NASA CR-72510
TRW NO. 08848-6002-R0-00

TELEVISION BROADCAST SATELLITE STUDY

by

J. Jansen, P.L. Jordan, et al.
TRW SYSTEMS GROUP

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Lewis Research Center

Contract NAS 3-9707
Robert E. Alexovich, Project Manager

Requests for copies of this report should be referred to

National Aeronautics and Space Administration
Scientific and Technical Information Facility
P.O. Box 33
College Park, Md. 20740

NASA CR-72510
TRW NO. 08848-6002-R0-00

TELEVISION BROADCAST SATELLITE STUDY

by

J. Jansen, P.L. Jordan, et al.
TRW SYSTEMS GROUP

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Lewis Research Center

Contract NAS 3-9707
Robert E. Alexovich, Project Manager

NASA CR-72510
TRW No. 08848-6002-R0-00

FINAL REPORT

TELEVISION BROADCAST SATELLITE STUDY

by
J. Jansen, P. L. Jordan, et al.

TRW Systems Group
One Space Park
Redondo Beach, California 90278

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

October 24, 1969

CONTRACT NAS 3-9707

NASA Lewis Research Center
Cleveland, Ohio

Robert E. Alexovich, Project Manager

ABSTRACT

The report discusses the various technical aspects relevant to development and design of television broadcast satellites and the user equipment for receiving satellite broadcasts. Three satellite configurations are outlined. Parametric cost data versus overall system performance are presented. Potential audiences are identified and benefits to education are discussed. Required development is identified.

CONTENTS

CONTENTS (Contents)

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

TABLES (Continued)

TABLES (Continued)

TABLES (Continued)

TABLES (Continued)

TABLES (Continued)

TABLES (Continued)

1. INTRODUCTION

This report presents the results of a study of the technological and cost factors affecting the feasibility of Television Broadcast Satellites in the 1975-1980 time period.

The television broadcast satellite services considered in the study were defined by the following guidelines and constraints:

- Launch vehicles of the Atlas and Titan class
- Synchronous, equatorial orbit
- Five-year minimum spacecraft life
- No broadcasting during eclipse.
- Spacecraft ERP between 50 and 75 dbw
- Amplitude modulation and frequency modulation
- Quality consistent with FCC standards and good engineering practice
- Efficient spectrum utilization
- Minimize interference with terrestrial services
- Spacecraft repeater capability of handling most TV standards, color and monochrome, is desirable.

Preliminary design of three spacecraft configurations was performed during the study to provide a realistic background to comparative evaluation of alternative subsystem configurations. Subsystem analyses were conducted with emphasis on providing a basis for evaluation of technology and definition of required research and additional development.

Parametric data on overall system performance and cost were determined through analyses in the areas of communication performance, satellite costs, and earth receiver performance and cost.

Effectiveness and audience analyses were conducted to determine potential audiences and the benefits of television broadcast services for culture and education.

2. COMMUNICATIONS PERFORMANCE

The ultimate objective for the design of a television broadcast satellite service is to provide the required quality by the most economical system. Quality of picture and sound is a subjective concept, since it is a measure of the degree to which deficiencies in the received signals are experienced by the viewers. The relation between this subjective quality and measurable signal deficiencies is, of course, an issue of vital importance to economic implementation of the service.

Both amplitude modulation with vestigial sideband (AM-VSB) and frequency modulation (FM) are considered for transmission of the video signal. For FM, appropriate choice of the frequency deviation leads to minimum power requirements.

The design objectives must be met within the constraints of spectrum availability and limits on allowable interference between the satellite broadcasting and terrestrial communication services.

These and other issues are examined in this chapter. The topics are:

- Television Standards and Signal Formats
- Picture Quality
- Amplitude Modulation with Vestigial Sideband
- Frequency Modulation
- Sound Channels
- Interference between Communication Services
- Propagation Medium
- Man-made Noise
- Earth-to-Satellite Transmission

2.1 TELEVISION STANDARDS AND SIGNAL FORMATS

Today, at least twelve different television broadcast standards are in use in the world. All these standards were originally established for monochrome broadcasting. Later, a number of methods were developed for expanding the monochrome systems to color systems compatible with the already existing monochrome broadcast facilities and receivers.

This compatibility implies that color receivers can receive monochrome broadcasts, while a monochrome receiver produces a monochrome picture from color broadcasts. A further implication is that color broadcasting uses the RF channel allocations established earlier for monochrome broadcasting. All existing color methods meet these compatibility requirements by adding a chrominance signal to the monochrome luminance signal.

In all standards, the monochrome signal has the general form shown in Figure 2-1. About 70 percent of the video voltage range is used for picture information. The remaining 30 percent is used for blanking and synchronization; any voltage in this range is outside the "black" limit of the picture signal range and therefore causes the flying spot on the picture tube screen to be blanked out, permitting an invisible return of the horizontal or vertical sweep.

Each (horizontal) line sweep, about 64 microseconds long, starts with an 11 to 12 microsecond long blanking interval for invisible return

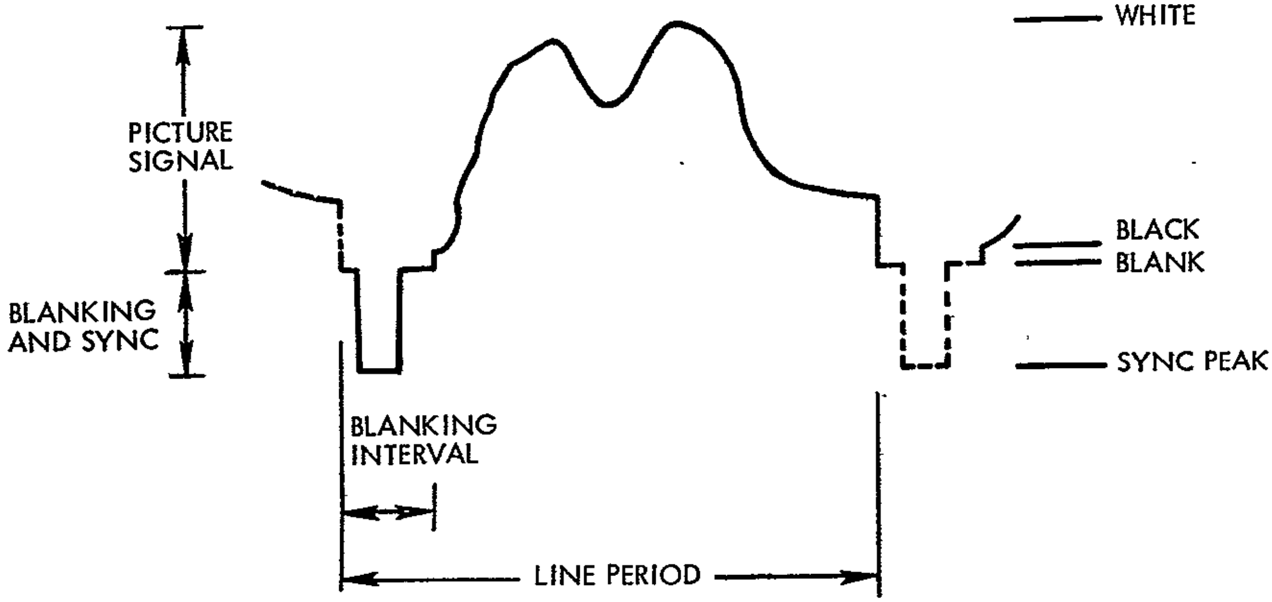


Figure 2-1. Luminance Signal

of the horizontal sweep. A 5 microsecond long synchronization pulse, transmitted in the blanking interval, synchronizes the line start with the received luminance signal. The remaining 52 microseconds are the active line time during which the spot intensity is controlled by the luminance signal.

All existing standards use a 2/1 interlace, in which one field consisting of the odd-numbered horizontal lines is transmitted and displayed on the receiver screen during one vertical sweep, and the field of even-numbered lines during the next vertical sweep. The complete frame, i. e., all lines, consists of two consecutive fields. In each field period, the active vertical sweep is preceded by a blanking interval during which the vertical sweep returns, and pulses for field and line synchronization are transmitted.

Among the compatible color systems, the NTSC system, adopted in the United States, was the first system to be developed and to become operational. In this sytem, the luminance signal Y is

$$Y = 0.30\ R + 0.59 + 0.11\ B$$

where R, G, and B are the video voltages produced by the red, green, and blue camera, respectively. The chrominance signal is a subcarrier consisting of two sinusoids in phase quadrature, amplitude-modulated by the color difference signals B-Y and R-Y, respectively, (see Figure 2-2). The subcarrier is in effect modulated in both amplitude and phase. The phase and amplitude represent the hue and saturation, respectively, of the color. The receiver recovers the two color difference signals by synchronous detection, using a color burst (transmitted during line blanking intervals) as phase reference.

The chrominance signal shares the video band occupied by the luminance signal. The periodicity of the line scan causes the power spectrum of the luminance signal to concentrate about multiples of the line frequency. Similar spectrum concentrations in the sidebands of the color subcarrier are prevented from coinciding with the luminance spectrum peaks by using a color subcarrier frequency equal to an odd multiple of half the line frequency. Thus, intermodulation between luminance and chrominance signals is reduced to tolerable levels.

The major disadvantage of the NTSC system is its sensitivity to phase variations in the transmission. In particular, variation of the subcarrier phase with the luminance signal requires attention, since the color burst used as phase reference in the subcarrier demodulation is transmitted when the luminance signal is at the blanking level, i.e., outside the picture signal range.

The phase sensitivity is reduced in the Phase Alternation Line (PAL) system, which is a variation of the NTSC system. The basic feature of the PAL system is polarity reversal, between consecutive lines, of the color subcarrier component in phase quadrature with the color burst. In effect, the color scale in Figure 2-2 is upside down during every other line, and consequently, a phase error results in opposite deviations of hue in adjacent lines, thus making the color deviations less perceptible.

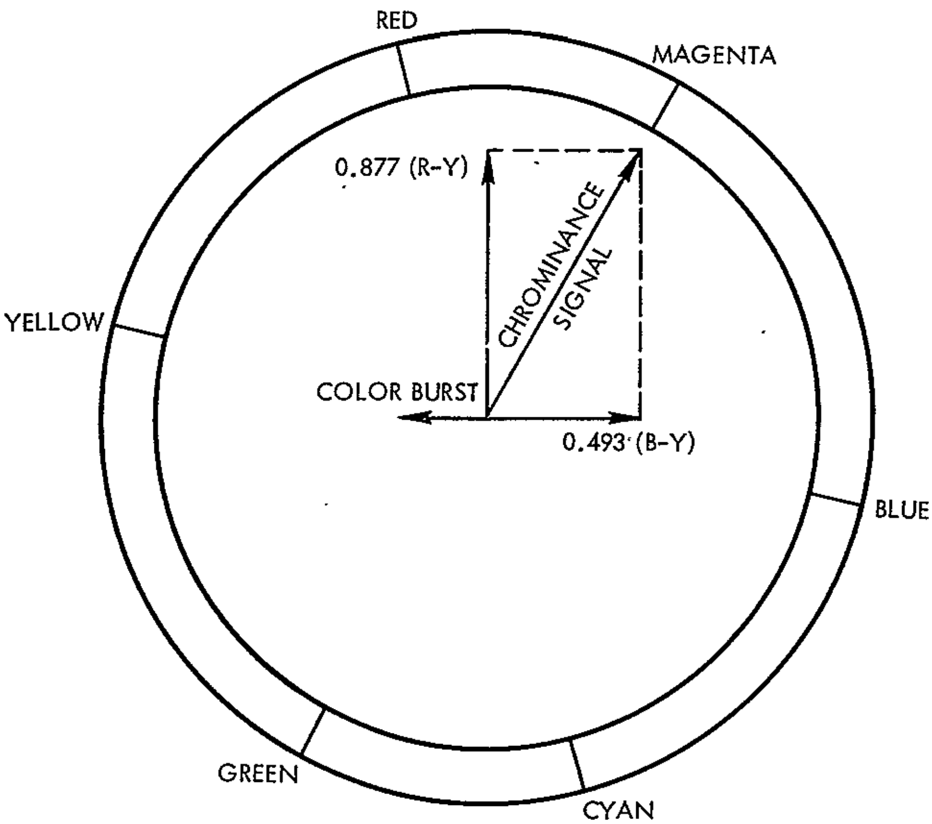


Figure 2-2. Color Subcarrier Modulation in The NTSC System

In the Séquentiel Coleur À Mémoire system, (SECAM III) the color subcarrier is modulated by only one color signal at a time. The color difference signals B-Y and R-Y alternate as modulation in consecutive line periods. The color displayed is derived from the real-time color signal and the color signal received during the preceding line and delayed by one line period in a delay line. The choice of FM for color subcarrier modulation greatly reduces the color sensitivity to phase deviations in the transmission.

Because of the similarity between NTSC and PAL systems, it does not seem inconceivable that a receiver capable of receiving alternatively NTSC and PAL transmissions could be built at little extra cost for the dual-standard capability.

For the design of transmission systems for either NTSC or PAL color television, it is important to note that the maximum peak-to-peak voltage of the color subcarrier alone is relatively large. With color saturations up to 75 percent, which is representative of average pictures, this peak-to-peak voltage varies between zero for white and 95 percent of the blank-to-white voltage range for red and cyan. Further, the composite video signal, i.e., the superposition of luminance and chrominance signals, for red or blue penetrates halfway into the blank-to-sync voltage range. (See Figure 2-1.)

The existing standards use either 405, 525, 625, or 819 lines per frame. The 525-line and 625-line standards are the most important ones, in view of both their total numbers of receivers in the world and present plans for expansion of television broadcast services. Nations that use 405-line or 810-line standards in the VHF TV bands are planning to use 625-line standards for TV broadcast services at UHF.

For these reasons, the present study considers only 525-line and 625-line standards. Table 2-1 shows video signal characteristics for these standards. This table is based on CCIR Recommandations and Reports in Reference 2-1. Some data represent a consensus of existing standards with only slight differences in details. The data shown for 525-line signals refer to the monochrome and color standards used in

Table 2-1. Video Signal Characteristics

Number of lines per frame Nominal video bandwidth		525 4.2 MHZ	625 5.0 MHz	625 5.5 MHz	625 6.0 MHz
Field frequency, fields/sec		60	50	50	50
Line frequency, lines/sec		15,750	15,625	15,625	15,625
Color subcarrier frequency, MHz		3.58	4.43	4.43	4.43
Relative video voltages	White level	0	0	0	0
	Black level		0.65	0.65	0.65
	Blank level, color burst bias	0.714	0.70	0.70	0.70
	Sync pulse top level	1.0	1.0	1.0	1.0
	Color burst amplitude	0.143	0.15	0.15	0.15
Signal component durations, μsec	Line period	63.5	64.0	64.0	64.0
	Line blanking, momochrome	10.8	12.0	12.0	12.0
	Line blanking, color	10.95			
	Line sync pulse, momochrome	4.95	4.7	4.7	4.7
	Line sync pulse, color	4.65			
	Color burst, NTSC	2.2 - 3.4	2.7 - 3.2	2.7 - 3.2	2.7 - 3.2
	Color burst, PAL		2.0 - 2.5	2.0 - 2.5	2.0 - 2.5
Rise times (10-90%) μsec	Blanking signal, monochrome	≤0.64	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4
	Blanking signal, color	≤0.48	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4
	Line sync pulse	≤0.25	0.2 - 0.4	0.2 - 0.4	0.1 - 0.3

Source: CCIR, Documents of the XIth Plenary Assembly, Oslo, 1966, Volume 5, Recommendations 212, 421-1 and 451, Reports 308-1, 309, 310-1, 404, 406 and 407. Single values in table are nominal value or center or range.

the USA and Canada. The data shown for 625-line transmission with a 5.5 MHz video bandwidth represent the 625-line standand established for UHF broadcasting in the United Kingdom. The latter standard is developed primarily for color broadcasting and detailed transmission requirements, including noise limits for the luminance and chrominance channels, have been published in CCIR Recomendation 451. Although its luminance channel bandwidth is limited to 5.0 MHz, the video channel bandwidth is 5.5 MHz in order to accommodate the chrominance channel.

Television broadcasting uses amplitude modulation with vestigial sideband (AM/VSB). Most standards are based on vision modulation with negative polarization, i.e., a larger RF amplitude corresponds to a lower luminance. The RF amplitude reaches its maximum during synchronization pulses and is lowest for the white level of the luminance signal. Only negative modulation is considered in this study, since the future use of positive modulation appears limited.

2.2 PICTURE QUALITY

The commonly used measures of picture noise are discussed. A relationship between the weighted picture signal-to-noise ratio and the carrier-to-noise ratio measured in TASO tests is given. The weighted picture signal-to-noise ratio is related to the subjective quality ratings by viewer panels in TASO tests. Noise limits for the chrominance channel are compared with those for the monochrome luminance channel.

2.2.1 Picture Signal-to-Noise Ratios and Weighting

The picture quality impairment by noise is a direct function of the relative level and spectral distribution of the video noise at the picture tube. A commonly used quality parameter is the picture signal-to-noise ratio (or picture-SNR), defined by

$$\left(\frac{S}{N}\right)_p = \left(\frac{\text{blank-to-white video voltage}}{\text{RMS voltage of video noise}}\right)^2 \qquad (2\text{-}1)$$

Its name, picture-SNR, refers to the fact that it compares the noise voltage with the voltage range of the picture signal. (See Figure 2-1.) In the definition of a similar signal-to-noise ratio, used by AT & T, the signal is the entire video voltage range, including the sync pulse as well. This leads to an approximately 3-db higher figure.

Neither of these definitions is a meaningful measure of the effect of noise on the picture quality as subjectively experienced by viewers, unless qualified by an indication of the video noise spectrum, because noise at the upper end of the video band is less objectional than equal noise power at the lower end. This ambiguity in the picture-SNR is to a large extent eliminated by the concept of weighted noise, defined as video noise measured with a weighting network which represents the spectral perception of noise by an average viewer. The power transfer characteristic of such a filter, used for the American 525-line system, is shown in Figure 2-3. Since noise weighting characteristics are normalized to 0 db at zero frequency, the weighted noise level is lower than the unweighted level.

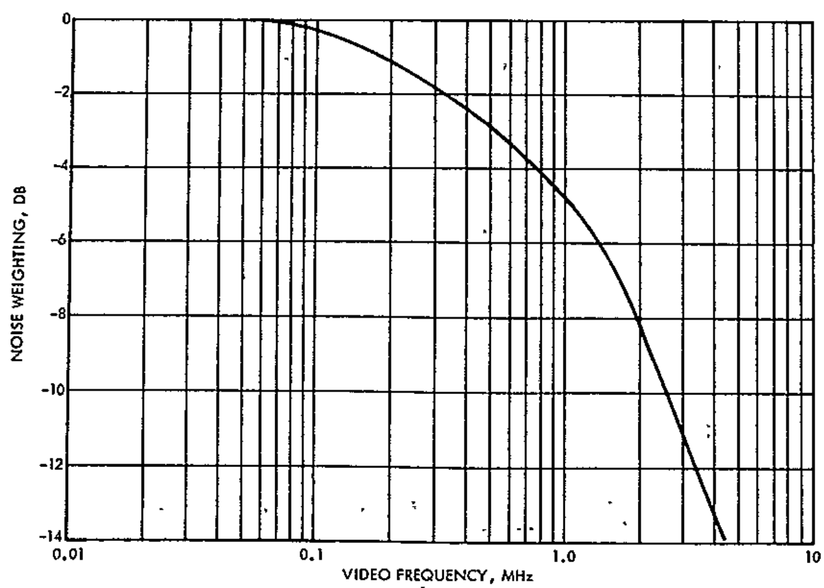


Figure 2-3. Noise Weighting for American 525-Line Television

The definition of picture-SNR based on weighted noise becomes

$$\left(\frac{S}{N}\right)_{p,w} = \left(\frac{\text{blank-to-white video voltage}}{\text{weighted RMS voltage of video noise}}\right)^2 \qquad (2\text{-}2)$$

where the subscript w refers to the weighting. The correlation of this quantity with subjectively graded picture quality is in essence independent of the video noise spectra. The "International Radio Consultative Committee" (CCIR) consistently uses the weighted picture-SNR for specification of noise limits.

The weighting factor, i.e., ratio by which weighting increases the picture-SNR, is:

$$W = 10 \log \frac{\int_0^{B_v} n(f_v)\,df_v}{\int_0^{B_v} n(f_v)\; w\,(f_v')\; df_v} \qquad (2\text{-}3)$$

where B_v = upper frequency limit of video band

f_v = video frequency

$n(f_v)$ = one-sided power spectral density of video noise

$w\,(f_v)$ = power transfer characteristic of the weighting network

While with AM transmission, the video noise spectrum is essentially flat, the power spectral density of video noise in FM systems is proportional to the square of the frequency. Compared with AM, FM shows a shift of noise power distribution to higher video frequencies, where the attenuation in the weighting network is larger. Therefore, the weighting factor for FM is larger than for AM.

Table 2-2 shows values for picture-SNR and weighting factors taken from CCIR Recommendations and Reports (References 2-1, 2-2 and 2-3) and from EIA Standard 250-A (Reference 2-4). The values for 525-line, 4.2 MHz transmission apply to the American NTSC Standard. The 625-line, 5.5 MHz system is system "I" in CCIR Report 308-1 and CCIR Recommendation 451 (Reference 2-1). The video bandwidth is extended to 5.5 MHz in order to accommodate the upper sideband of the modulated color

Table 2-2. Random Video Noise

Number of lines per frame / Nominal video bandwidth			525 / 4.2 MHz	625 / 5.0 MHz	625 / 5.5 MHz	625 / 6.0 MHz
Noise Weighting Factors, db	AM	Monochrome	6.1	8.5	6.5	9.3
		Color, composite video	4.0			
		Color, luminance channel			6.5	
		Color channel			1.5	
	FM	Monochrome	10.2	16.3	12.3	17.8
		Color, composite video	7.0			
		Color, luminance channel			12.3	
		Color channel			1.5	
Camera SNR, monochrome or color, weighted, typical values, db 1)		Image-orthicons	41 - 46			
		Vidicons	46 - 51			
Allowable video SNR, monochrome, weighted, db 1)		Long-distance transmission	56	52	52	57
		Communication satellites		55		
		Line-of-sight radio-relay links	56	52	52	57
Allowable video SNR, color, weighted, db 1)		Composite video	56			
		Luminance channel			52 2)	
		Color channel			46 2)	

1) Picture-SNR, as defined by Equation (2-2)
2) See Section 2.2.4

subcarrier. The luminance channel extends to 5.0 MHz, and luminance noise data apply to this latter bandwidth.

For television transmission by communication satellites, CCIR Recommendation 354 (Reference 2-3) recommends a video bandwidth of 5 MHz and a weighted picture -SNR of 55 db to accommodate monochrome television up to and including 625-line standards. These figures apply to a "hypothetical reference circuit" including modulator, transmitter, one uplink, one satellite, one downlink, receiver, and demodulator. For color television, no recommendation exists, but Report 208-1 (Reference 2-3) suggests that communication satellite systems be designed for 5.5 or 6.0 MHz video bandwidth to accommodate the 4.43 MHz color subcarrier (625-line standards) with its sidebands.

For transmission by line-of-sight relay links, the data shown in Table 2-2 for the 625-line systems apply to the 2500 km hypothetical reference circuit defined in CCIR Recommendations 390 and 421-1 References 2-1 and 2-2). The 56 db shown for the 525-line system applies to a 2500 km long circuit portion but is chosen to meet performance objectives for 6400-km (4000 st. mi.) circuits.

The data on allowable noise shown in Table 2-2 refer to distribution systems and, hence, reflect a better noise performance than achieved in broadcasting; they are listed in the table for reference only. It is important to note that the picture-SNR values recommended by CCIR apply to signal-to-noise ratios derived from noise measurements performed in the absence of signal transmission at a point where proper alignment will result in a given video voltage level (usually 1 volt sync-to-white). Consequently, the picture SNR's recommended by CCIR apply to noise from the long-distance circuit only. Source noise, such as television camera noise, is not included.

2.2.2 TASO Data

Noise performance requirements on broadcast transmissions have in the U. S. been the subject of extensive investigations by the Television Allocations Study Organization (TASO) (Reference 2-5). Viewer panels gave quality ratings to pictures displayed by conventional television sets that received AM/VSB 525-line television transmission from a closed circuit.

RF noise at controlled level was added to the RF signal transmission. These tests provided a correlation between the picture quality as subjectively experienced by viewers and the RF carrier-to-noise ratio at the receiver input. Table 2-3 shows the picture quality grades used by TASO and the carrier-to-noise ratios required to receive the respective grades or better from 75 percent of the test panel viewers.

The TASO noise data differ from the CCIR data in two important aspects. First, the TASO numbers are carrier-to-noise ratios at the RF input of the receiver, while the CCIR data are picture signal-to-noise ratios in a video channel. Second, the TASO numbers are results from tests with both picture transmission and noise present, while the CCIR data refer to noise measurements performed in the absence of signal transmission. The two quantities are different by definition and by measurement method, and are therefore not directly comparable.

2.2.3 Relationship Between Picture Signal-to-Noise Ratios and TASO Data

Unfortunately, adequate data on the correlation between subjectively experienced picture quality and signal-to-noise ratio are not available for FM transmission. The extensive test project required to obtain such data is beyond the scope of the present study. Therefore, the best approach is to convert the carrier-to-noise ratios in TASO's tests to weighted picture SNR's. Further, it must be assumed that FM transmission with a given weighted picture-SNR would rate the same subjective grade in a viewer panel test as AM transmission with the same weighted picture-SNR. In other words, it is assumed that the weighting network accounts exactly for the effect of spectral distribution of random video noise on the subjectively experienced interference. The conversion of TASO's carrier-to-noise ratios to weighted picture-SNR's is discussed in Section 2.3.2. The result is:

$$\left(\frac{S}{N}\right)_{p,w} = \left(\frac{C_s}{N}\right)_{TASO} + 0.9 \text{ db} \qquad (2\text{-}4)$$

where $\left(\frac{S}{N}\right)_{p,w}$ = weighted picture-SNR, in db

$\left(\frac{C_s}{N}\right)_{TASO}$ = carrier-to-noise ratios used by TASO to express its test results, in db.

The values of carrier-to-noise ratio stated by TASO relate to the controlled RF noise injected at the test receiver input. Consequently,

Table 2-3. TASO Grades for Picture Quality

Grade	Name	Description	Carrier-To-Noise Ratio (db)
1	Excellent	Extremely high quality, as good as could be desired desired.	46*
2	Fine	High quality providing enjoyable viewing. Perceptible interference.	38
3	Passable	Acceptable quality. Interference not objectionable.	31
4	Marginal	Poor quality; improvement desired. Interference somewhat objectionable.	25
5	Inferior	Very poor quality but could be watched. Definitely objectionable interference.	19
6	Unusable	Too bad to be watched.	

* For 65 percent of viewers, data for 75 percent not available.

these figures do not account for camera noise, which must have contributed to the interference rated by TASO's viewer panels. The camera noise performance indicated in Table 2-2 reflects the operational quality of cameras used in TV studios and are based on information obtained from ABC. Image-orthicons are used for life scenes and cameras of vidicon type for movies.

The condition for equal subjective picture quality in the TASO tests and in an actual broadcast application is:

$$\left(\frac{N}{S}\right)_{RT} + \left(\frac{N}{S}\right)_{CT} = \left(\frac{N}{S}\right)_{RA} + \left(\frac{N}{S}\right)_{CA} \qquad (2\text{-}5)$$

where $\frac{N}{S}$ denotes inverted, weighted picture-SNR, while the subindices indicate noise categories as follows:

RT, interference from RF noise in TASO tests

CT, camera noise in TASO tests

RA, interference from RF noise in actual application

CA, camera noise in actual application.

Manipulation of Equation (2-5) gives

$$\left(\frac{S}{N}\right)_{RA} = \frac{\left(\frac{S}{N}\right)_{RT}}{1 + \frac{\left(\frac{S}{N}\right)_{RT}}{\left(\frac{S}{N}\right)_{CT}} - \frac{\left(\frac{S}{N}\right)_{RT}}{\left(\frac{S}{N}\right)_{CA}}} \qquad (2\text{-}6)$$

TASO used flying spot color slider scanners, for which $(S/N)_{CT}$ is here estimated at a slightly optimistic 48 db. In actual broadcasting, either image-orthicons or vidicons are used, and therefore, 43 db seems a safe estimate for $(S/N)_{CA}$.

With these estimates, Equations (2-4) and (2-6) lead to the values for picture-SNR shown in Table 2-4.

Table 2-4. Weighted Picture Signal-to-Noise Ratios
Versus TASO Quality Grades
(Transmission noise only)

TASO Grade	Name	Weighted Picture-SNR
1	Excellent	49.5 db*
2	Fine	40.3 db
3	Passable	32.2 db
4	Marginal	25.9 db
5	Inferior	19.9 db

*A $(S/N)_{CA}$ value of 46 db, i.e., a poor vidicon or excellent image-orthicon, was assumed for TASO Grade 1. This grade is not feasible with $(S/N)_{CA}$ = 43 db (average image-orthicon), the value assumed for TASO grades 2 through 5.

2.2.4 Noise Requirements for Color Television

Comparisons between subjective quality tests for color and monochrome television give contradicting results. TASO reports that color television requires a slightly lower carrier-to-noise ratio than monochrome noise of equal subjective quality (Reference 2-5, Page 532 and 534, Figure 40). One would expect opposite results, since the color subcarrier detection process translates noise within the color subcarrier channel to low video frequencies, where the attentuation in the weighting network is less than near the color subcarrier frequency. This expectation is confirmed by results of subjective quality tests by Barstow and Christopher (Reference 2-6). They report that equal magnitudes of noise near the color subcarrier are noticeably more interfering in color pictures than in monochrome pictures. This observation is reflected in a hump in the weighting curve at the color subcarrier frequency, leading to a lower weighting factor for color pictures than for monochrome pictures. This effect is dependent on the degree of color saturation. The results of Barstow and Christopher's test with a flat noise spectrum indicate weighting factors of 6.5 db and 4.3 db for monochrome and color pictures, respectively.

In summation, while Barstow and Christopher's test indicates that amplitude-modulated color television requires a 2 db higher RF power than monochrome television, TASO test indicates practically equal power requirements. In this study, the power penalty for color in AM/VSB transmission is assumed to be 1 db.

CCIR Recommendation 451 (Reference 2-1) for the 625-line system with 5.5 MHz video bandwidth specifies separate signal-to-noise ratios and weighting curves for the luminance channel and the chrominance channel. For luminance, a weighted picture SNR of 52 db and weighting factors of 6.5 db for flat noise and 12.3 db for FM-noise are specified. For noise in the chrominance channel from 3.5 to 5.5 MHz, the weighted picture-SNR is 46 db, while the weighting for each of the subcarrier sidebands is approximately equal to the luminance weighting between 0 and 1 MHz.

Although these values for the signal-to-noise ratios do not apply to broadcasting, the relative impact of the luminance and chrominance noise performance requirements is definitely of interest here. By integration of the weighted chrominance channel noise over the frequency band 3.5 to 5.5 MHz, it was found that a flat noise spectrum (AM-noise) of the level corresponding to the specified luminance noise performance (45.5 db unweighted) results in 49 db weighted in the chrominance channel, i.e., 3 db better than required. A similar analysis for FM transmission (quadratic noise power spectrum, or triangular noise voltage spectrum) shows that a noise level corresponding to the luminance channel requirement (39.7 db unweighted) results in 41.4 db weighted in the chrominance channel, i.e., 4.6 db less than required.

2.3 AMPLITUDE MODULATION WITH VESTIGIAL SIDEBAND

A relationship between predetection carrier-to-noise ratio and post-detection picture signal-to-noise ratio is established. RF power requirements are determined. The analysis presented is used to convert TASO test data into equivalent weighted picture signal-to-noise ratios.

2.3.1 RF Power Requirements

All television broadcast system in operation today use amplitude modulation with vestigial sideband. Figure 2-4 presents the vestigial sideband characteristic of transmitters in the American 525-line system. Double sideband transmission is maintained for video frequencies up to 0.75 MHz. The RF selectivity characteristic of home receivers, presented in Figure 2-5, is matched to the vestigial sideband characteristic of the transmitter such that the overall video amplitude response in the double-sideband video frequency range becomes equal to that in the single sideband range.

The video demodulator in television sets is a diode operating as an envelope detector. It has been shown (Reference 7) that for a sinusoidal carrier of amplitude A, corrupted by narrow band, gaussian random noise with an RMS value σ, the probability density function p (v) of the envelope v is:

$$p(v) = \frac{1}{\sigma}\left(\frac{v}{2\pi A}\right)^{1/2} \exp\left[-\frac{(v-A)^2}{2\sigma^2}\right] \cdot \left[1 + \frac{1}{8}\frac{\sigma^2}{Av} + \frac{9}{128}\left(\frac{\sigma^2}{Av}\right)^2 + \cdots\cdots\right]$$

For large carrier-to-noise ratios, i.e., for $A \gg \sigma$, the distribution of v is concentrated to a range small compared to A, and the envelope will show a nearly gaussian distribution with RMS deviation σ about an average A.

With negative polarization of modulation, prevailing in most standards, the maximum carrier amplitude occurs during sync peak. Let this amplitude at the receiver input be E_s, while bE and wE are the

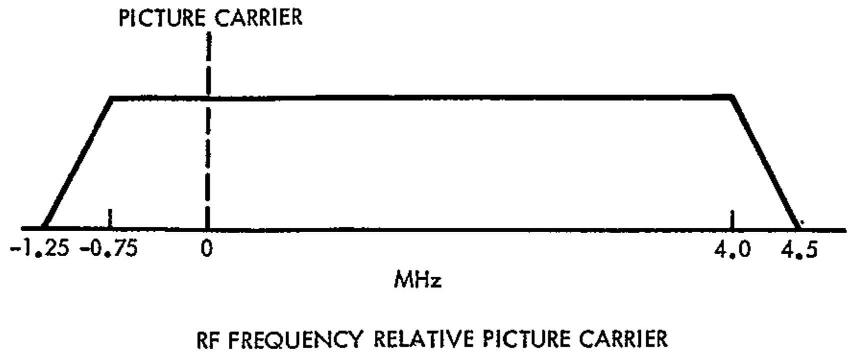


Figure 2-4. Vestigial Sideband Characteristics of Video Transmitters

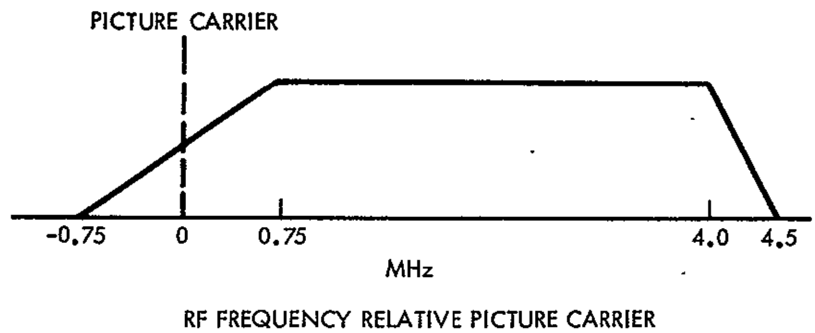


Figure 2-5. Receiver Selectivity for Vestigial Sideband Transmission

amplitudes corresponding to the blank and white levels, respectively, of the video signal. Then, the blank-to-white video voltage at the envelope detector output would be $(b-w)E_s$. However, the vestigial sideband filter at the receiver input reduces this voltage to $1/2\ (b-w)\ E_s$. If the effect of this filter on the noise level at the envelope detector input is expressed by an effective noise bandwidth B_n, we have

$$\sigma^2 = k\ T\ B_n$$

where σ^2 = noise power at envelope detector input

$k = 1.38 \times 10^{-23}$ watts/Hz$^{\circ}$K, Boltzmann's constant.

The unweighted picture-SNR, defined by Equation (2-1), is now seen to be

$$\left(\frac{S}{N}\right)_p = \frac{\frac{1}{4}(b-w)^2 E_s^{\,2}}{k\ T\ B_n}$$

or

$$\left(\frac{S}{N}\right)_p = \frac{1}{2}(b-w)^2 \frac{C_s}{k\ T\ B_n} \tag{2-7}$$

where $C_s = E_s^{\,2}/2$, the carrier power during sync peaks

This expression is of fundamental significance.

A natural expansion of Equation (2-7), taking into account the effects of predetection and postdetection filtering, and noise weighting, in the presence of an arbitrary RF noise spectrum at the receiver input, is the following expression for weighted picture-SNR.

$$\left(\frac{S}{N}\right)_{p,\,w} = \frac{1}{2}(b-w)^2 \frac{C_s}{N} \tag{2-8}$$

where

$$N = \int_o^{\infty} \Phi_v(f_v)\ \left| H_v(f_v) \right|^2 w(f_v)df_v \tag{2-9}$$

$$\Phi_v(f_v) = \left[\Phi(f_o - f_v)\left|H_r(f_o - f_v)\right|^2 + \Phi(f_o + f_v)\left|H_r(f_o + f_v)\right|^2\right] \tag{2-10}$$

The notations are:

$(S/N)_{p,\,w}$ = weighted picture-SNR at picture tube

C_s = vision carrier power during sync peaks

b = relative carrier amplitude for blank

w = relative carrier amplitude for white

f_v = video frequency

f_o = vision carrier frequency

$\Phi_v(f_v)$ = noise power spectral density (one-sided) at detector output

$\Phi(f)$ = noise power spectral density (one-sided) at the receiver input

$H_v(f_v)$ = transfer function of video transmission from detector to picture tube

$H_r(f)$ = predetection transfer function of receiver normalized to 1/2 at the vision carrier frequency

$w(f_v)$ = power transfer function of weighting network

In all practical situations, the RF noise spectrum at the receiver input is flat. Figure 2-6 shows the voltage and power transfer functions of the receiver's vestigial sideband filter, and also the video noise power spectrum $\Phi_v(f_v)$ at the detector output, determined by Equation (2-10) with a flat RF noise spectrum $\Phi(f) = kT$. Table 2-5 shows characteristics of vestigial sideband filters in different systems. Also shown in this table are the effective noise bandwidths to be used in Equation (2-7), provided that the noise at the picture tube is not further limited by postdetection filtering. The noise weighting factors, calculated as

$$10 \log \frac{\int_0^\infty \Phi_v(f_v)df}{\int_0^\infty \Phi_v(f_v)w(f_v)df}$$

are also presented in Table 2-5. These factors are slightly higher than for flat noise, due to the dip of the spectrum $\Phi_v(f_v)$ at low video frequencies.

The effective noise bandwidths and weighting factors in Table 2-5 were used together with Equation (2-7) in determining the RF power requirements for the picture quality grade "fine" (TASO Grade 2), presented in Table 2-6. For other quality grades, the difference in weighted picture-SNR, obtained from Table 2-4, gives immediately the correction to be applied to the value for C/T shown in Table 2-6.

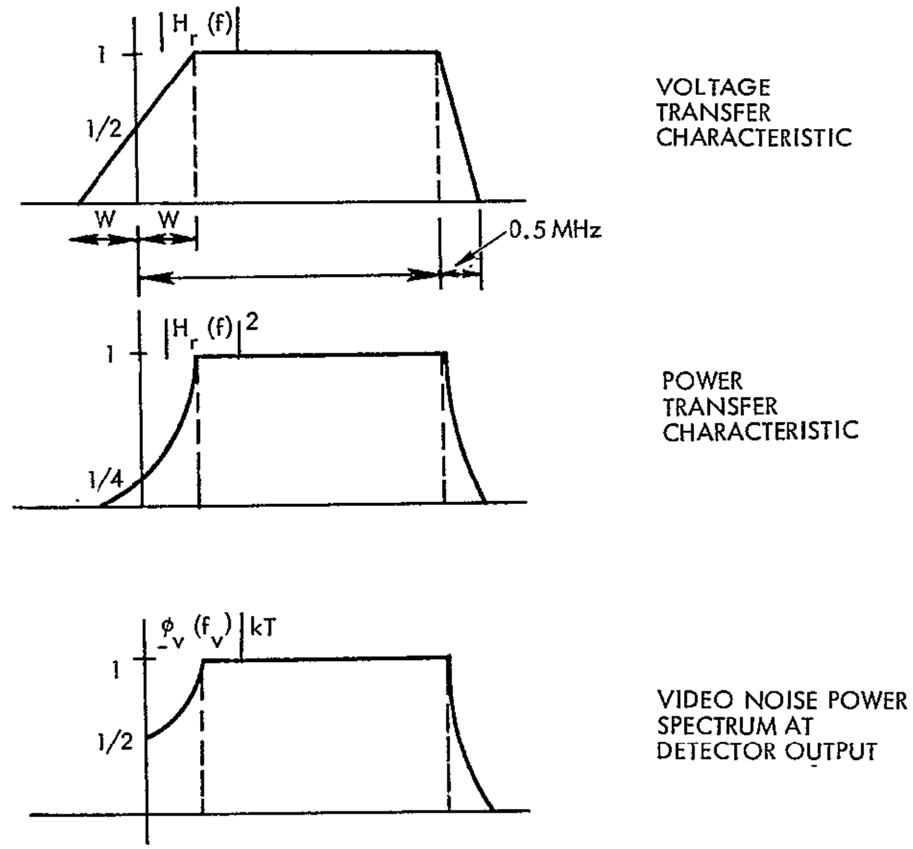


Figure 2-6. Prediction Filtering

Table 2-5. Effective Noise Bandwidths and Noise Weighting Factors

Lines per frame	525	625	625	625
Video bandwidth, MHz	4.2	5.0	5.5	6.0
Main sideband width (v), MHz	4.0	5.0	5.0	6.0
Vestigial sideband width (w), MHz	0.75	0.75	1.25	0.75
Effective noise bandwidth, MHz	3.92	4.92	4.75	5.92
Noise weighting factor, db	6.7	9.8	7.7	10.6

Lines per frame		525	525	625	625	625
Video bandwidth	MHz	4.2	4.2	5.0	5.5	6.0
		Monochrome	Color	Monochrome	Color	Monochrome
Weighted picture-SNR	db	40.0	40.0	40.0	40.0	40.0
Weighting factor for AM/VSB	db	6.7	6.0	9.8	7.7	10.6
Unweighted picture-SNR	db	33.3	34.0	30.2	32.3	29.4
20 log (b1-w)	db	- 4.4	- 4.4	- 4.0	- 4.7	- 3.7
$C_s/k\,T\,B_n$	db	40.7	41.4	37.2	40.0	36.1
Noise bandwidth B_n	MHz	3.92	3.92	4.92	4.75	5.92
C_s/T	dbw/°K	-122.0	-121.3	-124.5	-121.8	-124.8

C_s = average power during sync-peaks, dbw

T = systems noise temperature, °K

Table 2-6. RF Power Requirements for AM/VSB

2.3.2 Evaluation of TASO Test Data

The carrier-to-noise ratios stated by TASO are based on measurement of the RF noise fed to the receiver input. The power spectrum of this noise is shown in Figure 20 of Reference 5. Integration of this spectrum, after normalization to unity at the vision carrier frequency, gives an effective bandwidth of 5.5 MHz. Hence, the stated carrier-to-noise ratios must be interpreted as

$$\left(\frac{C_s}{N}\right)_{TASO} = \frac{C_s}{\Phi(f_o)B_T} \qquad (2\text{-}11)$$

with B_T = 5.5 MHz

Figure 21 of Reference 5 shows noise spectra at the picture tubes of different test receivers, resulting from the RF noise injected at the RF input. These spectra are $\Phi_v(f) \mid H_v(f_v) \mid^2$ in the notation of Equations (2-9) and (2-10). By adding noise weighting to the spectra, we obtain $\Phi_v(f) \mid H_v(f_v) \mid^2 w(f)$, i.e., the integrand in Equation (2-9).

Integration of these weighted spectra showed an average effective bandwidth of 0.82 MHz. In more exact terms, Equations (2-9) and (2-10), when applied to the average test receiver, would result in

$$N = \Phi(f_o)\ B_{N,w} \tag{2-12}$$

with $B_{N,w}$ = 0.82 MHz.

Combining Equations (2-8), (2-11) and (2-12) gives

$$\left(\frac{S}{N}\right)_{p,w} = \frac{1}{2}\,(b-w)^2\,\frac{B_T}{B_{N,w}}\left(\frac{C_s}{N}\right)_{TASO}$$

With the actual values of the tests, i.e., b = 0.75, w = 0.15, B_T = 5.5 MHz, and $B_{N,w}$ = 0.82 MHz, we find

$$\left(\frac{S}{N}\right)_{p,w} = \left(\frac{C_s}{N}\right)_{TASO} + 0.9\ \text{db} \tag{2-13}$$

This conversion of carrier-to-noise ratios stated by TASO into weighted picture-SNR's makes it possible to extend the validity of TASO's viewer panel tests to transmission systems using modulation other than AM/VSB.

A conversion developed earlier by TRW showed reasonably good agreement with the findings of Mr. J. J. Bisaga of Communications and Systems, Inc. The conversion rule presented above was derived by TRW, using analytical refinements suggested by Mr. Bisaga (Reference 8). The results of TRW's and C&S's analyses differ by 0.3 db, which is due to the limited accuracy in the two independent numerical analyses.

2.3.3 Average RF Signal Power

The RF power requirements in Table 2-6 are stated in terms of average RF power during sync-peaks. The average RF power over longer intervals (at least one line period) are dependent on the picture content. For AM/VSB modulation with negative polarization, used in practically all standards, the average RF power reaches its maximum for an all-black picture and its minimum for an all-white picture. Table 2-7, gives these extreme values of long-term (at least one-frame period) averages for different standards.

Table 2-7. Extreme Values of Average RF Power

Lines per frame	525	625	625
Video bandwidth, MHz	4.2	5.0	5.5
Maximum average (all-black)	0.55	0.54	0.59
Minimum average (all-white)	0.19	0.18	0.18

2.4 FREQUENCY MODULATION

In FM transmission of television, the weighted picture-SNR (as defined in Section 2.2.1) for transmission noise is

$$\left(\frac{S}{N}\right)_{p,w} = 3\,\frac{C}{k\ T\ B_v}\left(\frac{D}{B_v}\right)^2\ W \cdot I \qquad (2\text{-}14)$$

where

$$W \cdot I = \frac{\frac{1}{3} B_v^{\ 3}}{\int_o^{B_v} f_v^{\ 2}\,\frac{w(f_v)}{p(f_v)}\,df_v}, \qquad (2\text{-}15)$$

the combined effect of weighting and pre-emphasis. Without pre-emphasis, $p(f_v)$ becomes 1 and Equation (2-15) reduces to the expression for the noise weighting factor.

The notation used is

$\left(\frac{S}{N}\right)_{p,w}$ = weighted picture-SNR, defined in Section 2.2.1

C = carrier power, watts

$k = 1.38 \times 10^{-23}$ watts/Hz°K, Boltzman's constant

T = system noise temperature, °K

D = blank-to-white frequency deviation, measured with pre-emphasis removed, i.e., with $p(f) \equiv 1$, MHz

B_v = video bandwidth, MHz

W = weighting factor

I = ratio of increase in weighted picture-SNR by pre-emphasis

f_v = video frequency

$w(f_v)$ = power transfer function of noise weighting network

$p(f_v)$ = pre-emphasis function (power versus video frequency)

The RF bandwidth occupied by the FM transmission is by Carson's rule:

$$B_{rf} = 2B_v + \alpha\beta D \tag{2-16}$$

where

$\alpha = \dfrac{\text{sync peak-to-white video voltage}}{\text{blank-to-white video voltage}}$

β = ratio of change in peak-to-peak frequency deviation of composite video modulation due to pre-emphasis

The carrier-to-noise ratio at the FM demodulator input becomes

$$\frac{C}{N} = \frac{C}{k\ T\ B_{RF}} \tag{2-17}$$

The minimum value of C/N dictated by the FM-threshold of the demodulator limits the extent to which RF power requirements, for a given picture-SNR, can be reduced by increasing the frequency deviation D. Consequently, for a minimum-power design the frequency deviation must be chosen such that both $(S/N)_{p,w}$ and C/N are at their respective limits.

Elimination of (C/T) between Equations (2-14) and (2-17), followed by substitution of (2-16) for B_{RF} leads after some manipulation to

$$\frac{\left(\frac{S}{N}\right)^*}{\frac{C}{N}} = 3\,\frac{B_{RF}}{B_v}\left(\frac{B_{rf}}{B_v} - 2\right)^2 \tag{2-18}$$

where

$$\left(\frac{S}{N}\right)^* = \left(\frac{S}{N}\right)_{p,w} \frac{\alpha^2}{W} \cdot \frac{\beta^2}{I} \tag{2-19}$$

The RF bandwidth, B_{RF}, for a minimum power transmission can be determined by solving Equation (2-18) for B_{RF}/B_v, using the required minimum values for (S/N* and (C/N). With B_{RF} known, Equation (2-17) gives the RF power requirements in terms of the ratio C/T between the received carrier power and the system noise temperature.

The threshold for C/N is due to 2π-radian phase jumps of the sum vector of the carrier and the narrow-band noise, resulting in impulse noise at the demodulator output. This so-called threshold noise, which is not accounted for in Equation (2-14), leads to rapid degradation in link performance as the carrier-to-noise ratio is lowered to its threshold. The commonly used 1-db threshold is the carrier-to-noise ratio where the impulse noise degrades the overall postdetection signal-to-noise ratio by 1 db from that with only triangular FM noise. This threshold varies within a range of about 1 db for modulation indices between 1 and 4. However, different analytical approaches, based on Rice's threshold theory, differ about 2 db in the position of this 1 db range. Assumption of the carrier-to-noise ratio of 10 db as threshold reflects an engineering estimate within the uncertainty of analytical results.

Since the impulsive threshold noise has an essentially flat spectrum (at the demodulator output), it is subject to a lower weighting factor than the triangular noise. Therefore, the degradation in weighted video noise by threshold noise can be as large as 3 db at the so-called 1 db threshold. In view of these considerations, it was stipulated that the desired picture-SNR must be obtained with a nominal carrier-to-noise ratio of 16 db. With these two values inserted in Equations (2-18) and (2-19), the minimum-power design procedure results in the corresponding nominal RF carrier level. The threshold noise is then limited to negligible magnitude for RF carrier levels down to 3 db below nominal. At 6 db below nominal carrier level, the weighted threshold noise power approximately equals the weighted regular FM video noise, and consequently, the weighted picture-SNR for all video noise will then be 6 + 3 = 9 db below the objective.

With the values of $(S/N)_{p,w}$ and (C/N) defined, the power and bandwidth requirements are still dependent on the television standard and the pre-emphasis used, represented in Equation (2-19) by α^2/W and β^2/I, respectively.

For minimum-power transmission without pre-emphasis, i.e., with $\beta^2/I = 1$, Table 2-8 shows RF power and bandwidth requirements for fine and passable picture qualities (TASO grades 2 and 3, respectively), the quality levels most relevant for satellite broadcasting. Transmission in narrower RF bands is possible but requires more RF power.

The pre-emphasis parameter that determines the possible saving in power and bandwidth is β^2/I. For the pre-emphasis characteristic

Table 2-8. RF Power and Bandwidth Requirements for FM Transmissions

		Video Bandwidth MHz	Fine Quality (TASO Grade 2)		Passable Quality (TASO Grade 3)	
			C/T dbw/^{o}K	B_{RF} MHz	C/T dbw/^{o}K	B_{RF} MHz
525-line	monochrome	4.2	-140.3	16.9	-141.7	12.3
	color	4.2	-139.6	19.8	-141.2	13.8
625-line	monochrome	5.0	-140.6	15.7	-141.6	12.6
		5.5	-139.9	18.4	-141.2	13.8
		6.0	-140.0	18.0	-140.9	14.6
	color	5.5	-139.0	22.8	-140.5	16.0

Table 2-9. Advantages from Pre-emphasis (525-line monochrome television)

	Fine Quality (TASO Grade 2)		Passable Quality (TASO Grade 3)	
	C/T dbw/^{o}K	B_{RF} MHz	C/T dbw/^{o}K	B_{RF} MHz
Without pre-emphasis	-140.3	16.9	-141.7	12.3
With pre-emphasis	-141.8	12.2	-142.6	10.0
Saving by pre-emphasis	1.5 db	28%	0.9 db	19%

recommended by the CCIR (Reference 2-2) for monochrome 525-line television, the pertinent values are $\beta = 1/2$ and I - - 2.4 db, resulting in $\beta^2/I = -8.4$ db. Table 2-9 shows the savings in RF power and bandwidth attainable by this pre-emphasis.

For transmission of color television by FM systems without pre-emphasis, noise in the color subcarrier channel dominates the video noise requirements on the link design. This is due to the quadratic shape of the video noise spectrum. In Section 2.2.4, it was pointed out that with the quadratic video noise spectrum of FM transmission without pre-emphasis, the video noise level corresponding to the limit specified for the luminance channel exceeds the limit on the chrominance channel noise level by 4.6 db.

With pre-emphasis it would be possible to form a wide noise spectrum that meets both requirements simultaneously. However, such pre-emphasis would hardly result in savings in RF power and bandwidth. Since noise in the color subcarrier channel is the limiting factor, the improvement factor I would approximately equal the value of $p^2(f_v)$ at the subcarrier frequency. But, since the color subcarrier level for colors saturated to 75 percent (representative of normal picture material) alone creates a peak-to-peak frequency deviation equal to blank-to-white deviation (both without pre-emphasis), the ratio β^2 would also be approximately equal to the value of $p^2(f_v)$ at the color subcarrier frequency. Hence, β^2/I will be close to one, its value without pre-emphasis, and therefore, Equations (2-18) and (2-19) will lead to RF power and bandwidth requirements close to those found for transmission without pre-emphasis.

Although pre-emphasis in transmission of color is not justified by power and bandwidth considerations, it may well prove valuable for reduction of differential gain and phase in the color subcarrier channel.

2.5 SOUND CHANNELS

In most television systems, sound is transmitted by a frequency-modulated carrier. Satellite broadcasting in the time period 1975-80 will most likely be received by conventional receivers built to standards that differ no more than in minor details from present standards.

Economical and practical considerations dictate that requirements on adaption of conventional receivers to space broadcasting, to be achieved by additional user equipment, are held to a minimum. Therefore, sound channel transmission in space broadcasting must be achieved by carriers or subcarriers modulated in accordance with the present standards for sound carrier modulation. In nearly all television systems, the sound carrier is frequency modulated.

2.5.1 Sound Channel Performance

The audio signal-to-noise ratio in program channels is commonly defined as the ratio between the mean power of a test tone at 100 percent modulation and the mean power of psophometrically weighted audio noise within the nominal audio band.

For FM transmission of sound, this audio-SNR is:

$$\frac{S}{N} = \frac{3}{2}\frac{C}{\Phi B}\left(\frac{\Delta f}{B}\right)^2 \frac{R}{p(f_t)} \tag{2-20}$$

where

$$R = \frac{1/3}{\frac{1}{B^3}\int_0^B f^2 \frac{w(f)}{p(f)}\, df} \tag{2-21}$$

where C = audio carrier (or subcarrier) power

Φ = one-sided noise density in FM-channel

B = upper frequency of nominal audio band

Δf = peak frequency deviation of test-tone at 100% modulation level (i. e., specified maximum frequency swing).

f = audio frequency

f_t = test-tone frequency specified in the definition of audio-SNR.

$w(f)$ = psophometric weighting function, in terms of power ratio.

$p(f)$ = pre-emphasis function, in terms of power ratio.

The pre-emphasis function for sound transmission in TV broadcasting is

$$p(f) = 1 + (2\pi\tau f)^2 \tag{2-22}$$

where $p(f)$ = pre-emphasis, in terms of power ratio

τ = time constant, sec.

f = audio frequency, Hz

The parameters of sound channels in 525-line and 625-line television are as follows:

		525-Line Systems	625-Line Systems
Audio bandwidth B	kHz	15	10
Maximum frequency swing Δf	kHz	± 25	± 50
Time constant of pre-emphasis, τ	μsec	75	50
Test-tone frequency, f_t	Hz	400	1000
Pre-emphasis at test-tone frequency, $p(f_t)$	db	+0.2	+0.4
Predetection bandwidth	kHz	200	200
R in Equations (2-20) and (2-21)	db	+9.6	+1.5

The psophometric weighting referred to is that of the "C.C.I.T.T. Psophometer for Program Circuits," described in Reference 2-9. This function has value one at 1000 Hz (by definition) and near 9000 Hz and is larger than one between these frequencies, with a maximum of +8.4 db near 5000 Hz. C.C.I.T.T. Recommendations J. 21, J. 31 and J. 41 (Reference 2-10) for Program Circuits specify weighted audio-SNR's of 57 db for cable circuits and 49 db for open-wire circuits, respectively. These values apply to the 2500-km hypothetical reference circuit and were established under the assumption of a 40-db dynamic ratio of the audio signal.

The color carrier level must exceed the threshold at the discrimination input. Assuming a carrier-to-noise ratio of 16 db in the 200 kHz predetection bandwidth, or C/Φ = 69 db (Hz), Equation (2-20) gives a weighted audio-SNR of 42.4 db in 525-line systems and 46 db in 625-line systems. These values are 6.6 db and 3.0 db, respectively below the weighted audio-SNR recommended for open-wire program circuits. These C.C.I.T.T. noise objectives were set sufficiently stringent to make the noise contribution from program distribution to broadcast stations small compared with the contribution from the broadcast transmission to the users. Therefore, it appears that a carrier-to-noise density ratio, C/Φ, of 69 db in the sound carrier channel is a useful design criterion for satellite broadcasting.

2.5.2 Sound Carrier Power in AM/VSB Transmission

Television receivers of present design have a single IF amplifier shared by the vision carrier and the sound carrier. Mixing of these two carriers in the video detector produces the so-called intercarrier at a frequency equal to the carrier-separation. The transfer of amplitude modulation from the vision carrier to the intercarrier is held low by a small audio-to-vision carrier power ratio at the video detector output. The intercarrier is amplified and bandpass-filtered, whereafter the audio signal is extracted by a FM discriminator. Limiting action in this discriminator provides further reduction of the residual amplitude modulation.

The requirement for a low audio-to-carrier carrier power ratio required at the video detector input is met in part by the ratio of 0.1 to 0.2 between the effective radiated powers of the audio and vision transmitters of a broadcast station. This is not sufficient, and television receivers therefore attenuate the sound carrier by about 20 db relative to the vision carrier. Figure 2-7 shows the idealized amplitude versus frequency characteristic for transmission from the receiver RF input to the video detector input. The plateau at the sound carrier frequency accommodates a 200-kHz wide sound transmission.

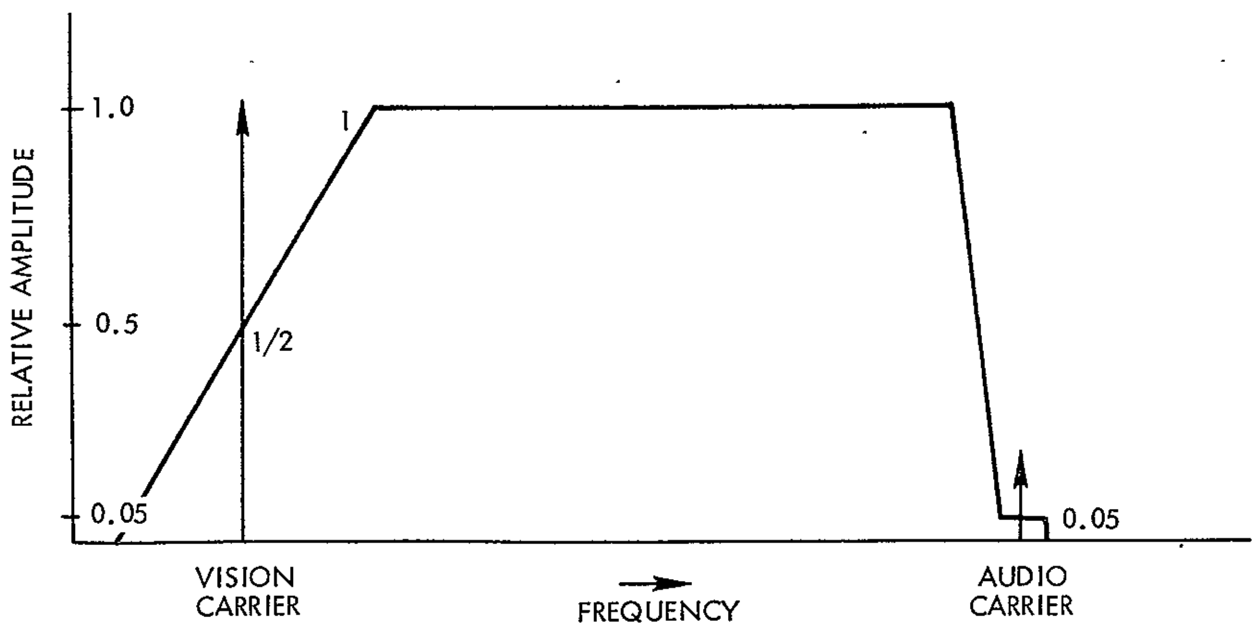


Figure 2-7 Amplitude Versus Frequency Characteristics of Prediction Amplification in Television Receivers

In some receivers, the 20-db sound-carrier suppression is in part achieved by a sound trap between the mixer and the IF amplifier. This increases the impact of IF amplifier noise, resulting in an increase in receiver system noise temperature for sound carrier reception only.

The total input into the video detector is $s_v(t) + s_a(t) + n(t)$, where $s_v(t)$ is the vision carrier of power C_v, $s_a(t)$ the sound carrier of power C_a, and $n(t)$ the random noise with (one-sided) power spectral density $\Phi(f)$. Assuming square-law detection, the detector output components within the passband of the intercarrier amplifier were found to be:

- Intercarrier power: $C_v C_a$
- Noise of category $s_a(t) \cdot n(t)$; one-sided power spectral density:

  $C_v \Phi(f_a)$ where f_a = sound carrier frequency
- Noise of category $s_a(t) \cdot n(t)$; one-sided power spectral density:

  $C_a \Phi(f_v)$, where f_v = vision carrier frequency
- Noise of category $n(t) \cdot n(t)$, one-sided power spectral density: analysis of upper bound showed this category to be negligible.

The ratio, (C/Φ), between the intercarrier signal power and the total power spectral density of the three categories of noise is:

$$\left(\frac{C}{\Phi}\right)_i = \frac{1}{\dfrac{\Phi(f_a)}{C_a} + \dfrac{\Phi(f_v)}{C_v}} \tag{2-23}$$

Let α be the ratio between vision carrier power and audio carrier power at the antenna terminals of the receiver. In terrestrial broadcasting, α is between 5 and 10. Further, let β be the ratio by which the effective noise temperature for sound carrier reception is raised by sound carrier attenuation near the receiver front end.

Then

$$\frac{\Phi(f_v)}{C_v} = \frac{1}{\alpha\beta} \frac{\Phi(f_a)}{C_a}$$

and Equation (2-23) may be written as:

$$\left(\frac{C}{\Phi}\right) = \frac{\frac{C_a}{\Phi(f_a)}}{1 + \frac{1}{\alpha\beta}} = \frac{\frac{C_v}{\Phi(f_v)}}{1 + \alpha\beta} \qquad (2\text{-}24)$$

The vision carrier power to be used here is the lowest level, i. e., the white level. For passable picture quality (TASO Grade 3), the lowest grade of interest here, $C/T = -150$ dbw/^{o}K, which yields $C/\Phi = 78.6$ db (Hz). Assuming a sound carrier level, at the receiver input, of 1 percent of the sync peak power, i. e., equal to the white level of the vision carrier, we have $\alpha = 1$. With a conservative estimate of 4 for β , Equation (2-24) gives $(C/\Phi)_i = 71.6$ db (Hz). This exceeds the criterion of 69 db (Hz) established in Section 2. 5. 1 and increases the calculated audio-SNR from 42. 4 db to 45 db.

Arvin (Reference 2-11) reported the results of sound channel performance measurements on a typical television receiver. This reference gives audio signal-to-noise ratios as a function of the vision carrier level, while the sound carrier level at the receiver input is held at 10 or 70 percent of the vision carrier level (sync peak value). The measurement results for a vision carrier-to-noise ratio of 21 db (as defined by TASO, see Section 2. 3. 2) with the sound carrier at the 10 percent level should be close to the calculated performance discussion above, since they were measured with a sound carrier level of a 10 times larger percentage of a 10 times lower vision carrier level (relative to noise). Actually, the measured data should be slightly poorer than the calculated data because of the lower vision carrier level. For the indicated case, Figure 15 in the reference gives an audio-SNR of 37 db when the vision carrier is modulated to its white level. This value was measured with a 30 percent modulation, without psophometric weighting. With 100 percent modulation and psophometric weighting, it would be 43. 8 db, which compares well with the calculated 45 db.

The experiments reported by Arvin were performed in the absence of vision carrier modulation, and, therefore, do not account for the possible adverse affect of intermodulation between components of the modulated vision transmission.

In veiw of all above considerations, it appears that in satellite broadcasting using AM/VSB transmission by the satellite, a sound carrier with an effective radiated power of 2 percent of the vision carrier (sync peak value) is satisfactory. In case of multiple sound channel transmission, the 2 percent applies to each sound channel. Transmission of several sound carriers by a common sound transmitter will require a transmitter saturation level of about 30 percent above the sum total of the sound carrier powers in order to allow for the back-off required to limit intermodulation. This conclusion is based on the assumption that the picture quality of space broadcasting will not be lower than TASO Grade 3 (passable quality).

In comparing the 2-percent ratio for space broadcasting with the 10 to 20 percent used in terrestrial broadcasting, it must be recognized that terrestrial broadcasting suffers from large variations in received field strength, with time and with receiver location. Terrestrial sound performance must therefore be satisfactory even when the picture quality is as low as marginal or even inferior. Space broadcasting above 6 GHz will suffer from fluctuations in received field strength due to attenuation in precipitation and clouds, but these fluctuations are relatively slow and therefore must be compensated for by adequate margin in transmission design.

2.5.3 Sound Subcarriers in FM Transmission

In satellite broadcasting using FM transmission of the video signal, sound channels can be transmitted by subcarriers located in the baseband above the video band. To simplify processing in the user equipment, these subcarriers should be frequency-modulated by the audio signal in accordance with the present standards for television sound carrier modulation.

For transmission to receivers without sound channel selection, the obvious choice of subcarrier frequency is the frequency spacing between vision and audio carriers of the standard to which the user receivers are built. For multiple-sound channel transmission, the subcarrier frequencies must be chosen such that none of the subcarrier bands coincide with third order products of intermodulation between other subcarriers and between any sound subcarrier and the color subcarrier. In addition, the vision-audio carrier spacing of the respective television standard should be avoided in the choice of subcarrier frequencies in order to simplify filter requirements in the sound channel selection circuitry of the users' adapter units. For four audio channels, a feasible arrangement for 525-line systems consists of 4.7, 5.5, 6.1 and 6.5 MHz, while 5.65, 6.45, 7.05 and 7.45 MHz can be used for 625-line systems with video bandwidths of 5.0 or 5.5 MHz.

If Φ_s is the (one-sided) spectral noise power density of a subcarrier frequency in the baseband, then the quadratic noise spectrum at the discriminator output results in an unweighted video noise power, N_p, of

$$N_p = \Phi_s \int_o^{B_v} \left(\frac{f}{f_s}\right)^2 df = \frac{1}{3}\, \Phi_s \frac{B_v^{\,3}}{f_s^{\,2}} \qquad (2\text{-}25)$$

where

f = baseband frequency

f_s = subcarrier frequency

B_v = video bandwidth

Further, let D_p be the blank-to-white frequency deviation of the video signal, and D_s the (one-sided) amplitude of the carrier frequency deviation by the subcarrier. Then,

$$\left(\frac{D_s}{D_p}\right)^2 = \frac{2C_s}{N_p (S/N)_p} \qquad (2\text{-}26)$$

where

C_S = subcarrier power

$(S/N)_p$ = unweighted picture-SNR, defined in Section 2.2.1.

Combining Equations (2-25) and (2-26) gives

$$\left(\frac{D_s}{D_p}\right)^2 = 6\,\frac{(C/N)_s}{(S/N)_p}\,\frac{B_s}{B_v}\left(\frac{f_s}{B_v}\right)^2 \tag{2-27}$$

where

B_s = subcarrier channel bandwidth

$(C/N)_s$ = subcarrier-to-noise ratio in subcarrier channels.

As indicated in Section 2.5.1, $(C/N)_s$ = 16 db in B_s = 200 kHz meets both threshold and audio-SNR requirements. With these data and the subcarrier frequencies mentioned earlier in this section, Equation (2-27) gives the value of $\Sigma D_s/D$ shown in Table 2-10.

The addition of sound subcarriers to the video signal in the baseband increases the total peak-to-peak deviation of the RF carrier from αD (See Equation (2-16) in Section 2.4) to $\alpha D + 2\Sigma D_s$, or by a ratio

$$R_s = 1 + \frac{2}{\alpha}\,\frac{\Sigma D_s}{D}$$

This increase in total deviation must be accounted for by replacing α by αR_s in Equation (2-16), and consequently also in Equations (2-18) and (2-19) for a minimum-power design of the FM transmission. This procedure was used to determine the ratio by which the RF carrier power required for transmission of the video signal only must be increased to accommodate sound transmission as well. Values of this ratio are shown in Table 2-10. The RF bandwidth of the FM signal increases by the same ratio as the power.

Table 2-10. RF Power and Bandwidth Requirements for Sound Channels

	Picture Quality	TASO Grade	$\left(\frac{S}{N}\right)_p$ db	Number of Sound Channels	$\frac{\Sigma D_s}{D}$	R_s^2 db	Power and Bandwidth Ratio*
525-line Monochrome	Fine	2	30.1	1	0.11	1.2	1.06
				4	0.58	5.2	1.30
	Passable	3	22.0	1	0.29	3.0	1.11
				4	1.46	9.6	1.48
625-line 5.5 MHz Monochrome	Fine	2	28.0	1	0.15	1.6	1.08
				4	0.65	5.6	1.31
	Passable	3	19.9	1	0.37	3.6	1.12
				4	1.65	10.4	1.48
625-line 5.5 MHz Color	Fine	2	32.6	1	0.09	1.0	1.06
				4	0.38	3.7	1.22
	Passable	3	24.5	1	0.22	2.3	1.10
				4	0.97	7.4	1.37

*The addition of sound to video requires that both the RF carrier power and the RF bandwidth is increased by the ratio shown in this column.

2.6 INTERFERENCE BETWEEN COMMUNICATION SERVICES

The constraints imposed by limits on tolerable interference between television broadcast satellite services and terrestrial services are discussed.

2.6.1 General Relationships

The interference discussions presented in the immediately following sections make use of the general relationships presented here. The notation is as follows:

$EIRP_{dbw}$ = effective isotropically radiated power of spacecraft transmission, dbw/m^2

H_{dbw/m^2} = 10 log H, where H is power flux density at earth receiver location, in $watts/m^2$

$E_{db\mu}$ = 20 log E where E is field-strength at earth receiver location, in μvolt/meter

$(C/T)_{dbw/^oK}$ = 10 log (C/T), where C is received carrier power in watts and T is system noise temperature in degrees Kelvin

$(D^2/T)_{ft^2/^oK}$ = 10 log (D^2/T), where D is receiver antenna diameter in feet, and T is system noise temperature in degrees Kelvin.

$L_{p,\ db}$ = attenuation in propagation medium, db.

ϕ = great-circle distance between receiver location and sub-satellite point, in degrees.

$R(\phi)$ = range function, db

$S(\phi)$ = interference suppression by terrestrial receiver antenna, db

At the earth surface the flux density of satellite transmission is:

$$H_{dbw/m^2} = -162.1 + EIRP_{dbw} - L_{p,\ db} - R(\phi) \qquad (2\text{-}28)$$

where $R(\phi)$ varies as follows:

ϕ deg	$R(\phi)$ db
0	0
20	0.1
30	0.2
40	0.4
50	0.6
60	0.8
70	1.0

Field strength relates to power flux density as

$$E_{db\mu} = 145.8 + H_{dbw/m^2} \qquad (2\text{-}29)$$

The power flux density required to meet a given C/T requirement in a receiver with antenna diameter D, an aperture efficiency of 55 percent, and a system noise temperature T, is

$$H_{dbw/m^2} = 14.0 + (C/T)_{dbw/^oK} - (D^2/T)_{ft^2/^oK} \qquad (2\text{-}30)$$

The discrimination of interference from satellite transmission by conventional television receiver antennas is a function of the angle of arrival. CCIR Recommendation 419 (Reference 2-1) gives directivity patterns recommended for planning purposes. For the UHF television band, this recommendation, converted into suppression versus receiver location, is

ϕ deg	$S(\phi)$ db
≤ 25	16.0
30	14.0
35	11.7
40	9.4
45	7.3
50	5.1
55	2.9
≥ 60	0.0

2.6.2 Broadcasts from Spacecraft and Terrestrial Stations in the UHF Television Band

The protection ratio required against co-channel interference between two AM/VSB television transmissions is about 30 db when a slight carrier frequency separation equal to an appropriate fraction of the line frequency is maintained. This requires that each carrier frequency is held within ±500 Hz from its nominal value. Then, co-channel interference is tolerable as long as the wanted carrier exceeds the unwanted carrier by at least 30 db.

The co-channel protection ratio could be reduced by about 10 db by maintaining the carrier separation at the appropriate multiple of the frame frequency. However, the very accurate carrier frequency control required heretofore, ±2.5 Hz, is impractical for satellite broadcasting.

Let at a given receiver location the field strengths of space and terrestrial broadcasting be E_s and E_t, respectively. With a maximum protection of 16 db by receiver directivity (Reference 2-1), a necessary condition for protection of terrestrial TV service against intolerable interference from space broadcasting is

$$\frac{E_t}{E_s} \geq 30 - 16 = 14 \text{ db} \tag{2-31}$$

Assuming a protection of 25 db by the directivity of the low-cost earth receiver antenna, the necessary condition for protection of space TV service against terrestrial service is

$$\frac{E_s}{E_t} \geq 30 - 25 = 5 \text{ db}$$

or

$$\frac{E_t}{E_s} \leq -5 \text{ db} \tag{2-32}$$

Obviously it is impossible to meet conditions (2-31) and (2-32) simultaneously. In other words, at no location can both services be protected adequately from interference by the other. Consequently, AM/VSB satellite broadcast service cannot share channels used by terrestrial broadcasting covering the same area.

Another pertinent question is whether space broadcasting can share channels used by terrestrial broadcasting outside the area covered by the satellite transmission. The issue here is whether radiation in the sidelobes of the satellite antenna can give rise to co-channel interference of intolerable magnitude. CCIR Recommendation 417-1 (Reference 2-1) stipulates that in planning of terrestrial television services in the upper UHF band (i.e., the frequency range of primary interest for satellite broadcasting at UHF), protection against interference should be sought for wanted signals of median field strength no less than +70 dbμ (db relative 1 μv/m) or 3000 μv/m. Allowing for a fading, it is assumed that terrestrial field strengths down to +54 dbμ or 500 μv/m must be protected. Further, it is assumed that the sidelobes of the satellite antenna can be maintained to at least 25 db below the main lobe; then, co-channel interference by sidelobe radiation is tolerable if the satellite EIRP (at the main beam center) does not exceed the value shown in Table 2-11 derived with the relationships of Section 2.6.1. The severity of this limitation can be appreciated by noting that for AM/VSB satellite broadcasting at 900 MHz to receivers with a 6-foot dish antenna, located in an urban area, a satellite EIRP of 75 dbw (at beam center) is required for picture quality between fine and possible (TASO Grade 2.5).

The feasibility of locating AM/VSB satellite broadcasting in a UHF television channel adjacent to a channel occupied by terrestrial television broadcasting in the area covered by the satellite depends on the acceptable limit for adjacent channel interference.

The pertinent protection ratio requirements are -6 and -12 db for interference from the lower and upper adjacent channel, respectively.

Table 2-11. Co-Channel Interference by Sidelobe Radiation Satellite EIRP Limits

Location Of Interfered Receiver (ϕ deg)	Maximum Satellite EIRP (Beam Center) (dbw)
0	82.3
20	82.2
25	82.2
30	80.1
35	77.7
40	75.3
45	73.1
50	70.8
55	68.5
60	66.1
70	66.3

Again stipulating that terrestrial field strengths down to 500 μv/m must be protected, the satellite EIRP is limited to the values shown in Table 2-12. These limits are 11 db and 17 db, respectively, higher than for co-channel interference by sidelobe radiation.

Similar considerations indicate that satellite broadcasting with an EIRP (at beam center) of 75 dbw is adequately protected at receiver locations where field-strengths from terrestrial broadcasting do not exceed 12,000 μv/m in the lower adjacent channel and 24,000 μv/m in the upper adjacent channel.

A discrimination of 20 db by the earth receiver was assumed. These limits will be exceeded in the principal city served by a terrestrial broadcast station, where the FCC stipulates a minimum field strength of 80 dbμ, or 10,000 μv/m. Consequently, space broadcasting with a satellite EIRP of +75 dbw should not have a channel adjacent to one used by terrestrial broadcasting within the satellite coverage unless an earth receiver antenna with a protection ratio larger than 25 db can be designed and then fabricated at low cost.

Table 2-12. EIRP Limits for Space Broadcasting in Adjacent Channel

Location of Interfered Receiver (ϕ deg)	Maximum EIRP (dbw) Satellite Transmits in Adjacent Channel Lower	Upper
0	93.3	99.3
20	93.2	99.2
25	93.2	99.2
30	91.1	97.1
35	88.7	94.7
40	86.3	92.3
45	84.1	90.1
50	81.8	87.8
55	79.5	85.5
60	77.1	83.1
70	77.3	83.3

Experiments on frequency sharing between AM/VSB television and FM television indicated that protection of the FM transmission requires a protection ratio of 21 db, while the more vulnerable AM/VSB transmission requires 43 db. (Reference 2-12). These ratios are between the average power of the FM carrier and the sync peak power of the AM/VSB carrier.

Similar considerations as discussed above show that frequency sharing between FM television transmission by a satellite and terrestrial AM/VSB broadcasting in the area covered by the satellite is in general not feasible; both services cannot be adequately protected from each other at any one receiver location.

The limitation on frequency sharing with terrestrial AM/VSB broadcasting outside the satellite coverage are easier than for satellites using AM/VSB. The protection ratio for FM interference on AM/VSB is 13 db higher than for AM/VSB on AM/VSB, but for given picture quality and receiver performance, FM transmission requires an approximately 17 db lower satellite EIRP than AM/VSB. The net advantage is 4 db.

2.6.3 Flux Density Limits

The CCIR recommends that the power flux density at the earth surface produced by radiation from a communication satellite shall not in any 4 kHz wide band exceed

$$-152 + \frac{\theta}{15}\ \text{dbw/m}^2$$

where θ is the angle of arrival, in degrees above the horizon. See CCIR Recommendation 358-1 (Reference 2-3). This new recommendation applies to any band in the range 1 to 10 GHz shared by communication satellite services and line-of-sight radio relay systems.

It is to be expected that the Radio Regulations eventually will be changed in accordance with CCIR Recommendation 358-1, and therefore, this recommendation is considered in this study.

Assuming that the transmission from television broadcast satellites using FM has an approximately uniform power spectrum in the RF bandwidth it occupies, the power flux density limit for the total transmission becomes

$$\left(H_{max}\right)_{dbw/m^2} = -128 + \left(B_{RF}\right)_{dbMHz} + \frac{\theta}{15} \tag{2-33}$$

using the additional notation $\left(B_{RF}\right)_{dbMHz} = 10 \log B_{RF}$, where B_{RF} is the occupied bandwidth in MHz.

The corresponding limit on field-strength is

$$\left(E_{max}\right)_{db\mu} = +17.8 + \left(B_{RF}\right)_{dbMHz} + \frac{\theta}{15} \tag{2-34}$$

Eliminating H between Equations (2-30) and (2-33) and relating θ to φ yields

$$\left(D^2/T\right)_{ft^2/^oK} = -26.6 + \left(C/N\right)_{db} - Q(\theta) \qquad (2\text{-}35)$$

where

$$\frac{C}{N} = \frac{C}{k\,T\,B_{RF}}$$

and Q(θ) is as follows:

Receiver Location (φ deg)	Q(θ) (db)
0	6.0
20	4.4
30	3.7
40	2.9
50	2.2
60	1.5
70	0.8

This equation gives the minimum performance, in terms of D^2/T, required of an earth receiver located at φ great-circle degrees from the subsatellite point in order to obtain the required C/T ratio by satellite transmission meeting the power flux density limit recommended by the CCIR.

In Section 2.4, the discussion on FM transmission concluded that the nominal value for C/N should be +16 db.

Among the frequency ranges to be considered in this study, the vicinities of 2.5 and 8.5 GHz are affected by the CCIR recommendation in its present form. Frequency ranges near 12 GHz are not affected now, since they are outside the 1 to 10 GHz range, but may be by 1975 if communication-satellite allocations above 10 GHz lead to a change in the validity range of the CCIR-recommended flux density limit.

At S-band, receiver systems with a bipolar transistor preamplifier will have a system noise temperature of typically 800°K for which Equation (2-35) with C/N = 16 db gives a minimum antenna diameter of 4.2 to 7.6 feet, depending on the receiver locations.

For low-cost X-band receivers, preamplifiers appear less promising than mixers using Schottky-barrier diodes. For 1975 production equipment, a noise figure of 7.0 db is predicted, or a system noise temperature of $1400^{\circ}K$. Satellite transmission then can stay below the CCIR flux density limited if receiver antennas have a diameter of at least 5.5 feet to 10 feet, again depending on receiver location. The beamwidth is then 0.6 to 1.0 degree and requires a pointing accuracy incompatible with low-cost user installations. Therefore, in any frequency range of the X-band where the CCIR limit applies, satellite broadcasting should be limited to special services where user installations at costs in the order of $1000 are justifiable. Such service could be community television, broadcasting to CATV networks, or educational broadcasting to schools where one special receiver and antenna serves sets in several classrooms.

The above considerations assume that wide-deviation frequency modulation is always maintained, either by the video signal or by a special dispersion signal applied in the absence of a video signal.

2.6.4 Frequency-Sharing with Terrestrial ITF Service

In the U.S., the frequency band 2500 to 2686 MHz is used by Instructional Television Fixed Stations. This instructional service for schools uses AM/VSB transmission with transmitter output powers usually not exceeding 10 watts (sync peak level).

This section discusses the conditions under which the FM satellite transmission near 2.5 GHZ, considered in this study, can share the frequencies used by ITF services.

Consider a school receiver with a 10 foot parabolic antenna and a system noise temperature of $1000^{\circ}K$ (receiver noise figure: 6.0 db). For passable picture quality, which requires $C/T = -130.0$ dbw/$^{\circ}K$ (Section 2.3.1, Table 2-6), Equation (2-30) gives a required flux density of -106 dbw/m^2, which corresponds to a field-strength of 100 μv/m.

Experiments on interference of FM television on AM/VSB television showed a protection ratio requirement of 43 db. Hence, with an estimated discrimination against satellite transmission of 20 db by the ITF receiver antenna, FM-TV satellite broadcasting is limited to a flux density of -129 dbw/m^2.

For picture qualities ranging between fine and passable (TASO Grades 2 and 3), the required C/T ratio for FM satellite transmission is at least -142.6 dbw/^{o}K (Section 2.4, Table 2-9). For meeting this requirement without exceeding the above flux density limit, Equation (2-30) indicates that the earth receiver must be designed for

$$\frac{D^2}{T} \geq 1.1 \frac{ft^2}{^oK}$$

With a system noise temperature of 800^{o}K (predicted for bipolar transistor preamplifiers by 1975), the antenna diameter would have to be 30 foot. With a cooled parametric amplifier resulting in a system noise temperature of 200°K, the required antenna size is 15 foot.

Whether improvements in protection of the AM/VSB transmission can be achieved by frequency dispersion of the FM transmission can hardly be established by analysis. The problem is quite different from FM interference on FM. Reliable conclusions can be obtained only by experiments.

2.7 PROPAGATION MEDIUM

2.7.1 Atmospheric Effects

In the frequency range of interest, from 0.9 to 12.0 GHz, the attenuation in oxygen and water vapor is small.

The attenuation in precipitation, clouds and fog is negligible at 900 MHz. Table 2-13 shows values for the three other frequencies of interest. This atmospheric attenuation is accompanied by a change in system noise temperature,

$$\Delta T_s = (1 - \frac{1}{L})(290 - T_c) \qquad (2\text{-}36)$$

where L = total atmosphere attenuation in terms of power ratio ($L > 1$)

T_c = contribution to the receiving system noise temperature from noise sources beyond the precipitation and clouds, as estimated without regard to atmospheric attenuation.

The total effect of attenuation and change in system noise temperature reduces the ratio C/T between received carrier power and system noise temperature by a factor.

$$L \frac{T_s + \Delta T_s}{T_s} = L + (L - 1) \frac{290 - T_c}{T_s} \qquad (2\text{-}37)$$

2.7.2 Ionospheric Effects

Ionospheric effects include absorption, scintillation, Faraday rotation, and phase dispersion. Each of these effects is strongest at the lowest frequency of interest, 900 MHz.

The strongest ionospheric absorption occurs at daytime during polarcap absorption events. During a sunspot maximum, attenuation peaks up to 3 db were observed occasionally at 100 MHz radiation arriving from zenith. Since this absorption is approximately proportional to the square of the inverted frequency, PCA events at 900 MHz can be estimated at 0.04 db for zenithal propagation paths.

Table 2-13. Attenuation in Precipitation and Clouds

Receiver Location 1)	Frequency Climate (GHz)	2. 5		8. 5		12. 0	
		Temperate	Tropical	Temperate	Tropical	Temperate	Tropical
0°	Precipitation 2) db Clouds 3) db	0. 1 0. 1	0. 1 0. 7	0. 6 0. 2	0. 2 2. 6	0. 9 0. 2	0. 3 4. 2
20°	Precipitation 2) db Clouds 3) db	0. 1 0. 1	0. 1 0. 8	0. 6 0. 2	0. 2 2. 8	1. 0 0. 3	0. 3 4. 6
40°	Precipitation 2) db Clouds 3) db	0. 1 0. 1	0. 1 0. 9	0. 8 0. 2	0. 3 3. 1	1. 3 0. 3	0. 4 5. 1
60°	Precipitation 2) db Clouds 3) db	0. 1 0. 1	0. 1 1. 4	1. 5 0. 4	0. 5 4. 8	2. 5 0. 6	0. 8 7. 9
67°	Precipitation 2) db Clouds 3) db	0. 1 0. 2	0. 1 1. 8	2. 1 0. 6	0. 7 6. 3	3. 6 0. 9	1. 2 10. 3
70°	Precipitation 2) db Clouds 3) db	0. 1 0. 2	0. 1 2. 2	2. 8 0. 8	0. 9 7. 5	4. 7 1. 2	1. 6 12. 2

1) Great-circle distance from subsatellite point, in degrees of earth center angle.

2) The values shown apply to 10 mm/hr. This rate is exceeded 10 hours per mean year in Washington, D. C., 40 hours in Manila, The Phillippines. The attenuation in db is proportional to the rainfall rate between 0 and 20 mm/hr except for the 70° receiver location where the proportionality extends to 10 mm/hr.

3) The values shown are conservative, based on severe conditions lasting several hours on each occurrence. Only sketchy information is available.

Data in this table were derived from W. Holzer, "Atmospheric Attenuation in Satellite Communications", Microwave Journal, March, 1965.

Absorption peaks of about 4 db might occur at 900 MHz, but only for waves arriving at low angles above the horizon and then only occasionally during sunspot maxima.

Scintillation's effect on the amplitude is small at 900 MHz, only a few percent during strong disturbances. The low scintillation rates observed in transmission from satellites, about 10 Hz, seem to indicate that the spurious frequency modulation by phase-scintillation is tolerable in transmission of television.

The Faraday rotation is quite considerable and dictates the use of circular polarization at the frequencies 900 MHz and 2500 MHz.

Dispersion of satellite transmission in the ionosphere causes group-delay distortion. An assessment of this distortion is of interest to the feasibility of FM in television broadcasting at 900 MHz.

The refraction index of the ionosphere near 900 MHz is approximately

$$n \approx 1 - \frac{1}{2}\left(\frac{f_p}{f}\right)^2 \qquad (2\text{-}38)$$

where $f_p = \sqrt{80.5N}$, the plasma frequency, Hz

$N =$ electron density, electrons/m^3

Hence, the differential path length is

$$\phi(f) = \frac{2\pi f}{c}\int (n-1)ds = \frac{\pi}{cf}\int f_p^2 \ ds$$

or

$$\phi(f) = \frac{80.5}{cf}\int N ds = \frac{80.5}{cf} N_T \qquad (2\text{-}39)$$

where the integrations are carried out along the transmission path, and N_T is the integrated electron density on the transmission path.

Using the expansion

$$\frac{1}{f} = \frac{1}{f_o}\left[1 - \frac{f-f_o}{f_o} + \left(\frac{f-f_o}{f_o}\right)^2 - \left(\frac{f-f_o}{f_o}\right)^3 \cdots\right] \qquad (2\text{-}40)$$

of $1/f$ about the center frequency f_o, in Equation (2-39) for $\phi(f)$, and taking the derivative $d\phi(f)/df$, gives after some manipulation:

$$\tau(f) = \frac{1}{2\pi} \cdot \frac{d\phi(f)}{df} \approx \tau(f_o) - \tau_1 \cdot (f - f_o) + \tau_2 \cdot (f - f_o)^2 \quad (2\text{-}41)$$

where

$\tau(f)$ = group-delay

$\tau_1 = 2.7 \cdot 10^{-10} \frac{N_T}{f_o^3}$ nanosecond/MHz, linear group delay

$\tau_2 = 4.0 \cdot 10^{-10} \frac{N_T}{f_o^4}$ nanosecond/MHz^2, parabolic group delay

f = RF frequency, MHz

f_o = RF center frequency, MHz

N_T = integrated electron density, electrons/m^2

With an integrated electron density of 10^{18} electrons/m^2, representative for satellite transmission arriving at a low angle above the horizon during unfavorable ionospheric conditions, the group-delay coefficients for 900 MHz become:

τ_1 = 0.37 nanosecond/MHz

$\tau_2 = 6.2 \cdot 10^{-4}$ nanosecond/MHz^2

The impact of these variations on picture quality is discussed in Section 3.3.1. Table 3-7 of that section gives allowable magnitudes for linear and parabolic group delay variations, based on CCIR limits on differential gain and phase of the color subcarrier in NTSC systems. A comparison between the above values and the allowable magnitudes in Table 3-7 shows one potential problem. The linear group delay variation due to ionospheric dispersion appears to cause a differential phase of ±3 degrees under the unfavorable conditions mentioned above. This exceeds CCIR limits for a 2500 km long circuit by 50 percent. Under average conditions, the ionospheric contribution to differential phase is an order of magnitude smaller.

In conclusion, ionospheric dispersion at 900 MHz appears not to be a critical problem.

2.8 MAN-MADE NOISE

Man-made noise affects the requirements on spacecraft power for television broadcast satellite services at 900 MHz, and perhaps at 2500 MHz.

The main sources of this indigenous noise are automobile ignition, electric power lines, rotating machinery, and switching transients. Man-made noise is typically impulsive with a high peak-to-RMS ratio. The description and definition of its semi-random time-function and its spectral properties is far more intricate than for thermal noise. Unfortunately, available experimental data are few and often not comparable because of differences in measurement methods and conditions. In some investigations, a quasi-peak value of the envelope was measured; in others, average power, average envelope voltage, or average logarithm of the envelope voltage. Measurements of the amplitude probability distribution (APD) permit some correlation between the results of different investigators. Little data is available on autocorrelation and other time-distribution characteristics. In addition, the impact of man-made noise on picture quality as subjectively experienced by viewers is not sufficiently understood to determine what specific characteristics of man-made noise are most meaningful for system design.

The man-made noise component of the antenna noise temperature is

$$T_A = \frac{1}{4\pi} \int_{4\pi} T_i \, G \, d\Omega \qquad (2\text{-}42)$$

In this integral over 4π steradians, T_i represents the effective brightness temperature of man-made noise, G is the antenna power gain relative to an isotropic antenna, while Ω is solid angle. Let ψ be the highest angle of arrival for man-made noise, and $\overline{G}_i$ the average gain over all directions with elevations between O and ψ. Then, if the brightness temperature is reasonably constant over these directions, Equation (2-42) can be simplified to

$$T_A \approx \frac{\overline{G}_i \psi}{2} \, T_i \qquad (2\text{-}43)$$

Clearly, experimental data stated in terms of antenna noise temperature must be viewed with the characteristics of the test antenna in mind.

Measurements with a vertical half-wave-dipole or short dipole antenna were reported by the Institute for Telecommunications Sciences and Aeronomy (ITSA) (Reference 2-14), by ITT (Reference 2-15), and by RCA (Reference 2-16). Conversion of these data to 0-db antenna gain at low elevations results in antenna noise temperatures at 900 MHz of 11,600°K, 8100°K, and 4600°K, respectively. The data from ITSA and RCA were measured in urban areas while the ITT data were presented as median values for the U.S.

Measurements performed at noisy locations in Cleveland, Ohio, by NASA Lewis Research Center (Reference 2-17), using a corner reflector antenna, gave average antenna noise temperatures at 950 MHz of 2400 to 6800°K with zero antenna elevation and 1150 to 4300°K with the antenna pointed 45 degrees above the horizon.

Recently, a survey of man-made noise in Phoenix, Arizona, was performed by the Convair Division of General Dynamics under contract with NASA Lewis. The results of these experiments are currently being processed. The few data available at this time (Reference 2-18) indicate an antenna noise temperature of 2500°K at 1 GHz. This value represents the maximum of RMS voltages for 3-second periods in an 8-minute test run. The antenna used was a helix with a gain of 11 db, a 34 by 37 degree beam, located about 20 foot above the ground and pointed in horizontal direction. From data in Reference 2-18, it is estimated that $\overline{G} = 0.25$ for $\psi = 0.44$ radians. Then, the antenna noise temperature for an omnidirectional antenna with 0-db gain at elevations below 0.44 radians would have been 2200°K. This value is low compared with the corresponding noise temperatures measured with dipole antennas mentioned above.

Clearly, the data discussed here are far from sufficient in number and definition to arrive at reliable predictions for television broadcast satellite applications. An antenna noise temperature of 2000°K at 900 MHz has been used in this study for a 6-foot parabolic antenna with a peak gain of 20 db and a 3-db beamwidth of 14 degrees. This estimate was made for urban residential areas. Considering that the antenna gain outside the main beam is in average a few decibel below zero, the measurement results discussed above do support rather than discredit the estimate of 2000°K, provided that the antenna is pointed sufficiently high, above 30 degrees, to keep sources of man-made noise outside the main lobe.

Experimental data seem to indicate that the level of man-made noise varies with frequency as $f^{-2.3}$. Noise temperatures at 2500 MHz are then 10 times lower than at 900 MHz, and therefore, 200°K was used in this study.

2.9 EARTH-TO-SATELLITE TRANSMISSION

The spacecraft antenna for reception of television transmission from a transmitting earth station must be given sufficient beamwidth to permit a choice of location for this station (relative to the area covered by the satellite transmission) dictated by the operational requirements of the particular application. On a satellite with an earth-oriented body, the receiver antenna could be body-mounted, provided that a sufficiently unobstructed location exists. On a satellite with sun-oriented body, the receiver antenna would follow the transmitter antenna in its rotation relative to the body. In either case, the need for separate gimbals for the receiver antenna should be avoided by using a sufficiently large beamwidth. Here, a beamwidth of 10 degrees is assumed as sufficient to allow for freedom in locating the transmitting earth station and to accommodate attitude errors of the antenna mount.

The stipulation of a minimum beamwidth for the satellite receiver antenna places a ceiling on the gain, in essence independent of the uplink frequency. For the assumed beamwidth of 10 degrees, the beam-edge gain is estimated at 21 db.

While the satellite receiver antenna is limited in gain, economical and practical considerations limit the diameter of the transmitter antenna at the earth station. The transmission loss (from transmitter antenna terminal to receiver antenna terminals; in ideal propagation medium) between a transmitter station with given effective aperture and a receiver station with given antenna gain is independent of frequency. Therefore, the variation in transmitter power requirements with frequency is due to only variations in the attenuation by the propagation medium and variations in the system noise temperature. This conclusion indicates a preference for the frequency range 2000 MHz to 10,000 MHz. An additional consideration is the size of the receiver antenna, which should be sufficiently small to minimize its impact on the spacecraft design problems. By selecting an uplink frequency above 3000 MHz, the 10-degree beamwidth can be obtained with an antenna diameter of 2.5 foot.

In conclusion, the preferred range for selection of the uplink frequency is 3000 to 10,000 MHz. The exact choice will depend on the frequency allocations available for the particular application.

For FM transmission from the spacecraft to the user receivers, FM is also the obvious choice for the earth-to-satellite transmission, both from the viewpoint of earth transmitter power conservation and simplicity of the satellite repeater. The uplink modulation is then fully identical to the downlink modulation, with magnitude of the frequency deviation chosen for minimum-power requirements by the design method outlined in Section 2.4. The satellite repeater merely converts the frequency and amplifies the FM signal.

By designing the uplink for a C/T-ratio, between carrier power and system noise temperature, 13 db higher than required at the user receiver, the uplink noise correction in the downlink sizing is limited to 0.2 db. For a typical C/T requirement of -139.6 dbw/^{o}K (picture quality: fine, TASO Grade 2) at the user receiver, the uplink must be designed for C/T = -126.6 dbw/^{o}K. The RF power budget in Table 2-14 shows that the requirement is met by an earth station with a transmitter output power of 1 kw and a 42-foot antenna. This budget was made for an uplink frequency of 5000 MHz, chosen for convenience only. As pointed out earlier in this discussion, the requirements on a transmitter power and antenna size are essentially independent of frequency.

For AM/VSB transmission from the spacecraft, use of the same modulation of the uplink would eliminate the need of modulation conversion of the satellite. For the picture quality "fine-passable," TASO Grade 2.5, C/T = -122.0 dbw/^{o}K is required at the user receiver. Again limiting the uplink noise correction to 0.2 db, the uplink must be designed for C/T = -109 dbw/^{o}K, which requires that the received signal power at the satellite is 17.6 db higher than in the FM case. With a 60-foot antenna at the earth station, the transmitter output power would have to be 50 kilowatts, (sync peak level), while the average output power would vary with picture content between 30 and 60 kilowatts.

Table 2-14. Uplink Power Budget

Transmitter output power (1 kw)	+ 30.0 dbw
Antenna gain (42 ft)	+ 54.4 db
Free-space loss	-198.2 db
Polarization losses and propagation medium losses	- 1.5 db
Satellite antenna gain	+ 21.0 db
Received power	- 94.3 dbw
Receiver system noise temperature ($T = 1800^{o}K$)	32.6 db (^{o}K)
C/T	-126.9 dbw/^{o}K

Because of this large power requirement, FM is recommended for the uplink even when the satellite transmit AM/VSB signals to the users. This requires that the satellite communication subsystem demodulates the received FM signal and modulates the downlink carrier. Uplink noise is thus converted to video noise at the satellite. In this case, it is the weighted picture signal-to-noise ratio, $(S/N)_{p,w}$ for uplink noise only that must exceed the value required at the user receiver by 13 db in order to limit the uplink noise correction in downlink sizing to 0.2 db. For picture quality "fine-passable," TASO Grade 2.5, $(S/N)_{p,w}$ must be 37 db, and therefore, the uplink must be designed for $(S/N)_{p,w} = 37 + 13 = 50$ db. For the latter criterion, minimum-power design of the uplink (i.e., selection of the optimum magnitude of the frequency deviation) leads to $C/T = -137.1$ dbw/^{o}K for the uplink noise only. This can be achieved by an earth station with a transmitter power of 200 watts and a 30-foot antenna.

This requirement is lower than for transmission to FM satellites. The reason, therefore, is that the demodulation of the FM uplink transmission makes the selection of uplink frequency deviation independent, and the deviation magnitude, therefore, can be optimized for the 13-db higher performance required from the uplink.

2.10 DOWNLINK POWER BUDGETS

The RF power budgets presented in Tables 2-15, 2-16,and 2-17 apply to the satellite configurations presented in Section 7.

The budget in Table 2-15 is for a satellite transmitting directly to home receivers. The frequency, at or near 900 MHz, is within the UHF band allocated for television broadcasting. By using AM/VSB, the RF bandwidth that must be cleared in the UHF-TV band is kept to a minimum, while the need for modulation conversion at the receivers is eliminated. The satellite transmitter antenna with a 3-db beamwidth of 3 degrees covers an area of 1 million square st. miles (2.7 million square kilometers) when pointed at the subsatellite point. The system noise temperature of 2500^{o}K, used in the budget, allows for an antenna noise temperature of 1500^{o}K or 2000^{o}K from man-made noise when the adapters at the earth receivers provide one or two stages, respectively, of preamplification by junction field effect transistors. The earth receivers are equipped with a 6 foot (1.8 m) parabolic antenna. The picture quality for color television, a function of C/T, is then 4 db below "fine" (TASO Grade 2) and 4 db above "passable" (TASO Grade 3). The satellite transmitter output has a peak envelope power of 13.2 kw (occurring during sync peaks), and averages between 2.5 kw and 7.3 kw, depending on the picture content.

The budget in Table 2-16 is for a FM-TV channel at 2.5 GHz. The satellite transmitter antenna has again a beamwidth of 3 degrees, resulting in an area coverage of 1 million square st. miles (2.7 million square kilometers) when pointed at the subsatellite point. The earth receiver antenna is again a 6 foot (1.8 m) parabolic dish.

The system noise temperature, 800^{o}K, is for an adapter with preamplification by one bipolar transistor stage. The picture quality is "fine" (TASO Grade 2) for color television with one sound channel. The satellite transmitter output power is 300 watts per television channel. The satellite configuration for 2.5 GHz (see Section 7), with an array power of 4 kw (at the end of 5-year life) supports seven TV channels. A requirement for four sound channels per television channel would reduce the capacity of the satellite to five TV channels, or six channels with slightly reduced picture quality.

Table 2-15. AM/VSB Broadcasting at 900 MHz

Transmitter Output Power	(13.2 kw)	+41.2 dbw
Circuit Losses		- 0.5 db
Antenna Gain	(30 ft, 3 deg)	+31.0 db
ERP at Beam-Edge		+71.7 dbw
Free-Space Loss		-183.2 db
Propagation Medium Losses		0 db
Polarization Losses		- 0.5 db
Receiver Antenna Gain	(6 ft, 14 deg)	+21.0 db
Received Power		-91.0 dbw
Receiver System Noise Temp.	(2500°K)	-34.0 db(/°K)
Uplink Noise		- 0.3 db
10 Log $\frac{C}{T}$		-125.3 dbw/°K)

C = Average during sync peak

Table 2-16. FM Broadcasting at 2.5 GHZ

Transmitter Output Power	(300 watts)	+24.8 dbw
Circuit Losses		-1.5 db
Antenna Gain	(10 ft, 3 deg)	+32.0 db
ERP (at Beam-Edge)		+55.3 dbw
Free-Space Loss		-192.2 db
Propagation Medium Losses		0 db
Polarization Losses		-0.5 db
Receiver Antenna Gain	(6 ft, 5.2 deg)	+27.0 db
Received Power		-110.4 dbw
Receiver System Noise Temp	(800 ^{o}K)	-29.0 db(/^{o}K)
Uplink Noise		-0.3 db
10 Log $\frac{C}{T}$		-139.7 dbw (/K^{o})

Table 2-17. FM Broadcasting at 12 GHZ

Transmitter Output Power	(5 kw)	+37.0 dbw
Circuit Losses		-1.5 db
Antenna Gain	(4.5 ft, 1.5 deg)	+38.0 db
ERP at Beam-Edge		+73.5 dbw
Free-Space Loss		-205.8 db
Propagation Medium Losses		-3.0 db
Polarization Losses		-0.5 db
Receiver Antenna Gain	(2 ft, 3 deg)	+31.0 db
Received Power		-104.8 dbw
Receiver System Noise Temp.	(2800 ^{o}K)	-34.5 db (/^{o}K)
Uplink Noise		-0.3 db
10 Log $\frac{C}{T}$		-139.6 dbw(/K^{o})

The budget in Table 2-17 is for a FM-TV channel at 12 GHz. The satellite transmitter antenna in this case has a beamwidth of 1.5 degree, covering an area of 0.25 million square st. miles (10.7 million square kilometers). The diameter of the parabolic receiver antenna of only 2 foot (0.6 meter) results in a beamwidth of 3 degrees. Then, the pointing accuracy required does not impose too stringent requirements on the rigidity of the building or pole on which the antenna is mounted or the technical capability and equipment for installing the antenna. The system noise temperature of 2800°K, used in the power budget, assumes a noise figure of 10 db, and an antenna noise temperature of 180°K due to precipitation and clouds. A temperate climate is assumed.. The 10-db noise figure is achievable with a state-of-the-art mixer without preamplification. The value for C/T in the budget is for color television of "fine" quality (TASO Grade 2) with one sound channels.

The system capacity can be improved by using a dual mixer with Schottky-barrier diodes in the receiver adapter. Without RF preamplifier, the noise figure attainable by 1975 is estimated at 7 db, yielding a system noise temperature of 1300°K. The satellite, with a solar array capacity of 8 kilowatts at the end of 5-year life, could then transmit two channels. Alternatively, the satellite could transmit one TV channel to receivers in tropical climate with an attenuation of up to about 6 db by precipitation and clouds, or up to 5 db when four sound channels are required.

SECTION 2 REFERENCES

2-1. CCIR "Documents of the XIth Plenary Assembly," Oslo, 1966, Vol. V; International Telecommunication Union, Geneva.

2-2. CCIR "Documents of the XIth Plenary Assembly," Oslo, 1966, Vol. IV, Part (1).

2-3. CCIR "Documents of the XIth Plenary Assembly," Oslo, 1966, Vol. IV, Part (2).

2-4. EIA Standard RS-250-A, "Electrical Performance Standards for Television Relay Facilities," Engineering Department, Electronic Industries Association, Washington, D. C.

2-5. "Engineering Aspects of Television Allocations," Report of the Television Allocations Study Organization to the Federal Communications Commission, March 16, 1959.

2-6. Barstow and Christopher, "The Measurement of Random Video Interference to Monochrome and Color Television Picture; AIEE Transactions," November 1962.

2-7. Davenport and Root, "An Introduction to the Theory of Random Signals and Noise," McGraw-Hill, 1958.

2-8. J. J. Bisaga, "The Application of TASO Random Noise Data to FM-TV System Design," Communications and Systems, Inc., Technical Memorandum NASW-1216, December 2, 1968.

2-9. C. C. I. T. T., IIIrd Plenary Assembly, Geneva 1964, Red Book, Vol. V.

2-10. C. C. I. T. T., IIIrd Plenary Assembly, Geneva, 1964, Blue Book, Vol. III.

2-11. J. Avins, "Sound Signal-to-Noise Ratio in Intercarrier Sound Television Receivers," BTR-9, July 1963.

2-12. Test results obtained from Mr. Robert Alexovich of NASA Lewis Research Center.

2-13. "Final Acts of the Extraordinary Administrative Radio Conference to Allocate Frequency Bands for Space Radiocommunication Purposes," Geneva, 1963, International Telecommunication Union, Geneva.

2-14. "Status of Information on Man-made Radio Interference," July 26, 1966, JTAC Subcommittee 63. 1. 3, Unintended Radiation.

2-15. "Reference Data for Radio Engineers," Fourth Edition, I. T. T.

2-16. "A Voice From Space," Final Report, Voice Broadcast Mission Study (Contract NASW-1476), May 1967, prepared for NASA Headquarters by Astro-Electronics Division, Defense Electronic Products, RCA, Princeton, New Jersey.

2-17. G. Anzic, "UHF Noise Measurement Results," January 1968, Internal Report, Spacecraft Technology Division, NASA Lewis Research Center.

2-18. "Measurement and Analysis of Radio Frequency Noise in Urban, Surburban, and Rural Areas," A. H. Mills, February 1, 1969; Final Report on Contract NAS3-9714, prepared for NASA by Convair Division of General Dynamics.

3. COMMUNICATIONS SUBSYSTEM

3.1 HIGH-POWER RF OUTPUT AMPLIFIERS

3.1.1 Efficiency Enhancement

Recent studies (References 3-1 through 3-5) of RF amplifiers for spaceborne broadcast transmitters resulted in the analytical designs listed in Table 3-1. In these studies, performed under contract with NASA/Lewis Research Center, primary emphasis was on achieving high overall efficiency. The methods considered herefore were multistage collector depression, voltage jumps between successive sections of the slow-wave circuit, output cavities with extended interaction (double-gap), and tapering of the axial phase velocity of the slow-wave circuit.

Table 3-1. RF Amplifier Design Studies

	Modulation	AM/VSB		FM		
	Frequency	850 (MHz)	2,000 (MHz)	2,000 (MHz)	8,000 (MHz)	11,000 (MHz)
	RF Output Power	7.5 (kw)	5.0 (kw)	5.0 (kw)	5.0 (kw)	5.0 (kw)
Type	Contractor					
Traveling-wave Tubes	Hughes	X	X	X	X	X
Electromagnetically Focused Klystrons	General Electric	X	X	X	X	X
Electrostatically Focused Klystrons	Litton	X	X	X	X	X
Crossed Field Amplifiers	SFD	X	X			
Crossed Field Amplifier	Litton			X		

Multistage collector depression is featured in all designs resulting from these studies. Such collectors, with the electrode potentials depressed below that of the slow-wave circuit (last section), decelerate the electrons before collection, thus reducing the power lost as heat by electron impact on the collector. The collector depression is a powerful tool since it affects the major loss in high-power RF amplifiers. Since RF output power is induced by electron velocity modulation, the velocity spread increases with RF output power. The multistage collector allows a larger electron energy recovery than a single collector by using electrodes at a range of potentials, selected such that each electron can be collected at a potential corresponding closely to its kinetic energy. The sorting of electrons between electrodes is achieved through dispersion by an electrostatic field and by a transverse magnetic field. The magnetic dispersion, incorporated in the TWT designs by Hughes and introduced in Litton's final report on electrostatically focused klystrons, is the more effective one, since it makes electron dispersion independent of space charge in the collection region, while deceleration is not needed until a fair degree of dispersion has been achieved. However, dispersion by space charge in the injection hole into the collection region is always present, regardless of sorting technique. Further, continuation of magnetic fields into the collection region establishes a risk of cycloiding instabilities.

