
3. System performance and long life reliability (system feasibility)
4. Subsystem feasibility
5. Development risk
6. Lead time

It should be noted that not all six criteria were applicable to all candidate technology programs.

Cost may be analyzed in two basic ways: first, the impact on system cost using sensitivity models, and second, the cost of the development program. Obviously, a technology for which the system cost impact is a maximum and development cost is a minimum is a high priority candidate.

Feasibility can be interpreted in two basic ways, technical and economic. Although a fundamental requirement of any TVBS system is that it be at least economically competitive with its equivalent TV terrestrial system, technical feasibility was considered more significant than economic feasibility for ranking purposes.

Development risk refers to the estimated probability of successfully achieving the improvements identified for a technology once an adequate development program is begun.

Lead time is an important criterion particularly for those technologies, such as high power space transmitter tubes, where long development cycles have been historically required.

The lines of demarcation between each of these six criteria are not always clear-cut. These are many interdependent aspects involved in the application of these criteria. For example, system weight, performance, and long life can, in a sense, each be considered to have a system cost impact. Reduction in the weight of any subsystem could result in a cost saving (e.g., smaller booster requirement). Alternatively, this weight might be diverted into the addition of improved performance features. A performance improvement, on the other hand, might conceivably result in a cost saving, or might bring about greater accuracy, better ground reception, or greater variety or flexibility of operation without effecting any cost saving. Long system life reflects itself in a cost saving because fewer broadcast satellites would have to be launched within any given number of years in order to maintain continuity of TV service.

It should also be noted that system weight and volume considerations often dictate whether a technology presents a feasibility, cost, performance, or long life reliability problem. For example, if weight and volume were not constraints, one could build a solar array deployment mechanism for large arrays by making the structural elements of the mechanism very rigid, thick and strong and, coincidentally, very heavy. The realistic limitations imposed upon the spacecraft weight by available boosters, however, force the designer to seek a lighter weight solution, the feasibility of which may still be uncertain. Thus, additional effort should be applied to such a technology in order to establish its feasibility.

Development risk and lead time may also be interdependent criteria. Occasionally, a decision that a particular R&D effort involves a significant development risk is a function of the date on which the improved technology is needed. If a short development cycle is necessary, the attendant risk may be high; conversely, if there is sufficient lead time before the technology state of the art needs to be improved, then the development risk may be relatively small.

8.3.2 PRIMARY MEASURES IN CRITERIA APPLICATION

In applying each ranking criterion, some measures must be employed to assess the magnitude of the effect for each candidate technology. Among these measures are:

1. Qualitative engineering judgment
2. Calendar time or schedule
3. Subsystem sensitivity models for cost and weight
4. Vehicle weight or power

The use of subjective engineering judgement in applying the various ranking criteria is necessitated by the fact that only estimates and predictions of future potential impact upon the system are available for the ranking procedure. Calendar time refers to the time period (e.g., early 1970's, mid-1970's, etc.) when the different types and sizes of broadcast satellite vehicles are estimated to be ready for launch. Thus, the criticalness of each technology was assessed in terms of when it might be needed for a broadcast satellite mission. In connection with this measure, three selected power ranges (low, medium, and high) were established (see Table 8-9) to be representative of the range of broadcast satellites in the next decade. Each critical technology was evaluated at each of these three power levels. It should be noted that, in some cases, although a technology might be considered critical for use in a high-power broadcast satellite application, it might not be a critical item for the low-power satellite, and vice versa.

The results of the subsystem sensitivity computer models developed during the study are presented in Figures 8-12 through 8-15 which illustrate the percentages of total system weight and total fabrication cost attributable to each major subsystem. These percentages are plotted as functions of total system weights or costs as applicable. The subsystems with the most significant effects are identified in Table 8-10.

Table 8-9. Satellite Categories for Technology Ranking

Broadcast Satellite Solar Array Power Range (kW)		Approximate Satellite Weight Range (lb)	Estimated Satellite Fabrication Cost Range ($ M)	Estimated Launch Date
Low Power	1 to 3	600 to 1000	2.7 to 5.5	Early 1970's
Medium Power	3 to 10	1000 to 2500	5.5 to 13.6	Mid-1970's
High Power	10 to 30	2500 to 6000	13.6 to 32.0	Late 1970's

Table 8-10. Major Subsystem Impac
(From Subsystem Sensitivity Model

Satellite Solar Array Power	System Weight Impact	System Fabrication Cost Impact
Low Power (1 to 3 kW)	Power S/S Structure Large Antenna (>15 feet) Attitude Control Transmitter	Power S/S Attitude Control Transmitter
Medium Power (3 to 10 kW)	Power S/S Structure Large Antenna (>15 feet) Transmitter Thermal	Power S/S Transmitter
High Power (10 to 30 kW)	Power S/S Structure Thermal Transmitter	Power S/S Transmitter

Table 8-11 indicates criteria applicable to each technology for the three assumed solar array power ranges. In this table, an asterisk (*) in any column indicates that no major problems are anticipated for this system category. Any N/A entry in a column signifies that the technology is not likely to be used for that generation of satellites.