Let P_b be the beam power at entry into the collector region, in the absence of RF drive. With RF drive present, a fraction η_i of P_b is converted into RF power. Of the fraction $1 - \eta_i$ left in the spent beam entering into the collector region, a fraction η_{rc} is recovered by collector depression. Consequently, the RF output power is

$$P_{rf} = \eta_i P_b \tag{3-1}$$

ignoring ohmic losses in the circuit, while the collector dissipation is

$$P_d = (1 - \eta_i)(1 - \eta_{rc})P_b \tag{3-2}$$

The collector power consumption becomes

$$P_c = P_{rf} + P_d \quad 1 - \eta_{rc}(1 - \eta_i) \quad P_b \tag{3-3}$$

Ignoring beam interception losses, RF circuit losses, heater power, and focusing power (if by solenoid), the overall efficiency is found to be

$$\eta = \frac{\eta_i}{1 - \eta_{rc}(1 - \eta_i)} \tag{3-4}$$

Without collector depression (i.e., $\eta_{rc} = 0$), the overall efficiency η equals the internal efficiency η_i. If, for instance, the internal conversion efficiency η_i is 40 percent, then recovery of 85 percent of the power in the spent beam raises the overall tube efficiency from 40 to 82 percent.

3.1.2 Amplifier Categories

The TWT designs (Reference 3-1) use a coupled bandpass filter cavity structure. The advantages of this type of slow-wave circuit over a helix are the greater power handling capability and the possibility of achieving high interaction impedance by designing for the small relative bandwidth required. High interaction impedance improves efficiency and gain per unit length. A multivoltage jump taper is used to gradually restore spent electron energy and thereby maintain synchronization with the constant axial phase velocity of the circuit. This scheme has the advantage over a velocity taper (gradually decreasing axial phase velocity along the circuit) that the interaction impedance is not reduced. Further efficiency enhancement is achieved by a four-stage depressed collector. The accurate velocity sorting required for efficient electron recovery is achieved by transverse magnetic deflection and electrostatic deceleration. The adverse effect of radial electron velocity in the spent beam is reduced by extending the magnetic beam focusing beyond the output coupler. For output amplifiers at 850 and 2000 MHz, periodic permanent focusing is used. The pole pieces are integrated with the coupled cavities. For 8000 and 11,000 MHz, focusing by a "wrapped-on" copper solenoid was found to be more advantageous from the viewpoints of total weight (including solenoid power supply) and state of the art.

For amplification of AM/VSB transmission, the final TWT stage operates with constant drive power and grid-controlled gain. The constant drive power and the varying grid voltage are derived from the AM/VSB signal by a limiter-driver chain and an envelope detector, respectively. In this scheme, the gain of the final stage is controlled by beam current modulation. The TWT then operates close to saturation over the entire dynamic range of the AM/VSB signal, thus avoiding the low average efficiency inherent with the conventional operation of linear amplifiers. The gain of the final TWT is modulated between 0 and 20 db. The phase modulation present in AM/VSB signals, because of the unsymmetry in RF spectrum, is present in the constant power RF drive signal since it is derived by limiting the AM/VSB signal.

The designs of magnetically focused klystrons (Reference 3-2) use four identical buncher cavities (five for 2000 MHz FM) and one output cavity. All cavities are double-reentrant and use a single gap. High internal conversion efficiency is achieved by using an optimum beam perveance of 0.5×10^{-6} A/$V^{3/2}$, detuning of the penultimate cavity, and by judicious cavity design. The other cavities are stagger-tuned to obtain the required bandwidth. Amplitude linearity of the AM/VSB designs is achieved by designing for an internal conversion efficiency η_i not exceeding 60 percent at sync peak level. Further improvement in overall amplifier efficiency is obtained by a four-stage depressed collector with radial electron sorting by an electrostatic field. For all amplifiers, focusing by solenoid is preferred from the viewpoint of total weight (including solenoid power supply).

The designs of electrostatically focused klystrons (Reference 3-3) use three buncher cavities (four for 2000 MHz FM) and a double-gap pi-mode, extended interaction output cavity. All cavities are double-reentrant. Low perveance was chosen for efficiency. The heavily loaded extended interaction output cavity limits the peak RF voltage across the gap of this cavity to approximately half the beam voltage, thereby reducing the velocity spread in the spent beam. The resulting improvement in the electron energy recovery coefficient η_{rc} is from 42 percent (for matched loading) to 84 percent, which leads to improvement in overall tube efficiency despite the decrease in internal conversion efficiency η_i.

For the same reason, i.e., the reduction of electron velocity spread, a voltage jump of 40 percent is applied between the penultimate cavity and the output cavity. This jump raises the velocity of slow electrons more than the fast ones. The collector depression incorporated in the klystron designs uses a three-stage collector with radial electron sorting by electrostatic field. A more efficient scheme, using five-stage collector with sorting through dispersion by a transverse magnetic field is suggested by Litton, but not incorporated in the klystron designs presented in the klystron study report (Reference 3-3).

Beam focusing is performed by electrostatic lenses placed between the successive cavities.

Designs of crossed-field amplifiers for AM transmission were carried out for 850 and 2000 MHz (Reference 3-4). The electron beam flows in a circular path, sustained by a transverse magnetic field, between a circular slow-wave structure and a circular sole. The circuit is a helix loaded bar circuit with 52 or 76 active sections. The depressed collector has 18 or 13 electrodes. Three of these electrodes are below cathode potential. These collect electrons that have absorbed energy from the RF field, and therefore require special power conditioning. The transverse magnetic field is provided by a permanent magnet. The gain of these amplifiers is 20 db at sync peak level. Major difficulties experienced with the velocity spread across the beam may render this design questionable.

A design of a crossed field amplifier for FM transmission was carried out for 2000 MHz (Reference 3-5). The general layout of slow-wave structure and beam is similar to the crossed-field amplifier mentioned above. The depressed collector has 16 electrodes, of which four are below cathode potential. The transverse magnetic field is provided by a permanent magnet. This design may be suitable for AM/VSB too.

3.1.3 Major Characteristics

Tables 3-2 and 3-3 show predicted major characteristics of the various RF amplifier designs. These are identified by the following nomenclature:

TWT	Traveling-wave tubes (Hughes)
EMFK	Electromagnetically focuses klystrons (General Electric).
ESFK 1	Electrostatically focuses klystrons with 3-stage conventional depressed collector.
ESFK 2	Electrostatically focuses klystrons with 5-stage depressed collector using transverse magnetic field.
CFA	Crossed-field amplifiers (SFD for AM/VSB, Litton for FM)

The weight data include the permanent magnet or solenoid for beam focusing, the permanent magnet (if any) for transverse magnetic electron sorting in the collector region, and thermal interfaces. The predicted performance needs a varying degree of verification for the individual amplifier types.

Table 3-2. High-Power RF Amplifiers for Spaceborne AM/VSB Television Transmitters

Frequency, RF Power	Type	Overall Efficiency, at sync peak Percent	Gain, db	Weight, lb (kg)	Largest Dimension, in. (cm)	Cathode Loading, ma/cm^2	Life Predictions, hr†	Focusing	Number of Circuit Voltages	Number of Collector Electrodes
850 MHz 7.5 kw††	TWT	66*	20	324 (142)*	67 (170)	78	50,000	PPM	8	4
	EMFK	76.5	39.5	102 (46)	58 (149)	100	50,000	Solenoid	1	4
	ESFK 1	71.5	40	125 (57)	42 (107)	35	50,000	ESF	2	3
	ESFK 2	81.0***	40	147 (67)	42 (107)	35	50,000	ESF	2	5
	CFA	<70	20	67 (30)**	11 (28)	500	20,000	Permanent Magnet	1	15 + 3
2000 MHz 5 kw††	TWT	69*	20	78 (31)*	26 (66)	142	50,000	PPM	6	4
	EMFK	77.1	49.7	57 (26)	30 (74)	300	>20,000	Solenoid	1	4
	ESFK 1	69.5	40	29 (13)	20 (50)	197	50,000	ESF	2	3
	ESFK 2	77.5***	40	34 (15)	20 (50)	197	50,000	ESF	2	5
	CFA	<70	20	34 (15)**	9 (23)	500-1000	20,000	Permanent Magnet	1	10 + 3

*Includes AM/VSB driver and separate FM amplifier for audio

**Includes AM/VSB driver

***Preliminary data

†See text

††Sync peak level

Table 3-3. High-Power RF Amplifiers for Spaceborne FM Television Transmitters

Frequency, RF Power	Type	Overall Efficiency, percent	Gain, db	Weight, lb (kg)	Largest Dimension, in. (cm)	Cathode Loading, ma/cm^2	Life Predictions, hr**	Focusing	Number of Circuit Voltages	Number of Collector Electrodes
2000 MHz 5 kw	TWT	79	40	70 (32)	35 (88)	142	50,000	PPM	6	4
	EMFK	80.3	47.2	74 (34)	34 (86)	300	>20,000	Solenoid	1	4
	ESFK 1	69.5	40	31 (14)	21 (54)	197	50,000	ESF	2	3
	ESFK 2	79.0	40	31 (16)	21 (54)	197	50,000	ESF	2	5
	CFA	<70	16	46 (21)	19 (48)			Permanent Magnet	1	16
8000 MHz 5 kw	TWT	73.5	40	34 (15)	12 (30)	470	50,000	Solenoid	4	4
	EMFK	75.3	40.2	30 (14)	18 (46)	1400	50,000	Solenoid	1	4
	ESFK 1	68	40	17 (8)	13 (34)	1010	50,000	ESF	2	3
	ESFK 2	77.5*	40	20 (9)	13 (34)	1010	50,000	ESF	2	5
11,000 MHz 5 kw	TWT	71.3	40	29 (13)	9 (24)	490	50,000	Solenoid	4	4
	EMFK	67.4	38.4	35 (16)	18 (45)	2700	>20,000	Solenoid	1	4
	ESFK 1	65	40	16 (7)	13 (33)	1340	50,000	ESF	2	3
	ESFK 2	74.0*	40	19 (9)	13 (33)	1340	50,000	ESF	2	5

*Preliminary data

**See text

The largest dimensions are for the final amplifier package including solenoid and/or magnet, but not thermal radiators.

As far as could be concluded from available data the O-type amplifiers for 850 and 2000 MHz (both AM/VSB and FM) presented in the design studies listed above (References 3-1 through 3-5) use oxide coated cathodes (BaO and SrO coating on nickel base with Zr and W as reducing agents), while the high cathode loading of amplifiers for 8,000 and 11,000 MHz dictate the use of impregnated tungsten cathodes (BaO and CaO impregnated in a matrix of porous tungsten), also called tungsten matrix cathodes or tungstate cathodes.

The amplifier design studies were for a minimum lifetime of 20,000 hours. The present system study considers technology for 5-year missions, or 45,000 hours. Hughes indicates a lifetime of 50,000 hours for its TWT amplifier designs (Reference 3-1). In Tables 3-2 and 3-3, a predicted lifetime of 50,000 hours is indicated when the cathode loading does not exceed 250 ma/cm^2 for oxide coated cathodes or 2000 ma/cm^2 for impregnated tungsten cathodes. For amplifiers exceeding these loadings the table shows that a minimum lifetime of 20,000 hours, as specified by NASA for the tube design studies and acknowledged by the respective contractors, is predicted.

3.1.4 Power Supply Requirements

The power supply requirements differ between types of tubes (klystrons, traveling wave tubes, crossed-field amplifiers). In general, the different tube categories all require the following categories of supply power:

- Heater power: a small, constant load at a voltage below 25 volts, regulated to ±3 percent.
- Field coil power (only for tubes using electromagnetic focusing by solenoid): a constant load on the order of 5 to 10 percent of the sync peak level of RF output power for AM/VSB or the constant CW power for FM, at a voltage below 100 volts, regulated to ±2 percent.

- Up to three voltages for acceleration of electrons. These voltages must be supplied up to 4 electrodes at different potentials, ranging from the lowest to the highest potential at the tube. The currents at these electrodes are constant and small, requiring a total supply power up to 5 percent of the sync peak level of output power for AM/VSB, or the constant CW power for FM. Regulation requirements can be as severe as ±0.05 percent for one voltage and ±0.5 percent for the other(s), if any.

- Collector power: A load distributed over a number of collectors at different potentials distributed over a substantial fraction of the total potential range at the tube. The collector power is the dominant portion of the total supply power required. Voltage regulation of about ±1.0 percent is required.

The power supply requirements for FM transmitters are less stringent than for an AM/VSB transmitter. An important feature of FM transmitters is that each electrode uses a constant current at a constant voltage.

For AM/VSB transmitters the collector load varies with modulation of the RF signal because of the multistage collector depression schemes used for efficiency enhancement. The collector consists of several electrodes at different voltage levels. The electrodes at higher voltage (relative to the cathode) will collect the faster electrons and the low-voltage electrodes, the slower electrons. Since the energy distribution of the spent electrons will vary with the RF output power, the amplitude modulation will affect the distribution of total collector current between the collector electrodes, thus modulating the collector power. All other electrodes use a constant current at constant voltage. An exception to this condition is the AM/VSB transmitter scheme proposed by Hughes (Reference 3-1), where the final TWT stage receives a constant RF drive power and the electron beam is modulated by a control grid. Here, all electrode currents are modulated between peak value and practically zero.

For AM/VSB amplifiers with constant beam power, the variation of total supply power with modulation of the RF output power is due entirely to the variation in collector supply power. From Expression (3-3) for the collector supply power, with $\eta_i = P_{rf}/P_b$ from Equation (3-1) we obtain

$$P_c = (1 - \eta_{rc})P_b + \eta_{rc}P_{rf}$$

Assuming a constant recovery fraction η_{rc}, P_c becomes a linear function of the RF output power P_{rf}. Since circuit losses are proportional to P_{rf}, while beam interception losses, heater power and solenoid power are constant, also the total power consumption becomes a linear function of the output power. This linear relationship is confirmed, at least to a close approximation, by data on overall efficiency at different RF output levels for the tube designs by General Electric, Litton and SFD.

Figures 3-1 and 3-2 show these relationships for AM/VSB transmitters for 850 and 2000 MHz. In these figures, the ordinate and abscissa show total DC supply power and RF output power, respectively, both expressed as fraction of the sync peak level of the RF output power, which is the level commonly used in stating the capacity of an AM/VSB television transmitter. For the CFA designs, the constant power consumption of the TWT driver is included.

The fluctuations in power consumption relate directly to the format of the video signal, which is described in Section 2.1. In most standards for AM/VSB transmission the polarity of the vision modulation is negative, i.e., a larger RF amplitude corresponds to a lower luminance. The RF amplitude varies essentially linearly with the video signal voltage. The rapid fluctuations in instantaneous collector power must be accommodated for by lowpass filters with adequate buffer capacity. However, variations in long-term average still remain. The RF power averages over a line period or a field period are dependent on the picture content. From Figure 2-1 in Section 2.1, it is clear that the largest averages result from an all-black picture and the smallest from an all-white picture. Table 3-4 shows these averages, expressed relative to the sync peak output power. The data on an "average" picture apply to picture signal with uniform voltage distribution over the picture signal voltage range. The field-period average remains constant for the duration of a scene, which can be several seconds, or even longer.

3.1.5 Amplifier Selections for Satellite Designs

In the design of satellite configurations presented in Section 7, the following amplifier types were assumed.

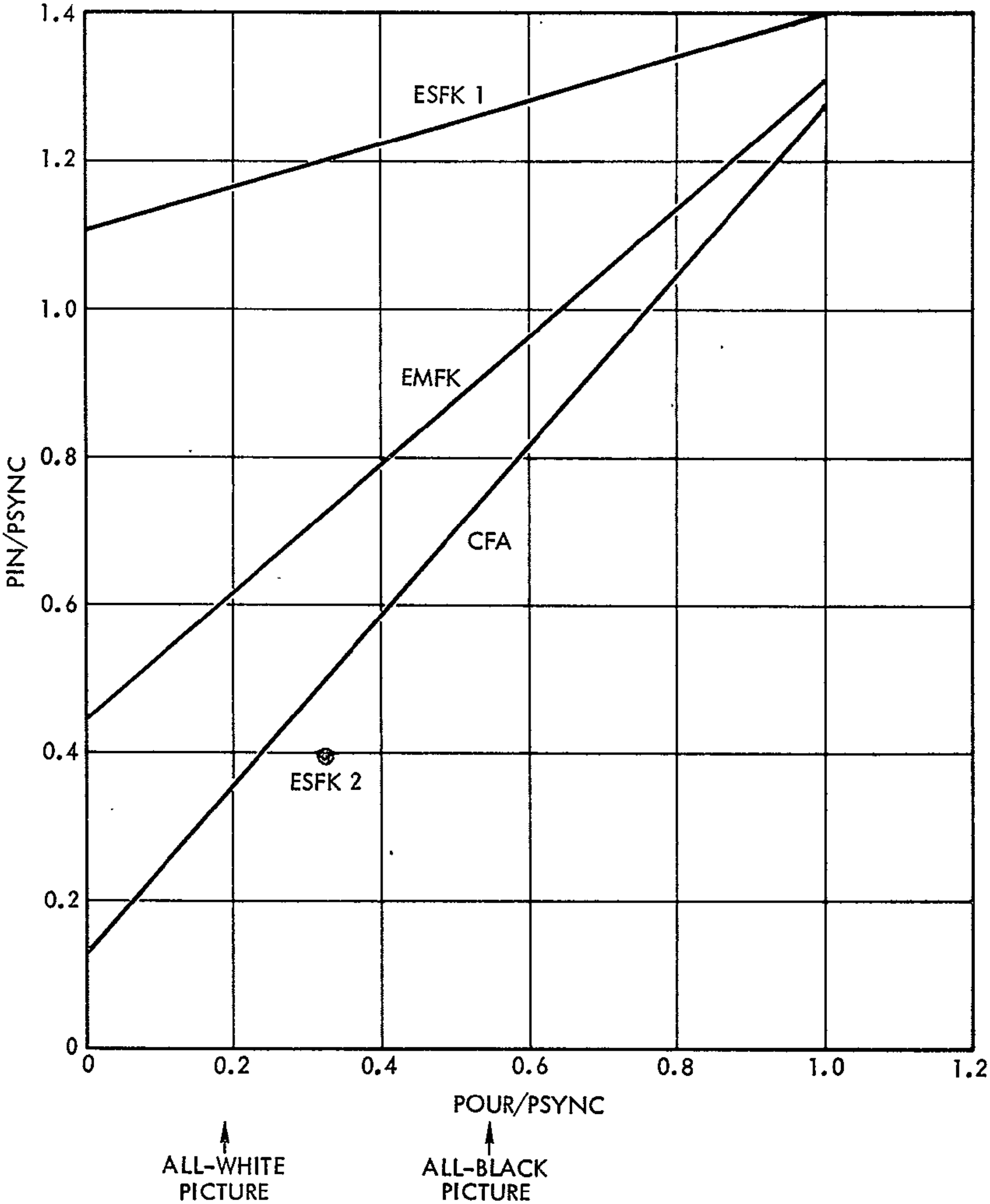


Figure 3-1. AM/VSB Amplifiers for 850 MHz Power Consumption Versus RF Output Power

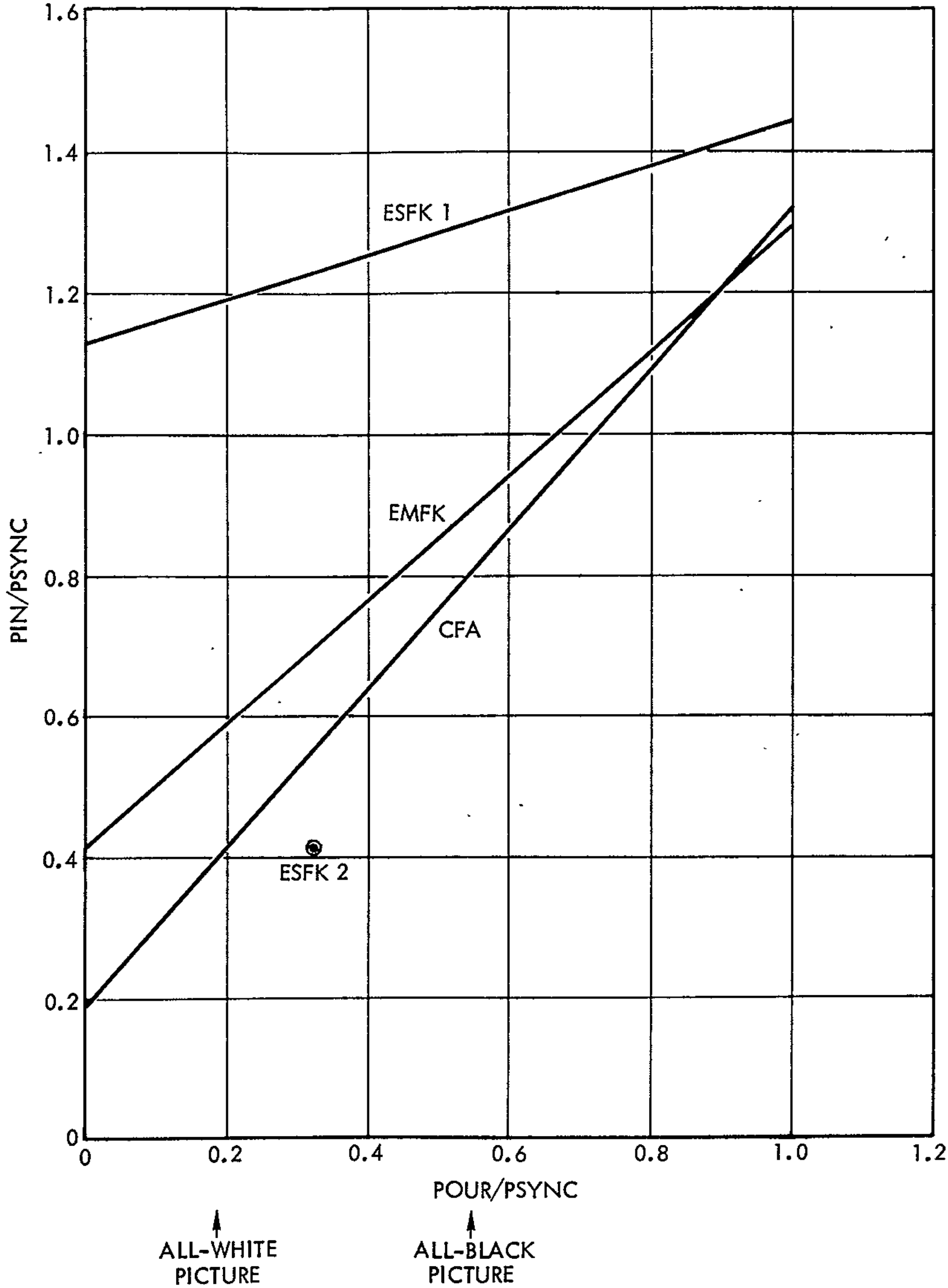


Figure 3-2. AM/VSB Amplifier for 2000 MHz Power Consumption Versus RF Output Power

Table 3-4. Average Values of Transmitter Output Power (Relative to Output Power During Sync Peaks)

	Average Over Line-period	Average Over Field-period
All-black picture	0.54	0.55
Average picture	0.30	0.33
All-white picture	0.15	0.18

3.1.5.1 AM/VSB

The CFA was assumed for AM/VSB transmission because of its low average power consumption, predicted initially, its low weight and small size (Table 3-2).

3.1.5.2 FM

TWT amplifiers are used for FM transmitters because of their high overall efficiency in combination with low cathode loading (Table 3-3), and their superior phase linearity.

3.2 REPEATER CONFIGURATIONS

General considerations on repeater design in Section 3.2.1 are followed by presentation of configuration concepts (Sections 3.2.2 through 3.2.5).

3.2.1 General Considerations

Examination of the earth-to-satellite transmission requirements led to the recommendation of using FM, whether the satellite-to-user transmission is AM/VSB or FM (Section 2.9). Therefore all repeater configurations presented in this report receive FM transmission. A second recommendation (Section 2.9) is to use an uplink frequency in the range from 3000 to 10,000 MHz. The choice of specific frequency band within this range depends on what allocations can be made available for the particular application.

Repeaters for broadcast satellites will have gains larger than found today on operational communication satellites. For television broadcast satellites transmitting FM signals to the users, a typical RF signal level at the repeater input is -94 dbw (Section 2.9). With RF signal power levels of 0.25 to 10 kw (Section 2.10) at the repeater output, the overall repeater gain required is 118 to 134 db, dependent on the particular application. For AM/VSB broadcasting, the repeater input level can be as low as -104 dbw. Overall gains up to 144 db are then required for output levels up to 10 kw.

For comparison, note that the Intelsat III repeaters have a gain of approximately 108 db.

The high transponder gain warrants consideration of three potential problems:

1) Saturation of the receiver input by transmitter output signals in the transmit frequency band.

2) Saturation of the receiver input by harmonics or intermodulation products in the transmitter output, which lie in the receiver frequency band.

3) Instability by feedback via various leakage paths.

The isolation required to eliminate front-end saturation can be provided by a combination of the following methods:

1) The use of different antennas for transmit and receiver with appropriate antenna positions, possibly augmented by shielding. An example of effective shielding by simple means is a short cylindrical collar around the periphery of the receive antenna, mounted in front of the transmit antenna feed. This approach is suitable for the 900 MHz, 12 kw satellite configuration presented in Section 7.2.

2) By attenuation below cutoff in waveguide feeder lines.

3) By filters at the receiver input or transmitter output, as appropriate, in combination with appropriate choice of the uplink frequencey.

4) By shielding the receiver front-end stages.

In cases where the uplink frequency is higher than the downlink frequency by a sufficiently large separation, the downlink frequency is below the highpass cutoff frequency of the waveguide feeder line from the receive antenna. Consequently, considerable attenuation of signals in the transmit band exist in the transmitter-to-receiver path via the antennas. For instance, a standard waveguide for a 5 gHz uplink would have a cutoff frequency of 3.95 gHz, and signals at a transmit frequency of 0.9 gHz will experience an attenuation of 213 db/ft (700 db/m). In another case (Figure 3-5), with an uplink frequency of 4 gHz and a downlink frequency of 2.4 gHz, a standard waveguide with a cutoff frequency of 3.3 gHz has an attenuation of 100 db/ft (325 db/meter). Hence, with proper shielding of the receiver front-end and its connection to the waveguide, saturation does not occur.

With an uplink frequency below the downlink frequency, which may be the case when the downlink operates in the X-band, a filter at the receiver input is the only means available to obtain larger isolation than already provided by the antenna configuration. If proper antenna positions and shielding result in a transmission loss of 40 db (estimated), the filter must attenuate transmit frequencies by up to 120 db.

To protect the receiver against saturation by harmonics and/or intermodulation products in the transmitter output, attenuation at the receive frequency band is required in the transmission from transmitter output to transmit antenna. In cases where the uplink frequency is below the downlink frequency by a sufficiently large separation, this attenuation can be provided entirely as attenuation below cutoff in the waveguide feeder to the transmit antenna. Even then, a filter is required at the transmitter output to prevent out-of-band transmission of the satellite from interfering with other communication services.

Instability of high-gain amplifier chains is an issue of concern. In FM-to-FM repeaters with double frequency conversion, the overall gain is achieved by amplification at three different frequencies, thus resulting in total gain requirements at any one frequency lower than in the single conversion alternative. Consequently, double-conversion repeaters are less prone to instability.

The repeater configurations presented in the following sections (Figures 3-3 through 3-7) use one or two local oscillator signals between 1500 and 10,000 MHz. These signals are derived from a crystal oscillator operating at a frequency on the order of 50 MHz, with a long-term frequency stability of 2×10^{-6}. In the repeater configurations with double frequency conversion, the two LO signals are derived as different harmonics of the same crystal oscillator output. Consequently, the transmitter output frequency variations resulting from frequency conversion are within $2 \times 10^{-6} \times$ (difference between transmit and receive frequencies). For all configurations shown, this variation is less than 10 kHz, an acceptable magnitude.

Derivation of the local oscillator signals from the crystal-controlled reference frequency is achieved by a solid state oscillator, phase-locked to a harmonic of the reference frequency. This oscillator operates at a frequency of about 500 to 1000 MHz dependent on the application. Further frequency multiplication is achieved by harmonic generation in varactors, and filtering. Frequency multiplication by injection phase-locking of an oscillator to a harmonic of a crystal oscillator output has the advantages over conventional varactor or step recovery diode multiplication that the oscillator output is free from spurious signals and has a low noise level. The spurious signals from subsequent frequency multiplication will be separated by at least 500 MHz from the desired mixer output signal and thus are easily removed by filters with a wide passband, attractive from the viewpoint of group delay distortion.

In view of the 5-year life required, solid state local oscillators should be considered. Both avalanche diode oscillators and bulk oscillators are suitable for injection phase locking (Reference 3-6). Avalanche diode oscillators today produce a few watts at frequencies above 5 gHz. At the frequencies of interest here, 500 and 1000 MHz, avalanche diodes in Trapped Plasma Avalanche Triggered Transit (TRAPATT) mode and bulk-effect devices will be able to provide several watts.

The development of solid state amplifiers and oscillators for all frequencies of interest here makes rapid progress. It appears quite possible that by 1975 the repeater configurations presented (Figures 3-3 through 3-7) can be entirely solid state except for the final RF output amplifier stage and, in some cases, the driver stage.

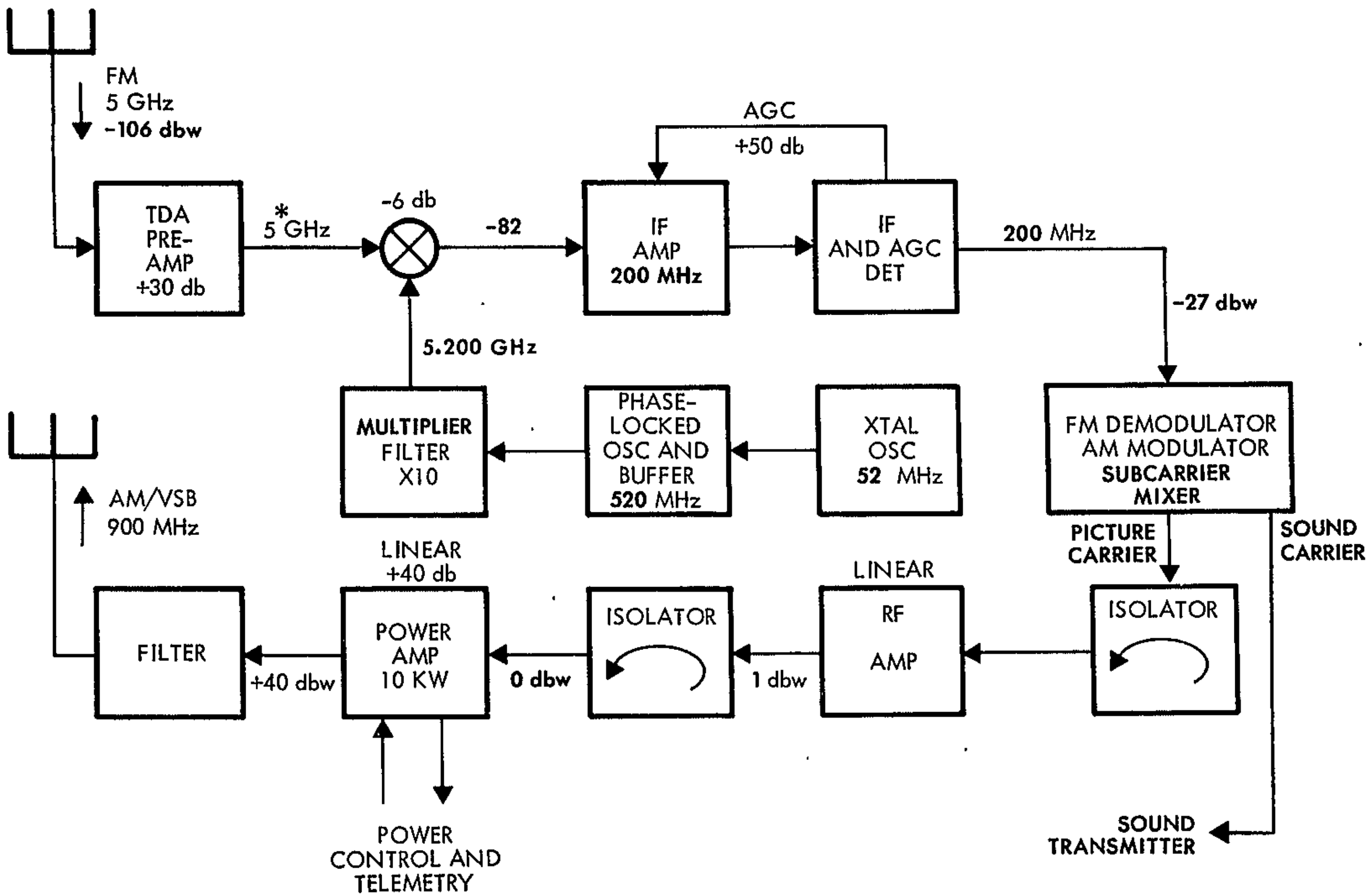
3.2.2 Repeater for AM/VSB Broadcasting at 900 MHz

The repeater configuration for AM/VSB broadcasting at 900 MHz, Figure 3-3, receives a RF carrier, frequency modulated by a baseband consisting of the video signal and a sound subcarrier. After amplification in a 3-stage tunnel diode amplifier, the received RF signal is down-converted to an IF frequency of 200 MHz. The mixer pump signal is derived from a crystal oscillator at 52 MHz with a frequency stability of 2×10^{-6}. A solid state oscillator, injection phase locked to the tenth harmonic of the reference frequency, provides 10 milliwatts at 525 MHz, which is multiplied by 10 to provide 1 mw at 5250 MHz.

The solid state IF amplifier has a bandwidth of 40 MHz. Its bandpass curve is controlled largely by a 5-section Chebyshev filter with a 0.1 db ripple and a 40 MHz wideband of equal ripple response. The out-of-band attenuation is 20 db at 30 MHz from the carrier, and 52 db at 60 MHz.

A conventional FM discriminator, which receives the IF signal at an AGC controlled level, is followed by a baseband diplexer that separates the sound subcarrier from the video signals.

The video signal is used to amplitude-modulate a 900 MHz picture carrier, generated in the repeater. A carrier frequency stability of ±1000 kHz is compatible with present UHF TV channel allocations and user equipment selectivity. The modulated picture carrier is amplified to +1 dbw in a transistorized linear amplifier. The output signal is via an isolator fed into the final amplifier package, which consists of a crossed-field amplifier with a TWT driver stage. The CFA stage and the driver stage each have a gain of 20 db, yielding an output power on the order of 10 kw (sync peak level).



*5 GHz IS ARBITRARY CHOICE

Figure 3-3. Repeater for AM/VSB-TV Broadcasting at 900 MHz

Shaping of the vestigial sideband is achieved in part by a filter at the AM modulator output and is completed by a filter at the final amplifier output.

The frequency of the sound subcarrier in the baseband and its frequency-modulation by the sound channel are in accordance with the intercarrier frequency and modulation characteristics of the TV standard to which the user TV sets are built. Mixing the subcarrier with the (unmodulated) vision carrier frequency, generated in the repeater, provides the frequency-modulated sound carrier. This carrier is amplified in a separate amplifier chain, not shown in Figure 3-3, with a TWT as final output amplifier. Its output power is 2 percent of the picture carrier output power (sync peak level).

3.2.3 Repeater for FM Broadcasting at 0.9 GHz

The repeater configuration for FM television broadcasting at 900 MHz, Figure 3-4, receives an RF carrier (or two RF carriers), frequency-modulated by a baseband consisting of the video signal and one or more sound subcarriers. This RF signal is translated to the downlink frequency of 900 MHz and amplified to the required output power level, which in most applications will not exceed 1 kilowatt per video channel. Repeater gain requirements will in general not exceed the 126 db gain of the configuration in Figure 3-4.

The configuration shown has single frequency conversion with total gains of 30 and 102 db at receive and transmit frequencies, respectively. Protection against spurious feedback is provided by splitting the total gain at 900 MHz between three amplifiers, contained in separate, shielded housings, and using separate, filtered, power conversion units.

All amplifiers ara solid state devices, except for the final amplifier which is a 1 kw TWT with a gain of +40 and a 3 db bandwidth of 60 MHz.

The mixer pump signal is derived from a crystal oscillator operating at 41 MHz. A solid state oscillator at 410 Mhz is injection phase-locked to the tenth harmonic of the reference. Its 10 milliwatt output is frequency-multiplied by 10 to provide a local oscillator signal of 1 mw at 4100 MHz.

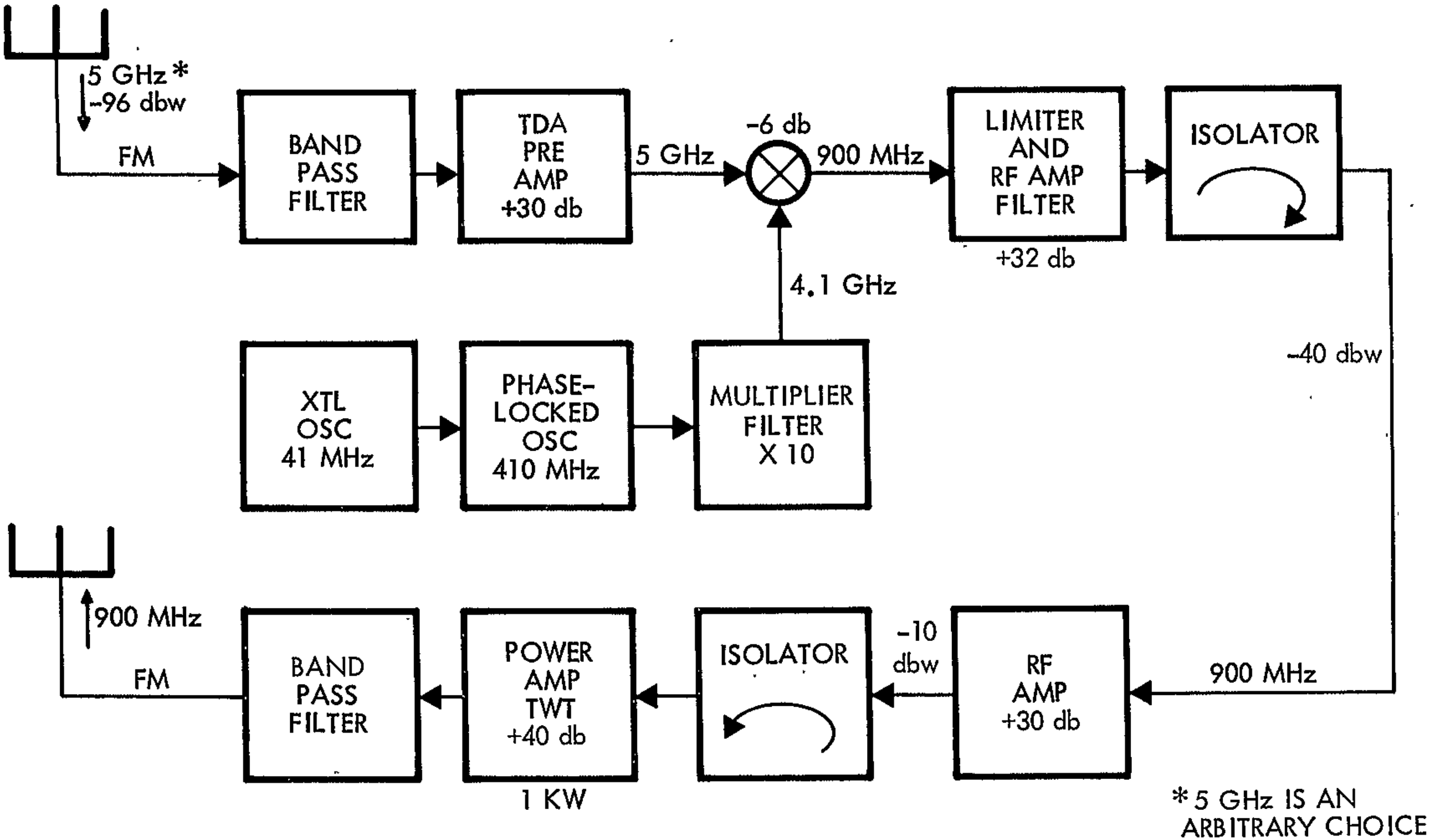


Figure 3-4. Repeater for FM-TV Broadcasting at 900 MHz

FM transmission of a single FM transmission requires a bandwidth of 20 to 40 MHz, dependent on picture quality, number of sound channels and type of demodulator at the user receivers. For color television with picture grade "Fine" (TASO Grade 2), four sound channels, and demodulation by a conventional discriminator, the Carson bandwidth is typically between 25 and 30 MHz. For control of the overall repeater bandpass response, a 5-section Chebyshev filter with a 0.1 db ripple and a 40 MHz wide-passband of equal ripple response is a good choice. Out-of-band attenuation of this filter is 20 db at 30 MHz from the center frequency and 52 db at 60 MHz. The group delay distortion caused by this filter is discussed in Section 3.3.1.

Transmission of two FM/TV signals in a common repeater would require slightly more than twice the bandwidth. The two-carrier saturation level of a TWT amplifier is 1 to 1.5 db below the single-carrier saturation level. In addition, an output power backoff of 1 db below the two-carrier saturation level is required to keep third order intermodulation products at RF within acceptable limits (Section 3.3.2). Therefore, the output amplifier efficiency for two-carrier operation is less than for single-carrier operation, approximately by a factor 1.5 for conventional TWT's, perhaps 1.2 with multistage collector depression (Section 3.1.1). In addition, TWT design for a larger bandwidth results in lower gain.

Two-carrier operation is feasible, but reduces efficiency. Even multicarrier operation of a repeater is possible, but not recommended because of the excessive impairment of efficiency (Section 3.3.2).

3.2.4 Repeater for FM Broadcasting at 2.5 GHz

Repeater output power requirements for frequency-modulated broadcasting at 2.5 GHz will in most applicators be less than 1 kilowatt per television channel (Sections 2.4 and 2.10). The overall repeater gain will be typically about 125 db. Figure 3-5 shows a linear translating repeater with single frequency conversion.

The uplink frequency of 4 GHz, an arbitrary choice (Section 2.9), is not harmonically related to the transmit frequency.

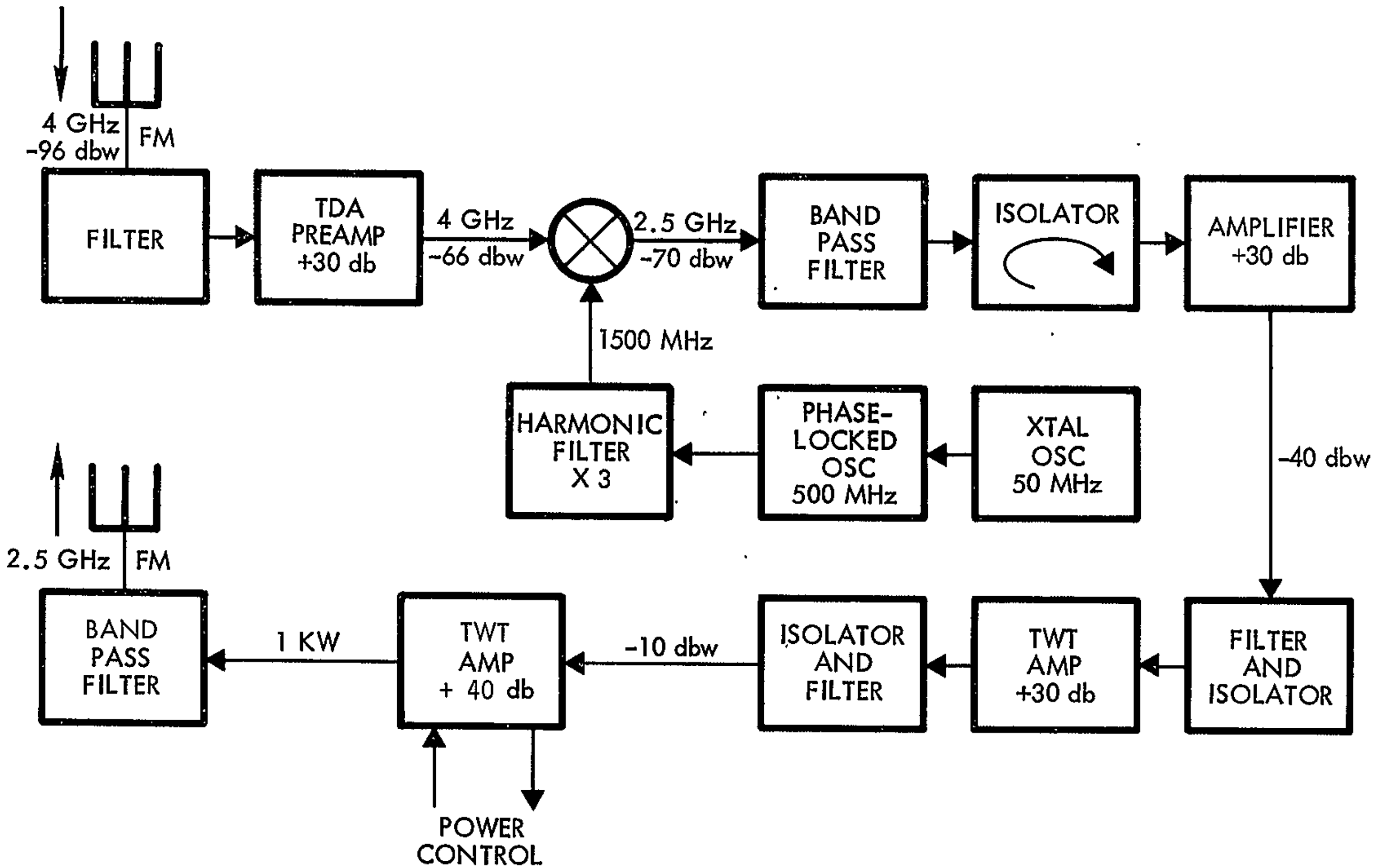


Figure 3-5. Repeater for FM-TV Broadcasting at 2.5 GHz

After amplification in a three stage tunnel-diode preamplifier, the received signal is down-converted to 2.5 GHz and amplified to the final output power of 1 kw. The total gain of 100 db at 2.5 GHz is provided by three amplifiers, in separate, shielded housings and with separate power converters, to prevent undesirable feedback. The first two amplifiers are transistorized (Section 3.4.1), while the final amplifier is a TWT with a gain of 40 db and an output power of 1 kilowatt. Solid state amplification at S-band is discussed in Section 3.4.1.

The local oscillator signal is derived from a crystal oscillator operating at 50 MHz with a long-term stability of 2×10^{-6}. A solid state oscillator, injection phase locked to the tenth harmonic of the 50 MHz reference provides 10 milliwatts at 500 MHz. Multiplication by a varactor then yields a 1 milliwatt mixer pump signal at 1500 MHz.

3.2.5 Repeaters for FM Broadcasting at 8.5 GHz and 12 GHz

Repeater output power requirements for broadcasting at the X-band frequencies 8.5 GHz and 12 GHz will tend to be higher than at 2.5 GHz for the following reasons:

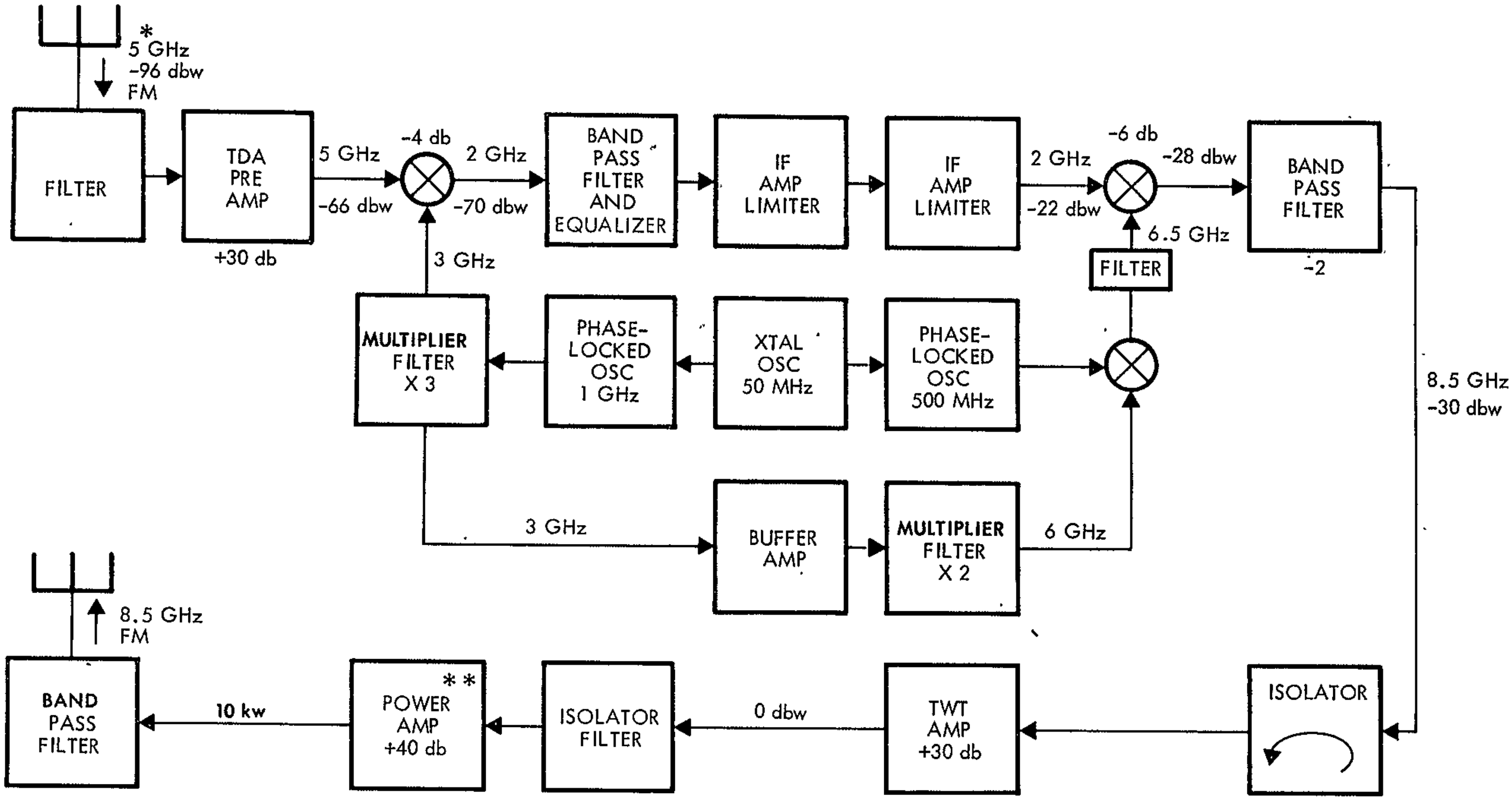
1) Effective apertures of user receiver antennas restricted by limitations on beam-pointing accuracy achievable with low-cost user installations

2) Higher receiver noise figures

3) Attenuation in clouds, fog and precipitation.

This tendency is reflected in Figure 3-6 and 3-7, which show repeater configurations with a 10 kilowatt output power for the two X-band frequencies of interest. The following description applies primarily to the 12 GHz repeater; values for the 8.5 GHz configuration are placed between parentheses.

Both repeaters are linear translators. Double frequency-conversion is chosen to allow maximum use of amplification by solid state devices. A second reason for this choice is that the 10 kw output level requires an overall transponder gain of 136 db, 10 db more than required for FM/TV broadcasting at 900 MHz and 2.5 GHz. Double frequency conversion splits this gain between three frequency bands, and thus relaxes the shielding requirements for control of undesirable feedback. The uplink frequency is 10 GHz (5 GHz), an aribitrary choice (Section 2.9).



* UPLINK FREQ IS AN ARBITRARY CHOICE

Figure 3-6. Repeater for FM/TV Broadcasting at 8.5 GHz

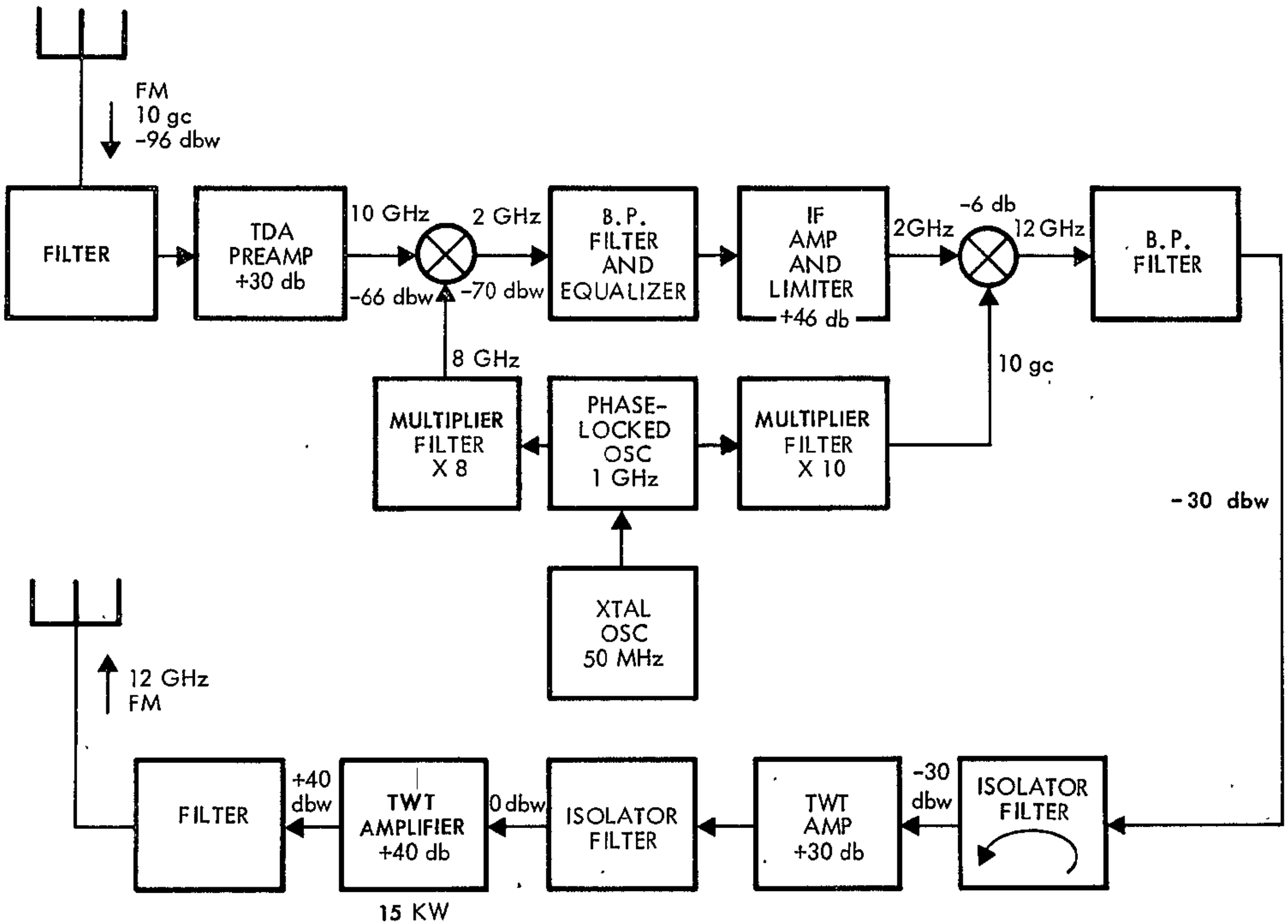


Figure 3-7. Repeater for FM/TV Broadcasting at 12 GHz

The IF frequency is 2 GHz. Solid state amplifiers for S-band are discussed in Section 3.4.1.

Both local oscillator signals are derived from the same crystal oscillator operating at 50 MHz with a long-term stability of 2×10^{-6}. Frequency fluctuations of this reference cause errors less than 4 kHz (7 kHz) in the transmit frequency. The solid state oscillator, operating at 1 GHz provide a 5 watt CW signal from which the two mixer pump signals are derived by a varactor multiplier and a filter. The relatively high signal level at the input of the second mixer, -24 dbw (-22 dbw) led to the choice of a mixer pump signal level on the order of 500 milliwatts to secure a sufficiently high mixer saturation level (Section 3.4.2). Varactor diodes are used in the second mixer.

3.3 LINEARITY

Three aspects of nonlinearity are discussed:

- The differential gain and phase of the color subcarrier, due to phase nonlinearity in the transmission path of FM/TV signals.
- The intermodulation between FM/TV signals, resulting from amplitude nonlinearity in the transmission path of FM/TV signals.
- Amplitude nonlinearity in AM/VSB transmission.

3.3.1 Group Delay Variations in FM Transmissions

Let the nonlinear variation in phase-angle versus frequency in the FM channel be approximated by

$$\theta(F) = \left(\frac{F - F_c}{F_e}\right)^2 \theta_2 + \left(\frac{F - F_c}{F_e}\right)^3 \theta_3 \text{ radians} \qquad (3\text{-}6)$$

where

F = stationary RF (or IF) frequency, MHz

F_c = center frequency of FM transmission, MHz

F_e = frequency distance, selected for convenience in computations, MHz

θ_2 = parabolic phase variation over frequency interval from F_c to $F_c + F_e$, radians

θ_3 = cubic phase variation over frequency interval from F_c to $F_c + F_e$, radians.

Then the group-delay variation is

$$\tau(F) = \frac{1}{2\pi}\frac{d\theta(F)}{dF} = \tau_1\left(F - F_c\right) + \tau_2\left(F - F_c\right)^2 \text{ microseconds}$$

where

$$\tau_1 = \frac{1}{\pi}\frac{\theta_2}{F_e^2}, \text{ the linear group-delay variation, microseconds/MHz}$$

$$\tau_2 = \frac{3}{2\pi}\frac{\theta_3}{F_e^3}, \text{ the parabolic group-delay variation, microseconds/MHz}^2$$

Table 3-5 presents the effects of linear and parabolic variation in group-delay on a two-frequency modulation. The undistorted baseband signal frequency-modulates the carrier with frequency swings $\pm D_1$ and $\pm D_2$ at modulation frequencies F_1 and F_2, respectively. The baseband distortion terms are expressed in terms of instantaneous frequency deviation of the carrier, in MHz. Each term in the table represents terms with i = 1 and k = 2, and terms with i = 2 and k = 1.

Table 3-6 presents differential gain and phase. Acceptable limits on this aspect of nonlinear baseband distortion are specified in terms of amplitude ratios and phase differences of the color subcarrier (or other video frequency) between measurements performed with different steady state levels of the luminance signal. In the table, L represents the steady state luminance level in terms of carrier frequency deviation, in MHz, relative to the carrier frequency corresponding to the level 1/2 (blank + white).

Both tables are the results of elaboration of the analytical approach of Carson and Fry, tailored to the values of modulation characteristics pertinent to FM broadcasting of television.

The luminance signal range over which the differential gain and phase must stay within the specified limits is black-to-white. The corresponding range $2L_{max}$ of frequency deviation (from $-L_{max}$ to $+L_{max}$), the black-to-white deviation, will be between 10 and 20 MHz for broadcast

Table 3-5. FM Distortion Due to Group Delay Deviations

	PARABOLIC PHASE (Linear Group Delay)	CUBIC PHASE (Parabolic Group Delay)
UNDISTORTED FREQUENCY MODULATION	$D_1 \cos 2\pi F_1 t + D_2 \cos 2\pi F_2 t$	
F_1; F_2	$-\theta_2^2\left(\frac{1}{2}\frac{D_i^3 F_i^2}{F_e^4} + \frac{D_i D_k^2 F_i^2}{F_e^4} + \frac{1}{2}\frac{D_i F_i^4}{F_e^4}\right)\cos 2\pi F_i t$	$-\theta_3\left(\frac{3}{4}\frac{D_i^3 F_i}{F_e^3} + \frac{3}{2}\frac{D_i D_k^2 F_i}{F_e^3} + \frac{D_i F_i^3}{F_e^3}\right)\sin 2\pi F_i t$
$2F_1$, $2F_2$	$-\theta_2\left(\frac{D_i^2 F_i}{F_e^2}\right)\sin 2\pi(2F_i)t$	
$3F_1$, $3F_2$	$-\theta_2^2\left(\frac{3}{2}\frac{D_i^3 F_i^2}{F_e^4}\right)\cos 2\pi\,(3F_i)t$	$-\theta_3\left(\frac{3}{4}\frac{D_i^3 F_i}{F_e^3}\right)\sin 2\pi\,(3F_i)t$
$F_1 \pm F_2$	$-\theta_2\left(\frac{D_i D_k (F_i \pm F_k)}{F_e^2}\right)\sin 2\pi\,(F_i \pm F_k)t$	
$2F_1 \pm F_2$ $F_1 \pm 2F_2$	$-\theta_2^2\left[\frac{1}{2}\frac{D_i^2 D_k (2F_i \pm F_k)^2}{F_e^4}\right]\cos 2\pi\,(2F_i \pm F_k)t$	$-\theta_3\left[\frac{3}{4}\frac{D_i^2 D_k (2F_i \pm F_k)}{F_e^3}\right]\sin 2\pi\,(2F_i \pm F_k)t$

Table 3-6. Differential Gain and Phase

UNDISTORTED BASEBAND SIGNAL	$L + D_c \cos 2\pi F_c t$ (luminance + color)	
	DIFFERENTIAL GAIN IN dB	DIFFERENTIAL PHASE IN RADIANS
LINEAR GROUP DELAY	$-8.5\ \theta_2^2\left(2\dfrac{L^2 F_c^2}{F_e^4}\right)$	$-\theta_2\left(2\dfrac{L\ F_c}{F_e^2}\right)$
PARABOLIC GROUP DELAY		$-\theta_3\left(3\dfrac{L^2\ F_c}{F_e^3}\right)$

quality FM transmission. For picture quality grade "Fine" (TASO Grade 2), 10 MHz is a representative value. With threshold extension the optimum black-to-white deviation (for minimum RF power requirement) will be between approximately 15 and 20 MHz, dependent on picture quality requirement and the number of sound channels.

For the color subcarrier in the American 525-line system, the specified limits are 1.2 db between maximum and minimum amplitude, and a phase variation of ±2 degrees. For 625-line systems, color standards have been defined only for the British 625-line system, identified as System I in CCIR documentation. CCIR Recommendation 451 (Reference 2-1) specifies a maximum amplitude deviation of ±8 percent and a phase deviation of ±4 degrees from the references measured with the luminance signal at the blanking level.

The above limits were established for long distance transmission circuits used in distributing programs to broadcast stations. They do not include group-delay variations caused in other elements of the overall studio-to-viewer transmission. Therefore, it is quite possible that differential gain and phase somewhat larger than the CCIR recommended limits is acceptable for satellite broadcasting. Accepted specifications for the overall studio-to-viewer transmission do not exist.

Table 3-7 shows the interpretation of the CCIR limits in terms of the quantities used in Table 3-6. The allocation of differential phase between its two contributions is arbitrary. The table also shows the corresponding limits on linear and parabolic variation of group delay, derived with the expressions in Table 3-6.

To appreciate the impact of these limits on group-delay variations, consider the case where the transponder selectivity is provided by a 5-section Chebyshev filter with a 50 MHz bandwidth (i.e., the bandwidth of equal ripple response) and a 0.1 db ripple.

From curves on group-delay versus frequency (Reference 3-7), it can be concluded that the group-relay in the 50 MHz bandpass filter has a linear variation of 0.19 nsec/MHz and a parabolic variation of 0.025 nsec/MHz^2.

Table 3-7. Differential Gain and Phase, Allowable Group Delay Variations

Television Standard			
Number of lines		525	625
Video bandwidth	MHz	4.2	5.5
Luminance bandwidth	MHz	4.2	5.0
Color subcarrier frequency	MHz	3.58	4.43
Linear Group Delay Variation			
Gain variation over range $O\text{-}L_{max}$	db	1.2	0.7
Allowable group delay variation			
for L_{max} = 5 MHz	nsec/MHz	4.73	2.92
varies with L_{max} as		L_{max}^{-1}	L_{max}^{-1}
Phase variation over range $O\text{-}L_{max}$	deg	1.6	1.6
Allowable group delay variation			
for L_{max} = 5 MHz	nsec/MHz	0.25	0.20
varies with L_{max} as		L_{max}^{-1}	L_{max}^{-1}
Parabolic Group Delay Variation			
Phase variation over range $O\text{-}L_{max}$	deg	1.6	1.6
Allowable group delay variation			
for L_{max} = 5 MHz	nsec/MHz^2	0.05	0.04
varies with L_{max} as		L_{max}^{-2}	L_{max}^{-2}

Further, a high-power TWT output amplifier for FM/TV satellite broadcasting is expected to contribute to the group-delay variation with an average of 0. 083 nsec/MHz (corresponding to 0. 015 degree/MHz^2, Reference 3-1).

Comparison of these contributions with the limits given in Table 3-7, considering that other minor contributions to group-delay variation will be present, indicate that requirements for equalization will be minor, if any at all.

3. 3. 2 Two or More FM/TV Signals in a Common Repeater

The primary limitation on multicarrier operation of a repeater channel is intermodulation due to amplitude nonlinearity.

Unfortunately, available statistical and spectral data on television signals are too few to permit an accurate analysis. Experiments on the particular repeater are needed to obtain a reliable performance evaluation of a system using a common repeater for two or more television transmissions.

Consequently, the approximate indications prevented here are based on two models chosen for visibility rather than accuracy.

In the first model, the baseband signal is assumed to be random with a Gaussian distribution. Figure 3-8 shows two transmissions and their third order intermodulation products of categories $2f_1 - f_2$ and $2f_2 - f_1$. Each of these categories occupies a band of width 3B, where B is the bandwidth occupied by one modulated RF signal. With the triangular intermodulation spectrum shown (based on flat RF signal spectra), the carrier-to-IM power density ration will not be less than (C/I) x 4. 5B within the signal transmission bands. Comparison with the carrier-to-thermal noise density (C/N) x B where C/N is nominally 16 db, shows that $C/I \approx 16$ db is acceptable. Experience with wideband repeaters using a wideband TWT output amplifier indicates that this C/I ratio requires an output power backoff of 1 db from the two-carrier saturation level, which itself is about 1 to 1. 5 db below the single-carrier saturation level.

In case of multicarrier operation, the IM spectrum tends to assume a Gaussian shape with a carrier-to-IM density ratio down to (C/I) x B within first order sidebands of the RF signal carriers. Then, an output power backoff of about 3 db below multicarrier saturation, or 4.5 db below single-carrier saturation is required to control the intermodulation level.

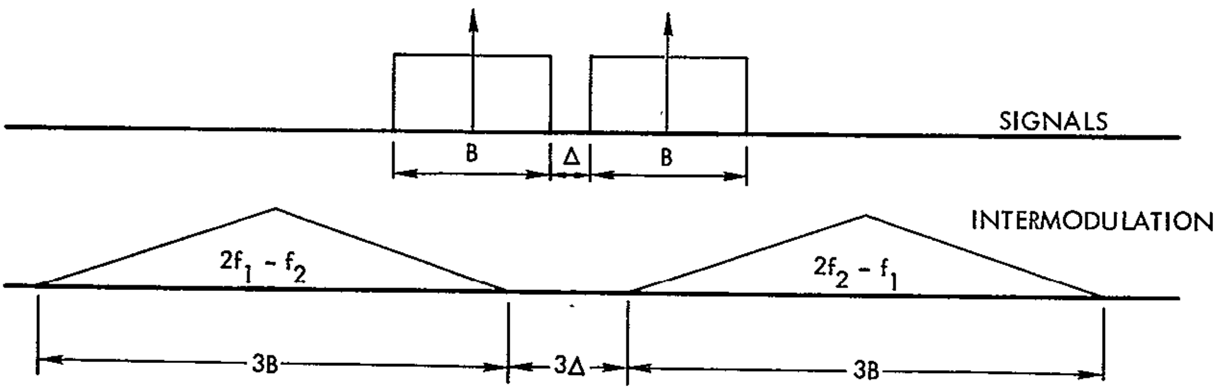


Figure 3-8. RF Power Spectra of Signals of Intermodulation

Thus far, a flat baseband spectrum has been assumed. The real video signal has a luminance spectrum declining towards higher baseband frequencies, and a relatively narrow chrominance spectrum with a peak at the subcarrier frequency. Further, the periodicity of the line and field scans give the video spectrum the character of a line with sidebands, with spectrum peaks at multiples of line and field frequencies.

For an additional viewpoint on intermodulation, consider the RF spectrum consisting of two RF carriers, each with first order sidebands of carrier modulation by an unmodulated color subcarrier and an unmodulated sound subcarrier (Figure 3-9).

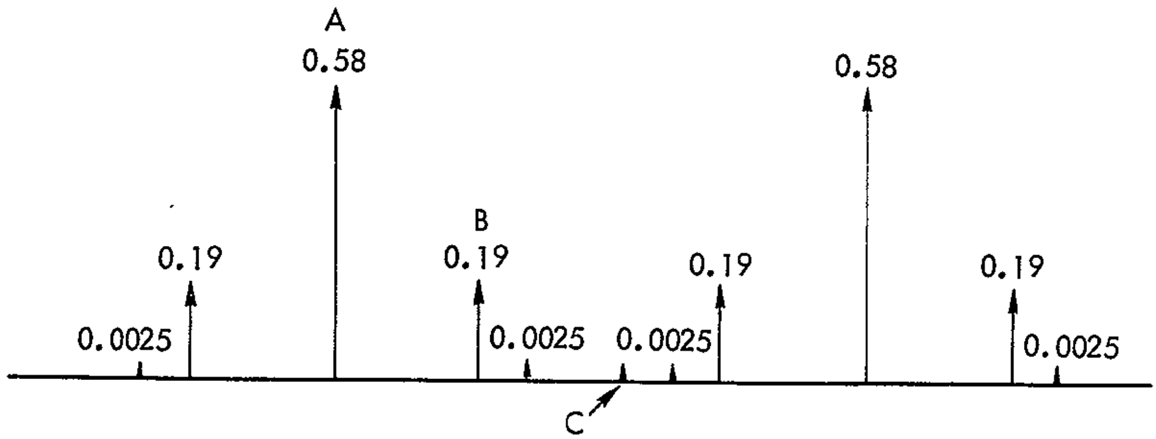


Figure 3-9. RF Line Spectra

From data in Sections 2.4 and 2.5.3, it follows that representative RF modulation indices are 1.0 and 0.1 for color subcarrier (of magnitude corresponding to high color saturation) and sound subcarrier, respectively. With these indices the RF power levels, relative total power of one RF signal, are as indicated in the Figure 3-9. As shown in Figure 3-9, intermodulation between a carrier component (A), and a color side frequency (B), gives an intermodulation product (C), of relative power 6×10^{-4} (assuming a 1 db output power backoff from 2-carrier saturation). With C within audio bandwidth from the nearest sound subcarrier component of the other RF signal, a spurious tone occurs in that sound channel. In the worst case, the spurious tone is near the top of the sound channel. Its level is then approximately 25 db below test tone (Section 2.5.1), which is not tolerable.

To avoid this sound channel interference the spacing between the two RF carriers must be selected such that intermodulation product C between carrier component and first order color sideband in one RF signal does not lie within audio bandwidth from the sound subcarrier component of the adjacent RF signal.

The above considerations were based on simplified models, and the quantitative evaluations arrived at are therefore not accurate. Two FM/TV transmissions in a common repeater (including TWT output amplifier) appears quite feasible with an output power backoff of about 2 db below single-saturation carrier level. The main penalty is then reduction of the output TWT efficiency by a factor of about 1.5. More than two FM/TV channels require a backoff of about 4.5 db below single-carrier saturation, resulting in a drastic reduction of transmitter efficiency, and is therefore not recommended. The final TWT amplifier, operated near saturation for reasons of efficiency, is the major contributor to intermodulation between RF signals. The use of a common, linear channel for more than two FM/TV transmissions appears still feasible. Limiting and final amplification must be performed in separate devices for each transmission or group of two transmissions.

3.3.3 Amplitude Nonlinearity in AM/VSB Transmissions

Deviations from a linear relationship between input amplitude and output amplitude of a AM/VSB channel causes distortion of the luminance scale and causes the color subcarrier amplitude to vary with luminance level.

The differential gain (i. e., the slope of output amplitude versus input amplitude) may not vary more than 12 percent.

To meet this requirement all devices in the AM/VSB transmission path must have sufficiently high saturation levels to assure linearity over the dynamic range of the AM/VSB signal. In the design studies (References 3-1 through 3-5) on transmitter output stages for television broadcast satellites, the amplitude linearity requirements were taken into consideration in the conceptual designs on tube configurations.

3.4 UNIT DESIGN CONSIDERATIONS

Design considerations are presented for

- Low-noise tunnel-diode preamplifiers and solid state S-band amplifiers.
- Mixers for down-conversion and up-conversion.
- Local oscillators, injection phase locked to a crystal oscillator.

3.4.1 Amplifiers

All configurations shown in Figures 3-3 through 3-7 in a tunnel diode preamplifier of moderately high gain, up to 30 db, implying a cascade of two stages. A typical tunnel diode amplifier stage, along with the microwave equivalent circuit, is shown in Figure 3-10 (Reference 3-8).

This is a reflection type amplifier circuit in that the tunnel diode and passive circuitry appear at the end of a transmission line. The real part of the impedance looking into the diode is negative so that the incident

RF wave is amplified at the diode and the power reflected is greater than the incident power. If $Z = -R + jX$, then the reflection gain is given by Equation (3-7):

$$G = \frac{(R_o + R)^2 + X^2}{(R_o - R)^2 + X^2} \qquad (3\text{-}7)$$

where R_o is the characteristic impedance of the transmission line (waveguide) and is assumed to be lossless.

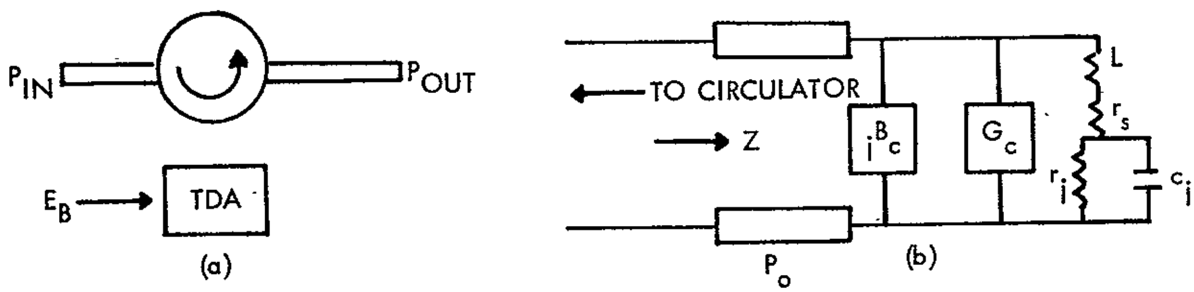


Figure 3-10. Tunnel Diode Amplifier and Equivalent Circuit

A circulator is used with the TDA of Figure 3-10 to separate the incident and reflected waves. Circulator coupled amplifiers are more stable than hybrid coupled (Reference 3-8) and are used extensively as microwave amplifiers. Broadband, low loss circulators are available for all the microwave bands in compact form.

A voltage-gain bandwidth product can be written under the assumptions: (1) L and r_s are negligible [Figure 3-10 (b)] (2) the passive circuit is a lossless inductance; and (3) the amplifier gain is high (Reference 3-8). Such an expression for gain bandwidth is:

$$G_v B = \left(\pi \left| r_j \right| c_j\right)^{-1} \qquad (3\text{-}8)$$

Larger gain bandwidths are possible by using matching networks at the input of the diode. This also improves the gain and phase response (Reference 3-9).

Scanlin and Lin have developed design curves for a tunnel diode amplifier of the configuration shown in Figure 3-11.

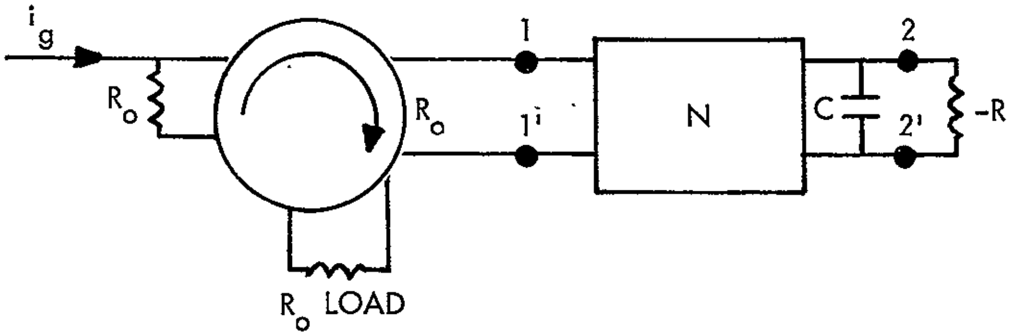


Figure 3-11. Tunnel Diode Amplifier with a Lossless Coupling Network N

The filter is Tchebyscheff and has the form given by Equation (3-9) for the transmission characteristic.

$$|t'|^2 = \frac{1}{1 + k^2 + h^2 Tn^2 (\omega)} \tag{3-9}$$

where

$Tn(\omega)$ = Tchebyscheff function of order n

$1/1 + k^2$ = zero frequency insertion loss

h = a parameter determining the ripple.

A Chebyschev filter with low ripple will yield better phase linearly then the Butterworth filter. This is fortunate since Scanlin and Lin (Reference 3-9) indicate that Chebyshev filter response will yield the largest gain bandwidth product for the tunnel diode filter combination. A five-section Chebyshev filter with a 50 MHz passband (i.e., band of equal ripple response and an 0.1 ripple has a group-delay variation of 22.4 nanoseconds between band center and band edge. The value follows immediately from the respective group-delay versus frequency curve give in Reference 3-7 for the equivalent lowpass filter. A second order approximation of the curve is:

$$\tau_{bp} = -4.77 \left(\frac{f - f_o}{\frac{B}{2}}\right) + 15.9 \left(\frac{f - f_o}{\frac{B}{2}}\right)^2 \text{ nsec} \qquad (3\text{-}10)$$

valid for

$$\left(\frac{f - f_o}{\frac{B}{2}}\right) \leq 0.8$$

where

f = RF frequency

f_o = center frequency

B = bandwidth (of equal ripple response)

For bandwidths other than 50 MHz, the total group-delay variation over the band and the coefficients in Equation (3-10) are easily determined since these three values vary inversely proportional with the bandwidth. For the 50 MHz bandwidth, the coefficients in Equation (3-10) indicate a linear variation of 0.19 nsec/MHz and a parabolic variation of 0.025 nsec/MHz^2. These values, although within the limits of 0.25 nsec/MHz and 0.05 nsec/MHz (Section 3.3.1), are too high for this single contribution to overall group-delay variation. Therefore, a wider filter bandwidth or an equalization circuit should be used. For a 100 MHz bandwidth, the variations become 0.048 nsec/MHz and 0.0032 nsec/MHz.

Other considerations for the tunnel diode amplifier include gain stability and noise figure. Although sufficiency conditions have not been fully established, it can be shown that the necessary conditions for stability are

$$\frac{r_s}{r_j} < 1 \text{ and } \frac{L}{|r_j|^2 C_j} < F(\theta) \qquad (3\text{-}11)$$

The terms of (3-11) are from the equivalent circuit of Figure 3-10(b) (Reference 3-8). $F(\theta)$ is a monotonically decreasing function of $r_s/|r_j|$ and varies from a value of 3 for $r_s/|r_j| = 0$ to a value of 1 for $r_s/|r_j| = 1$. Stability can be achieved for purely resistive loads if condition (3-12) holds

$$\frac{L}{|r_j|^2 C_j} < 1 \qquad (3\text{-}12)$$

If filter-type loads are used, as was discussed previously in connection with the Tchebyscheff filter, it is permissible for the left-side of (3-12) to exceed one slightly. This point is well discussed in Reference 3-9 where large gain bandwidth products were computed.

An expression for the tunnel diode noise figure, derived by Nielsen and stated in Reference 3-8 is

$$NF = \frac{1 + \left(\frac{qI_n}{2kT}\right)|r_j|}{\left(1 - \frac{r_s}{|r_j|}\right)\left[1 - \left(\frac{f}{f_r}\right)^2\right]} \qquad (3\text{-}13)$$

This equation indicates that the noise figure for a tunnel diode amplifier depends on three device factors:

1) The noise constant $I_n r_j$
2) The ratio of parasitic resistance, $r_s/|r_j|$
3) The ratio of operating frequency to cutoff frequency f/f_r

For low noise requirements a device is selected which minimizes the above three terms. If a device with high cutoff frequency is chosen such that $(f/f_r)^2 \ll 1$, then Equation (3-13) can be put in a simpler form.

$$NF \approx \left[1 + \left(\frac{qI_n}{2kT}\right)|r_j|\right]\left(1 + \frac{r_s}{|r_j|}\right) \qquad (3\text{-}14)$$

Sterzer points out (Reference 3-8) that low gain amplifiers have significantly lower noise figures than high gain amplifiers. However, a cascade of low gain amplifiers with high overall gain will have the same noise figure as a single high gain amplifier. This means that for a ≈ 30 db preamplifier gain (Figures 3-3 through 3-7), the choice between two, three or four stages would make no difference in the noise figure. Clearly, two stages are desirable from the standpoint of parts count, size, and weight.

Three materials are currently in use for the manufacture of tunnel diodes. Ge and GaSb diodes provide lower noise figures, but have a lower power handling capability than GaAs diodes. A good choice would be a two-stage cascade of either Ge or GaSb diodes, since the received power will not vary over a large dynamic range for the FM uplink signals. S-band amplifiers are used as RF amplifiers in the transponder for broadcasting at 2.5 GHz (Figure 3-5), and as IF amplifier for broadcasting at X-band (Figure 3-6 and 3-7).

Figure 3-12 shows a transmitter-amplifier stage for S-band, developed by TRW.

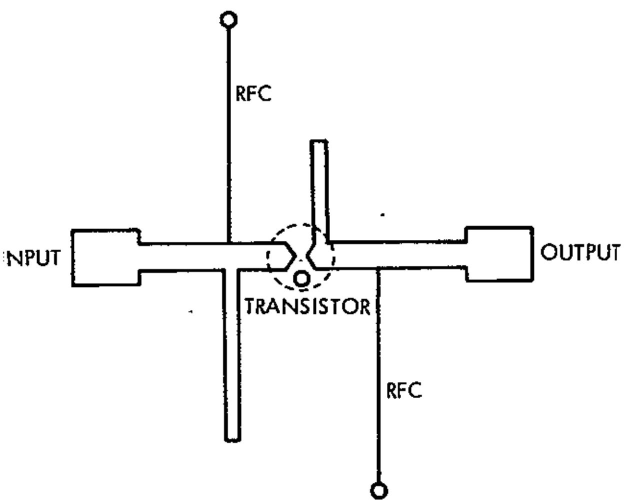


Figure 3-12. Single Stage Prototype Amplifier

This stage is a grounded emitter configuration with a center frequency at 2.25 GHz, using a TIXM05 transistor.

Figure 3-13 shows the gain and group-delay versus frequency.

For the 48 db IF amplifier in the X-band transponders (Figures 3-6 and 3-7), a minimum of eight stages, each with a midband gain of 6 db is required. The group delay curve indicates a linear variation of 0.023 nsec/MHz and a parabolic variation less than 4.10^{-4} nsec/MHz within a 30 MHz band, centered at 2.25 GHz. In most cases considered in Section 2.4, the FM-TV transmission will occupy a bandwidth not larger than 30 MHz. Some equalization is required to prevent the total linear variation of eight stages from becoming a significant contribution to the overall allowance of approximately 0.25 nsec/MHz.

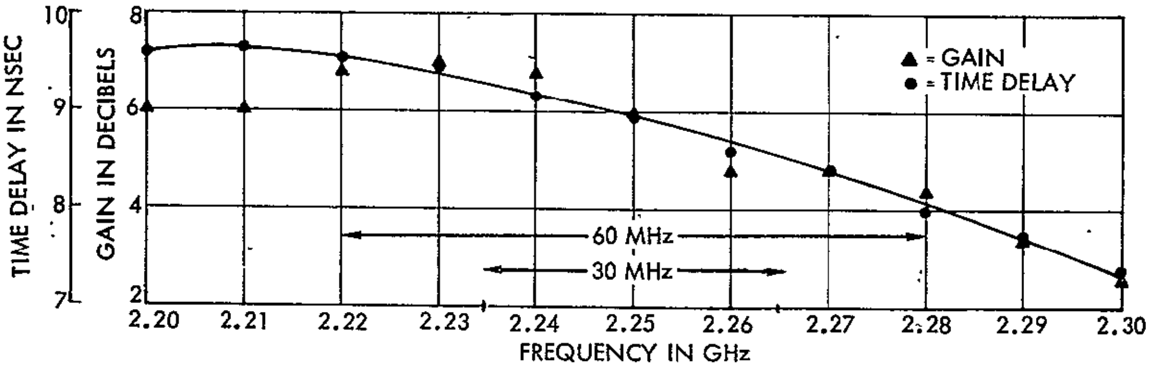


Figure 3-13. Single Stage Prototype Tests Over a 100-MHz Bandwidth

3.4.2 Mixers

All transponders require at least one mixer stage. Design considerations for mixers and their impact on local oscillator design are discussed here.

Consider an input signal consisting of two RF carriers at frequencies ω_{S1} and ω_{S2}, with $\omega_{S1} \approx \omega_{S2}$. The mixer is pumped at ω_{L0}.

The desired outputs are produced by second order cross product terms (V^2 terms) and are

$$\omega_{01} = \omega_{S1} - \omega_{L0}$$

$$\omega_{02} = \omega_{S2} - \omega_{L0}$$

The V^4 terms in the mixer output include intermodulation terms (IM terms) which lie in the output passband occupied by the transposed signal spectrum. Their frequencies, ω_{im1} and ω_{im2}, are

$$\omega_{im1} = 2\omega_{S1} - \omega_{S2} - \omega_{L0}$$

$$\omega_{im2} = 2\omega_{S2} - \omega_{S1} - \omega_{L0} \qquad (3\text{-}15)$$

See Figure 3-14.

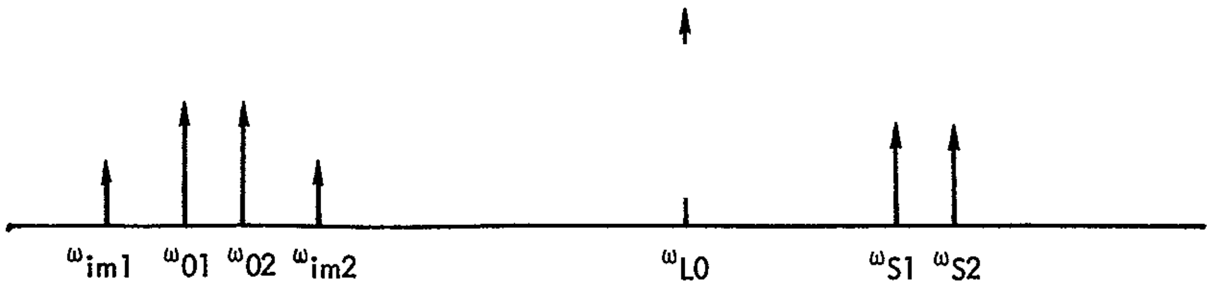


Figure 3-14. Spectrum for a Typical Frequency Converter

These fourth order intermodulation products could be interpreted as resulting from the third order products $2\omega_{S1} - \omega_{S2}$ and $2\omega_{S2} - \omega_{S1}$ generated as $V_1^2 V_2$ and $V_1 V_2^2$ by mixing between the input signal components. The transposed outputs of these products are generated by the fourth order terms $V_1^2 V_2 V_{L0}$ and $V_1 V_2^2 V_{L0}$.

As the signal levels are increased, more power is required from the local oscillator for frequency conversion. Because of limited pump power and changes in impedance presented to the pump, the gain from the signal input to output decreases. As a result of this mixer saturation, the mixer transfer characteristic (output signal power versus input signal power) becomes nonlinear and IM products increase in level.

These distortion mechanisms can be minimized by proper choice of mixer devices, and by optimization of the mixer operating dynamic range. Extending the dynamic range leads to reduced IM caused by gain saturation. This is achieved simply by increasing the pump power as shown in Figure 3-15. Each db increase in pump power yields a 1 db increase in saturation level, P_{OM} (Reference 3-10). It has been found empirically that for most microwave devices, the IM ratio for fourth order products is

$$\text{IMR} = 2\left(P_{0_{db}} - P_{0m_{db}}\right) - 19.5 \text{ db} \qquad (3\text{-}16)$$

Then it is seen from Equation (3-16) that if P_{0m} is increased by 1 db due to increased pump power, the IM ratio is improved by 2 db. This is, of course, upper bounded in cases where the mixer is the front-end stage of a receiver, because the mixer noise increases with pump power. Also, there is a limit to the amount of power the mixing device can dissipate before burnout. Ernst, et al. (Reference 3-10), points out that hot carrier diodes (HP 2100) are greatly superior to point contact diodes (IN21B) in this respect. For pump powers greater than about +3 dbm, the IN21B noise figure increases rapidly from 7 db to 10 db for a pump power of +16 dbm. The hot carrier 2100 diode noise figure increases only about 1 db (5.8 to 7 db) over the same pump power range. This clearly indicates that hot carrier diodes should be used where low intermodulation and low noise are requirements.

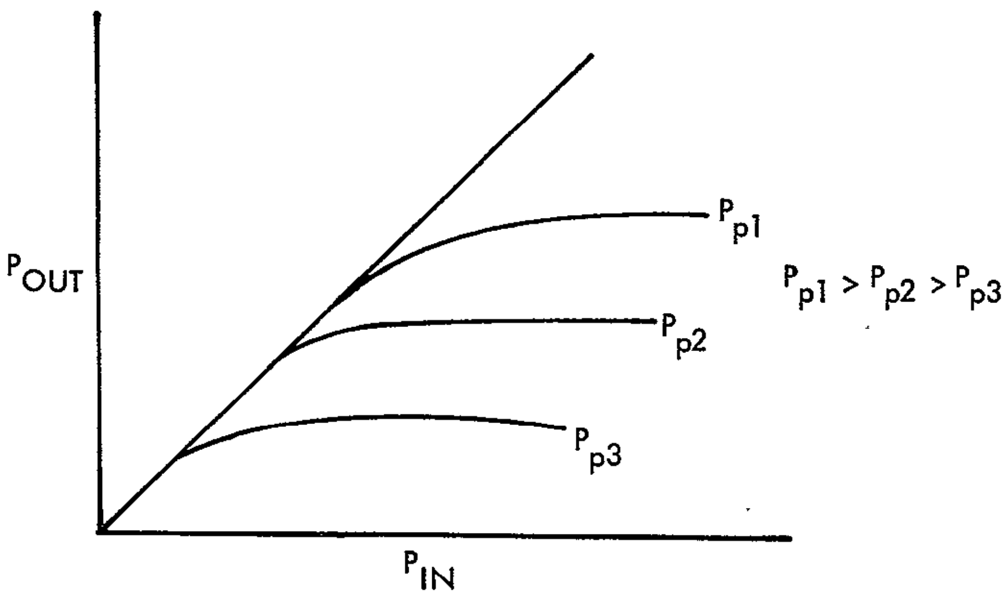


Figure 3-15. Saturation Characteristic of a Mixer as the Pump Power is Increased

For the upconverters (the second mixers of Figures 3-6 and 3-7), where the frequency conversion ratio is greater than one, a varactor diode will yield a larger dynamic range (Reference 3-11).

Since hot carrier diodes yield large dynamic range and low noise, they are appropriate for the down-converter mixers of the direct TV transponder. Tepoff and Cowley (Reference 3-12) indicate that IM ratios of 80 db are obtained for single ended hot carrier diode mixers by proper choice of the operating point. Still better performance is obtained by operating two hot carrier diodes in a balanced mixer configuration at different dc, operating points on the diodes. Over 100 db IM rejection is obtained in this manner. It may be concluded from the preceding discussion that hot carrier diodes with pump powers on the order of 200 dbm will perform with excellent IM rejection for the down-converters of the TV transponder. Added linearity can be obtained by using a balanced configuration.

The down-converters are better implemented with varactors. Perlman (Reference 3-11) reports up to 140 db of dynamic range for a pump power on the order of 1 watt.

3.4.3 Local Oscillators

Local oscillator signals are generated in all the transponders (shown in Figures 3-3 through 3-7) by means of microwave oscillators which are phase locked to a harmonic of a stable crystal oscillator. The scheme offers an advantage over the standard varactor or step recovery diode multiplication of a crystal source in that the oscillator output is practically free of spurious subharmonics. The concept of injection phase locking of microwave oscillators is not new; Day (Reference 3-6) quotes papers as far back as 1946. However, with the advent of recent avalanche diode devices, it is possible to generate reasonably high power outputs which have high stability and low FM noise by means of solid state devices.

The basic theory for the locked avalanche diode oscillator can be developed from the model shown in Figure 3-16.

The vector E_o rotates with angular velocity

$$\omega = \omega_1 + \frac{d\phi}{dt} \tag{3-17}$$

and when synchronization of the ADO is achieved, $\omega = \omega_1$, $\dot{\phi} = d\phi/dt = 0$, and ϕ = constant. When the locking signal is not present, E_i and E_o are in phase for an oscillator frequency of ω_o. At a frequency ω other than the free running oscillator frequency ω_o, the oscillator resonant circuit causes a phase difference $\theta(\omega)$ between E_o and E_i.

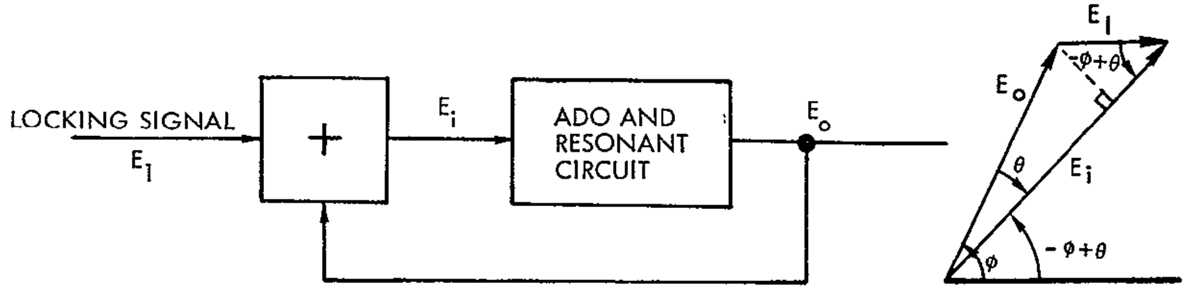


Figure 3-16. Locked Oscillator Model

With the locking signal $e_1 = E_1 \sin \omega_1 t$ present, it is added to the oscillator output $e_o = E_o \sin (\omega_o t + \phi)$. The sum of these signals is the input signal to the ADO with resonant circuit and thus must lead e_o in phase by θ, the phase delay in the resonant circuit. Hence, the sum signal is $e_i = E_i \sin [\omega_i t + \phi + \theta(\omega)]$. From the vector diagram in Figure 3-16, it follows that

$$E_1 \sin (\phi - \theta) = -E_o \sin \theta(\omega)$$

or

$$\sin \theta(\omega) \approx - \frac{E_1}{E_o} \sin \phi \tag{3-18}$$

assuming $\theta(\omega) \ll 1$ radian.

For a single tuned circuit

$$\theta(\omega) = \tan^{-1} Q\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right) \tag{3-19}$$

or approximately

$$\sin \theta(\omega) = \frac{2Q}{\omega_o} (\omega - \omega_o)$$

Defining $\Delta\omega_o = \omega_o - \omega_1$ and $\Delta\omega = \omega - \omega_1$, we have

$$\sin \theta(\omega) = \frac{2Q}{\omega_o}\left(\frac{d\phi}{dt} - \Delta\omega_o\right) \tag{3-20}$$

where it is assumed that the static phase characteristic (3-19) can be used for time varying frequencies.

Insertion of Equation (3-18) into Equation (3-20) yields

$$- \frac{E_1}{E_o} \sin \phi = \sin \theta (\omega) = \frac{2Q}{\omega_o} \left(\frac{d\phi}{dt} - \Delta\omega_o \right)$$

$$\frac{d\phi}{dt} = - \Omega \sin \phi + \Delta \omega_o \tag{3-21}$$

where

$$\Omega = \frac{E_1}{E_o} \frac{\omega_o}{2Q} = \left(\frac{P_1}{P_o} \right)^{1/2} \frac{\omega_o}{2Q} \tag{3-22}$$

P_1 = injection signal power

P_o = oscillator output power

Synchronization can occur only when $d\phi/dt = 0$, and therefore, a condition for lock is

$$\sin \phi = \frac{\Delta\omega_o}{\Omega}$$

which is possible only when

$$\left| \frac{\Delta\omega_o}{\Omega} \right| < 1$$

or, from (3-22),

$$\left| \frac{\Delta \omega_o \cdot 2Q}{\omega_o} \left(\frac{P_o}{P_1} \right)^{1/2} \right| < 1 \tag{3-23}$$

which gives the bandwidth for lock-on as

$$2 \Delta f_o = \frac{f_o}{Q_L} \left(\frac{P_1}{P_o} \right)^{1/2} \tag{3-24}$$

Equations (3-21) and (3-24) are identical to those given by Mackey (Reference 3-13) for injection phase-locked reflex klystrons.

These expressions are reported to be functionally correct for GaAs bulk oscillators (Reference 3-6); however, for these devices the locking bandwidth was found to depend on the specific GaAs sample as well as the circuit Q_L.

Recent research at TRW Systems has investigated the theory of injection phase locking using an IMPATT solid state device as the locked oscillator. The noise bandwidth (one sided) at the oscillator output was found to be

$$B_L = \frac{\Omega}{4} \tag{3-25}$$

Noise modulation on the locking signal is low-pass filtered by the transfer function H(S):

$$H(S) = \frac{\Omega}{S + \Omega} \tag{3-26}$$

whereas the noise spectrum present at the ADO (avalanche diode oscillator) output is

$$1 - H(S) = \frac{S}{S + \Omega} \tag{3-27}$$

Experimental work indicates good agreement between experiment and theory. In particular, the noise spectrum follows a 6 db/octave rise with frequency as in Equation (3-27), and the 3 db bandwidth is close to Ω.

SECTION 3 REFERENCES

3-1. O. G. Sauseng, A. Basiulis, and I. Tammaru, "Analytical Study Program to Develop the Theoretical Design of Traveling-Wave Tubes," Hughes Final Report, Contract NAS 3-9719, October 31, 1968.

3-2. G. M. Branch, and T. G. Mihran, "Analytical Designs of a Space-Borne Magnetically-Focused Klystron Amplifier," G. E. Final Report, Contract NAS 3-11514, October 28, 1968.

3-3. W. R. Day, and T. H. Luchsinger, "Analytical Study Program to Develop the Theoretical Design of Spaceborne Electrostatically Focused Klystron Amplifiers," Litton Final Report, Contract NAS 3-11515, 1968.

3-4. G. Bernstein, and W. C. Sylvernal, "Analytic Design of Spaceborne Axial Injection Crossed-Field Amplifiers," S-F-D Laboratories Final Report, Contract NAS 3-11516, September 30, 1968.

3-5. C. L. Jones, and J. E. Orr, "Analytic Design of a 2.0 GHz Space-borne Linear Injection Beam Crossed Field Amplifier," Litton Final Report, Contract NAS 3-11513, October 27, 1968.

3-6. W. R. Day, "Stabilization of Microwave Oscillators by Injection Phase Locking," Microwave Journal, pp. 35-39, March 1967.

3-7. Matthaei, Young, and Jones, "Microwave Filters Impedance — Matching Networks and Coupling Structures," McGraw-Hill Book Co., Inc., 1964.

3-8. Leo Young (Ed), "Advances in Microwaves," vol. II, Academic Press, 1967.

3-9. J. O. Scanlan, and J. T. Lin, "A Design Theory for Optimum Broadband Reflection Amplifiers," IEEE Transaction on Microwave Theory and Techniques, pp. 504-511, 1964.

3-10. R. Ernst, P. Torrione, W. Y. Pan, and M. Morris, "Designing Microwave Mixers for Increased Dynamic Range," WESCON paper, 1968.

3-11. B. S. Perlman, "Current-Pumped Abrupt-Junction Varactor Power-Frequency Converters," IEEE Transactions on Microwave Theory and Techniques, pp. 150-161, March 1965.

3-12. J. H. Tepoff, and A. M. Cowley, "Improved Intermodulation Rejection in Mixers," IEEE Transaction on Microwave Theory and Techniques, pp. 618-623, December 1966.

3-13. R. C. Mackey, "Injection Locking of Klystron Oscillators," IRE Transactions Microwave Theory and Techniques, pp. 228-235, July 1962.

4. ANTENNAS

4.1 INTRODUCTION

The ideal satellite transmitter antenna requires a minimum of RF power to provide the required field strength over the entire area to be covered. For satellites in synchronous orbit, the optimum radiation pattern would be nearly rectangular. Unfortunately, such patterns are not physically realizable. For a practically feasible antenna, the quantity that affects the RF power requirement is the lowest gain within the solid angle defined by the specified coverage.

Sidelobes must be held sufficiently low to avoid intolerable interference with communication services outside the area of coverage.

The requirements for high beam efficiency and low sidelobe levels tend to dictate tapered beam illumination in combination with oversized apertures.

Time zone and language considerations will lead to coverage areas on the order of a million square miles (2.5 million square km), requiring a beamwidth of about 3 degrees. Satellite power considerations then dictate a pointing accuracy of about 0.1 degree.

Dynamic and thermal distortion of the antenna has adverse effects on both the pointing accuracy and the sidelobe level.

Other aspects affecting the satellite antenna design are power handling capability, beam-steering capability, multiple-beam capability, compatibility with satellite weight and size, and deployment.

Representative requirements for the satellite transmit antennas are given in Table 4-1.

4.2 SYSTEMS CONSIDERATIONS

4.2.1 Gain Optimization for Sector Coverage

In the present application transmit antennas at the satellite must be designed to provide a given field strength at all locations within the area to be covered. The optimum antenna performs this function with a

Table 4-1. Representative Antenna Requirements

Frequency (GHz)	0.9	2.5	8.5	12.0
Polarization	Circular	Circular	Circular	Circular
Beamwidth (degrees)	1.5 to 5	1.5 to 5	1.5 to 5	1.5 to 5
Sidelobe levels (db)	-25	-25	-25	-25
Number of beams	1 to 3	1 to 3	1 to 3	1 to 3
Power handling capability (kw)				
AM	1 to 20*	--	--	--
FM	0.02 to 2	0.02 to 4	0.02 to 10	0.02 to 20
Lifetime (years)	5	5	5	5

*Average power during sync peak.

minimum of radiated RF power. Clearly, this requires that the lowest gain with the solid angle defined by the specified coverage be made as large as possible within existing constraints.

For pencil beams with monotonic main lobe, the lowest gain occurs at the angle θ_e, defined by the edge of coverage. In Figure 4-1, the three beam patterns correspond to different antenna aperture diameters, increasing in the order A, B, C. Pattern B shows a higher gain than pattern A, both at the beam center and at θ_e, the edge of coverage. Further increase in diameter, yielding pattern C, results in continued increase of the beam-center gain. However, the beamwidth is now narrowed to the extent that the edge loss between beam center and θ_e more than outweighs the increase in beam-center gain. Consequently, the gain at θ_e, i.e., the performance parameter to be maximized, is lower than for pattern B.

Relationships between beam width, beam shape, gain at θ_e, sidelobe levels, aperture size, and gain loss due to pointing errors are discussed in Sections 4.2.1.1 through 4.2.1.3.

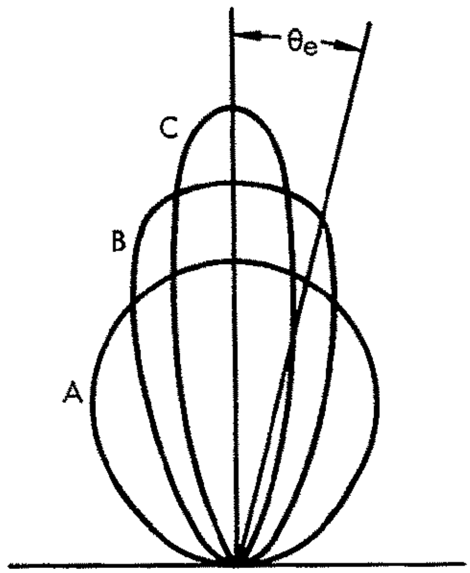


Figure 4-1. Three Beam Patterns

4.2.1.1 Beam Sizing

Consider a circular aperture with a circularly symmetric illumination pattern (field strength) given by

$$f(\rho) = (1 - \rho^2/a^2)^n \tag{4-1}$$

where ρ is the radial coordinate in the aperture plane, a is the aperture radius, and the integer n is a parameter of the illumination pattern. The illumination is uniform for $n = 0$, tapered for $n = 1, 2, 3, \ldots$.

For the class of illumination patterns which represent approximations adequate for the objective of this analysis, the normalized far-field power pattern is:

$$G_r(\theta) = [\Lambda_{n+1}(x)]^2 \tag{4-2}$$

where

θ = angle off beam center

$G_r(\theta)$ = relative gain; $G_r(o) = 1$

$$\Lambda_n(x) = 2^n n! \frac{J_n(x)}{x^n} \tag{4-3}$$

$$\begin{aligned} x &= \pi D_\lambda \sin \theta \\ D_\lambda &= \text{aperture diameter in wavelengths.} \end{aligned} \tag{4-4}$$

The beam-center gain is

$$G(o) = \eta\, (\pi D_\lambda)^2 \tag{4-5}$$

where η = aperture efficiency. Inserting D_λ from Equation (4-4) into Equation (4-5) yields

$$G(o) = \eta \left(\frac{x}{\sin\theta}\right)^2 \tag{4-6}$$

Hence, the absolute gain at a given offset angle θ is

$$G(\theta) = G(o) G_r(\theta) = \frac{\eta}{\sin^2\theta} \left[x \Lambda_{n+1}(x)\right]^2 \tag{4-7}$$

Since the radiation patterns of Equation (4-7) decrease monotonically with increasing angle θ, the lowest gain occurs at the edge of the required coverage. Optimization of this gain, at an angle θ_e defined by coverage and beam pointing errors, is a matter of selecting the appropriate aperture diameter D_λ. From Equation (4-7) it is seen that D_λ must be selected such that the resulting value of $x_e = \pi D_\lambda \sin \theta_e$ leads to a maximum value of $x_e \Lambda_{n+1}(x_e)$. Table 4-2 gives these optimum values of x_e and corresponding values of the relative edge-gain $G_r(\phi_e) = \Lambda^2_{n+1}(x_e)$. These data show that an edge gain of about 4.0 db below the beam-center gain is required to obtain maximum absolute edge-gain with either the uniform aperture illumination ($n = 0$) or with the tapered illuminations of $n = 1$ or $n = 2$.

Table 4-2 shows various quantities for two cases. In the case of optimum edge, the aperture diameter is sized to obtain the value of x_e that leads to the maximum absolute gain at θ_e, the angle corresponding to the edge of required coverage. In the case of half-power edge, the 3-db beamwidth is made equal to $2\theta_e$, the width of the required coverage. For both cases, the table shows the values of x_e.

Table 4-2. Beam Data

Illumination taper parameter n	0	1	2
<u>Optimum edge</u>			
x_e	1.84	2.30	2.68
Relative edge-gain $G_r(\theta_e)$ in db	-3.99	-4.07	-4.09
$D_\lambda \theta_e$	33.6	41.9	48.9
$G(o)\theta_e^2$	11,120	13,030	13,100
$G(\theta_e)\theta_e^2$	4,440	5,106	5,104
<u>Half-power edge</u>			
x_e	1.62	2.00	2.32
$D_\lambda\theta_e = K/2$	29.6	36.5	42.3
$G(o)\theta_e^2$	8,617	9,851	9,820
$G(\theta_e)\theta_e^2$	4,309	4,926	4,910

Note: θ_e is angle from beam center to edge, in degrees.

From Equation (4-4), the aperture diameter for a given value of x at a given angle θ is seen to be approximately

$$D_\lambda = 18.24 \frac{x}{\theta} \tag{4-8}$$

where θ is expressed in degrees and is assumed to be a small angle. Inserting this expression for D_λ into Equation (4-5) for the beam-center gain G(o) yields:

$$G(o) = 3284\, \eta \left(\frac{x}{\theta}\right)^2 \tag{4-9}$$

where θ is again expressed in degrees.

These two equations, with the appropriate values of x_e inserted for x, give the values of $D_\lambda\theta_e$ and $G(o)\theta_e^2$ shown in Table 4-2. The aperture efficiencies used are

$$\eta = \frac{2n + 1}{(n + 1)^2} \tag{4-10}$$

which are the efficiencies inherent to the illumination patterns of Equation (4-1). The efficiency of formula 4-10 does not take into account other degrading effects such as ohmic losses, aperture blockage, spill-over and surface errors, present in actual antennas. It is, however, a useful quantity for comparing and optimizing aperture illumination patterns.

The function $x\Lambda_{n+1}(x)$ has a very broad maximum. Therefore, the selection of x_e, or the aperture diameter D_λ for a given angle θ_e, is not very critical. Specifically, only 0.1 to 0.2 db is gained in $G(\theta_e)$ by using the optimum aperture diameter rather than the 13 percent smaller diameter for a 3-db edge at θ_e.

The beam sizing is also affected by the physical constraints on the size and weight of the satellite antenna, particularly for lower frequencies. For certain applications (narrow beams, low frequencies) a weight trade-off between the spacecraft antenna weight and the weight of power equipment may dictate a 3-db beamwidth larger than the coverage width.

Acceptance of such a larger beamwidth is constrained by considerations on interference with terrestrial communications in regions outside the desired coverage.

The analysis presented in this section is aimed primarily at sizing of the beamwidth and aperture, assuming a given illumination pattern, i.e., a given choice of n. The beam shape, determined by choice of n in Equation (4-1) or by a combination of functions with different n, is discussed in Section 4.2.1.3.

4.2.1.2 Losses From Beam Pointing Errors

A further point of consideration is the sensitivity of edge-gain to beam-pointing errors. From Equation (4-2) it can be derived that the relative change in edge gain is given by

$$\frac{\Delta G}{G(\theta_e)} = -\frac{x_e^2}{n+2}\left[\frac{\Lambda_{n+2}(x_e)}{\Lambda_{n+1}(x_e)}\right]\frac{\Delta\theta}{\theta_e} \qquad (4\text{-}11)$$

Expressed in decibels, this change in edge-gain is

$$10 \log \frac{G(\theta_e) + \Delta G}{G(\theta_e)} = 4.343 \log_e \frac{G(\theta_e) + \Delta G}{G(\theta_e)} \approx 4.343 \frac{\Delta G}{G(\theta_e)} \text{ db}$$

or

$$10 \log \frac{G(\theta_e) + \Delta G}{G(\theta_e)} = -4.343 \left(\frac{x_e^2}{n+2}\right) \left[\frac{\Lambda_{n+2}(x_e)}{\Lambda_{n+1}(x_e)}\right] \frac{\Delta\theta}{\theta_e} \text{ db} \tag{4-12}$$

With negative $\Delta\theta$, this expression gives the loss caused by a beam-pointing error of magnitude $|\Delta\theta|$.

For a 2 degree wide coverage (i.e., θ_e = 1 degree), the gain slope at the edge of coverage is about 0.62 db per 0.1 degree for a -3 db edge and 0.84 db per 0.1 degree for an optimum edge. The difference between these two slopes would be irrelevant if beam-pointing errors stayed within hard limits, since in either case the respective beamwidth would have to be matched to the solid angle of coverage enlarged by the maximum pointing error. However, beam-pointing errors show a statistical behavior with occasional peaks exceeding the 3σ value.

4.2.1.3 Beam Shaping

Let θ_o be the 3-db beamwidth. (Note that θ_o is measured between 3-db directions, while θ_e is measured from center to edge.) Then, Equation (4-8) can be formulated as

$$D_\lambda = \frac{K}{\theta_o} \tag{4-13}$$

where K = 36.48x and x has the value for the 3-db edge, while Equation (4-9) becomes

$$G(o) = \eta K^2 \left(\frac{\pi}{\theta_o}\right)^2 \tag{4-14}$$

Beam sizing for a 3-db edge is assumed in the following discussions on the selection of the shape of the aperture illumination pattern, i.e., the selection of n in Equation (4-1) or of a combination of patterns with different n. The relation between the absolute gain at the beam edge (the gain of primary interest to overall system performance) and that at beam center is then fixed.

Consequently, the product ηK^2 in Equation (4-14) for beam-center gain is now a relevant figure of merit.

The choice of aperture illumination pattern is constrained by two important considerations, sidelobe levels and realizability of feed patterns.

Sidelobes in the far field radiation pattern must be held within limits for two reasons: waste of RF power (which is small), and interference with other communication services outside the required coverage. Aperture illumination patterns yielding lower sidelobe levels (relative to the mainlobe level) will in general result in lower gain for a given aperture size. Uniform illumination gives the largest possible aperture efficiency, $\eta = 1$, but at the expense of a high sidelobe level, 17.6 db below the mainlobe in the absence of degrading effects such as blockage and surface errors. For low sidelobes the illumination pattern must be tapered from a maximum at the aperture center to a lower value at the edge. With a given aperture size, tapering leads to a larger half-power beamwidth and a loss in gain. However, when the aperture diameter is increased to restore the original beamwidth, the gain is higher than with the uniformly illuminated aperture of original size. The reason for this is, of course, that less power is wasted in the sidelobes. Techniques for sidelobe suppression in reflector type spacecraft antennas are discussed in Reference 4-15.

Consider the following circularly symmetric illumination pattern (field strength):

$$f(\rho) = b + (1 - \rho^2/a^2)^n \tag{4-15}$$

where ρ is the radial coordinate in the aperture plane, a is the aperture radius, and b and n are parameters of the illumination function which govern the amount of taper to the illumination function and the rate at which the taper is applied.

This family of patterns is an extension of the family given by Equation (4-1). A tapered illumination is now superimposed on a uniform pedestal (see Figure 4-2). The pedestal height b determines the illumination level at the aperture edge relative to the peak level.

Figure 4-2 and Table 4-3 show comparisons of antenna performance and size for tapered illumination with a uniformly illuminated aperture ($n = 0$, $b = 0$) sized for the same 3-db beamwidth.

The relative diameter and gain increase was determined by the expressions:

$$\frac{D'}{D} = \frac{K'}{K} \tag{4-16}$$

and

$$(\Delta G)_{db} = 10 \log \frac{(K')^2 \eta'}{K^2 \eta} \tag{4-17}$$

where the prime denotes the quantities for tapered illumination. These expressions follow immediately from Equations (4-13) and (4-14), considering that the comparisons are made on the basis of equal beamwidth θ_o. The values for K and η are available in the literature (Reference 4-1).

Figure 4-2 shows the advantage in gain (for the given beamwidth) obtained by using taper and the slight variation in gain with varying pedestal height.

The advantage of the pedestal is clearly seen in Table 4-3. The taper with pedestal ($n = 2$, $b = 0.25$) requires a 1.2 times smaller aperture diameter than the same taper without pedestal ($n = 2$, $b = 0$), while giving a 1.6 db lower sidelobe level and a slightly higher gain. The question arises now whether the taper $(1 - \rho^2/a^2)^2$ with a uniform pedestal of height 0.25 is a readily realizable feed pattern. Figure 4-3 compares this pattern with that of a standard waveguide horn. The horn pattern shown, which is corrected for variation in horn-to-reflector distance, does not match perfectly to the pattern discussed and, therefore, the relative level of the first sidelobe will be somewhat higher than -32.3 db.

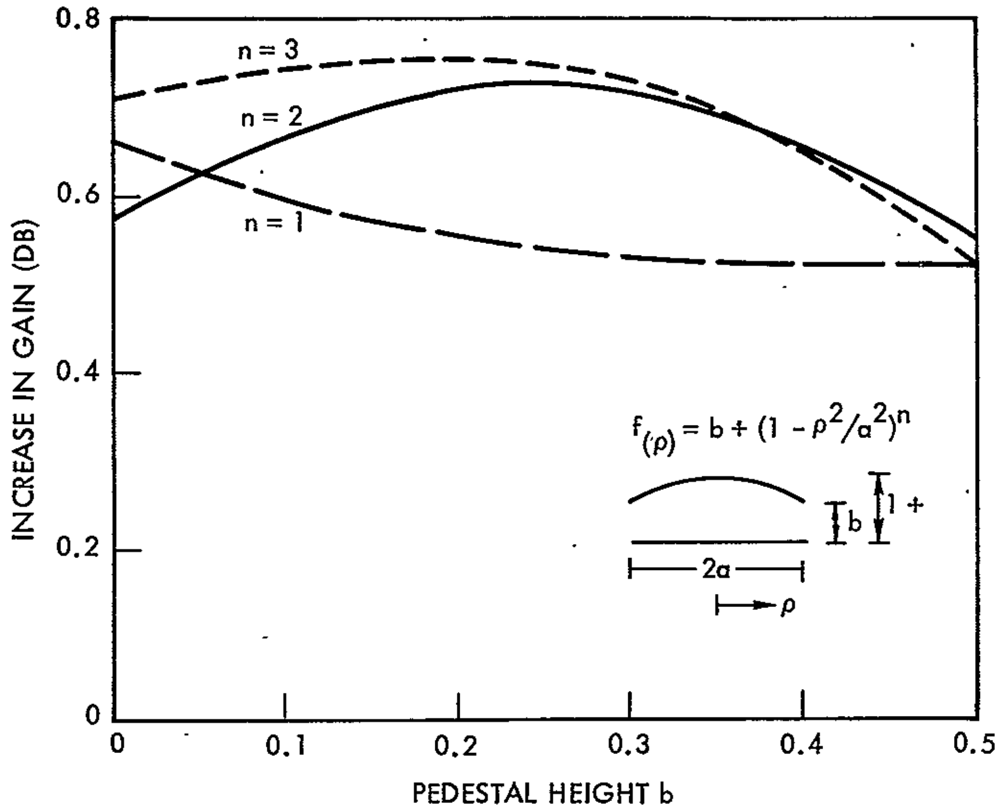


Figure 4-2. Increase in Gain Over a Uniformly Illuminated Circular Aperture for Tapered Distributions with Equal Beamwidths

Table 4-3. Comparison of Aperture Illumination Patterns (for given 3-db beamwidth of far-field pattern)

Taper Exponent (n)	Pedestal Height (b)	Taper Edge (db)	$K = \theta_o D_\lambda$ (deg)	Relative Diameter	Illumination Efficiency (η)	Gain Increase (db)	Sidelobe Level (db)
0	0	0	58.5	1.00	1.00	0	-17.6
2	0	-∞	84.3	1.44	0.56	+0.66	-30.7
2	0.25	-14	70.5	1.21	0.81	+0.72	-32.3
3	0	-∞	94.6	1.62	0.44	+0.62	-36.1

Further, the sidelobe levels mentioned above were derived from the aperture illumination. The degrading effects of blockage and surface errors were not taken into account. The actual sidelobe level, obtainable with an aperture diameter of D' = 1.21 D, will probably be between 25 and 30 db. The increase in sidelobe level above the value inherent with the aperture illumination pattern is discussed in detail in Section 4.4.3. (See also Ref. 4-15 for a study of reflector sidelobes.)

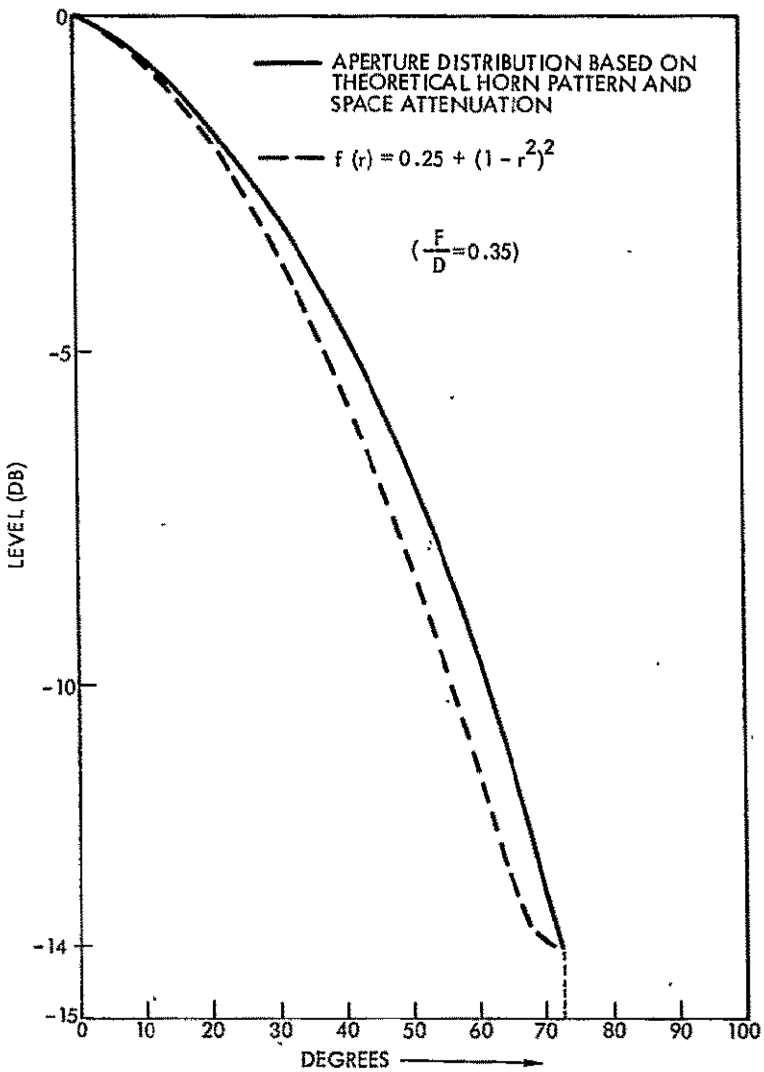


Figure 4-3. Low-Sidelobe Aperture Distributions

When more precise control of the aperture distribution is possible, such as in the case of phased arrays, the distributions for circular apertures derived by Taylor (Reference 4-2) provide an optimum compromise between aperture size and sidelobe level. This is analogous to the well-known work of Dolph (Reference 4-3) who generated the Dolph-Tchebyscheff distributions for linear arrays. The Dolph-Tchebyscheff optimization will generally require the smallest linear array length for a given sidelobe level, and the same is true for the diameter of a planar array of circular cross section with Taylor distribution.

4.2.2 Other Systems Considerations

4.2.2.1 Gain Loss Due to Aperture Excitation Errors

Excitation errors result in reduced gain and raised sidelobe levels. These problem areas will be given further attention in Section 4.4.1.

4.2.2.2 Beam Steering

Beam steering, when required, can be done either mechanically or electrically.

Mechanical beam steering can be accomplished by using a gimballed fixed beam antenna or by using a gimballed feed for a reflector antenna. The latter requires the feed gimbal system to be in the field of view of the reflector which causes additional losses and increased sidelobes due to the additional blockage. In addition, the limits of scan are constrained by coma. This will be discussed in Section 4.3.1.3. The use of an offset fed parabolic reflector virtually eliminates these blockage effects; however, coma constraints will still limit the scanning capability. The use of a dual axis gimbal for each reflector will provide the necessary beam steering for an antenna system for a synchronous satellite. Movement of the entire antenna system causes negligible loss in rf performance. Flexible wave-guides at the higher frequencies and coax cables at the lower frequencies allow sufficient movement of the antenna.

In phased arrays the beam is steered electronically by properly adjusting the phase of the signal transmitted by each element or groups of elements. This is advantageous because it eliminates dynamic interaction with the spacecraft attitude control system. In order to make an array weight effective, the number of elements and phase shifters must be minimized. Scanning an array beam through large scan angles limits the element spacings and hence increases the number of elements required. Fortunately, the steering angles required for the present application are relatively small.

A compromise between a phased array and a gimballed reflector antenna consists of a fixed reflector with a phased array feed. However, the same discussion as given for the gimballed feed apply; that is, blockage and coma degrade the electrical performance of the antenna.

4.2.2.3 Power Handling Capability

The power handling capability of an antenna system is determined by the geometrical configuration of the conductors. The spacing of conductors must be selected to avoid the existence regions of multipactor breakdown. In the component design of a spacecraft antenna system, special techniques are required to eliminate the resonance effects which cause breakdown for high power transmission. In addition, sharp edges and discontinuities are to be avoided to prevent normal electrical breakdown. Impedance mismatches which create points of unnecessarily high voltage must also be avoided. However, for the narrow bandwidths required for TV broadcasting the impedance mismatch can be minimized.

4.2.2.4 Impedance Match

For single-feed reflector antennas, where the length of the waveguide (or coax) from the transmitter output to the feed input is several wavelengths, very good impedance match (1.02:1 VSWR) is mandatory in AM television systems, because of the danger of ghosts caused by reflection. In a multi-element array this problem can be circumvented by placing transmitters directly at the feed points, thus avoiding long transmission line runs in the high-power portion of the system. The long transmission lines connecting the transmitters to the center of the spacecraft, where the rf drive signal originates, are then at a low power level, and good impedance match is more easily achieved, e.g., by isolators whose losses do not significantly change the overall efficiency.

4.2.2.5 Deployment Techniques

As the spacecraft antenna diameters increase, some folding technique becomes necessary to allow stowage inside the booster fairing. This is required for any TV broadcast frequencies at 2.5 GHz and below. A large number of deployment techniques have been proposed, investigated, and developed. A summary is contained in Appendix 4A.

4.3 CANDIDATE ANTENNA TYPES

In this section a representative cross-section of existing antenna types is discussed. Antennas obviously not applicable to the task at hand have been eliminated. These include log-periodics (too lossy, bandwidth not required, too heavy for required gains), rhombics (too lossy, bandwidth not required), spiral antennas (as log-periodics), and many others.

4.3.1 Reflector Antennas

Reflector antennas consist of the family of indirect radiators where the large aperture necessary to generate the desired directivity is obtained by a passive reflecting surface. Included in this class of antennas is the focal point feed parabolic reflector, variations of the parabolic reflector such as the parabolic cylinder, the Cassegrain reflector system, variations of the Cassegrain reflector such as the Gregorian system, (using an elliptical subreflector) and the Schwarzschild system, spherical reflector, and the flat plate reflector.

Since one of the prime considerations of the present study is the achievement of low sidelobes, it is important that proper control of the aperture distribution can be maintained. One of the major contributors to high sidelobes from reflecting systems is the aperture blockage presented by the feed. A phase distribution other than linear over the aperture can also increase the sidelobe level.

4.3.1.1 Single-Reflector Antennas

A single reflector antenna uses direct radiation on a reflecting surface to generate the radiation pattern. The most common type of single reflector antenna is the primary feed parabolic reflector. Because of its promise as a suitable spacecraft antenna it will be considered in detail in Section 4.4. Brief comments on the other single reflector systems are given below.

Spherical Reflector. The spherical reflector offers the advantages that multiple feeds can be used. The spherical surface, which does not have a true focal point for incident plane waves, causes the near sidelobes to be high. These sidelobes result from the perturbation to the phase distribution inherent in the geometry of the spherical reflecting surface. Although an array feed could be used which could be programmed to compensate for these errors, the resulting blockage would then increase the sidelobe levels. Techniques to minimize the effects of sidelobes due to blockage effects could be traded off with the advantages of using this antenna with an array feed capable of generating multiple beams.

Flat Plate Reflector and Cornucopia Horn. The flat plate reflector does not provide directivity to the radiated energy in the usual sense. The aperture necessary to generate a given beamwidth is required of the illuminating source, and can be either a paraboloid or a horn. The flat reflector gives only direction to the radiated beam. For spin stabilized spacecraft the flat plate reflector could be used in place of an RF rotary joint. The antenna aperture can be fixed to the spacecraft, radiating along the spin axis. The reflector, oriented at a 45 degree angle with respect to the aperture and to the direction of earth, directs the beam toward earth. The reflector can be used to despin the beam, thus either eliminating the need for a rotary joint for a spin stabilized spacecraft entirely, or (as in the Intelsat III cornucopia horn) replacing it with a simple concentric choke. The need for a bearing still exists, of course, to provide the despinning of the reflector. For the required narrow beamwidths, this approach lacks appeal due to the large structure.

4.3.1.2 Two-Reflector Antennas

The most common two reflector antenna is the Cassegrain system. Instead of locating the feed at the focal point, a subreflector is used which reflects and focuses the waves to a point near the vertex of the main reflector where the feed system is located. The major advantage of the Cassegrain system is that the feed network and associated electronic equipment can be located behind the primary reflector. The major disadvantage is that the subreflector represents considerable physical blockage to the main reflector. This contributes significantly to sidelobes.

The total efficiency of the antenna system is affected by the spillover losses of two reflectors. However, recent techniques have improved the spillover losses significantly so that this can no longer be considered a significant disadvantage of the Cassegrain system. The sidelobe levels are high, typically -15 db for a total antenna efficiency of about 70 percent.

The subreflector for a Cassegrain system is a hyperboloid. From geometrical considerations, it can be seen that an ellipsoid can also be used. Then, the two-reflector antenna is a Gregorian system, less compact than a Cassegrain system, although the subreflector size is in general slightly smaller.

4.3.1.3 Multiple Beam Reflector Antennas

For configurations which provide regional coverage by use of multiple antenna beams, it would be desirable to utilize a single reflector surface with multiple feeds to reduce weight and ease packaging problems. The direction of each beam relative to the reflector axis is determined by the off-axis displacement of the respective feed. The ratio of the beam displacement to the feed displacement is a function of the f/D of the reflector and the illumination function. This ratio, the beam deviation factor, ranges from about 0.6 to nearly 1.0 for practical reflector designs. The beam displacement results from a linear phase distribution across the reflector aperture. However, from geometrical considerations it can be seen that a cubic term is also introduced in the phase distribution. Its most significant effect on the far field radiation pattern is an increase in the sidelobe level. These raised sidelobes, called coma lobes, increase with the feed displacement. The dashed curves in Figure 4-4 show this increase for initial sidelobe levels of -26 db and -31 db.

The sidelobe levels are also adversely affected by mutual coupling between nearby feeds. This effect is shown by the solid lines in Figure 4-4. It can be seen from Figure 4-4 that if, for example, initial sidelobes of -31 db were achieved with a single beam, sidelobes for dual beams would be higher than -25 db, except for beam separations between 2 and 3 beamwidths. In addition to these effects, there are the additional effects on sidelobes due to increased blockage presented by the multiple feeds.

The use of a spherical antenna with multiple feeds or array feed to generate multiple-beam capability is discussed in Section 4.3.1.1.

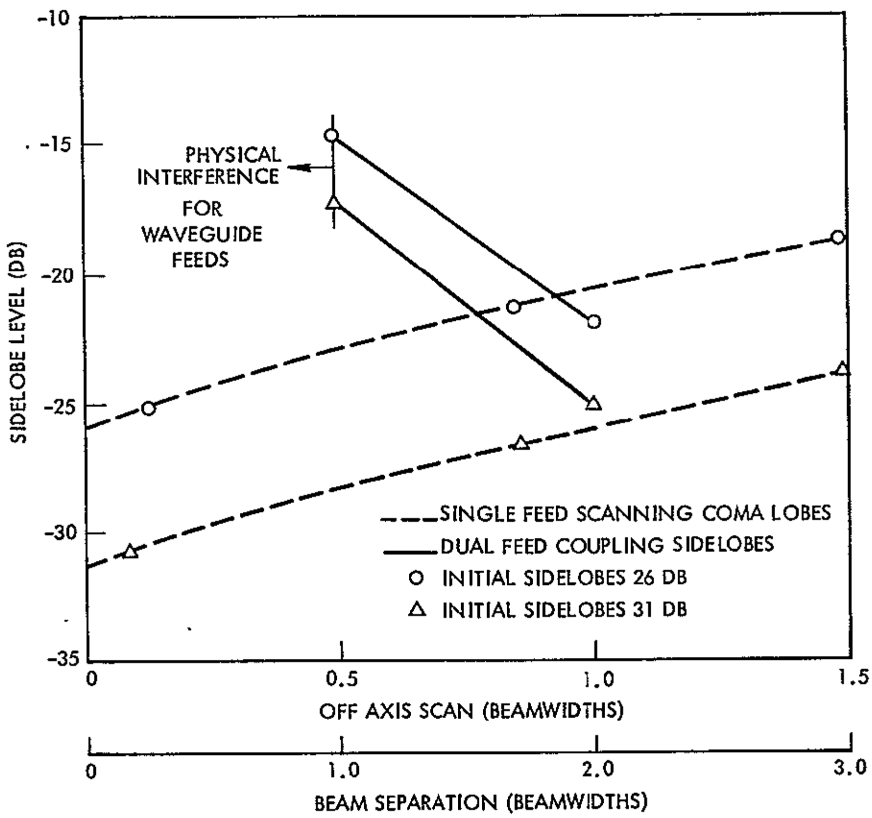


Figure 4-4. Sidelobe Levels Resulting From Dual Feeds For a Parabolic Reflector

4.3.2 Broadside Arrays

4.3.2.1 General Considerations

The total radiating aperture for an antenna may be composed of several smaller apertures to form an array antenna. The major advantages for the present application that can be realized by using an array as opposed to a reflector antenna are:

- More precise control of the illumination function
- A single aperture can be used to provide multiple beams, thus reducing stowage volume requirements
- Electronic beam steering
- Individual amplifiers for each element, thus reducing the power (and cooling requirement) of each amplifier.

The primary disadvantages are that:

- For some applications, the weight of the array and associated feed network is excessive
- Feed network losses may be high
- Cost and complexity may be excessive.

It was pointed out in Section 4.2.1.3 that a tapered amplitude illumination function is desirable for optimum gain coverage and required for low sidelobe levels. The amount of illumination tapering must be traded off with the increased antenna size and weight.

4.3.2.2 Hybrid Matrix Arrays

The generation of multiple beams from an array increases the complexity of the feed system. One of the major concerns is beam port isolation. Two solutions to this problem by Blass (Reference 4-4) and by Butler (Reference 4-5) are outlined below.

The Blass matrix (Figure 4-5) for an array of N elements with a capability of A beams has N columns and A rows. Each column is a feeder line to one of the elements, while each row is a feeder line from the array terminal for one beam. N x A directional couplers complete this series feed matrix, connecting each beam port to all feeder elements. Magnitudes and phases of element radiations are determined by appropriate coupler values and line lengths for each beam. The different coupler values have an adverse effect on production costs.

The Butler feed matrix (Figure 4-6) is a corporate (parallel) feed matrix which uses hybrid power dividers to provide beam port isolation. Depending on a tradeoff of the power requirements, weight, and insertion loss, the hybrid power dividers could be waveguide directional couplers, branchline couplers in waveguide, coax or stripline, parallel line couplers in coax or stripline. For the simple Butler array the amplitude distribution is uniform. The phase distribution across the aperture is fixed in such a way that the relative beam positions are fixed. That is, for a planar Butler array the beam crossovers occur at the -4 db values of each beam in the principal planes and -8 db in the diagonal planes. If for the specific application the beams can be made to cover the desired

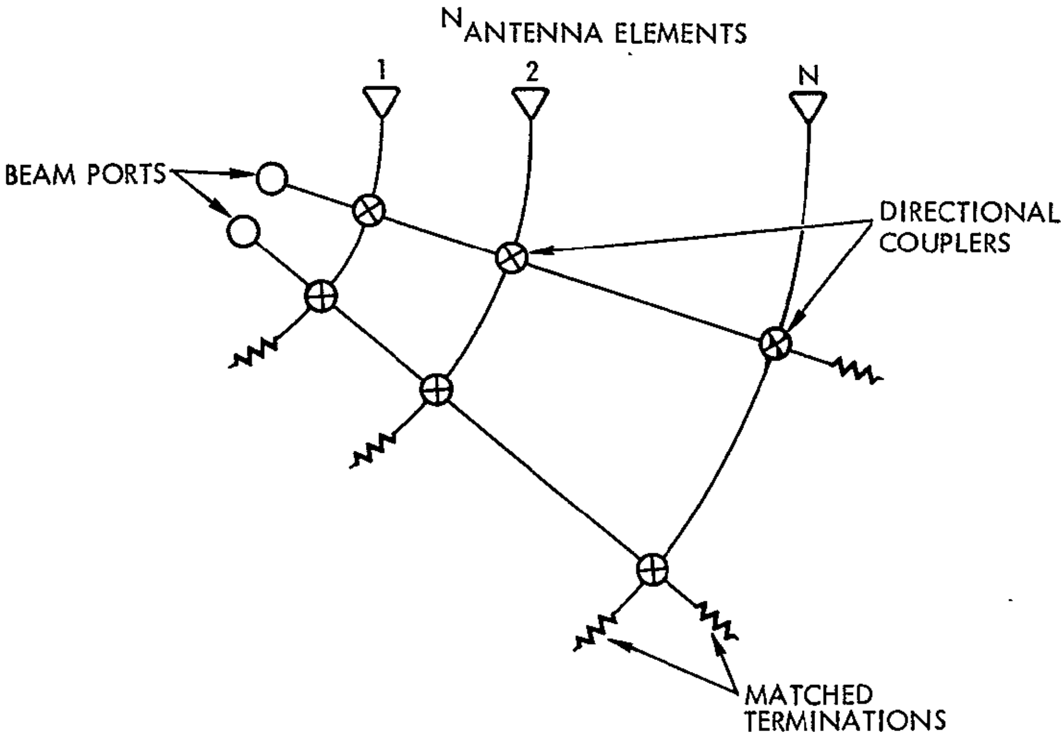


Figure 4-5. N-Element, Two-Beam Blass Matrix

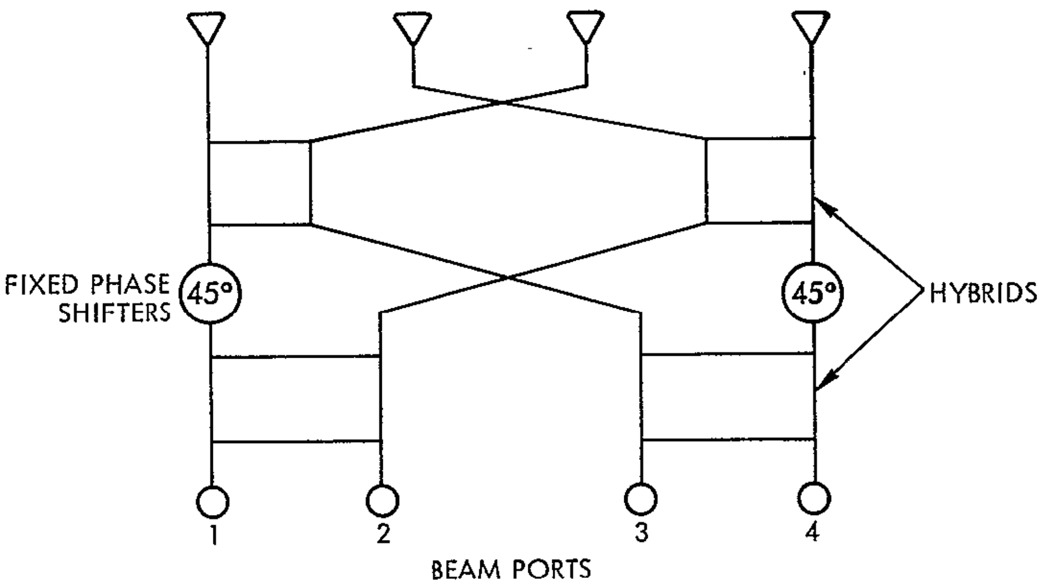


Figure 4-6. 4-Element Butler Matrix Array

region properly, which does not seem likely for the present application, then the Butler array is attractive, except for the high sidelobe levels which result from a uniform illumination. The illumination function can be tapered by the addition of beam combiners which result in a cosine or cosine squared aperture illumination function. The penalty paid is the additional circuitry and associated losses and required weight. Finally, if amplifiers are used at the elements anyway (see Section 4.5, Active Arrays), the complexity of the hybrid matrix, and the limited modularity, are not justified.

4.3.2.3 Digitally Phase-Steered Planar Arrays

If amplification is provided at each element (active array), then this approach provides maximum beam forming and steering flexibility, and weight effectiveness comparable to a parabolic reflector (see Section 4.5).

4.3.2.4 Retrodirective Array

A retrodirective antenna focuses energy back in the direction of arrival of a received signal. The most common passive retrodirective antenna is the corner reflector. The equivalent array antenna was designed by VanAtta (Reference 4-6). A signal incident on the antenna is returned in the direction of arrival by providing a conjugate phase to each element. The use of a retrodirective array for TV broadcasting would require a carrier to be transmitted to the satellite from the region or each region to be covered. The modulation signal can then be sent to the satellite via a separate antenna. The same antenna can be used if the transmitting station is in the mainbeam region of the satellite transmitting antenna. Use of the same satellite antenna also requires the design of an antenna which will cover both the frequency bands of transmit and receive. This either requires both frequency bands to be in the same range or an additional complexity in the design of a broadband antenna system.

4.3.3 Other Antenna Types

Horns are attractive for two reasons: first, the gain variation over a given coverage sector is less than for a paraboloidal reflector, e.g., the gain at the edge of the sector is higher. Secondly, the sidelobe levels are generally very low. However, for the beamwidths of interest, the size and weight of a single horn become prohibitive at 800 MHz, and the structural complexity makes it undesirable even at 12 GHz.

Various types of lenses are available. Of these, Luneburg lenses are too heavy for the required gains, and zoned lenses have to be steered mechanically, so that no particular advantage exists over reflector antennas. A hybrid lens type, the constrained lens, such as a R/2R bootlace lens, offers the possibility of electrical beam switching between a number of fixed beams, similar to the beams in a hybrid matrix array (see Section 4.3.2.2). It is doubtful, however, that the low weights of parabolic reflectors can be achieved with these systems for small beam numbers. In addition, continuous electric beam steering, such as may be required to compensate for attitude control errors, is only available through complex and lossy beam combining networks.

End fire arrays of driven elements as well as parasitic endfire arrays are generally much too long to be seriously considered for the high-gain beams required.

Helices also are extremely long for high gains, and there appears to be a reasonable upper limit in gain of approximately 20 db, beyond which increases in length will be mostly offset by decreases in efficiency.

Traveling-wave or standing-wave excited slot arrays can be very efficient (up to 70 percent), but for the same gain they are heavier than parabolic reflector antennas. Furthermore, they generally have to be mechanically sterred, and do not allow multiple beams from the same aperture. Table 4-4 summarizes the preliminary rating of the basic antenna types.

Table 4-4. Antenna Performance Summary

Antenna Frequency	Cassegrain	Single Reflector	Cornucopia Horn	Active Digital Array
800 MHz	Blockage Increases Sidelobes	Difficult to Deploy	Not Feasible	Good
8 to 12 GHz	Blockage Increases Sidelobes	Good	Heavy, Structurally Complicated	Heavy, Poor Efficiency

4.4 DESIGN OF PARABOLIC REFLECTOR ANTENNAS

The parabolic reflector is one of the most reliable antennas for spacecraft applications. The feed system is relatively simple and efficient. The reflector and support structure which contributes the majority of the weight to the antenna can be made as lightweight as the thermal environment and mechanical requirements can tolerate.

4.4.1 Gain and Efficiency

4.4.1.1 Illumination Function

The amplitude distribution on a parabolic reflector is a combination of the feed pattern and the variation in feed-to-reflector range associated with the geometry of the reflector system. Different f/D values give different amounts of range variations and different subtended angles at the feed. These differences permit some degree of flexibility in the control of the illumination function. In general, this selection is limited at high f/D values by the increased feed directivity required, and at the low f/D values by the axial ratio of the feed pattern for large aspect angles.

4.4.1.2 Efficiency

The design of a parabolic reflector for maximum aperture efficiency requires an illumination function which is as near uniform as possible. However, for coverage of a given region on earth, the antenna parameter relevant to overall system performance is the lowest gain within a given beamwidth. Optimization of this quantity generally requires a design with non-optimum aperture efficiency. Beamwidth efficiency is then raised at the expense of reduced aperture efficiency.

A tradeoff normally made to optimize the efficiency of a parabolic antenna system is to balance the effects of a loss in the efficiency of the system due to a tapered illumination function with the efficiency lost by radiation from the feed that is not intercepted by the reflector. This latter effect is known as spillover.

In addition to the aperture illumination efficiency, there are several other effects which decrease the gain of an antenna system. The gain from the antenna is reduced by some factor so that the actual gain of the antenna may be represented by

$$G = \eta(\eta_I G_o) \tag{4-18}$$

where

G_o = the gain for a uniformly illuminated aperture

η_I = the illumination efficiency

η = $\eta_F \eta_P \eta_{\text{¢}} \eta_B$, the efficiency resulting from all other effects.

Other contributors to a loss in efficiency are:

- Feed Efficiency, η_F - this includes ohmic losses in the feed and reflection of energy back into the feed.
- Polarization Efficiency, η_P - cross polarized components on the aperture of the reflector represent illumination that does not increase the gain from the reflector. The resultant efficiency can be approximated by

$$\eta_P \approx 1 - \frac{1}{96}\,\psi^4 \qquad \psi < 1 \tag{4-19}$$

where ψ is the half angle subtended by the reflector at the feed (see Reference 4-7).

- Phase Errors, η_ϕ - phase errors exist on the surface of the reflectors as a result of manufacturing surface tolerances, surface distortions, and improper location of the feed and from failure of the feed to produce a pure phase center. It is pointed out in the discussion on sidelobe control that the effects of RMS surface errors on sidelobes is much more significant than on gain for the present applications. The effects of these errors on the efficiency of the antenna can be approximated by

$$\eta_\phi \approx e^{-\delta^2} \tag{4-20}$$

where δ is a small RMS phase error in radians (Reference 4-8). For the above approximation a shallow paraboloid was assumed which yields a pessimistic value of efficiency (Reference 4-7) for low f/D values. Figure 4-7 gives η_ϕ for the RMS errors in degrees (360 degrees = 1 wavelength).

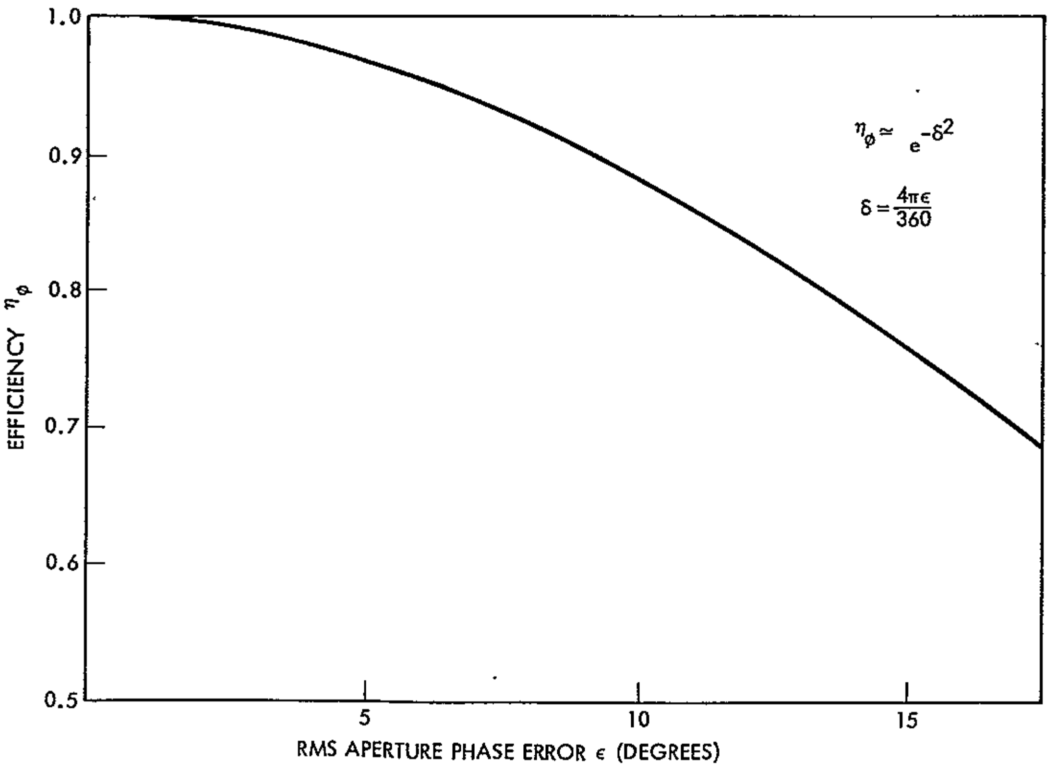


Figure 4-7. Gain Loss Due to Random Aperture Phase Errors

- Blockage Efficiency, η_B - a symmetrical focal point fed parabolic reflector requires a feed and feed support structure which physically obstructs the radiation. The associated loss in gain is represented by η_B. A monopod support structure virtually eliminates feed support blockage. The loss in gain due to a feed of diameter d for a total reflector diameter of D is given in Figure 4-8 (Reference 4-9). For narrow half-power beamwidth antennas the aperture is large compared to the feed dimensions. It can be seen from this figure that for a 3-db beamwidth of 3 degrees the loss due to blockage by a typical focal-point feed ($d/D \approx 0.035$) is negligible.

4.4.2 Physical Dimensions

The diameters required for beamwidths of 1 degree to 4 degrees are given in Figure 4-9. This data corresponds to aperture illumination functions which can be generated by typical feed designs using an $f/D = 0.35$ reflector. For configurations where packaging requirements dictate slightly smaller reflector diameters, such as multiple reflector configurations, some tradeoffs can be made with other system requirements

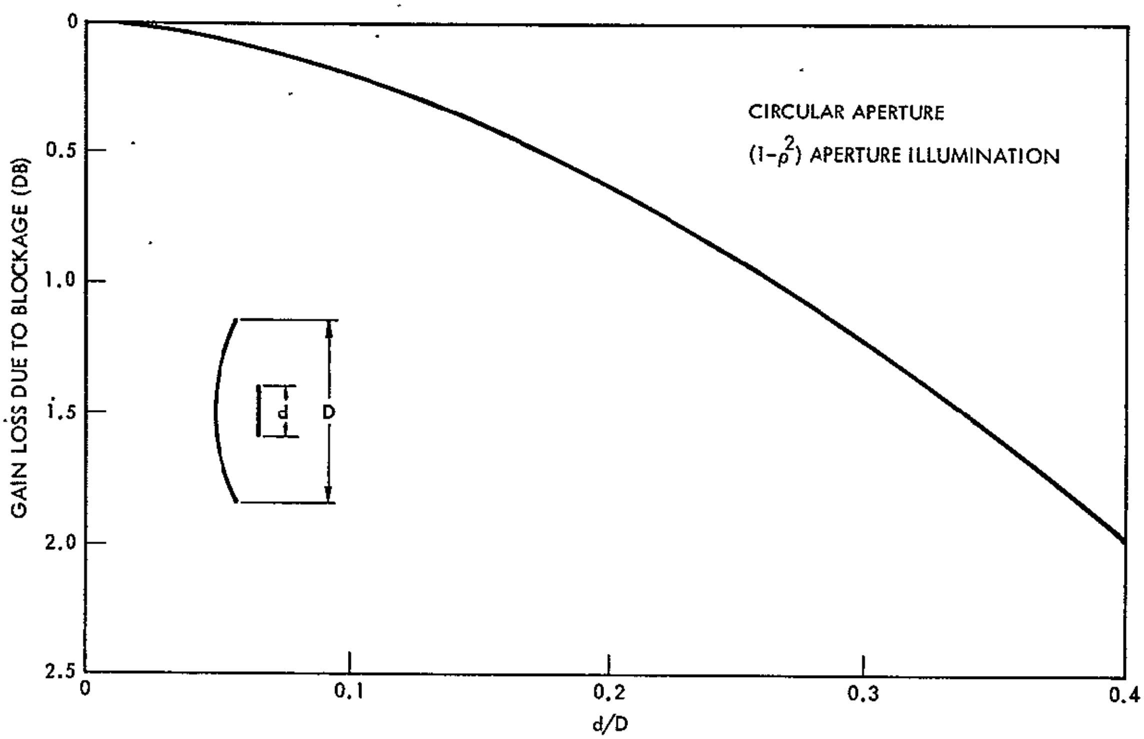


Figure 4-8. Gain Loss Due to Blockage

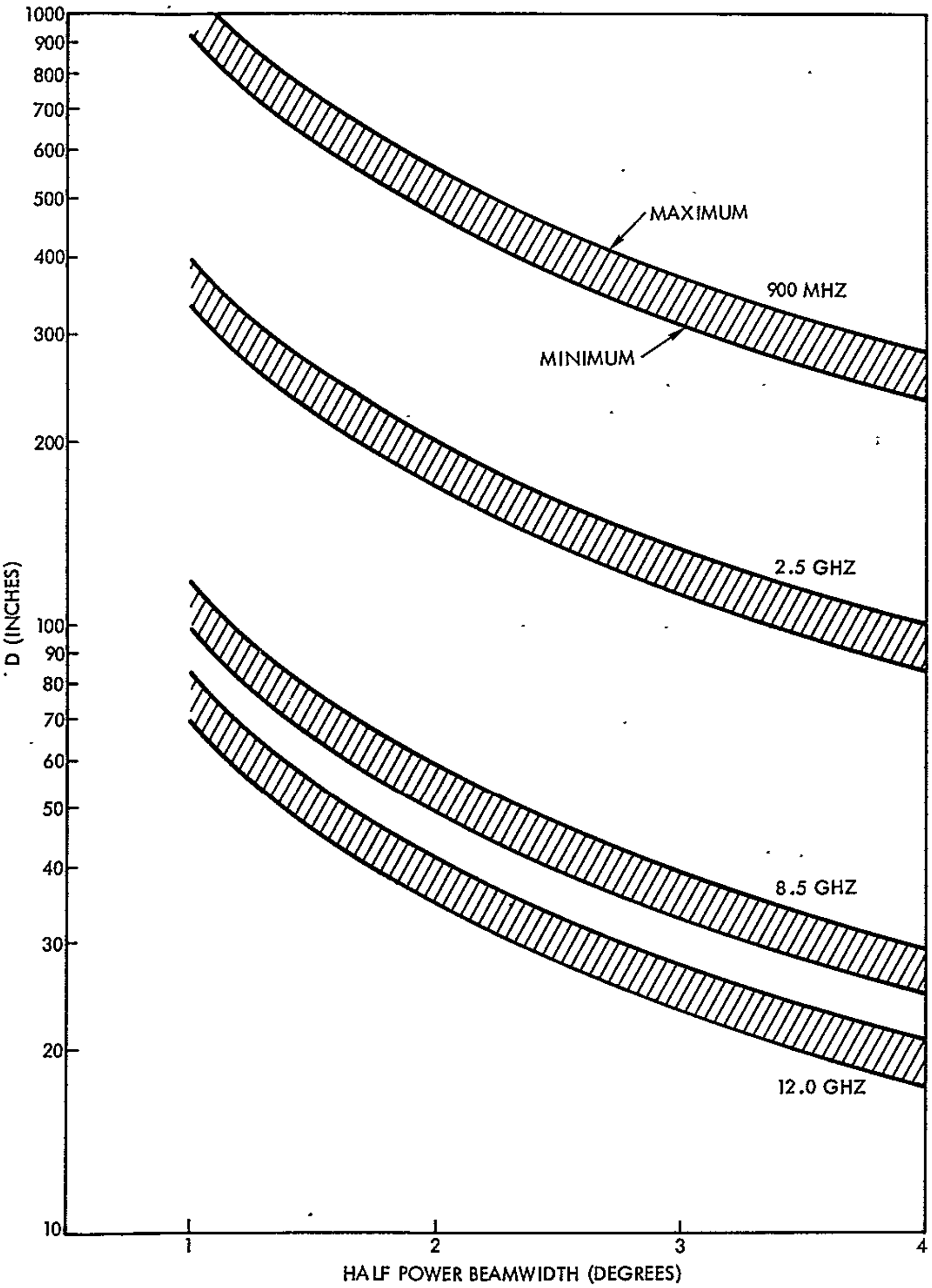


Figure 4-9. Minimum and Maximum Antenna Diameters Versus Beamwidth for Each Frequency Band

which could result in the use of smaller reflector diameters. The "minimum" diameters are based on the illumination function given in Equation (4-15) with b = 0.25 and n = 2. The "maximum" diameters are for b =0, n = 2.

It can be seen from these curves that deployable reflectors will be required for a single reflector at 900 MHz, and for the more narrow beamwidths also at 2.5 GHz. Actual diameters will fall somewhere inside the shaded bands, depending on feed design.

4.4.3 Realizable Sidelobe Levels

Sidelobe levels are major criteria in the selection of antenna designs suitable for television broadcast satellites. Proper control of the aperture phase and amplitude distribution is required. The RMS surface errors and the blockage must be kept minimal. The evaluation of RMS surface errors is a statistical process and requires careful consideration of the types of errors being considered to set up the correct mathematical model.

The effect of random surface errors on sidelobe levels are shown in Figure 4-10. The data used for the calculation of these curves was derived from Reference 4-10. It is seen that the achievement of low sidelobes requires stringent control of surface errors. The abscissa is given in radians; one-tenth of a radian corresponds to: 0.208 inch at 0.9 GHz; 0.075 inch at 2.5 GHz; 0.022 inch at 8.5 GHz; and 0.016 inch at 12.0 GHz. The effects of aperture blockage on sidelobe levels is shown in Figure 4-11 (Reference 4-11).

Since the resultant sidelobe levels are a function of the initial sidelobe levels inherent to the aperture illumination pattern, it is important that the initial designs of the illumination function give very low sidelobes.

4.4.4 Deployable Reflector Antennas

It can be seen from Figure 4-9 that for all beamwidths at 0.9 GHz and for beamwidths less than about 3 degrees at 2.5 GHz a deployable reflector is required for a single reflector. Figures 4-12 and 4-13 were generated for these types of deployable reflector antennas which are made by stretching a membrane between ribs to approximate a paraboloidal surface. The curves in Figure 4-12 show the maximum deviation of a flexible membrane deployable reflector from a true paraboloid as a function of the number of support ribs. Using the data of the curves given in Figures 4-10 and 4-12, the number or ribs required to maintain a -25 db sidelobe level was calculated for beamwidths from 2 degrees to 4 degrees. This curve is shown in Figure 4-13. Calculating the RMS surface error from the maximum deviation (Figure 4-12) is rather pessimistic, but it was felt that this is justified, since the thermal effects will contribute additional effective RMS surface errors.

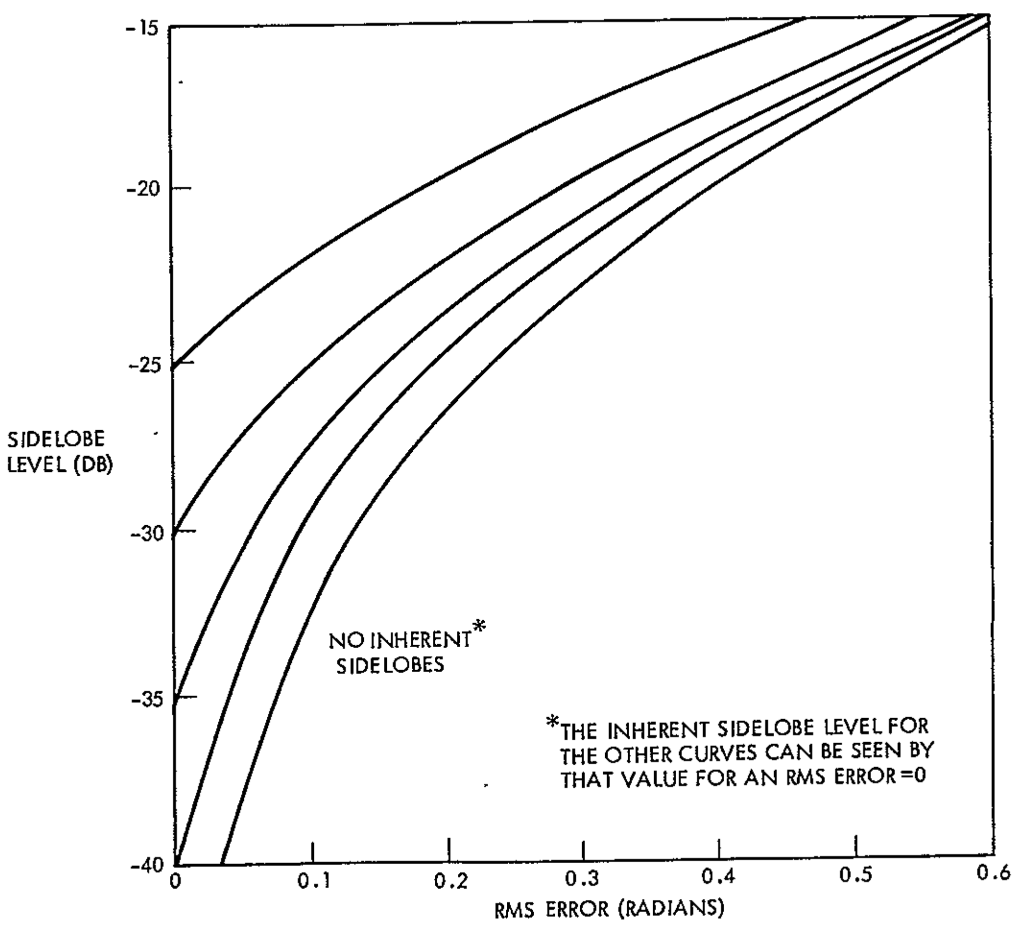


Figure 4-10. Sidelobe Level as a Function of RMS Surface Errors for Typical Parabolic Reflector

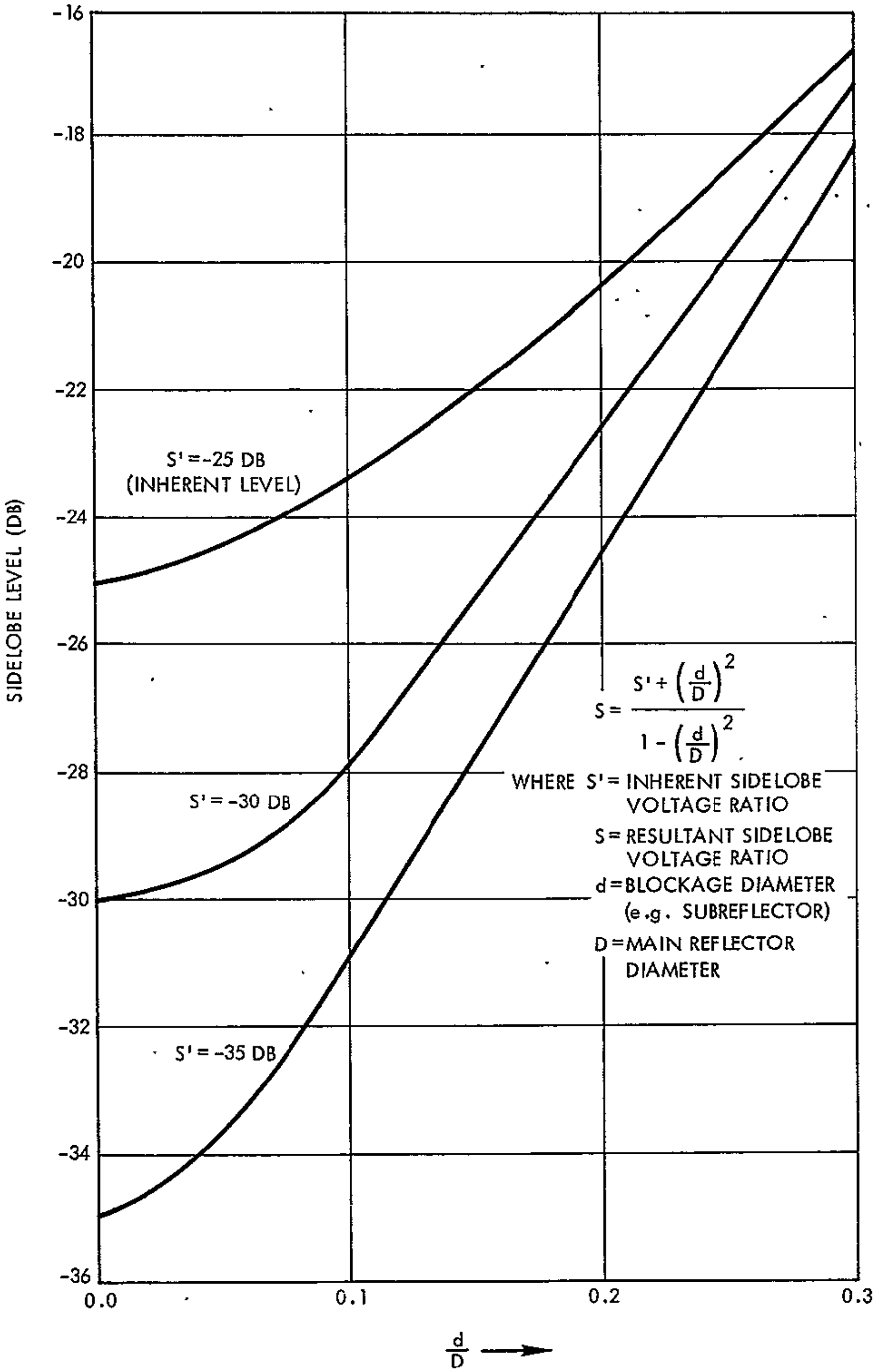


Figure 4-11. Sidelobe Level Increase Caused by Aperture Blockage

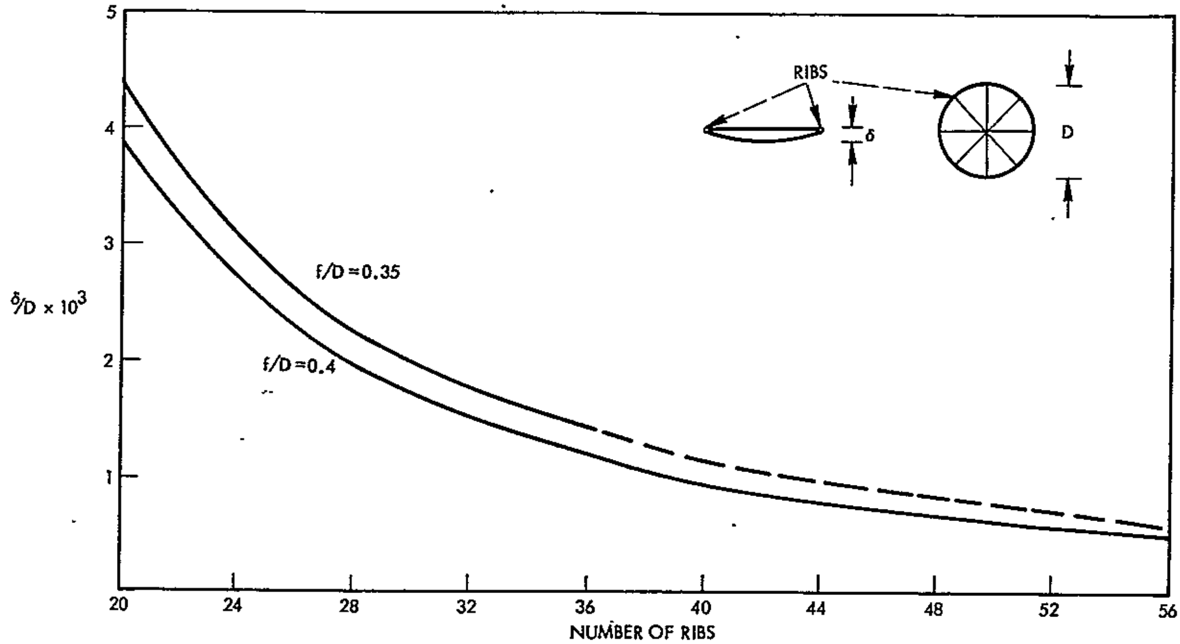


Figure 4-12. Deviation from a True Paraboloid Versus the Number of Ribs for a Stretched Membrane Deployable Reflector Antenna

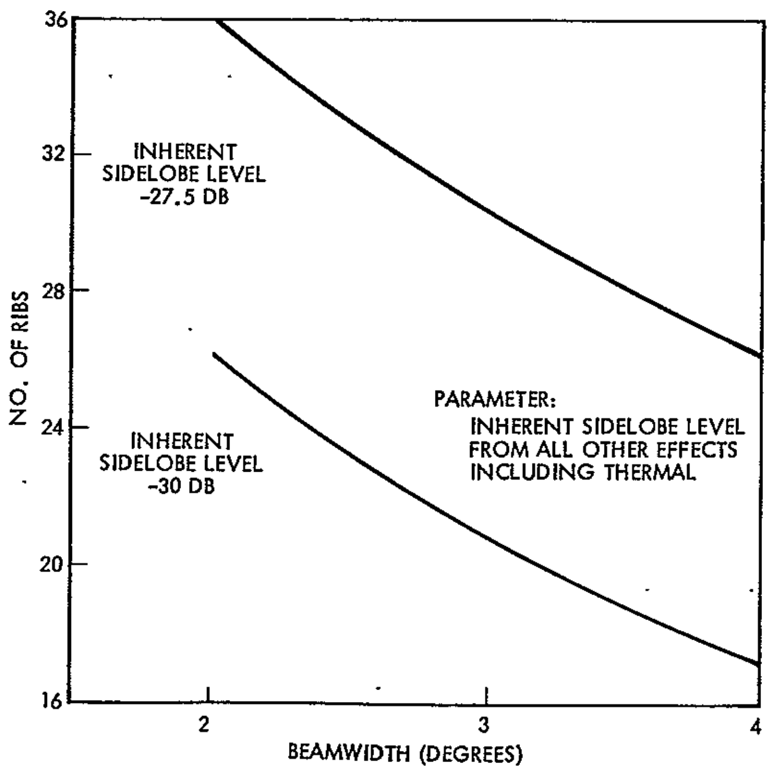


Figure 4-13. Number of Ribs Required to Obtain -25 db Sidelobes for Beamwidths from 2 degrees to 4 degrees— Typical Parabola $f/D = 0.35$

Fabrication of the reflector out of a grid structure reduces the reflector mass and solar pressure. The electrical performance of the antenna is not altered as long as the diameter of the wires making up the grid and the spacing between these wires are related such that total reflection at the surface occurs. A curve giving this relationship for a frequency of 900 MHz is given in Figure 4-14. A normalized curve which can be used for other frequencies is given in Figure 4-15. It should be kept in mind, however, that the ribs and back-up structure will also produce a significant obstacle to solar pressure, and these may indeed be the predominant factors.

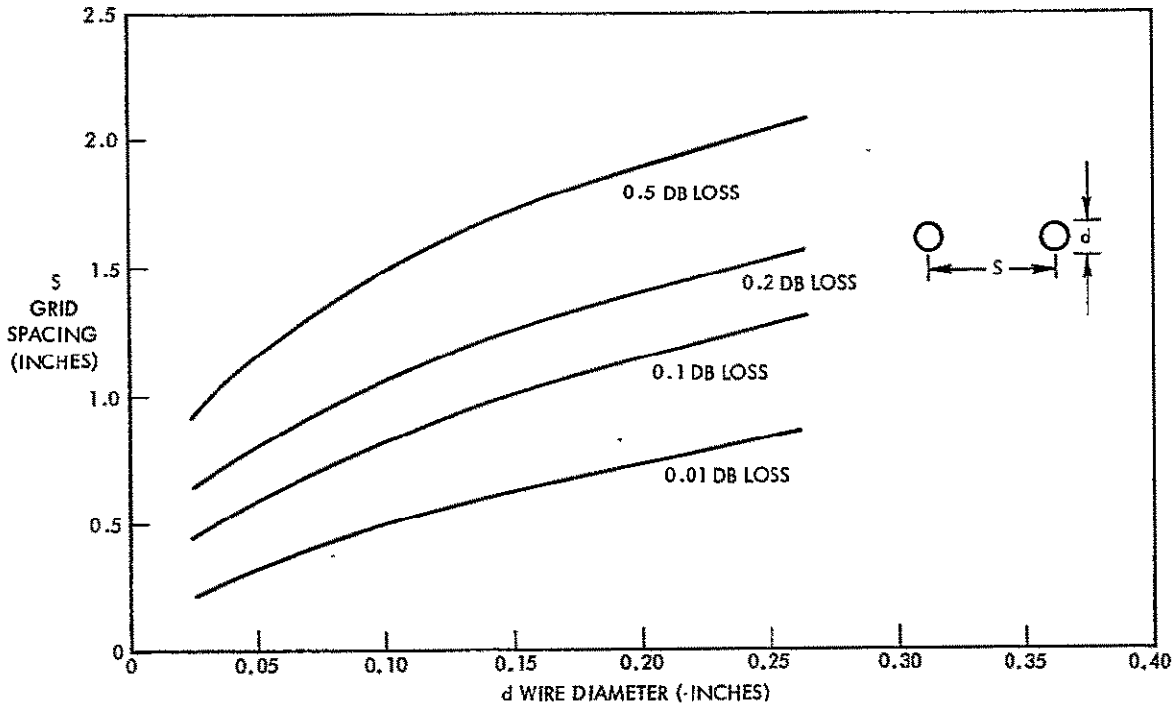


Figure 4-14. Grid Spacing Required for Transmission Loss of 0.01, 0.1, 0.2, and 0.5 db for Wire Grid Reflector as a Function of Wire Diameter, Frequency = 900 MHz

It is expected that by 1975 large deployable reflectors will have been successfully demonstrated in spacecraft applications. A single reflector would require minimum deployment complexity. The use of multiple reflectors for multiple beams and the use of deployable elements for arrays decreases the reliability of deployment with respect to a single deployment, but it will provide redundancy in the total antenna function. Various types of deployable reflector constructions are discussed in Appendix 4A.

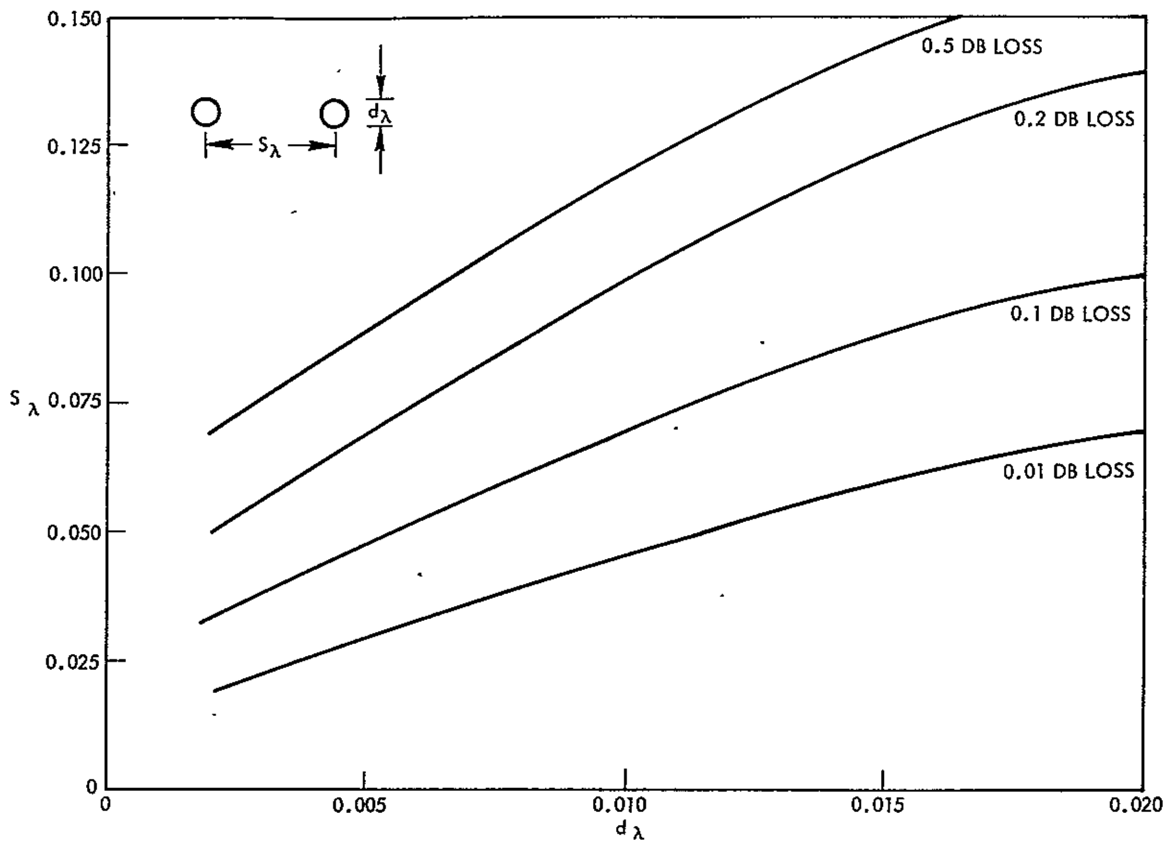


Figure 4-15. Grid Spacing Versus Wire Diameter - Normalized to Wavelengths

4.4.5 Thermal Considerations

The major thermal effects on a spacecraft antenna performance are the reduction in gain, increase in sidelobe level, and errors in beam pointing. A rigorous analysis is required to determine these effects for a given satellite antenna. The complete analysis requires a study of temperature distribution, followed by the determination of the mechanical distortions this distribution causes. The electrical performance is then determined for a reflector configuration with these perturbations.

The distortions of a rigid reflector depend primarily upon the material used for the reflector and the design of the reflector support structure. In addition, the design of the feed and feed support structure which can cause partial shadowing has some minor influence on the thermal gradients across the reflector. Finally, the thermal control, such as painting and insulation, will tend to minimize thermal gradients. The total residual effect on the reflector performance then consists of a beamshift, a loss in gain, and an increase of sidelobe level.

Another factor to be considered is that of relative motion of the feed with respect to the reflector. The most significant effect on the feed and feed support structure is due to the unequal thermal effects on the support struts of a typical tripod or quadrapod. These effects cause an off-axis movement of the feed which results in beam tilting. This is virtually eliminated with a monopod support structure, which is recommended for this application.

The calculated distortions on the surface of a 43-inch diameter parabolic reflector in synchronous orbit with an $f/D = 0.4$ are given in Figures 4-16 and 4-17. The two basic distortion effects shown are due to the longitudinal thermal gradient and the transverse thermal gradient. The curves of Figures 4-16 and 4-17 were obtained for a longitudinal temperature variation of $340^{\circ}F$ across the aperture and for a transverse difference of $1^{\circ}F$ between front and back which is fairly constant for reflector thicknesses from 1/16 to 1/4 inch. The longitudinal gradient is a worst-case value for a large number of sun-spacecraft orientations, and is also fairly constant with reflector thickness.

In order to minimize the weight of the reflector antenna, an aluminum honeycomb structure can be used instead of a spun aluminum reflector. The major disadvantage in the honeycomb is that the transverse thermal gradient will be larger, whereas it is minimized to negligible proportions in the case of the solid aluminum reflector. For a 0.25-inch aluminum honeycomb the transverse gradient has been estimated to be $2^{\circ}F$. From the curve of Figure 4-17 we see that this corresponds to a maximum deflection of less than 6×10^{-4} inches which is still nearly an order of magnitude less than the maximum deviation from longitudinal temperature gradients shown in Figure 4-16. The

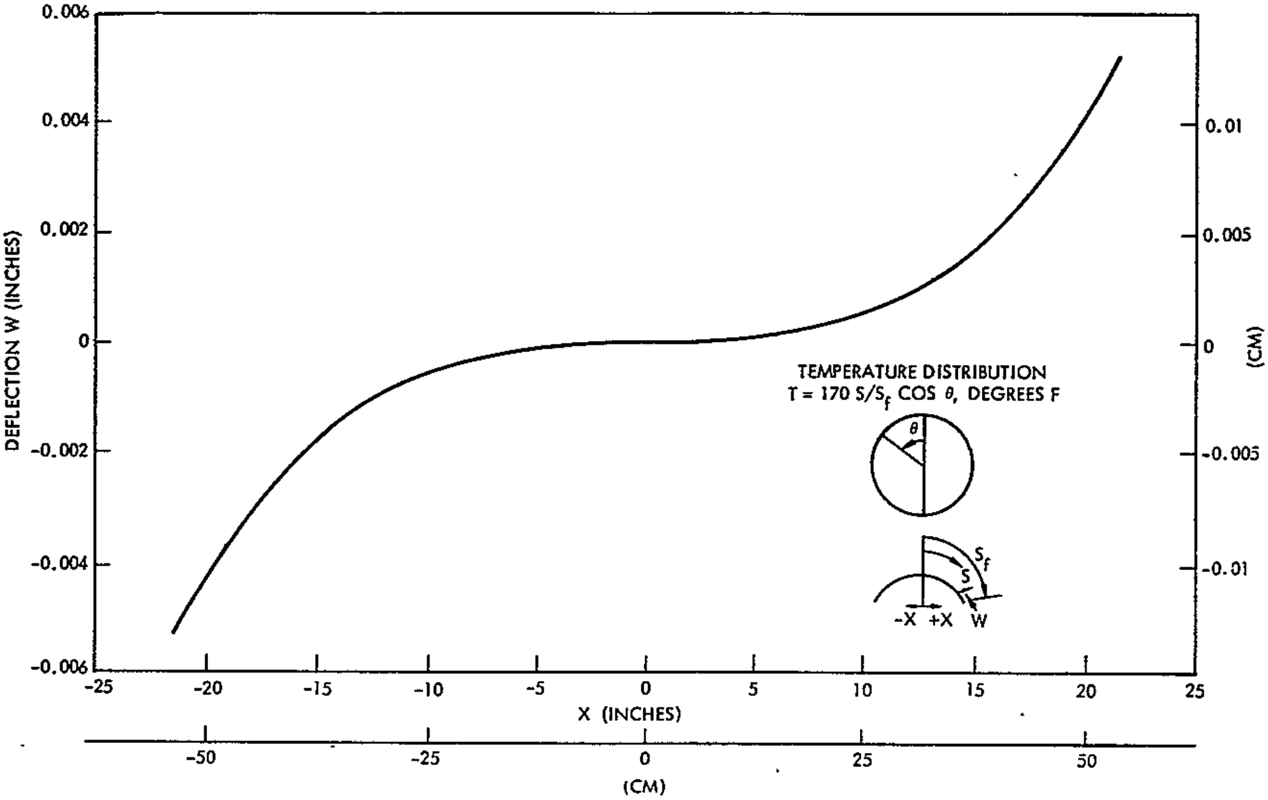


Figure 4-16. Deformation of 43-inch Parabolic Reflector f/D = 0.4, Due to Longitudinal Thermal Gradients - For Synchronous Orbit

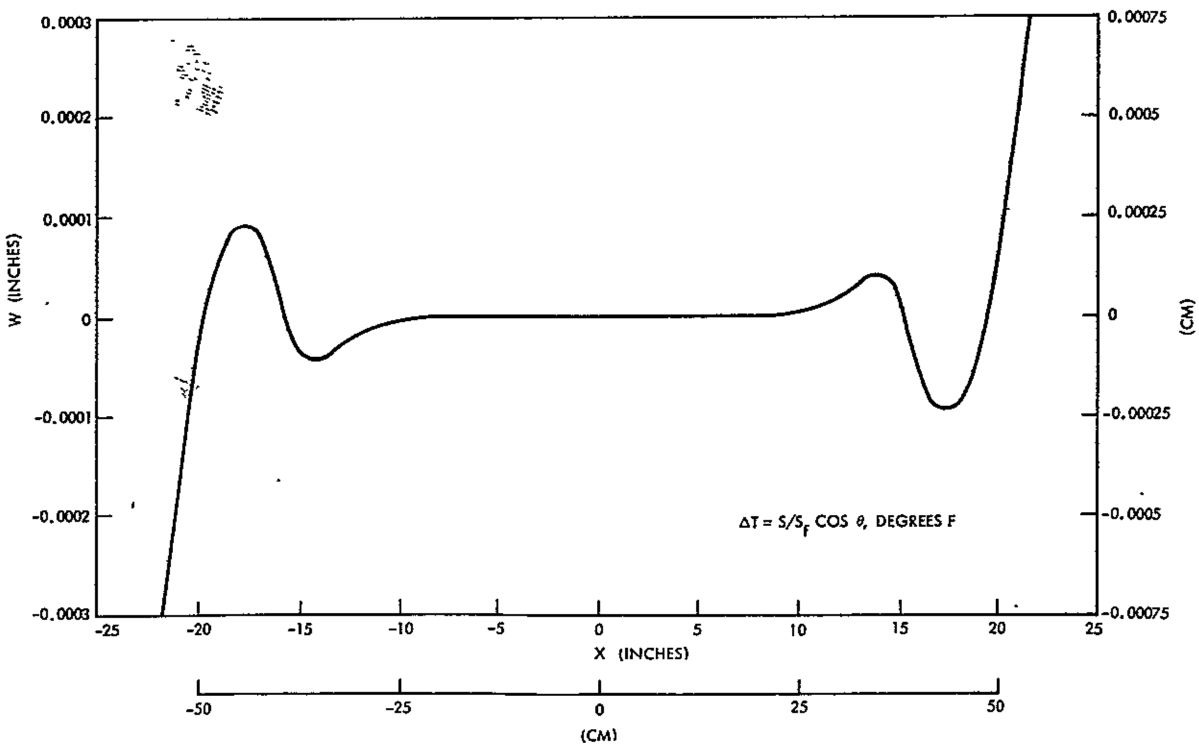


Figure 4-17. Deformation of 43-inch Parabolic Reflector, f/D = 0.4, Due to Transverse Gradients - Synchronous Orbit

honeycomb structure for the reflecting surface is thus generally superior to a solid sluminum reflector for frequencies up to about 8 GHz, because of its lighter weight. For frequencies above 8 GHz, the thermal deformations of a honeycomb dish using aluminum for both the core and the facesheets may be unacceptably high. However, an aluminum honeycomb core between facesheets of low thermal coefficient of expansion material, such as invar or a graphite-epoxy composition, can stay well within acceptable deformation limits for 8.5 GHz and 12 GHz. The weight is approximately 10 percent higher than an all-aluminum dish.

To determine the effects on the pointing of the antenna, the maximum deviation can be taken as a physical rotation of the antenna reflector. This corresponds to a beam tilt of 0.016 degrees for the 43-inch reflector. There will be an additional tilting due to the phase error across the surface equivalent to an off-axis feed displacement. For an $f/D = 0.4$ reflector this adds an additional 0.015 degree, giving a total of 0.031 degree. For this particular system the structure also contributed a 0.03 degree error to give a maximum of 0.06 degree beam tilt. These results show the order of magnitude effects of thermally caused distortions on the pointing accuracy of rigid reflectors.

Since the 43-inch reflector discussed here corresponds to the dimension of the reflectors considered for the 8.5 GHz and 12.0 GHz frequencies, a rough idea of the effects of these distortions on sidelobes can be estimated. Referring to Figure 4-10, we see that the maximum deviation of 0.006 inch does not contribute significantly to sidelobes.

To summarize the effects of the thermal environment on critical antenna parameters, it is safe to say that state of the art techniques in antenna and antenna thermal designs can reduce these effects sufficiently for rigid parabolic reflector systems. For the X-band frequencies, the use of beryllium reflectors can result in operation greatly superior to that provided by either solid aluminum or honeycomb, but a substantial amount of development work is required.

Very little is known about the thermal behavior of deployable antennas in general, and radial rib type reflectors in particular. Experiments to be conducted on ATS-F and ATS-G satellites should shed some light on this area.

4.4.6 Feed Design

The polarization of a reflector antenna is determined by the polarization of the feed for the reflector. The required circular polarization can be inexpensively obtained with a lightweight cupped turnstile feed on a monopod support structure. The radiation pattern from a reflector fed with this type of feed will have less than a 2 db axial ratio within the half-power beamwidth. Such a feed has already been developed for a fixed-beam spacecraft antenna. However, the power handling capability of this feed is limited to a few hundred watts, and an AM system is thus practically forced to use a simple square horn with orthogonal inputs and hybrid combining. Such a feed is considerably heavier and probably bigger.

4.4.7 Net Gain and Weight Estimates

4.4.7.1 Gain and Efficiency

The expected gain as a function of the half-power beamwidth is given in Figure 4-18.

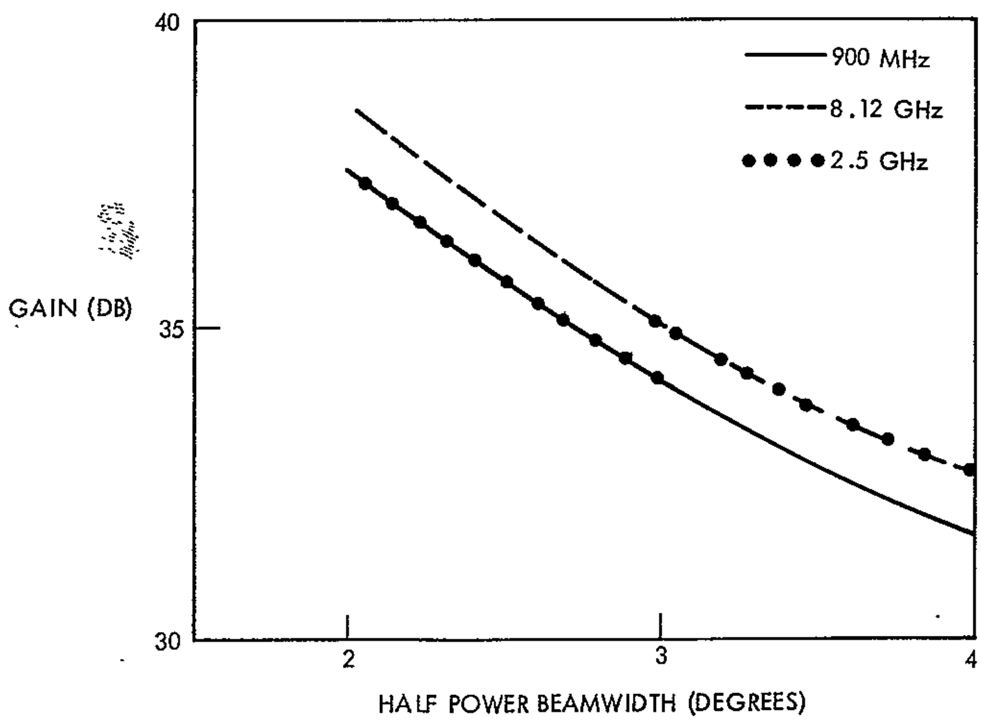


Figure 4-18. Gain Versus Beamwidth with Frequency as a Parameter

4.5 PHASED ARRAY DESIGN CONSIDERATIONS

4.5.1 Active Array Capabilities

In active arrays the radiated rf power is generated by active components of the array elements. The feed network then handles the lower rf drive power instead of the final output power.

It was shown in Section 4.3.1.3 that multiple-beam capability by a single reflector with multiple feeds was undesirable because of the resulting high sidelobe levels. Hence, multiple reflectors must be used for multiple beams. Because of shroud limitations on antenna stowage alone, a single multiple-beam array may prove to be the better choice for multiple beams at 900 MHz and possible at 2.5 GHz.

Current TRW in-house studies indicate that the most promising active arrays for 900 MHz and 2.5 GHz us an rf amplifier at each element. The feed network is at low power levels where the losses are not as significant to overall system efficiency. In addition, relatively lightweight cables can be used. The higher losses in these cables can be compensated for by additional low-level amplification at each element for a minimal penalty in weight and power. Major problems associated with this technique have been that the total weight of the individual amplifier components at all elements was greater than one single amplifier. Combining elements in small groups with each amplifier, or using high gain elements to reduce the number of elements and thereby the number of required amplifiers did lead to more power than the individual amplifiers were capable of handling. However, recent advances in solid state electronics have shown that transistor power levels are such that for 900 MHz and 2.5 GHz an array may well be the answer.

Figures 4-19 and 4-20 (from Reference 4-12) are updated with the latest information from TRW Semiconductors and show the state of the art and the projected state of the art in solid state microwave power generation. It can be seen that the TRW transistor 2N5178, which gives 50 watts at 500 MHz has extended the state of the art to where active arrays are attractive for high power levels at these low frequencies. Active phased array performance, for present state of the art in solid state power generation, can be considered as competitive with parabolic reflectors at 2.5 GHz, and at 900 MHz.

The efficiencies of 54 percent for rigid reflectors and 46 percent for deployable reflectors include all the gain reductions described in detail in Section 4.1 except the feed network. The lower value for efficiency for the deployable reflector systems include additional losses due to surface irregularities.

At 2.5 GHz one could use either a deployable or a rigid reflector for the 3 degree beamwidth. For the narrower beamwidths a deployable reflector is mandatory.

Also, the final system efficiency will have to include feed network losses in the coax or waveguide feed line, the actual element, and in rotary joints.

4.4.7.2 Weight Estimates

Table 4-5 compares the weights of isolated, but typical, reflector designs. Some have been implemented on actual spacecraft; others have gone through a laboratory prototype development. While the data is sketchy, trends are clearly visible. All of the reflectors shown are useful at 0.9 GHz and 2.5 GHz, but only the beryllium reflector and honeycomb reflector with a low thermal coefficient of expansion facesheet are good at X band. The dish weights include the main reflector and its support; the system weights also include feed, gimbals, and motors.

Table 4-5. Reflector Antenna Weights

Antenna	Dish Weight lbs	(Kg)	System Weight lbs	(Kg)
10-ft (3-m) Maypole (monopulse)	17	7.7	50	22.7
2-ft (0.6-m) Honeycomb (fixed beam)	0.8	0.36	2.2	1
6-ft (1.8-m) Beryllium (monopulse)	15	6.8	32	14.5
6-ft (1.8m) SEDA* (command-steered)	0.3	0.13	7	3.2

*Strained-energy deployable antenna (SEDA).

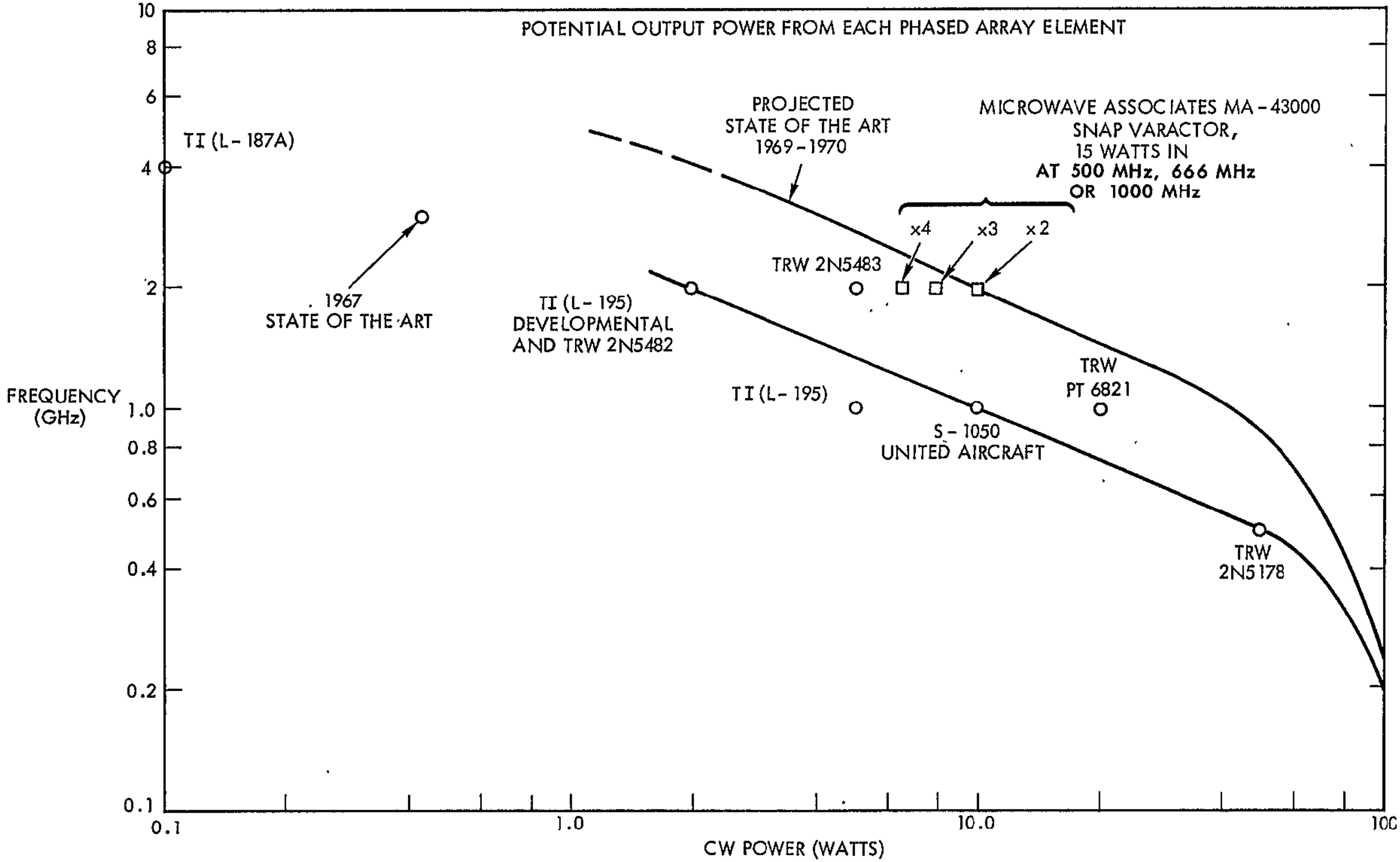
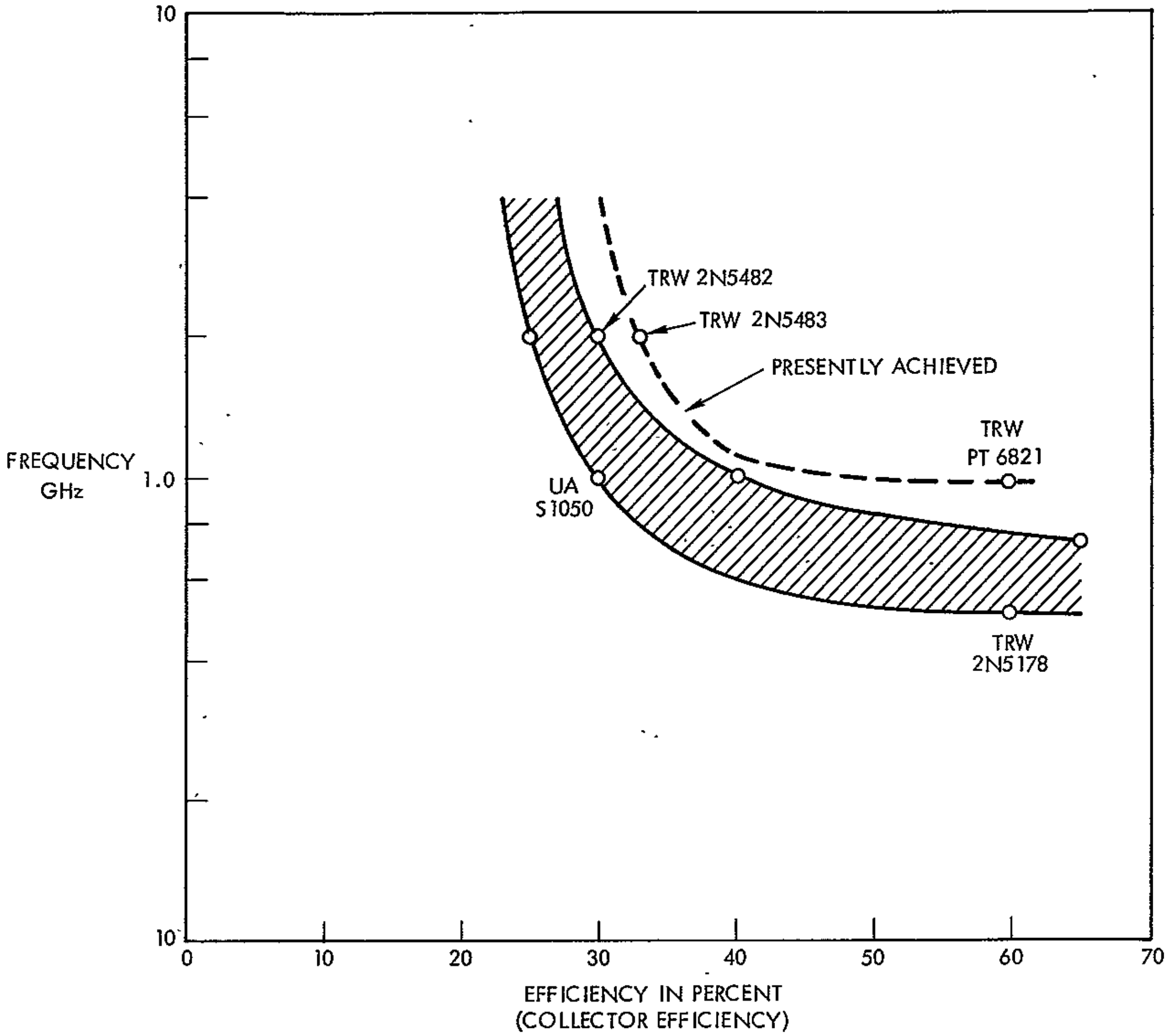


Figure 4-19. Microwave Power Generation from Single Transistors and Varactors



Figures 4-20. Microwave Power Generation from Single Transistors and Corresponding Efficiency

4.5.2 Element Designs

A crucial item in the phased array gain and weight budget is the array element. To make an array competitive with a reflector antenna, the weight of the element must be reduced to the minimum. Figure 4-21 shows an array of deployable helices which was developed by TRW in 1968. The helix proper weighs 1-5/8 ounces, and the total element weight (including groundplane, support and connector) is about 4 ounces. The helix is 30-inches long and about 2 inches in diameter. Figure 4-22 shows a spacecraft configuration concept using an array of helix elements.

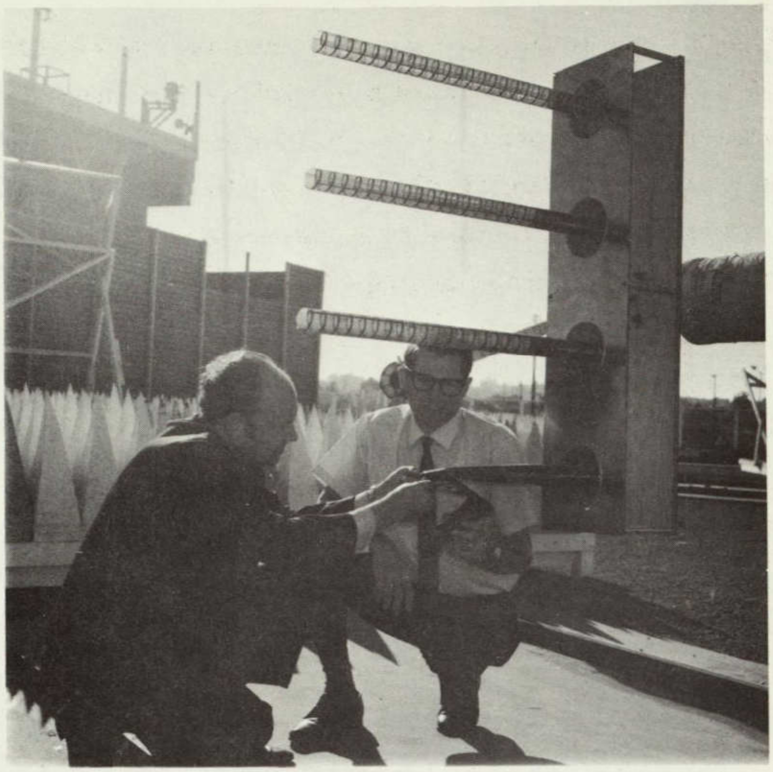


Figure 4-21. Array of Deployable Lightweight Helices

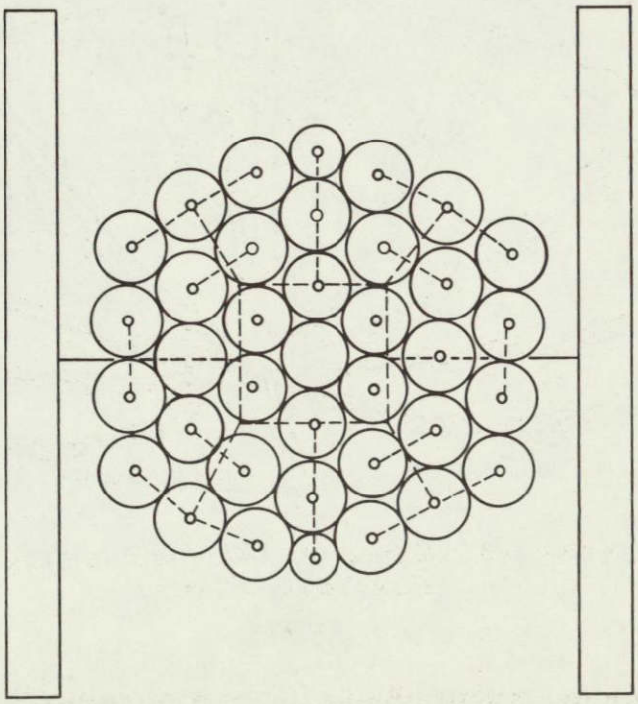


Figure 4-22. Phased Array Configuration Using Multiple Strain Energy Deployable Paraboloids (Center Reflector Rigid, Used for X-Band Up-Link) Top View

The helix and the disc-on-rod antennas are relatively low gain radiators (≤ 15 db). A very promising lightweight design for relatively high-gain elements is the strain-energy deployable reflector with flexible ribs. These are currently under development for large diameters, and appear very promising for the smaller diameters required for array elements. One such reflector being developed at TRW is shown in Reference 4-13. The reflector density is 0.04 lb/ft^2 and is shown in Figure 4-23, using a broadband cross-polarized complementary pair feed. The complementary pair will provide the required impedance match in the closely-coupled feed situation, which is in essence a short backfire antenna. A more detailed investigation would be required to determine the optimum feed configuration at 900 MHz. At 2.5 GHz, the power capability of solid-state devices will probably not increase rapidly enough to provide enough power per element in a reasonable amplifier package within the next few years to permit AM operation. The helix element will certainly be the optimum choice for an array for FM transmission at this frequency.

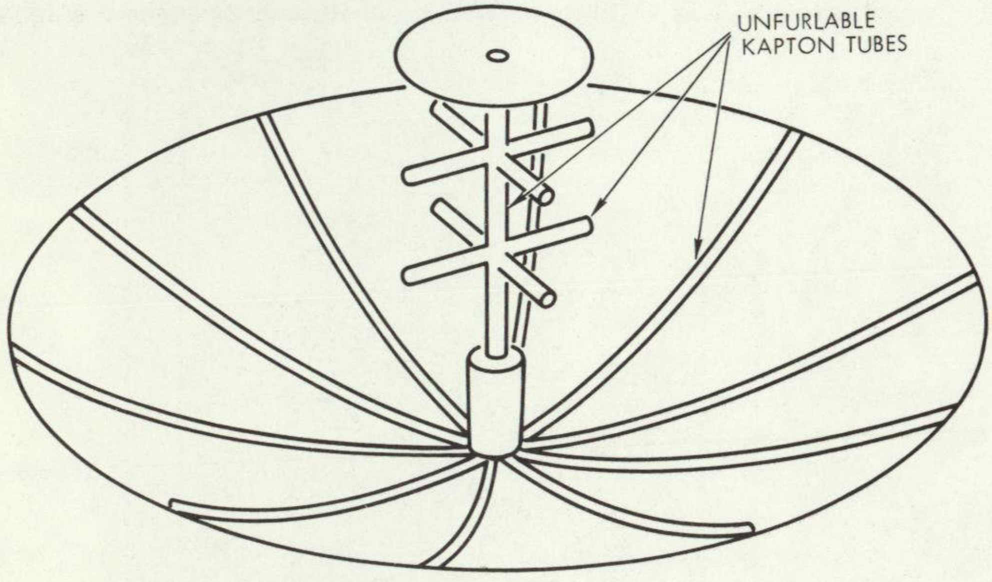


Figure 4-23. Deployable Complementary Pair and Parabolic Reflector

At X-band no reasonable projection of solid-state capabilities exists which would allow a phased array to be competitive with a reflector antenna system, even when four beams are required.

Cell data are tabulated in Table 5-1. The temperatures assumed for arrays are approximations based on past array designs. Lightweight structures will cause array temperatures to be lower than for conventional construction, and as temperature drops, voltage and the power output increases. The slightly higher temperatures of conventional arrays have been used, however, for conservatism. Figures 5-1 and 5-2 show current-voltage (I-V) characteristics of the bare, undegraded cells under AMO conditions, at 28°C.

Extensive tests at TRW on cells from various manufacturers have confirmed that solderless cells having TiAg contacts show severe degradation when subjected to a combination of high temperature and humidity. TRW tests have also shown that completely soldered covered cells exhibit insignificant degradation as a result of such exposure. Cells with a thin coating of solder just sufficient to make the cells humidity resistant have been developed. Array weights are based on the use of these relatively lightweight, humidity-resistant solar cells.

Cells of up to approximately 0.026 inch (0.066 cm) thickness provide increased power output as a function of cell thickness, since electron-hole pairs generated in the bulk material away from the junction have a sufficient diffusion length to allow the minority carrier to reach the junction and thus contribute to the power output. However, in the presence of ionizing irradiation, the diffusion length decreases. As a result, hole-electron pairs far from the junction may recombine before the minority carrier reaches the junction. Consequently, thinner cells which initially have a lower output may have the same output after corpuscular radiation and provide a higher net power efficiency. The study has shown that a 0.010-inch (0.025-cm) thick cell provides maximum power to weight effectiveness at end-of-life and is thus preferred

The resistivity of 10 ohm-cm was selected over 2 ohm-cm cells because of their higher end-of-life performance. Section 5.1.4 shows that for the environment specified the initial higher power output of the 2 ohm-cm cells is outweighed by the higher radiation resistance of the 10 ohm-cm cells at the end of mission.

5. POWER SYSTEM

5.1 SILICON SOLAR ARRAYS

The analysis of the solar array for the Direct Broadcast Television Satellite is based on the latest solar cell data available and is expected to remain valid for at least two years.

5.1.1 Silicon Solar Cells

Silicon solar cells of polarity N-on-P are preferred to P-on-N cells because they are more radiation resistant, and the mission imposed requires the use of the most radiation resistant solar cell type. A second reason for selection of N-on-P cells is their relative availability.

Silicon solar cells can be obtained in 1 x 2, 2 x 2, 3 x 3, and 2 x 6 cm sizes. In general, cost per unit area of silicon solar cells decreases as the cell area increases. For the 3 x 3 cm and 2 x 6 cm cells, lack of experience and the possibility of increased handling costs precludes their selection at this time. Cells of 2 x 2 and 1 x 2 cm have been successfully used on several satellites and are expected to remain standard through 1980. The cost advantage of the 2 x 2-cm cells relative to the 2 x 1-cm cells dictates their use for this mission. The cells have an active area of 0.589 in^2 (3.80 cm^2).

Data of the N-on-P, 2 x 2-cm silicon cell is tabulated in Table 5-1. The notations used in this table and in subsequent sections are:
are:

V_{oc}	=	Open-circuit voltage
V_{op}	=	Voltage at maximum power
I_{op}	=	Current at maximum power
I_{sc}	=	Short-circuit current
P_{op}	=	Maximum power
η	=	Efficiency
AMO	=	"Air mass zero", indicating solar radiation of intensity and spectrum prevailing in space at 1 AU.
Bare	=	Without cover glass

phase at f_1 relative to f_0, as compared to the case where the two path lengths are identical.

EXAMPLE

From Figures 2 through 4, we can obtain the maximum allowable signal bandwidth for a given aperture size, when the gain reduction at the band edge is not supposed to exceed a specified value. Allowing for a 1 dB gain reduction, e.g., and looking at a specific aperture size of 30 wavelengths, a maximum relative half bandwidth of about 1.1% is possible for a 60 degree scan (Figure 4). This means a maximum single-sideband information bandwidth of ≈50 megahertz for a received signal carrier frequency of 2.2 GHz. If the beam needs to be steered only to ±25 degrees, then the maximum relative half bandwidth is ≈2.2% or about 50 megahertz. A 30 foot aperture (with a peak aperture gain of about 47 dB) is roughly the size required for a data relay satellite in a synchronous orbit, when a low-gain "user satellite" has to be serviced. Altitudes up to about six thousand nautical miles can be covered with a 25 degree scan, and a 60 degree scan will generally give coverage for users in a synchronous equatorial orbit with an altitude of 22,000 nautical miles, assuming three satellites equally spaced in a synchronous equatorial orbit. A phased array for this application is thus limited in bandwidth to about 50 MHz within the 100 MHz frequency band from 2.2 to 2.3 GHz (Figure 2) for maximum user altitudes of six thousand nautical miles.

Clearly, if the same array has to service not only the uplink, but also a downlink at some other band (e.g., 1.8 to 1.9 GHz), then different phase shifters (or other beam steering devices) will be required to produce cophasal excitation in the desired direction.

REFERENCE

Donald L. Margerum, "Self-Phased Arrays" Chapter 5, p. 348, Microwave Scanning Antennas, Vol. III (Edited by R. C. Hansen); Academic Press, New York, 1966.