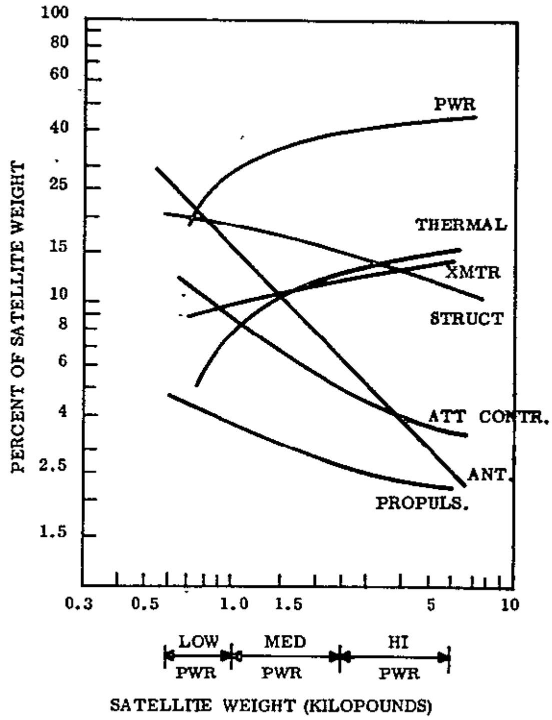

Figure 8-12. TVBS Subsystem Weight Sensitivity at UHF (0.8 GHz)

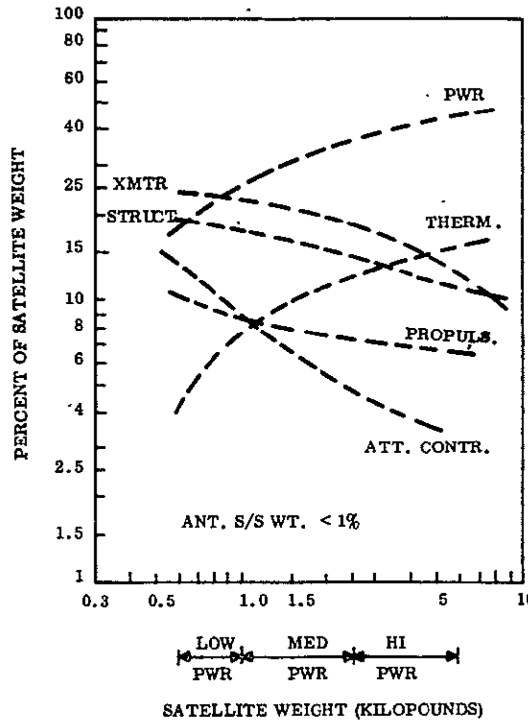

Figure 8-13. TVBS Subsystem Weight Sensitivity at X-Band (12.2 GHz)

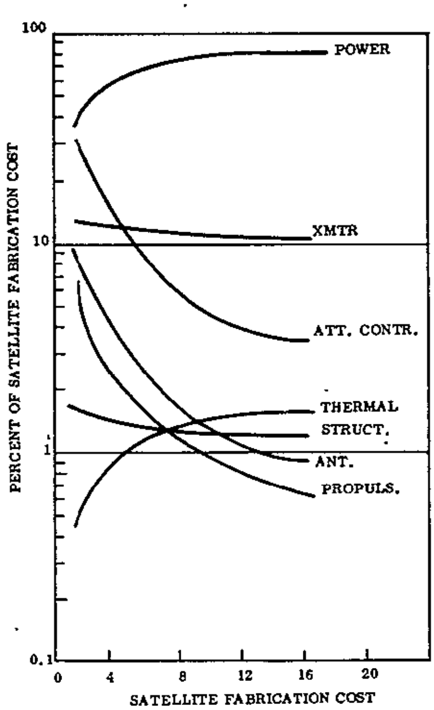

Figure 8-14. TVBS Subsystem Fabrication Cost Sensitivity for UHF (0.8 GHz)

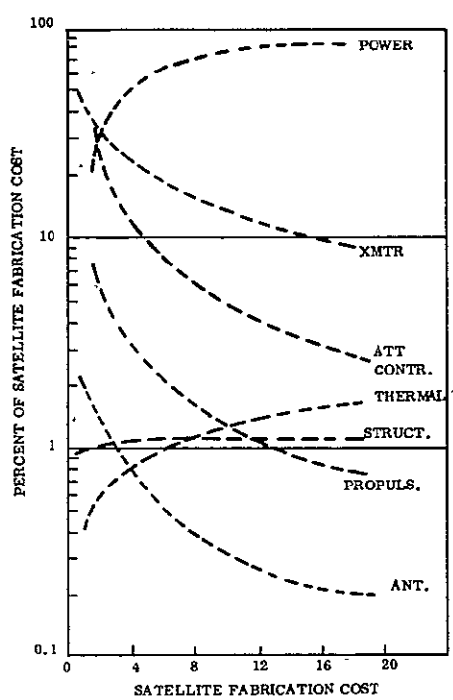

Figure 8-15. TVBS Subsystem Fabrication Cost Sensitivity for X-Band (12.2 GHz)