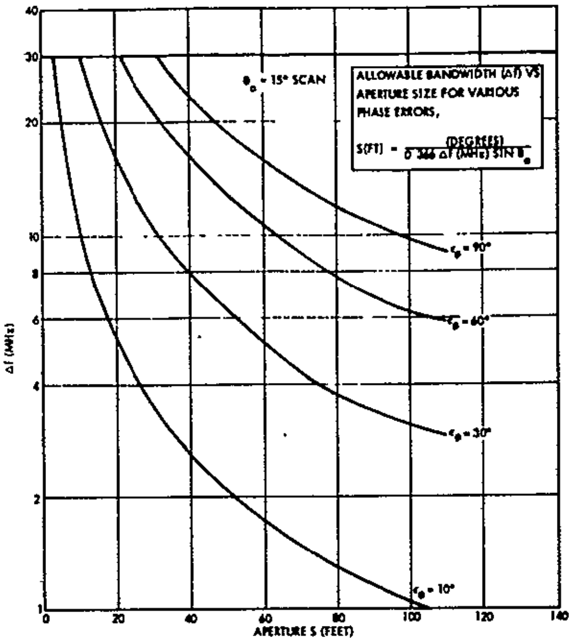


FIG. 10 - Bandwidth vs. Aperture Size (15° Scan)

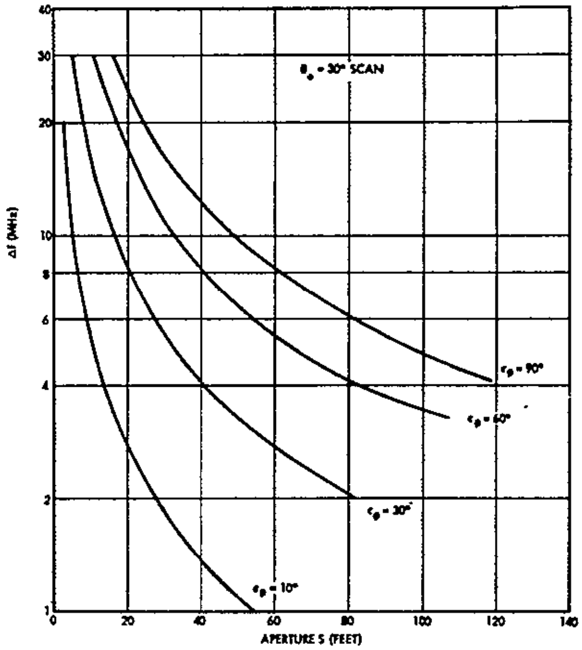


FIG. 11 - Bandwidth vs. Aperture Size (30° Scan)

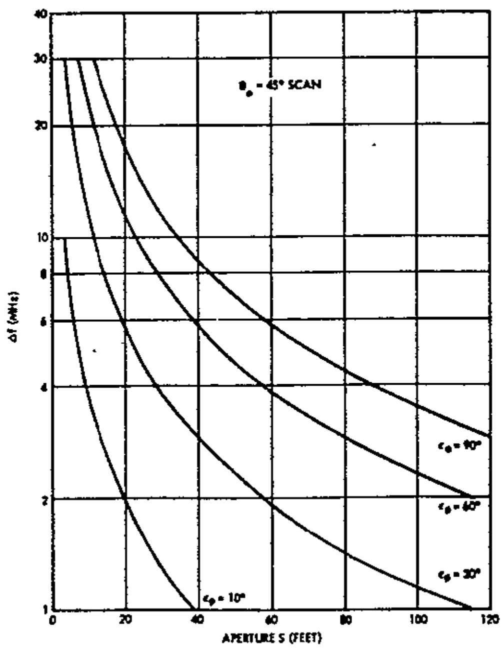


FIG. 12 - Bandwidth vs. Aperture Size (45° Scan)

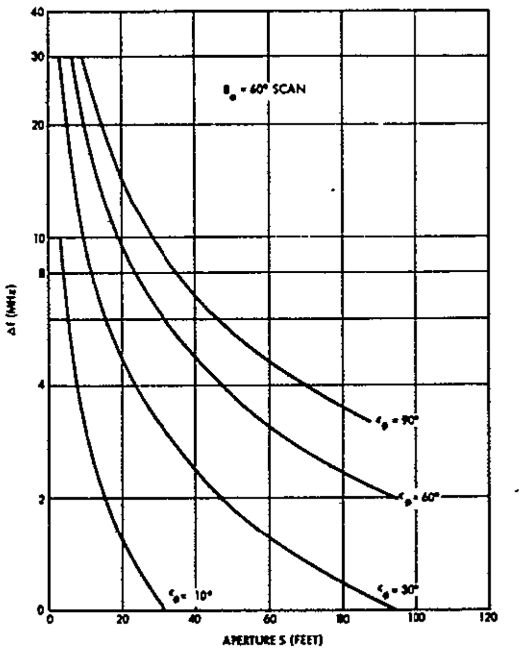


FIG. 13 - Bandwidth vs. Aperture Size (60° Scan)

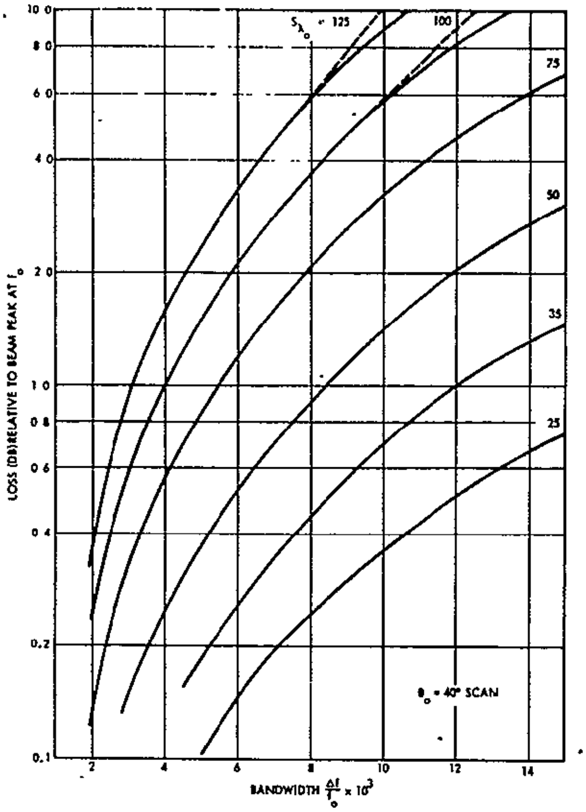


FIG. 6 - Gain Loss vs. Bandwidth (40° Scan)

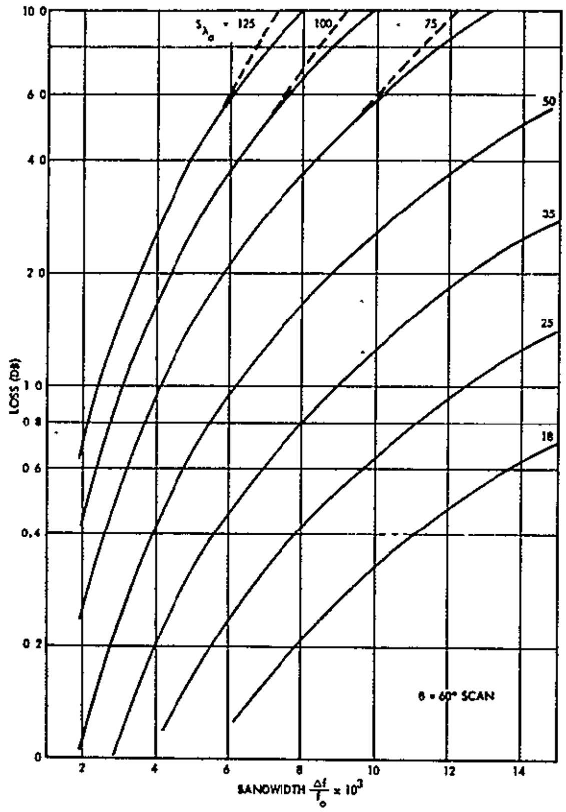


FIG. 7 - Gain Loss vs. Bandwidth (60° Scan)

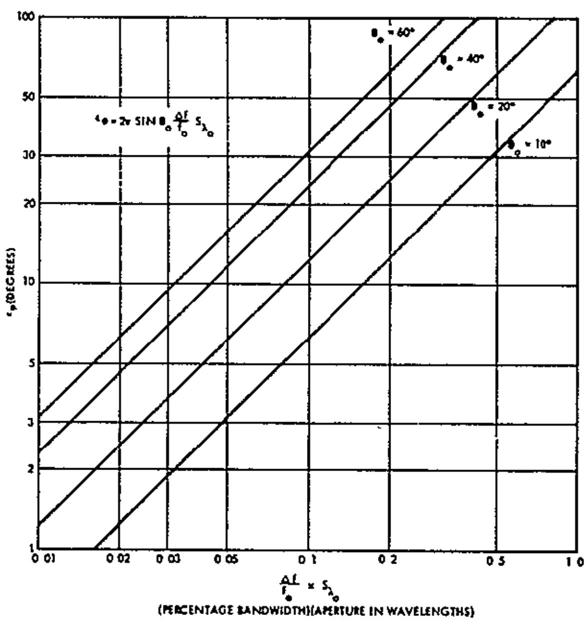


FIG. 8 - Phase Error vs. Bandwidth and Aperture Size

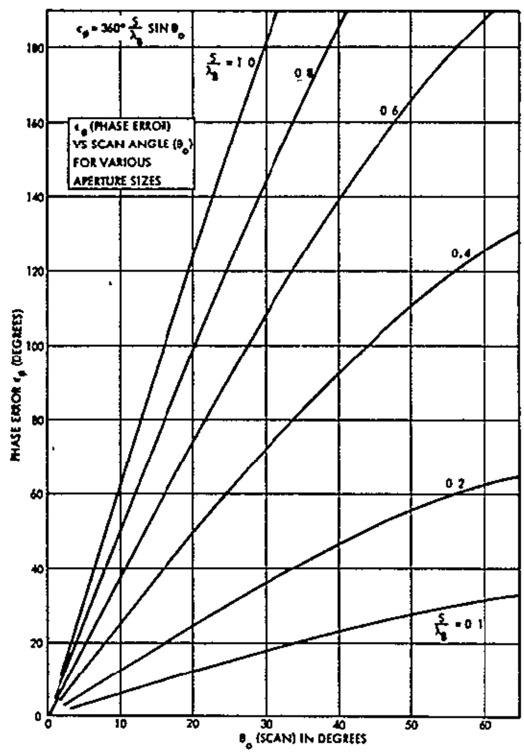


FIG. 9 - Phase Error vs. Scan Angle

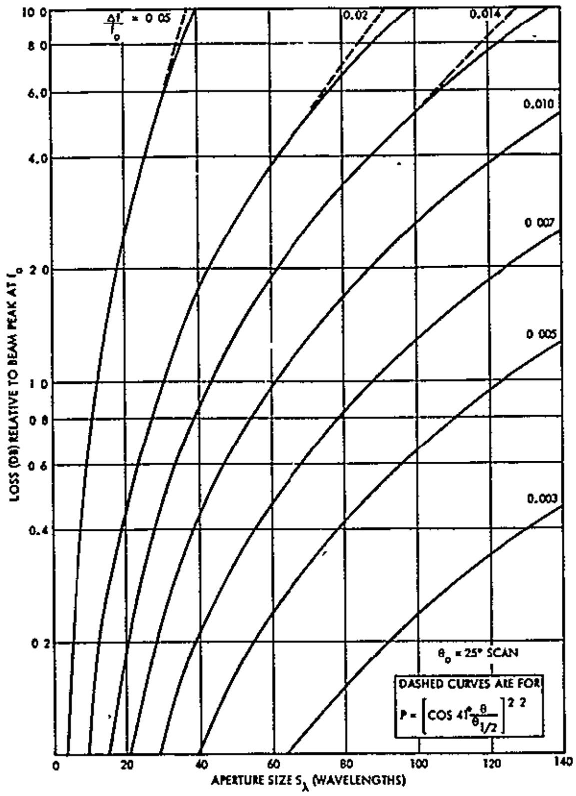


FIG. 2 - Gain Loss vs. Aperture Size (25° Scan)

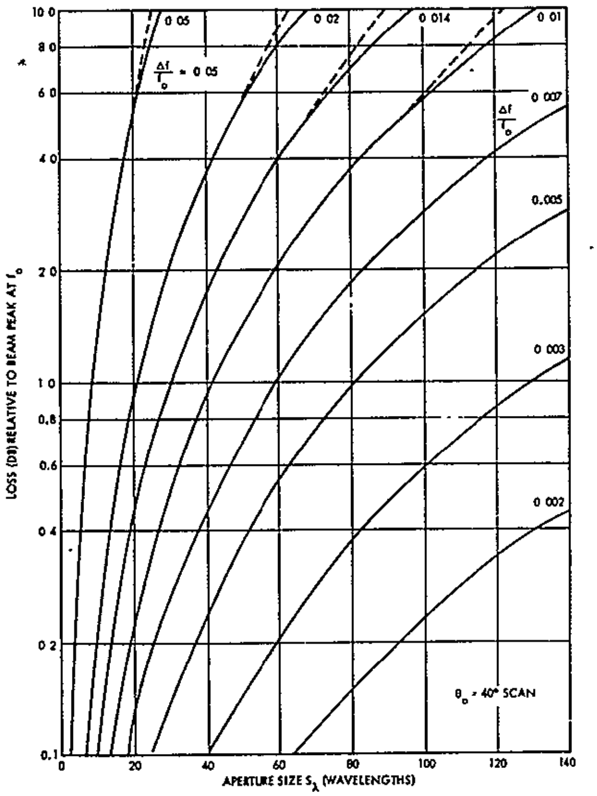


FIG. 3 - Gain Loss vs. Aperture Size (40° Scan)

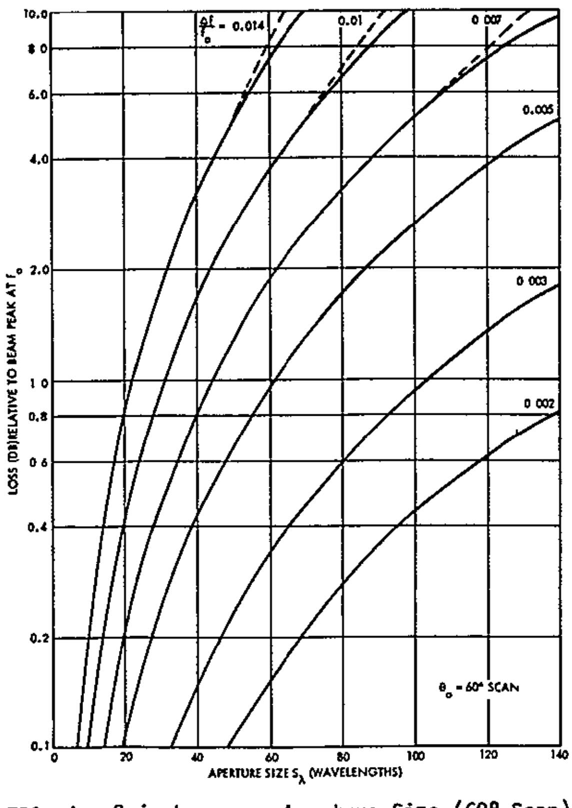


FIG. 4 - Gain Loss vs. Aperture Size (60° Scan)

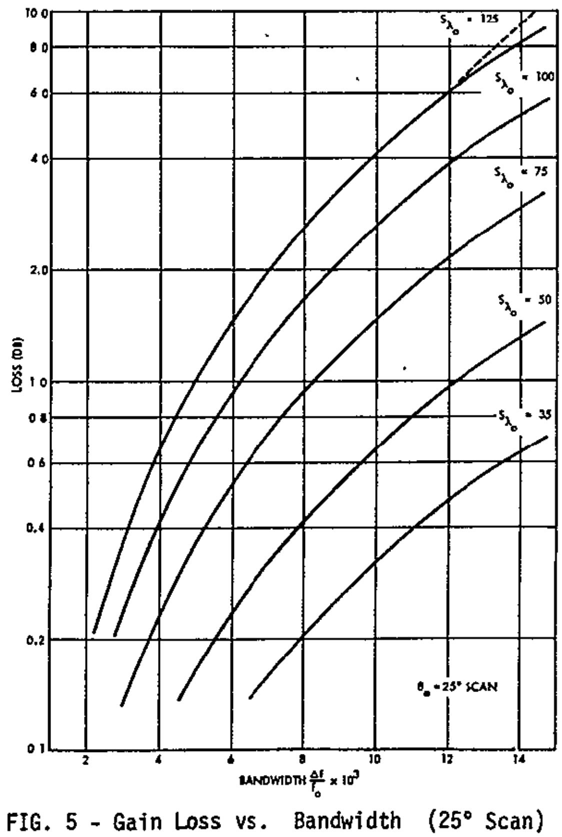


FIG. 5 - Gain Loss vs. Bandwidth (25° Scan)

The radiation pattern of an array is given to a close approximation as:

$$P = \exp\left\{-0.693\left(\frac{\theta}{\theta_{1/2}}\right)^2\right\} \qquad (2)$$

where $\theta_{1/2}$ is 1/2 the half power beamwidth and θ is measured from the beam peak. This equation holds well from beam peak down to about the -6 dB point. The pattern in dB form is therefore:

$$P(\mathrm{dB}) = -3\left(\frac{\theta}{\theta_{1/2}}\right)^2 \qquad (3)$$

The half power beamwidth of uniform apertures is approximated by:

$$2\theta_{1/2} = \frac{52}{A_\lambda}\ [\text{Degrees}] \qquad (4)$$

where A_λ is the real aperture in wavelengths. The aperture of the scanned array is its linear dimension reduced by a cos factor:

$$A = \frac{S}{\lambda_0} \cos \theta_0 \qquad (5)$$

where θ_0 is the angle of scan, measured from broadside, and (for uniform illumination):

$$2\theta_{1/2} = \frac{52\lambda_0}{S \cos \theta_0} \qquad (6)$$

hence

$$P(\mathrm{dB}) = -3\left[\frac{\theta S \cos \theta_0}{26\lambda_0}\right]^2 \qquad (7)$$

The angle θ is measured symmetrically about the beam peak at θ_0. At the angle θ_1, this assumes the value $|\theta_1 - \theta_0|$

hence

$$P(\mathrm{dB}) = -3\left[\frac{|\theta_1 - \theta_0|\ S \cos \theta_0}{26\lambda_0}\right]^2 \qquad (8)$$

and

$$P(\mathrm{dB}) = -3\left[\frac{\left|\arc \sin\left(\frac{f_0}{f_1} \sin \theta_0\right) - \theta_0\right|\ S \cos \theta_0}{26\lambda_0}\right]^2 \qquad (9)$$

We note from this that as f_0/f_1 differs from 1.0, the available power at f_1 will be reduced.

This equation is plotted on the following charts, Figures 2 through 7. Each chart is for a fixed scan angle, θ_0. 25°, 40°, and 60° have been chosen. In one group, signal reduction has been plotted against aperture size for various signal displacements from the carrier, f_0. The other group of three charts has signal reduction plotted against this signal displacement (1/2 the RF bandwidth) for various aperture sizes. The dotted lines represent a more accurate approximation of the standard beam beyond the 6 dB point, which is given by:

$$P = \left(\cos 41° \frac{\theta}{\theta_{1/2}}\right)^{2.2} \qquad (10)$$

or

$$P(\mathrm{dB}) = -22 \log \sec \left(41° \frac{\theta}{\theta_{1/2}}\right) \qquad (11)$$

The gain reductions for frequencies away from the center frequency can then be determined in a manner similar to the method outlined above. The general conclusion is, of course, that the large scan angle will cause the greatest problem and that even in this case, apertures of 60 wavelengths and fairly large bandwidths must be used to develop any significant amplitude reduction.

The relative array bandwidths shown in Figures 2 through 7 are bandwidths off the center frequency. In double sideband systems they are therefore identical with the available information bandwidth, whereas in single-sideband systems the shown relative bandwidths are equal to one half the information bandwidth.

Charts 8 through 13 are plots of phase error. This function: (See reference.)

$$\varepsilon_\phi = 2\pi \sin \theta_0 \frac{\Delta f}{f_0} S/\lambda_0 \qquad (12)$$

or, taking

$$\Delta f = c/\lambda_B (\lambda_B = \text{Wavelength of the bandwidth}) \qquad (13)$$

$$\varepsilon_\phi = 2\pi \frac{S}{\lambda_B} \sin \theta_0 \qquad (14)$$

is simply an equation of variation or difference in electrical path length for differing frequencies over differing paths. For example, path l_1 and l_2 may be substantially different in physical length but have the same electrical length (to within 2π) at f_0, but will not have the same electrical length at f_1. This equation thus gives the phase error as a difference of

APPENDIX 4B

BANDWIDTH LIMITATIONS FOR PHASE STEERED PLANAR ARRAYS IN SATELLITE APPLICATIONS

BY: W. F. Williams and K. G. Schroeder
TRW Systems
Redondo Beach, California

INTRODUCTION

Minimization of component weight is of paramount importance in satellites, because of the high cost of lifting the payload into orbit. The satellite antenna is one of these components, and reflector antennas are often selected because of their comparatively lower weight for a given gain. For phased arrays to be competitive, every possible effort must be made to minimize their inherently high weight density. One of the techniques available to the designer is weight reduction by means of element thinning. Another is the so-called "modulo 2π" beam steering technique, where multiples of 2π phase shift in the beam steering mechanisms are subtracted from the total phase shift required for true time delay compensation of the arriving wave front.

The character of any phased array with modulo 2π steering is that the phase progressions developed across the array aperture are not a function of frequency but the electrical spacing between elements is, of course, a function of frequency. Beam direction is a function of both this phase progression and the element spacing. Hence, for beam direction to remain fixed with frequency, either physical element spacing must vary (not practical) or phase progression must change with frequency to compensate for the variation in electrical spacing. As mentioned, this cannot be the case with modulo 2π steering and so at the band edges the peak of the received or transmitted energy will not be at the center frequency peak of the antenna beam. This problem is unique to this type of phased array and is not found in reflector antennas or in arrays with time delay steering. These beam direction errors are a function of the scan angle from broadside and are zero for the broadside beam.

Since different frequencies in the signal spectrum of a broadband channel, or different narrow-band channels in a group of channels, are received (transmitted) at an angle away from the peak of the main beam, a reduction in effective antenna gain is the result. A mathematical description of phase errors and gain reduction is now given.

GAIN REDUCTION CALCULATION

Figure 1 is illustrative of a phased array of linear dimension "S" and phased for transmission or reception of an antenna beam in the direction "θ_0" from broadside. The phase progression across the entire aperture is $\frac{2\pi S}{\lambda_0} \sin \theta_0$, developing the main lobe in the θ_0 direction

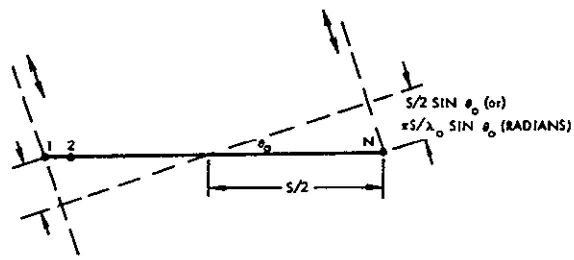


FIG. 1 - N-Element Linear Array with Phase Steering to Beam Direction θ_0

This progression is supplied by the array. It might be the result of control of phase shifters; the progression resulting from use of a hybrid matrix; the result of the retrodirective control; or perhaps other means. In any case, a beam in the direction θ_0 occurs for frequency f_0.

Now at a different frequency, f_1, the progressive phase shift essentially remains the same, as determined by the above mentioned techniques. For instance, the phase progression across the elements fed by a Butler matrix will be θ, 2θ, 3θ, etc., irrespective of the frequency as long as it remains within the operating band.

The values will remain constant with frequency across the bandwidth of the matrix. For the case of the progression being controlled by phase shifters, these may be frequency sensitive. However, the phase shifters may individually control a radiating element, and each may introduce a phase "error" as a function of frequency, but the errors will all be in the same direction and so the phase progression will be affected very little. In any event, except for the case of special control of frequency sensitivity of phase shifters, the phase progression across the array face will be constant.

But the array linear dimension is different when measured in wavelengths and the beam direction will be determined to be θ_1:

$$\sin \theta_1 = \frac{S/\lambda_0}{S/\lambda_1} \sin \theta_0 = \frac{f_0}{f_1} \sin \theta_0 \qquad (1)$$

16. "Experimental Reflector Orbital Shot (EROS)," ASD-TDR-63-266, Vol. I, Part I, April 1963.

17. "Program ROE (Reflector Orbital Experiment), Preliminary Design: Unfurlable Metal Petal Solar Reflector Concept," AFAPL-TR-64-132, Part II, December 1964.

18. "Unfurlable Solar Collector is Developed," by B. Miller, Aviation Week, 14 August 1961.

19. "Aerospace Expandable Structures Conference Transactions," Technical Report No. AFAPL-TR-65-108, Air Force Aero Propulsion Laboratory, March 1966.

20. Scipio, L. A., "Structural Design Concepts," NASA SP-5039, 1967.

21. R. A. Meyers, "Final Report - ENCAP Vehicle Resin System Development," Report 10522-6004-R000, TRW Systems Group, 24 June 1968.

22. "Final Report, 1967 Company Independent Research Program in Expandable Structures," by P. K. Dai, TRW Report EM 17-27-99900-6451-R000, 31 December 1967.

REFERENCES

1. "Large Space Structures Experiments for AAP," Mid-Term Presentation, General Dynamics, 1 March 1967.

2. "The Development of High Gain Deployable Antennas for Communications Satellites," AIAA Paper No. 66-306 by S. A. Milliken, Hughes Aircraft Co., El Segundo, May 1966.

3. "Final Report, 1966 Company Independent Research Program in Expandable Antenna Structures," by W. I. Berks, TRW Report No. 99900-6196-T000, 31 December 1966.

4. "Final Report 1967 Company Independent Research Program," by G. W. Dickinson, TRW Report No. 99900-6585-R000, 31 December 1967.

5. "Lightweight Antenna for Space Vehicles," Air Force/Space Digest International, January 1966. See also Product Engineering, November 22, 1965, p. 60.

6. "Final Report, Erectile Antenna Study," Neotec Corporation for JPL, Contract No. 951847, October 17, 1967.

7. "The Swirlabola, An Expandable S-band Antenna," Advanced Systems and Marketing, Goodyear Aerospace Corp., Akron, Ohio.

8. "Measurements and Calculations of the Effects of Distortions in the Collector Surface on Efficiencies of Umbrella-Type Solar Collectors," by V. R. Bond, NASA TN D-925, August 1961.

9. "Study of Umbrella-Type Erectable Paraboloidal Solar Concentrators for Generation of Spacecraft Auxiliary Power," by W. D. Nowlin and H. E. Benson, NASA TN D-1368, August 1962.

10. "Investigation of the Calorimetric Efficiency of a Split-rib Umbrella-type Paraboloidal Solar Energy Concentrator," by J. D. Camp and W. L. Nowlin, NASA TN D-2015, March 1964.

11. "Aerospace Expandable Structures," Transactions, First Aerospace Expandable Structures Conference, Dayton, Ohio, October 1963.

12. "Sunflower Solar Collector Final Report," NASA Report CR-46, TRW Inc., September 1963.

13. "Television Broadcast Satellite Study," TRW Proposal No. 08848.000 to NASA Lewis, 13 March 1967.

14. "ATS-4 RFP," GSFC, June 1, 1966.

15. "Final Report, Study and Design of Unfurlable Antennas," WADD TR 61-26, Vol. II, November 1960.

Table 3. Inflatable Reflectors

No.	Name and Source	Structural Concept	Data	Size	Wt. (lbs)	Unit wt. (lbs/sq. ft.)	Status	Remarks	Refs.
1	Lenticular Antenna Goodyear/AF Schjeldahl/NASA Langley	Photolizable film on copper wire mesh supported by a torus. Active deployment by inflation.	Freq.: 10 - 30 MHz	200' - 400' deployed	1,480	.03		Passive Reflector	2, 15, 17
2	Expandable Honeycomb GCA Viron/AFAPL	Reflective plastic surface bonded to sandwich type of fabric impregnated with rigidization resin. Active deployment by inflation.				0.5	10' model available	Developed for solar concentrator	16
3	Foam Rigidized Antenna NCR/AFAPL	Flexible polyurethane foam rigidized to provide stiffness for inflated antenna surface				0.5	10' models available		16, 21
4	Foam Rigidized Antenna Computing Devices of Canada	Flexible polyurethane foam rigidized to provide stiffness for inflated antenna surface	Freq.: C and X bands Gain: 32 db at 9 GHz				3' model available		16
5	Foam Rigidized Paraboloid Goodyear/NASA Langley	Thermally activated urethane foam rigidized and distributed to provide stiffness for inflated antenna surface					2' model available	Developed for solar concentrator	15, 16
6	Foam Rigidized Paraboloid Hughes/NASA	Epoxy syntactic foam rigidized to provide stiffness for inflated antenna surface. Antenna is stiffened by a torus at the rim. Surface has a mosaic pattern consisting of hexagons				0.4	5' model available	Developed for solar concentrator	16
7	Rigidized Aluminum Foil AVCO Corporation	Inflated aluminum foil antenna is rigidized by strain set and stiffened by a torus					6' model available		16
8	Double Concave Paraboloid LMSD/AF Reconnaissance Lab	Two inflated paraboloidal surfaces restrained by drop cords. Torus stiffener is provided at rim					Model not available		6, 15, 18
9	Foil Tubing Framework LMSD/AF Reconnaisance Lab	Flexible membrane attached to a system of inflated foil tubing framework					Model not available		6
10	Foam Rigidized Paraboloid LMSD-Goodyear/AFAPL	Rigidized foam provides stiffness to the inflated flexible paraboloid		10' deployed	162	2.	Model not available		19
11	Whirling Membrane NASA Langley	Flexible membrane deployed into a paraboloidal surface by rotation about its optical axis					10' models available	Developed for solar concentration	18, 20

types of chemical rigidization systems are:

1) plasticizer boiloff,

2) gas catalyst,

3) radiation-cured systems.

The best plasticizer boiloff system utilizes gelatin and water as a plasticizer. Such systems have been developed by Swift & Co., Monsanto Chemical Co., and Hughes Aircraft Co. for the Air Force. In the space environment, vacuum causes water migration out of the structure and produces rigidity. This system can be tested on earth, then replasticized and packaged for launch since gelatin can be replasticized repeatedly by exposure to humidity.

TRW has developed a gas-catalyzed rigidization system (Reference 21), during some work for Lockheed Missile & Space Co. as part of the ENCAP Vehicle Development Program sponsored by the Air Force. Other companies including Archer, Daniels & Midland, and the National Cash Register Co. have developed fast reacting systems for the Air Force that use a fine spray or gas catalyst. Most of these schemes have operational complexities that make their application to spacecraft antennas questionable at this time.

Working under the ENCAP Vehicle Development Program, TRW has also developed a heat activated system. Other radiation-cured systems have been developed by Hughes Aircraft Co. for the Air Force and NASA. These systems require exposure to solar radiation or other heat sources for initiation and/or continuation of the rigidification process.

Table 3 shows data for several rigidized inflatable paraboloids.

The application of inflatable structures to spacecraft antennas for reasonably long orbital lifetimes is beyond the current state of the art. Surface accuracy, shape maintenance, and feed location drift are some of the problems yet to be solved.

SPIN-STABILIZED

The spin-stabilized membrane reflector is also light in weight, but is difficult to maintain the surface accuracy. Great care is required in mounting and spinning the shell in order to prevent vibrations from being transferred to the reflector surface. Gyroscopic forces would be a problem when one tries to re-orient the reflector. Table 3 describes a spin-stabilized paraboloid developed as a solar concentrator.

INFLATABLE STRUCTURES

A circular membrane will assume the shape of a paraboloid of revolution if it is subjected to a uniform radial tension combined with uniform lateral pressure. This is described in Reference 19. This principle has been mechanized, and inflatable antennas of up to 20 feet in diameter have been constructed.

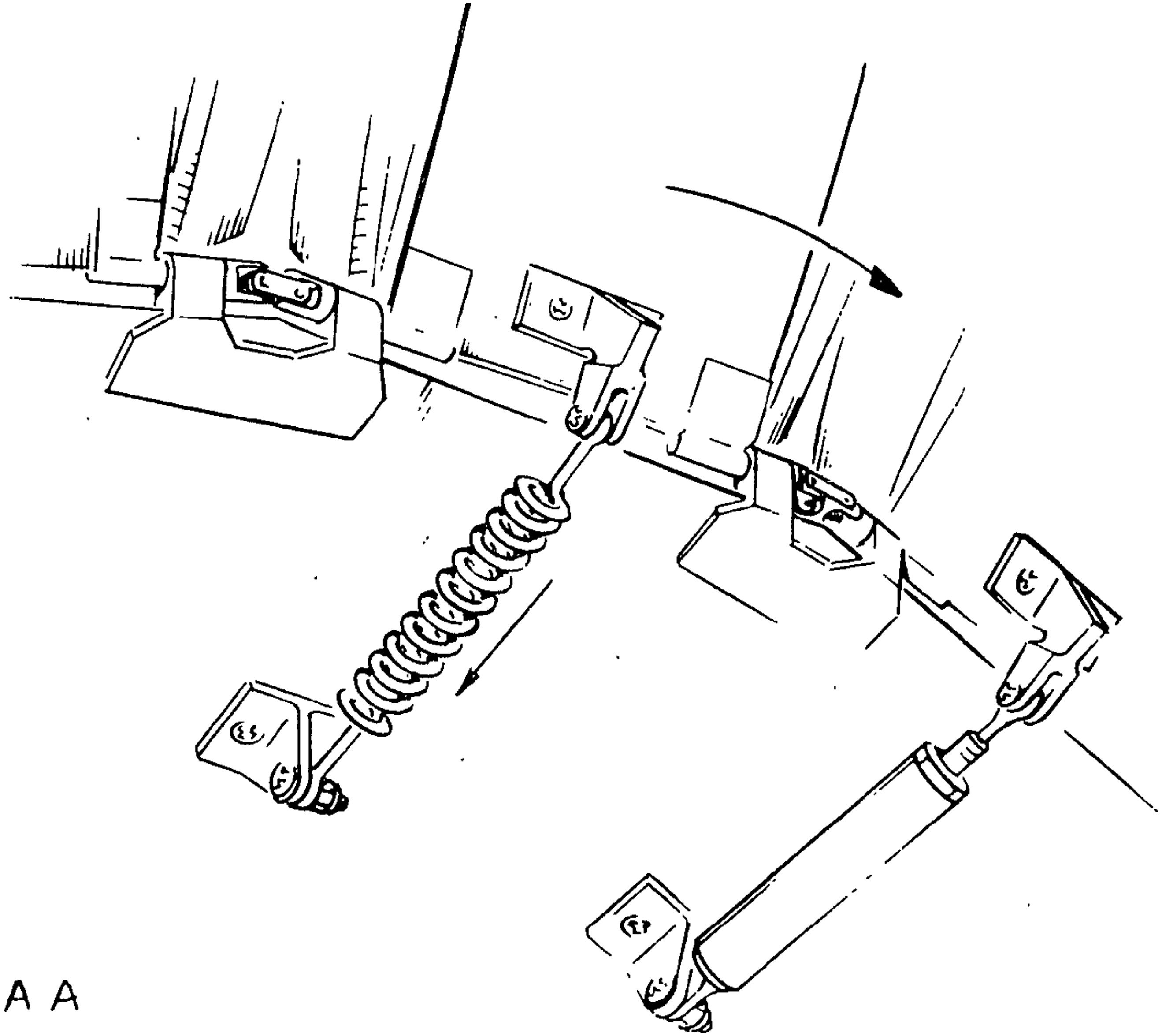
The required radial tension is generally supplied by an inflatable torus at the periphery of the circular membrane, which is coated with a reflective surface (e.g., the membrane may be metallized Mylar or aluminum foil/Mylar laminate). Another membrane, nonreflective and of circular periphery, is attached to the reflective surface to provide a closed volume which can be pressurized. The nonreflective membrane may also be in the form of a circle, similar to the reflective membrane, in which case the antenna assumes a lenticular shape upon inflation.

In the larger sizes (>10-foot diameter) application of the uniform radial tension becomes difficult. The reflector membrane cannot be formed without some seams, and the presence of seams with their additional materials disturbs the stress pattern: a uniform radial force at the periphery will not result in uniform radial stresses. An attempt to get around this has been made by piecing the circular reflective membranes from hexagonally shaped elements; these randomize the seam directions and tend to make the stresses more uniform. The success of this method is unknown.

A much higher pressure is required in the torus than between the two circular membranes, so the pressurizing systems are reasonably complex. Another problem is that the focus location of these antennas is very sensitive to the pressurizing levels.

For space applications a means of rigidization is required to maintain the parabolic shape because of the high probability of meteoroid puncture and subsequent loss of pressure. One scheme that has been tried is a foam-in-place process using the lenticular membrane as a mold. This rigidification system is complex and in large sizes the foam weight is unacceptably high; tests to date for the Air Force and NASA have shown it to be impractical (Reference 20).

Inflatable structures may also be given rigidity by means of a chemical reaction of a rigidifying resin which impregnates the membrane. Three basic



VIEW A A

Figure 5. Details of the Deployment Springs and Dampers of Antenna of Figure 3

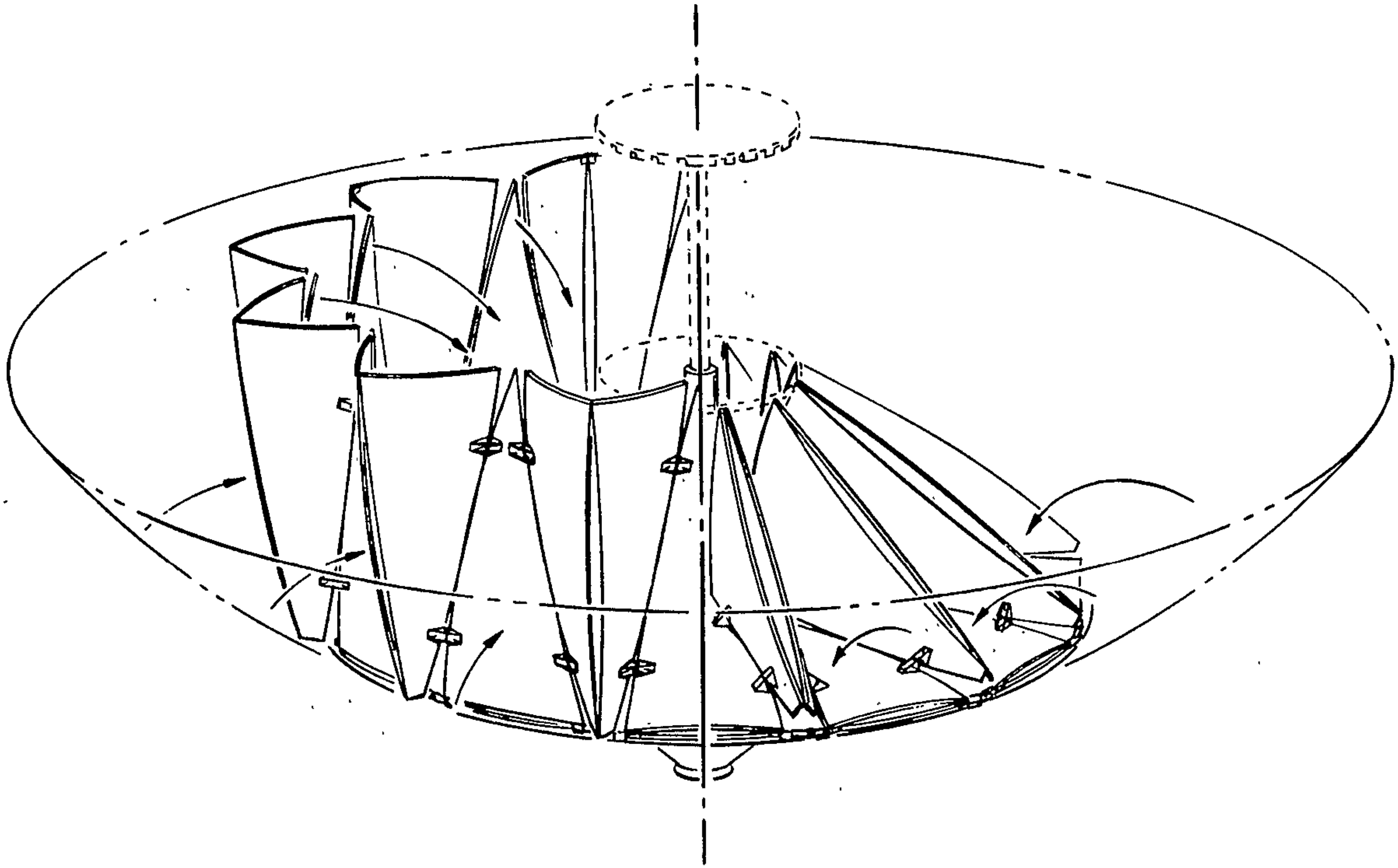


Figure 4. An Alternate Scheme of Folding a Rigid-Panel Parabolic Reflector

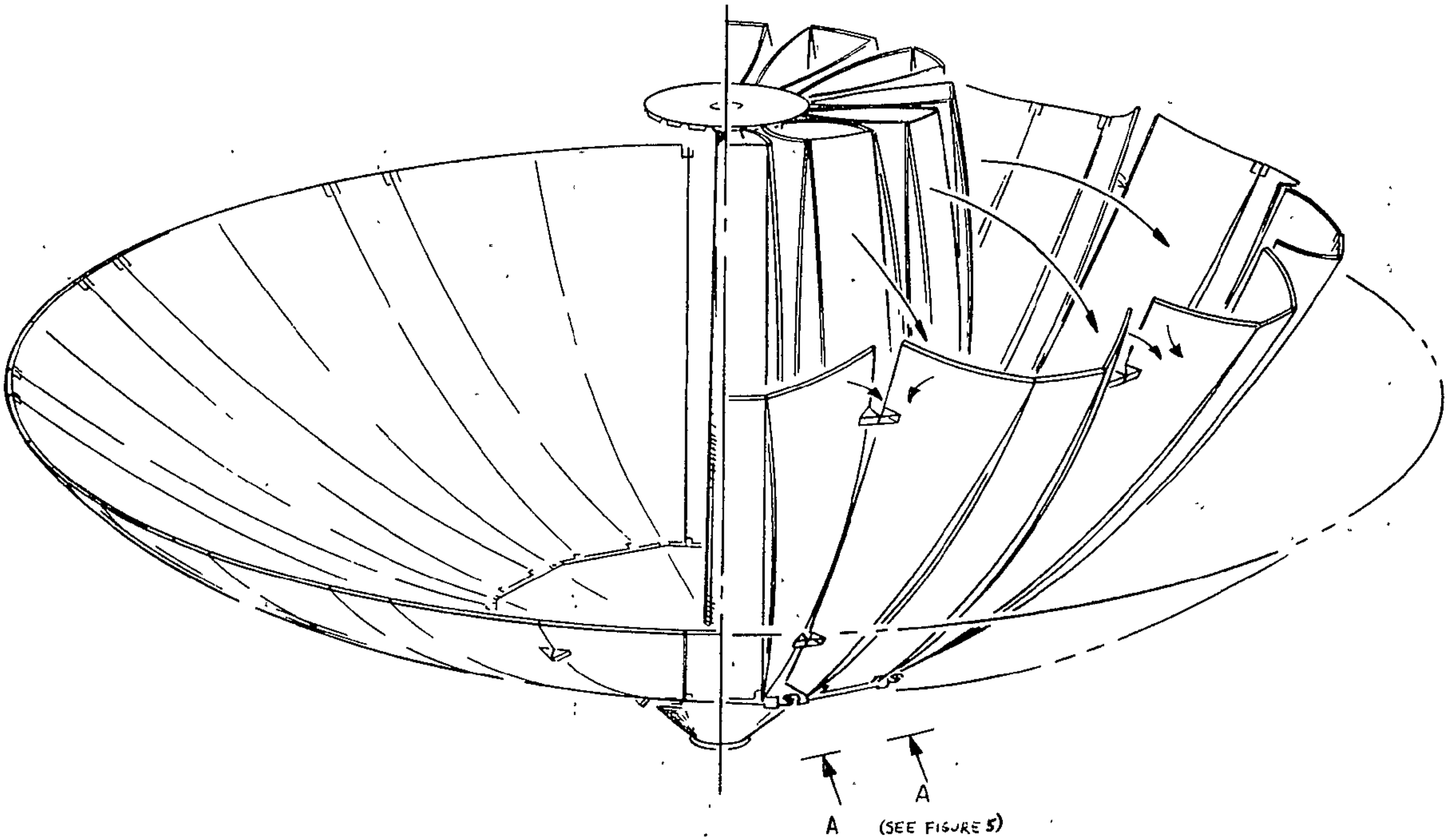


Figure 3. A Scheme of Folding a Rigid Panel Parabolic Reflector

Table 2. Concepts for Rigid Reflector Surface Paraboloidal Reflectors

No.	Name and Source	Structural Concept	Data	Size	Wt. (lbs)	Unit Wt. (lbs/sq.ft.)	Status	Remarks	Refs.
1	Sunflower (Circular Paraboloid) TRW/NASA Lewis	Central hub and interconnected radial petals; aluminum sandwich construction: passive deployment using torsion spring and viscous dampers	Freq. 1-10 GHz Beam 2.3°-0.23° Gain 37 db at 1 GHz 57 db at 10 GHz f/p 17.0/32.2 Surface Deviation at 1 AU: Slope - ±.5° max. Translation - ±1 in max. Natural freq. for deployed structure: Not available Life expectancy: 1 yr	32.2' Deployed 13' x 10' dia stowed	135	.26	Prototype built and ground tested 5' model is also available	Originally developed for solar concentrator	4, 12 13
2	ATS-4 Antenna Goodyear/NASA Goddard	Central hub and interconnected radial petals of rectangular and triangular shapes. Semiactive; deployment using linear actuators Fiberglass honeycomb construction	Freq. .4-8 GHz Gain 27 db at .4 GHz 50 db at 8 GHz f/p .5 Surface Deviation <.15 in Life expectancy: 2 years	30' deployed 12' x 10' dia stowed	Not Available		Under development.		5, 14
3	Folding-Petal Paraboloid Ryan	Radial petals hinged to the central hub and interlocked at the rim by scissors truss and tension cable. Aluminum honeycomb construction.	Freq. .6-7.4 GHz Beam 23°-0.19° Gain 17 db at 30 MHz 58 db at 7.4 GHz	50' deployed 21' x 12' dia stowed	3.020	.96	10' working model available		4
4	Rose Petal Circular Paraboloid LMSD/AF Reconnaissance Lab	Radial petals hinged to the central hub. Passive deployment using torsion springs. Magnetic latches and tension cable are used for locking. Petals are aluminum shell segments.	f/p .437 Beam 3.6° Gain 23 db at 5 GHz	4' deployed 1.5' x 1.5' dia. stowed			Demonstration model available.		15
5	ERCS Fresnel Solar Reflector GMAD/AF ASD	Conical electroformed Ni foils are attached in serration to several interconnected flat rigid frame panels of electro formed nickel	f/p .59 Natural Frequency: lowest 10 Hz	4' deployed 6' x 42" x 13" stowed	6.1	.5	4' model available.	Developed for solar reflector	16
6	RCE Unfurlable Petals LMSD-ECS/AFAPL	Electroformed nickel monocoque petals hinged to a central hub. Active deployment.		10' deployed 3' x 5' dia. stowed		.406	52' dia. model available	Developed for solar concentrator	17, 18
7	Hybrid	Rigid parabolic segments with flexible reflector between them.							5

RIGID REFLECTOR SURFACES

In this class the antenna is an assemblage of rigid segments of a circular paraboloid. Table 2 shows several concepts for reflectors of this type.

One highly developed form of this concept is the Sunflower, where an individual panel, or petal, of honeycomb construction, is rotated into position and locked to its neighbors on either side. The most critical problem for the Sunflower is insuring that its petals lock after deployment. This requires a reasonably complex series of spring-driven torquing and locking devices and viscous dampers. A 32-foot diameter Sunflower antenna has been demonstrated and tested successfully.

To eliminate some of the complex interlocking mechanisms alternate designs have been offered in which the rigid panels are hinged to each other. Figures 3 and 4 show two schemes of folding rigid parabolic reflector surfaces. Figure 5 shows details of the deployment springs and dampers and the universally-jointed axles between adjacent panels to minimize the number of deployment springs and increase reliability.

Goodyear-Aerospace has built an eight-foot diameter model of a parabolic reflector using rigid pie-shaped petals, each permanently attached to its two adjacent petals. A secondary series of ribs, similar to the ones used to deploy a rain umbrella, is used to deploy the antenna.

A considerable technology has built up in recent years in the development of lightweight, space compatible, solid surface paraboloidal reflectors for use in solar power conversion systems. Much of this technology is directly applicable and well suited to the requirements of spacecraft antennas. The main difference among the many solar concentrators being developed is their individual approaches to the petal design. Several designs for solar concentrators have been completed utilizing various petal materials: aluminum, honeycomb, electroformed nickel monocoques, and explosive-formed aluminum skins.

The problems of large diameter rigid-surface reflectors include high unit weight compared to flexible-surface reflectors, and difficulty in meeting fairing diameter constraints. These designs usually have ratios of deployed to furled diameters of 5 or less, compared to values of this ratio as high at 50 for some flexible surface concepts.

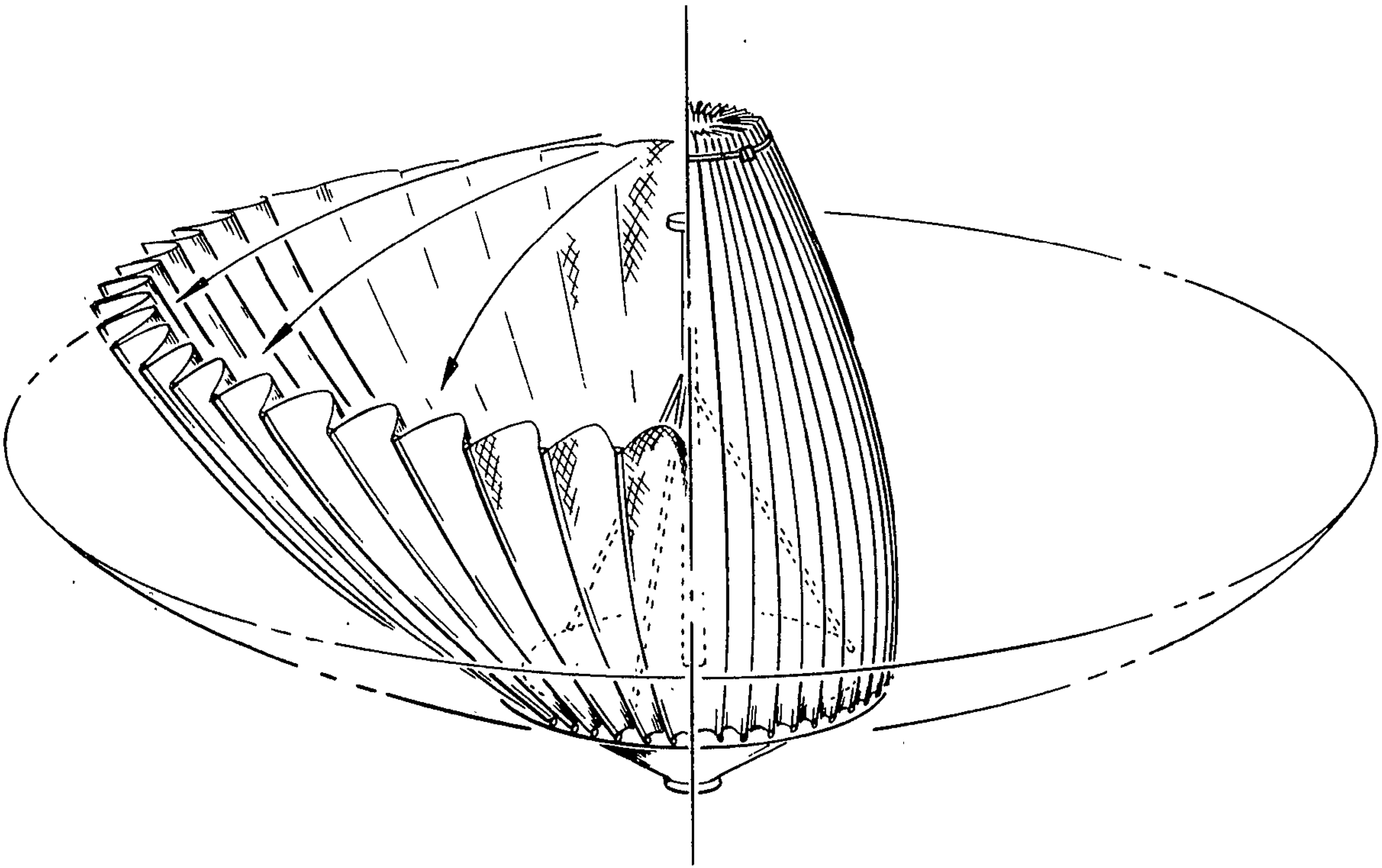


Figure 2. Flexible Surface Paraboloid with Rigid Ribs

An example of a flexible surface paraboloid with rigid radial ribs is No. 3 of Table 1, illustrated in Figure 2. Each rib is spring loaded; when the antenna restraining band is released the ribs open up, stretch the membrane, and attain the parabclic shape (Reference 2). Other methods of deploying the ribs such as a positive cable drive or compression struts (Nos. 3, 4, and 5) are also feasible.

The radial rib concept is also known as the French Umbrella, or umbrella, and many variations are possible. Generally these designs are simple and diameters are limited only by available fairing length which is the constraining dimension of the furled antenna. This concept appears to be one of the most attractive for very large apertures.

The Swirlabola, No. 8 of Table 1, is a mechanically erected spacecraft antenna. It uses curved radial ribs extending from a central hub to the periphery to support the flexible reflector surface segments and maintain the parabolic contour. This concept may be used with either a flexible reflector surface (e.g., wire mesh) or solid surface (honeycomb panels).

Another type of flexible surface furlable antenna consists of spirally-formed fiberglass rods supporting a metallic-coated plastic mesh, developed by Electro-Optical Systems (Reference 5). To fold this antenna the rods are wound up which greatly reduces overall volume. The elastic energy of the rods is then used for deployment, with the rate of expansion controlled by a braking device. In the expanded condition the shape is roughly a parabolic spheroid, with reflector material covering only one-half of the form. No data on size or performance is available.

A system of ribs supporting catenary cables which in turn define and support a paraboloidal reflector surface is another feasible concept particularly suited to very large apertures. In such a concept the ribs could be straight members using local standoffs to define paraboloidal coordinates and support catenary cables in both the radial and circumferential directions. The number of ribs would be relatively small compared to the surface accuracies attainable, and if the reflector surface is a mesh, thermal distortions of such an antenna would be expected to be small. An antenna concept of this type using deployable booms for ribs which permit a very small stowed envelope has recently been disclosed by TRW Systems.

Another TRW-developed concept is the elastic recovery umbrella, which uses self-erecting collapsible radial ribs to support a reflective mesh (No. 9 of Table 1).

Table 1. Flexible Reflector Surface Antenna

No.	Name and Source	Structural Concept	Data	Size	Weight (lbs.)	Unit Weight (lb/sq ft)	Status	Remarks	Refs.
1	Maypole Reflector, TRW Systems	Flexible ribs unwrap from toroidal storage package deploy flexible reflector at the same time. Cables are used to control rate of deployment, and to produce final tensioning which removes surface wrinkles.		3' deployed 1' x 1' dia. stowed		0.1	3' model available. 10' model under development		11
2	Flex-Rib LMSC	Flexible ribs unwrap from toroidal storage package and deploy reflective mesh.		Sizes up to 15' developed	150 lbs. for 30' dish	0.2	Successfully flown	Apertures >15' cannot be ground demonstrated	
3	Radial Rib Hughes, LMSC, others	Tubular beam ribs, hinged at central hub, erected by springs or compression struts driven along main boom. rib support reflective mesh.				0.1		Requires long nose shroud	
4	Umbrella-type Reflector RCA	Reflective mesh attached to metal radial ribs.	Freq.: 60-810 MHz Beam: 23°-2° Gain: 17 db at 60 MHz 39 db at 810 MHz	50' deployed			10' model available		4
5	Umbrella-type Reflector NASA Langley	Reflective membrane attached to metal ribs. Active deployment.	Natural freq. of deployed structure: 2 Hz	10' deployed 5' x 1' dia. stowed	24.5	0.312	Models available	Developed for solar concentrator	7, 8, 9, 10
6	Deployable Truss General Dynamics Convair/NASA Marshall	Reflective mesh attached to deployable space truss system. Passive deployment using a spring latch system.	Freq.: 0.9-2.8 GHz Beam: 5°-.16° Gain: 30 db at 0.9 GHz 58 db at 2.8 GHz	150' deployed 22' stowed	4,400	0.25	6' model of deployable truss available		4
7	Scissor Link Framework Fairchild-Hiller	Reflective mesh attached to a system of deployable radial scissor link frameworks. Passive deployment.	Freq.: .1-3.7 GHz Beam: 2,3°-.63° Gain: 17db at .1 GHz 48 db at 3.7 GHz	30' deployed 6' stowed	140	0.2	Models under development		4, 5
8	Swirlabola Goodyear	Reflective mesh or membrane attached to preformed curved Be ribs hinged to a central hub. Active deployment.	Freq. S-band Natural Freq. of deployed Structure: 1 Hz Surface Deviation (1 AU): ±15 in.	16' deployed 5' x 7' dia. stowed	26	0.13	Models available		5, 6
9	Elastic Recovery Umbrella-TRW Systems	Reflective membrane with collapsible radial ribs		6' deployed	1.2	0.04	Model Available		22

FLEXIBLE REFLECTOR SURFACE ANTENNAS

A flexible reflector surface such as metallized film or wire mesh can be supported by a system of ribs or cables which define and maintain the required paraboloidal shape. The ribs may be either rigid or flexible. Rigid ribs may be integral units or consist of several hinged elements, sliding or telescoping members, or be formed from a linkage. If flexible, they must have sufficient stiffness to maintain the desired surface accuracy under the orbital environment and yet be elastically deformed for packaging; upon release their stored potential energy must be sufficient to expand and rigidify the structure. Table 1 contains data on several flexible reflector surface antennas.

In each of these configurations the flexible reflector surface, or membrane, is stretched between ribs and assumes the form of a segment of an approximate parabolic cylinder between ribs rather than the double curvature of a paraboloid. An approximate formula for the surface standard deviation s in terms of antenna diameter D and number of ribs k is (Reference 2):

$$\frac{s}{D} = 0.41/k^2 \qquad (3)$$

Equation (3) may be used to compute the number of ribs required for a given deviation. Other rib-defined flexible surface errors are described in Reference 3.

The Maypole antenna uses ribs which are elastically deformed for packaging. Each rib winds spirally around a central hub which may support the feed. Rib elastic forces plus cable forces deploy the reflector and maintain it positively in its expanded parabolic form. This concept is described in detail in Reference 4; a 10-foot diameter demonstration model is being completed this year. While conceptually feasible for very large diameters, deployment demonstration in a 1 g field in sizes above about 30 feet would require elaborate fixturing because of rib instability during the deployment sequence.

The flex-rib concept uses ribs that are rolled on a drum together with their attached reflector. It is similar to the Maypole concept except its ribs are radial while the Maypole ribs are tangential to a central hub. Since only elastic energy is used to define and maintain the reflector shape deployment demonstration in a 1 g field would be equally difficult.

frequencies up to approximately 5 gHz, antenna surface qualities and deviations from a true paraboloid required to minimize reflector losses are such that a flexible reflector surface design is usually the preferred approach: rigid reflector surfaces provide unneeded accuracy, are heavier and are more costly. Inflatables present difficulties in mounting feeds and maintaining stable surfaces and required surface accuracies over orbital lifetimes.

Reference 1 describes some twenty concepts for deployable antennas for spacecraft application, including some that require astronaut participation. This report discusses several of these that are suitable for unmanned spacecraft application, plus many others that are described in the literature including several TRW-developed concepts.

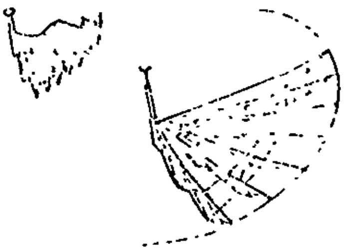
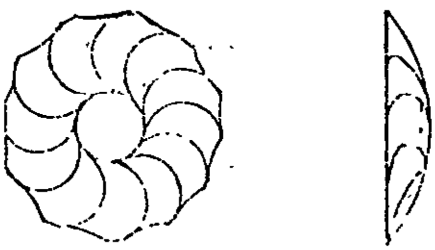
CONFIGURATION		DESCRIPTION
Sunflower		Individual petals, made of aluminum honeycomb construction or electroformed by nickel-plating a mandrel and then leaching the mandrel out. Multiple petals are hinged at center and deployed with springs.
Maypole		Flexible ribs unwrap from toroidal storage package deploy flexible reflector at the same time. Cables are used to control rate of deployment, and to produce final tensioning which removes surface wrinkles.
Radial Rib		Tubular Beam ribs, hinged at central hub, erected by springs, cables or hub compression struts driven along main boom. Ribs support reflective mesh.
Parabolic Scissors		The ribs are parabolic-shaped scissors linkages, with a flexible mesh.
Swirlabola		Ribs are tubular arc elements supporting a reflective mesh, folded around payload and deployed mechanically.

Figure 1. Some Typical Concepts for Deployable Parabolic Reflectors

The combination of frequencies and beamwidths required for communication satellites, interplanetary probes, and scientific spacecraft in general call for antenna diameters up to about 30 feet; secure communications and many military applications may require diameters of 100 feet or more. Launch vehicle fairing constraints and overall configuration efficiency dictate design concepts that allow the antenna to be folded during launch and then deployed to its paraboloidal shape after orbit is achieved.

Typical structural requirements for these antennas are:

- Good surface accuracy: RMS surface deviation and distortion should not be greater than $\lambda/16$
- Reliable deployment
- Long service life
- Light weight
- Small stowage volume
- Sufficient structural stiffness when deployed to prevent unacceptable control system interactions under attitude control forces
- Minimum distortions under the varying thermal environment

Deployable parabolic antennas may be classified into three groups according to their construction:

- Flexible reflector surfaces, whose paraboloidal shape is supported and maintained by a framework of ribs and/or cables
- Rigid reflector surfaces, which are mechanically deployed
- Inflatable structures, using internal pressure to form the paraboloidal reflector surface shape.

Combinations of these generic types are also possible. Figure 1 illustrates some typical concepts, which with others are described in more detail in the following sections.

The choice of a concept for a particular application depends on the antenna design frequency, spacecraft configuration constraints, and environmental factors. Some concepts are more suited to particular size classes. For

INTRODUCTION

Spacecraft antennas take on a variety of forms, depending on the intended application and desired operating frequency range. In general, they can be categorized into three basic classes:

- Linear conductors
- Waveguides (horn, slot)
- Reflectors and arrays

For missions requiring antennas with omnidirectional radiation and relatively low gain such as guidance in a near-earth orbit, linear conductor and waveguide antennas have been used extensively. For applications requiring high gain (>20 db) and directivity, reflector antennas and phased arrays are needed. Reflector type antennas have been preferred over phased arrays for high gain applications because they are simpler in design and lighter in weight for a given gain. While phased arrays do have certain advantages, particularly when the antenna is operated over a wide frequency band, their complexity, heavy weight, and difficulty in meeting launch vehicle fairing constraints have prevented their extensive use on spacecraft to date.

Thus over the near term most high gain directional spacecraft antennas will be parabolic reflectors. The size of a reflector is determined by the frequency range where the antenna is to be used and by the desired beamwidth. The following rule-of-thumb relates these parameters:

$$D \cong 70 \frac{\lambda}{\theta} \tag{1}$$

where D is the antenna diameter, λ is the wavelength, and θ is the half-power beamwidth in degrees.

Frequency and beamwidth dictate the required antenna diameter, in accordance with Equation (1). Antenna gain G is a further function of the aperture efficiency η, in accordance with Equation (2):

$$G = \eta \frac{\pi D^2}{\lambda} \tag{2}$$

η in turn is a function of surface tolerances, distortions, and reflectivity; its further discussion is beyond the scope of this report.

APPENDIX 4A

DEPLOYABLE SPACECRAFT ANTENNAS

SUMMARY

Frequency and beamwidth requirements for the TV Broadcast Satellite dictate parabolic reflector antenna diameters that may exceed the dynamic envelopes of candidate launch vehicle fairings. Because of such constraints these antennas will have to be furled for stowage on board the launch vehicle and deployed after nominal orbit is achieved. In addition furling may allow the antenna to react the acceleration and vibration launch environments through more direct load paths, resulting in lighter overall antenna weights. This report discusses some of the mechanical design considerations of deployable spacecraft antennas, describes their design criteria, and discusses many possible design concepts. Of the candidate concepts for the TV Broadcast Satellite application within the range of required diameters and surface accuracies, the particular selections will depend on spacecraft configuration parameters, launch vehicle and fairing constraints, and other mission-dependent variables.

SECTION 4. REFERENCES

4-1. R.C. Hansen, "Microwave Scanning Antennas," Vol. I, pp. 64-66, Academic Press.

4-2. T. Taylor, "Design of Circular Apertures for Narrow Beamwidth and Low Sidelobes," IRE Trans. on Antennas and Propagation, Vol. 8, pp. 17-22.

4-3. C. Dolph, "A Current Distribution for Broadside Arrays which Optimizes the Relationship between Beamwidth and Sidelobe Level," Proc. of the IRE, 1946.

4-4. J. Blass, "Multidirectional Antenna - A New Approach", IRE Convention Record, Vol. I, 1960.

4-5. J. Butler and R. Lowe, "Beam-Forming Matrix Simplifies Design of Electronically Scanned Antennas," Electronic Design, April 1961.

4-6. R. Hansen, "Microwave Scanning Antennas," Volume III, Academic Press, 1966.

4-7. P.D. Potter, "The Aperture Efficiency of Large Paraboloidal Antennas as a Function of their Feed System Radiation Characteristics," JPL Technical Report No. 32-149.

4-8. J. Ruze, "Antenna Tolerance Theory - A Review," Proc. IEEE, April 1966.

4-9. "Microwave Engineers Handbook," Horizon House, 1966.

4-10. J. Ruze, "Physical Limitations on Antennas," TR248, MIT Research Lab of Electronics.

4-11. S. Silver, "Microwave Antenna Theory and Design," McGraw Hill, 1949.

4-12. R. Arnold, M. Bichara, J. Eberle and L. Repert, "Microwave Integrated Circuit Applications to Radar Systems," Microwave Journal, July 1968.

4-13. R.F. Stengel, "Stored Strain Energy Unfolds Orbiting Antenna," Design News, September 1968.

4-14. K.G. Schroeder, "Low-Sidelobe Nonsymmetrical Binary Corporate Feeds for High-Power Phased Arrays," 1968 Fall URSI Meeting, 12 September 1968, Boston, Mass.

4-15. F.J. Goebels et. al., "Analytical & Experimental Investigation of Sidelobe Suppression Techniques for Reflector Type Spacecraft Antenna, Final Technical Report, NASA-CR-72462, Contract NAS 3-9717, General Electric Co, 1 September 1968.

Table 4-9. Comparison Summary of Reflector Antenna versus Active Array Antenna For Television Broadcast Satellite (f = 2.5 GHz)

	Reflector	Array
Total weight (antenna + transmitter)	Approximately same	
Shape	Approximately same for single beam	
Aperture efficiency	Medium	Medium
Pattern shaping capability	Good	Very Good
Power handling	Good	N/A for active array
Electronic beam steering	No	Yes
Thermal environment	May be problem	Effects minimized
Deployment reliability	Can be problem	High due to redundancy
Development required	Some	High
Multiple beam capability	With multiple reflectors	Yes - with multiple feeds
Development cost	High - (including transmitter)	High
Production cost	Medium	Medium to high

Table 4-8. Comparison Summary of Reflector Antenna versus Array Antenna for Television Distribution Satellite (f = 8 and 12 GHz)

	Reflector	Array
Weight	Lighter	Heavier
Shape	Approximately same, but separate aperture for each beam	Approximately same
Aperture efficiency	Slightly lower	Highest
Feed efficiency	Highest	Lower
Pattern shaping capability	Good	Best, but costly
Power handling	Best	Limits design
Electronic beam steering	None	Yes
Thermal environment	May be problem*	Minimization of effects are possible, but costly
Deployment reliability	High because of separate rigid reflectors for each beam	High
Required development	Some	Yes
Multiple beam	Requires multiple reflectors	Requires complex and lossy feed
Cost	Minimum	Highest

*May require reflector design using low thermal coefficient of expansion materials such as invar or graphite-epoxy compositions.

solution to multiple-beam capability at 900 MHz, unless very high packaging ratios for high-performance reflector antennas at 900 MHz are developed to allow storage of more than one reflector.

A comparison summary table for X-band antennas is given in Table 4-8 and for S-band antennas in Table 4-9. For 900 MHz, the array is superior even for a single-beam application, and is mandatory for two or more beams.

4.5.5 Comparison of Arrays with Reflector Antennas

The first guideline that must be used in the relative comparison of a phased array and a reflector is the number of beams required and the frequency range of interest. For the higher frequencies (8.5 and 12.0 GHz) considered in this study the parabolic reflector offers the most promising design, since packaging of multiple reflectors at these frequencies is not a significant problem. At the lower frequencies (0.9 and 2.5 GHz) where deployable antennas are required phased arrays become more promising.

Table 4-6. 30-Foot 900-MHz Phased Array Weight Budget

18 strain energy element clusters (126 deployable helices at 1 lb.)		126
12 support booms		20
Support boom deployment system		18
18 rf cables, micromin		18
18 dc distribution lines		18
18 rf line amplifiers		9
1 signal divider		4
Phase shifters and logic		18
126 element modules		126
10 percent contingency		36
	Total	396 lb

Table 4-7. 900-MHz Phased Array Gain Budget

Peak aperture gain (126 helices at 15 db gain)		36.0 db
Grating lobe efficiency	-0.5 db	
Element efficiency	-0.5 db	
	Total loss	-1.0 db
	Net gain (boresight)	35.0 db

Therefore, for a 3 degree HPBW and a spacing of 0.75λ the number of elements is N ≈ 780. However, selecting the element spacing of 2.0 wavelengths and a higher element gain, the number can be reduced to N ≈ 110. Increasing the element spacing and the gain of the elements still further can reduce the total number of elements. This then becomes a tradeoff between the weight of the N elements versus the selection of an element suitable for a deployable array.

The number of elements selected for this example is 126. Each element is a deployable helix about 5 feet long. With a power capacity of 100 watts per element, the array radiates 12 kw in a 3-degree wide beam. This power level is that required for AM/VSB transmission to home receivers with a 6 foot dish antenna and low-cost converter located in an urban environment (see Section 2.10). Even with 50 watts per element, the array capacity is still useful for AM/VSB transmission.

Table 4.6 gives a weight summary of the 12 kw phased array. It is seen that the array, which essentially contains all the required amplification, compares favorably with a reflector system using one concentrated tube-type amplifier. No cooling mechanism, such as a heat pipe, is required. For the low-power FM applications, the array weight should be under 300 pounds including all amplifiers, steering systems, etc.

For an active half-power beamwidth of 3 degrees at 900 MHz, the array weight is 396 pounds, including 126 pounds for 100 watt amplifier modules at the elements. This weight should be compared with the sum weight of a reflector antenna and a single rf amplifier, a total of approximately 350 pounds. The latter estimate includes redundant crossed-field amplifiers. The array element modules do not carry redundant amplifiers; a single amplifier failure results in a slight degradation in array gain.

In Table 4-7 the gain budget for the multi-element array is presented. It should be pointed out that the grating lobes fall well outside the 18-degree earth coverage cone.

For 900 MHz, the active phased array appears an attractive alternate to the reflector antenna with single rf power amplifier. For two or more beams, the array must definitely be considered. It is the only

A special case of a parallel feed is the familiar corporate feed. This feed system is composed of a series of two-way power splitters. Equal splits can be used, the required amplitude tapering being accomplished by different amplifications and different power levels in the final array amplifiers.

These feed networks all provide a single beam. If a broadside beam is required which does not need to be scanned, the phase shifters are not needed. For lower power levels this type of array feed network can be made relatively lightweight. For more than one beam, the feed networks can be diplexed at the elements.

A variation of the above corporate feed which can provide amplitude tapering is the nonsymmetrical corporate feed. This feed network is limited in achievable sidelobe level with minimum complexities (Reference 4-14). However, by combining it with non-uniform spacing, -25 db may be achievable.

4.5.4 Active Array for 0.9 GHz

Consider an active array for a half-power beamwidth of 3 degrees at 0.9 GHz. Assuming that the elements radiate different power levels to give a tapered illumination, the half-power beamwidth is given by

$$\theta_{HP} \simeq \frac{71}{D_\lambda} = 3 \text{ degrees}$$

yielding $D_\lambda = 23.6$ and $D = 26.2$ ft (8m).

To a rough approximation the number of elements required is

$$N = \frac{1}{d^2}\left(\frac{\pi}{4}\right)D^2$$

where

d = spacing between elements in a principle plane in wavelengths

D = diameter of aperture in wavelengths.

4.5.3 Beam Forming and Steering

An item of major concern in any array is the feed network. A planar two-dimensional array, which would be the type used for all applications for the present study, except for an electronically despun beam, can be fed in several ways. These consist of any combination of series feeding and parallel feeding. Typical configurations (Reference 4-6) are shown in Figure 4-24. Modulo-2π phasing will be used in all cases, the required bandwidths being sufficiently narrow to avoid gain degradation or increase in sidelobe level. A discussion of bandwidth limitations in phase-steered arrays is contained in Appendix 4B.

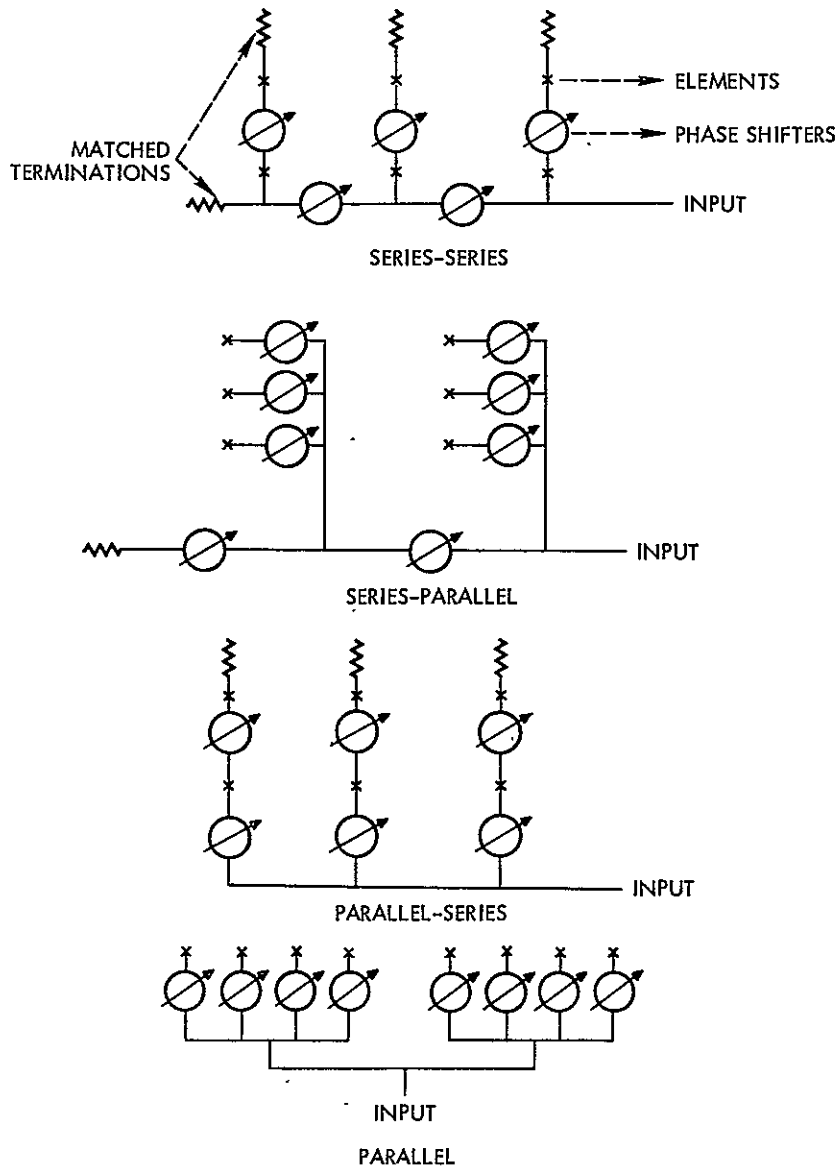


Figure 4-24. Typical Planar Array Feed Networks

Table 5-1. Cell Parameters for Three Thicknesses, Two Base Resistivities, and Three Cell Temperatures. Beginning of Life.

Cell Type	UNIT	2 x 2 cm, N-on-P, 2 ohm-cm											
Cell Thickness	inches	0.008 (0.020 cm)				0.010 (0.025 cm)				0.012 (0.03 cm)			
0.410 μ cutoff filter	inches	Bare	0.012 (0.03 cm)			Bare	0.012 (0.03 cm)			Bare	0.012 (0.03 cm)		
Cell Temperature	°C	28	28	20	55	28	28	20	55	28	28	20	55
V_{oc}	mV	578	572	589	512	582	576	593	516	587	581	598	531
V_{op}	mV	479	474	489	414	482	477	495	417	484	479	496	418
I_{op}	mA	120	110	110	110	122	112	112	112	124	115	115	115
I_{sc}	mA	125	115	115	115	128	118	118	118	131	121	121	121
P_{op}	mW	57.4	52.2	53.9	45.5	58.9	53.4	55.5	46.7	59.6	55.1	57.1	48.1
η	%	10.8	9.85	10.2	8.57	11.1	10.1	10.5	8.8	11.25	10.4	10.75	9.07
β	mV/°C	2.2				2.2				2.2			
		2 x 2 cm, N-on-P, 10 ohm-cm											
V_{oc}	mV	542	537	554	475	550	544	562	480	553	547	565	485
V_{op}	mV	430	426	444	364	434	430	448	366	437	433	451	371
I_{op}	mA	124	114	114	114	129	119	119	119	131	121	121	121
I_{sc}	mA	133	123	123	123	138	128	128	128	140	129	129	129
P_{op}	mW	53.2	48.6	50.7	41.6	55.9	51.2	53.4	43.7	57.0	52.4	54.5	45.0
η	%	10.0	9.16	9.56	7.85	10.5	9.65	10.0	8.25	10.8	9.88	10.25	8.5
β	mV/°C	2.3											

NOTE: Glassed cell degradation factors used are:

I_{sc}	assembly	0.970	V_{oc}	assembly temperature coefficient	0.990
	filter	0.975			
	mismatch	0.980			
	temperature cycling	0.985			
	Total	0.923			

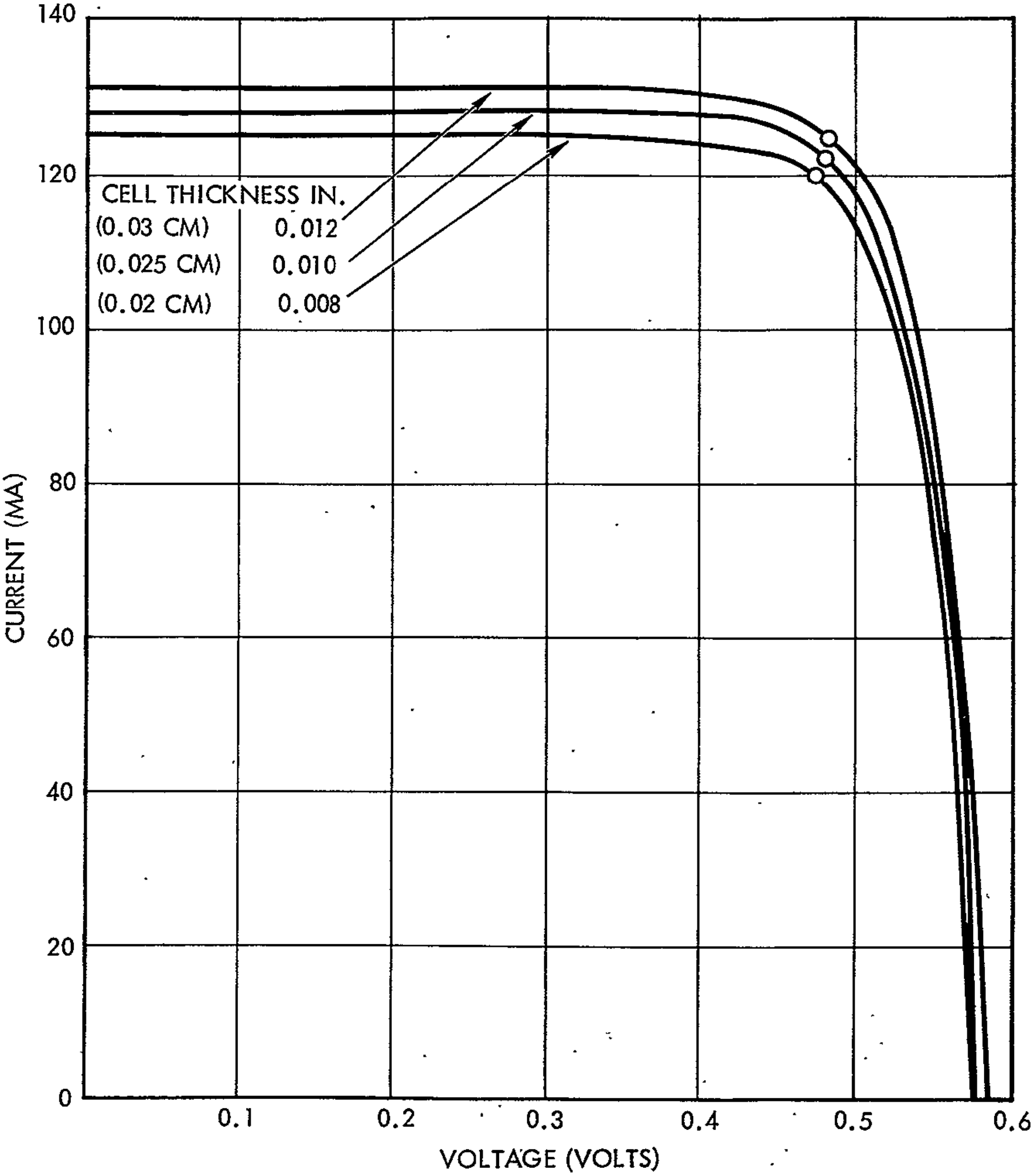


Figure 5-1. I-V Characteristics of 2x2 cm, 2 ohm-cm, N-on-P Cells (Bare, AMO, 28°C; Overage, Beginning of Life.)

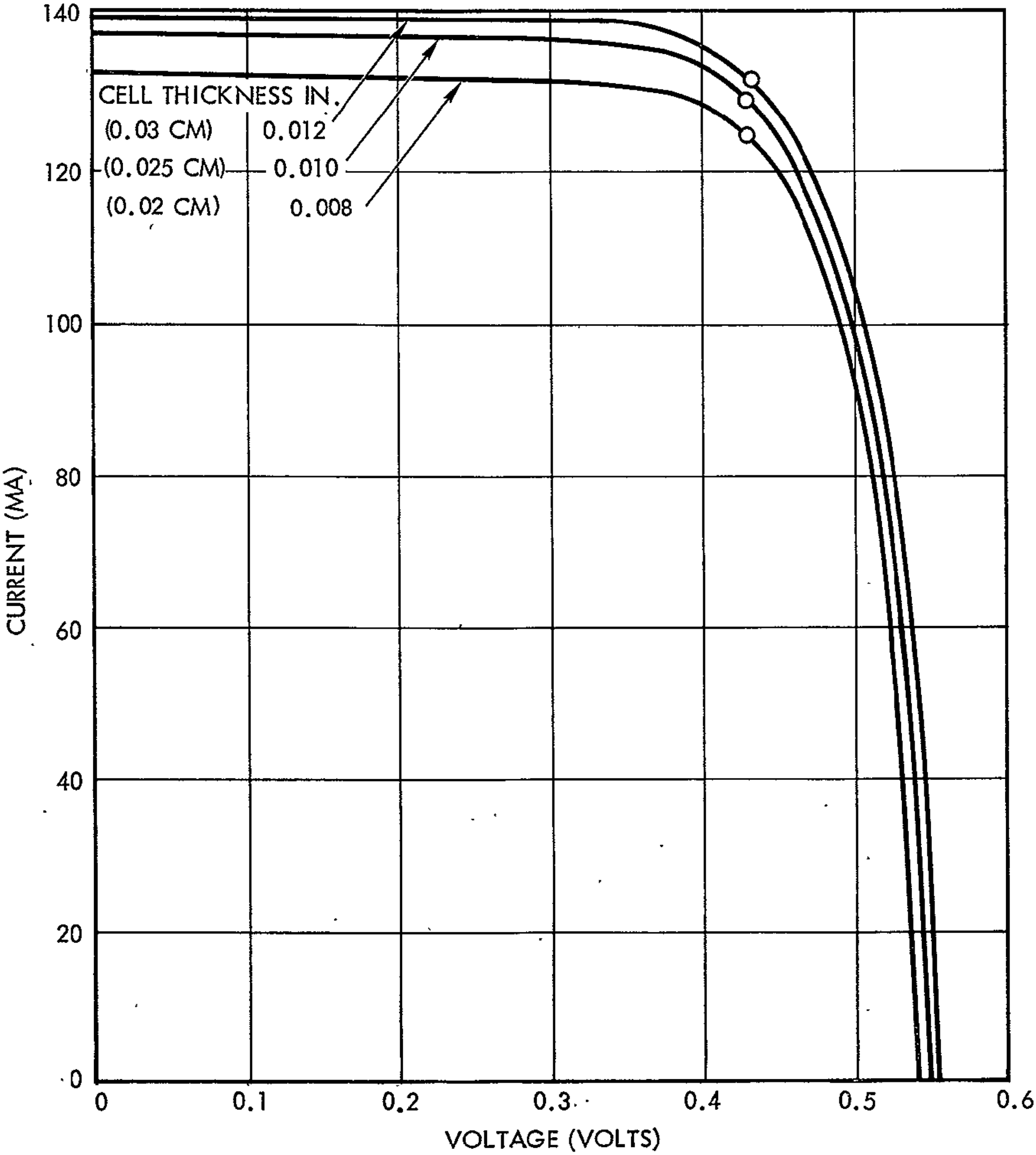


Figure 5-2. IV Characteristics of 2x2 cm, 10 ohm-cm, N-on-P Cells. (Bare, AMO, 28°C; Overage, Beginning of Life).

These selections are discussed in greater detail in the subsequent sections.

5.1.2 Radiation Effects

Recent data from ATS-1 revealed unexpectedly severe degradation to solar cell performance (23 percent) after 1 year. The cells are 1 x 2 cm (negative contact along the 2-cm dimension), N-on-P solder-covered contact cells. They were applied in such a way that a strip 0.005 inch (0.013 cm) wide along the 2 cm dimension remained uncovered. The unexpected damage is attributed to the effects of low-energy ($E < 5$ Mev) protons on the exposed cell area, and this assumption was confirmed by laboratory tests on similar assemblies. It was also determined that satisfactory protection from this effect is provided by a thin layer of material over the exposed area.

There are several methods by which the exposed cell area can be eliminated. One low-cost technique is to apply a thin layer of the cover slide adhesive (selected because it will not block light from the area to which it is applied) to the area exposed after the panels are assembled. The only cost is for a small amount of adhesive and application time. The extent of UV darkening of the exposed adhesive has not been completely evaluated, but even assuming total darkening, (no light transmission) less than 1 percent of the active cell area would be affected, providing thereby less than 1 percent reduction in output. Further evaluation of this method is warranted.

Another method is to use cover slides sized precisely to cover all of the active area of the cell. Although this method entails no loss of active cell area, it is also considerably more expensive. Consequently, the addition of adhesive to the exposed cell areas is considered the optimum choice. Although silicone RTV adhesives can satisfactorily bond to Kapton, General Electric SMBD 745 flexible epoxy adhesive is considered to be more desirable. Should the dielectric material be other than Kapton, other adhesives may be preferred.

This effect has, therefore, been neglected in determining the array performance over the complete mission and establishing output degradation.

Both 2 and 10 ohm-cm cells have been compared on the basis of using 0.012 inch (0.53 cm) thick covers. Flat panel and body-mounted arrays are considered.

In 1975, the twenty-first solar cycle should begin. A 5-year mission beginning then will experience solar flare activity ranging from maximum to minimum. However, since the mission would not occur at the peak of the cycle, as it would if launch were in 1978, the solar flare proton fluence assumed for this analysis is that of the 6-year average as shown in Figure 5-3. The fluence for trapped electrons at synchronous altitude is shown in Figure 5-4. For flat panel arrays, back radiation will also have an effect. Figures 5-5 and 5-6 show the equivalent 1 Mev fluence (e/cm^2) for all radiation versus cover slide thickness for a 1975 launch and for flat panel and body-mounted arrays. The same radiation environment is assumed for both cell types.

The resultant degradation is tabulated in Table 5-2 for cells with a 12 mil (0.03 cm) cover glass. Table 5-3 shows the effect, for one cell thickness, of varying cover thickness.

The cover slides, 0.012-inch (0.03-cm) Corning 7940 fused silica and 410 ±15 μ cutoff wavelength, are bonded to the cells using type XR-6-3489 adhesive. Figures 5-7 and 5-8 illustrate the nominal output versus mission duration, on an individual solar cell basis, for various cell thicknesses.

These figures need only be corrected for temperature to predict performance on a given mission.

The data for body-mounted arrays in Figure 5-7 must also be modified to take the spacecraft configuration into account since this figure is only for one cell normal to solar insolance. With any cover glass thickness between 0.006 inch (0.015 cm) and 0.020 inch (0.050 cm), the performance at the end of the 5-year mission would be within ±4.5 percent of that indicated for 0.012 inch (0.030 cm). This indicates that at the EOM both 2 and 10 ohm-cm cells, regardless of thickness, will result in the same output.

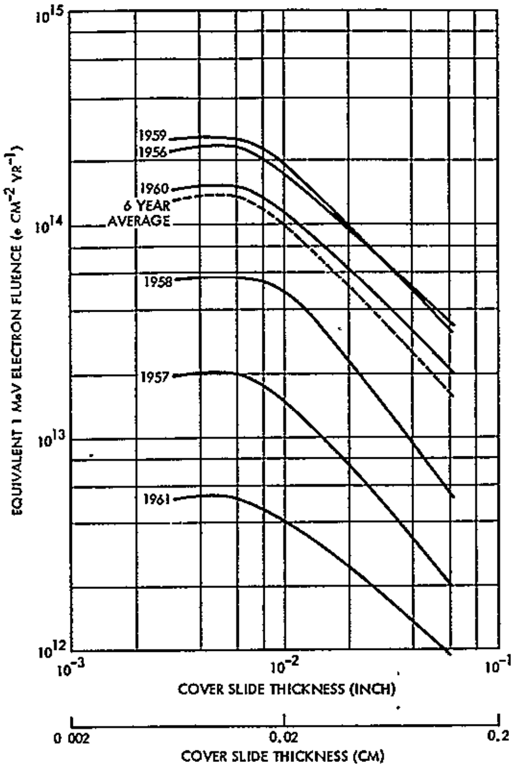


Figure 5-3. Equivalent 1 Mev Electron Fluence for Solar Flare Protons as a Function of Cover Thickness for 1956 through 1961.

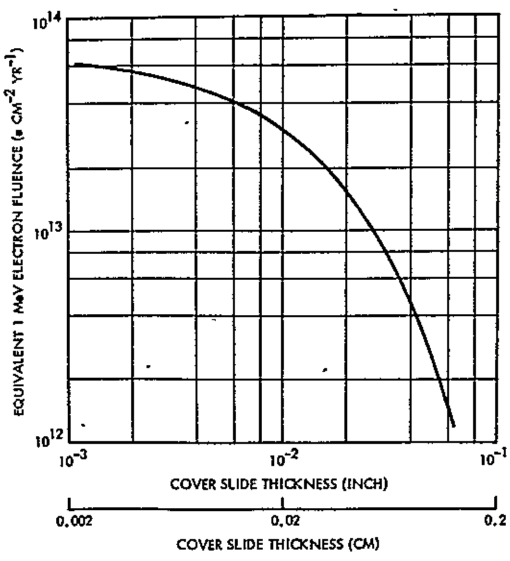


Figure 5-4. Equivalent 1 Mev Electron Fluence Per Year Corresponding to the Trapped Electron Environment at Synchronous Equatorial Orbit.

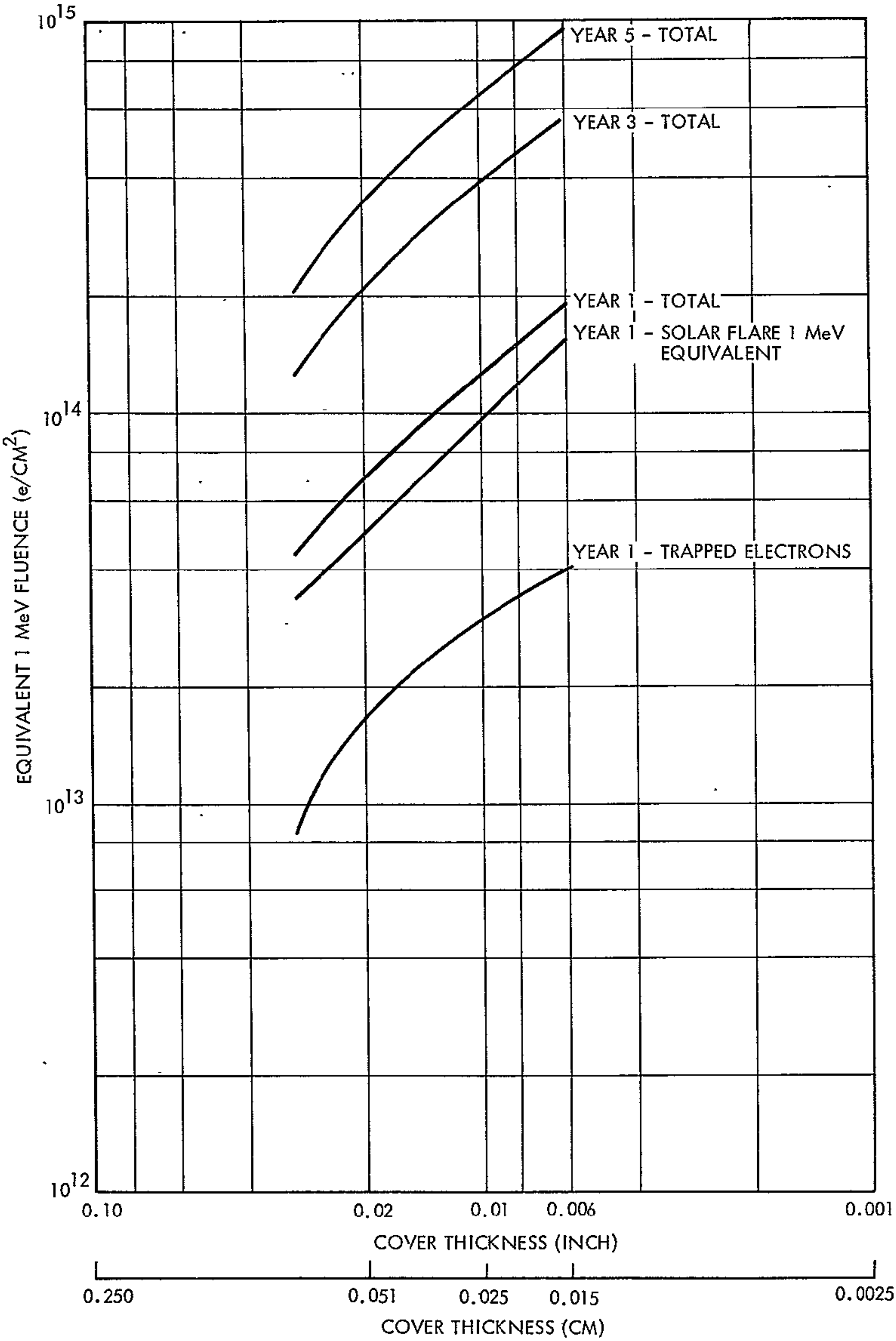


Figure 5-5. Fluence Levels Versus Cover Thickness for Bodymounted Solar Arrays Launched in 1975.

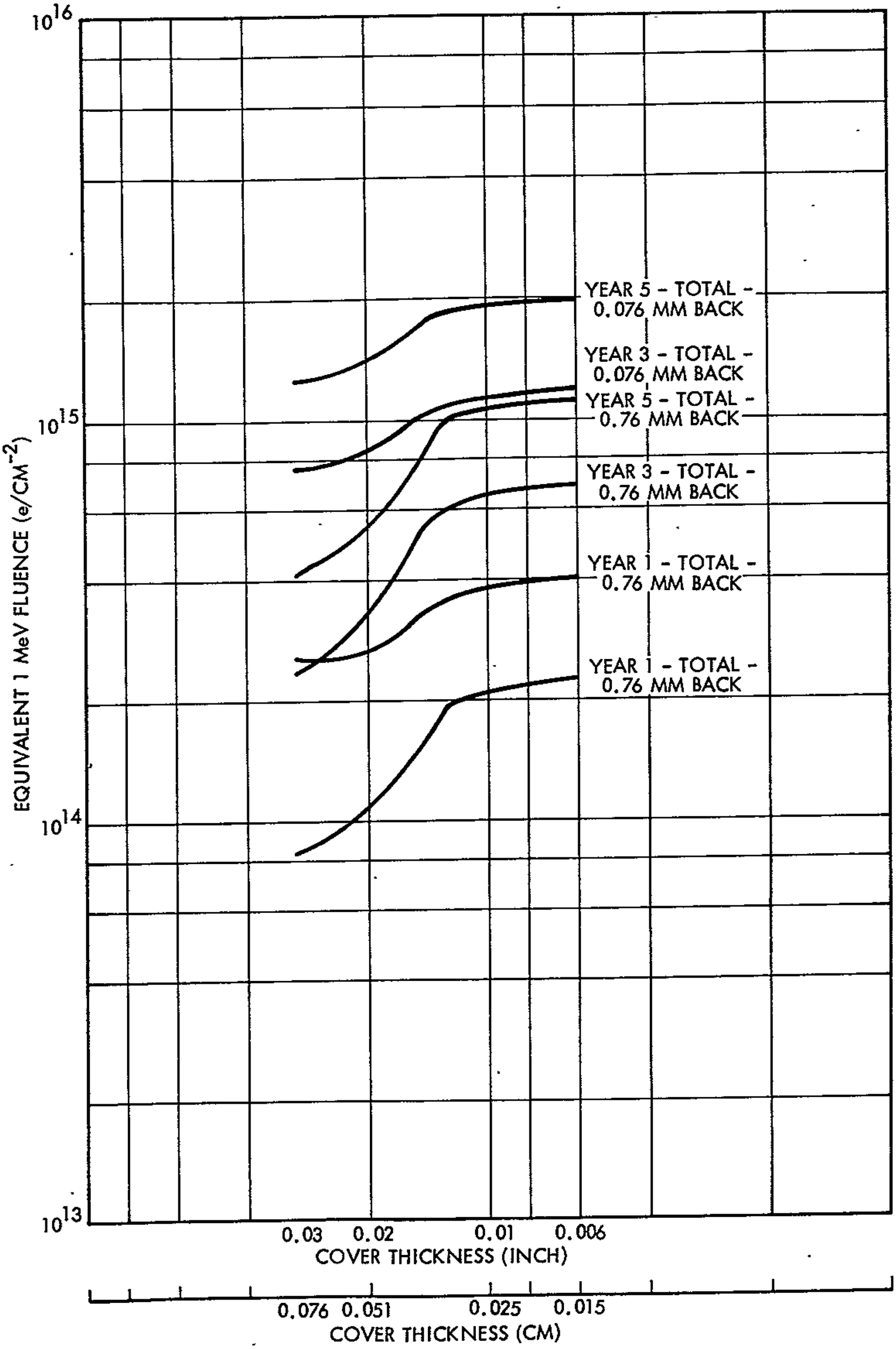


Figure 5-6. Fluence Levels Versus Cover Thickness for Flat Panels Launched in 1975

Table 5-2. Radiation Degradation at 28°C for Body-Mounted and Flat Panel Arrays Using 12-Mil Covers. Data for a Single Cell.

Year		0				1				3				5			
Total fluence (e cm^{-2})		0		0		$1.06x10^{14}$		$3.7x10^{14}$		$3.18x10^{14}$		$1.1x10^{15}$		$5.3x10^{14}$		$1.85x10^{15}$	
Type Array		Body		Flat panel		Body		Flat panel		Body		Flat panel		Body		Flat panel	
Micrometeroids						0.99		0.99		0.985		0.985		0.983		0.983	
Adhesive and cover (U. V.)						0.986		0.986		0.985		0.985		0.984		0.984	
Adhesive and cover (rad)						0.975		0.961		0.963		0.949		0.957		0.943	
Random failure						0.997		0.997		0.991		0.991		0.985		0.985	
Subtotal (1)		1.000		1.000		0.947		0.935		0.926		0.913		0.911		0.897	
(ohm-cm) Base Resistivity		2	10	2	10	2	10	2	10	2	10	2	10	2	10	2	10
I_{sc}(rad)	8 mil (0.02 cm)	115	123	115	123	118	128	109	121	110	122	101	113	107	119	97	109
	10 mil (0.025 cm)	118	128	118	128	119	130	110	122	111	123	101	114	107	119	97	109
	12 mil (0.03 cm)	121	129	121	129	120	132	110	122	112	124	101	114	107	119	97	109
V_{oc} (rad)	8 mil (0.02 cm)	512	537	512	537	552	529	536	512	539	515	522	500	532	510	515	493
	10 mil (0.02 cm)	576	544	576	544	552	530	636	513	639	516	522	500	532	510	515	493
	12 mil (0.03 cm)	581	547	581	547	552	531	536	513	539	516	522	500	532	510	515	493
8 Mil (0.02 cm)	I_{sc}(m A)	115	123	115	123	112	121	102	113	102	113	92	103	98	·108	87	98
	V_{oc} (m V)	572	537	572	537	552	529	536	512	539	515	522	500	532	510	515	493
	P_{op} (mW) (2)	522	48.6	522	48.6	48.8	47.5	43	43	43	43	35	37.3	40.6	40.5	34.5	356
10 Mil (0.025 cm)	I_{sc} (mA)	118	128	118	128	113	123	103	114	103	114	92	104	.98	109	87	98
	V_{oc} (mV)	576	544	576	544	552	530	536	513	539	516	522	500	532	510	515	493
	P_{op} (mW) (2)	53.4	51.2	53.4	51.2	48.9	47.5	43	43	43	43	35	37.4	40.6	40.5	34.5	356
12 Mil (0.03 cm)	I_{sc} (mA)	121	129	121	129	113	124	103	114	104	115	92	104	98	109	87	98
	V_{oc} (mV)	581	547	581	547	552	531	536	513	539	516	522	500	532	510	515	493
	P_{op} (mW) (2)	55.1	524	55.1	52.4	48.9	47.5	43	43	43	43		37.4	40.6	40.5	34.5	35

(1) Degradation from effects other than radiation.

(2) Multiply by subtotal (1) to account for all types of degradation.

Table 5-3. 10-Mil (0.025 cm) Cell After 5 Years in Orbit

Cover Thickness	0.006 In. (0.015 cm)				0.020 In. (0.051 cm)			
Fluence	9.5×10^{14}		2×10^{15}		3.4×10^{14}		1.4×10^{15}	
Base resistivity	2Ω-cm	10Ω-cm	2Ω-cm	10Ω-cm	2Ω-3m	10Ω-cm	2Ω-cm	10Ω-cm
	Body mounted		Flat Panel		Body mounted		Flat Panel	
Micrometeroids	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983
Adhesive and cover (UV)	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984
Adhesive and cover (Rad)	0.950	0.950	0.942	0.942	0.962	0.962	0.946	0.946
Failure, random	0.985	0.985	0.985	0.985	0.985	0.985	0.985	0.985
Subtotal (1)	0.904	0.904	0.895	0.895	0.916	0.916	0.900	0.900
V_{oc} (mV)	0.524	0.502	0.514	0.492	0.538	0.516	0.519	0.496
I_{sc} (mA)	93	103	85.6	97	101	113	89.1	100
(2) P_{op} (mW)	37.8	37.2	33.8	33.9	42.4	42.3	35.8	35.8

(1) Degradation from effects other than radiation

(2) Multiply by subtotal (1) to account for all types of degradation.

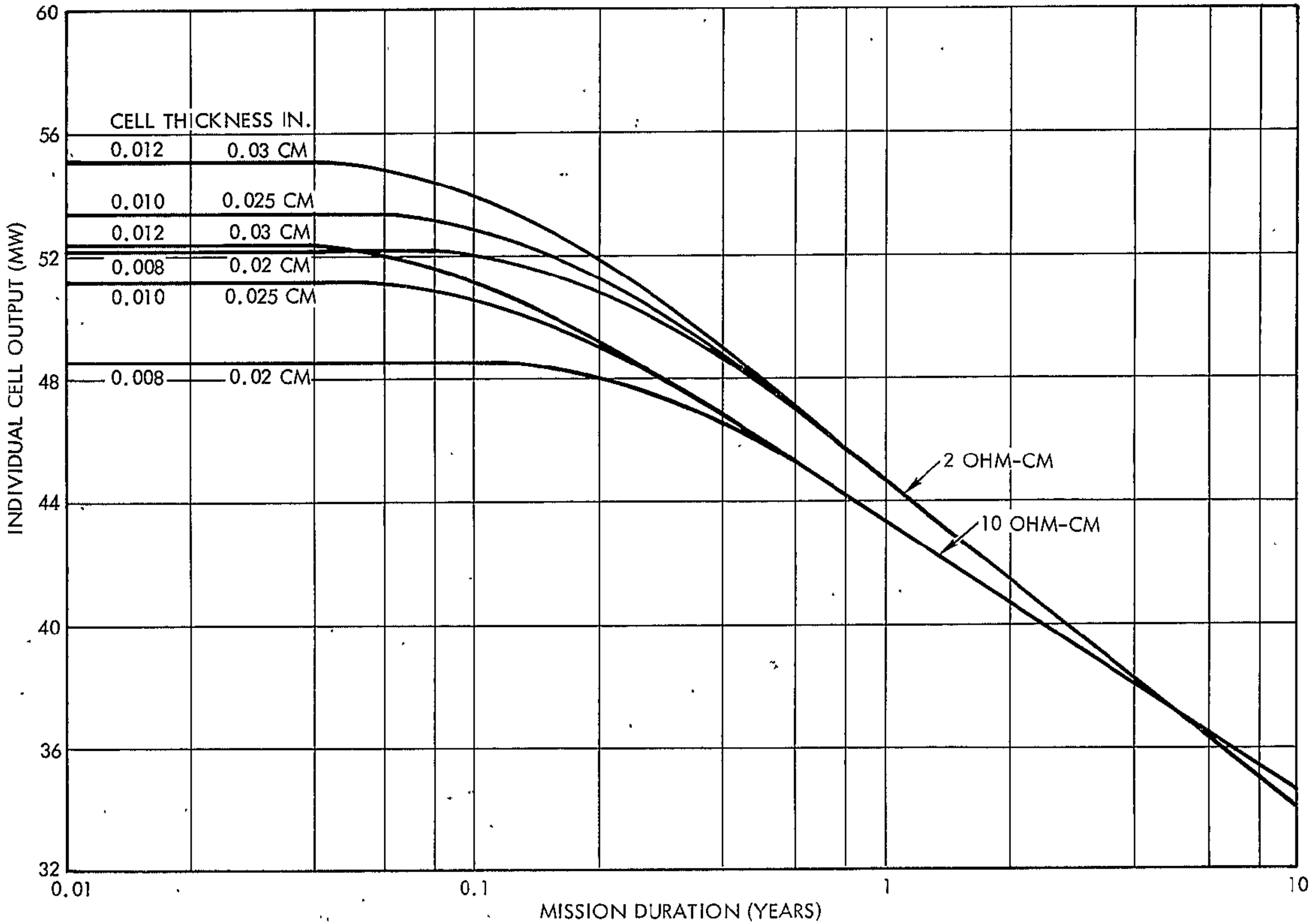


Figure 5-7. Individual Solar Cell Performance for Various Thicknesses of 2 and 10 ohm-cm Solar Cells at 28°C for Body-mounted Cells Which Are Normal to Solar Irradiation and Having 12-Mil Cover Slides.

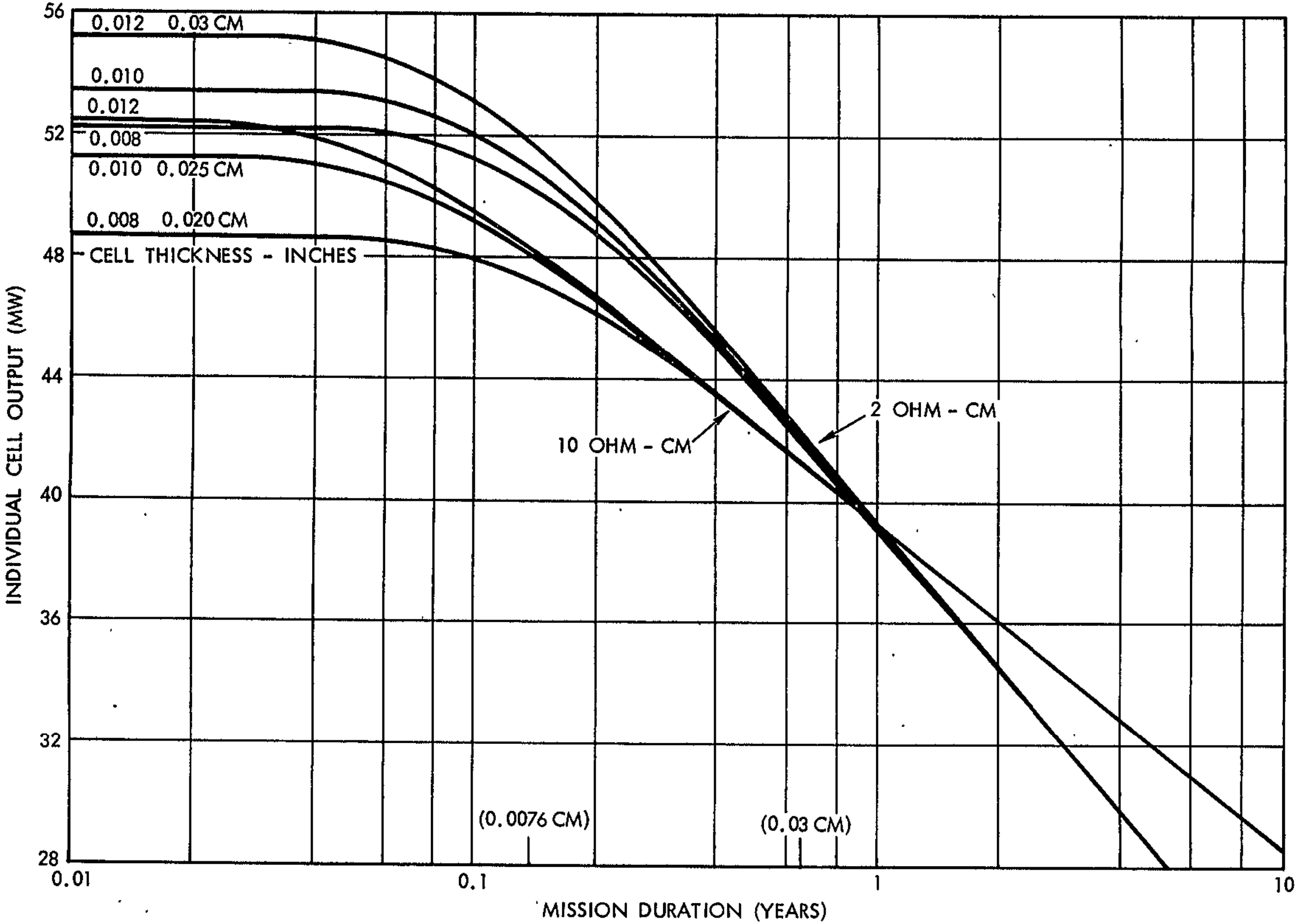


Figure 5-8. Individual Solar Cell Performance for Various Thicknesses of 2 and 10 ohm-cm Solar Cells at 28°C for Flat Panels Having Back Radiation Shielding Equivalent to 3 Mil (0.03 cm) Glass and Having 12-Mil Cover Slides

Figure 5-8 for flat panel arrays also shows how the EOM output would change with different cover slide thicknesses: -3 percent for 0.006 0.006 inch (0.015 cm) and +3 percent for 0.020 inch (0.050 cm). Back radiation protection of 0.003-inch glass equivalent has been assumed. In this case, as opposed to the body-mounted array, the 10 ohm-cm cell clearly has larger power output (by 12.5 percent) at the end of the 5-year mission. Also in this case, performance at EOM is irrespective of cell thickness.

5.1.3 Materials

In selecting the component parts of the solar array assembly for the direct broadcast television satellite, the following have been evaluated:

- Cover glass material and thickness
- Cover glass to cell adhesive
- Cell interconnect material
- Solar cell type, thickness, and base resistivity
- Solar cell to structure adhesive.
- Substrate

There are several alternate cover glass materials in use, i.e., various types of sapphire, fused silica (quartz), and microsheet. Because of its relatively low cost and stability in the space environment, quartz is selected.

The cover slides are coated with interference filters, one side with an ultraviolet reflective filter and the other side with an antireflective filter of MgF_2. The ultraviolet reflective filter is on the cell side of the cover slide, and it provides protection of the cell-to-glass adhesive.

Two basic types of filters are available; blue and blue-red. Blue-red filters can reduce the array temperature by an estimated $5^{\circ}C$, but the net result because of lower transmission efficiency is a reduction in power output of approximately 3 percent. This loss of output, together with their higher cost, makes the blue-red filters undesirable for this application. The use of blue filters is considered essential to prevent ultraviolet degradation of the adhesive used to attach the cover slides to the cells. A filter cut-off wavelength of 0.435 micron results in approximately 3 percent greater power loss than 0.410 micron cutoff filter, and the effect on the adhesive by the shift to the slightly larger cutoff wavelengths has been shown to be negligible on the basis of test results from the tetrahedral research satellite. Therefore, the filter suggested is the blue reflective filter with a cutoff wavelength of 0.410 micron.

Adhesives for bonding cover slides to solar cells are predominatly organic, high-polymeric materials. The basic polymer resins are modified by the molecular weight, degree of cross linking, and additives to improve specific properties. The principal adhesives of interest for space use are epoxies and silicones because of their superior ability to withstand ionizing radiation without structural changes or changes in the optical transmittance.

Photochemical decomposition results in adhesive darkening and increased solar absorptance. A consequence is a general increase in the operating temperature with resulting reduction in output. Degradation of optical properties can be minimized by using an adhesive with minimum photon absorption and distribution of UV energy along the polymer chain. Because silicones have this property of minimum absorption and distribution, they are preferred. Dow Corning's silicone type adhesive, XR6-3489, is suggested since laboratory tests have shown this adhesive to experience the least discoloration compared to other possible adhesives for solar arrays. Satellite experiments have shown that coloration of this clear adhesive by irradiation has not occurred for time-integrated fluxes corresponding to 3 to 5 years at the synchronous orbits.

Synchronous equatorial orbits also subject solar arrays to large temperature excursions during the mission. Temperatures range from 50°C during illuminated periods to -165°C during eclipse. Temperature cycling tests at TRW Systems have determined the optimum cell interconnect material and thickness to maximize the life of solar arrays in this orbit. The interconnection geometry is a small U-shaped part with stress relief loops. The materials considered during the evaluation program were copper, Kovar, and molybdenum. Failure was established when cracks, including microcracks, appeared in the solder near the joint.

The number of failed joints varied greatly with material, 85 percent for copper versus 7 percent for Kovar, and no failures for molybdenum after 100 cycles to $-175^{\circ}C$. A significant correlation was demonstrated between failure rate and temperature differential, and it was shown that it is important to have oxide-free surfaces. It was further demonstrated that proper interconnect plating is important and that temperature shock rate is not of great importance.

Specimens tested included those in a freely suspended state as well as those bonded to metallic substrates with silicon adhesives. The bonded specimens experienced the highest failure rates. Figure 5-9 shows that the percentage of failures after 300 thermal cycles rapidly decreases with decreased material thickness, attributing to the fact that the stress level in the 60-40 tin-lead alloy solder is greatly reduced at the low temperature range by the flexible, thinner materials. It has been determined that a stress reduction of 5 percent can reduce the failures by a factor of 5. These evaluation tests have established that Kovar interconnects of 0.001 inch (0.0025 cm) thickness are capable of surviving up to 300 thermal cycles. This material is thus suggested over molybdenum because of its solderability, cost, and its current use in several programs.

5.1.4 Cell Stack Selection

The weights assumed for substrate and other miscellaneous items for fabricating the flat panel arrays are:

	lb/ft^2	kg/m^2
Substrate (Kapton 0.002 in., 0.005 cm)	0.0160	0.078
Wire	0.0029	0.014
Solder	0.0250	0.122
Adhesives	0.0250	0.122
Diodes and Terminals	0.0276	0.135
Total	0.0965	0.471

The values used for cell and glass adhesives and interconnects are:

Cover adhesive	0.032 gm
Interconnect (Kovar 0.001 in., 0.0025 cm)	0.002 gm
Module adhesive	0.020 gm
Total	0.054 gm or 0.00012 lb/cell

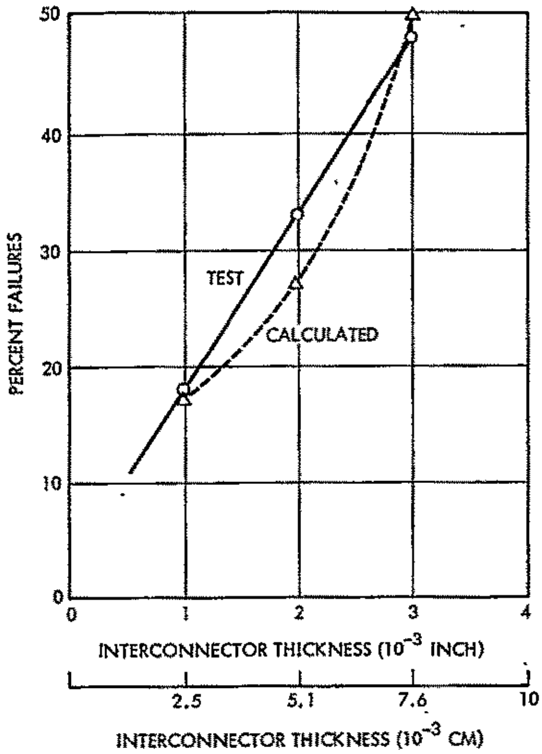


Figure 5-9. Solar Cell Joint Failure Level After 300 Thermal Cycles

Figure 5-10 shows the average weight for 2 x 2-cm zone soldered cells and cover slides, both as a function of thickness.

Table 5-4 summarizes the mass data for flat panel arrays using 2 x 2-cm silicon cells, with the thicknesses of the cell and the cover slide as independent variables. For the present mission, the dominant criterion in selecting these thicknesses is the power-to-mass ratio at the end of the 5-year spacecraft life. Figure 5-8 shows that cell performance after 5 years is independent of the cell thickness. Clearly, the lowest thickness then gives the best power-to-mass ratio. Attrition during handling and assembly of cells imposes a practical minimum. These considerations of the array power-to-mass ratio and the array manufacturability led to the recommendation of 0.010 inch (0.025 cm) cell thickness for television broadcast satellites with a life time of 5 years.

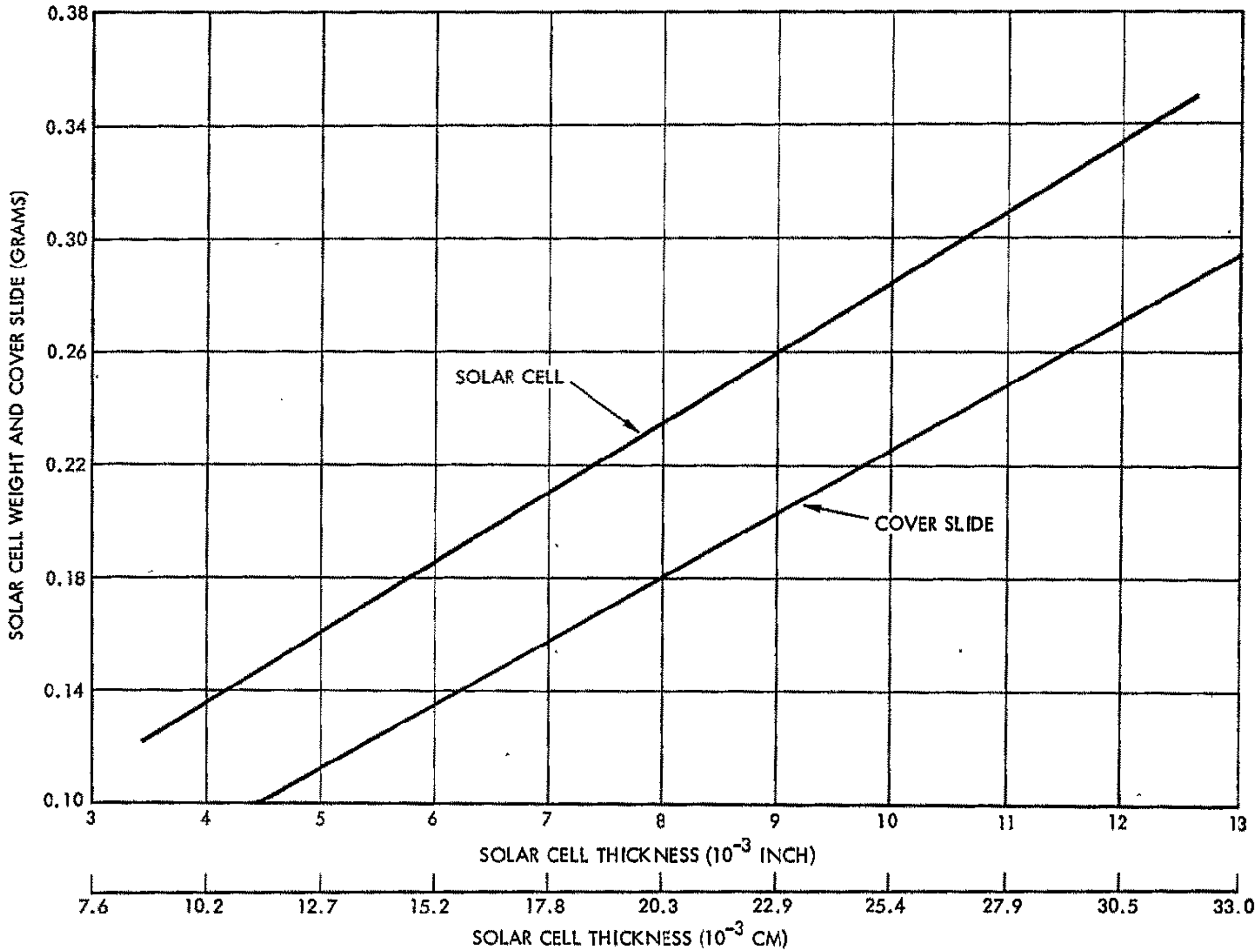


Figure 5-10. Solar Cell and Cover Slide Weight as a Function of Thickness for 2 x 2 cm Cells, Zone Soldered

Table 5-4. Mass Data on Flat Pannel Arrays
(2 x 2 cm Silicon Cells)

Component	1lb/ft^2	Milligrams/cell
Substrate and miscellaneous	0.0965	196.3
Cells	$0.018 + 0.0122t_c$	$37 + 24.75t_c$
Cover slides	$0.111t_g$	$22.5t_g$
Cell stack adhesives and interconnect	0.027	
Total	$0.142 + 0.0122t_c + 0.0111t_g$	$288.8 + 24.75t_c + 22.5t_g$

Cell packing: 223 cells/ft^2 (732 cells/m^2)

t_c = cell thickness, mils (cm)

t_g = cover slide thickness, mils (cm)

Table 5-5. Power-to-Mass and Power-to-Area Ratios for Flat Panel Arrays End of 5-Year Life
For: 10 mil (0.030 cm), N-on-P Silicon Cells
223 cells/ft^2 (2400 cells/m^2)

Cover glass thickness	mils	6	12	20
	cm	0.015	0.030	0.051
Mass/area	lb/ft^2	0.331	0.397	0.486
	kg/m2	1.615	1.936	2.37
		2 ohm-cm		
Power/cell	mw	30.25	30.95	32.22
Power/area	w/ft^2	6.75	6.90	7.18
	w/m^2	72.6	74.2	77.4
Power/mass	w/lb	20.4	17.38	14.80
	w/kg	45.0	38.3	32.6
		10 ohm-cm		
Power/cell	mw	30.34	31.93	32.22
Power/area	w/ft^2	6.77	7.12	7.18
	w/m^2	72.8	76.5	77.4
Power/mass	w/lb	20.4	17.92	14.80
	w/kg	45.1	39.6	32.6

Table 5-5 shows power-to-mass and power-to area are ratios for flat panel arrays with the recommended cell thickness of 0.010 inch (0.025 cm). These data, for 2 ohm-cm and 10 ohm-cm cells and three cover slides thicknesses, were derived from the data on cell performance after 5 years shown in Tables 5-2 and 5-3 and the mass data in Table 5-4.

The data in Table 5-5 show clearly that a cover thickness of 6 mil (0.015 cm) compared with 20 mil (0.051 cm) results in a 1.27 times larger power-to-mass ratio, despite the 1.05 times lower cell performance (or power-to-area ratio). Clearly, the saving in mass for given array area obtained by selecting thinner glass covers outweighs the increased cell degradation. In conclusion, the 6-mil (0.015 cm) cover thickness is preferred, except in cases where a 5 percent increase in area is very critical.

The effect of base resistivity on the power-to-mass and power-to-area ratios is insignificant. The 10 ohm-cm resistivity shows only a slight advantage over 2 ohm-cm for the fluence levels used in the above tradeoff. For larger fluence levels, the 10 ohm-cm cell has a definite performance advantage over the 2 ohm-cm cell.

The cell polarity N-on-P was selected earlier (Section 5.1.1) because of its superior radiation resistance, obtained without penalty in weight or area. The cell size, 2 x 2 cm was chosen because of its availability, proven performance, and cost, (Section 5.1.1).

In conclusion, the recommended cell stack for the television broadcast mission is a 10 mil (0.025 cm) thick 2 x 2 cm, 10 ohm-cm N-on-P cell with a 6 mil (0.015 cm) thick cover glass. The thickness of the cell stack, including substrate, is approximately 0.020 inch (0.050 cm) for a flat cell lay-up.

5.1.5 Array Voltage

The solar array can be designed to provide almost any voltage at any given power level. The concern centers on reliability and the power loss at a given voltage and power. Past studies on electric propulsion power systems evaluated the effect on array reliability for various voltages up to 1000 volts, including arrays protected by shunt diodes and those without shunt diodes. Since eclipses will be experienced at the synchronous orbit, shunt diodes are required. For this case, an array reliability of 0. 999999 is realized at any array operating voltage if the allowable power loss from the array is 0. 12 percent. When shunt diodes are included across each cell string, variation in operating voltage levels do not significantly affect array reliability.

If the load is compatible with the array voltage, a converter may not be required. If the load can utilize that voltage over some nonregulated range, the regulation system may be simple. However, the common load is often a composite of several voltage levels and varying degrees of regulation requirements and, thus, must be specifically designed. One possible way of relieving the power conditioning complexity is to design hybrid arrays, i.e., arrays with separate circuits for high and low voltages. Hybrid arrays can reduce the weight of the power conditioning system by as much as 20 percent. The weight of power conditioning components is, however, a fraction of the total array weight and, thus, hybrid power systems may not result in a significant sytem weight saving to warrant their use. Independent of the effect of the conditioning and control equipment the recommended voltage for arrays requiring articulation is 200 volts, maximum, limited by power transfer considerations (assuming slip ring power transfer is utilized). Above this level problems of slip ring circuit insulation become significant.

5.1.6 Deployment Schemes

The configurations of Section 7 utilize both foldout and rollout schemes for deploying the solar cell arrays. The rollout method of deployment differs from the foldout scheme only in the manner in which the array/substrate is packaged. The rollout winds the array on a drum approximately 10 inches in diameter, similar to a window shade. Cell protection during launch is provided by foam rubber between each layer.

The foldout method "zee" folds the array into a flat pack against the spacecraft body. Cell protection is provided by preloading the cell stack with honeycomb panel doors. This concept of packaging has been verified by testing at TRW.

5.2 THIN-FILM SOLAR ARRAYS

Cadmium sulfide solar cells, the most promising in the thin-film category, is expected to offer several advantages in the areas of cost, stowage efficiency, and radiation resistance. Efficiencies of 3.3 percent (AMO, 25°C) have been measured for today's cells encapsulated with 0.001 inch (0.0025-cm) thick Kapton. Mylar-encapsulated cells yield slightly higher efficiencies, but the Mylar degrades quickly in the presence of UV radiation and after some time becomes embrittled and may delaminate. Kapton, although causing initially lower cell output, does not degrade in the space environment.

Measured characteristics are corrected for time-independent degradation by the following ratios

I_{sc} -	assembly	0.970
	mismatch	0.980
	temperature cycling	0.900
	Total	0.853
V_{oc} -	assembly	0.990

Parameter	Unit	Cds Solar Cell Performance (3 x 3 cm cell)	
Temperature	°C	28	55
V_{oc}	mV	448	405
V_{op}	mV	340	275
I_{op}	mA	594	570
I_{sc}	mA	784	736
P_{op}	mW	202	157
η	%	2.55	2.05
β	mV/°C	-1.68	
fill factor		0.63	0.55

These data apply to cells with a 0.001 inch (0.0025 cm) Kapton cover, in AMO. The notations are identical to those used in Section 3. This degraded performance results in the cell quantity, array area, and array weights shown in Table 5-6. Table 5-7 lists the time-dependent degradation.

Table 5-6. Thin Film Solar Cell Mass and Area at AMO, 55°C

Cell Thickness with 0.001 inch (0.0025 cm) Kapton Cover	Efficiency AMO, 55°C	Power/Cell mW at 55°C	Cells/kW	Weight/kW (lb) (kg)				Total Array Area at 15 Cells/ft^2	Power to Area Ratio	Power to Weight Ratio
				Structure etc.	Electric Misc.	Cells	Total			
(in.)(cm)	(Percent)	(mW)	(quantity)					(ft^2) (m^2)	(w/ft^2) $\left(\frac{w}{m^2}\right)$	(w/lb) $\left(\frac{w}{kg}\right)$
0.0045 (0.0114)	2.05	157	6370	42.5 (19.3)	8.7 (3.9)	24.5 (11.1)	75.7 (34.3)	425 (39.4)	2.35 (25.3)	13.2 (29.2)
0.0045 (0.0114)	3.3	252	3970	18.1 (8.2)	4.9 (2.2)	14.0 (6.3)	37.0 (16.7)	265 (24.6)	3.78 (40.7)	27 (59.6)

Table 5-7. Time Dependent Degradation (Nominal) Factors for CdS Arrays, at AMO, 28°C

Year	0	1	3	5
Total fluence 1 Mev equivalent (e/cm^2)	0	1×10^{15}	3×10^{15}	5×10^{15}
(1) Micrometeroid damage	0	0.98	0.97	0.96
(1) Random cell failure	0	0.99	0.989	0.987
Subtotal (2)	1.00	0.970	0.960	0.946
*I_{sc} degradation due to particle radiation (mA)	784	760	753	743
*V_{oc} degradation due to particle radiation (mV)	448	448	448	448
*P degradation due to particle radiation (mW) (3)	202	196	194	191

*H. Brandhorst and R.E. Hart, "Radiation Damage to Cadmium Sulfide Solar Cells," NASA Lewis, TN-02932, May 1968.

(1) Assumed values.

(2) Degradation from effect, other than radiation

(3) Multiply by subtotal (2) to account for all types

These data indicate that for Kapton covered cells 6 percent degradation in power can be predicted at the end of a 5-year mission at fluence levels more than two times that predicted for the silicon cell trade study. (Proton radiation fluence has been assumed.) To be conservative, since extensive space environment and array assembly data is not yet available on these cells, all degradation factors and fluence levels assumed for CdS solar cells are higher than those predicted for silicon.

As with the silicon-cell array, structural weights do not increase linearly with power level, and thus the relatively low power to weight ratio predicted would increase slightly to 14.5 w/lb (32 w/kg). CdS solar cells were procured in 1966, and as shown in Figures 5-11 and 5-12, the power-to-mass ratio corresponds to that predicted.

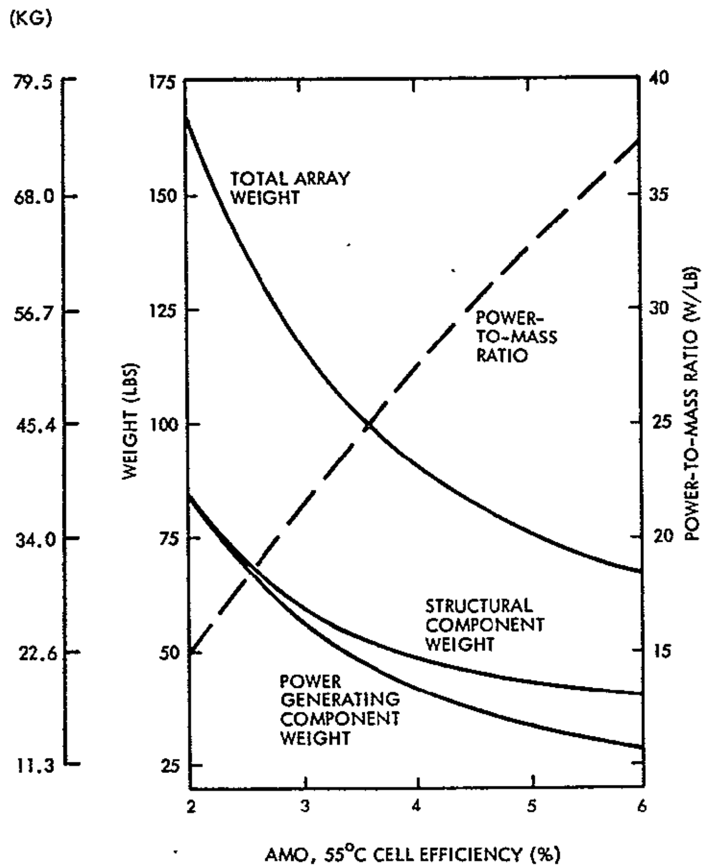


Figure 5-11. 2.5 KW Thin Film Solar Array Weight and Power-to-Mass R tio at 55°C Versus Cell Efficiency

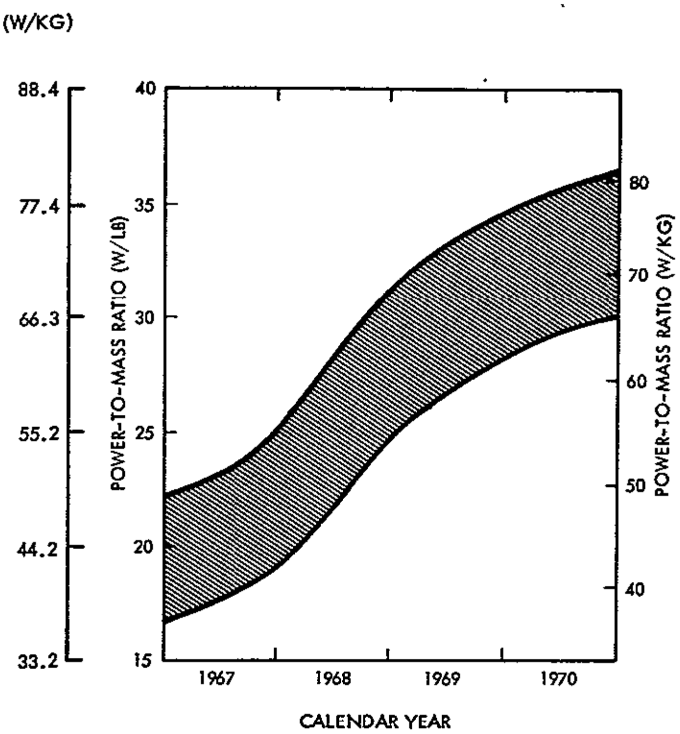


Figure 5-12. Forecast of Power-to-Mass Ratio for 2.5 kw Thin Film Array at Operating Temperature. (Upper Limit for Cells with Clear Encapsulating Material. Lower Limit for Kapton Encapsulated Cells.)

The present status of CDS solar cells can be summarized as follows:

- ADVANTAGES

  High stowage efficiency

  Low cost. Less than half that of silicon arrays (≈$100/watt). Attrition due to handling assembly and test minimized. Substrate cost eliminated.

  Flexibility. Physical flexibility permits unrestricted array and spacecraft configurations at any power level.

  Weight. Competitive with present silicon arrays for earth orbit.

  Radiation resistance. One hundred times better than silicon. Moreover, after exposure to high fluence levels, at any energy level, an array exposed to low light intensities for 1 month can regain its original output. This is attributed to the polycrystaline characteristics of the cell.

- DISADVANTAGES

  Area. Based on present measured efficiencies and degradation assumptions two to three times the area of a silicon array is required at a given power level.

  Stability. Presently sensitive to thermal cycling in vacuum.

  Availability. Only one known supplier.

- STATUS

  a) Array availability depends solely on cell development.

  b) Mechanical assembly techniques have been demonstrated.

  c) Thin film solar cells (CdS) attractive at present efficiencies if space-qualified cells can be procured.

  d) Further efforts in cell design and materials engineering are in progress.

  e) NASA Lewis Research Center is pursuing further research on thin film cells.

5.3 SOLAR ARRAY WEIGHT AND SIZE

The parametric data on array weights and size shown in Figure 5-13 and 5-14 are based on the analyses and design selection of Sections 5.1.4 and 5.2.

The arrays using the silicon cell are based on the following cell design:

0.006 in. cover glass (0.0015 cm)
10 ohm-cm resistivity
0.010 in. thick (0.025 cm)
2 x 2 cm size

The thin film arrays are based on 3x3 inch (7.64 x 7.6 cm) CdS cells with an efficiency of 3.3 percent (AMO, 55°C). The weights and sizes include estimates for the adhesives, interconnects, substrate, frames, cover glass, and other miscellaneous items required for fabricating the solar arrays.

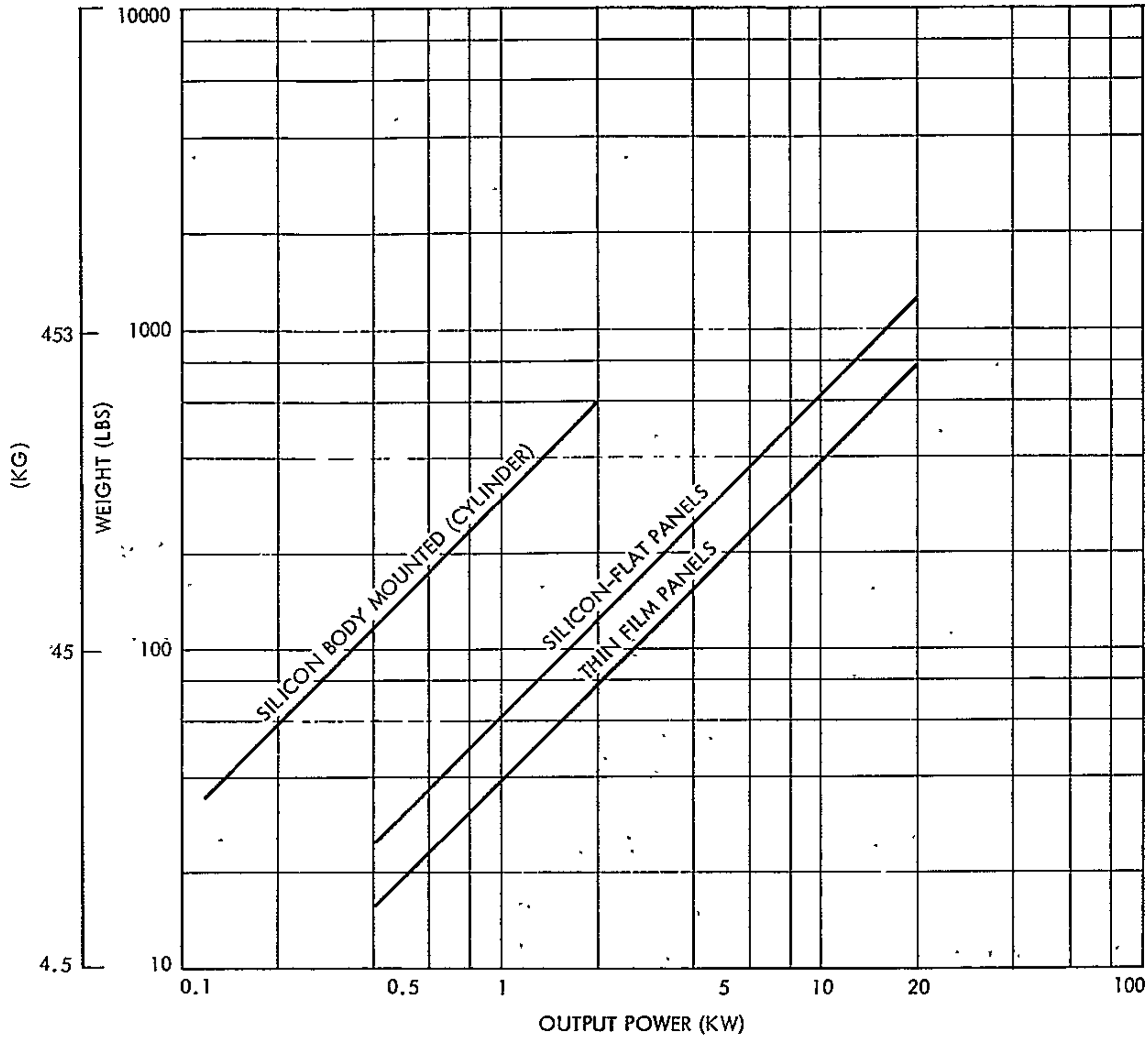


Figure 5-13. Solar Array Weight (Based on Power Demand at End of 5 Years)

5.4 ROTATING POWER TRANSFER DEVICES

The devices discussed in this section transfer prime power between the two spacecraft components while allowing rotation over unlimited angle between their components. In television broadcast satellites these devices can transfer power from the ion-oriented array to either an earth-oriented spacecraft body or to a spin-stabilized body.

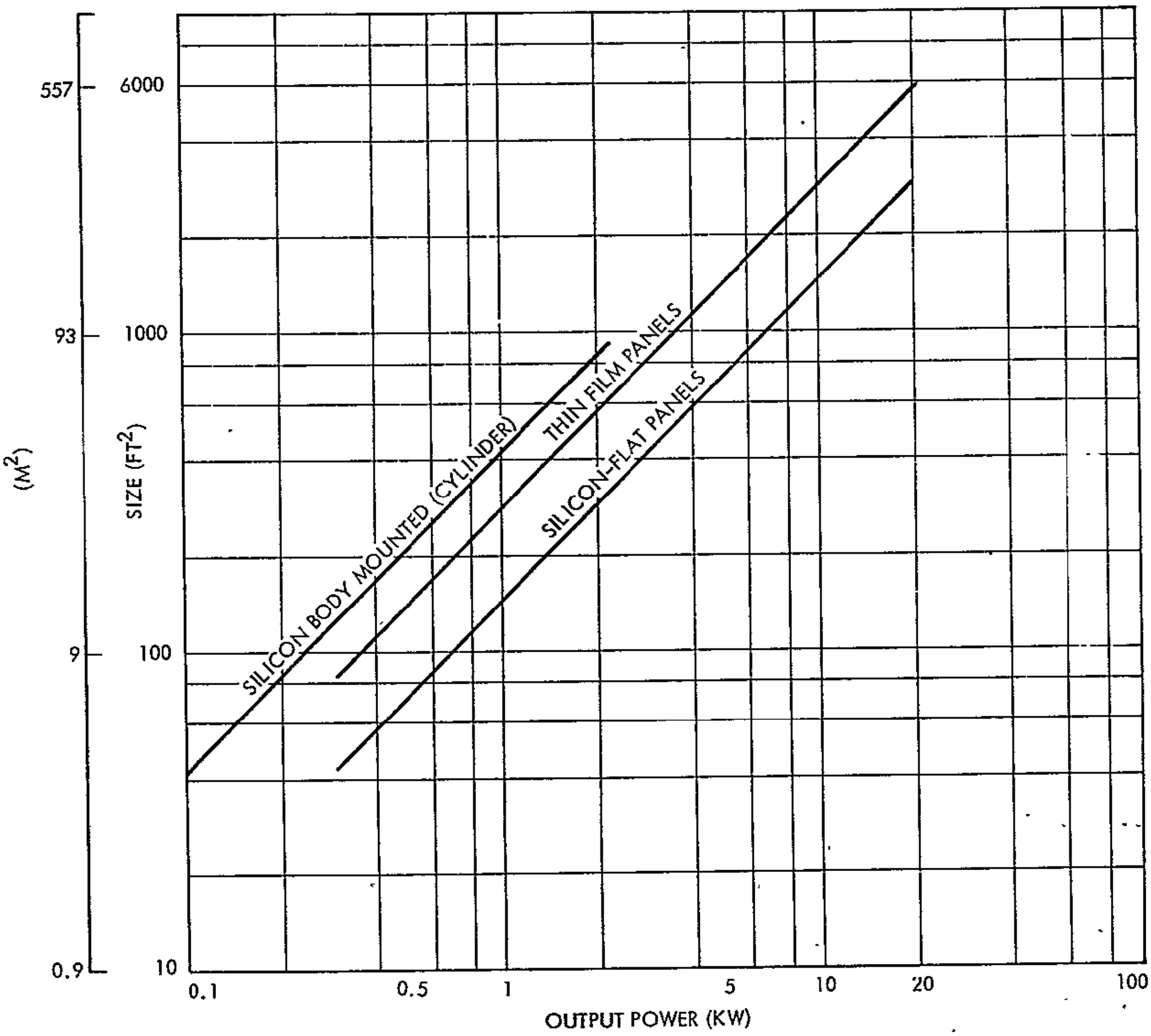


Figure 5-14. Solar Array Area (based on Power Demand at End of 5 Years)

Two types of rotary joints have been investigated; slip rings and rotary transformers. The following conditions have been assumed in this investigation:

Pressure: vacuum (10^{-6} Torr or less)

Temperature: 20 to 120°F (-7° to +40°C)

Power: 1 to 25 kw per assembly

Vibration: Launch environment (nonworking)

Life: 5 years

Speed: 0.1 to 100 rpm

5.4.1 Slip Rings

Slip rings have considerable history; assemblies have been built for high power and for vacuum environment. The combination of these two requirements is new, however, and will require special attention in the design. Experience with slip rings in space is summarized in Table 5-8, which shows that over 55 units have been space flown or laboratory tested for over 150 x 10^3 hours and 130 x 10^6 revolutions.

Table 5-8. Flight Performance and Laboratory Test Data for Slip Ring Assemblies Used for Power and Signals.

	Maximum Continuous Vacuum Exposure			
	Quantity	Hours x 10^3	Revolutions x 10^{-6}	Duration (Months)
OSO I (S16)	1	5.1	6.1	24
OSO II (S17)	1	6.5	8.0	16
OSO III	1	8.8	10.5	9
OSO IV	1	3.7	4.0	1.5
LIDOS	1	2.8	0.3	4
OSO Development	25			6.0
OSO Second Source	6	26.5	47.0	6.0
AF 191	5	0.4	0.7	0.1
LES	1		0.1	
Classified 1	1	3.0	5.0	4.0
Classified 2	1	3.0	5.0	4.0
Classified 3	1			3.0
Classified 4	4	75.0	31.0	6.0
Classified 5	3	0.2	0.3	0.1
Development	2		0.2	

Slip ring assemblies come in three basic forms: drum with vertical stacking, drum with flat rings, and concentric (pancake). The concentric has the disadvantage of higher speed on the outer rings. Flat rings have proven cumbersome with respect to debris from brush and ring wear. To provide room for this debris out of the way of the contact area, rings are designed as V grooves.

Two types of brushes are being used in low current (less than 50 amperes) applications. The button type, in which a curved cylindrical button is welded to a spring, and the wire type, in which a wire of the chosen brush material is bent to make contact with both sides of the V groove, as shown in Figure 5-15.

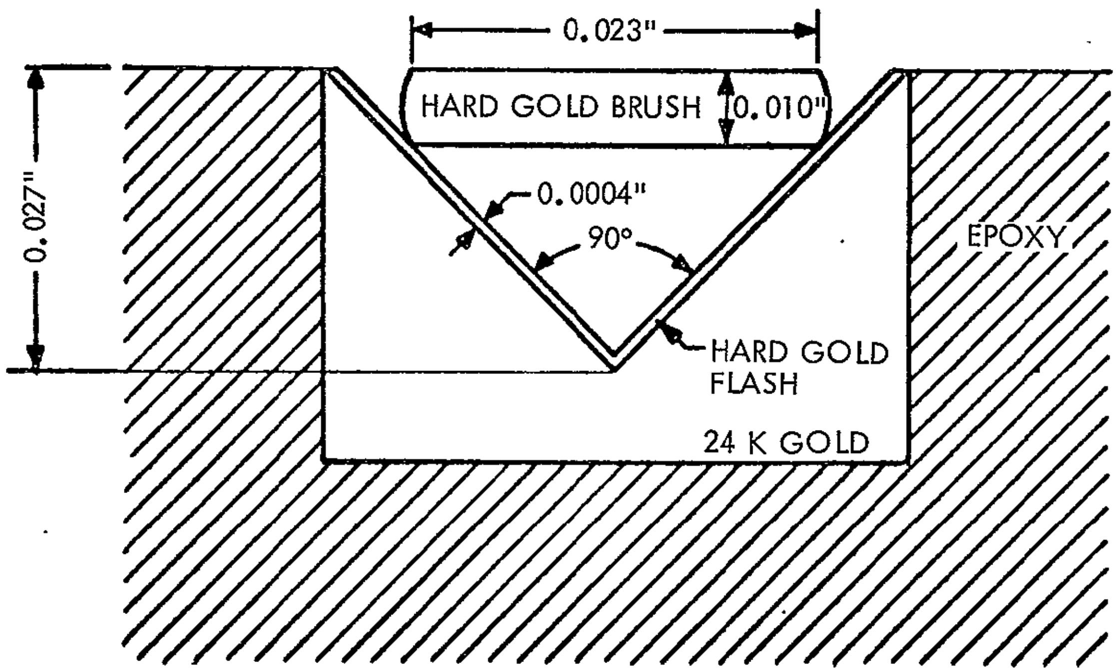


Figure 5-15. Cross Section of Poly-Scientific Brush-Ring, Type 1709

The choice of brush and ring material and type depends not only on the amount of power to be handled but also on the speed and the desired life of the assembly. In the application of interest here, the speed is one revolution every 24 hours. At this low speed, gold on gold has better wear characteristics than silver graphite brushes on coil silver rings, and both wire and button brushes are possible. Current densities up to 500 A/in^2 (78 A/cm^2) or more can be handled by both types of brushes.

All brush-ring combinations are based on either silver or gold, but usually they are combined into some alloy, either to improve the slide characteristics or to provide a dry lubrication which minimizes the possibility of vacuum welding. Aside from copper, materials that have been alloyed with silver for these purposes have a molydenum or selenium base. This dry lubrication, however, has not proven sufficient for long space applications. Ball Brothers has developed the Vac-Kote process, which reduces wear by almost an order of magnitude. The material and the components on which it is used are degassed in vacuum at elevated temperatures. Then the components are immersed in the lubricant in vacuum and pressure cycled. After some quality assurance steps, the components have a thin, tightly adhering film on all surfaces. This film evaporates at a very slow rate and additional lubricant is added from sintered nylon reservoirs. Vac-Kote is an insulator in bulk form but conducts in thin films without adding appreciably to contact resistance.

A low contact resistance is desirable to keep down losses and heat rise and to reduce noise. An industry-wide standard value is 5 milliohms per contact. Noise varies not only with contact resistance but also with speed and load and is difficult to specify for all conditions. Noise increases linearly with current up to a maximum and then decreasea again. The position of this maximum can be varied with brush force and speed. The variation in noise does not seem to be accompanied by a corresponding variation of contact resistance. This resistance (at least in a test with silver alloy materials) was a few milliohms but increased as much as 50 percent with high current in vacuum. Increased brush force can improve the resistance but at the expense of torque. At extreme pressures (more than 50 gram) wear would also be affected.

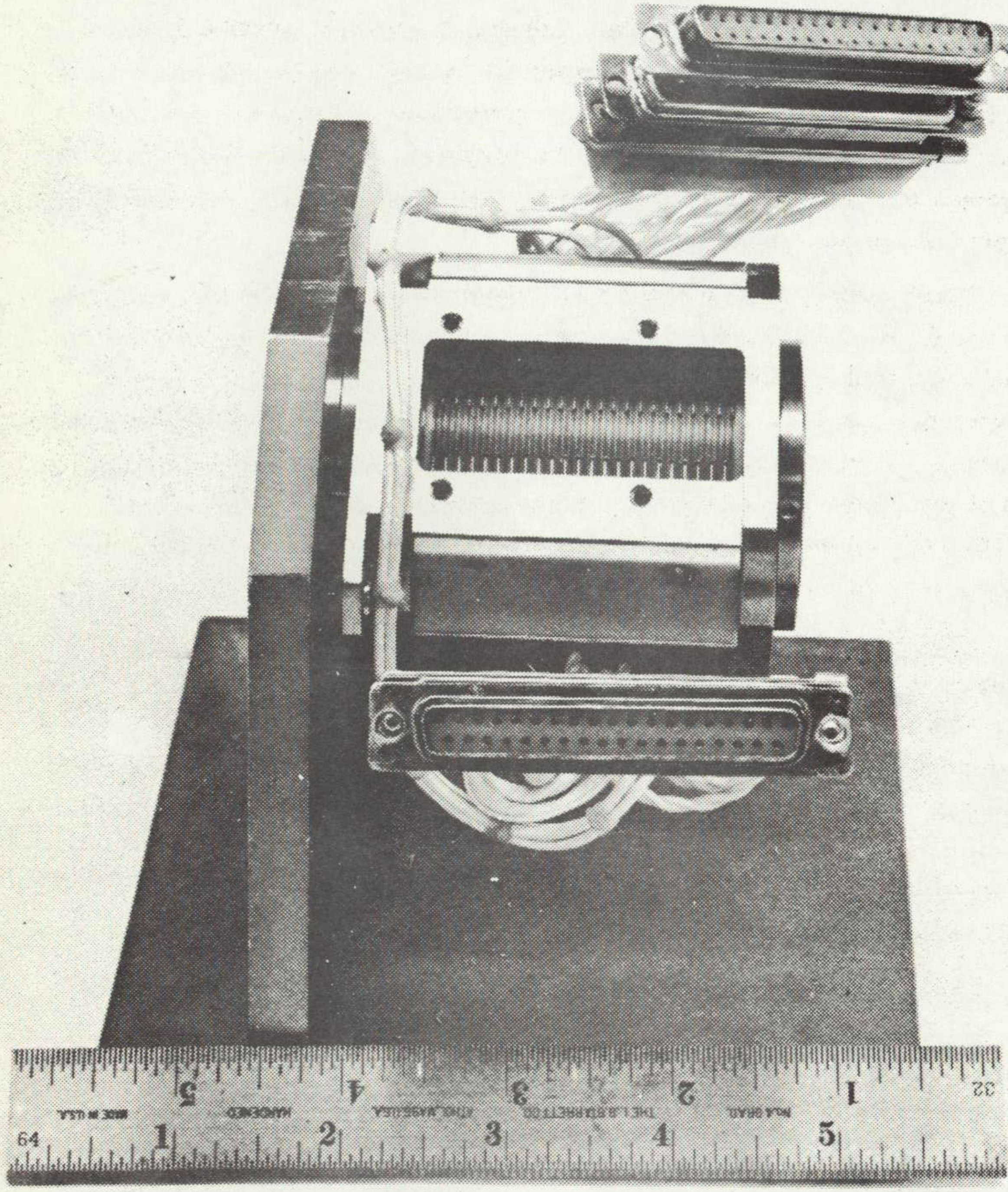
At this early stage of the TV broadcast satellite design, the choice between current and voltage to transfer up to 20 kw across rotary joint is still open. While present arrays generally work in the 20 to 50 V range, it seems desirable to raise this value to reduce the current across the contacts. A value of 200 V seems reasonable. It will require better and longer creepage control paths and strict material control to avoid arcing from outgassing. The current, in this case up to 100 amperes, can be split into several ring-brush assemblies, so that a single contact is not required to carry more than 10 amperes. For reliability over the required long life, parallel contacts can be used in such a way that no single failure can cause breakdown.

Preliminary design details have been discussed with two prospective vendors. Ball Brothers suggests as a basis a unit it is building for TRW solar array drive, shown in Figure 5-16. This unit contains 20 power rings rated at 3 amperes, so that 60 A could be transferred without redundancy. It also contains 26 signal rings, some of which could be traded for power redundancy or longer creepage paths. The overall dimensions are about 3-1/2 inch length x 3 inch diameter, the weight under 2 pounds.

The Poly-Scientific Division of Litton suggest silver-copper-niobium diselenide-graphite brushes of increased size on silver rings for a 10 kw unit. The 200 V working voltage causes some increase in length and the 50 ampere current is to be handled by 10 rings carrying 5 amperes each. Including redundancy for a 10-year life at 30 to 60 RPM, Litton estimates the dimensions at 15 inches long by 3 inches diameter (38 x 7.6 cm) and the weight as 5 pounds (2.3 kg). Starting torque is about 16 in-oz, (0.0113 M-Newton).

The tradeoffs on the slip rings are as follows:

Advantages	Disadvantages
Simple and well proven	Debris (protect bearings)
Inexpensive	Friction (may increase in time especially on bidirectional rotation)
Simple installation	Selected material (many proprietrary)
Light weight	Characteristics change with wear
Direct DC/DC transfer	Precision assembly and mounting, and precision adjustment of brush pressure
Easy redundancy	
Low crosstalk with signal channels	
Low noise	



H68-47

Figure 5-16. Solar Array Drive Slip Ring Assembly

A tentative slip ring specification for a 10 kw unit would be as follows:

Environment:	
Temperature:	20^{o} to 120^{o}F (-7^{o}C to $+49^{o}$C)
Vacuum:	10^{-5} to 10^{-10} Torr
Vibration:	Boost environment, nonworking
Voltage:	200 vdc
Current:	50 adc
Current/ring:	10A or less
Speed:	2 configurations: ● 60 RPM ● 0.1 RPM (bidirectional)
Noise:	● 100 mV RMS or less at design load and 60 RPM ● 20 mV RMS or less at design load and 0.1 RPM
Insulation resistance:	1000 Megohms, 50 vdc
Dielectric strength:	1000 volt RMS, 60 Hz, 1 minute
Dynamic resistance:	5 milliohms maximum for power circuits at 0.1 ampere and 0.1 RPM
Losses:	Commensurate with allowable temperature rise
Crosstalk:	60 db down for adjacent signal rings at 1 Hz to 100 kHz
Redundancy:	Single component failure (ring, brush, lead wire) may not cause catastrophical failure.
Life:	10 years at design speed
Size:	120 cubic inches maximum (0.002 m^3)
Weight:	5 pounds maximum (2.3 kg)
Starting torque:	20 in-oz max. (0.14 M-Newton)

5.4.2 Rotary Transformers

The rotary transformer couples alternating current from a stator through an air gap to a rotating secondary winding. Since it is an ac device, it also needs a chopper and a rectifier/filter for the required dc/dc conversion (Figure 5-17). Rotary transformers have been built for power transfer up to about 100 watts, but most existing models are used for signal transfer at very low power levels.

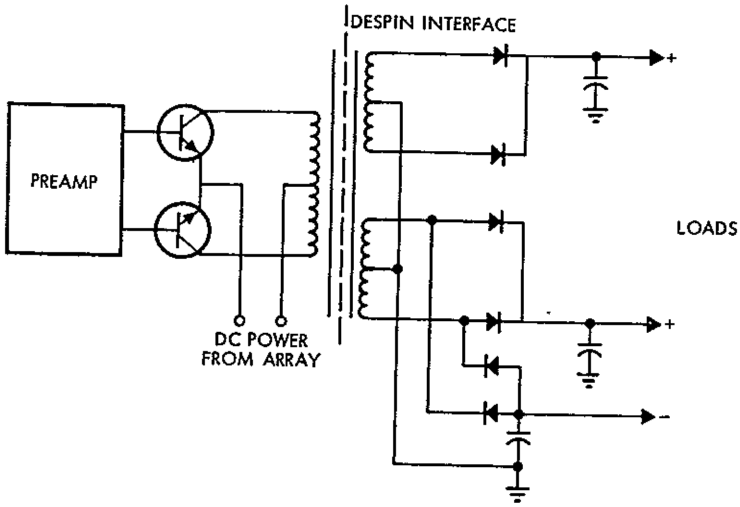


Figure 5-17. Rotary Transformer

Efficiencies of 98 percent have been reached in power transformers, but the temperature and vibration environment on a spacecraft make 95 percent more likely. The 5 percent losses pose a considerable heating problem in high power applications. Further losses must be accepted in the associated nonrotating circuitry, so that a total conversion efficiency of about 90 percent may be expected.

Several other drawbacks become apparent:

- If a low conversion frequency is used, size and weight go up.
- If a high conversion frequency is used, a significant interference problem will occur, aggravated by the necessarily large air gap.
- Eddy current drag will influence a despin system.
- The many required insulating materials will pose a severe outgassing problem, especially when high voltages are used.
- If power and signal channels are combined, a serious cross-talk problem will arise.

Estimates of size and weight are vague because a unit at high power rating has not been built. Based on present 100 w transformers, the following is estimated for a 1 kw unit.

Size: 60 cubic inches for a transformer (0.001 in^3)

100 cubic inches for associated circuitry (0.0016 in^3)

Weight: 4 pounds (1.8 kg) for transformer and 3 pounds (1.35 kg) for the associated circuitry.

The following table summarizes rotary transformer tradeoffs:

Advantages	Disadvantages
Unlimited life (bearing life)	High cost
No debris	Precision assembly and mounting
No arcing or brush noise	Additional electronics
Low running torque	Interference at switching frequency and its harmonics
No lubrication required	Heavy

5.4.3 Recommendations

The required power levels and life, slip rings have decided advantages over rotary transformers, for the forseeable future. Slip rings offer the following reliability advantages over the transformer:

- Redundancy can be built into a slip ring assembly by adding a few channels.
- While the transformer, out of economic necessity, must transfer the total power, each slip ring/brush assembly need transfer only part of it.

To make full use of a slip ring assembly, some system design considerations should be applied as follows:

- The system must either be able to live with some slip ring noise (<200 mv) or filters must be added. The noise can be measured on ground and should not increase in space; possibly there can be a reduction as the assembly runs itself in.
- Especially if high voltages are used (>100 V), turn-on should take possible outgassing problems into account.
- In spite of the added complications, it may be advantageous to consider a spare set of brushes that could replace the original brushes on ground command. This exchange should be accompanied by a purge of accumulated debris. This requires development.

5.5 BATTERIES

Three battery types are available for spacecraft: nickel-cadmium, silver-cadmium, and silver-zinc. Only the nickel-cadmium system offers a long enough life for a 5-year satellite.

Battery System	Cycles Obtainable to 50 percent DOD	Recommended Useful Life
Silver-zinc	50	1 to 2 years
Silver-cadmium	250	2 to 3 years
Nickel-cadmium	500	5 to 10 years

In addition, the nickel-cadmium system is the only one offering reliably sealed individual cells and rugged electrode construction. Both silver type cells have relatively fragile electrodes, which also react with the interplate separator material.

The following data on individual NiCd cell size, weight, and estimated unit cost is based on present procurements.

Nameplate Rating	Dimensions (inches) LXWXH (top of terminal)	Weight (Pounds)	(kg)	Cost ($)
6 A.H.	2.12 x 0.83 x 3.64 5.39 2.11 9.25 in.	0.62	0.28	139
9	2.97 x 0.880 x 3.70 7.54 2.24 9.40 in.	0.87	0.39	145
12	2.97 0.880 x 4.61 7.54 2.24 11.70	1.21	0.55	170
15	2.97 x 0.903 x 5.03 7.54 2.29 12.70 in.	1.45	0.66	250
20	2.97 x 0.880 x 6.58 7.54 2.24 16.72 in.	1.90	0.86	275
50	4.94 x 1.35 x 6.14 12.53 3.43 15.60 in	4.30	1.95	special order
100		8.60	3.90	special order

5.5.1 Effect of System Voltage

As system voltage increases, the number of cells in series must be increased. The individual cell voltage is nominally 1.20 volts, while 1.5 volts of charge voltage must be supplied for each cell.

To attain 5-year life individual cell properties in a series, string must be carefully matched to avoid failures due to capacity and voltage divergence. As the number of cells in series increases, the battery reliability decreases exponentially. Through the use of electronic individual cell protection, it is possible to improve reliability. Another major problem inherent in high voltage systems is the packaging inefficiency associated with a large number of small cells. The ratio of active material to hardware (case, terminals, battery hardware) is high for small cells. Considerable work on weight-reliability tradeoffs was done under the LES-7 Power Systems Study (MESAC).

From the standpoint of reliability, the multiple battery concept with up-down converters between each series battery string offers an excellent approach. However, the added complexity, weight, and cost must also be considered.

5.5.2 Degradation with Time

A general value cannot be placed upon degradation with time because of the many influencing factors. The charge control method, temperature extremes, amount of reconditioning, depth of discharge, and operating rates will all influence the rate of degradation. In general, it may be said that over a 5-year period battery degradation will not affect performance if temperature extremes are held to $50^{\circ}F$ to $95^{\circ}F$ ($10^{\circ}C$ to $35^{\circ}C$) operating, periodic reconditioning is carried out, depth of discharge does not exceed 50 percent, and charge control is carefully integrated into the spacecraft design.

5.5.3 Charge Control Methods

Methods of charge control available for consideration in a satellite-type application are listed below:

a) Constant current charging at a continuously acceptable rate (no voltage control used).

b) Modified constant voltage charging, in which the battery is charged at the maximum rate compatible with the available current from the power source until it reaches a predetermined voltage and, thereafter, is charged at constant voltage. The limiting voltage may be a function of battery temperature.

c) Voltage-actuated switch-down methods in which the battery is charged at relatively high currents until its terminal voltage reaches a predetermined level, after which it is switched down to trickle charge in one or more steps. The preset voltage level may be temperature-compensated.

d) Measurement of the coulombic input and output of the battery, and restoration of the withdrawn charge, plus an additional amount to compensate for inefficiency. Either electronic ampere-hour meters or electrochemical coulometers (such as the cadmium-cadmium device) may be used.

e) Measurement of internal oxygen pressure generated by the overcharge reaction. This may be implemented either by pressure sensors or by auxiliary electrodes.

f) Measurement or control on an individual cell basis. This includes cell voltage sensing for current switch-down and cell bypass techniques.

The relative merits of the various charge control schemes vary with the application and depend, to a large extent, upon the level and range of temperature of the battery in the charge-discharge cycling mode. Each is discussed below.

- Constant Current Charging

  Tests reported by Kipp and NAD Crane show that for 24-hour synchronous orbits, a minimum of 200 percent recharge power is required at 75°F to 85°F, (24°C to 29°C) using constant current, to keep end-of-discharge voltage above 1.1 v per cell at 50 to 60 percent depth of discharge. For the 22-plus-hour charge period between eclipses, this requires at least a C/20 charge rate. At temperatures as low as 30°F (-1°C) this rate causes high cell voltage and pressure on over-charge.

  At temperatures of 90°F to 100°F (32°C to 38°C), the efficiency at this charge rate is too low to permit complete recharge. Thus, this method is effective only if the temperature can be maintained in a narrow band centered about 65°F (18°C).

- <u>Modified Constant Potential Charging</u>

  Without temperature compensation, modified constant potential charging (electronically implemented) works well at low temperatures, restoring charge efficiently and protecting against overpressure. At the end of charge, or at high temperature, the battery tends to enter thermal runaway. This condition may be controlled by switching to trickle charge at a predetermined temperature.

  Electronic compensation of the voltage limit for battery temperature can protect against thermal runaway effectively, at a modest reduction in the state-of-charge achievable at high temperatures. This has the effect of narrowing the operating temperature range of the battery. Introduction of temperature compensation requires a separate control element for each battery if two or more are used in parallel to prevent thermal instability and to assure effective recharge of all batteries.

- <u>Voltage Actuated Switchdown Methods</u>

  Voltage switchdown to trickle charge has been used effectively by TRW on the Intelsat III program and two classified Air Force Programs. The switchdown actuation depends on the rise in end-of-charge voltage observed in nickel-cadmium cells. Because the charge voltage characteristic is temperature dependent, the voltage limit must be temperature compensated for operating-temperature ranges in excess of 30°F (-1°C). Temperature compensation of the voltage limit has been applied to the Intelsat III application with an operating temperature range of 40°F to 80°F (4°C to 29°C). Above 85°F (29°C) the rise in end-of-charge voltage becomes less sharp and tolerances involved in voltage sensors make accurate switching less dependable. For this reason, a thermal switch is provided on Intelsat III as a backup to the voltage limit switch. For other synchronous orbit missions studied by TRW, the temperature of the battery normally varies during a 24-hour eclipse orbit period with the highest temperature occurring during discharge and the lowest temperature occurring during high-rate recharge. For this type temperature profile with a 100°F (30°C) peak occurring during discharge, it is believed that the voltage switchdown method will be appropriate for 20 amp-hr batteries in a synchronous orbit satellite. For batteries employing larger cells, the greater difference between cell skin temperature and cell internal temperature may require adoption of a different charge technique.

- Coulometric Limiting of Charge

At low internal cell temperatures, where charging efficiency is high, either the electronic or electromechanical ampere-hour meter can work effectively as a charge controller. At temperatures above 70°F (21°C), however, the charge efficiency of the positive electrode of the nickel-cadmium cell becomes quite sensitive to temperature and charge rate and, thus, an uncompensated coulometer ceases to be an accurate representation of the cell behavior. Coulometric charge control has been shown by tests at the NASA Goddard Space Flight Center to be adequate when battery temperature, charge rate, and charge-discharge cycle are all held constant. No tests have been run over the range of temperatures and depths of discharge to be encountered in a synchronous orbit. Although some data on charge efficiency versus charge rate and temperature is available, a coulometer compensated for these characteristics would be unduly complex and appears to offer no net advantage over a properly compensated voltage limit.

- Measurement of Internal Oxygen Pressure

Although pressure sensors have been used for limit switches in nickel-cadmium cells, little has been done with electrical or electromechanical pressure sensors for charge control because total internal pressure can be misleading due to the possibility of residual hydrogen or nitrogen pressure. The auxiliary electrode, which is an electrochemical oxygen pressure sensor, has been extensively investigated and has been determined to be effective in signaling the acquisition of full charge over a fairly wide temperature range while protecting the battery against overtemperature and overpressure. The electrode delivers a signal which preferably should be compensated for battery temperature. For operation over a wide temperature range, service-life data are unavailable for 5 years, but there appears to be no obvious failure mechanisms that would prevent extended life.

The auxiliary electrode may deliver a false full charge signal for a short period immediately after discharge, temporarily preventing battery charging. In a 24-hour orbit application, this is not likely to be a major disadvantage. The effectiveness of this device at the relatively low charge rates that may be considered for 24-hour cycles has not been adequately demonstrated. This approach is especially attractive for batteries using large ampere-hour cells.

- Control by Individual Cell Response

  Voltage limiting methods may be implemented by sensing the potential at each cell and controlling the battery current on the basis of a voting gate output. This has the advantage of controlling the battery charge according to the requirements of the few lowest capacity cells at the cost of considerable increase in electronic complexity.

  Alternative and electronically simple devices for implementing cell level charge control are the stabistor and the amp-gate diode. Both these devices have the characteristics of a crude shunt voltage limiter. The stabistor is uncontrolled in temperature; the amp-gate diode is mounted on a heat sink designed to allow the diode to enter thermal runaway when current flows through it, thus using the negative temperature coefficient of voltage of the diode to sharpen the regulation curve. Both the stabistor and the amp-gate diode have the disadvantage of conducting appreciably at high-cell discharge voltage and during the middle stages of charge. The energy lost and heat generated in this bypass process is significant for spacecraft application. The stabistor's limiting characteristic is inadequate for protection of a low temperature cell against high pressure behavior. The amp-gate diode's characteristic approaches the desired form more closely; however, the design complications resulting from the three-way interface between battery, diode heat sink, and thermal control subsystem make use of this method unattractive.

  Transistorized circuits may be used to provide a better characteristic at the expense of increased complexity.

5.5.4 Battery Sizing

The battery recommended for use on the television broadcast satellite is a nickel-cadmium battery. Since the battery rating cannot be determined until one of the candidate satellite configurations is selected and loads are defined, the following parametric data is provided to estimate battery size as an aid in evaluating candidate satellite configurations.

Figure 5-18 estimates required battery capacity as a function of connected load during eclipse. Figure 5-19 makes no provision for battery redundancy and if 100 percent redundancy were required the determined capacity would have to be doubled.

Figure 5-19 estimates the additional load on the array during sunlight to recharge the batteries as a function of the required battery capacity.

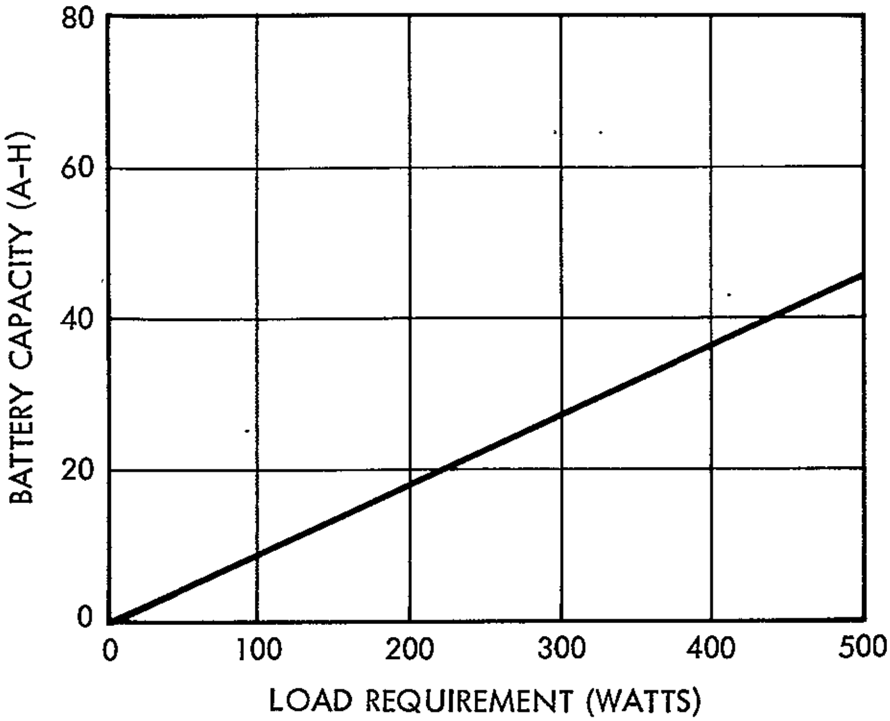


Figure 5-18. Required Battery Capacity 24-Hour Synchronous Orbit (No Redundancy - 80 Percent of Discharge)

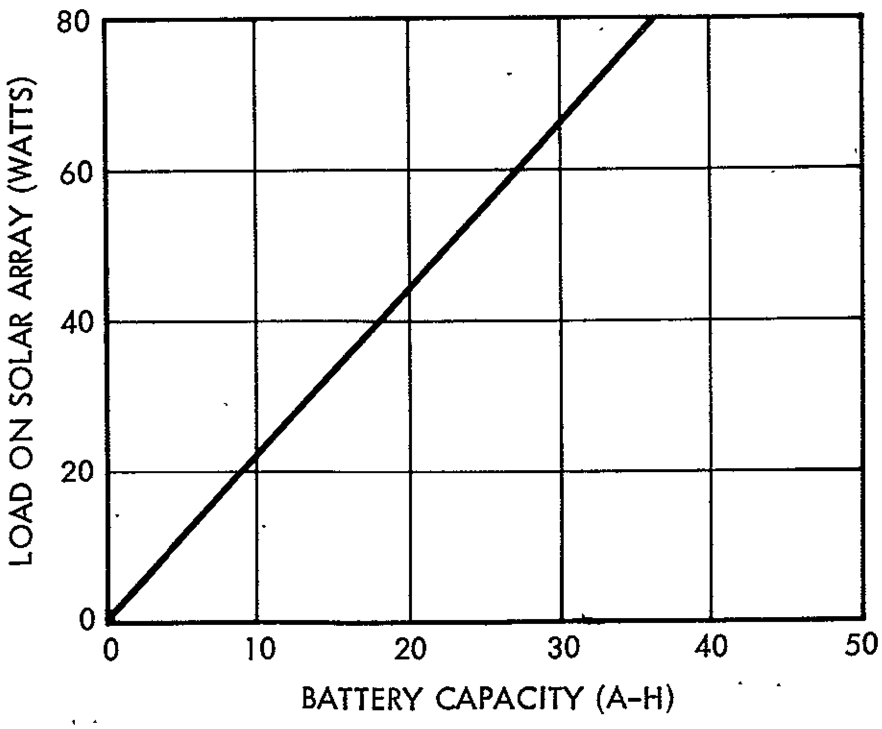


Figure 5-19. Average Power Required from Solar Array to Charge Batteries

Figure 5-20 depicts battery weight and volume as a function of battery capacity for 22-cell nickel-cadium batteries.

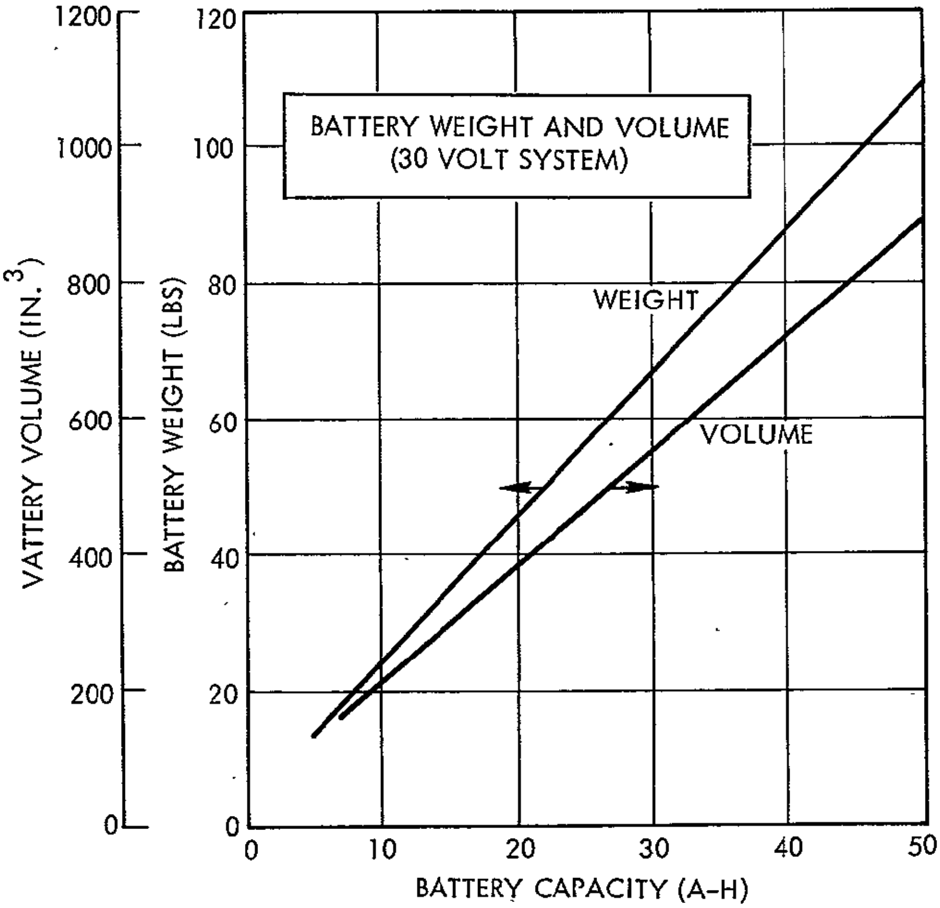


Figure 5-20. Battery Weight and Volume (30-Volt System)

5.6 ELECTRICAL DISTRIBUTION EQUIPMENT

An electrical distribution system for a spacecraft consists of the following two categories of equipment:

a) A primary distribution system consisting of all cables, connectors, relays, and associated distribution equipment between the primary power source (solar array) and the input to the conditioning and/or utilization equipment.

b) A secondary distribution system consisting of all interconnecting wiring, connectors, relays, fuses, etc. between the batteries, conditioning equipment, and loads.

The distribution equipment can represent a substantial percentage of the total power system weight and the spacecraft weight. As an example, the OGO satellite power system (approximately 300-watt load) has 110 pounds of wiring harnesses. The weight of the required distribution equipment must, therefore, be considered in tradeoff analyses of power system configurations. It is difficult to make an accurate weight estimate in the early evaluation stages of spacecraft and power system designs.

The factors affecting distribution weight are:

- Geometry of the spacecraft
- Equipment layout within the spacecraft
- Quantity and type of load and conditioning equipment
- Allowable power loss and/or voltage drops
- Voltage levels
- Power types and total power requirements
- Shielding requirements
- Protection schemes

In general, wire is the major weight component of the distribution system and can be reduced by increasing voltage level. The primary distribution system normally utilizes one distribution voltage that could be selected to minimize overall power system weight.

The secondary distribution system harnesses are normally designed on the bases of selecting wire sizes to limit voltage drop between connection points to a maximum of 0.25 volts. Utilizing this limitation, a figure of 12 percent of the weight of the sum of all interconnected black boxes (control, conversion, and conditioning equipment) has been found to be a fairly good first approximation of the weight of the secondary distribution system.

The primary power distribution system weight will consist mainly of cabling. As stated previously, the cable weight will be greatly affected by the distribution voltage and will also vary as a function of line length, line resistance, and total power transmitted. The line resistance is a function of cross section, temperature, and length.

Consider a cable consisting of No. 20 AWG stranded copper wires connected in parallel. This wire has a resistance of 10 ohms per 1000 foot at a temperature of 25°C and a weight including insulation of 4.5 pounds per 1000 foot.

For any number of AWG 20 wires connected in parallel, the total cable weight including the return cable for a cable length (one-way) of L is

$$W_c = 18 \times 10^{-5} \frac{L}{R_1} \text{ pound}$$

where R_1 is the cable resistance (including return) per foot of one-way length. The differential array weight for covering the cable loss is

$$W_a = 0.05\, I^2 R_1 L \text{ pound}$$

The sum $W_c + W_a$ has a minimum for

$$R_1 = \frac{6 \times 10^{-2}}{I}$$

or

$$\Delta V_1 = 0.06 \text{ volt/ft}$$

where ΔV_1 is the voltage drop per foot of (one-way) length. The cable weight is then

$$W_c = 3 \times 10^{-3}\, I\, L \text{ pound}$$

The preceding analysis is based on a conductor temperature of 25°C. The cable weights, power loss, and voltage drops will be different for any other temperature. Figure 5-21 gives a correction factor which can be used to modify these parameters if the conductor is at a temperature of other than 25°C.

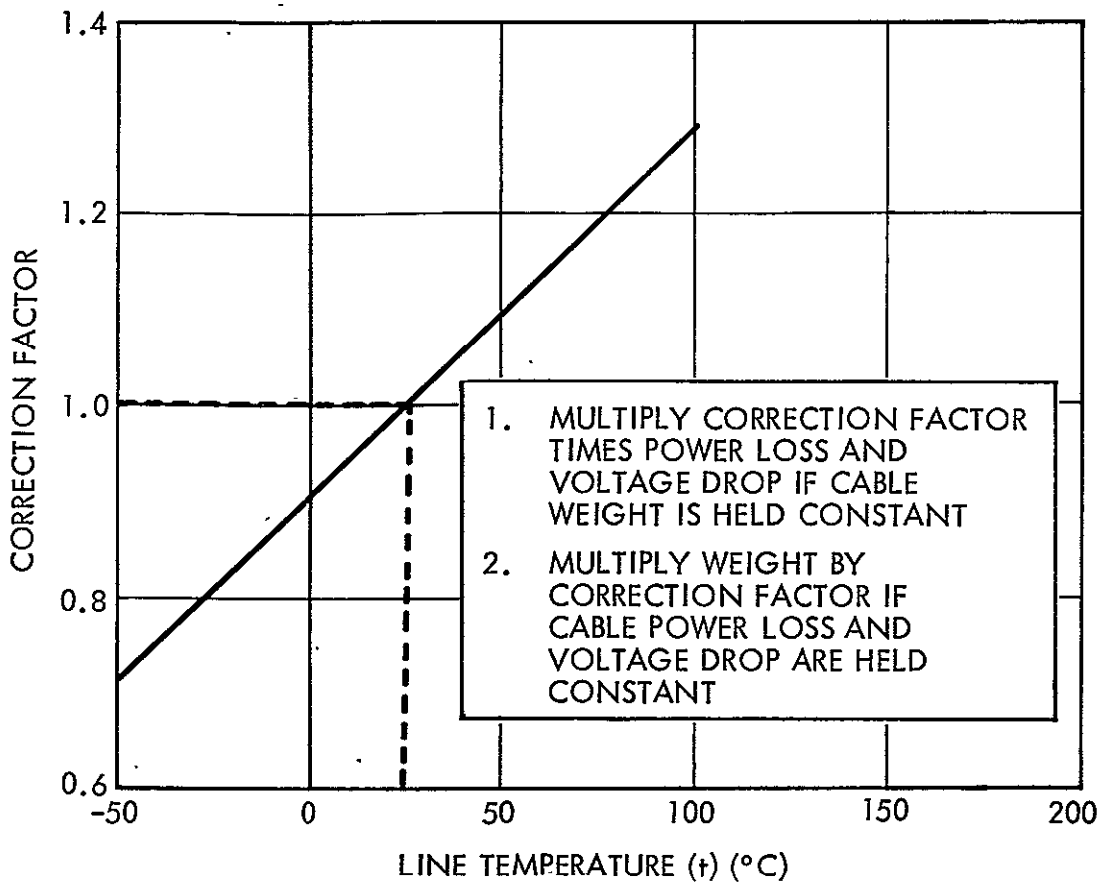


Figure 5-21. Cable Correction Factor for Variable Line Temperature

Where the main solar array power bus is unregulated and/or the voltage requirements of the load differ greatly from each other or the solar array output, power conditioning is necessary. The functions can be incorporated in converters or inverters which may be utilized separately or combined for reliability.

Pulsewidth modulated (PWM) regulator-converters are very appropriate for the general requirements for power conditioning. The theory and operation of these regulators is well known and have been described in previous studies conducted for NASA (References 5-1 and 5-2). In general, a PWM regulator converter consists of an input filter, a pulsewidth power modulator, a transformer, a rectifier assembly, and an output filter. A number of converters may be arranged in a parallel input, series output configuration where very high output power and voltage is required. Characteristics are given parametrically for regulator-converters versus load power as a function of input voltage (Figures 5-23 and 5-24). Where redundant arrangements are used the weight will be higher and the efficiency lower. This is the case for the data noted in Figure 5-25 for the housekeeping loads.

5.7 POWER SUBSYSTEM SIZING

5.7.1 Subsystem Configuration

The recommended configuration is given in Figure 5-22. As shown, system loads have been separated into three categories: RF power amplifier No. 1, RF power amplifier No. 2, and houskeeping loads.

The parametric data utilized for the power system components are given in Figures 5-23 through 5-29. Figure 5-23 plots weight versus output load for a regulated converter for an RF power amplifier. Figure 5-24 shows the corresponding volume and power loss. The power amplifier will require several different voltage levels. The collector supply will represent more than 90 percent of the total power requirement. The estimates are based on supply voltage levels up to 20 kv. The power level to be used in Figures 5-23 and 5-25 is the maximum average of the total power consumed by the RF power amplifier. Weight and efficiency estimates are based on parametric data provided under contract NAS 7-546, "Analysis of Aerospace Power Conditioning Component Limitations." The regulator converter has been considered to use pulse-width modulation. Packaging and signal circuits have been considered to represent between 30 and 40 percent of the total weight, with the lower value applicable to ratings above 10 kw.

Figure 5-25 gives weight, volume, and losses as a function of load for the power conditioning equipment associated with the housekeeping loads. For these estimates, the housekeeping loads are considered to be 60 percent dc power, 20 percent single phase ac power, and 20 percent three-phase ac power.

Figure 5-26 presents estimates for the weight, volume, and average required charge power for batteries and associated battery charge control as a function of battery load for a nominal 30-volt system. The weight and volume of the battery control are taken as the maximums of the various types of battery control (see Section 8.3).

Figure 5-27 estimates the weight and power loss for the power cables (from output of array to input of power conditioning equipment) as a function of load power for various distribution voltages.

The data apply to cables of optimum size. The weight is the total of positive and negative cable per 100 feet (30.5 m) one-way length. The cable volume is approximately 4 cubic inches per pound (0.145 m^3/kg).

Figure 5-28 gives the weight and volume of a slip ring assembly as a function of output power. Efficiency is taken as 99.75 percent.

Figure 5-29 estimates the weight and area for a flat panel solar array utilizing silicon solar cells as a function of output power. The weight and area given are that which provide the output power at the end of five years.

Given the configuration of Figure 5-22, Figure 5-30 gives these power system parameters as a function of total load for a nominal 100-volt main distribution and a 30-volt battery system. Sensitivity to the main distribution voltage is shown in Figures 5-31 and 5-32, which show system weight, system losses, equipment volume, and array area versus total load as a function of voltage (30, 100, and 300 volts), In all cases a power cable length of 20 feet (6.1 meters) is assumed.

Figures 5-30 through 5-32 are for quick estimates. A more accurate power subsystem sizing, taking into account the actual load division, is obtained by a step by step procedure using the matrix in Table 5-9. This procedure is as follows:

- Determine loads and place in 1A, 2A, and 3A
- Determine input power, weight, and volume of Items 1 and 2 using Figures 5-23 and 5-24
- Determine input power, weight, and volume of Item 3 using Figure 5-25
- Set Item 4 load equal to Item 3B
- Determine Item 4 input power, weight, and volume using Figure 5-26
- Set Item 5 load equal to Item 4B
- Determine Item 5 input power, weight, and volume using Figures 5-23 and 5-24
- Item 6 load equals sum of Items 1B, 2B and 5B
- Determine weight of Item 6 from Figure 5-27. Multiply this weight by ratio of assumed length to 100 foot and enter in 6C. 6B equals 1.01 times 6A. 6D equals 4 in^3/lb x 6C
- Item 7 load equals Item 6B
- 7B = 7A/0.9975. Determine 7C and 7D from Figure 5-28
- Item 8 load equals Item 7B
- Determine weight and area from Figure 5-29.

Table 5-9. Power System Parametric Matrix

Item No.	Equipment	A Load	B Input Power	C Weight	D Volume or Area
1.	Power Conditioning for Power Amplifier No. 1				
2.	Power Conditioning for Power Amplifier No. 2				
3.	Power Conditioning for House-keeping Loads				
4.	Batteries and Battery Control				
5.	Power Conditioning-Main Bus to Battery Bus				
6.	Power Cables				
7.	Slip Rings				
8.	Solar Array				

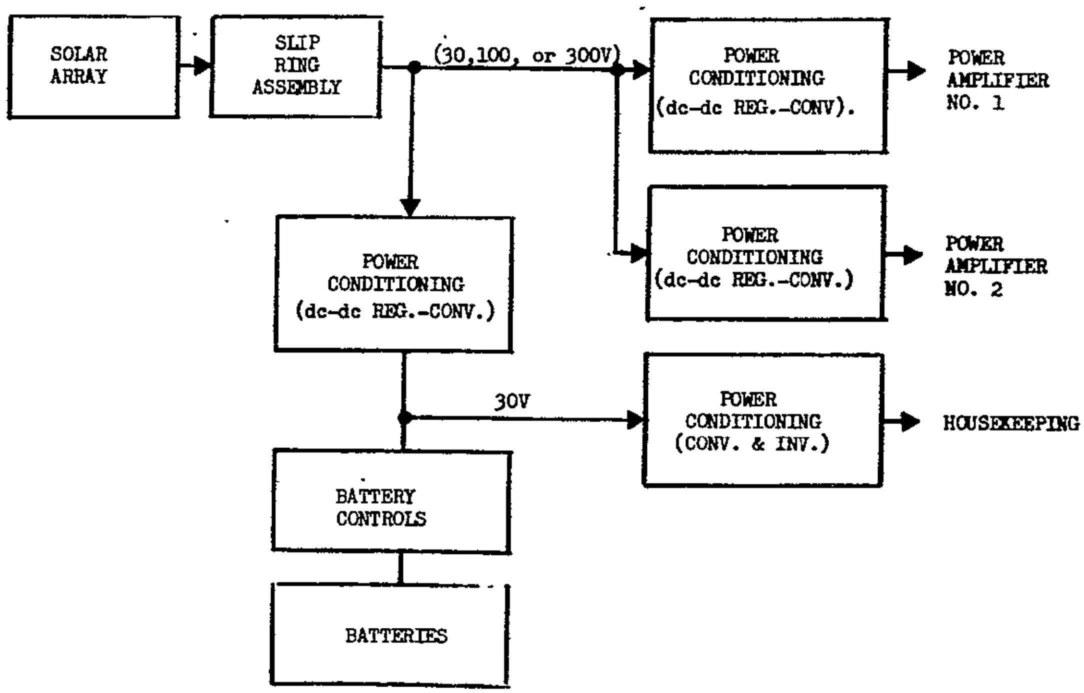


Figure 5-22. Power System Configuration

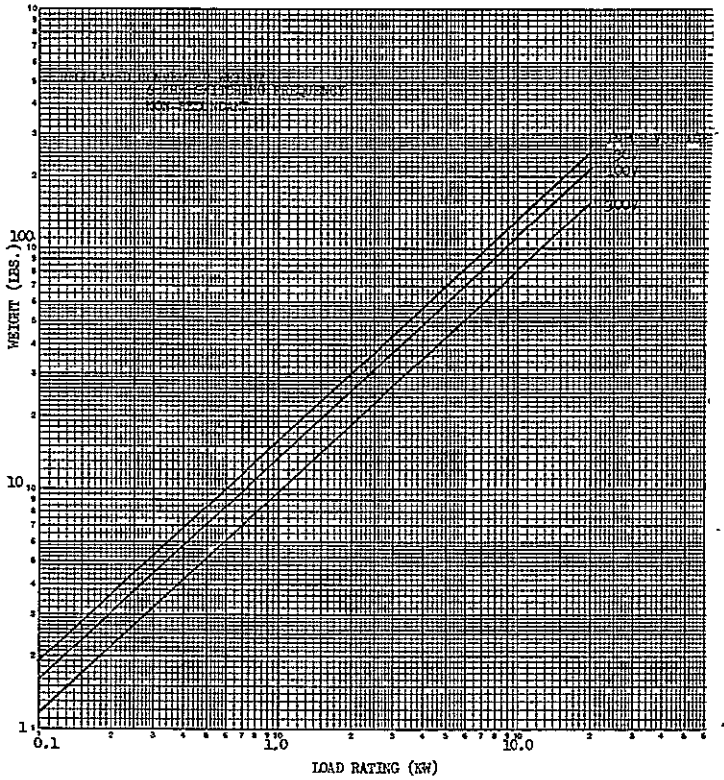


Figure 5-23. Regulated Converter Weight (6 KHz Switching Frequency, Nonredundant)

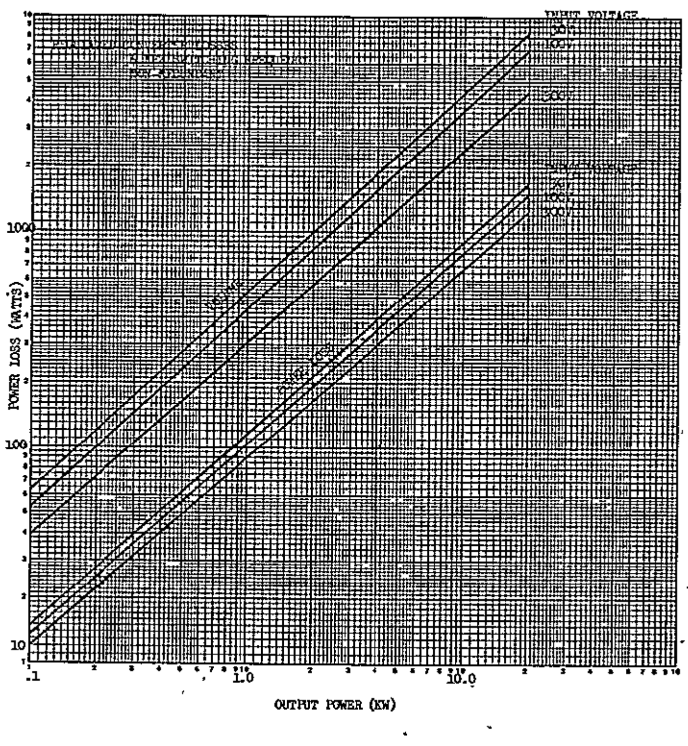


Figure 5-24. Regulated Converter Losses and Volume (6 KHz Switching Frequency; Nonredundant)

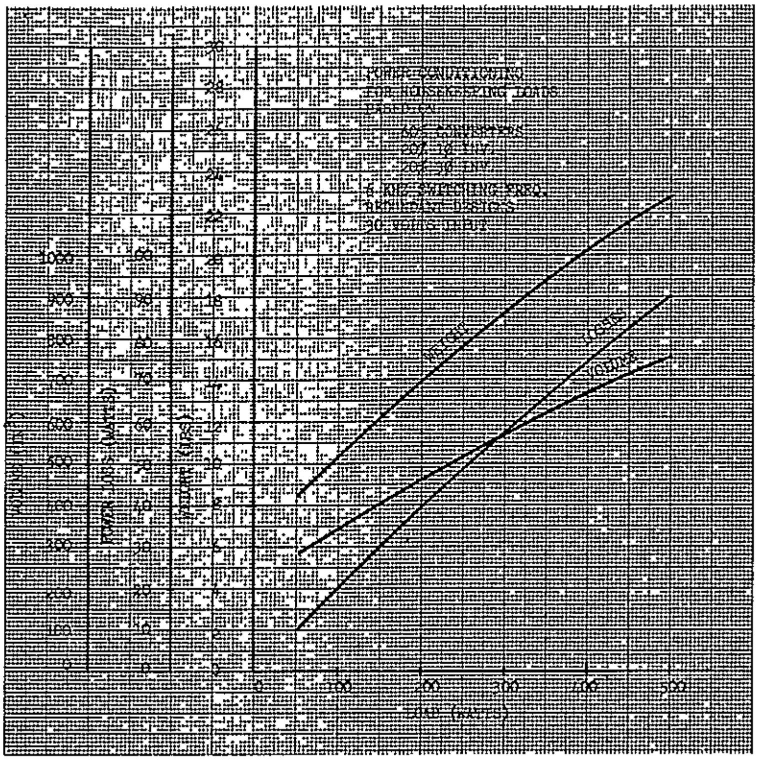


Figure 5-25. Power Conditioning for Housekeeping Loads

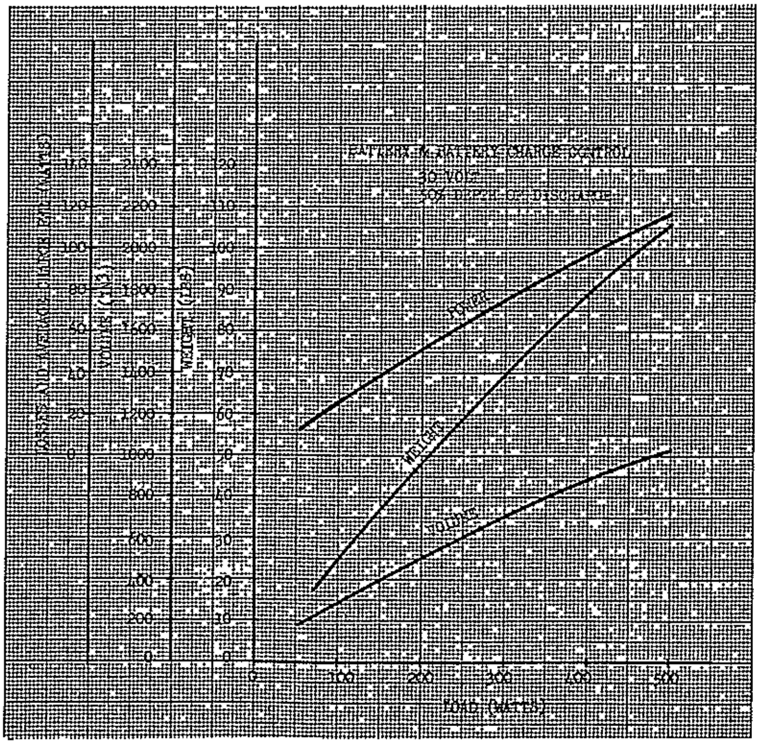


Figure 5-26. Battery and Battery Charge Control 30 Volt, 50 Percent Depth of Discharge

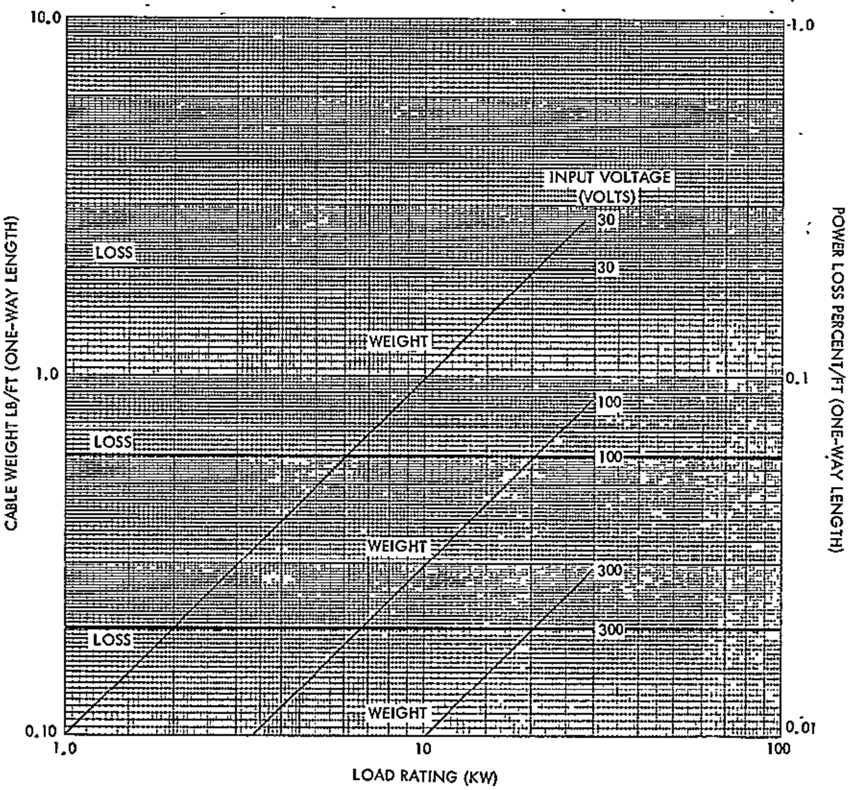


Figure 5-27. Cable Weight and Losses

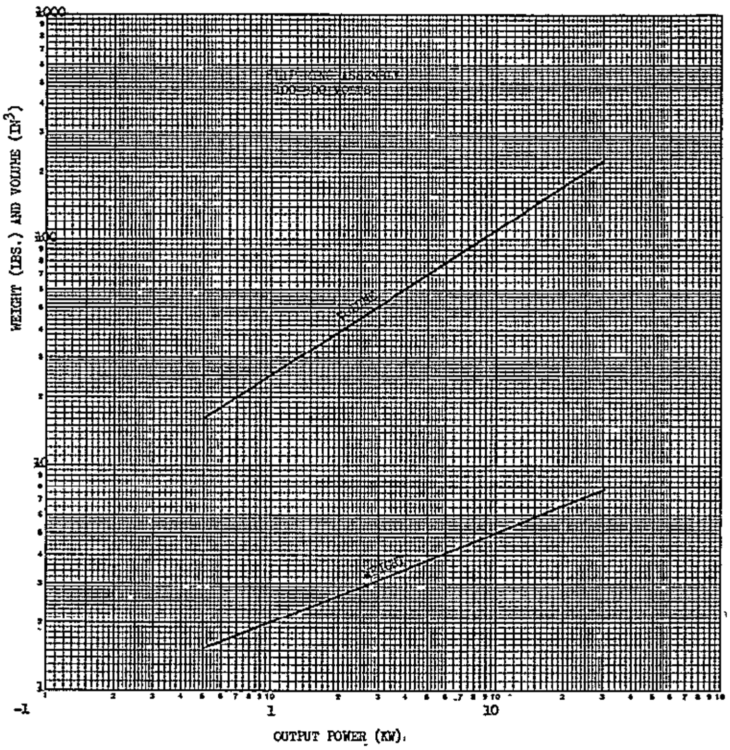


Figure 5-28. Slip Ring Assembly (100-300 Volts)

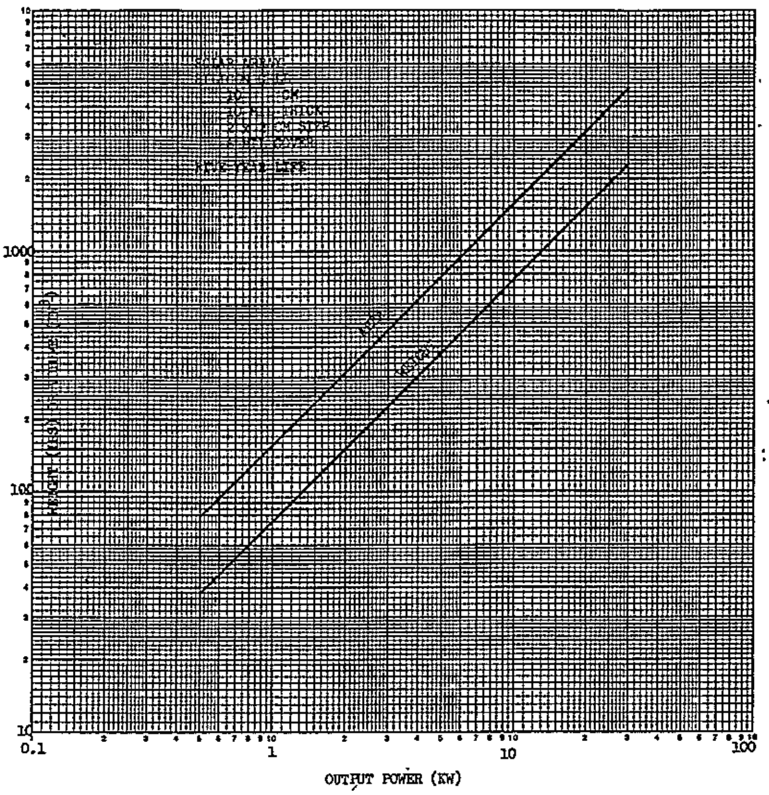


Figure 5-29. Solar Array Area and Weight Silicon Cell 10-CM, 10 Mil Thick, 2 x 2 cm Size, 6 Mil Cover, Five Year Life

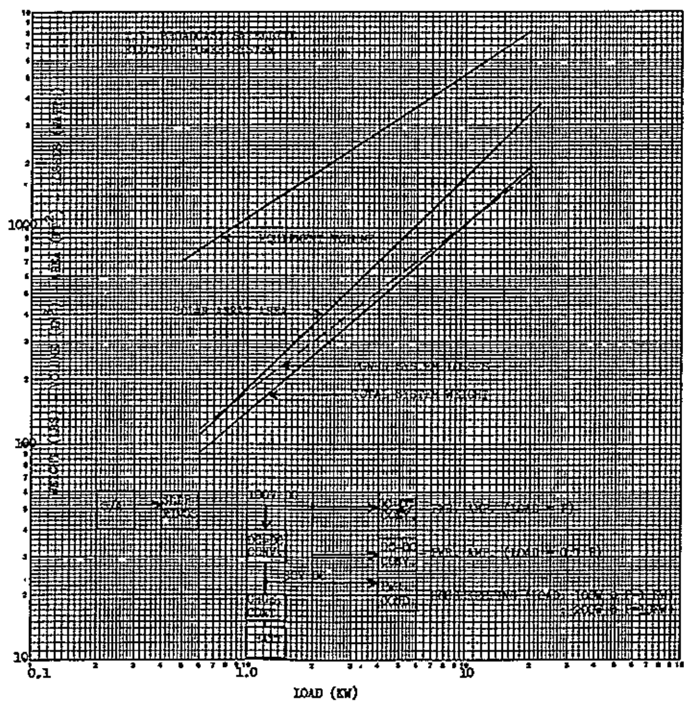


Figure 5-30. TV Broadcast Satellite Electric Power System

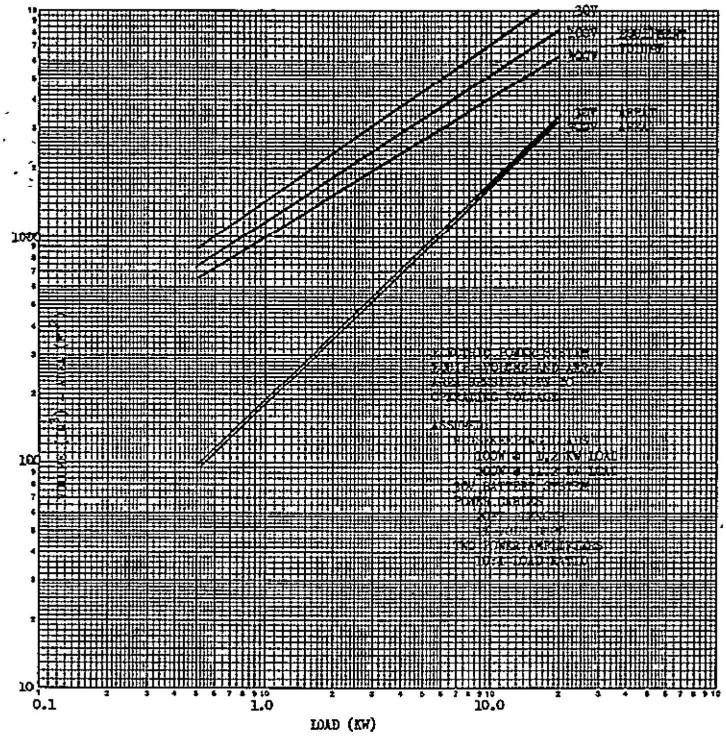


Figure 5-31. Electric Power System Equipment Volume and Array Area Sensitivity to Operating Voltage

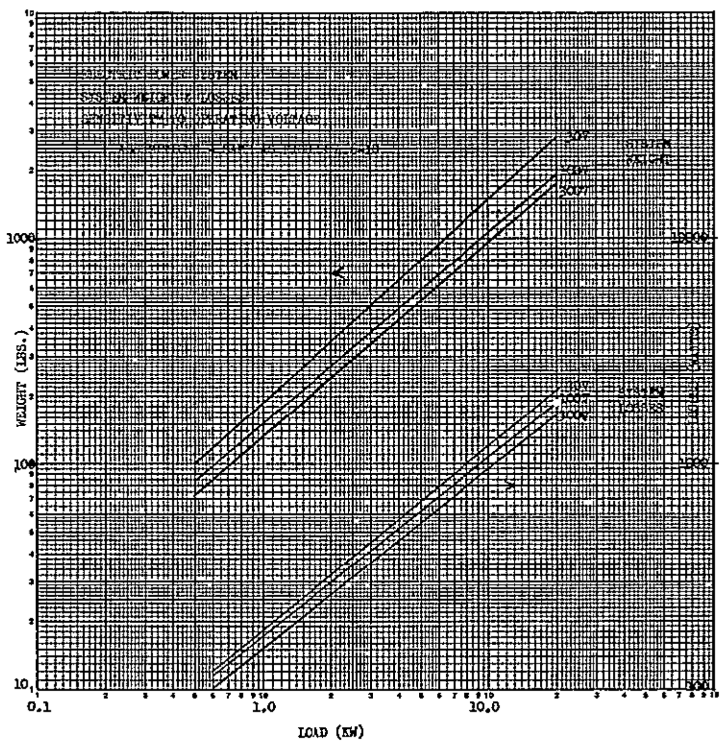


Figure 5-32. Electric Power System, System Weight and Losses, Sensitivity to Operating Voltage Assumptions (same as Figure 5-32).

SECTION 5 REFERENCES

5-1. TRW Report No. 04898-6001-R000, "Study and Analyses of Satellite Power Systems Configurations for Maximum Utilization of Power" dated 9/1/67. Prepared for NASA Goddard SFC under Contract No. NAS 5-9178.

5-2 "Power System Configuration Study and Reliability Analysis," TRW Report No. 07171-6001-R000, prepared for JPL, sponsored by NASA under Contract No. 951574, September 18, 1967.

6. LAUNCH ANALYSIS

To identify potential boosters for television broadcast satellites, all available launch vehicle combinations in the Atlas and Titan class and some feasible modifications of these have been evaluated in terms of the following mission requirements:

- Launch in 1975-80 period.
- Synchronous equatorial orbit.
- In-orbit satellite weight: 1000 to 10,000 pounds (454 to 4540 kg)

It is assumed that the launch vehicle will perform the injection into synchronous orbit (apogee burn) and the initial orientation of the satellite. Trim maneuvers for removal of launch vehicle injection errors are achieved by the spacecraft propulsion upon separation from the final stage.

6.1 CANDIDATE LAUNCH VEHICLES

Many launch vehicle combinations are available from the Atlas and Titan families. Some are currently operational, and others are feasible modifications which could be operational in 1975.

Titan IIIB is a third-generation Titan incorporating the first and second stage liquid engines common to all Titans. The Titan IIIB alone cannot place a payload in orbit but when combined with the (improved) I-Centaur and Burner II as upper stages, it can place 1500 pounds (680 kg) in that orbit. Currently there is no capability for launching a Titan IIIB from ETR, but with some modifications a launch pad could be made available. Such modifications are scheduled to support Intelsat IV.

Titan IIIC is a third-generation Titan consisting of the first and second stage liquid engines common to all Titans, five-segment solid strapons and the transtage. With its multiple restart capability, the transtage can perform the final burn to parking orbit as well as the perigee burn and the apogee burn to circularize at the synchronous altitude. One feasible modification of the Titan IIIC consists of replacing the five-segment solid strapons with seven-segment motors. Since the seven-segment motors are in development for the MOL program, it is reasonable to assume that they will be available by 1975. The transtage currently has a 6.5-hour lifetime, limited by its batteries and coolant. Starting with flight article no. 17, closed-loop radiators will elimate the coolant constraint. The Martin Company also indicated that if the 150 amp-hour batteries are replaced by 450 amp-hour batteries, the orbit lifetime of the transtage could be increased to approximately 24 hours. This modification is not difficult but would degrade the synchronous payload capability by approximately 150 pounds (68 kg).

Titan IIIC Mod I is a growth version of the Titan IIIC that has been proposed by the Martin Company. It derives increased capability from proposed changes in helium tanks, batteries, transtage wiring, elimination of excess instrumentation, use of transtage mixture ratio control, and improvements in the injector and guidance system. These modifications could be incorporated by 1975, but no cost figures are available.

Titan IIIC Mod II is a second-growth version of the Titan IIIC. This vehicle utilizes all the modifications proposed for Mod I except for the improved guidance system.

Titan IIID is a third-generation Titan. The Titan IIID is essentially the Titan IIIC without the transtage. Although the Titan IIID alone cannot perform the synchronous mission, combined with the large tank Agena as an upper stage its capability is adequate for 4900 pounds (2220 kg) in orbit. The Titan IIID has the same ETR launch pad problem as the Titan IIIB.

SLV-3C is an updated version of the Atlas. The SLV-3C is 51 inches (1.3 meters) longer than the regular Atlas. It has been developed for use with a Centaur upper stage. In this survey, the SLV-3C is mated with a Centaur D/Burner II combination and an I-Centaur/Burner II.

SLV-3X, defined by General Dynamics, has higher performance than the SLV-3C. Mated with the Centaur D, it can inject 14 percent more payload to synchronous equatorial orbit than the SLV-3C/Centaur D/ Burner II. General Dynamics indicates that development of the SLV-3X vehicle probably will not be undertaken, but it is still a possibility.

Agena-D is a high-energy, liquid-propulsion system developed by Lockheed. Lockheed is proposing a growth version with larger propellant tanks, increasing the propellant load to 35,000 pounds (15,800 kg). Where the current TIIID/Agena uses a bi-elliptic transfer orbit for synchronous equatorial missions, the long-tank Agena utilizes a 100-n mi (185-km) parking orbit, with the Agena supplying the impulses for injection into the final parking orbit, as well as the perigee and apogee impulses. This second approach is preferable for television broadcast satellites.

Centaur-D can be used advantageously in either a two or three burn mode for synchronous missions. For missions requiring long coast periods, the performance of this stage is degraded as a result of propellant loss through boiloff. This problem is most prominent in the three burn mode.

I-Centaur is an improved version of Centaur D. The improvement consists of a radiation shield for reduction of propellant boiloff and improved reliability. It is reasonable to assume that these improvements can be incorporated by 1975.

Burner II is a small, solid propellant stage built by the Boeing Company. It includes the TE-M-364-2 solid motor, a preprogramed strapdown inertial guidance system, a battery powered electrical system, and a telemetry system.

Agena E is sometimes referred to as the "Super Agena" or the "N_2O_4 Agena." The latest information from LMSC indicates that this motor will not be developed.

Bell 8533 is the N_2O_4 engine proposed for the Agena E.

Synchronous equatorial payload data is presented for each of the candidate vehicles in Table 6-1 to aid in vehicle selection. Additional data such as cost, availability, reliability, and payload diameter are also listed when available. These data have been verified where possible but must be considered as preliminary data.

6.2 PAYLOAD FAIRINGS

Figures 6-1 and 6-2 show payload fairings for the Titan IIIC and Titan IIIC follow-on, respectively.

Table 6-1. Potential Launch Vehicles

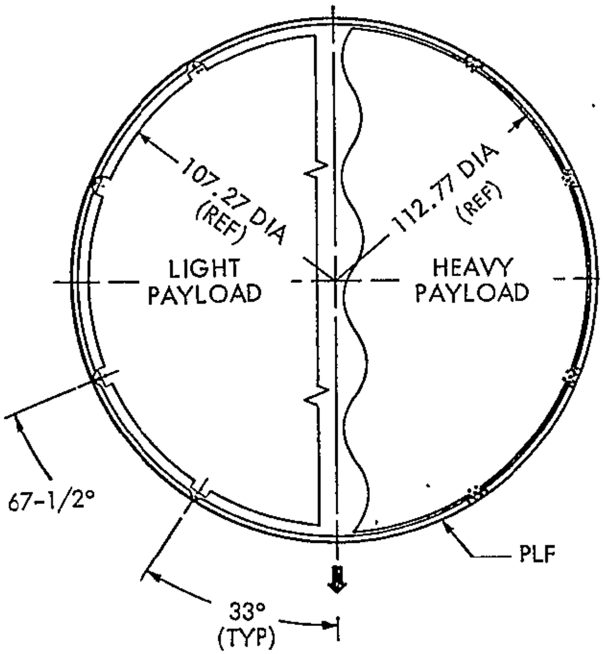
Vehicle	Payload (in synchronous equatorial orbit)**		Cost per Launch	Payload Diameter		Availability	Reliability
	lb	kg	(10^6 $)	ft	m		
SLV-3C/I-Centaur/Burner II	1450	660		10***	3		0.90*
SLV-3C/Centaur D/Burner II	1495	680	12.5	10***	3	Now	0.94
SLV-3X/Centaur D	1700	770	14.0	10	3		0.90*
T IIIC	2160	980	17.6	10	3	Now	0.90-0.95
T IIIC Follow-on	2350	1070		10	3		0.90*
SLV-3X/Centaur D/Burner II	2500	1135		10***	3		0.90*
T IIIC - MOD I	3638	1650	20* to 25* estimated	10	3		0.90*
T IIIC (7-Segment Solids)	3670	1670		10	3	1970	0.90*
T IIIC - MOD II/Burner II	4006	1820		10***	3		0.90*
T IIID/Agena D (Large Tank)	4900	2220		10***	3		0.90*

* Estimate, not verified.

** Payload data shown are degraded for payload fairing of compatible size.

*** With appropriate fairing, mounted on next-to-last stage, otherwise 5 ft (1.5 m).

CONFIG NO.	L (ISL)	A	B	C	D
XX15 FT	180	3.00	3.00	3.00	84
XX20 FT	240	3.00	3.00	3.00	144
XX25 FT	300	3.00	3.00	3.00	144
XX30 FT	360	3.00	3.10	3.60	144
XX35 FT	420	3.00	3.70	4.20	144
XX40 FT	480	3.00	4.30	4.80	144
XX45 FT	540	3.00	4.90	5.40	144
XX50 FT	600	3.00	5.50	6.00	144



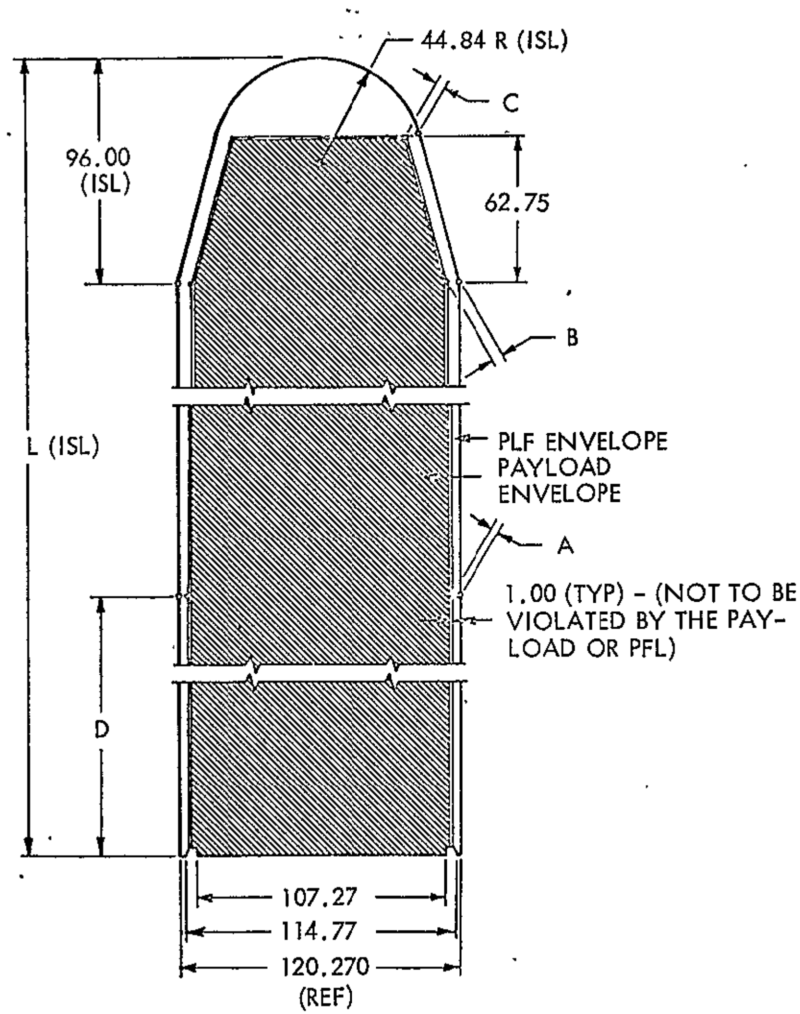


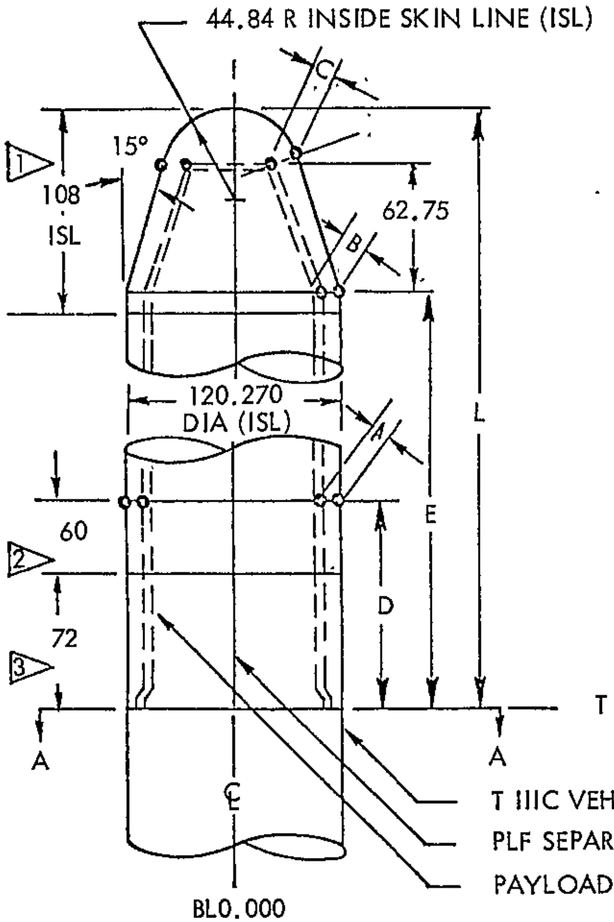
Figure 6-1. Titan IIIC Payload Envelope

DESIGN AND CONSTRUCTION FEATURES (CONT'D)

1 PAYLOAD FAIRING ENVELOPE

NOTES:

1. STD NOSE SEGMENT
2. TYP INTERMEDIATE SEGMENT
3. STD AFT SEGMENT



PLF STRUCTURE AND DYNAMIC ENVELOPE DIMENSIONS - STRUCTURE ENVELOPE NOT TO EXCEED 1.5 IN INBOARD OF ISL

CONFIG NO.	L (ISL)	A	B	C	C	E (ISL)
XX15	180	3	3	3	84	84
XX20	240	3	3	3	144	144
XX25	300	3	3	3	144	204
XX30	360	3	3.1	3.6	144	264
XX35	420	3	3.7	4.2	144	324
XX40	480	3	4.3	4.8	144	384
XX45	540	3	4.9	5.4	144	444
XX50	600	3	5.5	6.0	144	504

(ALL DIMENSIONS IN INCHES)

Figure 6-2. Titan IIIC Follow-on Payload Fairing System Primary Design Requirements

The SSLV and OAO fairings, shown in Figures 6-3 and 6-4, respectively, can be used on a Centaur stage equipped with a payload support skirt and structure. Both these fairings can be made to a length matched to the spacecraft size and can accommodate a Burner II upper stage.