Table 8-11. Ranking Criteria Applicability
(not in priority order)

Sub-System	Critical Technology	Approximate Launch Date / Solar Array Power	Broadcast Satellite System Categories: Early 1970's 1 to 3 kW	Mid-1970's 3 to 10 kW	Late 1970's 10 to 30 kW
Power	Solar array deployment		*	*	C
Power	2-axis solar array drive		*	D	D
Power	Solar cell and array manufacture		N/A	N/A	A, D
Power	High voltage solar array		C, D	C, D	C, D, E
Power	High power dc rotary joint		C, D	C, D	C, D, E
Power	High voltage power conditioning		B, C, D	A, B, C, D	A, B, C, D, E
Power	High voltage handling		C, D	C, D	C, D, E
Transmitter	High efficiency gridded tubes		A, B, D	A, B, D	A, B, D
Transmitter	UHF transmitter circuits		A, B, D	A, B, D	A, B, D
Transmitter	High efficiency microwave tubes		A, B, D, F	A, B, D	A, B, D
Transmitter	Microwave tube transmitter circuits		A, B, D	A, B, D	A, B, D
Transmitter	High power RF components		B, D	B, D	B, D
	High power RF rotary joint		D	C, D	C, D, E
Antenna	Reflector antenna power handling		C, D	C, D	C, D, E
Antenna	Reflector antenna beam pointing		C, D	C, D	C, D
Antenna	Reflector multi-beam antenna		B, D	B, C, D	C, D, E
Antenna	Mechanically steerable antenna array		N/A	B, C, D	C, D
Antenna	Electronically steerable antenna array		N/A	N/A	C, D, E
Struct	Attitude control of flexible structures		N/A	A, B, F	A, B, C, D, E
Thermal	Heat pipes		D	D	A, D
Thermal	Thermal control interfaces with transmitter tubes		C, D	C, D	C, D
Ground Rec.	Ground receiving systems		A, B	A, B	A, B

Legend

A – System cost
B – System weight
C – Subsystem feasibility
D – System performance and long life reliability
E – Development risk
F – Lead time
N/A – Technology not applicable
* – Not a technology program

8.3.3 PRIORITY LISTING

Table 8-12 is a listing of the critical broadcast satellite technologies in descending order of priority. The final order was arrived at by a combination of assessing the state of the art, applying the six ranking criteria, employing best engineering judgement, and evaluating the overall criticalness of each technology to the broadcast satellite program over the next decade. Differences in priority among the items in any one category are considered to be relatively small, whereas major priority differences exist between the first, second, and third priority categories for each generation satellite.

It should be noted that the 22 technologies on the list were selected as the most critical ones from a larger potential candidate list during the course of the broadcast satellite study. Thus, all the items shown in Table 8-12 should be considered technologies to which additional R&D effort should be applied.

Table 8-12. TVBS Subsystem Technology Priority List

Priority Category \ Satellite Class	Low Solar Array Power (1-3 kW; early 1970's)	Medium Solar Array Power (3-10 kW; mid 1970's)	High Solar Array Power (10-30 kW; late 1970's)
First	High Efficiency Microwave Tube Ground Receiving Systems High Voltage Power Conditioning High Efficiency Gridded Tube UHF Transmitter Circuits	High Efficiency Microwave Tube Ground Receiving Systems High Voltage Power Conditioning Attitude Control of Flexible Structures Solar Array Deployment High Efficiency Gridded Tube UHF Transmitter Circuits	Attitude Control of Flexible Structures High Efficiency Microwave Tube Ground Receiving Systems High Voltage Power Conditioning Solar Array Deployment High Efficiency Gridded Tube UHF Transmitter Circuits High Voltage Handling High Voltage Solar Array Thermal-Transmitter Interface
Second	Solar Array Deployment High Voltage Handling Thermal-Transmitter Interface Heat Pipes DC Rotary Joint RF Rotary Joint	High Voltage Handling Thermal-Transmitter Interface Heat Pipes DC Rotary Joint RF Rotary Joint High Voltage Solar Array High Power RF Components 2-Axis Solar Array Drive	Heat Pipes DC Rotary Joint RF Rotary Joint High Power RF Components 2-Axis Solar Array Drive Solar Cell and Array Manufacture Reflector Antenna Power Handling Reflector Antenna Beam Pointing Reflector Antenna Multi-Beams Microwave Transmitter Circuits
Third	High Voltage Solar Array High Power RF Components Reflector Antenna Power Handling Reflector Antenna Beam Pointing Reflector Antenna Multi-Beams Microwave Transmitter Circuits	Reflector Antenna Power Handling Reflector Antenna Beam Pointing Reflector Antenna Multi-Beams Microwave Transmitter Circuits Mechanically Steerable Antenna Array	Mechanically Steerable Antenna Array Electronically Steerable Antenna Array

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