Payload degradation due to the addition of a payload fairing can be reasonably estimated using the payload fairing sensitivity coefficient $\partial W_{PL}/\partial W_{FAIR} = 0.066$, and for a 1000 pound fairing the synchronous equatorial payload would be reduced by 0.066 x 1000 or 66 pounds.

6.3 ASCEND TRAJECTORIES AND LAUNCH SEQUENCE

The basic launch sequence is as follows:

- Lift-off and injection into a 100 n mi (185 km) parking orbit at a nominal azimuth of 90 degrees (93 degrees for Titan IIIC).
- Coast to first equator crossing.
- Perigee injection into a Hohman transfer orbit with apogee at synchronous altitude, combined with a plane change of a few degrees.
- Coast to synchronous altitude.
- At apogee of the transfer orbit, circularization and plane change for injection into a nearly circular, equatorial drift orbit.
- Initial satellite orientation, performed by the upper stage.
- Separation of spacecraft from upper stage.
- Trim maneuvers for correction of launch vehicle injection errors.
- Deployment of spacecraft solar arrays and antennas.
- Drift to required position.
- Tracking for determination of spacecraft orbit.
- At the required final position, removal of drift velocity.

The drift orbit is required because, in general, the longitude at transfer apogee does not coincide with the required final position.

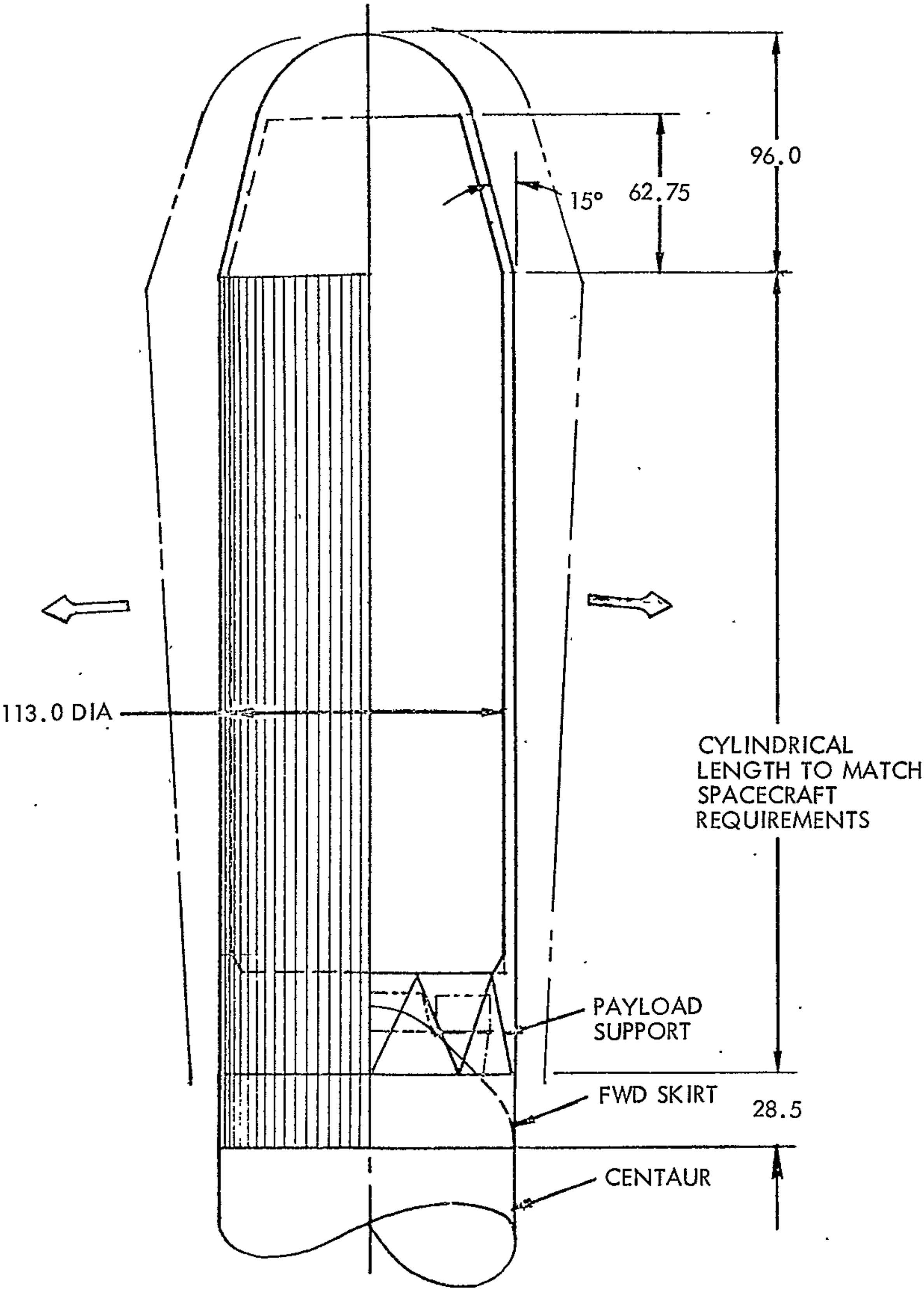


Figure 6-3. SSLV Type Payload Fairing

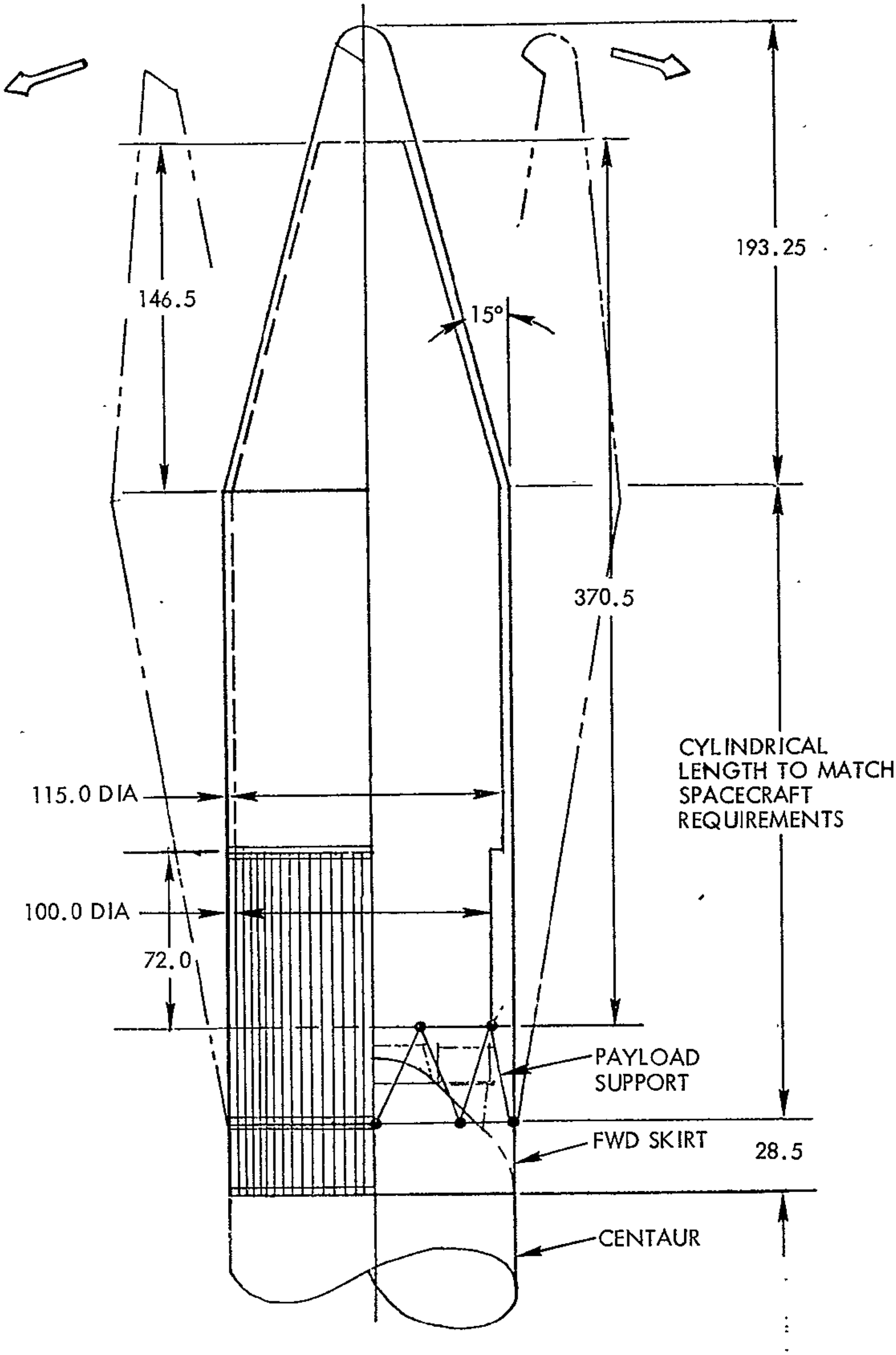


Figure 6-4. OAO Type Payload Fairing

Drift orbits for westward or eastward drift are slightly elliptical orbits with a period slightly larger or smaller, respectively, than the synchronous orbit. The drift orbit is determined by adjustment of the magnitude and direction of the apogee injection impulse. Generally, the apogee or perigee of the drift orbit is at synchronous altitude with the orbit period chosen such that the spacecraft reaches its final position when at synchronous altitude. The westward drift requires a larger apogee impulse than injection into synchronous orbit, with the eastward drift requiring a smaller impulse. (A larger impulse gives initially a larger inertial velocity but results in a larger orbit period due to exchange between kinetic and potential energy.) Therefore, the eastward drift is preferred from the viewpoint of payload capability.

The ΔV required for apogee injection into synchronous orbit or nearly synchronous drift orbit is shown in Figure 6-5 as function of inclination of the transfer orbit and the drift rate after injection. The transfer orbit inclination is usually about 2 degrees less than the inclination of the parking orbit. The latter is given in Figure 6-6 as function of launch azimuth. The ΔV capability required for drift removal (i. e., circularization) by the spacecraft propulsion system is related to the angular rate $\Delta \dot{\alpha}$ of position drift by

$$\Delta V = 9.3 \Delta \dot{\alpha}$$

where ΔV is in ft/sec and $\Delta \dot{\alpha}$ in degrees/day.

The fuel requirement therefore is 1.35 percent of the spacecraft weight per 100 ft/sec, assuming hydrazine with an I_{sp} of 230 seconds. The position drift rate is 8 degrees/day per percent of satellite weight allowed for drift removal at the final position.

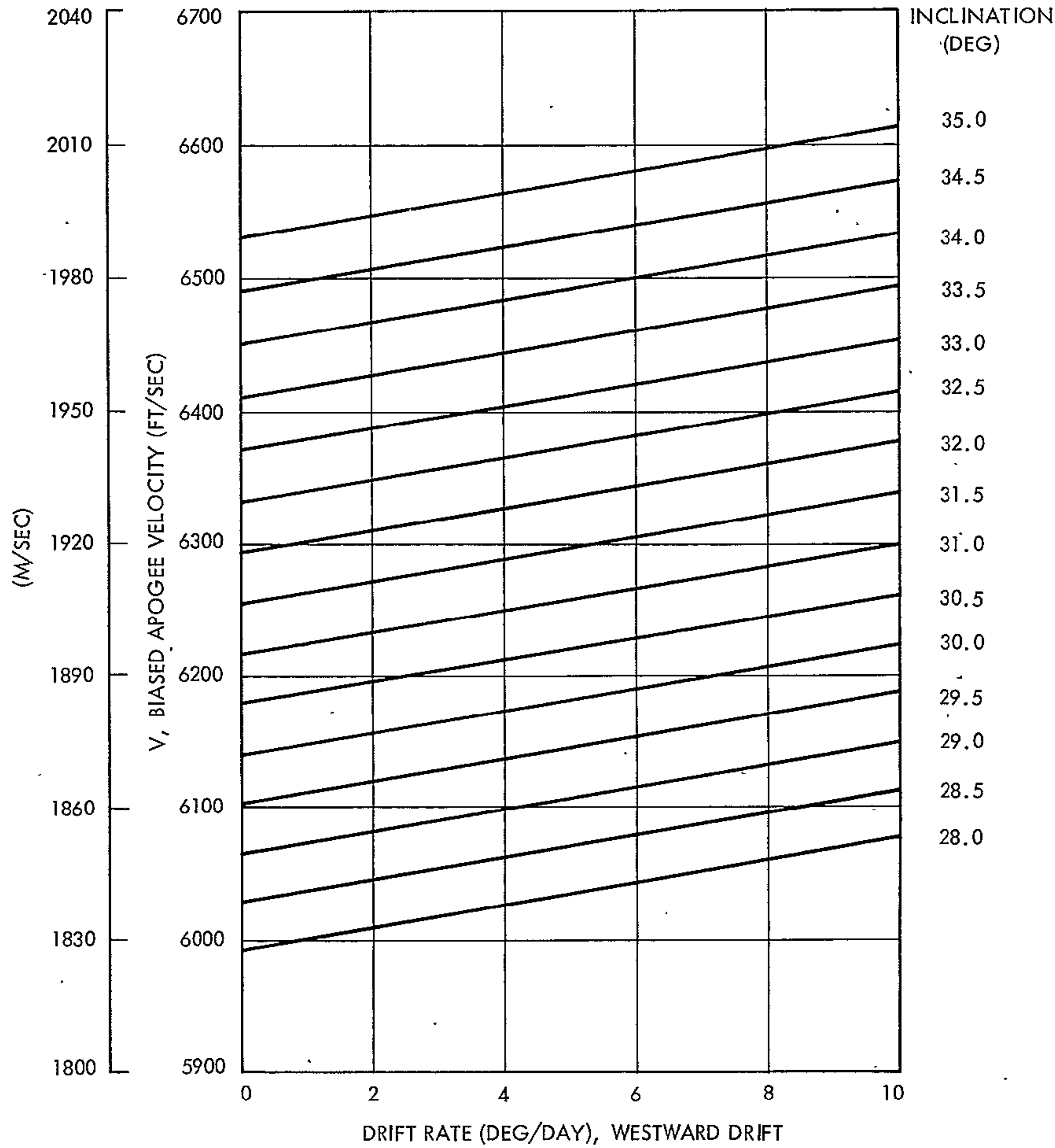


Figure 6-5. Apogee Burn ΔV Versus Drift Rate and Parking Orbit Inclination

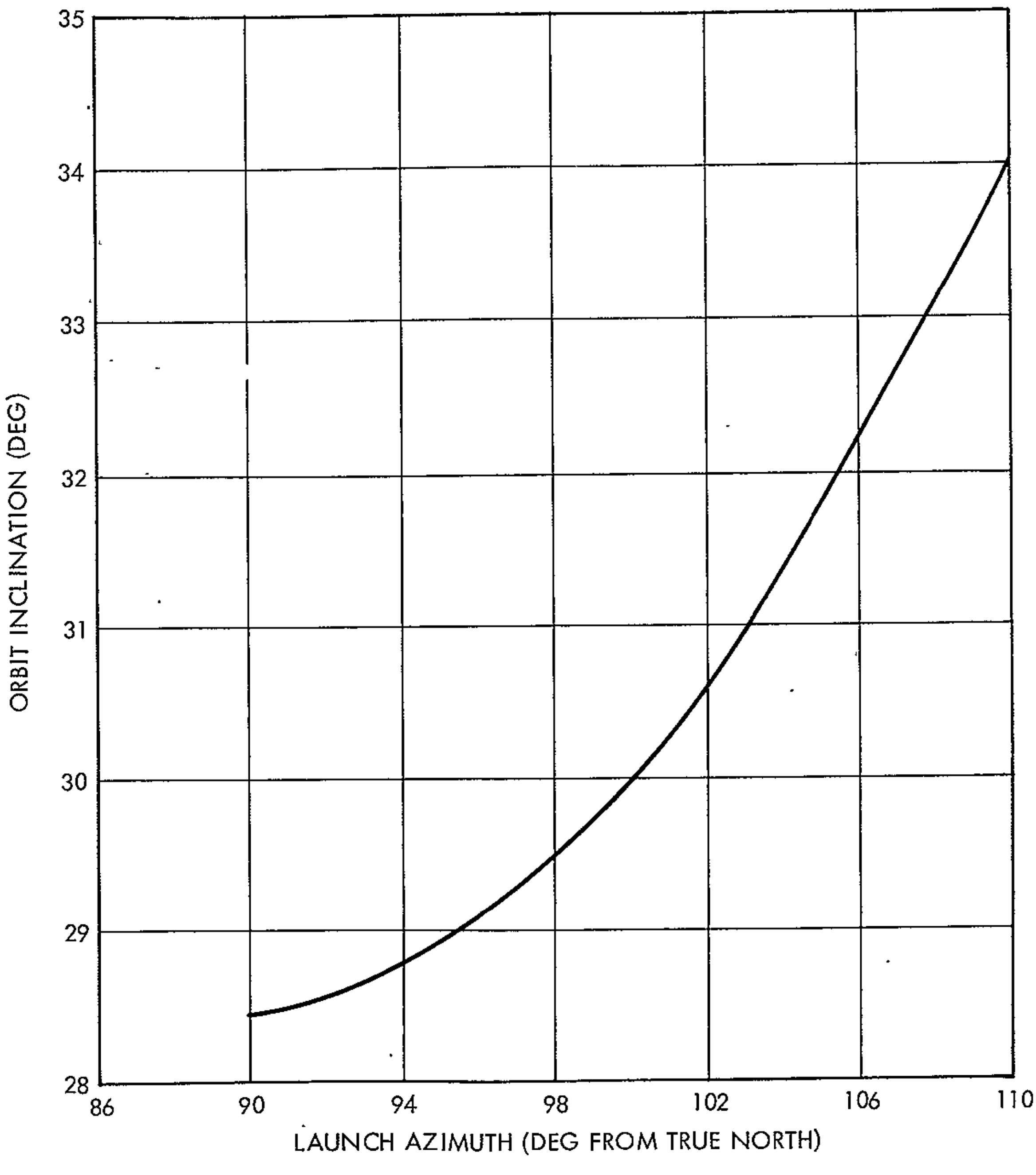


Figure 6-6. Effect of Launch Azimuth on Parking Orbit Inclination

The apogee burn must be carried out at a longitude visible from the ground station that commands the apogee motor firing, initial satellite orientation, separation, trim maneuvers, deployment of satellite arrays and antennas, tracking the satellite to determine the drift ephemeris, and the removal of the drift velocity at the required final position. This requirement limits the drift length to a longitude interval of about 60 degrees when all above functions are controlled by one ground station located in or near the area to be covered by the television broadcast satellite.

6.4 CONTROL OF APOGEE INJECTION LONGITUDE

Limitations on drift length, discussed in Section 6.3, may require deviations from the basic launch sequence outlined in that section to change the longitude of the transfer apogee. This can be achieved by one or more of the following methods:

- Launch Azimuth

  Variation in launch azimuth provides a vernier adjustment of the longitude at which the low altitude parking orbit crosses the equator. Figure 6-7 shows the longitude displacement as a function of launch azimuth. In general, the launch azimuth will not be varied by more than about 20 degrees from due east since large variations adversely affect the vehicle performance. In addition, range safety restrictions limit the possible launch azimuth range. Figure 6-8 shows the allowable range for any vehicle launched from ETR. Also, additional restrictions exist for some launch vehicles; the Titan IIIC, for example, cannot be launched at an azimuth north of 93 degrees so the second stage does not enter over Africa.

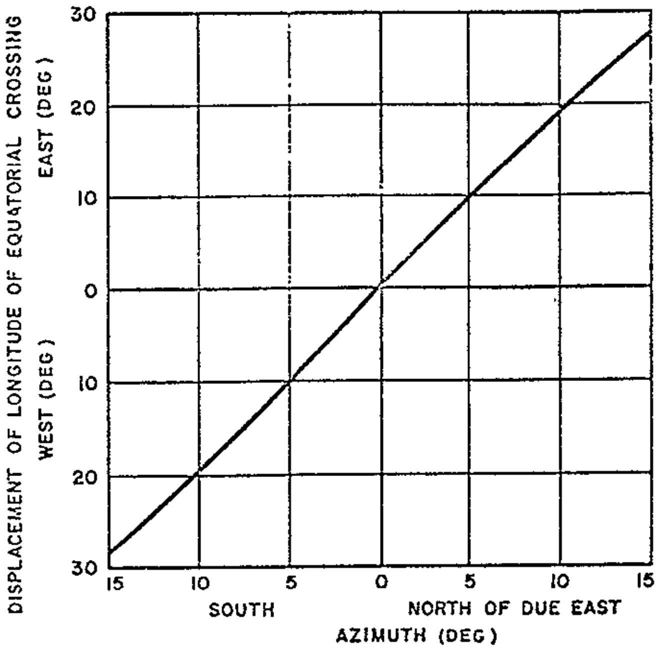


Figure 6-7. Longitude Displacement Due To Variable Launch Azimuth

- Extended Coast in Parking Orbit

The injection into transfer orbit can be delayed until a later earth equator crossing. Delay from the first crossing (in southerly direction) to the second (in northerly direction) moves the longitude of apogee injection westward by 191 degrees, a large step. Between consecutive crossings of the same direction (southerly or northerly), the longitude is shifted 22 degrees westward. Launch vehicle constraints such as fuel boiloff, drift of inertial reference, or battery capacity may require that the injection is achieved from the first southerly or first northerly equator crossing. Table 6-2 shows the transfer perigee and apogee longitudes for the different extensions of low-altitude coasting.

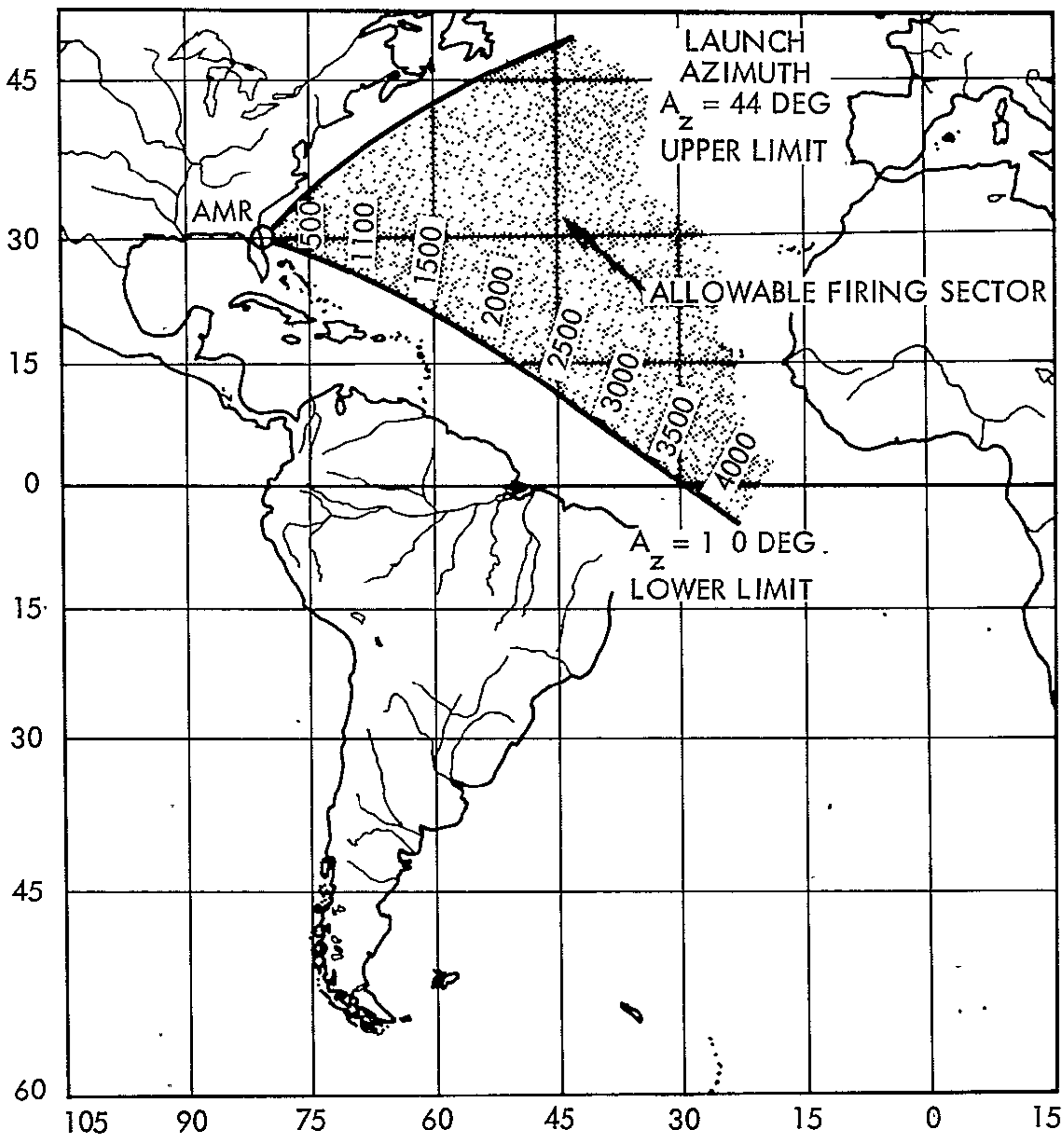


Figure 6-8. Atlantic Missile Range Firing Sector

Table 6-2. Low Altitude Parking Orbit

Transfer on a Southerly Crossing			Transfer on a Northerly Crossing		
Revolutions	Transfer Longitude	Apogee Longitude	Revolutions	Transfer Longitude	Apogee Longitude
0	4.0°E	105.0°E	1/2	173.0°E	86.0°W
1	18.1°W	82.9°E	1-1/2	150.9°E	108.1°W
2	40.2°W	60.8°E	2-1/2	128.8°E	130.2°W
3	62.3°W	38.7°E	3-1/2	106.7°E	152.3°W
4	84.4°W	16.6°E	4-1/2	84.6°E	174.4°W
5	106.5°W	5.4°W	5-1/2	62.5°E	163.5°E
6	128.6°W	27.5°W	6-1/2	40.4°E	141.4°E
7	150.7°W	49.6°W	7-1/2	18.3°E	119.3°E
8	172.8°W	71.7°W	8-1/2	3.8°W	97.2°E
9	194.9°W	93.8°W	9-1/2	26.9°W	75.1°E

Notes:

1) Based on due east launch from 82°W longitude.
2) The longitudes are approximate and will vary a little for different booster vehicles.
3) The parking orbit altitude is 100 n mi.
4) A Hohmann transfer ellipse requiring 5.25 hours is assumed.

- Bi-elliptical Transfer Orbit

  A large measure of transfer apogee longitude is made available by using a bi-elliptical transfer trajectory instead of the single-elliptical Hohman transfer. In this method, the transfer trajectory consists of two ellipses, cotangential at the apogee of the first ellipse which is either above or below the synchronous altitude; Figure 6-9 shows these two possibilities. The cotangential point is then the apogee or perigee of the second ellipse, which has its perigee or apogee, at synchronous orbit, respectively. The freedom in selection of the cotangential altitude provides control of flight-time in the transfer trajectory and thereby of the longitude of injection into synchronous orbit.

  A disadvantage of this approach is the need for an additional burn for transfer from the first ellipse to the second.

- Extended Coast in Hohman Transfer Orbit

  An alternative way of controlling injection longitude by varying the flight time in transfer to synchronous altitude is to delay the apogee injection until a later apogee passage. Between consecutive apogee passages, the injection longitude is moved westward by 158 degrees, the rotation of the earth in the 10. 5 hour Hohman orbit period.

The use of bi-elliptical transfer, extended coast in parking orbit, or in Hohman transfer orbit all prolong the flight time from launch to injection into synchronous (or nearly synchronous orbit). These approaches are therefore limited by the lifetime of the upper stage.

The transtage with extended lifetime, 24 hours, must be fired at first or second apogee passage in the Hohman transfer orbit which leaves the choice of one 158 degree increment in apogee longitude. The Centaur will suffer from payload capacity degradation through propellant boiloff for any extension of coast time. This is illustrated in Figure 6-10 which shows the apogee positions and payload reduction resulting from extensions of the coast in low altitude parking orbit for the SLV-3X/Centaur equipped with radiation shield to reduce the boiloff. The Burner II, a solid stage, does not suffer from boiloff. Still, extended coast in the Hohman transfer may result in performance degradation due to drag at perigee.

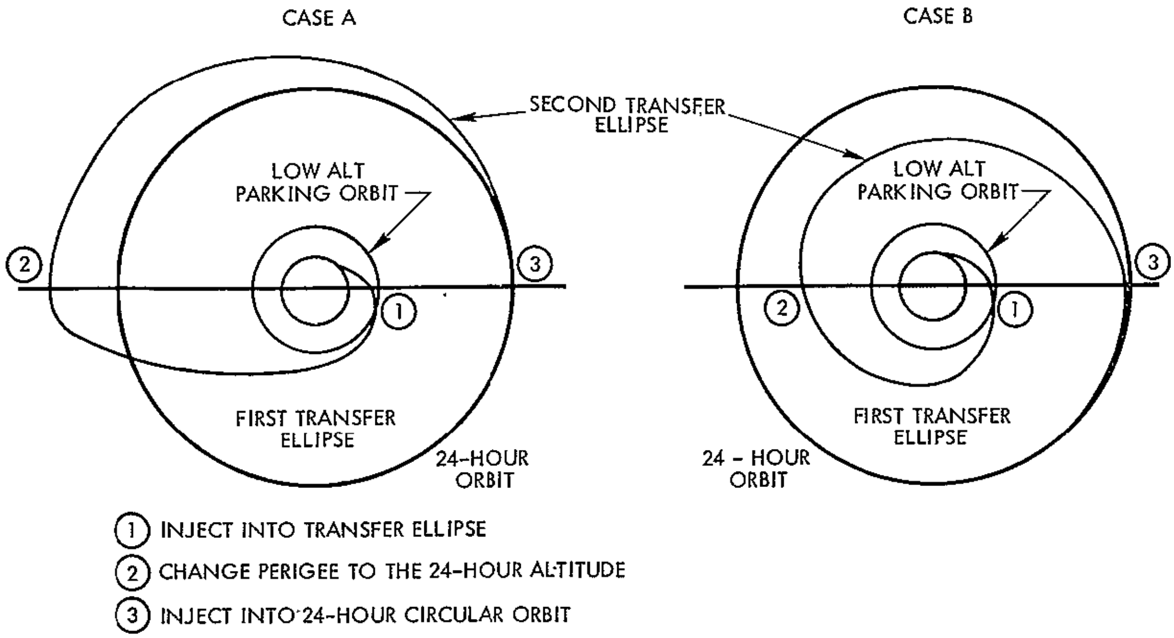


Figure 6-9. Bi-Elliptic Transfer Trajectory

The appropriate method for selection of apogee longitude varies with the final position required and the launch vehicle combination used. Also, the control of apogee injection longitude must be traded off against drift in nearly synchronous orbit over a longer longitude interval. Such tradeoff should consider the use of more than one ground station to allow control by command at the beginning and end of a longitude drift longer than 60 degrees. The use of existing NASA tracking stations or temporary deployment of a tracking ship are possibilities to provide this capability.

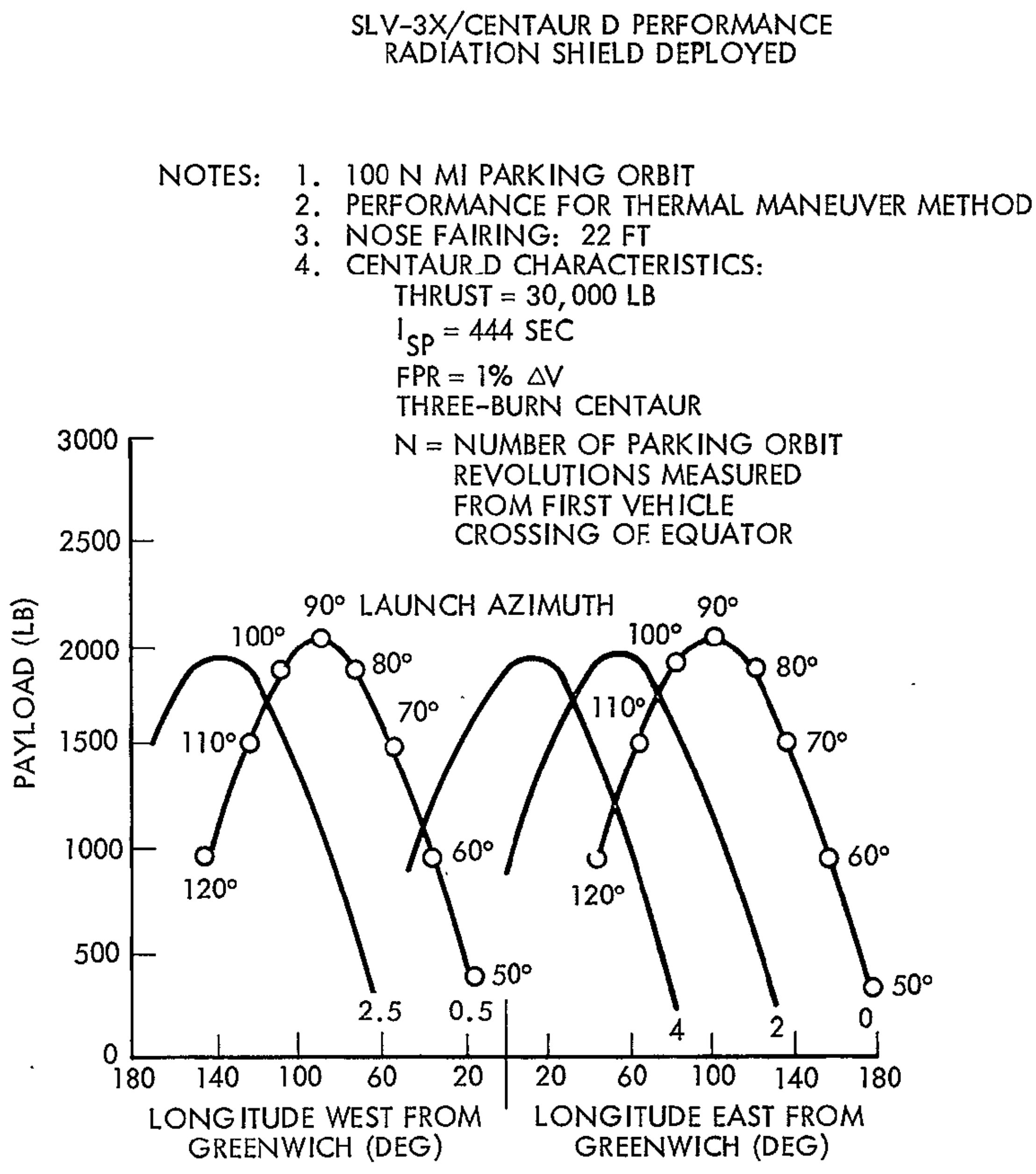


Figure 6-10. Synchronous Longitude Selection Capability

7. SATELLITE CONFIGURATIONS

7.1 INTRODUCTION

Three satellite configurations representative of three broadcast concepts are presented. All three configurations have the following features in common:

a) Synchronous equatorial orbit

b) Three-axis stabilized

c) Propulsion System. Attitude control uses cold gas nitrogen; initial positioning makes use of monopropellant hydrazine; stationkeeping uses a colloid system.

The configurations vary as to broadcast frequency (0.9 GHz, 2.5 GHz, and 12 GHz), antenna size and configuration, and solar array output power (12 kw, 4 kw, and 8 kw). The body orientation (sun- or earth-oriented), type of solar array (foldout or rollout), and launch vehicle also vary with each of the configurations.

One of the major constraints was to accommodate the requirement for sun-orientation of solar arrays in conjunction with earth-pointing of broadcast antennas. The requirement for large arrays and large broadcast antennas required their storage and subsequent deployment to maintain overall spacecraft volume within the launch vehicle fairing constraints. A significant characteristic of all three configurations is large, external light-weight structures whose flexibility introduces dynamic interactions.

7.1.1 Attitude Control

The required broadcast antenna pointing accuracy is 0.1 degree; spacecraft body pointing to this accuracy is difficult to achieve because of the flexible structure dynamics. Therefore, the spacecraft body is oriented to within ± 5 degrees and the required antenna pointing is obtained through the use of interferometer or other high accuracy sensor techniques (the antennas are decoupled from the spacecraft body through gimbals). Although a pitch momentum wheel could be used to store the momentum variations from cyclic distrubance torques about the pitch axis, it was not used since only insignificant fuel savings would result due to the small magnitudes of these torque components. Yaw reference will be provided either by Polaris or Canopus star sensors or a gyro compass. Spacecraft axes are defined in Tables 7.5, 7.6, and 7.7 for the three configurations.

The two satellite configurations with earth-oriented central body (0.9 GHz and 2.5 GHz satellites) maintain the spacecraft body yaw axis oriented towards the earth center. Body control is maintained to ± 5 degrees; earth horizon sensors and a Polaris star sensor are utilized for three-axis reference. Colloid engines provide the required attitude control torques and stationkeeping thrust. The solar array is dual-axis controlled to achieve sun-orientation to within ± 1 degree; a sun sensor provides the required reference. The antenna is controlled to within ± 0.1 degree of its desired earth pointing direction through use of an antenna-mounted interferometer.

The satellite with sun-oriented central body (12 GHz configuration) uses sun sensors in pitch and roll to maintain the solar arrays normal to the spacecraft/sun line, and a Canopus star tracker for yaw sensing; an earth sensor is used during eclipse and for initial acquisition. The antenna is controlled to the required ±0.1 degree through the use of an interferometer. Colloid engines are used for attitude control and stationkeeping.

7.1.2 Power Generation

All three configurations make use of solar arrays for power generation. The flat panel solar arrays have a power-to-weight ratio of 13.2 w/lb (29 w/kg) and provide 6.3 w/ft^2 (68 w/m^2), at the end of 5-year life. The chosen solar cell configurations use N-on-P silicon cells of 10 mil (0.025 cm) thickness with 6 mil (0.015 cm) cover glass. The cells are 2 x 2 cm and have a 10 ohm-cm base resistivity. Spacecraft batteries are used during eclipse operation only to maintain normal spacecraft housekeeping functions; no broadcast operation is provided during eclipse. The batteries are nickel-cadmium and are sized to provide a 50 percent depth of discharge over a 5 to 10 year useful life period. There are two categories of power conditioning equipment: communication (broadcast) power amplifier power conditioner and housekeeping load conditioner. Low-power communication functions are included in housekeeping. The housekeeping power requirements are approximately 200 w, and only low voltage equipment is required. The communication power amplifiers require high voltage power supplies of two types: constant power for the FM power amplifier and variable power for the AM type. Multiple voltages up to 20 kv are required. A summary of the power requirements for all three spacecraft configurations is given in Table 7-1.

Table 7-1. Satellite Power Requirements (Watts)

Subsystem \ Configuration	0.9 GHz	2.5 GHz	12.0 GHz
Transmitter	10,700*	3,360	7,000
Housekeeping	200	200	200
Regulated Converter (Transmitter)**	866	385	580
Regulated Converter (Housekeeping)** †	40	40	40
Batteries and Control	60	60	60
Housekeeping Converter** ††	36	36	36
Cable and Slip Ring Losses	200	50	120
Required Solar Array Output Power	12,102	4,130	8,036

*Worst-case average; short-time peaks exceeding this value are provided by reactive storage.

**Converter losses.

†Converts array voltage to regulated 30 volt housekeeping bus voltage.

††Converts housekeeping bus to various voltages required.

7.1.3 Thermal Control

Both passive and active thermal control techniques are required to maintain spacecraft component temperatures to within required limits.

Thermal coatings, isolators, and insulation are used on the various antenna systems while active radiators base-plate and heatpipe combinations are required for the high power, high temperature components (RF tube). Insulation, heat sinks, and thermal coatings are used on the various attitude control components.

A summary weight statement for the three satellite configurations is given in Table 7-2. Gross satellite weights range from approximately 1500 to 3500 pounds; launch vehicle payload adapter weights are not included in these estimates.

Descriptions of the various spacecraft configurations are given in the following paragraphs; Table 7-3 and 7-4 summarize the characteristics of all three configurations.

Table 7-2. Satellite Weight Summary (Pounds)

Subsystem \ Satellite Configuration	0.9 GHz; 12 kw*		2.5 GHz; 4 kw*		12 GHz; 8 kw*	
Communication Electronics	400 lbs	101 kg	210 lbs	68 kg	150 lbs	96 kg
Antenna Assembly	105	48	50	29	65	23
Solar Array Assembly	1065	484	300	282	620	136
Power and Distribution	606	275	304	200	440	138
Attitude Control	255	116	170	82	180	77
Initial Positioning and Stationkeeping	230	104	110	68	150	50
Structure	355	161	155	100	220	71
Thermal Control	110	55	50	34	75	23
Contingency Provision	418	190	100	111	245	45
Satellite Gross Weight	3544 lbs	1614 kg	1449 lbs	974 kg	2145 lbs	659 kg

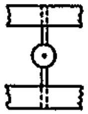
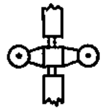
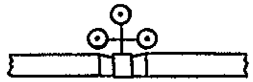
*Array Power at End-of-Life (5 Years)

Table 7-3. Satellite Summary Descriptions

	Configuration		0.9 GHz	2.5 GHz	12.0 GHz
Communications	Modulation		AM/VSB	FM	FM
	Number of Video Channels		1	7	1-2(3)
	RF Output Power/Channel	(kw)	13.2(1)	0.30	5.0
Antenna	Number of Transmitter Antennas		1	2	2
	Transmitter Antenna Diameter (ft)		30	10	4.5
	Receiver Antenna Diameter (ft)		2.5		
Configuration	Body Orientation		Earth-center	Earth-center	Sun
DC Power	Array Power	(kw)	12.2	4.13	8.0
	Communications Power Load	(kw)	10.8	3.36	7.0
High Temperature Dissipation	RF Output Amplifier(s) at maximum output	(kw)	2.5	1.26(2)	2.0
	RF Output Amplifier(s) at minimum output	(kw)	1.8	N/A	N/A
Low Temperature Dissipation	Transmitter(s)	(kw)	0.10	0.20(2)	0.1
	Pwr Conditioner for Xmitter(s)	(kw)	0.87	0.38(2)	0.58
	Other Power Subsystem Units	(kw)	0.14	0.14	0.14

(1) Sync. peak power
(2) Total for all transmitters (including redundancy)
(3) Dependent on user installation and climate conditions

Table 7-4. Television Broadcast Satellite

Item			
Configuration	Earth Oriented "H" Configuration	Earth Oriented "I" Configuration	Sun-Oriented Body Configuration
Power - Frequency	12.4 kw - 900 MHz	4 kw - 2500 MHz	8 kw - 12,000 MHz
Solar Array	Roll Out 1950 Sq ft^2 (181 m^2) Axis parallel to orbit plane	Fold Out 630 Sq ft (58 m^2) Axis normal to orbit plane	Fold Out 1280 Sq ft^2 (119 m^2) Axis parallel to orbit plane
Body Orientation	Earth Center	Earth Center	Sun
Rotary Joint	Slip Ring	Slip Ring	RF Rotary Joint
Antenna Arrangement	(1) 30 ft (9.15 m) diameter transmitter antenna dish (1) 2-1/2 diameter (0.8 m) receive antenna	(2) 9 ft (2.8 m) diameter antenna dish transmitter	(3) 4-1/2 (1.4 m) diameter antenna
Satellite Weight	3600 lb (1630 kg)	1600 lb (7730 kg)	2200 lb (1000 hg)
Booster	Titan IIIC modified 7 Seg/Std Stg I/Stretch Transtage	SLV IIIC/Centaur/Burner II	TIIIC 5 Seg/Stg I/Transtage
Propulsion • Attitude control • Initial positioning • Station keeping	 Cold gas (N_2) Hydrazine Colloid system	 Cold gas (N_2) Hydrazine Colloid system	 Cold gas (N_2) Hydrazine Colloid system

7.2 CONFIGURATION (12 KW, 0.9 GHz)

This configuration operates at 0.9 GHz and produces 13.2 kw of RF power at sync peak. An engineering drawing of this configuration is given in Figure 7-1 while Figure 7-2 shows a perspective view. The solar array provides 12.1 kw of dc power at end of its 5-year lifetime and is composed of 1950 ft^2 (181 m^2) of solar cell area. The satellite in-orbit weight is 3544 (1610kg) pounds and is placed into synchronous equatorial orbit by a Titan IIIC. The spacecraft central body is earth-oriented and the 30 foot (9.15 m) transmitter antenna (3 degree beam) is gimbal-mounted to point to the desired terrestrial location. Antenna earth coverage is 1×10^6 square statute miles (2.6×10^6 square km), and the spacecraft communications capability provides TASO Grade 2.5 (fine/passable) service to receivers with a 6-foot dish in an urban environment (T = 2500°K).

The spacecraft is arranged in an "H" shape with four rollout solar arrays and a single 30 foot (9.15 m) broadcast antenna. The large antenna feed is supported by a truss structure which, in turn, supports the receive antenna, earth sensors, and sun sensors. The large parabolic antenna is a fold out petal type with rigid panels providing the most conservative approach with respect to stowed volume. The S-band receive antenna is 2.5 foot (0.8 m) in diameter and is mounted on the forward end of the truss structure. The solar array assembly rotates 360 degrees every 24 hours with respect to the spacecraft body. Torque and power transfers to the spacecraft body are provided by slip rings and solar array drive assembly. Actuated booms deploy the solar arrays after separation from the launch vehicle. The silicon cells are mounted on a plastic substrate. The spacecraft is shown installed on a Titan IIIC (modified) booster within a Titan XX35 fairing.

The attitude control system uses hydrazine and colloid engines to provide the required control torques; pitch and roll attitude references are provided by IR horizon sensors while RF sensors are used for accurate antenna pointing. Yaw reference is provided by a Polaris star sensor (a possible alternative is an inertial sensor).

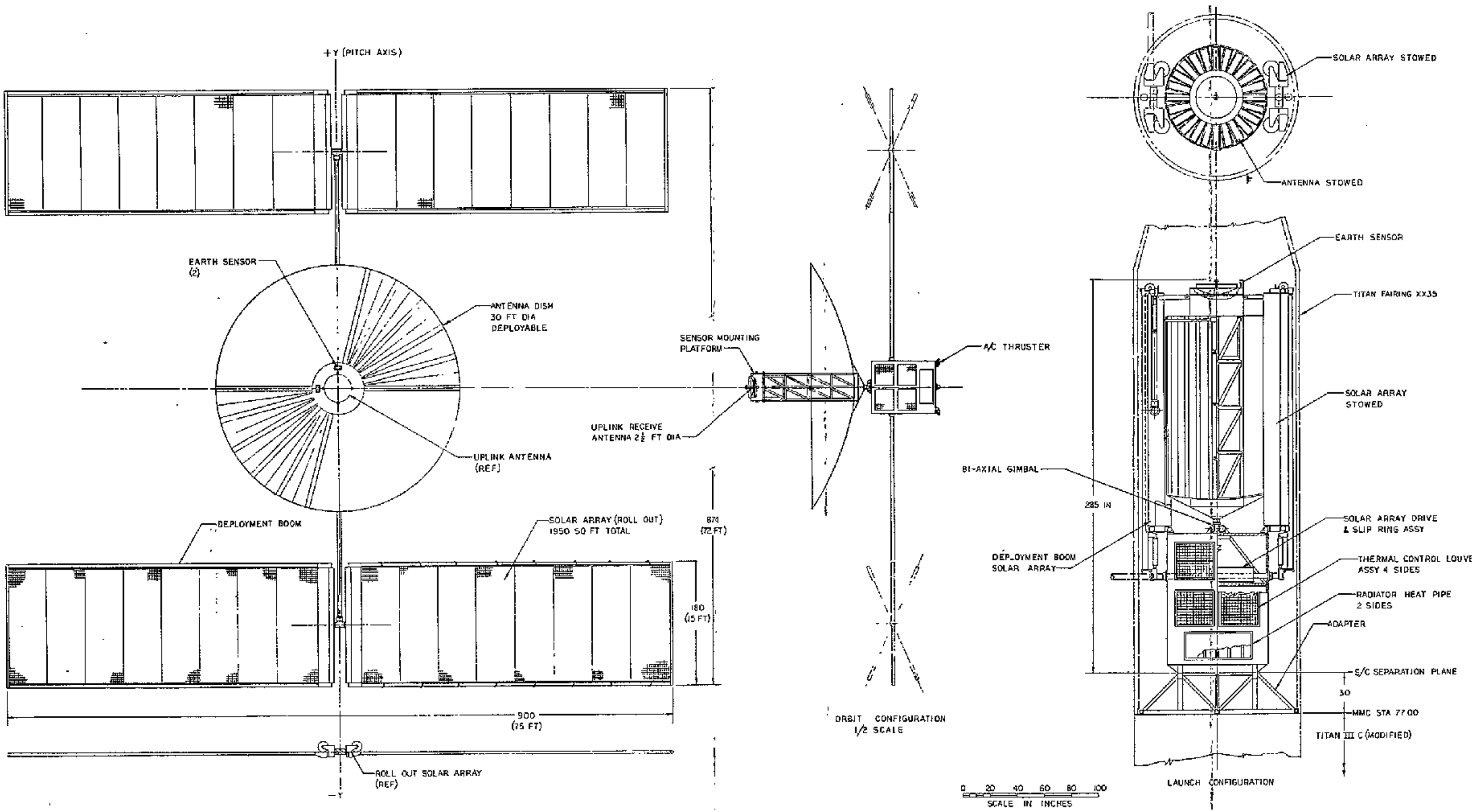


Figure 7-1. Television Broadcast Satellite Earth Oriented H Configuration (0.9 GHz; 12 kw)

1

FOLDOUT FRAME

2

FOLDOUT FRAME

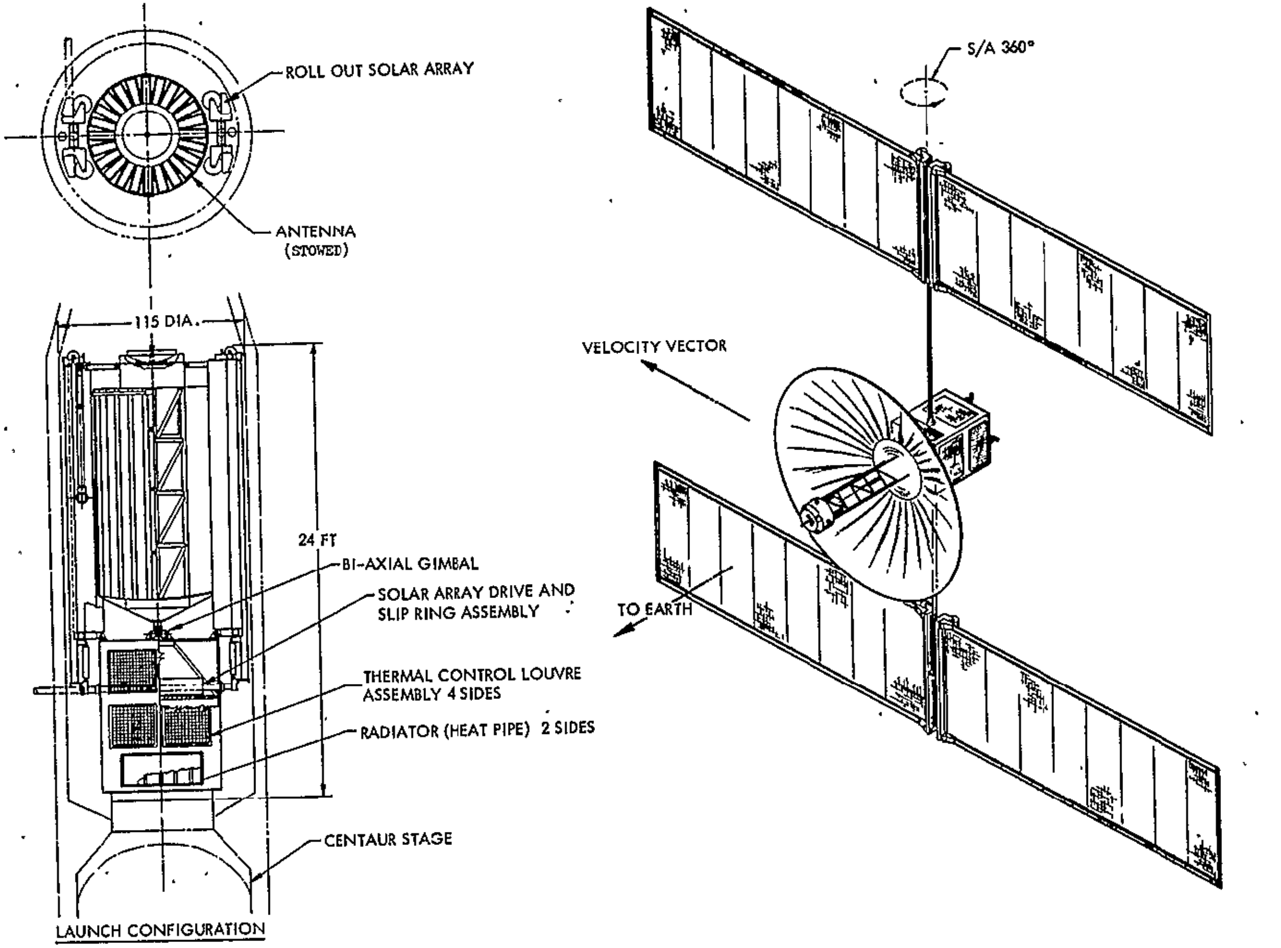


Figure 7-2. Perspective View Earth-Oriented H Configuration
(0.9 GHz; 12 kw)

Each 0.9 GHz 30-foot (9.15 m) antenna has a 3 degree 3-db beamwidth; the antenna focal length is 10.5 foot (3.2 m) and overall depth is 5.3 foot (1.6 m).

The AM/VSB repeater downlink uses amplitude modulation with vestigial sideband; the uplink makes use of frequency modulation with the sound on an FM subcarrier. The final amplifier is a 13 kw crossed-field amplifier with 20 db gain.

Second surface mirrors for thermal control are required in this configuration. The required louver area on the spacecraft is 87 ft^2 (8.1 m^2); approximately 2.5 kw are required to be dissipated from the RF tube, requiring a total radiator area of 20.6 $feet^2$ (19.1 m^2).

A summary of the spacecraft mass properties is given in Table 7-5.

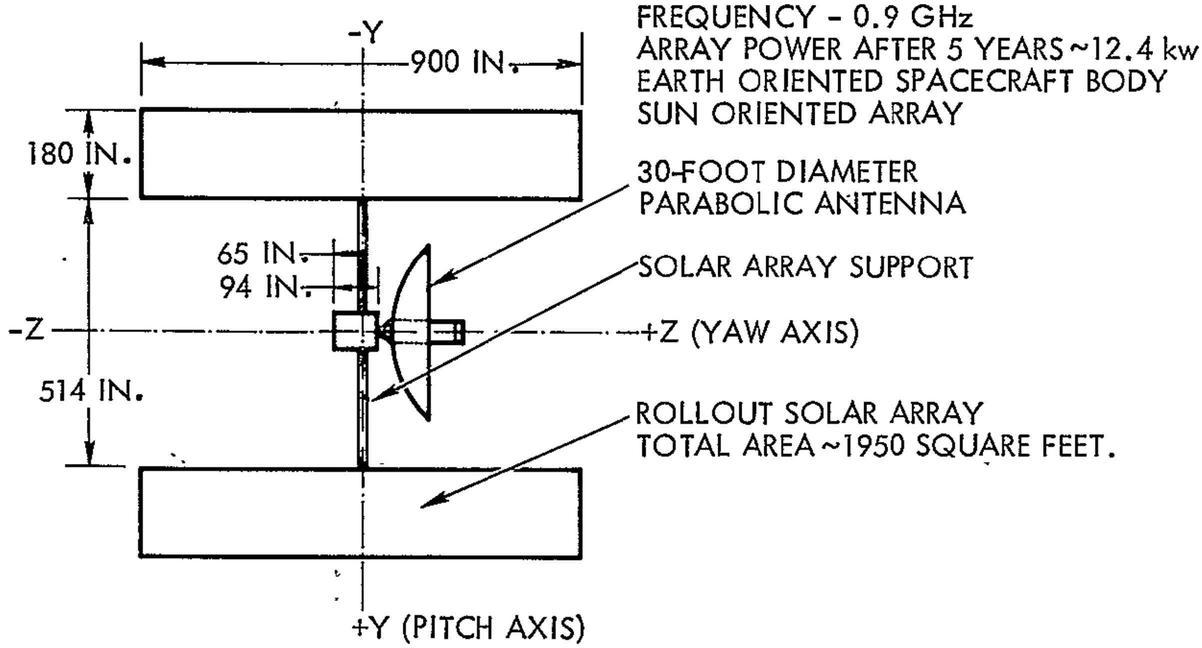
7.3 CONFIGURATION (4 KW, 2.5 GHz)

Seven broadcast channels at 2.5 GHz are provided by this FM/TV broadcast configuration; output RF power is approximately 300 w per channel. The solar array provides 4.13 kw at end-of-life from 630 ft^2 of solar cells. The satellite in-orbit weight is 1450 pounds (660 kg), and it is placed into synchronous equatorial orbit from an SLV-3C/Centaur/Burner II. The spacecraft central body is earth-oriented and two gimbal-mounted 9.25 ft (2.6 m) transmitter antennas point towards the desired terrestrial location. Each antenna has a 3 degree beamwidth and covers 1.1×10^6 square statute miles. TASO Grade 2 (fine) service is provided to receivers with a 6-foot dish and a transistor preamplifier ($T = 800^\circ K$).

The spacecraft configuration is shown in Figure 7-3. The antennas are deployed on booms such that the axis is parallel to the orbit plane; a limited biaxial gimbal is provided on each antenna. The solar array is in an "I" arrangement with two foldout solar arrays deployed by booms on opposite sides of the spacecraft. The solar arrays are deployed along the pitch axis of the satellite, normal to the orbit plane, and consist of silicon cells mounted on a plastic substrate which, in turn, is stored in "zee" folds. The solar array rotates 360 degrees every 24 hours and requires slip rings and solar array drive. The earth sensors and electronics are

Table 7-5. Mass Properties Summary - 0.9 GHz Configuration

COORDINATE REFERENCE AXES AND NOTATION SYSTEM



MASS PROPERTIES SUMMARY

- WEIGHT ~ 3544 POUNDS
- CENTER OF GRAVITY

$\bar{X} \sim 0$
$\bar{Y} \sim 0$
$\bar{Z} \sim -5.3$ INCHES

- MOMENT OF INERTIA -5.3 INCHES

$I_x \sim 45{,}224$ SLUG-FT^2
$I_y \sim 16{,}684$ SLUG-FT^2
$I_z \sim 29{,}490$ SLUG-FT^2

(WITH ARRAYS ROTATED 90 DEGREES)

$I_x \sim 30{,}362$ SLUG-FT^2
$I_y \sim 16{,}684$ SLUG-FT^2
$I_z \sim 44{,}352$ SLUG-FT^2

- CENTER OF GRAVITY TO CENTER OF PRESSURE OFFSET ~10 IN.

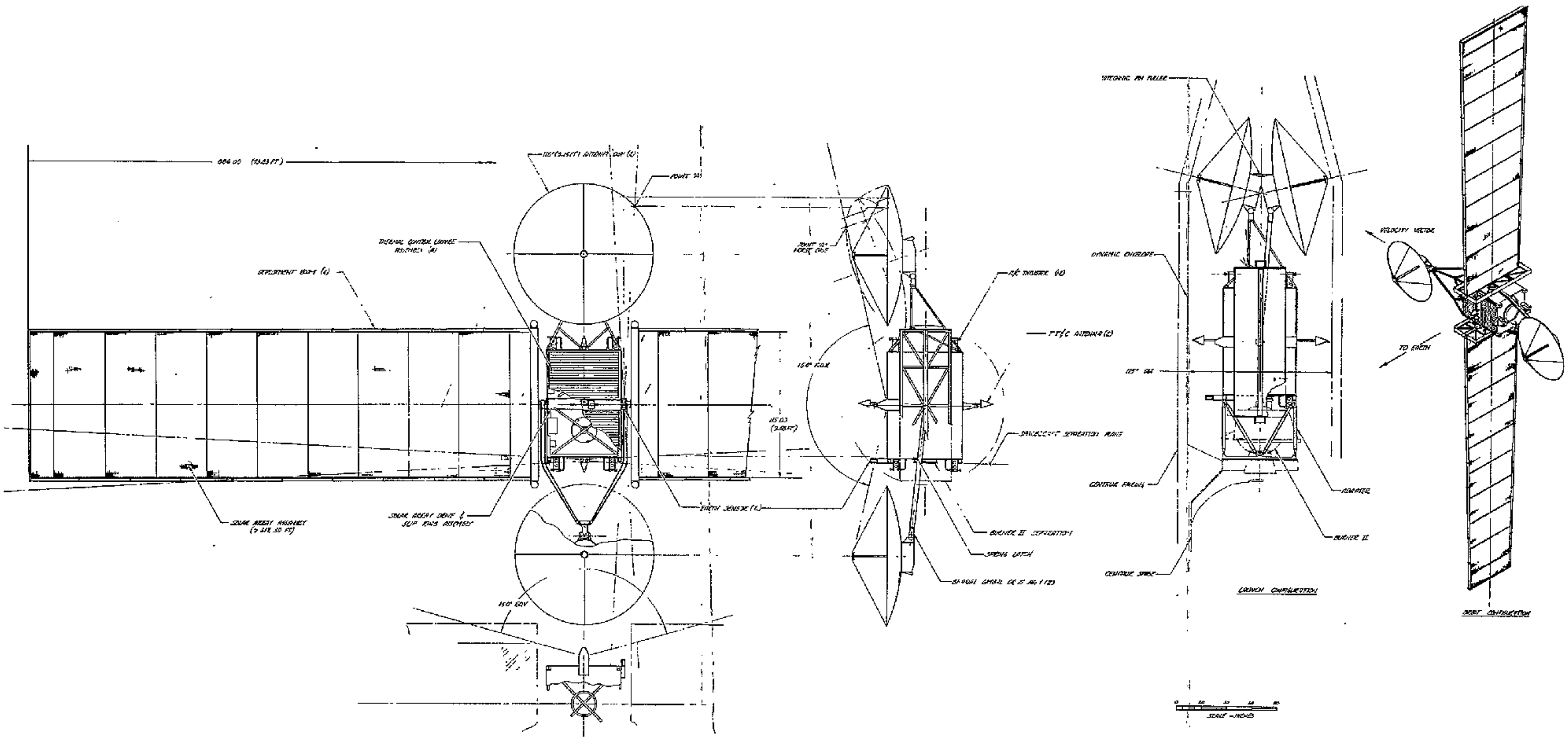


Figure 7-3. Television Broadcast Satellite (4 kw, 2.5 GHz, Two 9.25 Foot Diameter Antennas)

1.
FOLDOUT FRAME

2.
FOLDOUT FRAME

body-mounted. The spacecraft is shown installed on an Atlas SLV-3C/ Centaur/Burner II booster within an improved Centaur fairing.

The attitude control system is basically similar to that described in Paragraph 7.1. It makes use of hydrazine and colloid engines to provide the required control torques; pitch and roll attitude reference is provided by IR horizon sensors with yaw attitude reference obtained by a Polaris star sensor. Interferometers are used for accurate antenna pointing. Stationkeeping is performed by colloid engines.

The antenna 3-db beamwidth is 3 degrees; focal length is 3.2 ft (1.0 m); overall depth is 1.6 ft (0.5 m).

Approximately 1.2 kw of power are required to be dissipated from the RF tube; 6.9 ft^2 (0.7 m^2) of radiator area is needed. Louver area of 29 ft^2 (2.7 m^2) is required to dissipate 0.4 kw of power from the power control section. Second surface mirrors are required on the louver radiator area.

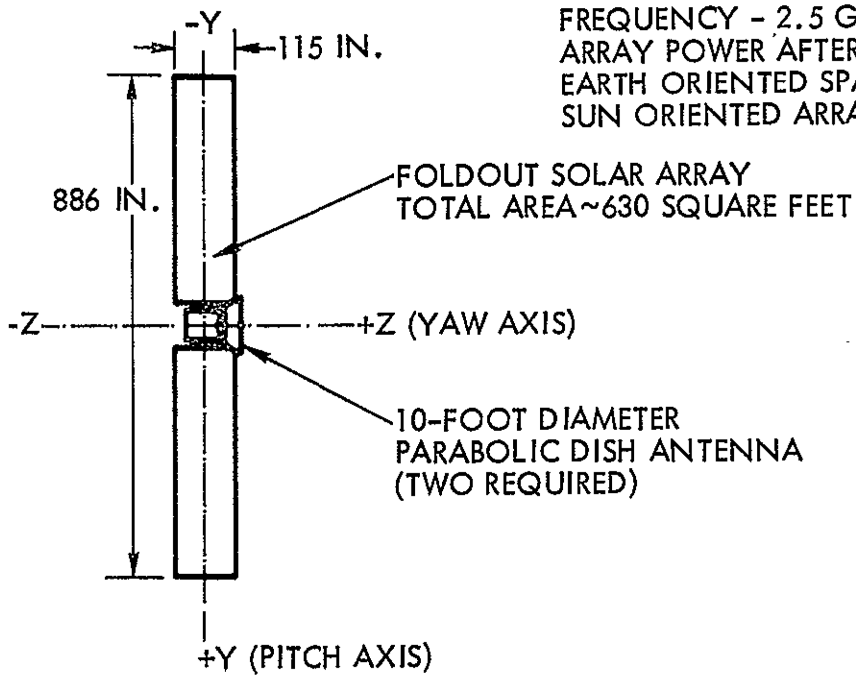
A summary of the satellite mass properties is given in Table 7-6.

7.4 CONFIGURATION (8 KW, 12 GHz)

This configuration provides FM/TV broadcast at 12 GHz and has the capability of one 5-kw output channel or two 2.5-kw channels. The solar array provides 8 kw of dc power at end-of-life and is composed of 1280 ft^2 (119 m^2) of solar cells. The satellite in-orbit weight is 2145 pounds (980 kg); the launch vehicle is a Titan IIIC or Titan IIIC follow-on. The spacecraft central body is sun-oriented with fixed solar panels; the two gimbal-mounted transmitter antennas maintain the desired earth pointing direction. Each antenna is 4.5 ft (1.4 m) in diameter with a 1.5 degree beam; each beam covers 2.5 x 10^5 square statute miles (7.0 x 10^5 square km). The broadcast capability provides TASO Grade 2 (fine) service and has a single beam capacity with 2800°K receivers or a dual beam capacity with 1400°K (Schottky diode, balanced mixer) receivers.

Table 7-6. Mass Properties Summary - 2.5 GHz Configuration

COORDINATE REFERENCE AXES AND NOTATION SYSTEM



FREQUENCY - 2.5 GHz
ARRAY POWER AFTER 5 YEARS~4 kw
EARTH ORIENTED SPACECRAFT BODY
SUN ORIENTED ARRAY

MASS PROPERTIES SUMMARY

- WEIGHT ~ 1450 POUNDS
- CENTER OF GRAVITY

  $\bar{X}$ ~ 0
  $\bar{Y}$ ~ 0
  $\bar{Z}$ ~ 1.0 IN.

- MOMENT OF INERTIA

  Ix ~ 5336 SLUG-FT^2
  Iy ~ 510 SLUG-FT^2
  Iz ~ 5508 SLUG-FT^2

  (WITH ARRAYS ROTATED 90 DEGREES)

  Ix ~ 5251 SLUG-FT^2
  Iy ~ 510 SLUG-FT^2
  Iz ~ 5593 SLUG-FT^2

- CENTER OF GRAVITY TO CENTER OF PRESSURE OFFSET < 1.0 IN.

The spacecraft configuration is shown in Figure 7-4. The antenna system has 3 degrees of freedom relative to the spacecraft. An RF rotary joint provides continuous antenna motion about the spacecraft pitch axis. A two-axis gimbal with flexible waveguides (not shown in Figure 7-4) provides ± 2.4 degrees motion about two orthogonal axes. Error reference signals are obtained from an antenna-mounted earth sensor (RF). The solar arrays consists of two foldout array panels deployed by booms which are parallel to the orbit plane. The antenna array consists of three 4.5 foot (1.4 m) parabolic dishes, one of which is used as a receive antenna. Interferometers mounted to the antenna array truss provide for antenna attitude orientation sensing. The stowed spacecraft is shown installed on a Titan IIIC booster within a Titan XX25 fairing. The spacecraft is sun-oriented using a 3-axis stabilized attitude control system; sun sensors are used in pitch and roll and a Canopus star tracker for yaw. Hydrazine is used for velocity trim and attitude acquisition. Colloid engines are used for long-term attitude control and stationkeeping.

The antenna focal length is 1.50 foot (0.46 m) with an overall depth of 0.80 foot (0.25 m).

In this configuration both the up and down links are frequency modulated with the sound on an FM subcarrier. Double frequency conversion with a transistorized 2 GHz IF strip is used together with a traveling wave tube driver (30-db gain). The final output amplifier is a 5-kw output at 12 GHz.

Approximately 2.0 kw of power must be dissipated from the RF tube, requiring 11 ft^2 (1.0 m^2) of radiator areas; 0.6 kw of power must be dissipated from the power control unit requiring 11.8 ft^2 (1.1 m^2) of louver area; no second surface mirrors are required on the louver radiator area.

A summary of the spacecraft mass properties is given in Table 7-7.

7.5 RELIABILITY ESTIMATES

This section presents a preliminary reliability assessment of three configurations of the Television Broadcast Satellite. Areas in the subsystem where redundancy is recommended are pointed out.

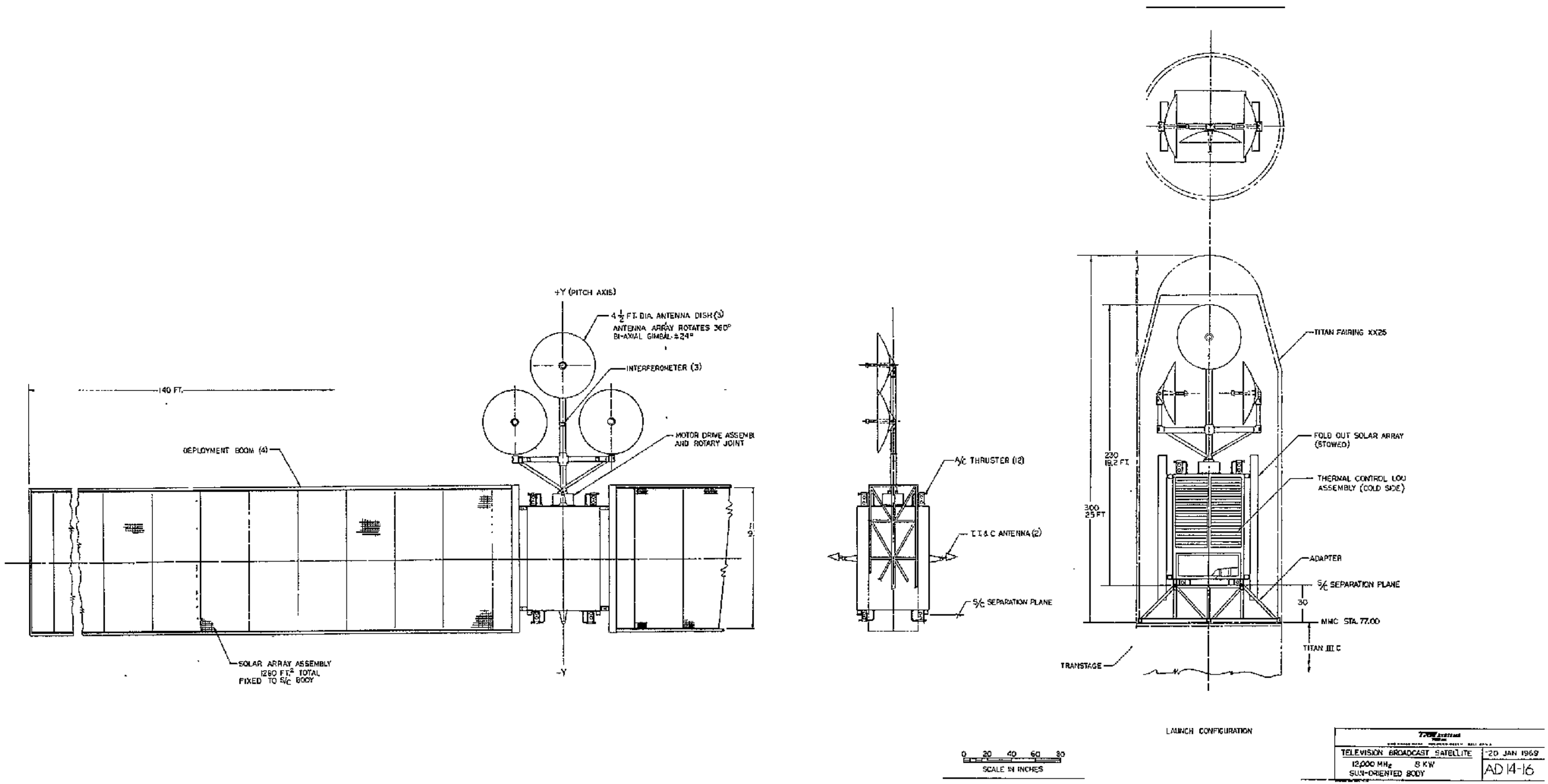


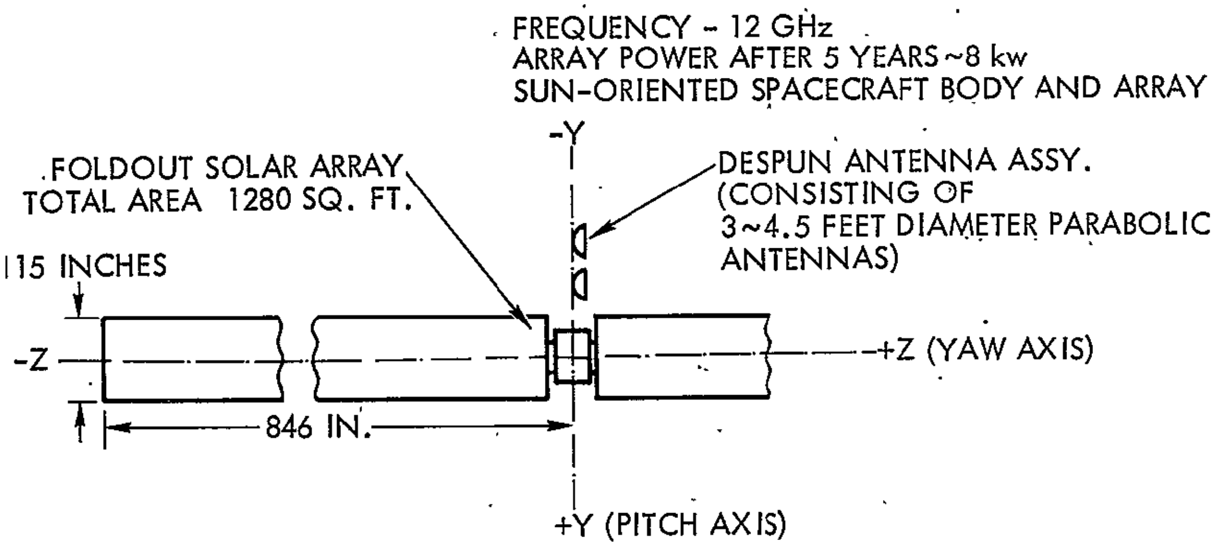
Figure 7-4. Television Broadcast Satellite Sun-Oriented Body (8 kw, 12 GHz)

1.
FOLDOUT FRAME

2.
FOLDOUT FRAME

Table 7-7. Mass Properties Summary - 12 GHz Configuration

COORDINATE REFERENCE AXES AND NOTATION SYSTEM



MASS PROPERTIES SUMMARY

- WEIGHT ~ 2145 POUNDS
- CENTER OF GRAVITY

  $\bar{X} \sim 0$
  $\bar{Y} \sim -4.2$ INCHES
  $\bar{Z} \sim 0$

- MOMENT OF INERTIA

  Ix ~ 37,176 SLUG-FT^2
  Iy ~ 36,688 SLUG-FT^2
  Iz ~ 709 SLUG-FT^2

  (WITH ARRAYS AND SPACECRAFT BODY ROTATED 90 DEGREES)

  Ix ~ 692 SLUG-FT^2
  Iy ~ 36,688 SLUG-FT^2
  Iz ~ 37,193 SLUG-FT^2

- CENTER OF GRAVITY TO CENTER OF PRESSURE OFFSET <1.0 IN.

The reliability assessments for the three satellite configurations for a 5-year mission are as follows:

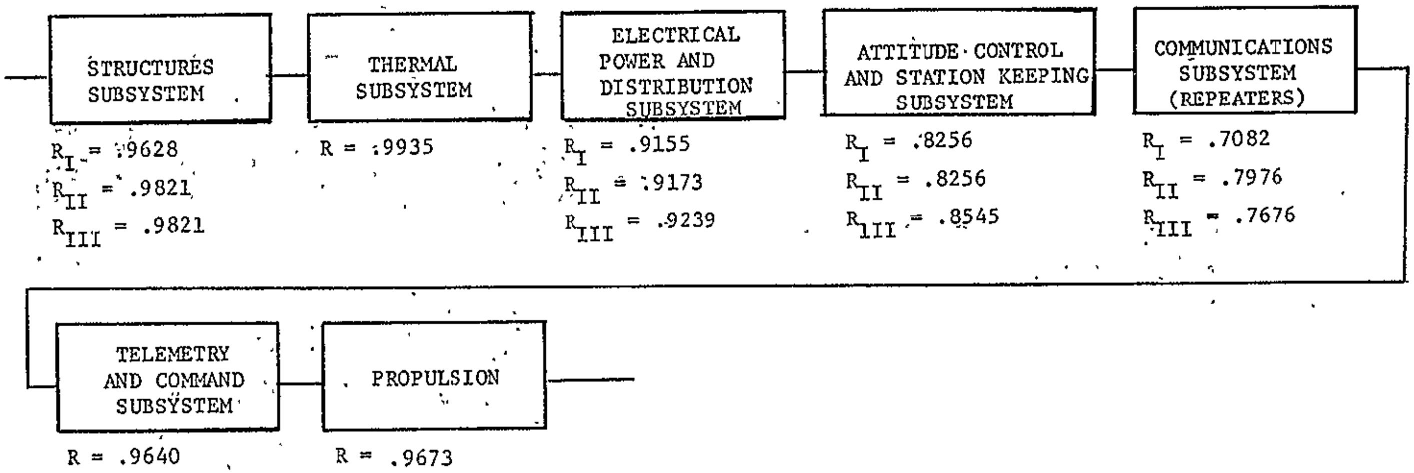
Configuration I: (900 MHz)	0.477	
Configuration II: (2.5 GHz)	0.550	(reliability of one given channel; satellite carries seven channels)
Configuration III: (12 GHz)	0.544	

For this analysis the satellite is segregated into the following subsystems:

- Communications
- Telemetry and command
- Attitude control and stationkeeping
- Electrical power and distribution
- Structures
- Thermal control
- Propulsion

Figure 7-5 depicts the reliability block diagram for the satellite and lists the reliability of each subsystem and the overall satellite reliability for each configuration. The repeaters are the largest contributors to the satellite unreliability. Standby redundant repeaters are recommended for future design efforts.

Communications Subsystem. Figures 7-6, 7-7, and 7-8 contain the reliability block diagrams of the communications subsystem for the three satellite configurations. These diagrams reflect the functional block diagrams in Figures 7-9, 7-10, and 7-11. The failure rates for the elements were obtained from similar equipment found on other TRW satellite designs. Failure rates for the high power amplifiers were extrapolated from lower powered amplifiers. Redundancy is recommended as shown in the diagrams for all the power amplifiers, except for Configuration II when graceful degradation of number of channels is acceptable. This is a common practice in most TWTA and Klystron



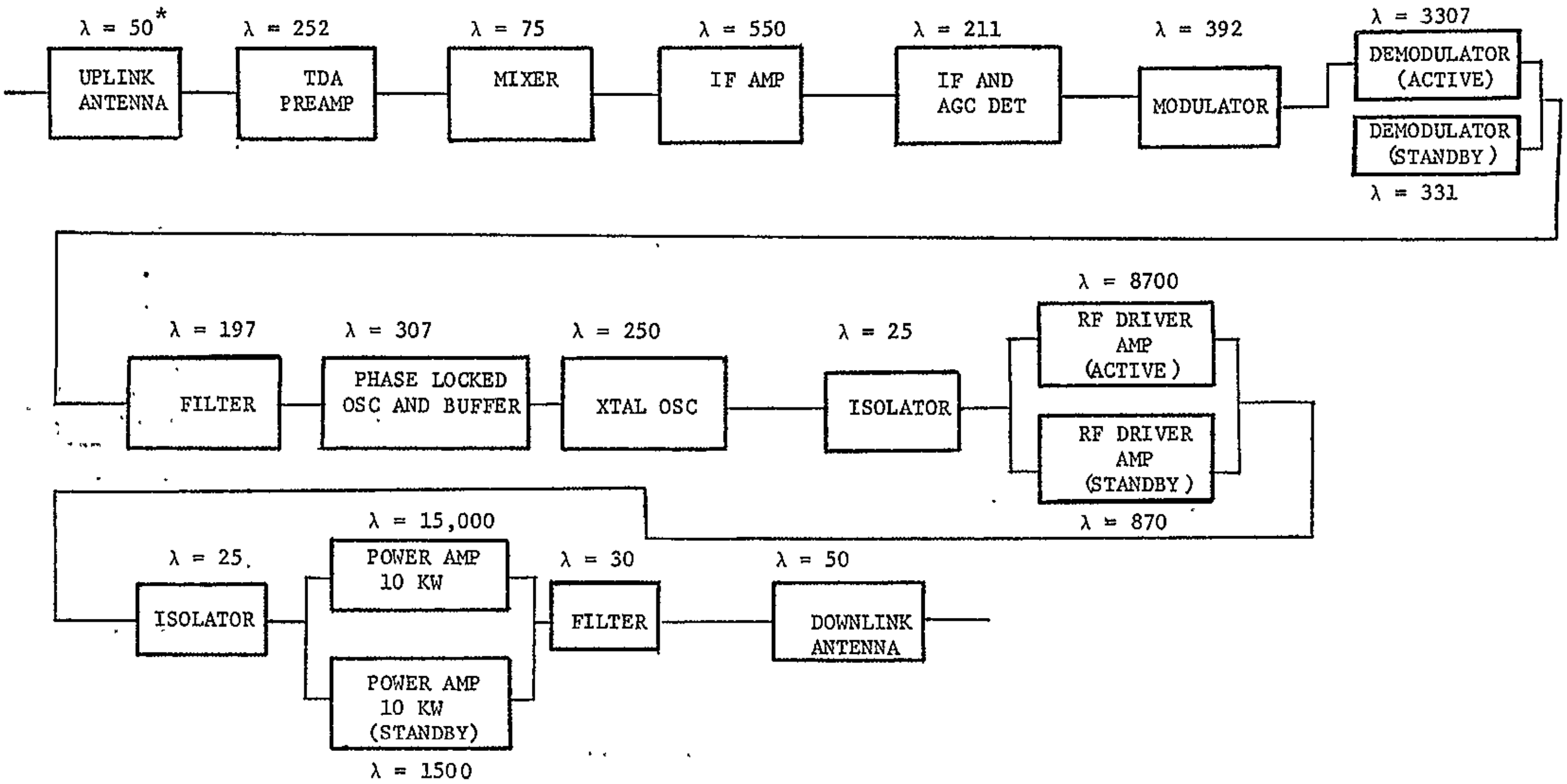
Total spacecraft reliability for each configuration for five years,

$R_I = .4774$

$R_{II} = .5496$

$R_{III} = .5441$

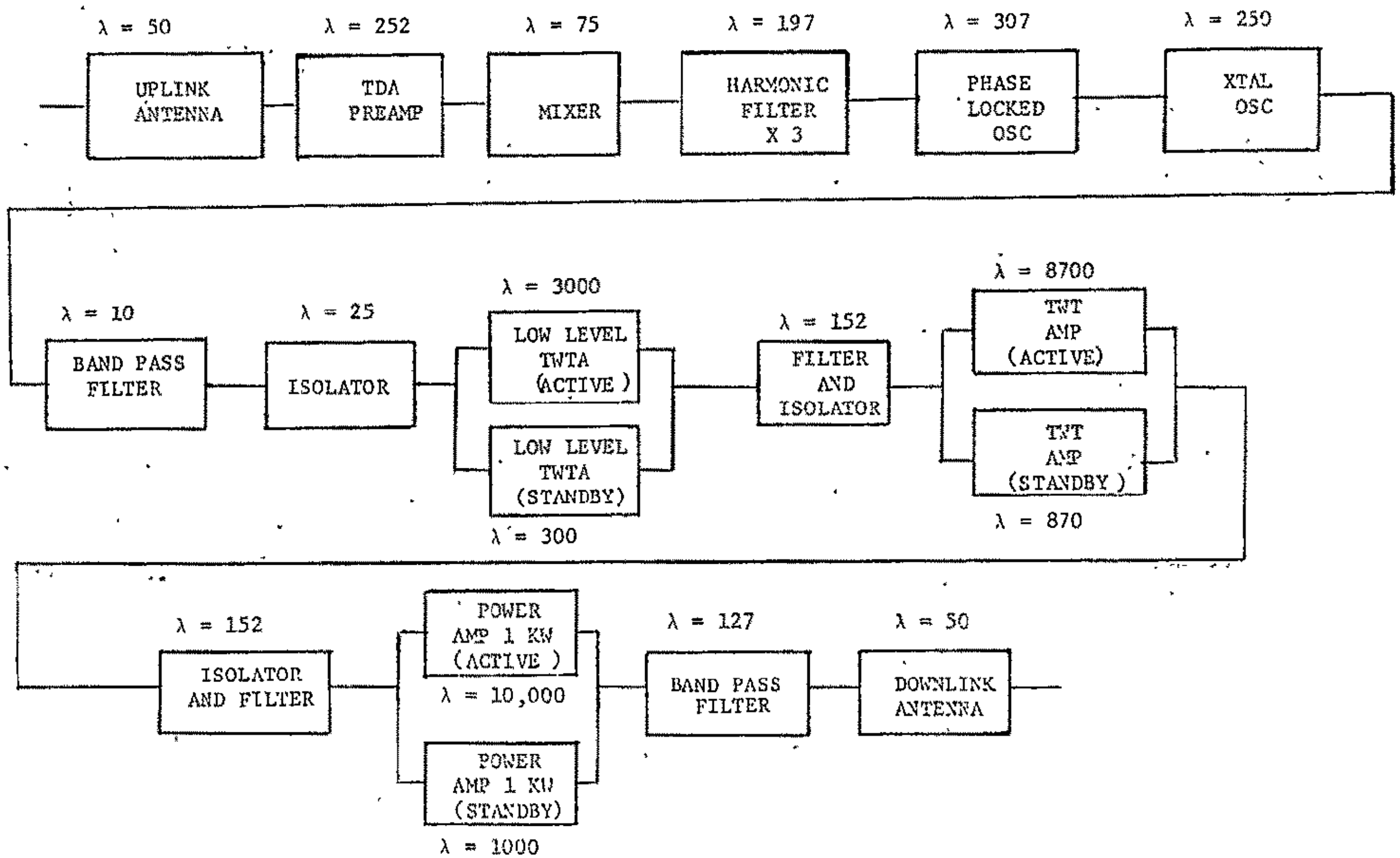
Figure 7-5. Satellite Reliability Block Diagram



Overall Reliability for five years, R = .7082

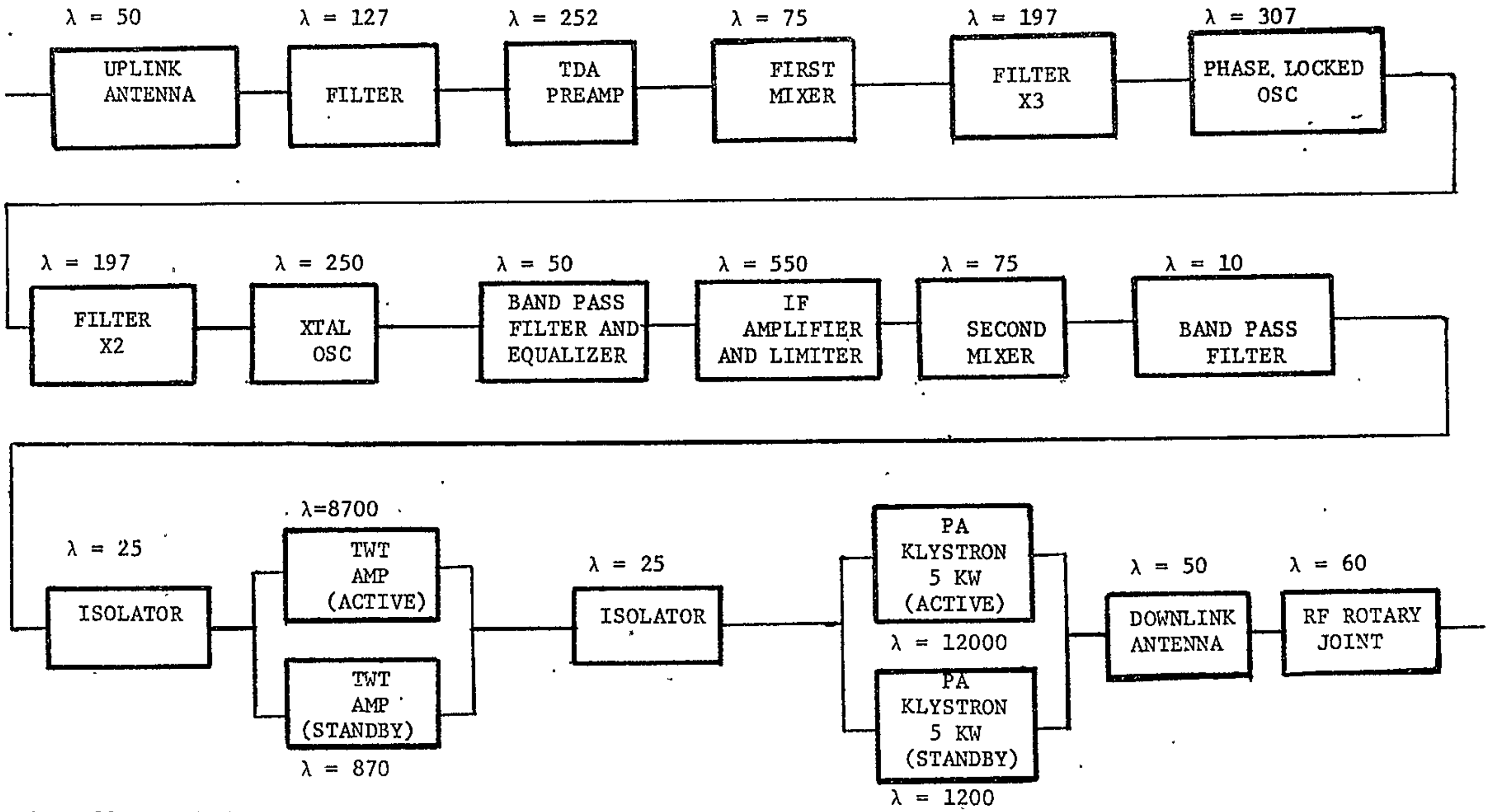
* Failure rates are $\lambda/10^9$ hours.

Figure 7-6. Communications Subsystem Configuration I (900 MHz) Repeater Channel



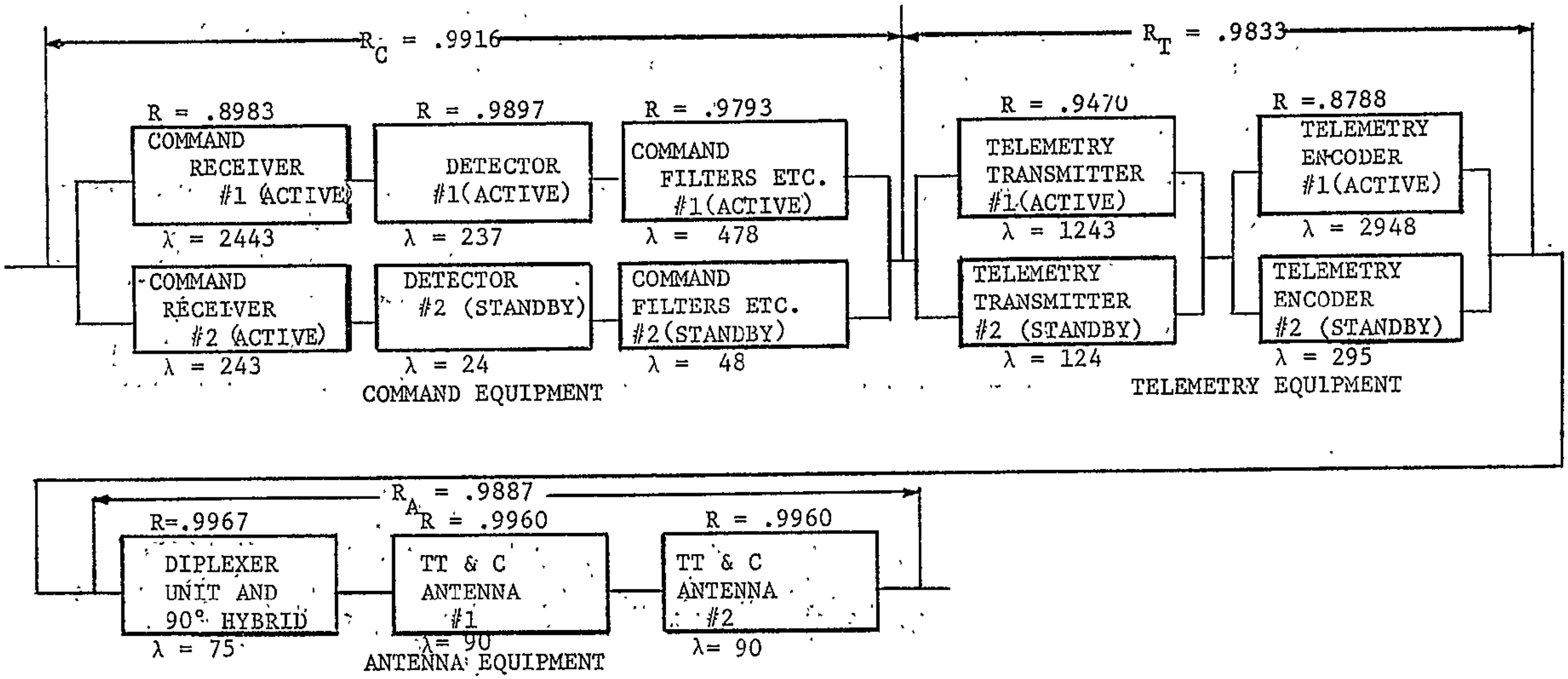
Overall Reliability for five years, R = .7976

Figure 7-7. Communications Subsystem Configuration II 2.5 GHz Repeater Channel



Overall Reliability for five years, R = .7576

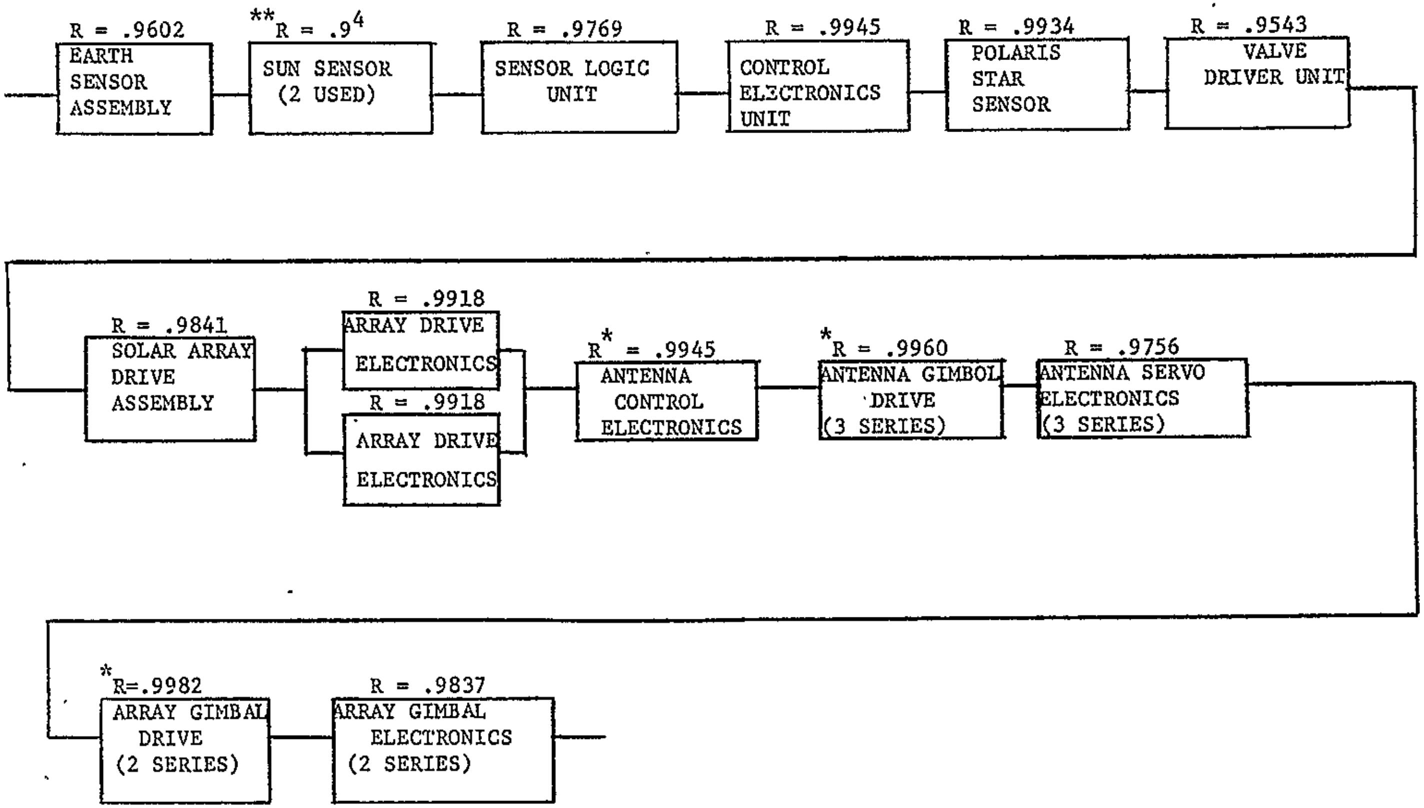
Figure 7-8. Communication Subsystem Configuration III 12 GHz Repeater Channel



TOTAL RELIABILITY FOR TELEMETRY AND COMMAND FOR FIVE YEARS

$$R = R_C \times R_T \times R_A = .9916 \times .9833 \times .9887 = .9640$$

Figure 7-9. Telemetry and Command Subsystem Reliability Block Diagram



* Must contain internal redundancy

** $.9^4 = .9999$

Total Reliability = .8256 For Earth Oriented Spacecraft For 5 Years

Total Reliability = .8545 For Sun Oriented Spacecraft For 5 Years

Note: This diagram reflects the earth oriented spacecraft configuration which is more complex than the sun oriented configuration. The sun oriented version can be obtained by eliminating the solar array drive, array drive electronics, array gimbal drive and array gimbal electronics.

Figure 7-10. Attitude Control Subsystem Reliability Block Diagram

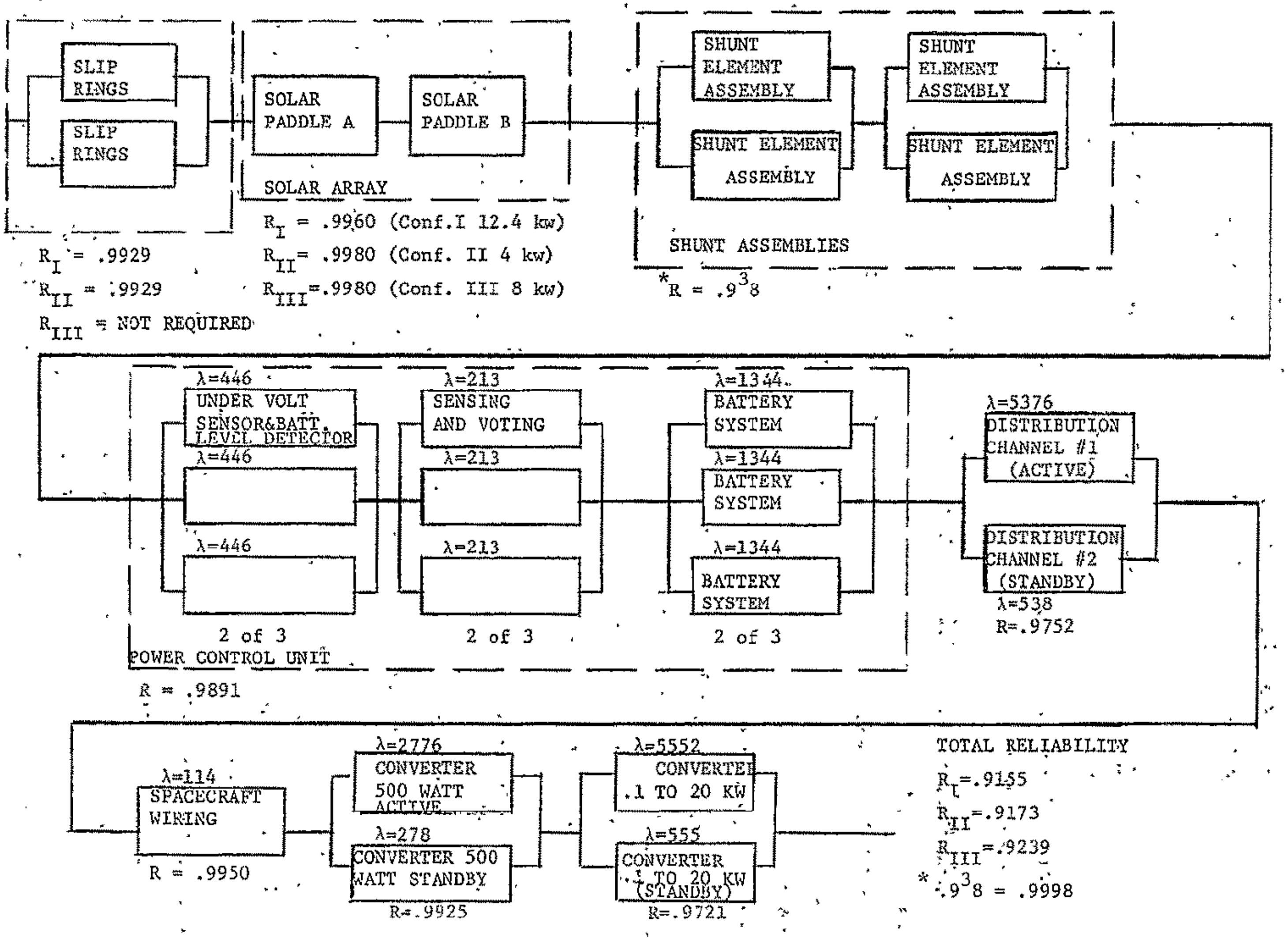


Figure 7-11. Electrical Power and Distribution

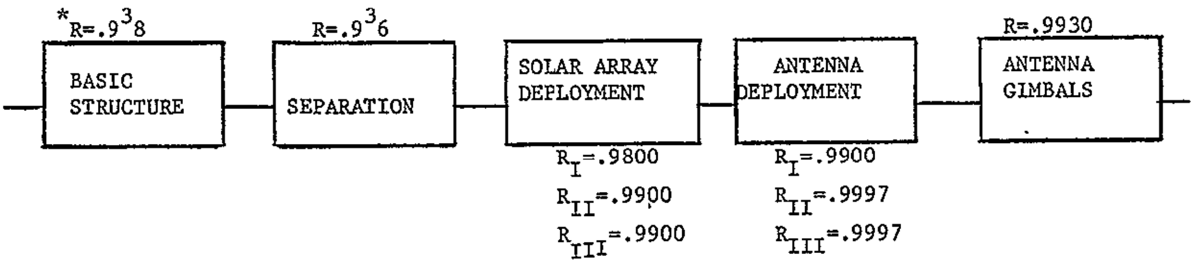
amplifier applications due to the uncertain life expectancy of these components. An RF rotary joint is required in the Configuration III antenna system.

Telemetry and Command. Figure 7-9 shows the reliability block diagram for the telemetry and command subsystem. Standby redundant command and telemetry channels are employed. Dual antennas are used to provide proper coverage.

Attitude Control and Stationkeeping. Reliability block diagram is shown in Figure 7-10. Two different design concepts of attitude control are currently being considered for the Television Broadcast Satellite, the earth-oriented version and the sun-oriented version. The earth-oriented version is more complex in that it must provide an additional function over the sun-oriented version of solar array alignment with the sun. Configurations I and II employ the earth-oriented concept while Configuration III employs the sun-oriented concept. Failure rates for the elements of the attitude control system are from similar elements used on TRW satellite programs.

Electrical Power and Distribution. Figure 7-11 shows the reliability block diagram for this subsystem. A three battery system is depicted. Heavy redundancy is evident in the power control unit, shunt assemblies, distribution circuits, and converters. The failure rates are typical for electrical power subsystems. The reliabilities of the solar paddles were determined by extrapolation from OGO and other solar arrays, assuming the same design philosophy is being employed to assure an overdesign safety factor against anticipated cell degradation. The reliability of the high power converters was obtained by a comparison with existing power converters. Further emphasis should be placed on substantiating the reliability of high voltage (up to 200 volts) slip rings since little data were available for this analysis. Also further study from a reliability standpoint should be placed on the high power converters used in spacecraft applications.

Structures. Figure 7-12 is a reliability block diagram for the structures subsystem. The solar array is much larger (up to 1950 square feet) than present operational satellites. Account has been made for the increased complexity of deploying large surface arrays for the array deployment probability. The antenna deployment probability was determined from other studies of similar equipments at TRW.



TOTAL RELIABILITY

R_I = .9628

R_{II} = .9821

R_{III} = .9821

* $.9^3 8$ = .9998

Figure 7-12. Structures Subsystem

Thermal Control. Figure 7-13 accounts for the reliability of the thermal control subsystem. Four sets of louvers with 40 louvers per set were used in the analysis. No account has been given for the heat pipes since they are expected to contribute very little to the unreliability of the satellite because of their particular design.

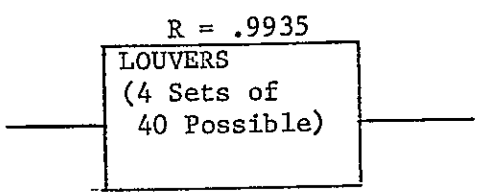


Figure 7-13. Thermal Control

Propulsion Subsystem. The propulsion subsystem is expected to consist of cold gas for attitude control, hydrazine for initial positioning, and a colloid system for stationkeeping. The reliability was estimated for this subsystem (Figure 7-14).

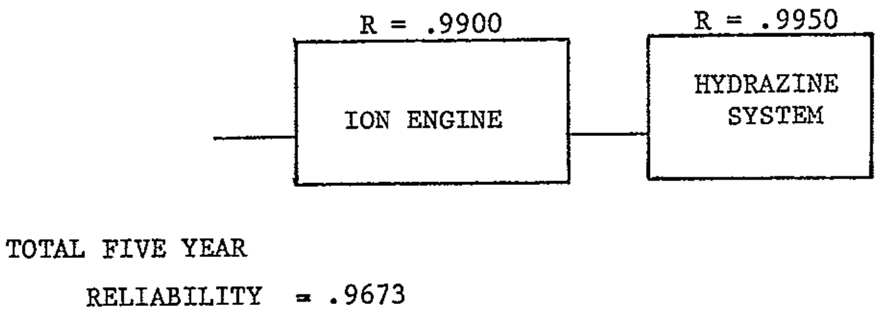


Figure 7-14. Propulsion Subsystem

8. ATTITUDE CONTROL AND STATIONKEEPING

This section discusses attitude control, gimbal control and stationkeeping for TV broadcast satellite configurations. System configuration tradeoffs are presented and key technology areas are identified. Typical control and stationkeeping systems are sized, with preliminary hardware component definition.

8.1 INTRODUCTION

The TV broadcast satellite presents several control problems which are not found in current operational spacecraft, but which are representative of a variety of projected 1970-1980 applications. Characteristics which are particularly significant to the control system include:

a) Large vehicle size and mass
b) Significant flexible dynamics
c) Large articulated external structures
d) Five-year minimum spacecraft life
e) Precision antenna pointing requirements

These features play a major role in spacecraft configuration/control tradeoffs.

The vehicle configurations considered are described in Section 7. Included are two which are earth-oriented, with two degree-of-freedom solar arrays and three degree-of-freedom antenna systems, and a third which is sun-oriented, with a fixed solar array and a "despun" and gimballed antenna system. Configuration characteristics are summarized in Table 8-1. The variations in size, shape, weight and orientation are clear.

8.2 CONTROL CONCEPTS

Considering each of the configurations of Table 8-1, there are several conceptual alternatives in control system mechanization, concerning both interbody control (i.e., antenna and array control) and spacecraft attitude control.

Table 8-1. Summary of TVBS Configuration Characteristics

Power (kw)	Config Freq (GHz)	Char Shape	Overall Size, ft (m)	Weight, lb (kg)	Description
8	12	"I"	140 x 20 (43 x 6)	2150 (980)	Sun-oriented body with fixed array; despun antenna system
4	2.5	"I"	29 x 74 (9 x 23)	1550 (705)	Earth-oriented body; gimballed antenna and array
12	0.9	"H"	75 x 72 (23 x 22)	3550 (1620)	Earth-oriented body; gimballed antenna and array

8.2.1 Attitude Control

The requirements placed upon antenna and array pointing have significant leverage in selecting an attitude control concept:

a) Antenna pointing: geodetically oriented to within ±0.1°

b) Array pointing: sun-oriented to within ±1.0°

In addition, antennas with a noncircular beam cross section (e.g., elliptical) require orientation control above the centerline of the beam to maintain correct coverage.

Note that there are no stringent orientation requirements on the spacecraft body, so that it can be free, fixed to the solar array, or fixed to the antenna system, provided that thermal control is designed accordingly. The first two approaches are considered in Table 8-1.

The 8 kw, 12 GHz vehicle is sun-oriented to within 1 degree required by the solar array. The antenna system is mounted to the body by a rotary drive system, which provides for unrestricted motion about the pitch axis, and a gimbal system.

With the rotary drive axle oriented normal to the ecliptic plane, to allow the use of body-fixed bearings, the unlimited rotation must be given a cyclic modulation at the rate of one cycle per orbit. The gimbal system required at the antenna end of the drive axle is a one-axis gimbal for a single beam with a circular cross section, a two-axis gimbal for other beam configurations. In the latter case, the second axis provides orientation about the beam centerline, compensating for the nutation (up to ±23 degrees) of the rotary drive axis with respect to the earth axis, at a rate of one cycle per orbit.

An alternative solution is to maintain the rotary drive axis normal to the earth equatorial plane by means of a one-axis gimbal between the spacecraft body and the rotary drive bearing. Then, the unlimited motion can be maintained at constant speed. Gimballing at the antenna end of the rotary drive axle can be required for two reasons:

1) Change of coverage; one gimbal axis for north-south movement.
2) Compensation for error in orientation of the rotary axis; one axis for rotation about the beam centerline; required only for beam configurations without circular symmetry, when orientation of rotary drive axis is not sufficiently accurate.

Sun orientation can be maintained in several ways, including:

a) Active control (mass expulsion and reaction wheels)
b) Active control (mass expulsion only)
c) Semiactive control (solar trim, for example)
d) Hybrid (e.g., reaction wheels with solar trim)

Antenna control can be accomplished using gimbal torquers acting on error signals from antenna-mounted sensors (e.g., earth-sensors or RF sensors) and offset pointing commands.

The available options for control of the 4 kw, 2.5 GHz and 12 kw, 0.9 GHz earth-oriented vehicles are more varied. Body control can be loose (e.g., 5 degrees or so) with accurate closed-loop antenna control using antenna-mounted sensors as above and solar array control via sun sensors. An alternative is maintaining spacecraft orientation with sufficient accuracy to allow open loop control of the antenna system via gimbal angle readouts. In either case the spacecraft can be oriented using active control, semiactively, or, in theory, semipassively or passively.

Active earth orientation can be accomplished with earth or RF attitude sensors for pitch and roll attitude determination, with yaw sensing via inertial instruments (e.g., updated rate integrating gyros), RF (polarization) sensing or star sensing. Actuators could include momentum storage devices (reaction wheels), but a mass expulsion system should be adequate. Table 8-2 summarizes several candidate concepts.

Table 8-2. Earth Oriented Attitude Control System Candidates

Control System	Performance	Attitude Reference Requirement	Remarks
Three-axis mass expulsion with inertia wheel (pitch momentum bias)	Can maintain body pointing of ±5.0 degrees. Body pointing to ±0.1 degree may be difficult.	Earth horizon sensors for pitch and roll. Yaw reference via roll/yaw coupling	Not much fuel saving due to small cyclic torque components
Three-axis mass expulsion with solar pressure trim	Can maintain body pointing of ±5.0 degrees. Body pointing to ±0.1 degree may be difficult.	Earth horizon sensors for pitch and roll. Polaris star sensor or gyrocompass for yaw	Solar pressure trim net weight saving questionable. Requires very sensitive gyro for gyrocompass yaw reference.
Three-axis mass expulsion	Can maintain body pointing of ±5.0 degrees. Body pointing to ±0.1 degree may be difficult.	Earth horizon sensors for pitch and roll. Polaris star sensor or gyrocompass for yaw.	Appears to be the best system.

Less active control concepts can be considered in less accurate options, but are probably not to be recommended. One such approach is semiactive, using pitch bias momentum to provide a high degree of roll/yaw coupling and so eliminating the troublesome yaw sensor requirement; however, the required bias momentum can become large.

Gravity gradient control of the body is conceivable, the main problem being that TVBS spacecraft configurations are not favorable. Yet a third possibility is a semipassive approach, with a pitch momentum bias to produce roll/yaw stability in spite of the unfavorable spacecraft configuration and inertia augmentation to yield pitch stability. It should be noted that the dominance of the array in determining the spacecraft inertias and the rotation of the array relative earth make any approach based on gravity gradient effects very questionable.

The baseline attitude control system selected here is active, using mass expulsion torquers, and sensors appropriate to the configuration in question. Section 8.3 defines these systems.

8.2.2 Interbody Control

In each of the three configurations interbody control systems are required to orient large external structures. Common to all is the earth-oriented antenna system which requires relatively tight control. Only the earth-oriented vehicles have an orientable solar array.

The ideal interbody control and suspension system would dynamically isolate the external structures from the vehicle body while orienting the antenna or array to within the desired accuracy. Short of essentially detaching these structures and providing them with their own attitude controllers this ideal is not readily attainable, particularly when the hinge point is remote from the mass center of the external structure as in the case of the antenna system.

The conventional approach to controlling antennas and arrays, that of using gimbal bearings and associated drive systems, is used here. The array drives required for the 4 kw, 2.5 GHz and 12 kw, 0.9 GHz configurations are two-axis arrangements, with one axis driven continuously at an average rate of 15 deg/hr and the other stepped infrequently by ground command to accommodate the varying sun-earth geometry (a range of approximately ±23.5 degrees). This implies a low-pass controller will rather low cutoff frequency for the array, if acquisition considerations are not considered.

The antennas need a more responsive drive system, since accurate geodetic control from a coarsely-controlled spacecraft is required. The range of travel will be application and configuration dependent, ranging from ± 20 degrees with a coarsely controlled earth oriented spacecraft to higher values with the solar oriented configuration. In addition, the sun-oriented 8 kw, 12 GHz vehicle requires a continuous motion "despin" mechanism for the antenna structure, analogous to the continuous array drive of the earth-oriented vehicles. Table 8-3 summarizes the array/ antenna control requirements for three attitude control approaches.

Table 8-3. External Structure Control Summary

Body Orientation	ACS Performance	Antenna Drive Requirement	Solar Array Drive Requirement	Remarks
Earth	±5.0 degree body control ±0.1 degree antenna pointing	Three-axis antenna, platform slaved to pointing errors.	Two-axis sun sensors, 24-hour drive pitch plus yearly gimbal drive.	Complex antenna pointing subsystem. Reduces spacecraft flexible body control problem.
Earth	±0.1 degree body pointing	±9.0 degree antenna gimbal actuator with open loop control	Two-axis sun sensors, 24-hour drive pitch plus yearly gimbal drive.	Simple antenna control, offset pointing. Complex spacecraft body pointing due to flexible body dynamics.
Sun	±1.0 degree sun oriented body pointing. ±0.1 degree antenna pointing.	Continuous pitch motion of antenna. Antenna drives with earth reference plus offset pointing bias.	None—body fixed arrays.	Complex antenna pointing. Moderate sun pointing body requirement. Appears to be the best ACS approach.

8.3 BASELINE ATTITUDE CONTROL SYSTEM DESCRIPTION

8.3.1 Earth-Oriented Configurations

A block diagram of the baseline ACS is shown in Figure 8-1. This system uses nitrogen gas and colloid engines to provide the control torques with the pitch and roll attitude references provided by infrared horizon sensors or RF sensors. The yaw attitude reference is provided by a Polaris star sensor with an inertial instrument as a possible alternative. An RF polarization sensor is another candidate, but would have difficulty in meeting the ±0.1-degree accuracy due to the Faraday rotation effect of the ionosphere.

The attitude errors measured with respect to body axes are directed into the control electronics. The control electronic unit consists of lead-lag networks and pulse modulators for conditioning the high level and low level thruster commands. The pulse modulator issues commands to fire the thrusters for a specific duration depending upon error magnitudes. In the undisturbed condition the low thrust pulse modulator issues a minimum impulse command to keep the spacecraft in a limit-cycle mode.

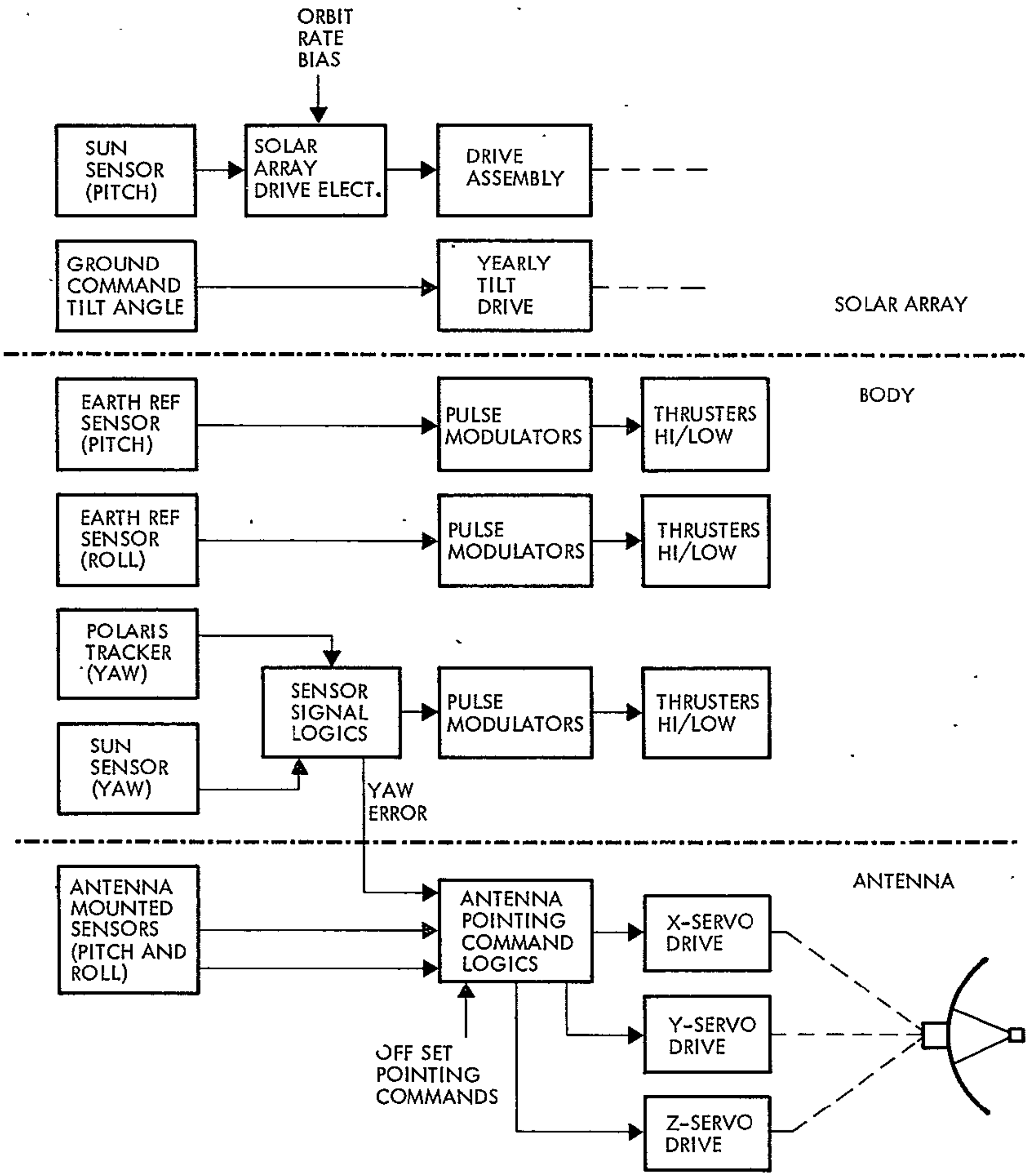


Figure 8-1. Earth-Oriented ACS

A dual level system, with heated nitrogen thrusters for acquisition and colloid engines for steady-state operation is recommended both for system weight and performance.

8.3.2 Sun-Oriented Configuration

As shown in Figure 8-2 the spacecraft is sun-oriented via a simple three-axis ACS, using sun sensors in pitch and roll and a Canopus star tracker for yaw sensing. Again nitrogen (with nozzle heaters) is the baseline high-level propellant for acquisition with colloid engines used for long term attitude control and stationkeeping.

The antenna system is provided with three degrees of freedom relative to the spacecraft, including the required continuous despin motion about the spacecraft pitch axis. In the baseline configuration error reference signals are from an earth sensor system (horizon or RF) which is antenna mounted. An alternate would be the use of accurate sun sensors and gimbal transducers; however, the servo commands would be more complex and otherwise unnecessary requirements would be imposed upon other system components. Long-term correction factors (e.g., yearly) and offset commands are ground controlled.

8.3.3 Acquisition

In general, the spacecraft must have acquisition capability from random orientation, either for initial acquisition or possible reacquisitions. In this case the acquisition operation has two basic steps.

a) The spacecraft must be able to null the tipoff rate imparted to the spacecraft during separation.

b) The spacecraft must acquire the terminal attitude reference (e.g., sun, earth).

Sun sensors offer the most convenient all-attitude reference and, therefore, it is most realistic to initiate acquisition by sun orienting one spacecraft axis. For the sun-oriented configuration, star reference is then attained by a slow search about the sun line. Antenna lock-on is then effected by ground command of the antenna servos.

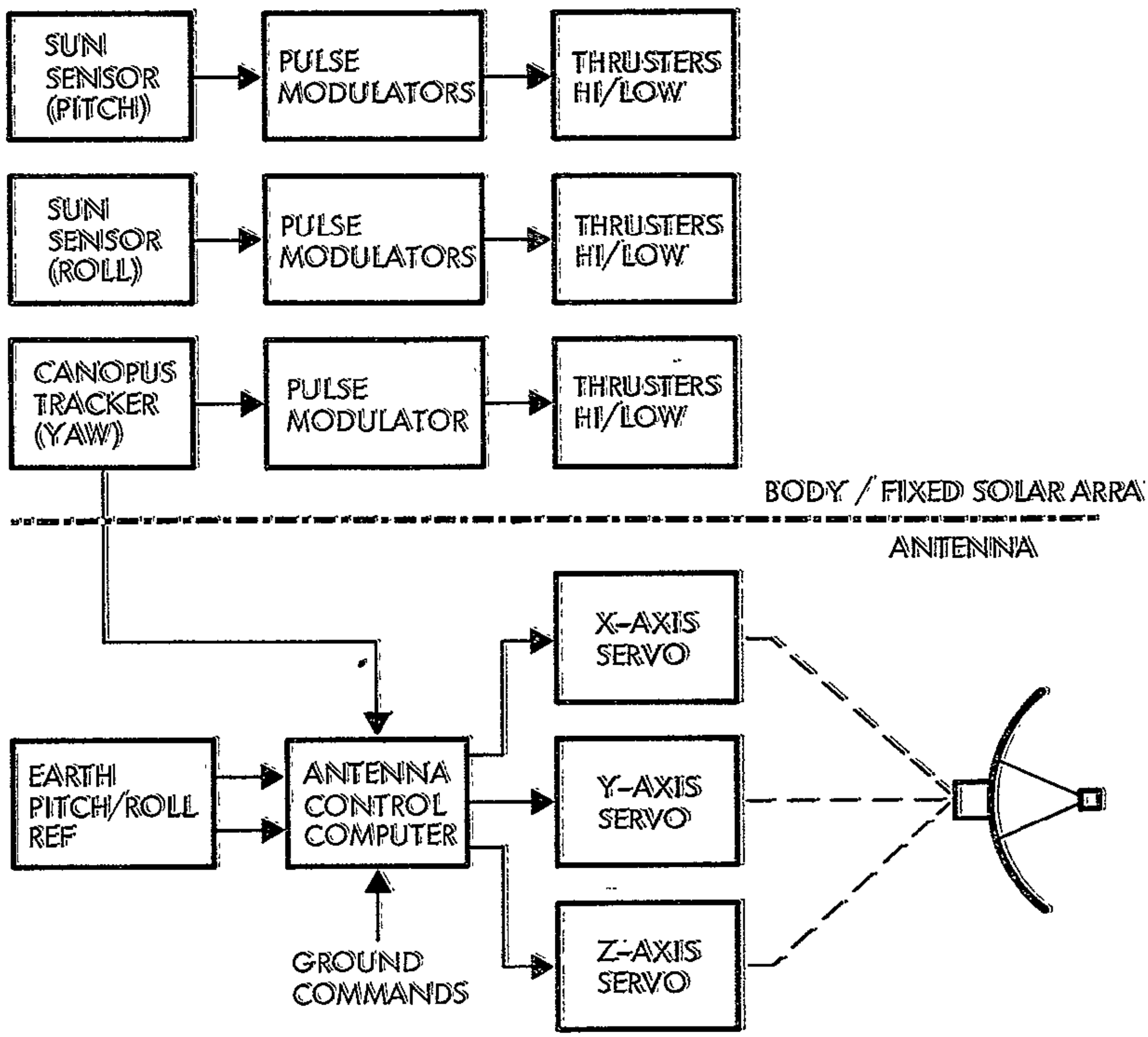


Figure 8-2. Sun-Oriented ACS

A similar search will serve to locate the earth for the earth-oriented configurations. Control of the pitch and roll axes is then transferred to the earth sensors, with sun sensor control of yaw. At some later time yaw control is transferred to the primary yaw reference and antenna reference is acquired.

8.3.4 Impulse Requirement

A key subsystem parameter is the control impulse required. Table 8-4 summarizes the estimated control impulse consumption due to several effects. Environmental disturbances are outlined in Appendix 8.A while stationkeeping disturbances are based upon the data of Section 8.4 with an assumed offset of 0.1 foot (2.5 centimeters). Acquisition estimates are based upon a single-axis model with an initial rate of 0.25 deg/sec and 0.1 pound (45 gram) thrust. Lever arms of 5 feet (1.5 meters) are used in each axis.

Table 8-4. Control Impulse Requirements for a 5-Year Mission

Item	Configuration					
	8 kw, 12 GHz		4 kw, 2.5 GHz		12 kw, 0.9 GHz	
	lb-sec	kg-sec	lb-sec	kg-sec	lb-sec	kg-sec
Environmental Disturbance	8, 600	3900	1500	680	9, 400	4300
ΔV Disturbance	1, 300	590	900	410	2, 100	950
Acquisitions (2)	1, 200	550	100	45	2, 000	910
Total	11, 100	5040	2500	1135	13, 500	6160

Not included here is impulse consumption due to limit cycling. This omission is logical since in a properly sized system the limit cycle should be torque-loaded, with thrusting only in the direction necessary to nullify disturbance effects. A dual-level system is required to achieve this goal without producing undesirable acquisition characteristics.

Table 8-5 summarizes the control propellant weight required for three mass expulsion systems, assuming 5 foot (1.5 meter) lever arms and a single level system. The weight of the nitrogen systems will almost double when tankage is included, while that of the ammonia system will not be so strongly affected.

Table 8-5. Propellant Weight with Single-Level System for 5-Year Mission

System	Configuration					
	8 kw, 12 GHz		4 kw, 2.5 GHz		12 kw, 0.9 GHz	
	lb	kg	lb	kg	lb	kg
N_2	160	73	35	16	195	89
N_2 with heated nozzles	85	39	20	9	100	45
NH_3	110	50	25	11	135	61

These results indicate the desirability of using microthrusters for long-term attitude control with cold gas or ammonia for acquisition. Use of colloid engines, with heated nitrogen for acquisition, yields the following attitude control propellant weights:

- 8 kw, 12 GHz : 19.1 pounds (9 kilograms)
- 4 kw, 2.5 GHz: 3.2 pounds (1.5 kilograms)
- 12 kw, 0.9 GHz: 26.9 pounds (12.2 kilograms)

Obviously the reduced propellant weight must be traded against system weight increases, reliability, power, etc. In the long run ion thrusters may be preferred, trading power for weight. The question of using reaction wheels to store nonsecular momentum components should also be considered in the design phase of a spacecraft development when accurate disturbance analysis is available.

8.3.5 Implementation

Tables 8-6 and 8-7 summarize mechanization requirements for two typical systems, including propulsion for attitude control and stationkeeping.

Table 8-6. Attitude Control and Stationkeeping System Hardware (Earth-Oriented, 12 kw, 0.9 GHz Configuration)

Major Component/Subsystem	U[illegible] per Spacecraft	Weight per Unit	Total Weight (lb)	Power per Subsystem	Total Power (W)
Earth Sensor Subsystem	1	8	8	12	12
Sun Sensor	2	1.5	3.0	0.4	0.8
Sensor Logic Unit	1	3	3	5.0	5.0
Control Electronics Unit	1	7	7	6.5	6.5
Polaris Star Tracker	1	8	8	6.0	6.0
Solar Array Drive Assembly	1	30	30	10	10.0
Array Drive Electronics	1	5	5	5	5.0
Antenna Gimbal Drive	3	10	30	6.0	18.0
Antenna Servo Electronics	3	3	9	4.0	12.0
Array Gimbal Drive	2	10	20	0.1	0.2
Array Gimbal Electronics	2	2	4	0.2	0.4
Antenna Control Electronics	1	6	6	5.0	5.0
Nitrogen Propulsion System*	1	30	30	1.0	1.0
Colloid Propulsion System**	1	212	212	25.0	25.0
Miscellaneous Cables and Hardware			40	0	0
Total per Spacecraft			342 (155 kg)		107

*System I_{sp} = 65 (heated)

**System I_{sp} = 667

Table 8-7. Attitude Control and Stationkeeping System Hardware (Sun-Oriented, 8 kw, 12 GHz Configuration)

Major Component/Subsystem	Unit per Spacecraft	Weight per Unit	Total Weight (lb)	Power per Subsystem	Total Power (W)
Earth Sensor Subsystem	1	8	8	12	12
Sun Sensor	2	1.5	3.0	0.4	0.8
Sensor Logic Unit	1	3	3.0	5.0	5.0
Roll Bias Control	1	4	4	3.0	3.0
Control Electronics Unit	1	7	7	6.5	6.5
Canopus Star Tracker	1	8	8	6.0	6.0
Antenna Gimbal Drive	2	10	20	6.0	12
Antenna Servo Electronics	2	3	6	4.0	8
Antenna Command Logic Unit	1	8	8	5.0	5
Antenna Tilt Drive Unit	1	6	6	0.2	0.2
Tilt Drive Electronics	1	4	4	3.0	3.0
Nitrogen Propulsion System*	1	20	20	1.0	1.0
Colloid Propulsion System**	1	135	135	25.0	25.0
Miscellaneous Cables and Hardware	1		40	0	0
Total			275 (125 kg)		88.0

*System I_{sp} = 65 (heated)

**System I_{sp} = 667

8.4 STATIONKEEPING

The yearly ΔV requirements are approximately 7 fps due to asphericity effects, 185 fps due to lunar-solar gravitational effects, and 29 to 42 fps due to solar pressure. The corresponding propellant requirements for a 5-year mission are given in Table 8-8 for three fuel options. Note that the low thrust systems will be preferred from an attitude control viewpoint (to minimize transient disturbances), and provide weight advantages. However, this is not a complete tradeoff, owing to the power consumed by the micropound thrusters (greatest for the ion engine). Moreover, a high thrust (e.g., hydrazine) system may in some applications be required for spacecraft repositioning. The colloid system is selected at this time.

Table 8-8. Stationkeeping Propellant Weight for 5-Year Mission

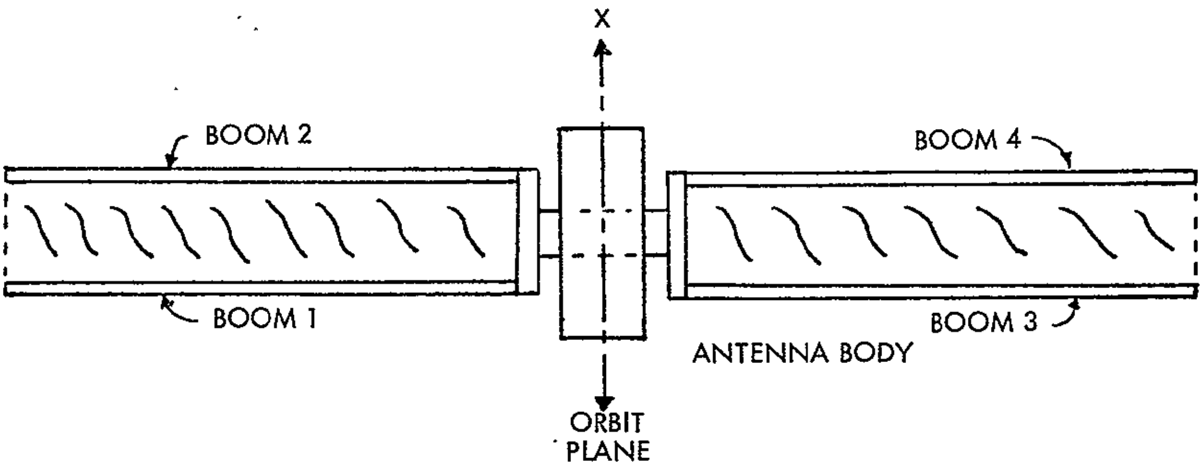
System	Configuration					
	8 kw, 12 GHz		4 kw, 2.5 GHz		12 kw, 0.9 GHz	
	lb	kg	lb	kg	lb	kg
Hydrazine (I_{sp} = 230)	347	157	239	109	565	257
Ion Engine (I_{sp} = 4000)	20	9	14	6	32	15
Colloid Engine (I_{sp} = 1000)	80	36	55	25	130	60

8.5 CONTROL IMPLICATIONS OF VEHICLE ELASTICITY

Solar array and/or antenna flexibility can be important factors in designing a control system for a TVBS spacecraft. In order to examine these phenomena, detailed modal analyses were conducted for a representative "I" configuration.

8.5.1 Structural Model

The structural model used is shown in Figure 8-3. The half of the array on each side of the spacecraft was modeled as two booms with the surface between booms included in the mass distribution but neglected in determining the stiffness. The system was assumed to be symmetric about the centerline. It was assumed that the two booms on a given side would bend differentially, normal to the array surface, in torsional modes, and would bend together, normal to the surface, in bending modes. The bending in the plane of the array is reacted by tension and compression in the booms with shear in the web surface, and the natural frequencies will be sufficiently high that these modes can be neglected for this study.



BOOM CHARACTERISTICS

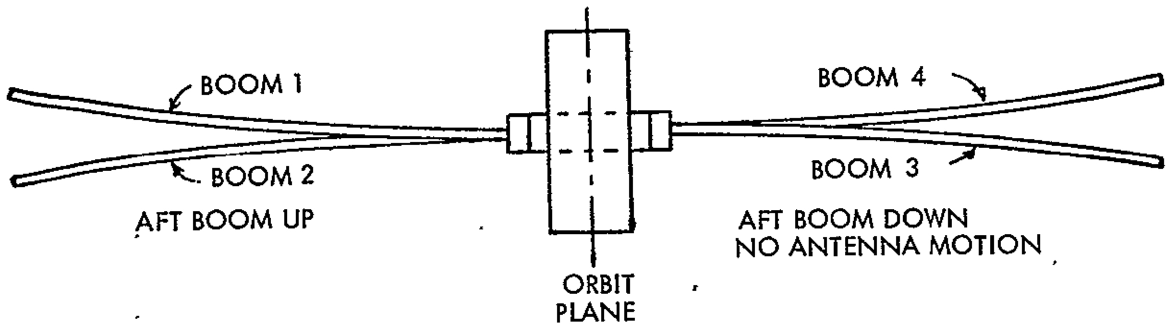
LENGTH	=	100 FT
EI	=	330 LB-FT^2
σ	=	0.107 SLUG/FT
CENTER MASS	=	100 SLUG
CENTER MASS I	=	1800 SLUG-FT^2

Figure 8-3. Structural Model

8.5.2 Array Structural Modes

8.5.2.1 Nonsymmetric Torsion Modes

In the nonsymmetric torsion modes the left side of the array is oscillating against the right side and due to the symmetry of the configuration the center mass or antenna has no motion (Figure 8-4). These modes will have little or no effect on the attitude of the antenna providing the array drive cannot respond to the resulting elastic deflection. This requirement will necessitate that the sun sensors controlling the array motion be placed on the rigid center portion of the array. As an alternate a distributed system may be used with sensors located symmetrically on the array with the outputs averaged.



- TWO ENDS OF ARRAY ROTATE OPPOSITE
- NO TORQUES TRANSMITTED TO ANTENNA
- ARRAY DRIVE MUST NOT RESPOND TO THESE DEFLECTIONS

MODE	RAD/SEC	CYCLIC/ORBIT
1	0.0196	269
2	0.1223	1685
3	0.3425	4715

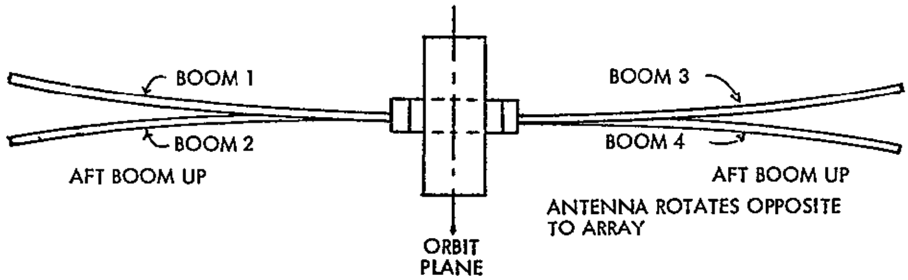
Figure 8-4. Nonsymmetric Torsion Modes

8.5.2.2 Summetric Torsion Modes

In the symmetric torsion modes the two sides of the array will move together and will oscillate against the center body or antenna (Figure 8-5). These modes have natrual frequencies somewhat higher than the non-symmetric mode frequencies and can only exist if torques at these frequencies can be transmitted between the array and body plus antenna. Therefore, only those symmetric torsion modes with frequencies within the passband of the array drive can exist. Lowering the cutoff frequency (e.g., below 0.02 rad/sec) will eliminate all symmetric torsion modes. The desired cutoff frequency must be established by a tradeoff between response to these modes and the transient response of the system required during limit cycle control and eclipse.

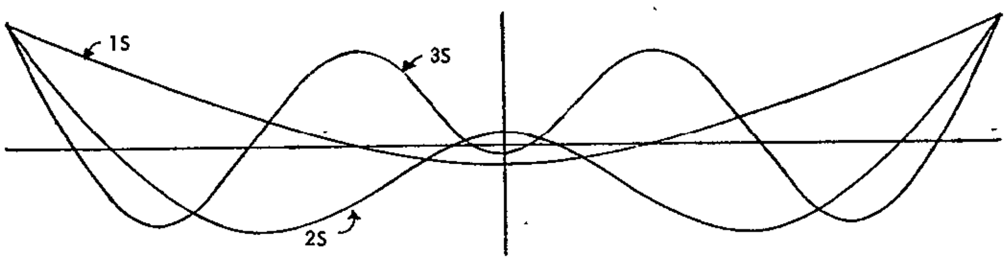
8.5.2.3 Symmetric Bending Modes

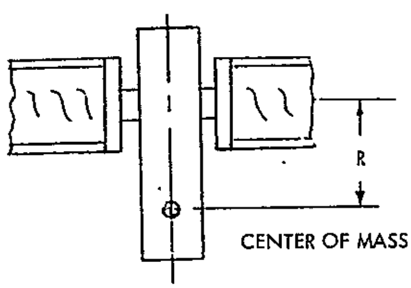
The symmetric bending modes result in only translational motion of the center mass or antenna normal to the plane of the array (Figure 8-6). In general, the center of mass is offset from the array center by an effective arm R. As a result, the symmetric bending modes will produce



- TWO ENDS OF ARRAY ROTATE TOGETHER
- ANTENNA ROTATES OPPOSITE TO ARRAY
- TORQUE MUST BE TRANSMITTED THROUGH ARRAY DRIVE
- FREQUENCIES ARE HIGHER THAN FOR NONSYMMETRIC MODES
- IF THE BANDPASS OF THE DRIVE SYSTEM IS BELOW 0.02 RAD/SEC ($270 \times \omega_o$) THE SYMMETRIC TORSION MODES CANNOT EXIST

Figure 8-5. Symmetric Torsion Modes





SYM MODES	FREQ (RAD/SEC)	CYCLIC/ORBIT
1S	0.0104	143
2S	0.0259	356
3S	0.0420	577
4S	0.0652	892

Figure 8-6. Symmetric Bending Modes

a slight pitching motion of the spacecraft. Since the center of total spacecraft mass is the point in orbit, the rotation of the earth pointed antenna will cause the arm R to vary sinusoidal once per orbit and the pitching oscillation will be modulated at a rate of one cycle per orbit. The effect of the symmetric bending mode may be minimized by making the arm R a minimum. Since this criteria will also reduce the cycle solar disturbance torques due to the array, every effect should be made to reduce R to zero. This requires that the antenna rotates about its mass center. In the event that two axis sun sensors are used to orient the array, the sensors must be located such that they will not sense elastic bending deflections.

8.5.2.4 Nonsymmetric Bending Modes

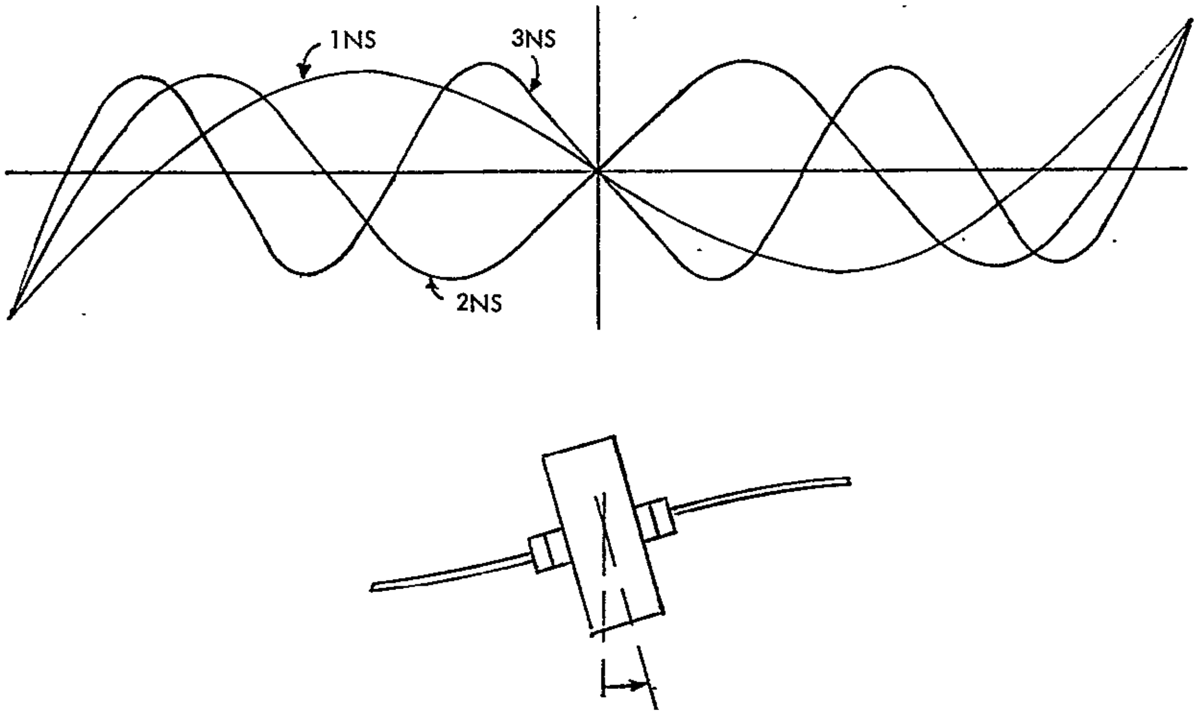
The nonsymmetric bending modes result in only rotational motion of the center mass and antenna about an axis normal to the array axis (Figure 8-7). If the array drive is rigidly attached to the spacecraft body about an axis in the array plane and normal to the array drive axis, the nonsymmetric array bending modes will produce oscillatory motion of the antenna about the first axis. These oscillations will be seen by the roll sensors and stable operation must be provided for by the antenna pivoting system and the limit cycle control system.

When roll/yaw orientation of the array is employed for better solar energy efficiency, the additional limited angle gimbal can be placed such that the nonsymmetric mode oscillations are about this axis. A low passband controller could then be provided which would prevent the torques from being transmitted to the antenna. The resulting oscillatory motion at the center of the array would then not be transmitted to the antenna.

8.5.3 Control Considerations

This preliminary study indicates that transmission of symmetric torsion and nonsymmetric bending oscillations to the antenna are potential problem areas. In the event that a detailed analysis shows that these oscillations greatly degrade the system performance, it may be necessary to provide a special array drive to dynamically isolate the array from the antenna. The need would be for a direct, low-passband array drive, gimballed and driven about two axes. The internal gimbal requires

360 degree continuous rotation and system of high current slip rings. This drive would respond only to the low frequency output of the sensors and allow free rotation at high frequencies. The center gimbal requires limited motion (±30 degrees) with bandpass characteristics similar to the inner drive.



NONSYM MODES	FREQ (RAD/SEC)	CYCLES/ORBIT
1NS	0.0252	347
2NS	0.0431	592
3NS	0.0586	805
4NS	0.0795	1090

Figure 8-7. Nonsymmetric Bending Modes

During any studies of such a drive mechanism, consideration should be given to the installation of sensors at each gimbal axis to sense the magnitude and phase of any relative high frequency motion. The output of these sensors could then be used to damp elastic oscillations by means of external applied forces or with the drive itself.

The degree of interaction between structural flexibility and the attitude control system can only be determined through detailed analysis. However, certain problem areas have been noted together with possible corrective measures. The extent to which these measures must be applied is a function of the degree to which the elastic deformation degrades the performance of the system. In general, the passband of the solar array and limit cycle control systems should be low while that of the antenna gimballing system should be higher. The low-pass array drive will tend to provide dynamic isolation preventing the critical array oscillations from being coupled to the spacecraft body and antenna. The low passband limit cycle control will tend to prevent the control system from responding to such oscillations which do couple to the antenna. Lowering the system passband will degrade the transient response of the system and a tradeoff exists between elastic response and transient response. The primary source of transients are the mass expulsion system and the thermal effect of entrance and exit from eclipse. In a system sensitive to high frequency disturbance with a low-pass control system, it is desirable that the control impulses have low torque levels.

APPENDIX 8A

DISTURBANCE TORQUE ANALYSIS

This appendix presents a preliminary disturbance torque evaluation for the TVBS satellite configurations. With a goal of developing tradeoff rationale, various simplifications have been used. Phenomena considered are solar radiation pressure, RF radiation pressure and gravity gradient torques. Specifically excluded are magnetic torques (small due to current balancing in the array and the weak environmental magnetic field) and thermal radiation pressure.

8A.1. SOLAR PRESSURE EFFECTS

8A.1.1 Solar Pressure Torque

The major area in each of the TVBS configurations is the solar array. For this analysis only this area, normal to the sun line, is considered. Figure 8A-1 shows the geometry assumed. The $\bar{z}_s$ axis is to the sun with $\bar{y}_s$ and $\bar{x}_s$ defining the plane of the array. The hinge (or gimbal), h is the origin of the coordinate frame and is displaced from the center of mass by the vector $\bar{R}$ (having fixed components in the geocentric orbital reference set) and from the center of pressure by the vector $\bar{L}$ (having fixed components in the sun-referenced coordinate frame of Figure 8A-1).

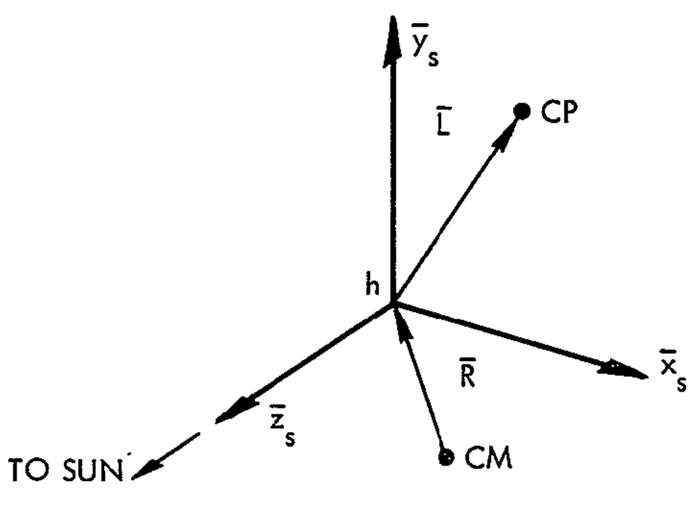


Figure 8A-1. Solar Pressure Torque Geometry

The solar pressure torque is evidently

$$\bar{T}_s = (\bar{R} + \bar{L}) \times \bar{F}_s \tag{8A-1}$$

where

$$\bar{F}_s = -VA\ (1 + \nu)\ \bar{z}_s \tag{8A-2}$$

with A the area of the array, $V = 0.94 \times 10^{-7}$ lb/ft^2(0.46 milligram/m^2), and ν the reflectivity of the solar array.

For those configurations with the vehicle earth-oriented, control activity occurs in the geocentric (x_r, y_r, z_r) frame with $\bar{x}_r$ along the velocity vector, $\bar{z}_r$ to nadir and, $\bar{y}_r$ completing the right-hand frame. Denote the unit vectors in column matrix form as

$$\bar{\bar{X}}_s = \begin{pmatrix} \bar{x}_s \\ \bar{y}_s \\ \bar{z}_s \end{pmatrix} \qquad \bar{\bar{X}}_r = \begin{pmatrix} \bar{x}_r \\ \bar{y}_r \\ \bar{z}_r \end{pmatrix} \tag{8A-3}$$

Then

$$\bar{v} \cdot \bar{\bar{X}}_s = \begin{pmatrix} \bar{v} & \cdot & \bar{x}_s \\ \bar{v} & \cdot & \bar{y}_s \\ \bar{v} & \cdot & \bar{z}_s \end{pmatrix}$$

is a column matrix of the components of the vector $\bar{v}$ in $\bar{\bar{X}}_s$ coordinates. The two coordinate frames defined are related by

$$\bar{\bar{X}}_r = \begin{pmatrix} \cos\mu & \cos S' \sin\mu & -\sin S' \sin\mu \\ 0 & -\sin S' & -\cos S' \\ -\sin\mu & \cos S' \cos\mu & -\sin S' \cos\mu \end{pmatrix} \bar{\bar{X}}_s \tag{8A-4}$$

where S' is the angle made by $\bar{z}_s$ with the orbit plane normal ($64.5 \le S' \le 113.5$ degrees) and μ is the spacecraft orbital position measured from the projection of the sun line in the orbit plane.

From the above the solar pressure torques can be written in the coordinate frames of interest as

$$\bar{T}_s \cdot \bar{\bar{X}}_s = VA\ (1 + \nu) \begin{pmatrix} -L_y - R_x \cos S' \sin \mu + R_y \sin S' - R_z \cos S' \cos \mu \\ L_x + R_x \cos \mu - R_z \sin \mu \\ 0 \end{pmatrix} \tag{8A-5}$$

$$\bar{T}_s \cdot \bar{\bar{X}}_r = VA\ (1 + \nu) \begin{pmatrix} -L_y \cos \mu + L_x \cos S' \sin \mu + R_y \sin S' \cos \mu - R_z \cos S' \\ -L_x \sin S' - R_x \sin S' \cos \mu + R_z \sin S' \sin \mu \\ L_y \sin \mu + L_x \cos S' \cos \mu + R_x \cos S' - R_y \sin S' \sin \mu \end{pmatrix} \tag{8A-6}$$

To evaluate the control impulse required to maintain zero error for one orbit in the presence of these torques, they should be expressed in the control coordinate frame ($\bar{\bar{X}}_s$ for one case, $\bar{\bar{X}}_r$ for the other two), rectified, and integrated over an orbit. This is not a trivial task for torque components with more than one frequency present (e.g., constant terms and μ dependent terms), unless done numerically.

For this analysis $R_x = R_z = 0$ is assumed, thus placing the center of mass and the hinge along the pitch spacecraft axis (nominally corresponding to $\bar{y}_r$). Then

$$\bar{T}_s \cdot \bar{\bar{X}}_s = VA\ (1 + \nu) \begin{pmatrix} -L_y + R_y \sin S' \\ L_x \\ 0 \end{pmatrix} \tag{8A-7}$$

$$\bar{T}_s \cdot \bar{\bar{X}}_r = VA\ (1 + \nu) \begin{bmatrix} (-L_y + R_y \sin S') \cos \mu + L_x \cos S' \sin \mu \\ -L_x \sin S' \\ (L_y - R_y \sin S') \sin \mu + L_x \cos S' \cos \mu \end{bmatrix} \tag{8A-8}$$

Notice that this simplification retains all secular torques while discarding those which are inertially periodic.

The coefficient R_y can be closely controlled and will be assumed equal to its nominal value. The offsets L_x and L_y are nominally zero but will have small nonzero magnitudes, they are assumed to be proportional to the corresponding spacecraft dimension

$$L_x = \eta D_x \qquad L_y = \eta D_y$$

Table 8A-1 summarizes the significant parameters for each case.

Table 8A-1. Key Spacecraft Parameters

Configuration		D_x		D_y		R_y		A	
Power	Frequency	ft	m	ft	m	ft	m	ft^2	m^2
8 kw	12 GHz	141	43	10	3	-0.4	-0.1	1280	119
4 kw	2.5 GHz	10	3	74	23	0	0	630	58
12 kw	0.9 GHz	75	23	73	22	0	0	1950	181

A typical value of η is 0.005, yielding a cp uncertainty of one-half foot (15 cm) for each 100 feet (30 m) of span. For the reflectivity $\nu = 0.5$ will be used.

Under the above conditions the solar torques in body coordinates may be evaluated for each configuration. The angle S' is chosen as 90 degrees (sun in orbit plane).

<u>8 kw, 12 GHz</u>

$$\bar{T}_s \cdot \bar{\bar{X}}_s = 1.82 \times 10^{-4} \begin{pmatrix} 0.45 \\ 0.71 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.82 \times 10^{-4} \\ 1.29 \times 10^{-4} \\ 0 \end{pmatrix} \text{ft-lb}$$

4 kw, 2.5 GHz

$$\bar{T}_s \cdot \bar{\bar{X}}_r = 0.89 \times 10^{-4} \begin{bmatrix} 0.37 \cos(\mu + \mu_o) \\ 0.05 \\ 0.37 \sin(\mu + \mu_o) \end{bmatrix} = \begin{bmatrix} 0.33 \times 10^{-4} \cos(\mu + \mu_o) \\ 0.045 \times 10^{-4} \\ 0.33 \times 10^{-4} \sin(\mu + \mu_o) \end{bmatrix} \text{ft-lb}$$

12 kw, 0.9 GHz

$$\bar{T}_s \cdot \bar{\bar{X}}_r = 2.76 \times 10^{-4} \begin{bmatrix} 0.53 \cos(\mu + \mu_1) \\ 0.38 \\ 0.53 \sin(\mu + \mu_1) \end{bmatrix} = \begin{bmatrix} 1.46 \times 10^{-4} \cos(\mu + \mu_1) \\ 1.05 \times 10^{-4} \\ 1.46 \times 10^{-4} \sin(\mu + \mu_1) \end{bmatrix} \text{ft-lb}$$

8A.1.2 Control Impulse

The disturbance torque will be assumed cancelled by control torques applied in body coordinates. The angular impulse per orbit can be derived by integrating the absolute value of each component over an orbit (P = 86,400 sec) and then adding. The 5-year impulse is obtained by multiplying the daily figure by 1820. Table 8A-2 summarizes the results.

Table 8A-2. Control Impulse Consumption due to Solar Pressure

Configuration	ΔH/day		ΔH/5 yr	
	ft-lb-sec	m-kg-sec	ft-lb-sec	m-kg-sec
8 kw, 12 GHz	18.2	2.52	33,000	4600
4 kw, 2.5 GHz	4.2	0.58	7,600	1050
12 kw, 0.9 GHz	25.0	3.46	46,000	6400

8A.2 GRAVITY GRADIENT EFFECTS

8A.2.1 Gravity Gradient Torque

The major contribution is due to the solar array. Therefore the torque will be computed in the $\bar{\bar{X}}_s$ frame. The basic expression for the gravity gradient torque on a vehicle in a circular orbit is

$$\bar{T}_g = 3\omega_o^2 \; \bar{z}_r \times (\bar{\bar{I}} \cdot \bar{z}_r) \qquad (8A\text{-}9)$$

where $\bar{\bar{I}}$ is the spacecraft inertia tensor. In the $\bar{\bar{X}}_s$ frame

$$\bar{z}_r = - \sin \mu \bar{x}_s + \cos S' \cos \mu \bar{y}_s - \sin S' \cos \mu \bar{z}_s \qquad (8A\text{-}10)$$

while $\bar{\bar{I}}$ is essentially constant (Table 8A-3).

Table 8A-3. Inertias in Sun-Referenced Coordinates

Configuration	I_{xs}		I_{ys}		I_{zs}	
	slug-ft^2	kg-m^2	slug-ft^2	kg-m^2	slug-ft^2	kg-m^2
8 kw, 12 GHz	700	950	37,000	50,000	37,000	50,000
4 kw, 2.5 GHz	5,300	7,200	500	680	5,600	7,600
12 kw, 0.9 GHz	30,000	41,000	17,000	23,000	44,000	60,000

From Equations (8A-9) and (8A-4)

$$\bar{T}_G \cdot \bar{\bar{X}}_s = 3\omega_o^2 \begin{bmatrix} -(I_{zs} - I_{ys}) \sin S' \cos S' \cos^2 \mu \\ (I_{xs} - I_{zs}) \sin S' \sin \mu \cos \mu \\ -(I_{ys} - I_{xs}) \cos S' \sin \mu \cos \mu \end{bmatrix} \qquad (8A\text{-}11)$$

Considering S' + 90 degrees, only the $\bar{y}_s$ component is nonzero

$$\bar{T}_g \cdot \bar{y}_s = \frac{3}{2} \omega_o^2 (I_x - I_z) \sin 2\mu \qquad (8A\text{-}12)$$

yielding the following numerical results

$$12 \text{ GHz} - T_{gys} = 2.8 \times 10^{-4} \sin 2\mu$$

$$2.5 \text{ GHz} - T_{gyr} = 2.4 \times 10^{-6} \sin 2\mu$$

$$0.9 \text{ GHz} - T_{gyr} = 1.1 \times 10^{-4} \sin 2\mu$$

8A.2.2 Control Impulse

In the absence of other effects the control impulse consumption due to gravity gradient torques will be:*

$$\Delta H/\text{day} = \frac{3}{2} \omega_o^2 (I_x - I_z) \cdot \frac{2P}{\pi} \tag{8A-13}$$

Table 8A-4 summarizes the impulse required.

Table 8A-4. Control Impulse Consumption due to Gravity Gradient Torques

Configuration	ΔH/day		ΔH/5 yr	
	ft-lb-sec	m-kg-sec	ft-lb-sec	m-kg-sec
12 GHz	15.5	2.15	28,000	3900
2.5 GHz	0.1	0.01	200	28
0.96 GHz	6.1	0.85	11,000	1500

8A.3 RF PRESSURE

An antenna radiating a power P into free space will produce a reaction force on the satellite given by

$$\bar{F}_{RF} = -\frac{P}{C} \bar{z}_r \tag{8A-14}$$

*It is assumed that no momentum storage devices are employed.

where

P = radiated power in watts

C = the speed of light (3 x 10^{-8} m/sec)

F_{RF} = force in Newtons (1 Newton = 0.225 lb)

$\bar{z}_r$ = unit vector in direction of antenna beam

This torque is of significance only for the 12 GHz configuration which has an unbalanced antenna system with an effective lever arm of about 11.3 ft (3.4 m): $\bar{L} = 11.3\ \bar{y}_s$. The power in this case is 5 kw, giving a force of 0.38 x 10^{-5} lb (0.17 x 10^{-5} kg) and a torque, in $\bar{\bar{X}}_s$ coordinates

$$\bar{T}_{RF} \cdot \bar{\bar{X}}_s = 4.2 \times 10^{-5} \begin{pmatrix} \sin S' \cos \mu \\ 0 \\ -\sin \mu \end{pmatrix} \text{ ft-lb} \qquad (8A-15)$$

For S' = 90 degrees the resulting momentum requirement is 4.6 ft-lb-sec/day (0.64 kg-m-sec/day) or 8400 ft-lb-sec (1160 kg-m-sec) in 5 years.

8A.4 TOTAL ANGULAR IMPULSE

By RSS combination of the preceding results a rough estimate of the total required control impulse can be derived (Table 8A-5). This is not a rigorous procedure; rather the individual torques should be summed, then rectified, and finally integrated for the range of S'. However, the results of the table are sufficiently accurate for preliminary design.

Table 8A-5. Estimated Total Control Impulse

Configuration	RSS $\Delta H/5$ yr	
	ft-lb-sec	kg-m-sec
8 kw, 12 GHz	43,000	6000
4 kw, 2.5 GHz	7,600	1050
12 kw, 0.9 GHz	47,000	6500

9. THERMAL CONTROL

9.1 INTRODUCTION AND SUMMARY

The dominant parameters affecting the temperatures of the spacecraft are:

- Natural and induced environment
- Orientation
- Internal heat dissipation

Several thermal control concepts were investigated during the study. A careful review was made of all the concepts used during previous TRW studies and on existing TRW spacecrafts. From the review of the possible concepts, a conceptual thermal control design was selected for each of the three configurations presented in Section 7.

The primary power requirements for television broadcast spacecraft range primarily from 2 to 20 kw. This is so far in excess of the typical communications satellite heat dissipation (i.e., INTELSAT III 175 watts) that existing thermal control methods must be expanded and new ones developed.

Most of the spacecraft internal dissipation will occur in the power conditioning equipment and the final RF amplifier. These two areas of high heat dissipation have very different thermal control requirements. Power conditioning equipment will have a relatively low heat density but must be controlled to temperature limits between about 0 to 100°F. The RF tube will have a high power density and will have a much wider allowable temperature range. Thermal control of these components must be integrated with that for other spacecraft body-mounted equipment which typically have different temperature limits (i.e., batteries, propellant tanks, solar array drive mechanism, etc.).

Thermal control must also be supplied for externally mounted equipment. Distortion because of thermal gradients in the parabolic antenna must be minimized. Solar array temperatures during illumination should be kept as low as possible to obtain the maximum electrical output.

An additional design requirement is the 5-year lifetime. Specification of thermal control coatings must consider the degradation which occurs over 5 years. The long lifetime also will impose severe requirements on design of moving parts in any active system.

Thermal control of the power conditioning equipment can be accomplished by use of a thermal louver system. Orientation of the vehicle along the solar vector results in a substantial reduction in radiator area and weight required as compared to an earth-oriented vehicle.

For heat removal from the RF power tube, conceptual designs are given for a heat pipe system and for a fluid loop system.

9.2 THERMAL CONTROL TECHNIQUES

Thermal control of a spacecraft and its components is accomplished by maintaining a thermal balance between internally generated heat, external heat sources, and external radiant emission at temperature levels within the allowable temperature limits of components. The system must conform to these limits for all phases of the mission, must provide repeatable thermal performance, and must be reliable. The basic tradeoffs in the thermal design are between various thermal control techniques such as insultation, thermal coatings and finishes, louvers, and fluid loops.

TV broadcast satellites will be in a 24-hour equatorial orbit and hence experience a maximum solar eclipse time of approximately 72 minutes and undergo seasonal variations in sun angle to the orbit plane of ± 23.5 degrees. The antenna is earth pointing. The spacecraft body may be either earth pointing or solar oriented. The following sections give a discussion of applicable thermal control techniques and the effect of spacecraft orientation. TV broadcast satellites require an integrated design incorporating a number of specific thermal control techniques.

9.2.1 Passive Thermal Control Techniques

Thermal Coatings and Finishes. Thermal coatings and finishes with a wide range of thermophysical properties have been developed for spacecraft applications. Properties typical of those developed are given in Table 9-1. Intermediate properties can be achieved by proportioning the area of the various coatings to form a mosaic.

Table 9-1. Thermal Coatings and Finishes

Performance Category	Type	α_s/ϵ	α_s	ϵ	Comments
Low α_s/ϵ	Z-93 white paint	0.21	0.19	0.90	Difficult to maintain during assembly and integration. Increase in solar absorptance for 5-year mission will be be high.
	Second surface mirror (aluminum or silver vacuum-de deposited on quartz)	0.125	0.1	0.8	Very little degradation.
Intermediate α_s/ϵ	Silicone aluminum paint	1.4	0.33	0.24	Relatively stable in space environment.
Low ϵ	Electro-plated nickel	5.5	0.22	0.04	Can easily be applied to complex and multiple surfaces.
	Electro-plated copper	11.8	0.47	0.04	
	Vacuum deposited aluminum	2.5	0.10	0.04	Can be applied directly to surface or can use tape with vacuum deposited aluminum surface.

α_s = solar absorptance

ϵ = IR emittance

Insulation. In an insulated concept, a closed, insulation envelope minimizes the effects of environmental extremes and orientation. It also permits predictable control of component temperatures by means of appropriate radiation areas.

An uninsulated spacecraft would require thermal shielding of spacecraft components. This imposes higher heat dissipation requirements on the thermal control during hot conditions and high heater power requirements on the system during the cold conditions. The uninsulated concept would be more complicated and less predictable.

For TV broadcast satellites, use of an insulated concept with sized radiators will provide the desired thermal control at a temperature level that is suitable for the various components.

9.2.2 Active Thermal Control Techniques

Louvers. Louvers are utilized to keep temperatures within allowable limits when environmental conditions or heat dissipation vary. The louver system gives a variable emittance as a function of temperature. The controllable emittance range of developed hardware is typically 0.2 to 0.8. If solar energy impinges on the louver surfaces, an external radiator plate must generally be added to prevent trappage of solar energy by the louver blades. Approximate weight figures are 0.84 lb/ft^2 (4.1 kg/m^2) without external radiating plate and 0.94 lb/ft^2 (4.6 kg/m^2) with second surface mirror external radiator.

Heat Pipes. Heat pipes provide technique for the transfer of heat with small temperature gradients. As shown in Figure 9-1, a heat pipe involves six distinct processes in a closed cycle:

- Conduction of heat through the pipe wall and wick to the working fluid surface.
- Heat transfer by evaporation of a working fluid at the high temperature end.
- Vapor flow of the working fluid to the low temperature end.
- Heat transfer by condensation at the cool end.
- Conduction of heat through the wick and pipe wall to a sink.
- Liquid flow of the working back to the high temperature end by capillary action of a wicking material.

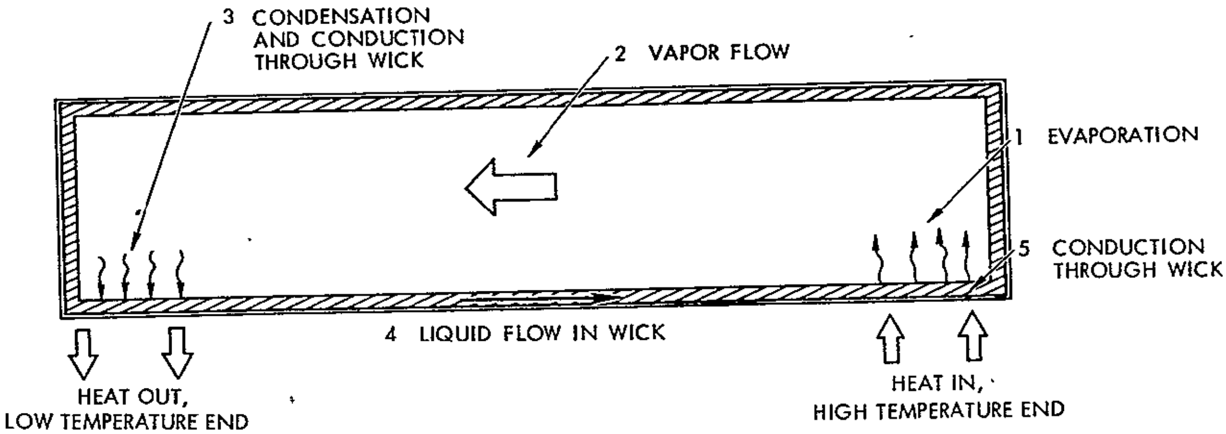


Figure 9-1. Heat Pipe Mechanisms

By taking advantage of the latent heat of vaporization, high heat flow rates per unit cross-sectional area are achieved. There is no simple way to characterize the performance parameters of a heat pipe. Any one of the six mechanisms may limit operation. For the present application, it is likely that the most critical item will be the heat density at the evaporation end.

Heat pipes have been built and flown on spacecraft. It was shown that the launch and orbital environments had no detrimental effects on the heat pipe performance.

Active Liquid Cooling. Use of an active liquid loop has certain advantages for TV broadcast satellites. Very high heat densities can be dissipated with an extended surface radiator and compact heat exchangers. Better control of component temperature can be realized with a liquid loop system than with the heat pipe. With the heat pipe system the distance over which heat can be transferred is limited by the relatively low pumping capacity of capillary action. Since pressure drop in liquid lines of an active fluid loop will probably not be significant, considerable freedom is available with respect to location of components and radiator. As with the heat pipe system, the vehicle skin can be used as the radiating panel.

Main elements of an active fluid loop system are shown in Figure 9-2. An accumulator is provided to absorb expansions and contractions of the system and to provide a pressure reference. The radiator panel is sized for the highest dissipation rates. At lower rates, a thermostatically controlled valve bypasses some of the flow around the radiator to maintain a constant tube temperature.

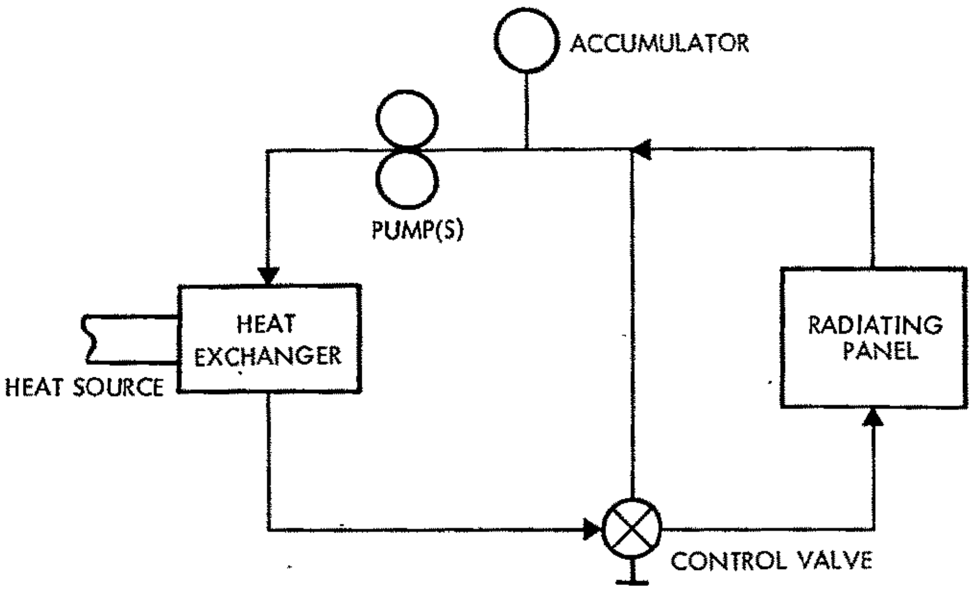


Figure 9-2. Active Liquid System

Active heat rejection systems of this type have been built and successfully flown on Gemini and Apollo. The major drawback to application on TV broadcast satellites is the long lifetime requirement. Components on Gemini and Apollo are designed for approximately 21-day reliable lifetime. Obtaining a reliable motor-pump combination for a 5-year lifetime would require development and inclusion of redundancy.

9.3 SATELLITE BODY

Enclosed in the satellite body are components which have widely differing thermal control requirements. Typical solid-state electronic components have temperature limits on the order of $0^{\circ}F$ ($-18^{\circ}C$) to $100^{\circ}F$ ($38^{\circ}C$). Propellant tanks and batteries will have temperature limits which are narrower, $40^{\circ}F$ ($4^{\circ}C$) to $90^{\circ}F$ ($32^{\circ}C$), but inside the $0^{\circ}F$ ($18^{\circ}C$) to $100^{\circ}F$ ($38^{\circ}C$) limit. Maximum temperature limit of RF power amplifier will probably by about $350^{\circ}F$ ($175^{\circ}C$). To keep radiator area at a minimum, operation of the radiator as near as possible to the maximum allowable tube temperature is desirable. This leads to the necessity of having two independent heat rejection systems, one for rejection of low temperature component heat and one for rejection of high temperature (RF tube) heat. Insulation must be provided internal to the spacecraft to prevent excessive heating of the low temperature components by RF power amplifiers.

9.3.1 Power Conditioning Equipment

A satellite in a synchronous equatorial orbit experiences wide variations in thermal conditions during a complete orbit in addition to seasonal variations. External surfaces are alternately irradiated by the sun or fully shadowed for long periods. During solar eclipse periods, the internal dissipation decreases drastically. In addition, uncertainties and degradation in thermophysical material properties must be considered.

It is unlikely that a fully passive thermal control system for the main compartment can cope with the wide range of conditions and maintain the internal thermal environment range required. The need for some semi-passive control means is indicated. A simple and effective means of thermal control is provided by temperature-sensitive louvers as utilized on OGO and Pioneer.

There are two alternate systems depending on the manner of satellite body orientation. If one axis of the vehicle is oriented along the solar vector, sides of the spacecraft receive minimal solar energy and system (a) in Figure 9-3 can be used. For body orientation along the earth vector,

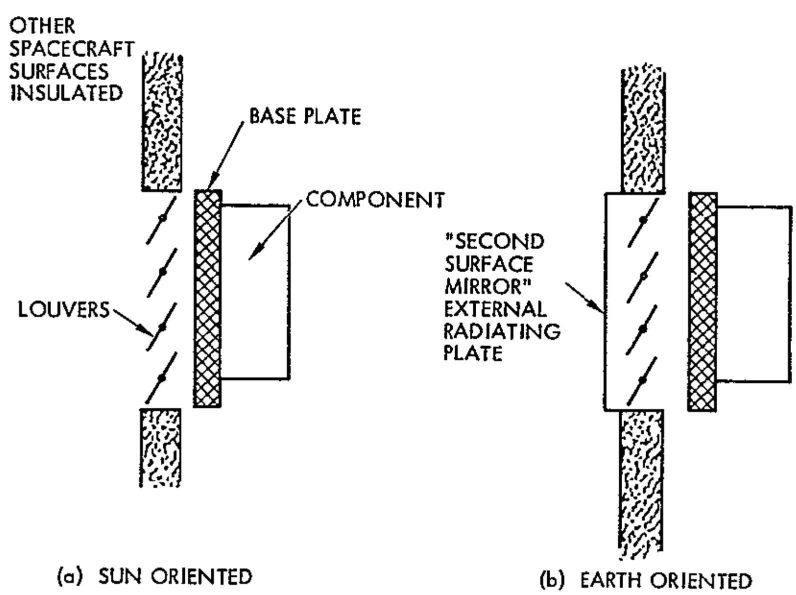


Figure 9-3. Thermal Louver Configurations

all sides at some time during the orbit receive solar heating and, therefore, system (b) is preferred. Figure 9-4 shows effect of solar energy on the heat rejection capabilities of a louver system with blades fully open. The cross-over point of heat rejection capability per unit area for these two louver configurations is at a sun angle of 60 degrees. However, it must be considered in tradeoffs that control action of sunlit louvers is generally not as satisfactory, and overheating of the louver blades is a potential problem.

Effect of the second surface mirror radiator with solar heating is to increase the required louver area. From thermal considerations alone, a sun-oriented system is highly desirable. Table 9-2 summarizes effect of solar orientation on the thermal control of the power conditioning equipment. The figures are based on the following typical ground rules:

- Component temperature = $100^{\circ}F$ ($38^{\circ}C$)
- Baseplate conductance = 10 Btu/hr-ft^2 - $^{\circ}F$ (2.04×10^5 joules/hr-m^2-$^{\circ}C$)
- Interface conductance = 20 Btu/hr-ft^2 - $^{\circ}F$ (4.08×10^5 joules/hr-m^2-$^{\circ}C$)
- Component mounting heat density - 50.0 watts/ft^2 (540 watts/m^2)
- Louver open emittance - 0.8

Table 9-2. Thermal Louver Characteristics

	Solar Orientation	Earth Oriented (66.5° Sun Angle)
Louver area/kw	29.4 ft^2(2.73 m^2	72.5 ft^2 (6.72 m^2)
Radiating Surface Temperature	$80^{\circ}F$ ($26^{\circ}C$)	$4^{\circ}F$ ($-16^{\circ}C$)
Louver weight/kw	24.6 (11.2 kg)	68 (30.8 kg)

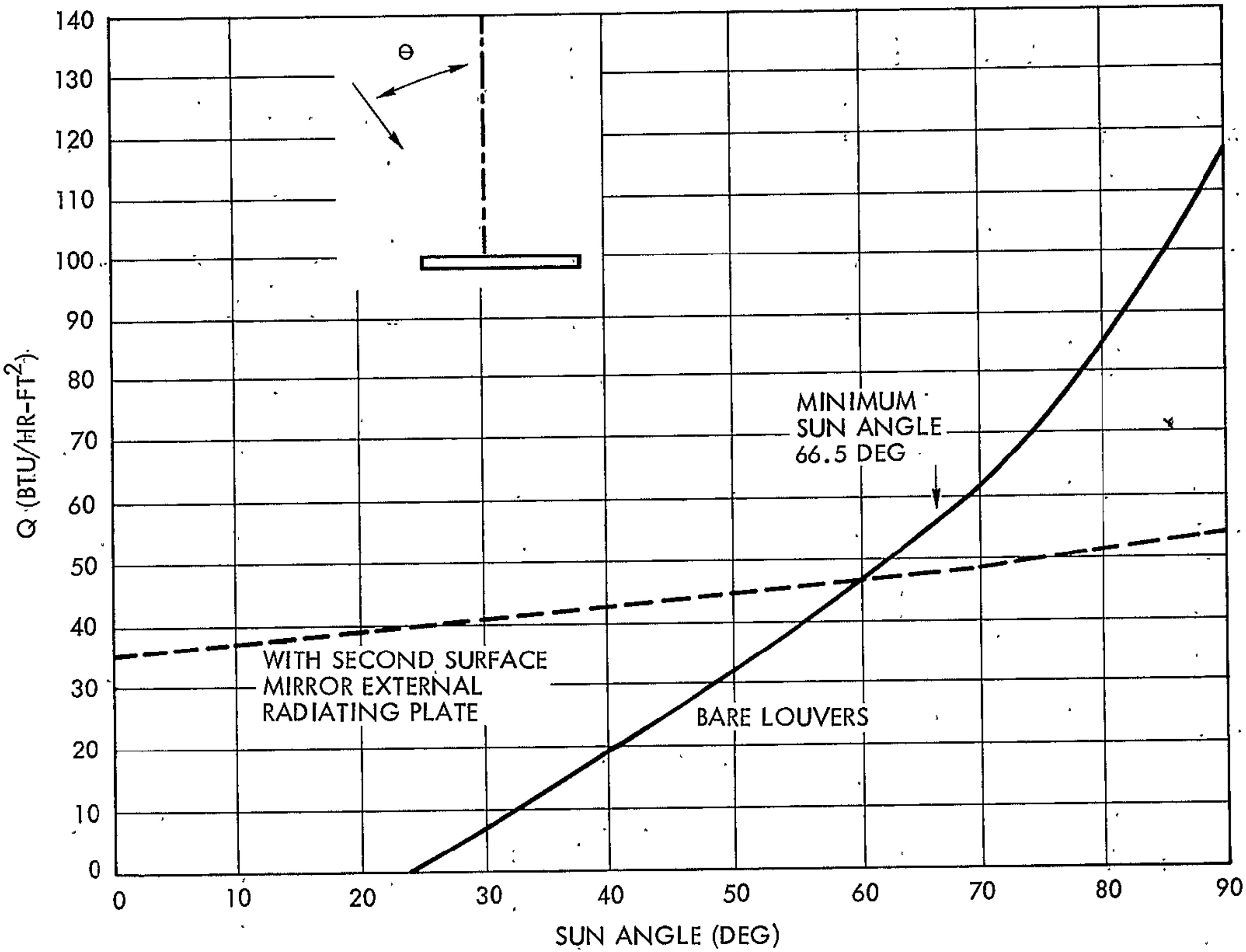


Figure 9-4. Louver Heat Rejection 80°F Radiating Temperature

9.3.2 RF Power Amplifier

Cooling of the RF tube presents a difficult design problem primarily because of the high heat density normally associated with such a device. Heat densities achievable with radiation cooling only would result in extremely high temperatures at the collector in most applications. Table 9-3 gives radiation black body energy densities as a function of temperature.

Expected watt densities on the order of 1 to 2 watts/cm^2 are expected on the RF tube. This precludes the use of direct radiation for heat rejection at desired tube temperature (300°F to 400°F). Two alternates, heat pipes and active liquid systems, were investigated for RF tube heat rejection.

Table 9-3. Black Body Intensity

Temperature (°F)		Black Body Intensity (watt/cm^2)
°F	°C	
100	38	0.0529
300	148	0.180
500	260	0.456
700	370	0.975
900	480	1.84

Heat Pipe System. Heat pipes can be utilized to remove heat at the high density source and transfer energy to a radiating plate at the expenditure of only a small temperature gradient.

A heat pipe rejection system is shown in Figure 9-5. The radiator part of the system is very similar to a configuration developed at TRW during 1968. Heat removal from the collector is by means of a dielectric inner heat pipe. This gives a zero potential surface which can be grounded to the spacecraft. The temperature drop in this heat pipe for a 2 watt/cm^2 heat density is estimated to be on the order of 10 Fahrenheit degrees (5.5 Centigrade degrees).

The problem of low temperature startup due to loss of dielectric strength can be solved by the addition of a non-condensible gas reservoir on the condenser which pressurizes the heat pipe cavity at low temperatures. At operational temperatures, the non-condensible gas is driven into the reservoir and the heat pipe operation is unaffected.

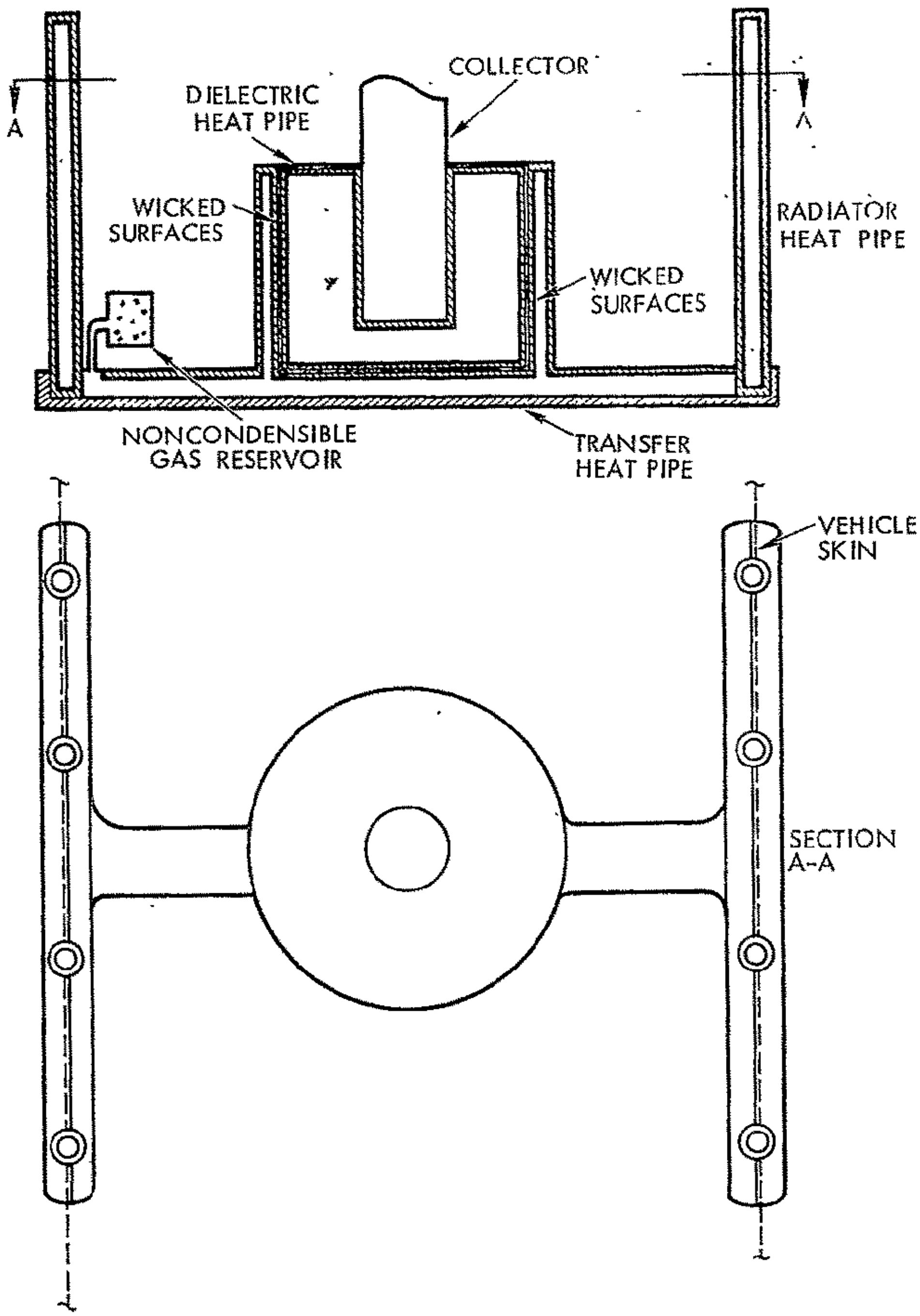


Figure 9-5. Heat Pipe System

A wicked surface is bonded on the outside of the dielectric heat pipe and a transfer heat pipe formed to transfer heat to the outer shell of the spacecraft. A radiator with heat pipes is built as an integral part of the vehicle outer skin for rejection of heat to space. The radiator heat pipes are inserted into the distributor heat pipe where RF tube heat is absorbed. Vapor chambers of the exterior and distributor heat pipes are not connected, and a puncture of an external heat pipe would only result in partial deterioration of heat rejection capabilities.

Control to prevent undercooling of the RF tube in eclipse periods during which the transmitter is shut off can be provided by a noncondensable gas reservoir connected to the transfer heat pipe. Pressure in the reservoir is maintained at a predetermined value. As the heat input to the tube decreases, the temperature and vapor pressure in the heat pipe will decrease. Decrease in pressure will result in the inert gas being drawn into the heat pipe, and the condensing end will be blanketed greatly reducing the heat loss to space. A subsequent increase in heat rate will result in an increase in heat pipe vapor pressure, and the inert gas will be driven to the coldest point (condensing end) and into the reservoir.

Effectiveness of the radiator and hence the area required will depend on the spacing of the outer surface heat pipes. Figure 9-6 shows radiator area required and number of external heat pipes as a function of the spaceing between heat pipes. An outer skin thickness of 0.01 inches (0.025 cm) and a radiator height of 24 inches (61 cm) were assumed. The number of tubes required and hence the weight penalty of the system, assuming no penalty for the fin material, decreases with increasing area available for the radiator. For a fixed area available, a tradeoff can be made between fin thickness required and number of heat pipe tubes. Figure 9-7 shows the relation between thickness and tubes required for a 300°F (148°C) heat pipe system with an area availability of 8.75 ft^2/kw (8.1 m^2/kw) and a radiator height of 24 inches (61 cm).

Active Liquid System. The second system investigated was an active liquid system. As shown in Figure 9-8, heat is absorbed from the RF tube collector by the transfer fluid and rejected by an external radiator panel. As with the heat pipe system, the vehicle skin can probably be used as the radiator panel with tubes added to increases the effectiveness.

The conceptual active fluid system design shown in Figure 9-8 is for a 1.25 kw dissipation. The design is based on the use of Dow Corning 331 heat transfer fluid. DC-331 is only one of several potential fluids which could be used. No comparison to obtain an optimum fluid was made.

Surface coating of the radiator was assumed to be a white paint with an emittance of 0.86 and solar absorptance of 0.25. Total radiator area required is 12 square feet with 14 tubes required for the two radiators. Flow rate of the heat transfer fluid is 300 lb/hr. Estimated pump power required is 30 watts.

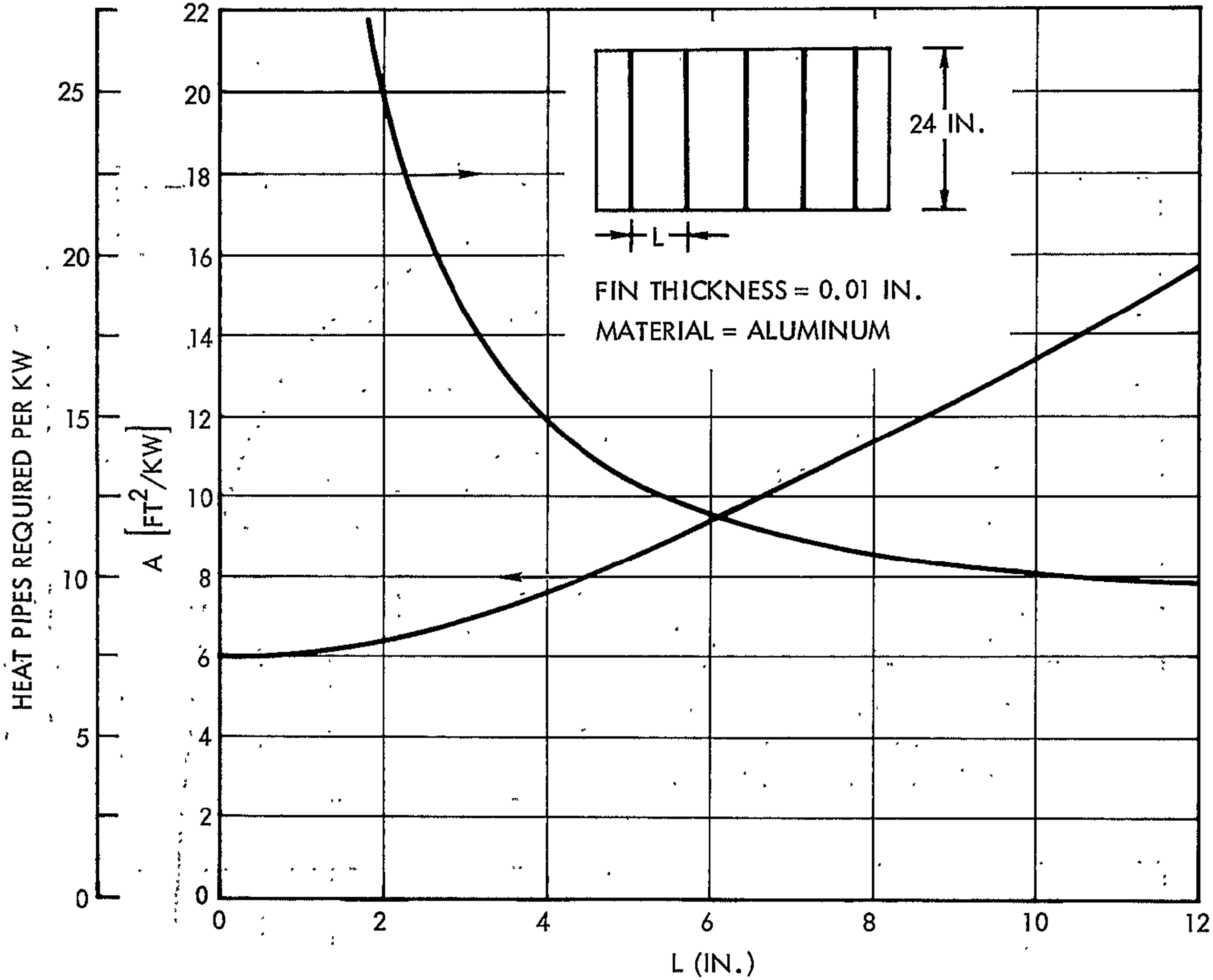


Figure 9-6. Heat Pipe Radiator

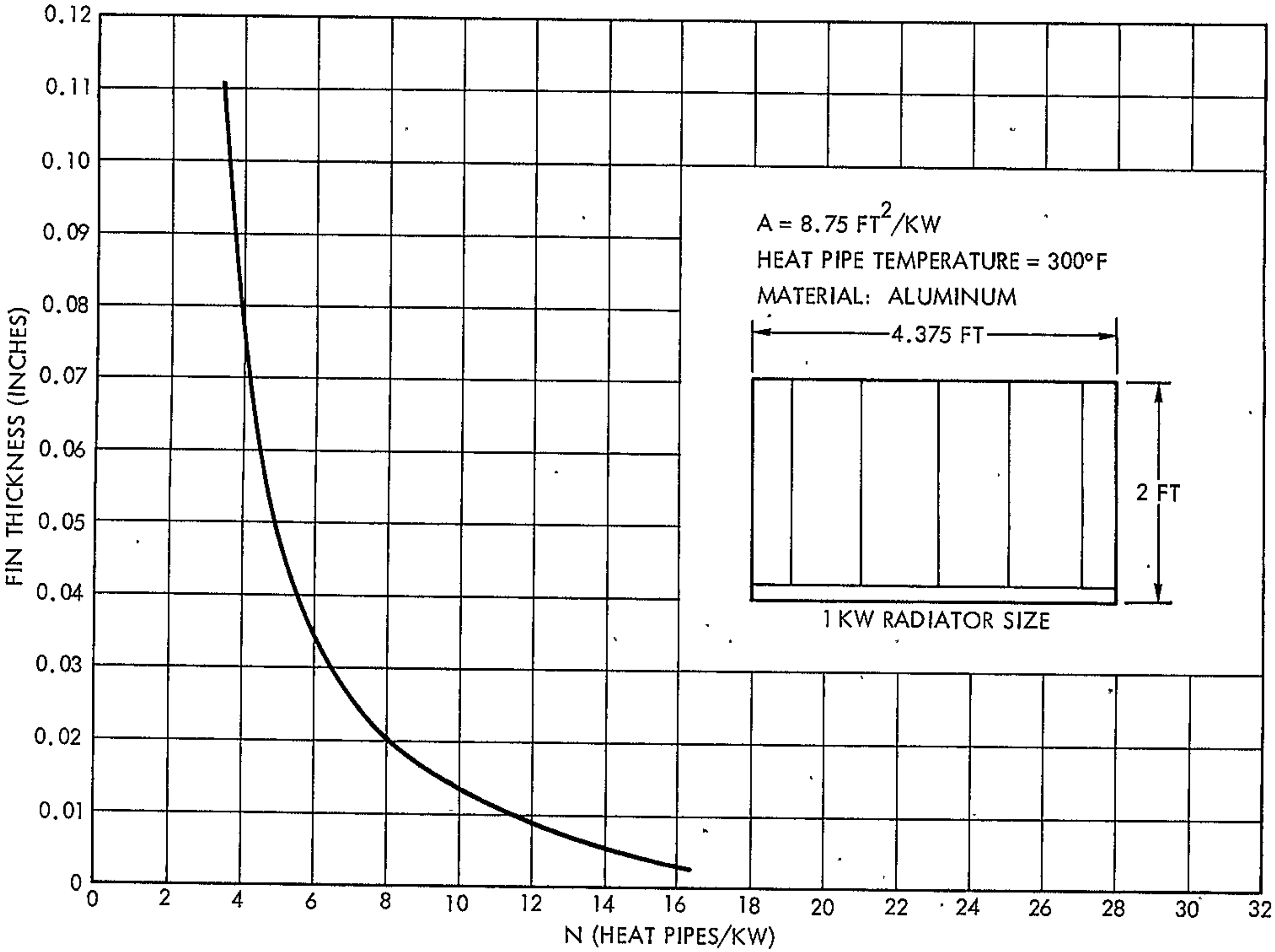


Figure 9-7. Fin Thickness — Heat Pipe Relation

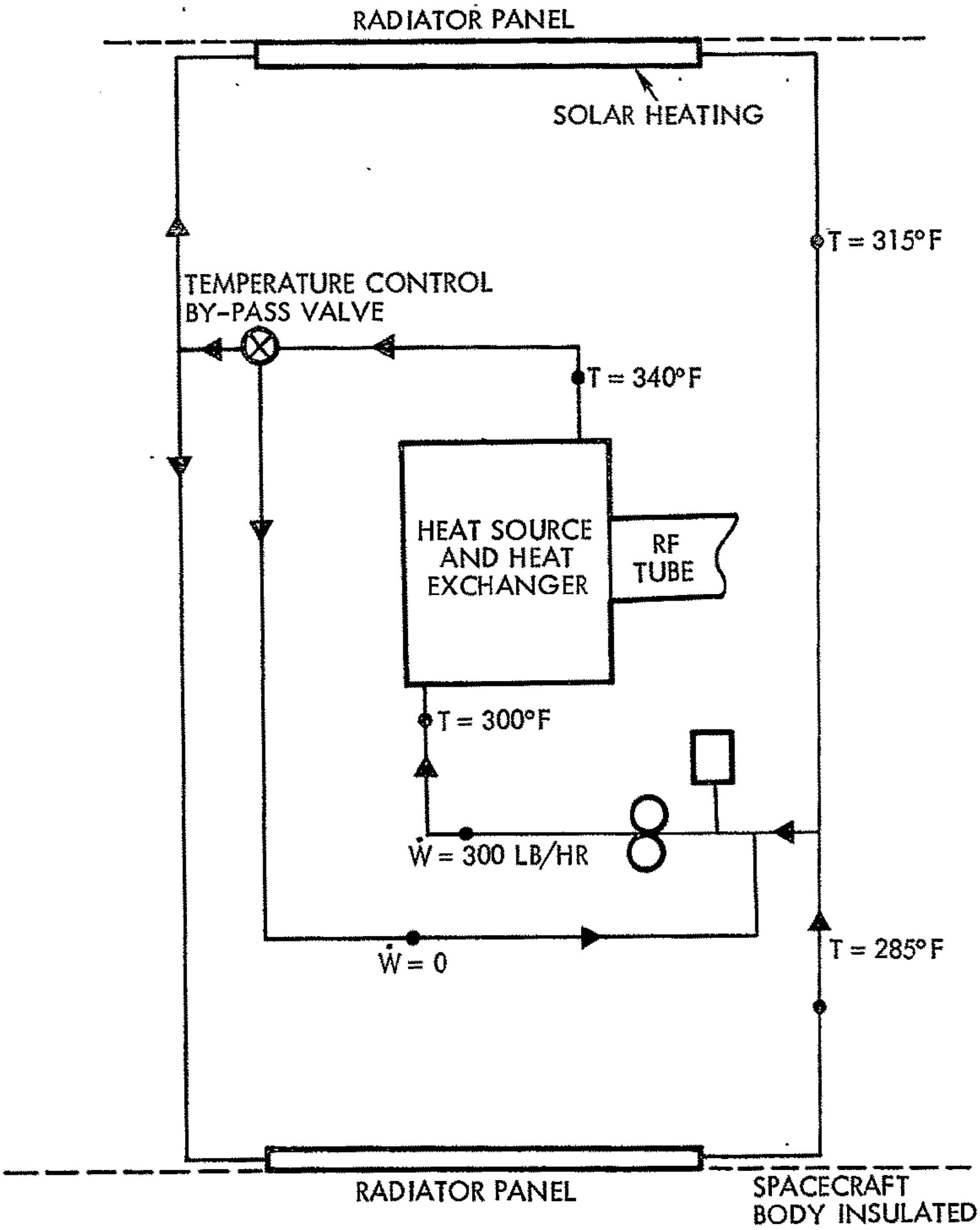


Figure 9-8. Active Liquid System

9.4 EXTERNAL EQUIPMENT

In addition to components mounted in the main compartment, thermal control must be provided for externally mounted elements. Of prime interest are the antenna and solar arrays. Other items (such as sensors, support booms, gimbal motors, etc.) must be considered but should present no problems unique to TV broadcast satellites.

9.4.1 Solar Array

The goal of the thermal control on the solar arrays is to keep the array temperature as low as possible during solar illumination such that electrical power output is maximized. A high emittance coating is put on the array rear surface to minimize array temperatures. Temperature of the array will also be influenced by solar constant, angle between the sun and array normal, and the cell efficiency. Table 9-4 shows approximate array temperatures for the expected range of the above parameters.

9.4.2 Antenna

An exposed antenna in a synchronous orbit will experience wide variations in thermal environment ranging from sun incidence headon to a fully shaded condition. Exacting limitations on acceptable structural distortion and misalignment require that temperature excursions and gradients induced by the environment be maintained within stringent bounds. Preliminary analyses indicate that passive means will provide adequate thermal control. These means include careful selection on materials, thermal control coatings, mounting techniques, insulation, etc. Weight and system performance tradeoffs must be made to determine the most effective passive thermal control techniques for each antenna configuration considered, including optimum selection of the above parameters. Thermal control of the antenna mounted actuators and transmitters has been encountered previously and can be satisfactorily achieved with a judicious choice of radiation coatings, insulation, and possibly electrical heaters during nonoperative periods.

Table 9-4. Typical Solar Array Temperatures

SUN NORMAL

Solar Constant		η = 0.0 T		η = 10% Array Temperature	
Btu/hr-ft^2	joules/hr-m^2	°F	°C	°F	°C
420	$4.7 \cdot 10^6$	126	52.2	111	43.9
430	$4.9 \cdot 10^6$	130	54.5	115	46.1
440	$5.0 \cdot 10^6$	133	56.1	118	47.8
450	$5.1 \cdot 10^6$	136	57.8	121	49.5
460	$5.2 \cdot 10^6$	140	60.0	125	51.7

η = cell efficiency

SUN 23.5° FROM NORMAL

Solar Constant		η = 0.0 T		η = 10% Array Temperature	
Btu/hr-ft^2	joules/hr-m^2	°F	°C	°F	°C
420	$4.7 \cdot 10^6$	113	45.0	99	37.2
430	$4.9 \cdot 10^6$	117	47.2	102	38.9
440	$5.0 \cdot 10^6$	121	49.5	105	40.5
450	$5.1 \cdot 10^6$	124	51.1	108	42.2
460	$5.2 \cdot 10^6$	127	52.8	112	44.5
η = cell efficiency					

9.5 SATELLITE CONFIGURATIONS

Conceptual thermal designs were developed for the three satellite configurations presented in Section 7.

- 4 kw with a frequency of 2.5 GHz
- 8 kw with a frequency of 12 GHz
- 12 kw with a frequency of 0.9 GHz

Three designs were used to evaluate the various possible thermal control techniques. Table 9-5 presents a summary of the physical characteristics of the three configurations.

Figure 9-9 presents the 2.5 GHz, 4 kw configuration with the body earth oriented. As a result the sides of the spacecraft are illuminated by the sun at varying sun angles. The thermal concept is an insulated one with two radiator areas: one of 10.9 ft^2 for dissipation of the high temperature component heat (1.25 kw); and one of 52 ft^2 for dissipation of the low temperature component heat (0.72 kw). Since the sun will illuminate the sides of the spacecraft where the louvers are, the radiator surface will have to be covered with second surface mirrors to get high emittance and low absorptance.

Table 9-5. TV Broadcast Satellites

(Thermal Control Summary for Three Configurations)

Orientation	Total Power (kw)	Frequency GHz	Thermal Dissipation From RF Tube (kw)	Required Radiator Area (350°F RF Tube)	Thermal Dissipation From Power Control	Required Louver Area	Requires Second Surface Mirrors on Louver Radiator Area
Earth	4	2.5	1.25	10.9 ft^2 (1.01 m^2)	0.72	52 ft^2 (4.82 m^2)	Yes
Sun	8	12.0	2.0	13.6 ft^2 (1.26 m^2)	0.92	27 ft^2 (2.50 m^2)	No
Earth	12	0.9	2.5	22 ft^2 (2.04 m^2)	1.4	102 ft^2 (9.46 m^2)	Yes

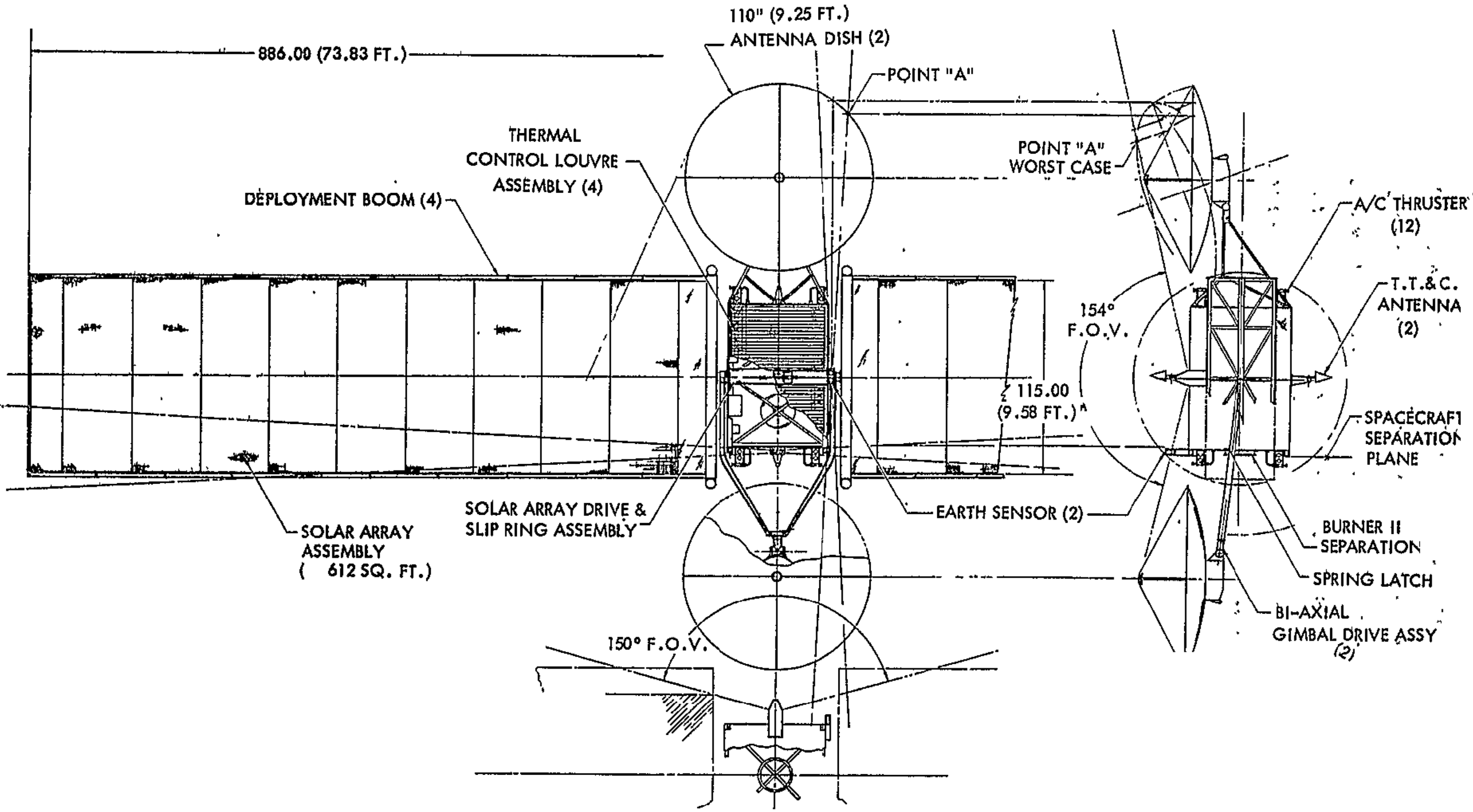


Figure 9-9. Earth Oriented "I" Configuration 2. 5 GHz 4 kw

The 12 GHz, 8 kw configuration is sun oriented. As a result the sides of the spacecraft are not illuminated by the sun. The thermal concept is an insulated one with two radiator areas: one of 13.6 ft^2 for dissipation of the high temperature component heat (2.0 kw); and one of 27 ft^2 for dissipation of the low temperature component heat (0.92 kw). Since the sun will not illuminate the side of the spacecraft where the louvers are, there is no requirement for second surface mirrors.

The 900 MHz, 12 kw configuration is earth oriented (Figure 9-10). As a result the sides of the spacecraft are illuminated by the sun at varying sun angles. The thermal concept is an insulated one with two radiator areas: one 22 ft^2 for dissipation of the high temperature component heat (2.5 kw); and one of 102 ft^2 for dissipation of the low temperature component heat (1.4 kw). Since the sun will illuminate the side of the spacecraft where the louvers are, the radiator surface will have to be covered with second surface mirrors to get high emittance and low absorptance.

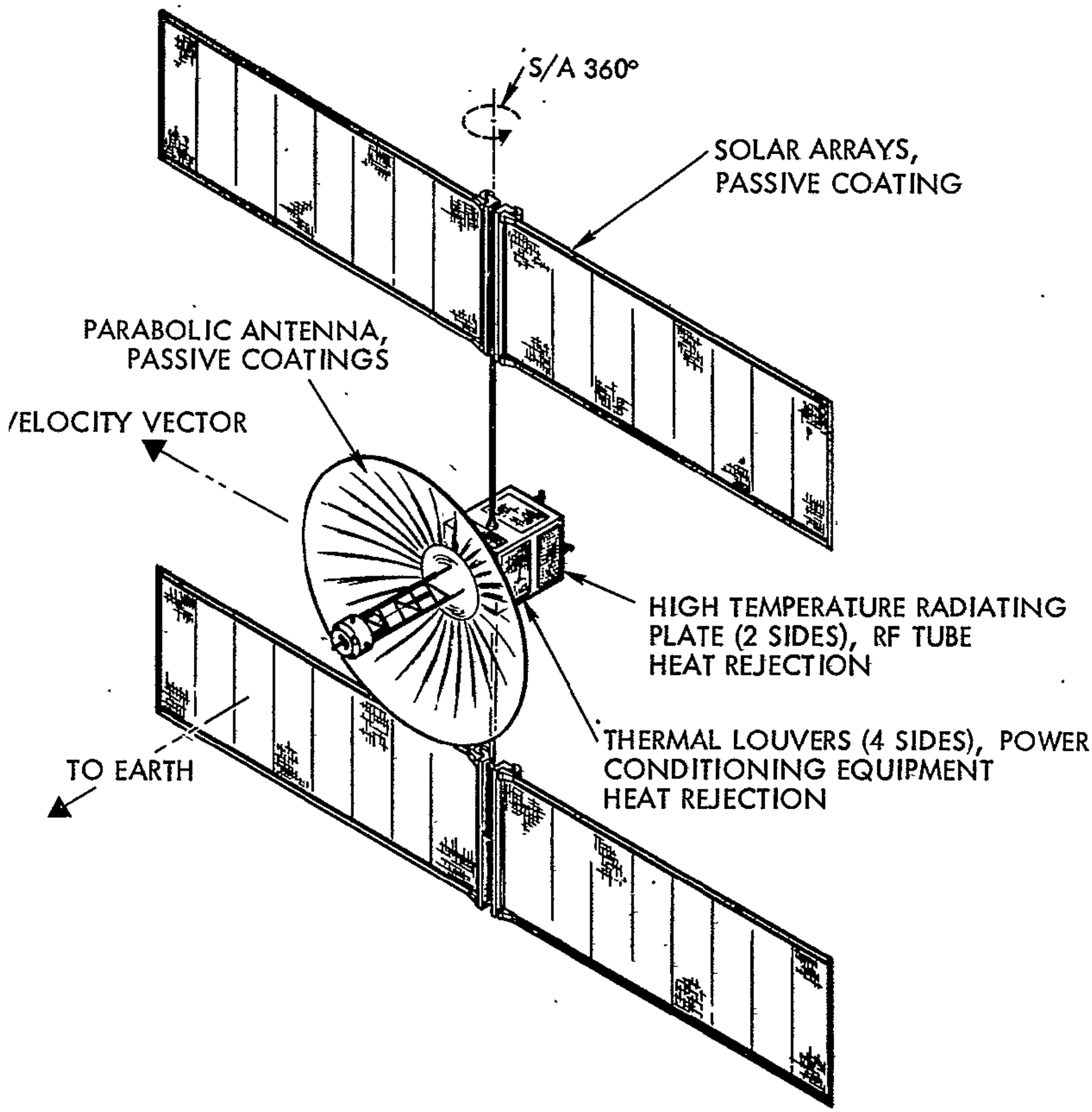


Figure 9-10. TV Broadcast Satellite Thermal Control

10. GROUND RECEIVERS

10.1 INTRODUCTION

Reception of television broadcasting from satellites by conventional consumer-market television receivers requires a space-oriented antenna. In most cases, an adapter will be needed to perform one or more of the following functions:

- Provide a sufficiently low system noise temperature
- Convert the frequency of the RF signal received from the satellite to a VHF or UHF channel within the capability of the television set.
- Convert modulation to AM/VSB of conventional standard.

The combination of adapter functions required for a given satellite broadcast system depends on the frequency, modulation, and ERP of the satellite transmission.

The adapter circuits considered here are proposed extensions of the current state-of-the-art, expected to be available for the 1975-1980 period. The adapters can employ functions which are already well understood. Integrated circuit techniques received the utmost consideration in the interest of low cost and high production reproducibility. Economic viability of satellite broadcasting dictates minimum production costs. Therefore, monolithic and hybrid integrated circuits and gross reduction of point-to-point wiring are used extensively in the adapter concepts introduced in the following sections. Modern computer-aided designs of the various circuit functions can drastically reduce, and in some cases entirely eliminate the test and tuning steps in the adapter manufacture.

The adapters discussed in the following sections receive the input RF signal from the space-oriented antenna and feed a converted RF signal into the antenna terminals of the conventional television sets. This scheme implies some duplication, in the adapter, of functions already present in the conventional television set. Such duplication could be removed by permitting the adapter entry into the television set at other points than the antenna terminals. However, the internal circuit functions of television sets are today not sufficiently standardized to permit interfaces other than the antenna terminals.

For clarity, the following discussions are aimed only at adapters for frequency-modulated satellite transmission, requiring modulation conversion to AM/VSB. Adapter designs for AM/VSB satellite transmission are in essence stripped-down FM adapter designs.

Figure 10-1 shows a block diagram of the FM adapter functions. It can be logically divided into two sections. The first section, "RF and IF Circuits," provides selectivity, amplification and demodulation. The second section, "Video and Audio Remodulation," separates audio from video, selects the audio channel, and remodulates these two component signals onto a suitable VHF carrier to produce the RF signal format of conventional television broadcasting.

10.2 RF AND IF CIRCUITS

10.2.1 General Discussion

The RF and IF section of the adapter is a single-conversion, super-heterodyne unit suitable for amplifying and demodulating wideband FM television transmission. By proper selection of suitable RF preamplifier, mixer, and local oscillator functions, any of the four specified carrier frequencies can be accommodated. The intermediate frequency is chosen to accommodate any of the four RF frequencies (0.9, 2.5, 8.5 and 12 GHz) considered in this study. The composite baseband from the FM demodulator is routed to the video and audio remodulation section.

One function often found in selective receivers is absent in the project scheme. An RF preselection filter is not used. Since the entire adapter is projected to employ integrated circuits, such a filter would also logically be an IC element, and would impose unreasonable insertion losses. To effectively filter out the image channel antenna noise the filter would necessitate a small fractional bandwidth, especically at 12 GHz. A loss of 3 to 5 db can be expected of such a filter.

The rectangular substrate to the right of Figure 10-2 is a 6-section Tchebychef bandpass filter centered at 6 GHz. The bandwidth is commensurate with the requirement, and the insertion loss is 4 db. Since this loss increases the overall receiver noise figure, other methods of image channel noise control, such as the use of a balanced mixer, are prescribed. A

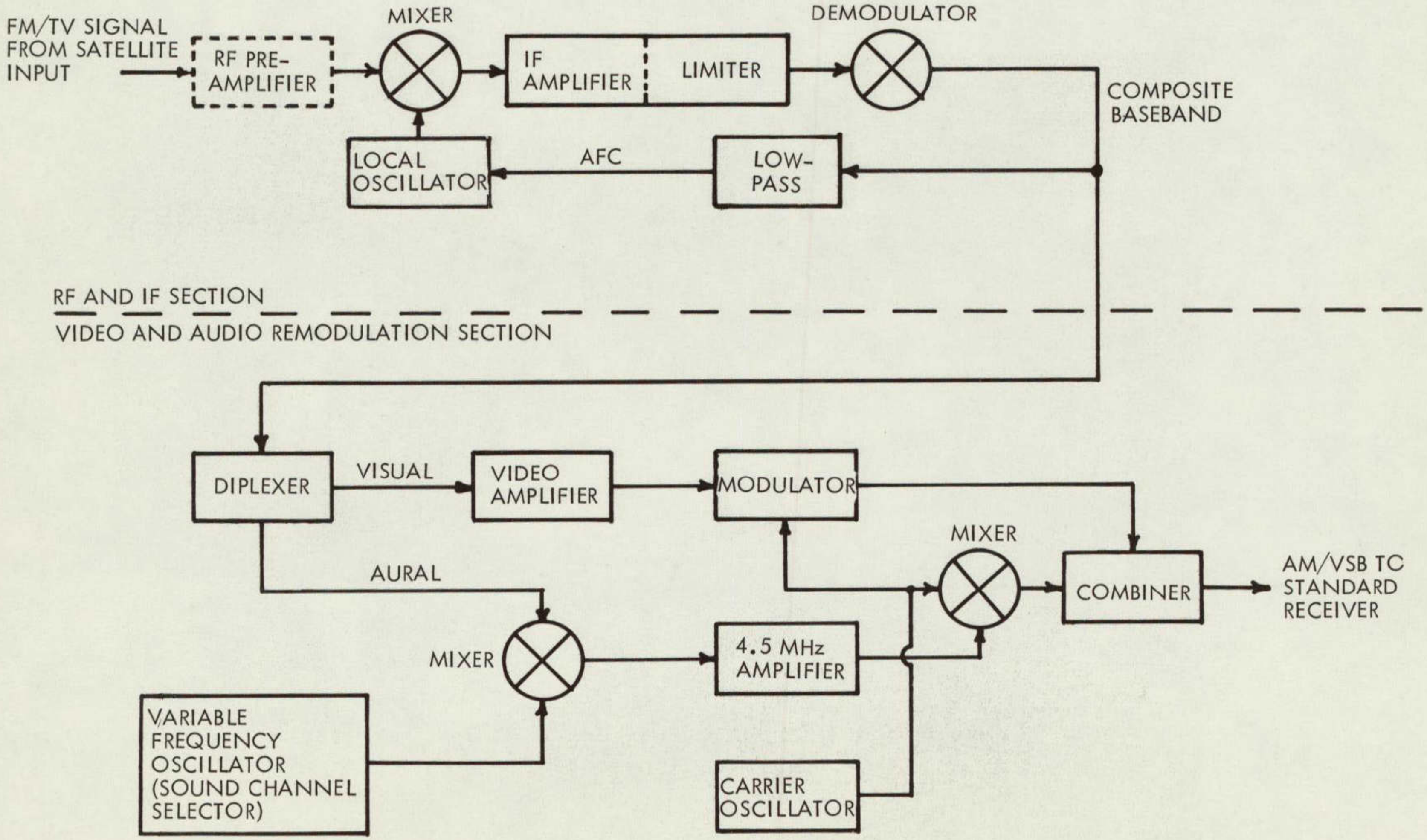


Figure 10-1. Adapter - Block Diagram

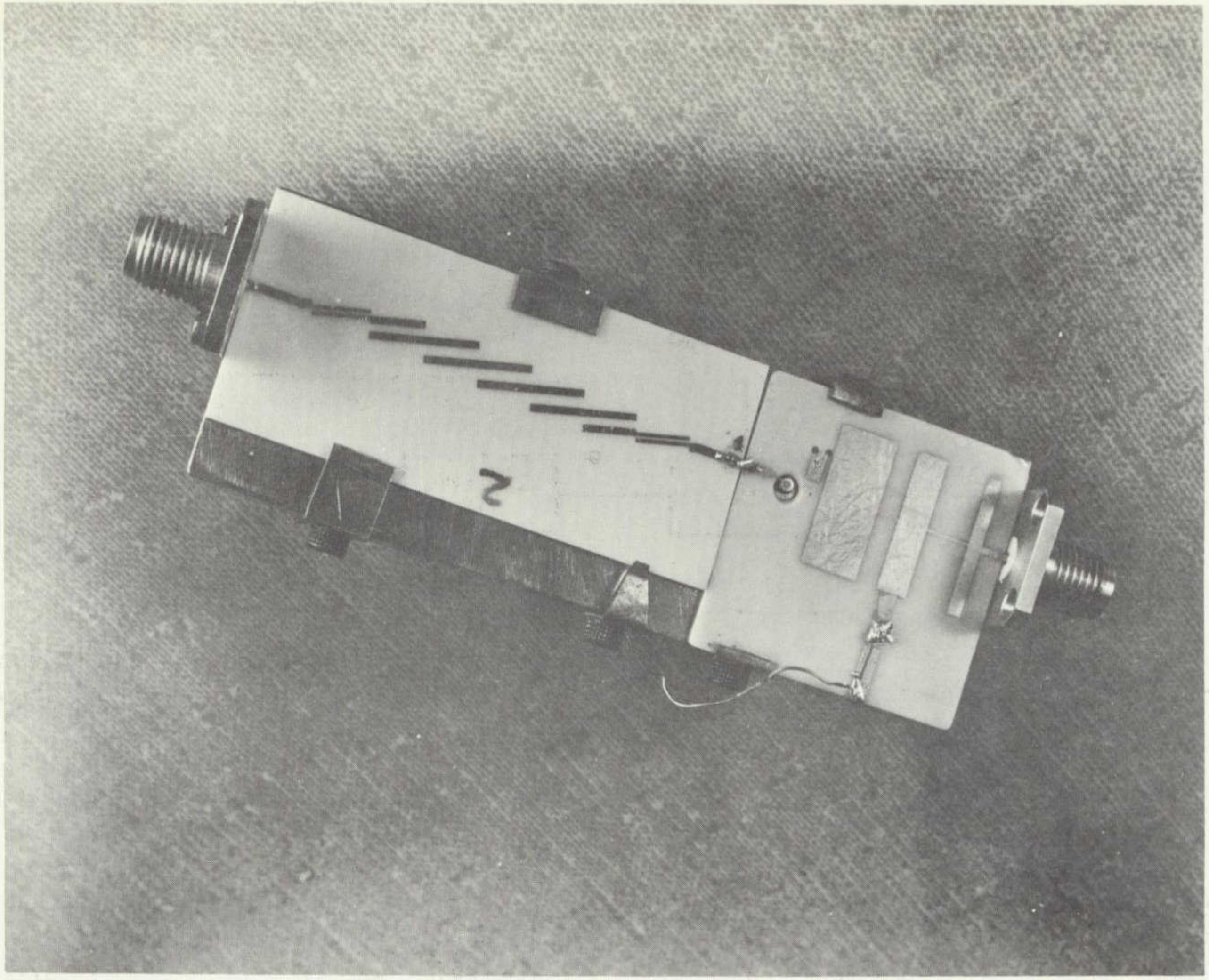


Figure 10-2. Diode Frequency Multiplier with companion Microwave Bandpass Filter for a 6 GHz Output. (Excellent response is attained at some expense as to insertion loss.)

wider filter could be employed to reduce cross modulation from out of band signal power. The space-oriented antenna may provide some protection. For these and economic reasons, a preselector is not warranted.

10.2.2 RF Preamplifier

Figure 10-1 shows an RF preamplifier as the front-end unit. Low cost amplifiers are available for the two lower carrier frequencies, 0.9 and 2.5 GHz.

At 8.5 and 12.0 GHz either a balanced tunnel diode or a parametric amplifier would provide the necessary gain and noise figure. The preamplifier should exhibit a gain of 8 db or greater and have a noise figure significantly less than the mixer which follows. At these two higher frequencies, transistor devices do not now exist which provide these performances. Therefore, the block diagram denotes this circuit block as tentative, depending on the RF carrier frequency.

At present, a junction field effect is available for less than $1 in quantities of 1000, which at 900 MHz will yield a gain of 8 db with a noise figure of 3.3 db. Assuming a noise figure of 1.5 db for the IF amplifier, the combination of mixer and IF amplifier has an overall noise figure of 5.5 db. With the junction field effect transistor as RF preamplifier, the overall receiver noise figure is reduced from 5.5 db to 4.05 db, as is easily determined with the familiar expression

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1}$$

At 2.5 GHz the bipolar transistor shows promise. An amplifier has been constructed at TRW Systems which exhibits a 4.5 db noise figure and a 15.5 db power gain at 2.0 GHz. The bandwidth is greater than one octave. It is reasonable to predict that both this gain and noise figure will still be attainable at 2.5 GHz if the design were shifted to this frequency and the bandwidth is reduced to the 30 MHz necessary for FM/TV satellite transmission. At 2.5 GHz, the combination of mixer and IF amplifier would have a noise figure of about 6.0 db. With the bipolar transistor amplifier, the overall receiver noise figure is reduced from 6.0 db to 4.95 db, assuming that the transistor gain is reduced from the achievable 15 db to a more economic 10 db.

For consumer use, the 900 MHz device is clearly in the right price range even at present prices. The 2.5 GHz devices are still quite expensive; the cost of such a transistor is tens of dollars. However, at present only limited quantities are produced, and development and engineering costs are still the major part of the cost basis. Since the device is not difficult to manufacture, production runs on the order of a million items will reduce the unit cost to a few dollars.

Figure 10-3 shows an S-Band transistor power amplifier which represents near state-of-the-art methods at the present time. Though the performance characteristics are not the same as the preamplifiers considered for the adapter, the overall circuit approach is very similar. The substrate shown in the figure is 1 inch (2.5 cm) on each side, and either the 0.9 or 2.5 GHz RF preamplifier would conveniently be produced using these methods.

For 8.5 GHz and 12 GHz, both the balanced tunnel diode and the negative resistance parametric amplifier are reasonable candidates. They also lend themselves to microcircuit techniques, since both types have been modeled in laboratories. Of course, the paramp requires a microwave pump signal, perhaps attainable from a bulk effect, free running oscillator. The use of a microwave circulator for impedance stabilization is suggested for either form, particularly if the VSWR of the reception antenna varies over a large range for any cause.

A single stage tunnel diode amplifier with a gain of 15 db and a noise figure of 4.5 db at 8.5 GHz or 5 db at 12 GHz is within today's state-of-the-art. The current retail price is on the order of 500 dollars per unit for small quantities. For a production quantity of 10^6, the retail price by 1975 will probably be about 50 dollars.

Tunnel diodes are not considered for 0.9 GHz and 12 GHz, since they do not give a better noise figure than attainable at lower cost with a transistor amplifier.

An uncooled, single-stage parametric amplifier reduces the adapter noise figure to 2.2 db at 0.9 GHz or 3.3 db at 12 GHz. The present retail

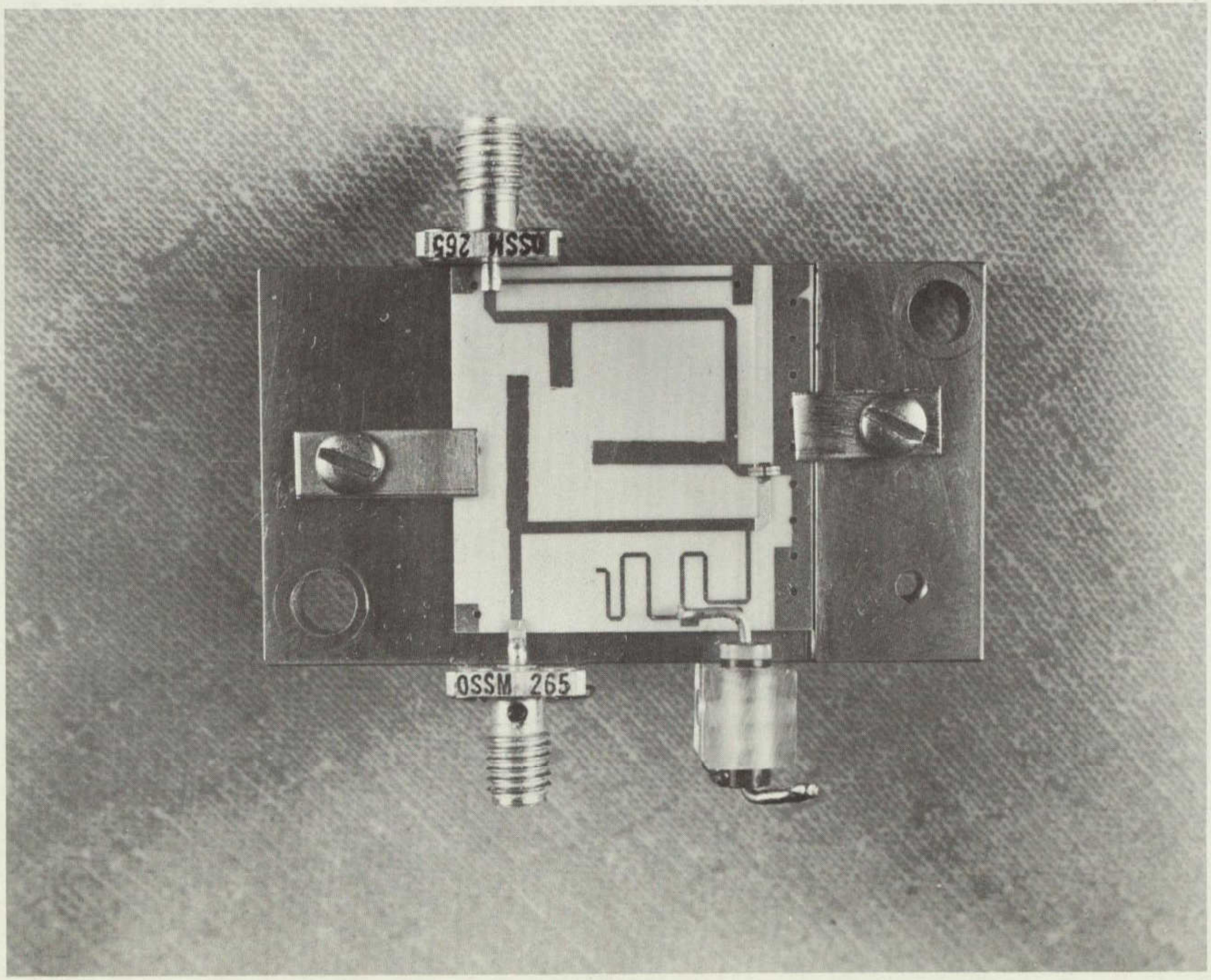


Figure 10-3. Integrated Microwave Amplifier. Large signal 2.3 GHz amplifier with 5 watt output, 5 db gain and 35 percent efficiency. (Bias, resonator, and device changes would provide linear, low-noise performance)

price of about 5000 dollars applies to small quantities. For 1975, a reduction to 200 dollars is anticipated for production in quantities of 10^6, using microcircuit techniques and a bulk effect oscillator.

10.2.3 Microwave Mixer

Within the advent of the Schottkey-barrier diode, microwave mixers or down-converters are showing exciting improvements. Based on device parameters demonstrated in several laboratories, the following list of noise figures are predicted for 1975 production equipment.

Frequency (GHz)	Noise Figure (db)
0.9	5.5
2.5	6.0
8.5	6.5
12.0	7.0

These noise figures are single-sideband values (image noise either filtered or canceled out) based upon an IF amplifier noise figure of 1.5 db, available from 10 MHz to over 200 MHz.

Hybrid microelectronic mixers, balanced and single ended, are readily available from numerous suppliers. The costs are still high for consumer use, but these are established by the relatively low production levels. A reasonable prediction of this circuit function is a couple dollars for large quantity production in 1975.

Image-noise cancellation by dual mixers is not new. Such schemes have been employed for some time in radar and other microwave receivers. Figure 10-4 illustrates one method for practically realizing the dual mixer. The incoming RF signal is equally split to the two identical mixer elements. One leg is phase shifted with respect to the other. The local oscillator injection signal is also split to drive both mixers. The resulting pair of IF signals are brought into phase summation in the IF combining hybrid. The desired carrier voltage will recombine at the IF output while the image voltage combines in the termination resistor. The initial RF signal splitting hybrid will exhibit a very low insertion loss, less than half a db. Therefore, the theoretical 3 db noise improvement due to image noise cancellation gives way to a practical 2.7 to 2.8 db improvement.

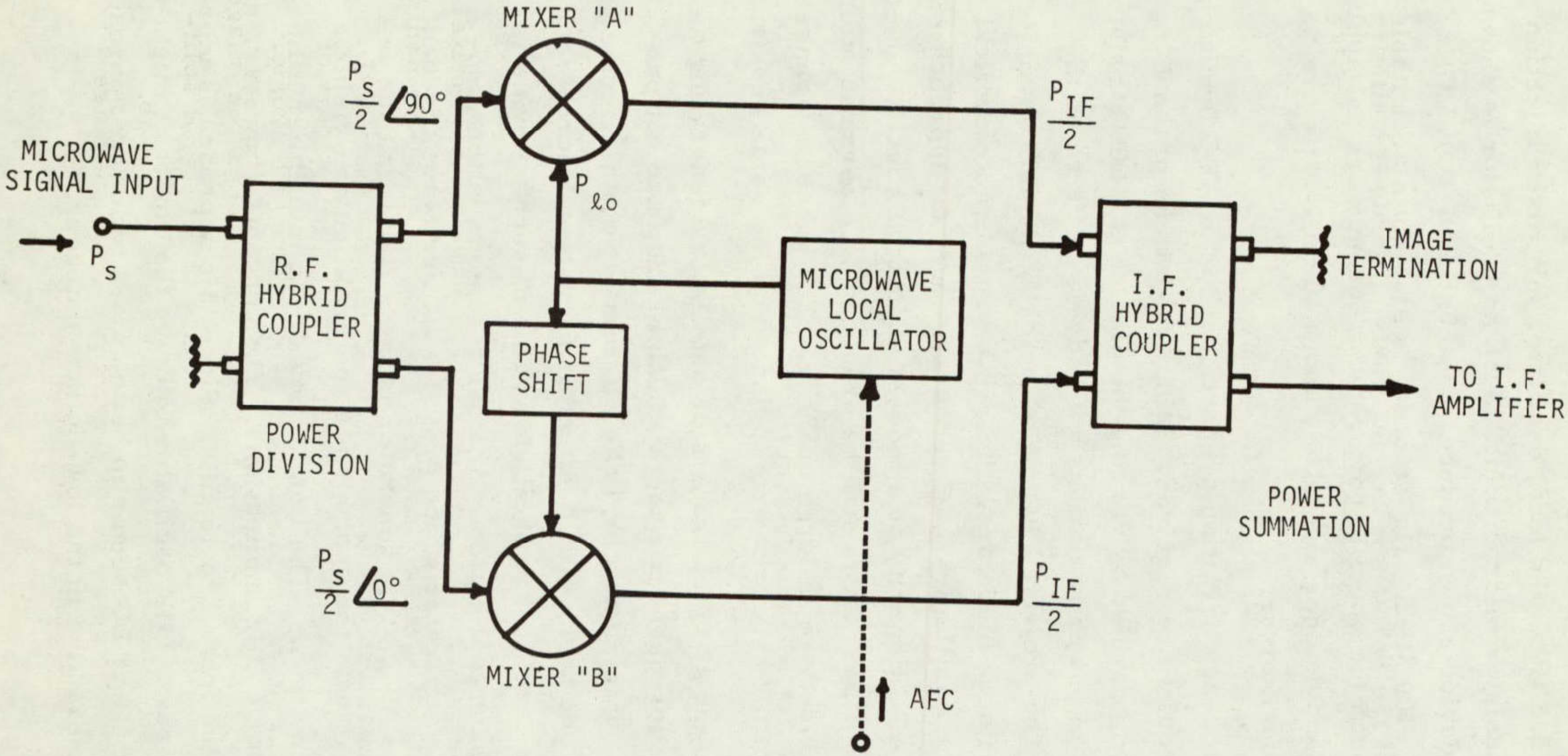


Figure 10-4. Dual Mixer Arrangement for Image Noise Cancellation

10.2.4 Microwave Local Oscillator

At 0.9 GHz and 2.5 GHz, the local oscillator for mixer injection would be a bipolar transistor microcircuit. Such an oscillator is shown in Figure 10-5. The device shown produces over 0.5 watt at 1.3 GHz with a tuning range of ±100 MHz. The stability is also quite acceptable for this adapter. Though the specific power and frequency are not applicable, the techniques and devices are. Only about 10 milliwatts are required to drive the dual mixer.

To provide a frequency deviation proportional to the AFC feedback voltage, additional circuits are required. Minor deviations of the LO output frequency can be provided by varying the bias on the LO transistor. This normally results in power variations with adverse effects on the mixer performance. The projected LO more logically should contain a voltage variable capacitance diode or Varicap® to provide an electrical tuning adjustment of the oscillators L-C networks. Such an approach results in reasonable AFC linearity at a modest additional cost. The entire local oscillator with AFC can still be produced on a ceramic microcircuit for two or three dollars in large quantity. The necessary phase shifting and power splitting networks are implanted on the same substrate.

For the 8.5 GHz and 12 GHz, transistor oscillators generating the LO frequency without subsequent frequency multiplication are not projected as practical consumer items by 1975. Rather, two other techniques are indicated. On the one hand, a bulk-effect or Gunn type microcircuit oscillator may be considered. The oscillator noise of such a device is acceptable for the present application. Another technique is the step-recovery diode impulse generator which provides a microwave frequency power comb. In Figure 10-2, this generator is the structure at the left. The filter at the right selects the appropriate spectral line and yields a highly purified injection signal. The figure shows a X6 multiplier-filter arrangement suitable for 6 GHz applications. The concepts, however, have been successfully applied from 1 to 16 GHz. Since this approach is more complex and also requires a VHF oscillator to drive the diode, it might be impractical. The bulk effect LO seems to be the more practical approach. The cost of this function is also in the low-dollars category.

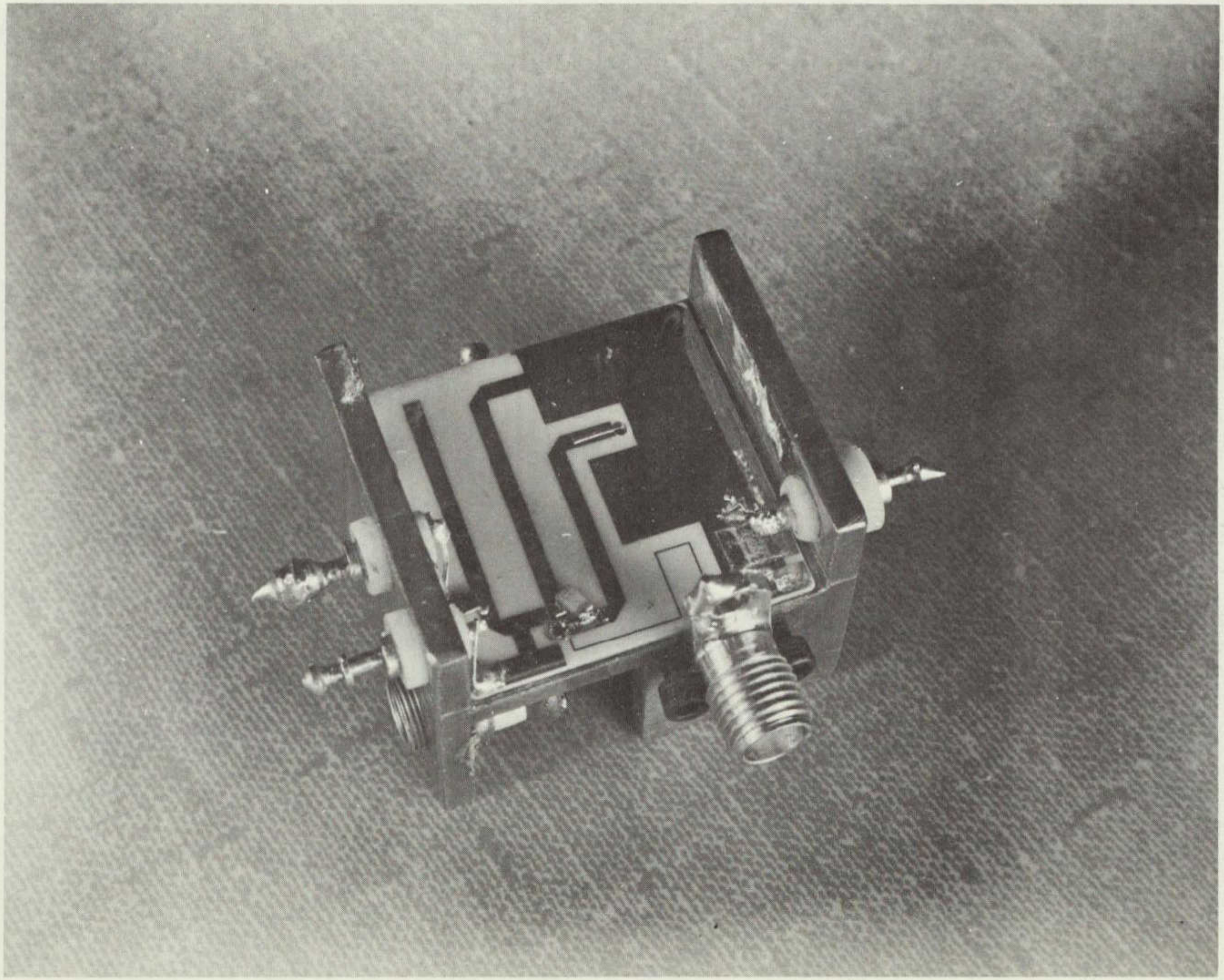


Figure 10-5. Microwave Integrated Transistor Oscillator. Though this circuit provides 0.5 watt at 1.3 GHz with a 200 MHz tuning range, device and circuit modifications would provide receiver LO characteristics.

10.2.5 IF Amplifier and Limiter

The hybrid-recombined IF signal power leaving the dual mixer, enters the intermediate frequency amplifier shown in Figure 10-1. The center frequency is a compromise chosen to accommodate all four carrier frequencies considered. A bandwidth of 30 MHz is indicated for the system. The center frequency would be in the region of 150 MHz to promote reasonable filter design and band shaping. Recent IF amplifier designs employing IC devices normally render the band shaping elements in one group with the gain elements surrounding this filter.

On the current market, a monolithic IC amplifier circuit can be purchased for slightly over one dollar. Such an amplifier has a signal gain of 60 db at 10 MHz. For a few cents more, the device can include the diode matrix necessary for angle detection and the last stage limiting function required for FM detection.

A reasonable extrapolation of the present technology growth in this specific IC area would provide a similar unit at 150 MHz by 1975. As usual, the cost will be quantity dependent. A safe estimate would price a three stage IF amplifier in hundred thousand quantities at under $5. Sufficient gain, bandwidth, limiting, and frequency detection would be realized. The mechanical carrier for the devices would likely be the normal copper laminate, printed circuit board in the interest of cost reduction. The only point-to-point wiring required would involve the addition of lumped L-C filter elements, and the modest number of lead connections to the prepackaged IC units.

For massive consumer quantities, an entirely monolithic amplifier possessing all of the required performance criteria might be considered. The only outboard hybrid elements for such a design would be a few lumped inductor and capacitor discrete components to satisfy the frequency response requirements. Additional monolithic video and DC amplifier chips could be included to drive the diplexer and AFC local oscillator inputs, respectively.

Figure 10-6 portrays an extremely wide band phase detector used for a frequency locking application at TRW Semiconductors. The band of operation covers a range from a few megacycles to the 6 GHz region. Though not immediately applicable to the adapter discussed herein, it shows the promising future of film techniques in similar applications.

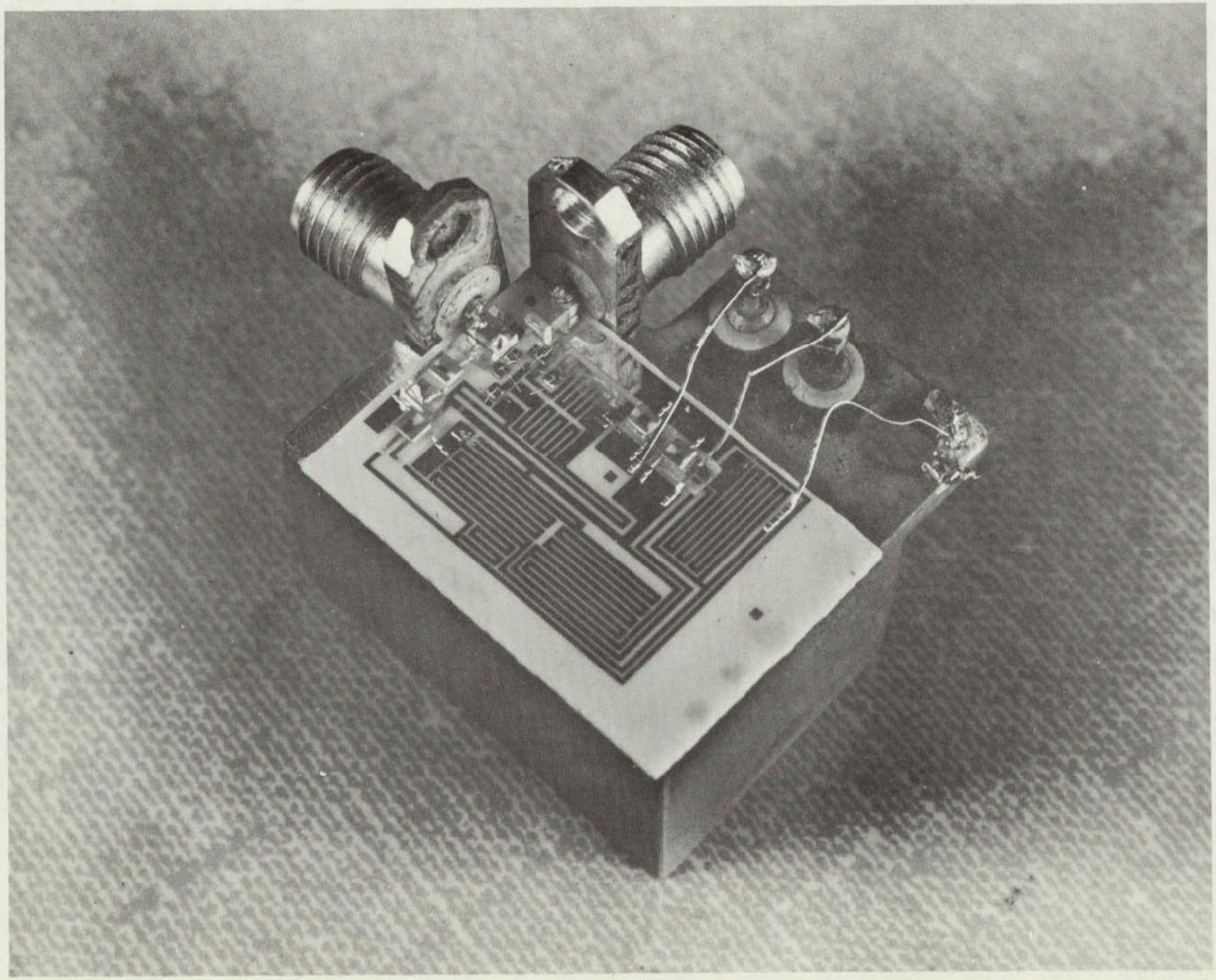


Figure 10-6. Wideband Microelectronic Phase Detector. Phase and impedance linear performance from the low MHz to 6 GHz is displayed. Sensitivity is 200 millivolts per radian of $\Delta\phi$.

10.3 VIDEO AND AUDIO REMODULATION

The signal entering the video and audio remodulation section of the adapter is a composite baseband consisting of a video signal (luminance and chrominance, or luminance only) and one or more audio subcarriers. See Section 2.5.

The remodulation section separates the audio subcarriers from the video signal and uses these two signals to generate the RF signal format of conventional television broadcasting, for which the television set is designed. Specifically, an RF carrier at one of the standard vision carrier frequencies is amplitude modulated by the video signal. The audio FM carrier is generated by transposing the selected audio subcarrier to the standard intercarrier frequency and mixing it with the output of the vision carrier generator.

10.3.1 Video Diplexer

The diplexer separates the sound subcarrier(s) from the video signal. It is fixed-tuned and could be realized from lumped LC components. In complexity it is comparable to perhaps two conventional IF transformers. The manufacturing cost of an IF transformer is today about 15 cents in the U.S. and in the neighborhood of 8 cents in Korea or Taiwan. It is not to be expected that labor cost will decrease by 1975 and therefore one can assume that the diplexer cost if it were assembled from discrete LC components would be in the neighborhood of 20 to 25 cents. However, by 1975 this network will probably not be fabricated from discrete components but rather as a printed corral capacitor assembly on a substrate which may be an ordinary printed circuit board or a low cost glass or ceramic. European TV sets now make extensive use of printed circuits in the sound IF strip and to some extent in the video circuits and it is to be expected that this technique will find much wider use in the future. The TRW Components Division is presently developing printed tuned circuit assemblies for use in FM voice broadcast receivers. These circuits are competitive in price and in performance with conventional filters as they are manufactured now in the Orient. For 1975 when probably all manufacture of mass produced consumer type electronic components will be in the Orient, a cost of not much more than 10 cents of today's value can be projected for the diplexer.

10.3.2 Modulator-Mixer

After the diplexer follows a video amplifier and a de-emphasis network. It is questionable whether the amplifier is needed. The de-emphasis network can very well be combined with the diplexer. The resistors could be fabricated by thick film techniques. This is no problem if a ceramic substrate is used. Even on ordinary printed circuit board very low cost resistors can be deposited. This technology has been developed by the Resistor Division of TRW Electronics (formerly IRC). The cost of a trimmed thick film resistor is projected to be 0.8 cents.

Video amplification becomes unnecessary if the video modulator is sensitive enough to modulate fully with millivolt inputs. This demand can be met by one of the monolithic integrated circuits for similar applications, which are just now entering the market. Typical of this kind of integrated circuit is the RCA type CA3028A. Currently these devices sell in large quantities for less than a dollar, and further price reductions will occur until the mid 70's. It appears safe to assume that by 1975 the price of relatively simple integrated circuits will be no more than the price of today's epoxy type of high frequency transistor, which lies in the neighborhood of 10 cents. A similar IC can perform the function of mixing the audio subcarrier signal with the vision carrier to produce the audio carrier.

For production quantities of hundreds of thousands or more, it will be worthwhile to combine the video modulator and the audio mixer into one circuit. This circuit then would have inputs for the video, audio, and carrier oscillator and an output terminal with the proper impedance level necessary to drive a cable which connects the satellite TV adapter to the antenna input of a normal TV set. The complexity of this monolithic integrated circuit would be no greater than that of the operational amplifiers which are presently manufactured in monolithic form. In large quantities these circuits presently sell for approximately $2. If produced in quantities of millions, the price will drop below $1, probably in the range of 25 to 40 cents.

The carrier oscillator must be relatively stable but need not be crystal controlled. It may be advantageous to make this oscillator frequency variable since the regular TV channels free for satellite boardcasting would depend on the area where the adapter is used. In cost there.

is not too much difference between a good stable variable frequency oscillator VFO and a crystal controlled oscillator. It is safe to assume that a frequency variable oscillator of this kind, mass produced, including all electrical and mechanical parts, will have a manufacturing cost of substantially below 50 cents.

10.3.3 Sound Channel Selection

The satellite TV system may have several sound carriers. To be compatible with standard TV receivers these subcarriers will be FM modulated and occupy approximately 100 kHz. A converter is needed to transpose the various sound channels to the intercarrier frequency of the respective standard. The local oscillator must be tunable from approximately 9 to 11 MHz and could simultaneously serve as mixer in an audiodyne type of circuit. If continued adjustment of the sound carrier frequency range is desired, permeability tuning would be the most economical means. If the various sound subcarriers should be accessible through push button operation, one might consider electronic tuning. Since the range to be covered is only 10 to 15 percent wide, and the frequencies are relatively low, the most simple variable capacitance diode will be sufficient. Such diodes are priced in the 10 to 20 cent range and may become even cheaper in 1975. The bias voltages required can be obtained from small preset trimpots in very much the same way that European TV sets today achieve channel selection. It is also feasible to employ a thick or thin film resistor network to supply the individual bias voltages needed, which would then be applied to the tuning diode via microswitches.

Material cost for this stage would be approximately 25 to 30 cents for the push-button switch assembly, about 10 cents for the oscillator transistor, and 10 to 15 cents for the oscillator coil and small resistors. The output transformer will be about 8 cents. Further IF amplification on 4.5 megacycle is not considered necessary because of the sensitivity of the subsequent monolithic mixer which has been discussed earlier in connection with the video modulator. Price for audiodyne mixer did not consider the trimpot assembly or the preset resistor bias divider network and if trimpots are used, these will be between 5 and 10 cents a piece.

10.3.4 Integration with the Television Set

The adapter discussed thus far uses the video signal and an audio subcarrier at standard intercarrier frequency to generate the RF signal format of conventional television broadcasting, consisting of an amplitude modulated vision carrier and a frequency modulated audio carrier. The television set then recovers the video signal and the audio intercarriers, both signals already present in the adapter.

The sole reason for this remodulation and subsequent demodulation is to permit connection of the adapter to the regular antenna terminals of the television set. It could be avoided by equipping the television set with two additional input jacks, one for video and the other for the audio intercarrier. This would require standardization of levels, frequency responses and other characteristics for these additional jacks.

The elimination of remodulation and second demodulation will result in a slight improvement in picture quality. The simplification of the adapter consists of elimination of the proposed integrated circuit for RF carrier generation, video modulation, and audio mixing. The saving in adapter cost will be significantly offset, or even outweighted, by price increase of the modified set. Additional jacks must be installed, provisions must be made for disabling the regular IF strip, and special, shielded cables will be required to feed video and intercarrier into the television set.

Another approach is to integrate the IF amplifier and FM demodulator of the adapter with the television set. The remaining adapter functions, i.e., RF amplification (if used) downconversion to IF, and IF preamplification, could then be performed by an antenna-mounted unit.

10.4 TV SETS FOR SATELLITE BROADCASTS

The difference in cost between a straight satellite TV receiver and ordinary receivers will be only minor. The microwave frequency converter for 0.9 GHz or 2.5 GHz will not be more expensive than the TV tuner with a multiple channel selection capability. Whether the IF strip is centered around 30 to 40 MHz or 100 MHz will not make much difference, and the only additional function really required is the multiple sound carrier selection circuit.

10.5 FUTURE TRENDS

Present color schemes have deficiencies brought about by the requirement of compatibility with monochrome receivers. It is not inconceivable that an entirely new TV transmission system using specialized receivers will benefit from the absence of compatibility restrictions in using a new scheme for color transmission, resulting in quality improvement and/or cost saving.

It is very likely that in 1975 the TV sets with the exception of the picture tube will be entirely solid state. We can expect that by 1975 most of the functional blocks will be manufactured in the form of hybrids with thick film integrated circuits. These hybrid circuits will of course contain many monolithic IC's in chip form which are bonded to the remainder of the circuit. One large manufacturer has designed a complete color TV set which consists entirely of thick film functional subassemblies. The main reason for the introduction of integrated circuits is to offset the ever rising labor costs.

For examples of circuitry details, consider first the video amplifier. The present trend is to separate the functions of selectivity (or bandpass shaping) and amplification, and it is safe to assume that in the future we will have a lumped gain function in the form of a high gain monolithic circuit and a separate selectivity function in the form of a printed filter network. We may also find some active filters. They will most likely first appear in the chroma amplifiers, where frequencies are relatively low and bandpass requirements rather simple.

The familiar IF transformers in cans will disappear. Two possible new solutions have already been introduced. One is the use of piezoelectric filters. These filters are now available from several Japanese sources at prices which are somewhat below the price of conventional LC tuned circuits.

There is also a good possiblity that the sound IF amplifier and discriminator as we know it now will no longer be used. Sprague introduced some time ago a new integrated circuit which performs these functions without tuned circuits or a ratio detector. An auxiliary carrier spaced about 200 kilocycles away from the sound intercarrier is mixed with the sound information to produce a relatively low frequency beat output. These frequencies can be amplified in resistor capacitor coupled monolithic circuits up to the level where they can be limited. The frequency modulation is then converted to pulse width modulation and the resulting wave shapes integrated to recover the sound information. This scheme appears complicated, but it does have the advantage that it can be constructed in monolithic circuit form. Sprague developed such circuits for ordinary FM radios and TV receivers.

There will also be some changes in the tuners. At present, the dart type tuner for VHF and the continuously tunable UHF tuner are used in the United States. Electronic tuning is used in Europe and it is presently being introduced in the U. S. Push-button tuning will be largely electronic. Varicap® tuning will eliminate the need for mechanical arrangements. A bias voltage for each channel can be obtained from small trimming parts and small switches for channel selection. It is also to be expected that the entire tuner will be built in hybrid microelectronic form. One of the leading tuner manufacturers designed such a circuit, a ceramic substrate with the coils on the varactor chips, and some transistor chips.

10.6 ANTENNAS

Link analysis indicate that user antenna gains of 20 db and higher are preferred. Therefore, the parabolic reflector antenna appears the best choice of type for the present application.

Present techniques for fabrication of the parabolic reflector are:

- Stamping of steel or aluminum sheet metal.
- Spinning of aluminum sheet metal.
- Fiberglass-on-foam sandwich with a sprayed reflective surface.

Stamping is the simplest method, requiring the least number of manufacturing operations and time. The high cost of stamping tools is a disadvantage of production in quantities less than 10,000. For larger quantities, 100,000 and over, the tool cost becomes a small fraction of total production cost. Stamping is then a competitive method, if not the most economic choice among the three manufacturing methods mentioned above. Further, stamping has the capability of producing expanded metal reflectors, having less weight and experiencing less windload than solid reflectors, a feature of special value for the larger diameters required at the lower frequencies (0.9 and 2.5 GHz).

Tables 10-1 thru 10-4 give performance and price data for parabolic reflector antennas. The gain values and beamwidths in the table are based on an illumination pattern for low sidelobe levels, of importance for rejection of manmade noise and earth radiation. The antenna noise temperatures given include galactic noise, noise due to atmospheric attenuation (oxygen and water vapor), and earth radiation. These components of antenna noise temperature were calculated for a boresight elevation of 20 degrees, corresponding to a great-circle distance of 62 degrees between receiver location and sub-satellite point.

The values in the columns "Sun Noise Temperature" are the effective antenna noise temperatures of solar radiation when the sun is in the main lobe. This addition to antenna noise temperature is proportional to $(\text{beamwidth})^{-2}$, reaching several thousands degrees Kelvin at beamwidths of one to two degrees. For receiver locations at latitudes between 50 degrees south and 50 degrees north, the sun is in the main lobe during approximately $(\alpha/15)^2$ percent of the time, where α is the beamwidth in degrees.

The prices in Tables 10-1 thru 10-4 are expected retail prices for purchase and installation, in the 1975-80 period, of circularly polarized reflector antennas. These prices, based on production quantities of 10^6 units, are estimates derived by judicious use of present retail prices and learning curves, with consideration to the effect of frequency on surface accuracy requirements. Stamped reflectors of expanded aluminum were assumed for 0.9 GHz and 2.5 GHz, solid steel for 8.4 GHz and 12 GHz.

Antenna noise temperature components generated by external sources, such as earth radiation and manmade noise, are given by the equation

$$T_A = \frac{1}{4\pi} \int_{4\pi} TG \, d\Omega = \frac{1}{4\pi} \int_{\theta=-\pi/2}^{+\pi/2} \int_{\phi=0}^{2\pi} T(\theta,\phi)G(\theta,\phi) \cos\theta \, d\phi \, d\theta \tag{10-1}$$

Table 10-1. Earth Receiver Antennas for 0.9 GHz: Performance and Retail Price

Diameter (ft)	Diameter (m)	Gain (db)	Beamwidth (3 db) (deg)	Antenna Noise Temp (°K)	Sun Noise Temp (°K)*	Retail Price ($)**
4	1.22	18	21	86	86	40
6	1.83	21	15	80	169	55
8	2.44	24	11	73	314	78
10	3.05	26	8.5	71	528	130

*Sun in the main lobe.
**For installed antenna; production quantities of 10^6.

Table 10-2. Earth Receiver Antennas for 2.5 GHz: Performance and Retail Price

Diameter (ft)	Diameter (m)	Gain (db)	Beamwidth (3 db) (deg)	Antenna Noise Temp (°K)	Sun Noise Temp (°K)*	Retail Price ($)**
4	1.22	27	7.6	55	224	80
6	1.83	30	5.5	52	433	105
8	2.44	33	3.8	50	900	145
10	3.05	35	3.0	49	1440	230

*Sun in the main lobe.
**For installed antenna; production quantities of 10^6.

Table 10-3. Earth Receiver Antennas for 8.5 GHz: Performance and Retail Price

Diameter		Gain	Beamwidth (3 db)	Antenna Noise Temp	Sun Noise Temp	Retail Price
(ft)	(m)	(db)	(deg)	(°K)	(°K)*	($)**
2	0.61	32	4.3	56	293	165
4	1.22	38	2.1	54	1230	180
6	1.83	41	1.5	51	2400	220
8	2.44	43	1.2	50	3750	300
10	3.05	45	1.0	50	5400	430

*Sun in the main lobe.
**For installed antenna; production quantities of 10^6.

Table 10-4. Earth Receiver Antennas for 12 GHz: Performance and Retail Price

Diameter		Gain	Beamwidth (3 db)	Antenna Noise Temp	Sun Noise Temp	Retail Price
(ft)	(m)	(db)	(deg)	(°K)	(°K)*	($)**
2	0.61	35	3.0	59	422	190
4	1.22	41	1.5	57	1690	210
6	1.83	44	1.1	55	3140	265
8	2.44	46	0.85	55	5300	450
10	3.05	48	0.7	55	7750	710

*Sun in the main lobe.
**For installed antenna; production quantities of 10^6.

where

θ = elevation above the horizon, radians.

ϕ = azimuth, radians.

Ω = solid angle, sterads.

$T(\theta, \phi)$ = brightness temperature of the external noise source, °

$G(\theta, \phi)$ = power gain pattern of the antenna.

For general consideration of manmade noise; earth radiation; tropospheric noise; and noise due to precipitation, clouds and fog; the brightness temperature can be assumed to be independent of azimuth and to vary relatively slowly with θ. Hence, for approximate calculation of T_A, the brightness temperature can be given a constant value T_k in each annular zone bounded by the limits θ_{k-1} and θ_k of a small elevation interval. See Figure 10-7.

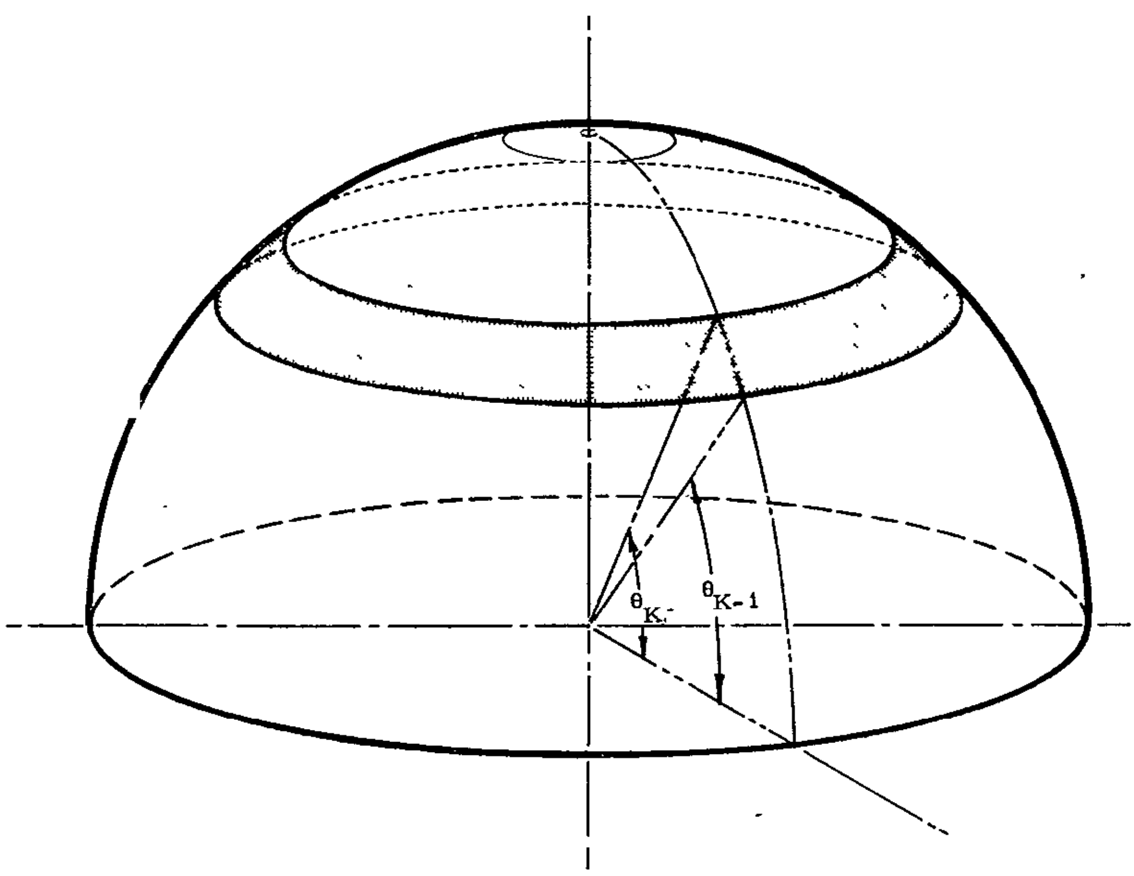


Figure 10-7. Annular Zones

Expression (10-1) is then approximated as follows:

$$T_A = \sum_{k=1}^{n} T_k F_k \qquad (10\text{-}2)$$

with

$$F_k = \frac{1}{4\pi} \int_{\theta_{k-1}}^{\theta_k} \int_{\phi=0}^{2\pi} G(\theta,\phi) \cos\theta \, d\phi d\theta \qquad (10\text{-}3)$$

where the summation must be carried out over the entire elevation range of interest.

Each zone factor F_k is dependent on the elevation limits θ_{k-1} and θ_k of the zone, the elevation of the antenna beam, and the beamwidth.

The zone factors F_k have been determined, by computer calculations, for elevation intervals of 5 degrees between 0° and $+30^\circ$, for intervals of 10 degrees between $+30^\circ$ and $+90^\circ$, and for the interval from -90° to 0°. Tables 10-5 through 10-8 show these values for different beam elevations and beamwidths. For instance, the antenna noise temperature of earth radiation can be calculated simply by multiplying the effective radiation temperature of the earth surface (normally 290°K) with the appropriate factor for the elevation range 0° to -90°.

10.7 COST AND PERFORMANCE DATA

The model used here to determine the total retail price and performance of the required user equipment, in addition to the regular television receiver, consists of:

- A parabolic antenna, circularly polarized.
- An antenna-mounted unit including an RF pre-amplifier (optional), downconverter, and IF amplifier.
- An indoor unit consisting of a demodulator section, a video-audio modulator section, power supply, antenna switch, cables and enclosures.

Table 10-5. Zone Factors

(a) Antenna Beamwidth = 5°

ANTENNA ELEVATION	5°	10°	15°	20°	25°	30°	90°
ZONES	ZONE FACTORS						
80° to 90°	0.000113	0.000084	0.000090	0.000119	0.000168	0.000213	0.89
70° to 80°	0.00028	0.00037	0.00042	0.00047	0.00059	0.00076	0.046
60° to 70°	0.00051	0.00062	0.00085	0.00107	0.00130	0.00172	0.0150
50° to 60°	0.00092	0.00115	0.00140	0.00192	0.0028	0.0042	0.0074
40° to 50°	0.00152	0.0020	0.0029	0.0044	0.0071	0.0132	0.0055
30° to 40°	0.0031	0.0045	0.0073	0.0136	0.034	0.38	0.0028
25° to 30°	0.0028	0.0047	0.0091	0.026	0.36	0.53	0.00043
20° to 25°	0.0047	0.0092	0.026	0.36	0.53	0.033	0.00151
15° to 20°	0.0093	0.026	0.36	0.53	0.033	0.0112	0.00027
10° to 15°	0.026	0.36	0.53	0.033	0.0110	0.0057	0.00029
5° to 10°	0.36	0.53	0.032	0.0109	0.0056	0.0034	0.00077
0° to 5°	0.53	0.032	0.011	0.0055	0.0033	0.0023	0.00081
-90° to 0°	0.68	0.037	0.027	0.022	0.0180	0.0167	0.029

(b) Antenna Beamwidth = 10°

ANTENNA ELEVATION	5°	10°	20°	30°	90°
ZONES	ZONE FACTORS				
80° to 90°	0.00027	0.00032	0.00023	0.00042	0.82
70° to 80°	0.00080	0.00073	0.00118	0.0014	0.083
60° to 70°	0.00103	0.00156	0.00199	0.0036	0.028
50° to 60°	0.0020	0.0022	0.0040	0.0082	0.0128
40° to 50°	0.0035	0.0042	0.0086	0.025	0.0081
30° to 40°	0.0064	0.0089	0.026	0.39	0.0087
25° to 30°	0.0047	0.0107	0.071	0.38	0.0044
20° to 25°	0.0108	0.0157	0.33	0.114	0.00067
15° to 20°	0.0158	0.071	0.37	0.0172	0.00199
10° to 15°	0.072	0.33	0.113	0.0147	0.0023
5° to 10°	0.33	0.37	0.0168	0.0053	0.0019
0° to 5°	0.37	0.112	0.0143	0.0057	0.00153
-90° to 0°	0.183	0.073	0.044	0.035	0.183

(c) Antenna Beamwidth = 15°

ANTENNA ELEVATION	10°	20°	30°	90°
ZONES	ZONE FACTORS			
80° to 90°	0.00048	0.00062	0.00033	0.63
70° to 80°	0.0146	0.00133	0.0030	0.22
60° to 70°	0.00178	0.0038	0.0047	0.064
50° to 60°	0.0043	0.0052	0.0153	0.0109
40° to 50°	0.0054	0.0162	0.038	0.022
30° to 40°	0.0167	0.039	0.37	0.0031
25° to 30°	0.0093	0.126	0.27	0.0021
20° to 25°	0.030	0.25	0.161	0.0040
15° to 20°	0.127	0.27	0.046	0.0042
10° to 15°	0.25	0.159	0.0109	0.0035
5° to 10°	0.27	0.045	0.0125	0.0026
0° to 5°	0.157	0.0106	0.0085	0.0020
-90° to 0°	0.122	0.071	0.053	0.040

(d) Antenna Beamwidth = 20°

ANTENNA ELEVATION	10°	20°	30°	90°
ZONES	ZONE FACTORS			
80° to 90°	0.00060	0.00098	0.00085	0.43
70° to 80°	0.0021	0.0023	0.0026	0.39
60° to 70°	0.0030	0.0032	0.0096	0.022
50° to 60°	0.0037	0.0107	0.0128	0.052
40° to 50°	0.0114	0.0135	0.076	0.0137
30° to 40°	0.00191	0.078	0.33	0.0044
25° to 30°	0.0180	0.134	0.21	0.0062
20° to 25°	0.062	0.20	0.158	0.0066
15° to 20°	0.135	0.21	0.081	0.0056
10° to 15°	0.20	0.156	0.026	0.0043
5° to 10°	0.21	0.079	0.0083	0.0032
0° to 5°	0.154	0.025	0.0083	0.0025
-90° to 0°	0.146	0.088	0.075	0.0109

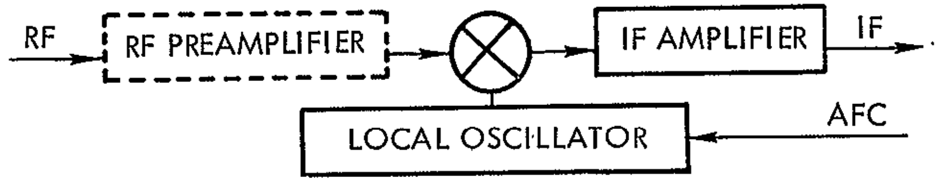
The retail price of the outdoor equipment, i.e., the antenna and antenna-mounted unit, is dependent on the RF frequency and on performance in terms of G/T, the ratio between antenna gain and system noise temperature.

Retail prices and performance data on the antenna are given in Tables 10-5 (a) through (d).

Figure 10-8 presents a functional diagram and major characteristics of the antenna-mounted unit. For reception of FM satellite transmission, the IF amplifier has a center frequency of 150 MHz and a bandwidth of typically 35 MHz. For AM/VSB satellite transmission the IF amplifier is a linear amplifier operating in one of the channels of conventional television broadcasting. The combination of preamplifier (if any), mixer and local oscillator can be implanted on a single substrate. Table 10-6 gives noise figures and estimated retail prices (based on production quantities of 10^6) of the antenna unit. For each of the four frequencies three alternatives are given: without RF preamplifier, with transistor or tunnel diode preamplifier, and with uncooled parametric amplifier. The retail prices given for these alternatives are estimates derived by judicious use of the technical discussion in Section 10.2, present retail prices, and learning curves.

The retail price of the indoor unit differs between AM/VSB and FM satellite transmissions, but is independent of RF frequency and G/T. Frequency modulation is converted to AM/VSB in the demodulator section (Figure 10-9) and the video/audio modulator section (Figure 10-10). In addition to these sections, the indoor unit includes a power supply unit for all adapter electronics, and an RF switch for switching the receiver input between the adapter and the antenna for terrestrial broadcasting. These items are placed in the same enclosure as the demodulator and modulator sections.

The total retail price of the indoor unit for FM is estimated at $27, assuming production quantities of 10^6. This price estimate is based on the production costs down in Figures 10-9 and 10-10 for the demodulator and modulator sections, respectively, and an estimated production cost of



RF FREQUENCY GHz	0.9	2.5	8.5	12.0
MIXER	DUAL MIXER WITH SCHOTTKY-BARRIER DIODES; REJECTS IMAGE NOISE			
LOCAL OSCILLATOR	BIPOLAR TRANSISTOR; VARIABLE CAPACITANCE DIODE FOR AFC; CERAMIC MICROCIRCUIT		BULK-EFFECT (GUN TYPE) OSCILLATOR; VARIABLE CAPACITANCE DIODE FOR AFC; CERAMIC MICROCIRCUIT	
IF AMPLIFIER	INTEGRATED CIRCUIT AND LUMPED L-C ELEMENTS, ON COPPER-LAMINATE PRINTED CIRCUIT BOARD. ALT: AMPLIFIER ENTIRELY MONOLITHIC, FEW L'S AND C'S ARE OUTBOARD HYBRID ELEMENTS. IF FREQUENCY: 150 MHz; IF BANDWIDTH: 35 MHz			

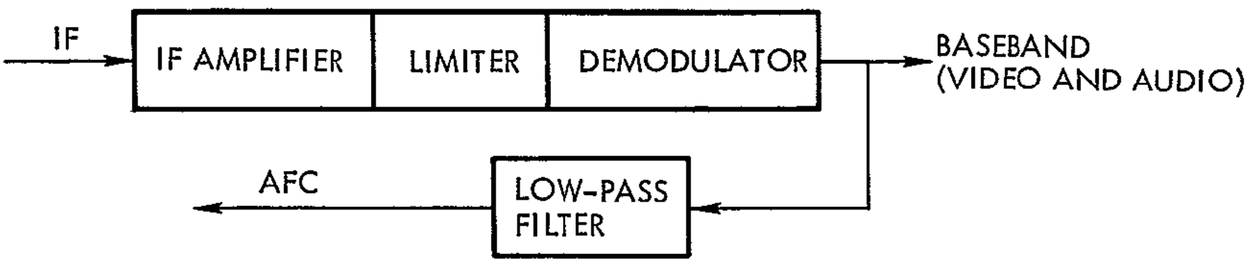
Figure 10-8. Antenna-mounted Unit

Table 10-6. Antenna-Mounted Units: Price Versus Noise Figure

Frequency (GHz)	0.9	2.5	8.5	12.0
Preamplifier Type	No preamplifier	No preamplifier	No preamplifier	No preamplifier
Noise Figure* db	5.5	6.0	6.5	7.0
Cost** $	18.00	18.00	24.00	24.00
Preamplifier Type	Junction field-effect transistor	Bipolar transistor	Tunnel diode	Tunnel diode
Noise Figure* db	4.05	4.95	4.6	5.2
Cost** $	20.00	30.00	74.00	74.00
Preamplifier Type	Uncooled Paramp	Uncooled Paramp	Uncooled Paramp	Uncooled Paramp
Noise Figure* db	2.2	2.7	3.0	3.3
Cost** $	218.00	218.00	224.00	224.00

*Noise figure of antenna unit.

**Projected retail prices, based on production quantities of 10^6.



IF CENTER FREQUENCY	150 MHz
IF BANDWIDTH	35 MHz
DESCRIPTION	INTEGRATED CIRCUIT AND LUMPED L-C ELEMENTS ON COPPER LAMINATE PRINTED CIRCUIT BOARD. ALTERNATIVELY: AMPLIFIER ENTIRELY MONOLITHIC WITH FEW L'S AND C'S AS OUTBOARD HYBRID ELEMENTS. ADDITIONAL VIDEO AND DC AMPLIFIER CHIPS TO DRIVE VIDEO/AUDIO MODULATOR SECTION AND AFC.
PRODUCTION COST OF SECTION	\$7.00 (IN QUANTITIES OF 10^6)

Figure 10-9. Indoor Unit: Demodulator Section

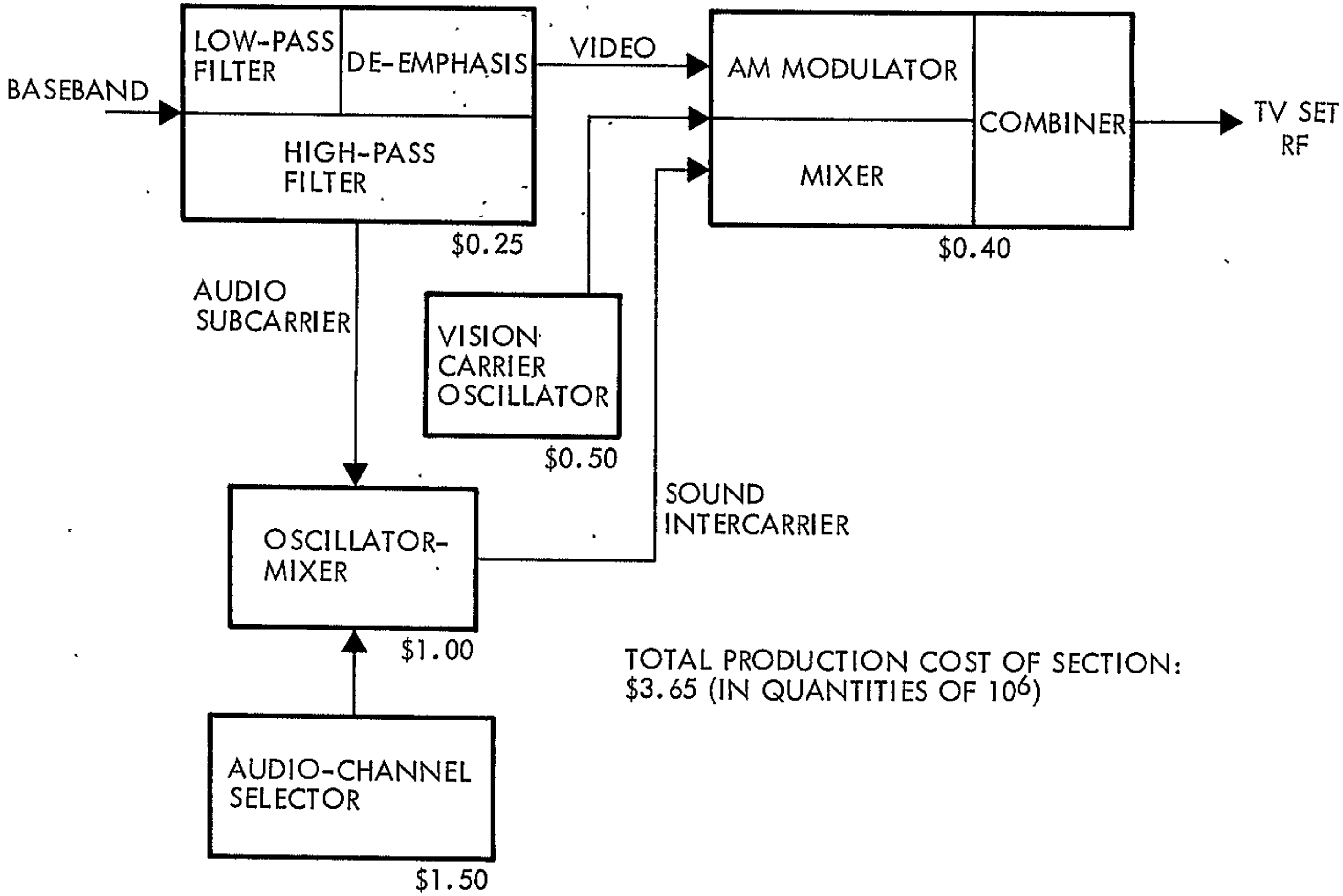


Figure 10-10. Indoor Unit: Video/Audio Modulator Section

$3 for the remaining equipment of the indoor unit. Retail prices for the type of equipment considered here is estimated at twice the production costs.

For AM/VSB transmissions, the demodulator and remodulator sections are not required and the retail price of the indoor unit is consequently reduced to $6.

In summation, the total retail price of the user equipment (not including the regular television receiver) is the sum of

- The antenna retail price, obtained from Tables 10-5 (a) through (d).
- The retail price of the antenna-mounted unit, obtained from Table 10-6.
- The indoor unit retail price of $27 for FM or $6 for AM/VSB.

Total retail prices obtained in this manner are shown in Tables 10-7 through 10-10 for the four frequencies of interest. For each frequency, different combinations of antenna size and adapter noise figures are presented. The prices shown are based on production quantities of 10^6, and include installed antennas.

The system noise temperatures shown in Tables 10-7 through 10-10 were obtained as

$$T_S = T_A + \frac{NF - 1}{290}$$

where

T_S = system noise temperature, ^oK.

T_A = antenna noise temperature, ^oK.

NF = adapter noise figure (Table 10-6), db.

The antenna noise temperatures used are those stated in Tables 10-5 (a) through (d), which do not include noise due to attenuation in precipitation, fog or clouds, nor manmade noise or solar noise. The system noise temperature thus obtained was used to determine the values in the column "G/T, Dry" in Tables 10-7 through 10-10.

Table 10-7. User Equipment for Reception at 0.9 GHz: Estimated Total Retail Price versus System Performance

ELECTRONICS		ANTENNA			SYSTEM			RETAIL PRICE ($)*	
Preamplifier	Noise Figure (db)	Diameter (ft)	Diameter (m)	Beamwidth (3 db) (deg)	System Noise Temp (°K)	G/T Dry (db/°K)	G/T Wet (db/°K)	AM/VSB	FM
None	5.5	4	1.22	21	826	-11.2	-11.2	64	85
		6	1.83	15	820	- 8.1	- 8.1	79	100
		8	2.44	11	813	- 5.1	- 5.1	102	123
		10	3.05	8.5	811	- 3.1	- 3.1	154	175
Transistor	4.05	4	1.22	21	534	- 9.3	- 9.3	66	87
		6	1.83	15	528	- 6.2	- 6.2	81	102
		8	2.44	11	521	- 3.2	- 3.2	104	125
		10	3.05	8.5	519	- 1.2	- 1.2	156	177
Uncooled Paramp	2.2	4	1.22	21	276	- 6.4	- 6.4	264	285
		6	1.83	15	270	- 3.3	- 3.3	279	300
		8	2.44	11	263	- 0.2	- 0.2	302	323
		10	3.05	8.5	261	+ 1.8	+ 1.8	354	375

*Based on production quantities of 10^6. Prices do not include the regular television set.

Table 10-8. User Equipment for Reception at 2.5 GHz: Estimated Total Retail Price versus System Performance

ELECTRONICS		ANTENNA			SYSTEM			RETAIL PRICE ($)*	
Preamplifier	Noise Figure (db)	Diameter (ft)	Diameter (m)	Beamwidth (3 db) (deg)	System Noise Temp (°K)	G/T Dry (db/°K)	G/T Wet (db/°K)	AM/VSB	FM
None	6.0	4	1.22	7.6	915	- 2.6	- 2.7	104	125
		6	1.83	5.5	912	+ 0.4	+ 0.3	129	150
		8	2.44	3.8	910	+ 3.4	+ 3.3	169	190
		10	3.05	3.0	909	+ 5.4	+ 5.3	254	275
Transistor or TDA	4.95	4	1.22	7.6	671	- 1.3	- 1.4	116	137
		6	1.83	5.5	668	+ 1.8	+ 1.6	141	162
		8	2.44	3.8	666	+ 4.8	+ 4.6	181	202
		10	3.05	3.0	665	+ 6.8	+ 6.6	266	287
Uncooled Paramp	2.7	4	1.22	7.6	302	+ 2.2	+ 2.0	304	325
		6	1.83	5.5	299	+ 5.3	+ 5.0	329	350
		8	2.44	3.8	297	+ 8.3	+ 8.1	369	390
		10	3.05	3.0	296	+10.3	+10.1	454	475

*Based on production quantities of 10^6. Prices do not include the regular television set.

Table 10-9. User Equipment Cost for Reception at 8.5 GHz: Estimated Retail Price versus System Performance

ELECTRONICS		ANTENNA			SYSTEM			RETAIL PRICE ($)*	
Preamplifier	Noise Figure (db)	Diameter (ft)	Diameter (m)	Beamwidth (3 db) (deg)	System Noise Temp (°K)	G/T Dry (db/°K)	G/T Wet (db/°K)	AM/VSB	FM
None	6.5	2	0.61	4.3	1056	+ 1.8	- 0.5	195	216
		4	1.22	2.1	1054	+ 7.8	+ 5.5	210	231
		6	1.83	1.5	1051	+10.8	+ 8.5	250	271
		8	2.44	1.2	1050	+12.8	+10.5	330	351
		10	3.05	1.0	1050	+14.8	+12.5	460	481
TDA	4.6	2	0.61	4.3	596	+ 4.3	+ 1.7	245	266
		4	1.22	2.1	594	+10.3	+ 7.7	260	281
		6	1.83	1.5	591	+13.3	+10.7	300	321
		8	2.44	1.2	590	+15.3	+12.7	380	401
		10	3.05	1.0	590	+17.3	+14.7	510	531
Uncooled Paramp	3.0	2	0.61	4.3	346	+ 6.6	+ 3.6	395	416
		4	1.22	2.1	344	+12.6	+ 9.6	410	431
		6	1.83	1.5	341	+15.7	+12.6	450	471
		8	2.44	1.2	340	+17.7	+14.6	530	551
		10	3.05	1.0	340	+19.7	+16.6	660	681

*Based on production quantities of 10^6. Prices do not include the regular television set.

Table 10-10. User Equipment for Reception at 12 GHz: Estimate Retail Price versus System Performance

ELECTRONICS		ANTENNA			SYSTEM			RETAIL PRICE ($)*	
Preamplifier	Noise Figure (db)	Diameter (ft)	Diameter (m)	Beamwidth (3 db) (deg)	System Noise Temp (°K)	G/T Dry (db/°K)	G/T Wet (db/°K)	AM/VSB	FM
None	7.0	2	0.61	3.0	1229	+ 4.1	+ 0.5	220	241
		4	1.22	1.5	1227	+10.1	+ 6.5	240	261
		6	1.83	1.1	1225	+13.1	+ 9.5	295	316
		8	2.44	0.85	1225	+15.1	+11.5	480	501
		10	3.05	0.70	1225	+17.1	+13.5	740	761
TDA	5.2	2	0.61	3.0	719	+ 6.4	+ 2.5	270	291
		4	1.22	1.5	717	+12.4	+ 8.5	290	311
		6	1.83	1.1	715	+15.4	+11.5	345	366
		8	2.44	0.85	715	+17.4	+13.5	530	551
		10	3.05	0.70	715	+19.4	+15.5	790	811
Uncooled Paramp	3.3	2	0.61	3.0	384	+ 9.2	+ 4.7	420	441
		4	1.22	1.5	382	+15.2	+10.7	440	461
		6	1.83	1.1	380	+18.2	+13.7	495	516
		8	2.44	0.85	380	+20.2	+15.7	680	701
		10	3.05	0.70	380	+22.2	+17.7	940	961

*Based on production quantities of 10^6. Prices do not include the regular television set.

The values for "G/T Wet" were calculated for bad weather conditions in an average temperate climate with a precipitation rate exceeding 10mm/hours in 1 percent of the time. A receiver location at a great-circle distance of 60 degrees from the sub-satellite point was assumed. For these conditions, the total additional attenuation is estimated as follows

Frequency (GHz)	Attenuation (db)	Noise Increment (at antenna) (^{o}K)
0.9	0	0
2.5	0.1	7
8.5	1.9	103
12.0	3.1	150

The values in the column "G/T Wet" reflect both the increase in system noise temperature and the signal attenuation (in other words, T is the increased system noise temperature at the topside of the troposphere).

11. COSTS OF OPERATIONAL SYSTEMS

Nonrecurring and recurring costs of satellites and subsystems are presented. Satellite costs and costs of user equipment given in Section 10.7, are used to determine investment costs for establishing and maintaining an operational system. Annual costs of investment amortization and operation are given for all system segments. Costs of terrestrial broadcasting are presented for comparison.

11.1 SATELLITE AND SUBSYSTEM COST

Tables 11-1 through 11-3 present cost estimates for the three satellite configurations described in Section 7. Cost estimates are shown by subsystem with totals for each satellite configuration. Nonrecurring costs include those costs necessary to conduct research, design, development, and test of operational television broadcast satellites plus the costs of breadboards, engineering model, thermal model, structural model, and qualification model spacecraft. These costs cover in essence Program Phases B through D, i.e., "Definition" through "Development/Operations," as defined in the NASA publication, "Phased Project Planning Guidelines" (NHB 7121.2; August 1968 Edition). The nonrecurring costs also include the supporting research and technology initiated to meet the requirements identified in Phase A (Preliminary Analysis). The total cost of breadboards and models, included in the nonrecurring costs, is approximately twice the recurring cost for one flight article. Recurring costs are shown for the procurement of one flight spacecraft.

The primary source of cost information for the Television Broadcast Satellites has been the TRW Systems data bank. Historic costs were adjusted for time of performance and for subsystem complexity. Extraneous costs, such as those occasioned by schedule delays and other nonrepeating cost effects, were deleted so that cost estimates represent a basic cost for each subsystem as appropriate for the Television Broadcast Satellites. All costs have been burdened (less profit) and adjusted to 1969 dollars.

Table 11-1. Costs of 12 Kilowatt, 0.9 GHz Satellite as Described in Section 7.2
($000)

Subsystem	Nonrecurring*	Recurring/Spacecraft	Total
Structure	$ 4,700.0	$ 1,500.0	$ 6,200.0
Thermal	4,000.0	600.0	4,600.0
Attitude control	9,000.0	2,200.0	11,200.0
Electrical power	16,000.0	7,000.0	23,000.0
Electrical integration	5,000.0	1,600.0	6,600.0
Communications and antennas	13,000.0	2,750.0	15,750.0
Adapter	600.0	250.0	850.0
Mechanical GSE and integration	2,500.0	800.0	3,300.0
Spacecraft integration and test	6,100.0	1,900.0	8,000.0
Electrical operating ground support equipment	7,700.0	-	7,700.0
Spares	3,200.0	-	3,200.0
Quality assurance	2,700.0	800.0	3,500.0
Program management	8,500.0	2,200.0	10,700.0
	$83,000.0	$21,600.0	$104,600.0

*Includes one engineering model and one qualification model.

Table 11-2. Costs of Four Kilowatt, 2.5 GHz Satellite as Described in Section 7.3

($000)

Subsystem	Nonrecurring*	Recurring/Spacecraft	Total
Structure	$ 3,600.0	$ 750.0	$ 4,350.0
Thermal	3,100.0	400.0	3,500.0
Attitude control	6,000.0	1,300.0	7,300.0
Electrical power	10,000.0	4,700.0	14,700.0
Electrical integration	3,000.0	1,000.0	4,000.0
Communications and antennas	9,800.0	2,200.0	12,000.0
Adapter	400.0	150.0	550.0
Mechanical GSE and integration	1,400.0	400.0	1,800.0
Spacecraft integration and test	3,800.0	1,000.0	4,800.0
Electrical operating ground support equipment	4,800.0		4,800.0
Spares	2,000.0		2,000.0
Quality assurance	1,500.0	600.0	2,100.0
Program management	5,600.0	1,300.0	6,900.0
	$55,000.0	$13,800.0	$68,800.0

*Includes one engineering model and one qualification model.

Table 11-3. Costs of Eight Kilowatt, 12 GHz Satellite as Described in Section 7.4
($000)

Subsystem	Nonrecurring*	Recurring/Spacecraft	Total
Structure	$ 4,600.0	$ 1,000.0	$ 5,600.0
Thermal	3,500.0	500.0	4,000.0
Attitude control	7,500.0	1,700.0	9,200.0
Electrical power	15,000.0	6,000.0	21,000.0
Electrical integration	4,000.0	1,300.0	5,300.0
Communications and antennas	10,000.0	2,400.0	12,400.0
Adapter	500.0	200.0	700.0
Mechanical GSE and integration	2,200.0	700.0	2,900.0
Spacecraft integration and test	5,200.0	1,500.0	6,700.0
Electrical operating ground support equipment	6,600.0	-	6,600.0
Spares	2,600.0	-	2,600.0
Quality assurance	2,200.0	700.0	2,900.0
Program management	7,100.0	1,800.0	8,900.0
	$71,000.0	$17,800.0	$88,800.0

*Includes one engineering model and one qualification model.

11.2 OVERALL COSTS OF SPACE BROADCASTING

11.2.1 Investment Costs

The investment costs presented here are budgetary estimates of the recurring costs for establishing and maintaining space broadcast services, using equipment previously developed.

Recurring investments will be required for three equipment categories:

- Spacecraft
- Earth station for transmission of the television programs to the spacecraft and for control of the spacecraft
- User installations

The cost to users of the equipment required to adapt a regular television receiver to satellite braodcasting is given in Section 10.7 for different rf frequencies and different performance levels.

The recurring spacecraft cost is related to the type and quality of service, the size of the area to be served, and the performance of the user installations. To examine this relation, it is convenient to express the beam-edge gain of the satellite antenna as:

$$G_t = g\,\frac{4\pi}{\Omega} = g\,\frac{4\pi}{S/R^2} \qquad (11\text{-}1)$$

where G_t = beam-edge gain of the satellite antenna.

g = beam factor.

Ω = the solid angle at the spacecraft, subtended by the earth surface area to be covered.

S = central projection of the covered area on a spherical surface at maximum range, R.

The ideal spacecraft antenna would radiate with a nearly uniform intensity within the solid angle Ω, without spilling any power outside this angle. The beam-factor g would then equal one. Realizable antennas have a lower beam-edge gain than the ideal antenna, which is reflected in a value of g lower than one. The factor g is related to beam-edge gain and beam width by the equation:

$$G_t \theta^2 = 52,500 \text{ g} \tag{11-2}$$

where θ = 3-db beamwidth, degrees.

For the present cost analysis, $G\theta^2$ is assumed to be 15,800 for antennas with solid reflectors (2.5, 8.5, and 12 GHz) and 13,800 for antennas with wire-mesh or grid reflectors (0.9 GHz). The corresponding values of g are 0.30 and 0.26 respectively.

With the expression (11-1) for the satellite antenna gain, the required satellite tramsmitter output power, per video channel, can be expressed as:

$$P_t = 4\pi \frac{L}{\lambda^2 g} S \frac{C/T}{G/T} \tag{11-3}$$

where P_t = transmitter output power, watts.

L = miscellaneous losses.

λ = wavelength.

g = beamfactor, defined above.

S = central projection of covered area.

C/T = ratio between received carrier power level and receiver system noise temperature, watts/°K.

G/T = ratio between receiver antenna gain and receiver system noise temperature, $°K^{-1}$.

The wavelength λ and the S must be expressed in terms of the same unit of length. The quantity L includes circuit losses between satellite transmitter and antenna, polarization loss, loss due to errors in satellite antenna pointing, and a correction for uplink noise. A total of 1.5 db is assumed, 2.5 db if a diplexer or multiplexer is used to connect two or more transmitters to a common satellite antenna.

The quantity C/T is determined by the type of downlink modulation and the picture quality grade. Table 11-4 gives values for various alternatives.

The ratio G/T is a performance parameter of the earth receiver installations. Values are given in Tables 10-7 thru 10-10 of Section 10. The effect of precipitation, fog, and clouds on the transmitter power requirement, are taken into account by appropriate correction of the G/T values (Section 10.7).

It is convenient to rewrite equation (11-3) in logarithmic formulation

$$P_{t,\,dbw} = A + 10 \log S + (C/T)_{dbw/°K} - (G/T)_{db/°K} \qquad (11\text{-}4)$$

with values of A given in Table 11-5.

For a satellite with n channels, each with a transmitter output power of P_t watts, the required array power at the end of a 5-year life is approximately

$$P_a = 0.0011 \frac{nP_t}{\eta} (1 + m\epsilon) + 0.350 \text{ kilowatts} \qquad (11\text{-}5)$$

where η is the respective transmitter efficiency, while m is the number of sound channels per video channel. Table 11-6 gives values of η and ϵ.

The array power level is used as input for estimating the recurrent satellite cost by the following expression:

$$C_s = 7.8 \; P_a^{0.405} \qquad (11\text{-}6)$$

where C_s = recurring spacecraft cost, ($\$10^6$).

P_a = array power at end of 5-year life, killowatts.

The recurring costs in Tables 11-1 through 11-3 are within two percent of the values indicated by equation (11-6).

Table 11-4. C/T Data

Monochrome/ Color	Picture quality Name	TASO Grade	Sound channels per video channel	C/T** dbw/°K
	AM/VSB Transmissions			
Monochrome	Fine	2	*	-122.0
Color	Fine	2	*	-121.3
Monochrome	Passable	3	*	-130.1
Color	Passable	3	*	-129.4
	FM Transmissions			
Monochrome	Fine	2	1	-139.6
Color	Fine	2	1	-138.7
Monochrome	Passable	3	1	-140.7
Color	Passable	3	1	-140.0
Monochrome	Fine	2	4	-138.7
Color	Fine	2	4	-138.1
Monochrome	Passable	3	4	-139.5
Color	Passable	3	4	-139.1

*C/T of AM/VSB carriers is not affected by the number of sound channels, since sound is transmitted by separate transmitter.

**For AM/VSB, C is sync peak level of carrier power.

Table 11-5. Values of A

Frequency GHz	A db For S in $(st. mi.)^2$	A db For S in $(km)^2$	Note
0.9	92.0	87.8	Add 1 db to A for satellite using transmit diplexer or multiplexer.
2.5	100.3	96.1	
8.5	110.9	106.7	
12.5	113.9	109.7	

Table 11-6. Values of η and ϵ

Modulation	Frequency	$\eta^{(1)}$	ϵ
AM/VSB Sound on separate FM carrier	0.9 2.5	1.30 1.25	$\epsilon = 0.03$ for one sound channel; $\epsilon = 0.04$ for two or more.
FM Sound on subcarriers	0.9 2.5 8.5 12.0	0.80 0.79 0.73 0.71	$0^{(2)}$

(1) For AM/VSB, η is ratio between sync peak level of transmitter output power and maximum average power consumption. For FM, η is transmitter efficiency.

(2) Sound transmission on subcarrier(s) is taken into account in C/T values.

This satellite cost model is reasonably accurate for general planning purposes when used for satellites with array power (at the end of 5-year life) between 2 and 20 killowatts.

Launch costs, including both the launch vehicle and launch operations, depend primarily on satellite weight. Inspection of satellite and subsystem weight estimates lead to the following weight model:

$$W_s = W_o + 204\ P_a \tag{11-7}$$

where W_s = satellite weight, pounds.

P_a = array power (at end of 5-year life); kilowatts.

W_o = constant term, between 700 and 1000 pounds.

The term W_o will be near upper end of its 700-1000 pounds range for satellites broadcasting at 0. 9 GHz, because of the larger weight of communication equipment and antenna at this low frequency. For higher frequencies, W_o should be chosen closer to 700 pounds. Further, the weight of communications and power conditioning equipment in satellite transmitting several television programs simultaneously will be higher than for a single channel satellite with the same array power requirement. Consequently, a conservative estimate of W_o is warranted for multi-channel satellites.

The weight estimates obtained by equation (11-7) apply to satellites without apogee motor. It is assumed that the upper stage of the launch vehicle performs the apogee firing as well as a coarse, initial orientation. The satellite performs trim maneuvers after separation from the upper stage.

The launch cost C_ℓ follows from launch vehicle selection based on the satellite weight W_s. Table 6-1 gives payload capacities of launch vehicle configurations of the Atlas and Titan families.

Investment cost of the earth station used for transmission of television programs to the broadcast satellite and for satellite control is estimated at $\$1.75 \cdot 10^6$.

In summation, the recurring investment costs of establishing, maintaining, and using a television broadcast satellite service are estimated as follows:

- C_s, satellite cost given by equation (11-6).
- C_ℓ, launch cost (including launch vehicle and launch operation) of the launch configuration, selected on a basis of satellite weight given by equation (11-7).
- C_m, cost of master earth station, $\$1.75 \cdot 10^6$.
- NCu, cost of N user installations, each at a cost C_u given in Tables 10-7 through 10-10 of Section 10. 7.

11.2.2 Annual Costs

Annual costs include the level annual costs of investments and the costs of operation.

For a spacecraft life of 5 years and a launch probability of 0.9, the level annual cost of the space segment is $0.263\ (C_s + C_\ell)$ based on an interest rate of 6 percent.

For the master station and the user installations a lifetime of 10 years is assumed, which lead to level annual costs of 13.6 percent of the investment.

Annual operation costs (including maintenance) of the master station are estimated at \$250K.

Total annual costs, in $\$10^6$, of providing television broadcast satellites is:

$$C_{a1} = 0.263\ (C_s + C_\ell) + 0.136\ C_m + 0.25 \tag{11-8}$$

with $C_m = 1.75 \cdot 10^6$ dollars.

The total annual cost of using the service by N receiver installations

$$C_{a2} = 0.136\ N\ C_u \tag{11-9}$$

11.3 COSTS OF TERRESTRIAL BROADCASTING

For a meaningful cost comparison between satellite broadcasting and terrestrial broadcasting, cost estimates for terrestrial broadcasting must be established in terms of a directly comparable type of cost for service comparable to that provided by satellite broadcasting. Annual costs, including both level annual cost of capital investments and annual operation costs, are used as directly comparable cost type. For comparable services, the function of terrestrial broadcasting which differs in cost from satellite broadcasting, is the transmission of television programs (picture and sound) from a point of origination to the antenna terminals of all television sets involved. The cost of program origination, i.e., program production, recording, storage, and playback, as applicable, is the same in both cases.

In the terrestrial broadcasting model shown in Figure 11-1, broadcast transmitters, T, each with a service radius, R, are arranged in a pattern providing full area coverage. With this arrangement, each station is used to cover an area 2.60 R^2 or 83 percent of the area within the circle of radius R

The station used for this cost model has an antenna height of 1000 feet above average terrain, giving a radio horizon distance of 50 statute miles. Typical ERP requirements for providing at least Grade B quality at a 50-mile radius are 100 kilowatt for channels 2 through 6, 300 kilowatts for channels 7 through 13, and 2000 kilowatts for UHF channels. Investment costs were found to vary between \$350,000 and \$450,000. An average of \$400,000 is used in the cost model. Approximately 65 percent of this total is the cost of communication equipment, for which an amortization period of 10 years is assumed; the other 35 percent is amortized over 20 years. The level annual cost of capital amortization is then \$47,600 per station, assuming an interest rate of 6 percent.

The annual operation cost, including maintenance, for broadcast stations of the capacity presently considered is approximately \$60,000, not including studio operation.

In conclusion, the total annual cost for a broadcast station providing at least Grade B service within a radius of 50 statute miles is \$107,600. This station covers 7,800 square statute miles; however, in the arrangement for full area coverage shown in Figure 11-1, it is used to cover 6,500 square statute miles. Full coverage of one million square statute miles requires 154 stations at a total annual cost of \$16.6 x 10^6.

In the minimum length microwave network shown in Figure 11-2, the broadcast stations are located along the east-west lines, which correspond to the east-west lines in Figure 11-2. The separation between stations, $50\sqrt{3} = 86.5$ statute miles, dictates the use of two repeaters between adjacent broadcast station sites.

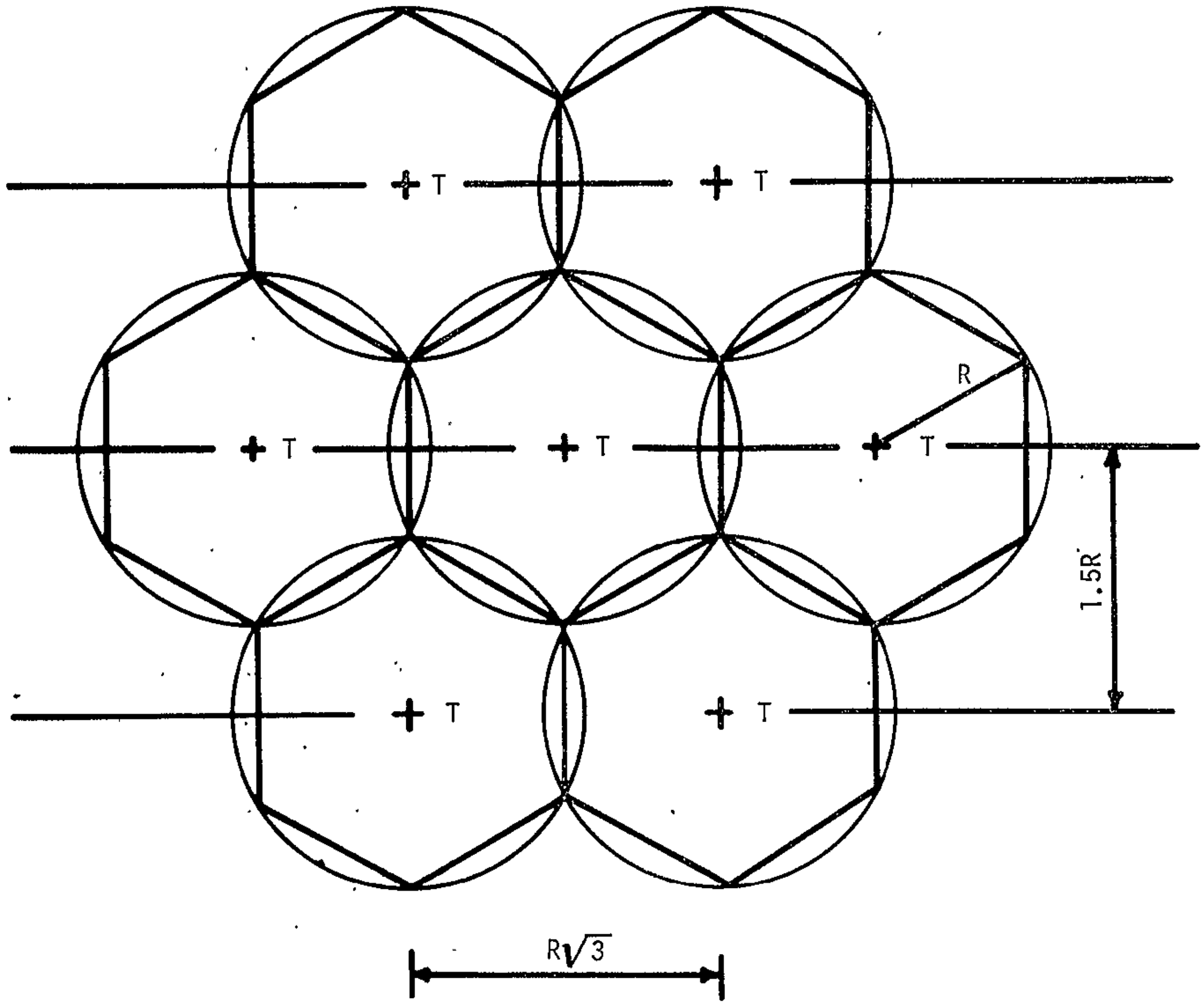


Figure 11-1. Terrestrial Broadcast Model

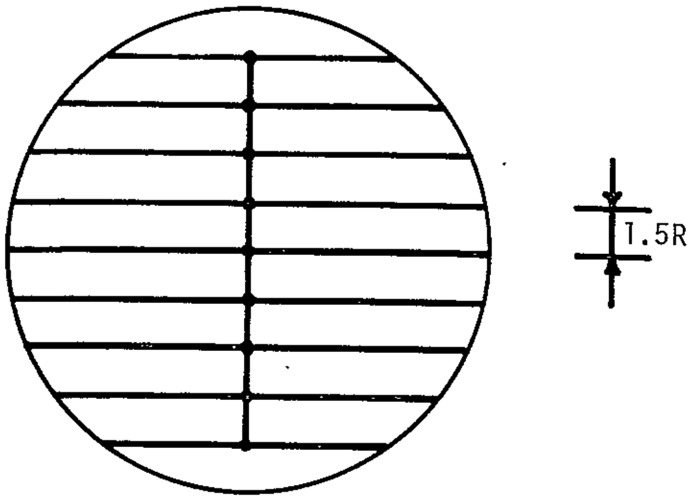


Figure 11-2. Microwave Network

Since topographical limitations on the selection of microwave tower sites increase the circuit length to about 20 percent above straight-line distance, the repeater spacing averages at 35 statute miles. Consequently, the east-west lines require three microwave towers per broadcast transmitter, of which one is equipped with branch-off circuitry (at the IF amplifier output) and a demodulator.

The north-south line interconnects the east-west lines.

All microwave stations should have two-way capability to provide program routing redundancy, remote control, telemetry, and two-way voice circuits for service purposes.

On the basis of available cost data, the capital investment cost is estimated at \$6000 per route-mile. Annual operation costs, including maintenance, are estimated at \$500 for each microwave station at a broadcast transmitter site and at \$2500 for other stations.

For an area of 1×10^6 square statute miles, the total circuit length is 17,300 route-miles requiring a capital expenditure of $\$104 \times 10^6$. The level annual cost of amortization in 10 years is $\$14.1 \times 10^6$, assuming an interest rate of 6 percent. Annual operation costs, including maintenance of the approximately 500 towers, of which 154 are located at broadcast transmitter sites, total \$942,000.

Table 11-7 summarizes the cost data for broadcast stations and microwave circuits. The cost totals are approximately proportional to the area covered, from 0.3×10^6 square statute miles.

Table 11-7. Costs of Terrestrial Broadcasting

(In thousands of dollars)

	Capital Investment	Annual Costs	
		Amortization	Operation
Broadcast transmitter station	400	47.6	60
Microwave circuit, one mile	6	--	--
Microwave station at broadcast transmitter site	--	--	0.5
Other microwave station	--	--	2.5
<u>For 1 x 10^6 sq st miles</u>			
154 Broadcast transmitter stations	61,600	7,340	9,240
17,300 St miles microwave circuit	103,800	14,100	--
154 Microwave stations at broadcast sites	--	--	77
346 Other microwave stations		--	865
Total, annual		21,440	10,182

12. EFFECTIVENESS AND AUDIENCES

12.1 SUMMARY AND CONCLUSIONS

SUMMARY

One of the most significant potential applications of space-based telecommunications is television broadcasting. As a first step in establishing the technical specifications and costs of a TV satellite system, analysis of the characteristics of potential audiences and estimation of expected benefits or effectiveness of the system must be undertaken. The television medium is used in three major applications: education, entertainment, and cultural. Because of the difficulties in describing or measuring the results of entertainment and cultural programming, the major efforts in this study are associated with educational programming. Educational television is defined as that programming which is purposefully instructional. The audiences investigated are chiefly citizens of the developed countries, with preliminary consideration given to those of developing countries. For the developed economies, current social and economic theories are assumed to apply, and standard forecasting techniques may be used to indicate the quantitative effects of television broadcasting. For the developing countries, it is recognized that the sociology and economics do not rest on a firm body of theory. Further, demographic and economic statistics are scarce for developing countries and, where available, are often unreliable. Consequently, the treatment of developing regions is more qualitative than quantitative, more subjective then objective.

<u>Education</u>

The rapid advance of technology in developed nations stimulates the flow of investment into high-productivity equipment and facilities, and requires new or enlarged skills on the part of workers, managers, administrators, and teachers who make the socieoeconomic system function. These skills can only be achieved through formal or informal education.

Statistics on enrollments and scholastic achievements in United States schools indicate a need for expanding the United States education system qualitatively and quantitatively; and this need for expansion is presumed to exist for all other developed countries. Developing countries have an even more stringent need for expansion of their education systems since they are typified by a general lack of trained personnel and too few institutions for providing the needed training.

Education Television (ETV)

The use of mass communications media for educational purposes promises great expansion of the education process. Already, ETV is increasingly used for instruction. Some ETV projects worthy of note are:

1) American Samoa: ETV is used as the main core of the teaching program for grades 1 through 12. This project was used to replace an underdeveloped education system.

2) Hagerstown, Maryland: This project used ETV as a supplement to an established developed unitary school system, and provides the most extensive measures of results currently available.

3) Midwest Program on Airborne Television Instruction (MPATI): The MPATI is an example of ETV coverage across many political boundaries and education systems.

4) Telescuela Popular Americana (ETPA) in Peru: ETPA was established to provide ETV to students not formally enrolled in the school system.

From the many research papers on educational television, it may be concluded that ETV, if properly used, can add significantly to the output of an education system. In the Hagerstown project, gains in "efficiency" of teaching as high as 117 percent were observed. Using the available Hagerstown data to calculate the cost elasticity of performance as a measure of sensitivity of educational output to expenditures on ETV, elasticities ranging from 1.7 to 16.7 were derived, depending on the performance measure used.

To provide a measure of effectiveness of an ETV broadcast satellite for the United States, the costs and benefits of a hypothetical, national, satellite-based ETV system serving all U. S. public elementary and secondary schools were compared. The system comprised four 6-TV channel satellites broadcasting to low-cost antennas/converters in the 100,000 public elementary and secondary schools in the U. S.; 1.7 million

23-inch color receivers would be required (one per classroom). All programs originate from one ground station. System costs include: satellites — $20 million each; antenna/converters — $1000 each; receivers — $250 each; ground station — $10 million; programming — $10 million annually; and estimates of operating, maintenance and repair costs of the ground hardware. System benefits were imputed from projections of effective student-hours added by gains in teaching (or learning) efficiency (estimated at 12 percent and 31 percent) derived from using ETV in U. S. schools at an estimated $0. 81 per student-hour.

Considering satellite life to be five years, and benefits to begin after three years of operation, system costs and benefits and their present values (at 4 and 6 percent discount rates) were calculated and compared for a fifteen-year period. If the project is continued through ten years of benefits, an increased efficiency of only 1. 36 percent is required to achieve a zero net present value. If the 12 and 31 percent gains in teaching efficiency are considered too optimistic, a net present value of zero would obtain if performance gains are only three percent in the first year of benefits and the project is discontinued thereafter. After the hypothetical system has been in operation for three years (first year of benefits), the cumulative benefits far exceed the cumulative costs, both in absolute terms and in discounted present value terms. That is, the net present value ranges from $751 million in the first year of benefits, to $44, 886 million in the tenth year of benefits, discounted at six percent, or $885 million to $54, 708 million over the same period discounted at four percent.

In addition to the imputed benefits of added effective student-hours, reduction in the economic costs of crime, reduction in welfare payments, increases in tax revenues and many other social benefits with potential economic implications may be obtained.

For developing countries, potential benefits and costs arising from satellite-based ETV must be assessed from study of the existing education system and the political, social and economic characteristics of the specific country of interest. Development projects for education, health, agriculture, industry and infrastructure must compete for scarce financial and human resources. To indicate the potential effectiveness of implementing ETV projects in developing countries a theoretical model linking growth in national output to improvement in education is discussed in an appendix to this study. It implies that expansion of the student body and improvement of educational quality or efficency are the keys to increased productivity.

To investigate the need for improvement in the education systems of developing countries, economic and education statistics of 97 countries were examined. Considering countries with annual per capita gross domestic products greater than $750 to be developed, and all others to be developing, typical education and economic statistics for the two categories were derived. The typical annual education budget per student in the developing countries is seen to be an order of magnitude less than in the developed countries. The ratio of students to teachers is significantly greater in developing countries; the ratio of students to total population significantly less; and the ratio of education expenditures to gross domestic product is also significantly less. If it is accepted that developing countries must emulate the typical education system characteristics of developed countries to achieve the types and quantities of educated personnel needed to achieve and maintain a developed, competitively productive economy, then it must be concluded that efficient and timely means of expanding and improving their education systems, such as nationwide educational television, must be employed. However, planning decisions must be taken in light of all identifiable development needs and resource availabilities. A resource-rich country (perhaps Libya) may more efficiently achieve planned output goals by emphasizing industrial expansion at the expense of educational expansion; a resource-poor country (such at Ethiopia) may maximize economic growth by emphasizing expansion of education. Expansion paths of developing countries must be determined according to their individual circumstances.

From a list of candidate developing regions or countries in which satellite-ETV may be fruitfully used, Central America, Brazil, and India present potential audience areas of feasible geographic size. The use of ETV in Central and South America requires detailed study to derive quantitative cost-benefit analyses. ETV in India has received a great deal of attention but available statistics are insufficient to permit other than general conclusions on the quantitative benefits to be derived from satellite-based (or other) ETV. A study of the total system requirements, including electrification, school buildings, roads, books, personnel and programming is needed to provide a basis for optimal expansion of the Indian Education System.

Costs of Alternate Systems

Projection of costs of optimum combinations of microwave, cable, and satellite broadcasting require engineering and operations analyses comparable to the engineering portion of this study. However, a rough estimate of alternate costs can be made to permit order of magnitude comparisons.

First, consider the primary capability of satellite-based TV: complete coverage of the entire nation with acceptable-grade TV signals. If one assumes that the three million square miles of the conterminous United States were geometrically square and could be completely illuminated by a square array of evenly spaced transmitters, each with a 50-mile radius of coverage, approximately 370 transmitters would be required. In this square-square array all 370 transmitters may be connected to one properly located point of origin by a minimum of 38,000 route-miles of microwave relay.

Comparison of costs for a hypothetical microwave-connected transmitter system and the previously hypothesized satellite system providing six channels of color ETV to all United States public elementary and secondary schools shows that the cumulative outlays and 1970 present values of the microwave system exceed those of the satellite system in every analyzed year from 1970 to 1984.

CONCLUSIONS

1. Nationwide educational television, comprising six channels of color television for all United States public elementary and secondary classrooms, appears to be a highly effective method of improving the United States public education system.

2. Imputed benefits from an operational six-channel color TV broadcast satellite system broadcasting to all United States public elementary and secondary classrooms greatly exceed the costs of such a system.

3. Six-channel color educational television for all United States public elementary and secondary schools can be achieved by a satellite system at significantly lower costs than by a microwave network.

4. Satellite-based educational television may greatly improve the education systems of developing countries, but studies of the social and economic structures and the development plans of the individual countries are required to permit valid cost-benefit analyses or comparisons with other means of implementing educational television.

12.2 EDUCATION

For developing as well as developed nations, economic growth may be directly associated with increased utilization of labor and capital to produce the industrial, agricultural, and service goods that make up their gross domestic products. The rapid advance of technology not only enables a flow of investment into high-productivity equipment and facilities, but also requires increasing investments in the stock of human capital; for the increased productivity promised by the new techniques and equipment calls for new or enlarged skills on the part of workers, managers, administrators, and teachers.

REQUIREMENTS FOR EXPANDING EDUCATION SYSTEMS IN THE U. S.

In an attempt to measure the total stock of "educational capital" in the United States at various points in time, Schultz (89, pp 571-583) added the estimated potential annual income foregone by students in the formal schools to the expenditures for formal education of all types and derived an estimate of the total annual investment in education in the United States, for the period 1900 to 1957, by decades. He found that the total stock of "educational capital" ranged from $63 billion in 1900 to $535 billion in 1957.

Schultz also found that during that period, "resources allocated to education rose about three and a half times (a) relative to consumer income in dollars, (b) relative to the gross formation of physical capital in dollars..." (90, pp 60)

Other economists have attempted to either measure the costs of education (62, Chap. IV) or determine the contribution to the gross national product of resources devoted to education (94, pp 312-330; 95, pp 76-86; 24, pp 124-128). These efforts, though far from providing theoretical laws of the quantitative effects of education on economic growth, at least serve to highlight the general importance of education to economic growth and to give planners a "feel" for the magnitudes of economic costs and benefits associated with education.

In growth economics the question of balance is ever present. Should industrial development take precedence over agricultural expansion? Should emphasis be placed on training teachers, farmers, scientists, or physicians? Should capital be allocated to steel mills or school buildings? Obviously, the answers to such questions will depend on the characteristics of the economy being studied.

In developed, market economies, the "free" market is relied upon to regulate, through the wage/price mechanism, not only the stocks and flows of goods and services, but also the supplies of trained personnel. The regulatory mechanism is not perfect, since education and training is time-related, and lags associated with the length of time required to obtain appropriate training generally hamper real-time equilibration of demand and supply. But, since wages are related to the equilibrium prices of goods and services, the composition of the output of the educational system, and hence the composition of enrollments, should be a reflection of the efficiency of the market as an allocator of manpower.

Statistics on 1966 school enrollments in the United States are shown in Table 12-1. One may infer from these data that increases in enrollments in the system may be achieved in the pre-school and first-grade age groups and in the secondary and higher schools. However, the potential for qualitative change exists, at least theoretically, at all levels. It is also possible that wuantitative changes may be induced by changes in quality (where vocational courses encourage high school students to remain in the system to learn a trade rather than drop out to take entry-level jobs).

There is a need for a quantitative expansion of the U. S. educational system. The current Head Start programs have clearly demonstrated that pre-school exposure to cultural norms can significantly improve the primary grade performance of culturally deprived children. Also, recent studies have shown that as early as two years of age, children can efficiently learn complex language skills, including reading and rudimentary writing (83, pp 92). This potential might be exploited by expanding the educational system to include pre-kindergarten age groups (2 to 5 years old). It may be that a likely avenue for achieving this

Table 12-1. 1966 School Enrollments in the United States

Age (Years)	Population ($x 10^{-3}$)	Enrollments ($x 10^{-3}$)	Percent
5	4, 243	3, 087	72. 8
6	4, 167	4, 069	97. 6
7 to 9	12, 367	12, 283	99. 3
10 to 13	15, 721	15, 612	99. 3
14 to 17	14, 191	13, 293	93. 7
18 to 19	6, 724	3, 176	47. 2
20 to 24	12, 789	2, 547	19. 9
25 to 29	11, 136	720	6. 5
30 to 34	10, 482	283	2. 7

Source: 97, pp 112

*The term "wages" is meant here to include all emoluments, fringe benefits, social rewards, etc., derivable from a specific employment.

expansion would be through nursery/day-care centers of the Head Start type. The Head Start experience indicates that formal pre-school training as a precursor to primary school, can improve the efficiency of the primary school system and possibly reduce the number of drop-outs, by giving under-achievers the basic skills for successful performance in the primary grades.

In the higher grade-levels, quantitative expansion of the school system can be achieved by the addition of enrichment courses providing more thorough knowledge in the various disciplines in the curricula. This enrichment would be useful to students preparing for entrance in the colleges and universities, but should also be of value in the sense of making life more enjoyable. Of more importance, expansion of vocational education can provide the individual a higher wage potential, and, since higher wages reflect the individual's increased productivity, a higher national output. Further, according to Rivlin (77, pp 161-162), "Vocational courses may supply the potential drop-out with motivation for staying in school and learning more than a specific job skill. It is easier in a school context to make the program flexible, to teach skills useful in several different occupations, and to give the student an opportunity to learn about and transfer into a different course or a different curriculum. ...Finally, school courses do not have to be tied to the needs of local industry. This may be especially important in a declining area where students need to be trained for jobs in other parts of the country."

The steadily increasing U.S. school enrollment for the period 1950 through 1966 and projected enrollment through 1985, are shown in Table 12-2. It may be seen from the table that enrollments at the college level, projected through 1985, increase by 60 to 95 percent, according to the assumed level of female fertility. Using the 1964 value of $22,874,718,000 (37) for plant and plant funds for all U.S. institutions of higher learning and assuming that per-student investment in plant and plant funds will remain essentially the same over the projected period, the projected growth in college enrollments implies an increased investment in plant and plant funds of 16 to 25 billion dollars over the 20-year period, 1965 to 1985. In 1964, current expenditures in institutions of higher education on instruction, administration, research, and other operating expenses amounted to $7.425 billion (97, pp 133). Again, assuming per-student expenditure ratios to remain the same over the period 1965 to 1985, the projected growth in student enrollments implies a 1985 annual operating expenditure of 12.7 to 15.5 billion (1964) dollars.

Clearly, projected expansion of the education system, due to population growth, or curriculum enlargement, portends to be a multi-billion dollar annual expense. The opportunity to achieve substantial savings by using new techniques, such as educational television, to reduce student-specific capital investments or to increase student-faculty ratios must therefore be vigorously pursued.* If only a one percent saving in capital

---

*It is interesting to note that the current and historically held concept of an optimum student-teacher ratio of 25- or 30-to-one has been traced back to the Talmud Baba Bathra which states: "One teacher is to have twenty-five pupils; if they be fifty, then two teachers must be appointed; if they be forty, the teacher must have an assistant." Vide Sir Eric Ashby, FRS, "Reflections on Technology in Education," the Joseph Wunch Lecture, 1966 (Haifa: Technion, Israel Institute of Technology, 1967).

Table 12-2. School Enrollment — Estimates, 1950 to 1966 and Projections, 1970 to 1985

Year and Series	Total Enrolled	Elementary School	High School	College
Estimates				
1950	30,276	21,406	6,656	2,214
1955	37,426	27,086	7,961	2,379
1960	46,259	32,441	10,249	3,570
1965	53,769	35,120	12,975	5,675
1966	55,070	35,624	13,364	6,085
Projections				
Series B-1:				
1970	58,899	36,471	15,005	7,424
1975	61,858	36,088	16,310	9,459
1980	67,572	40,684	15,706	11,181
1985	76,867	47,675	17,345	11,846
Series B-2:				
1970	58,228	36,419	14,762	7,047
1975	60,433	35,965	15,903	6,565
1980	65,381	40,451	15,212	9,718
1985	74,040	47,361	16,751	9,927
Series D-1.				
1970	58,899	36,471	15,005	7,424
1975	59,428	33,659	16,310	9,459
1980	59,156	32,381	15,593	11,181
1985	61,498	35,632	14,278	11,588
Series D-2:				
1970	58,228	36,419	14,762	7,047
1975	58,041	33,573	15,903	8,564
1980	57,050	32,233	15,099	9,718
1985	58,880	35,404	13,781	9,695

(In thousands, as of fall of year. Prior to 1960, excludes Alaska and Hawaii. Elementary includes kindergarten and grades 1-8, high school, grades 9-12 and postgraduates. Series shown represent projections based on different combinations of assumptions about population and enrollment rates. Enrollment Series 1 and 2 are both based on the assumption that age-specific enrollment rates will continue to increase. Series 1 assumes a relatively rapid increase in the rate following the experience of the period 1950-52 to 1963-65, the projected rates are adjusted to tie in with the estimates for 1965. Series 2 assumes a more moderate increase based on an average of the projected rates in Series 1 and rates in 1965. The underlying projections of fertility were computed by the "cohort" method and imply that completed fertility of all women (i.e., the average number of children per 1,000 women at end of childbearing) moves gradually toward the following levels: Series A, 3,350; Series B, 3,100; Series C, 2,775; and Series D, 2,450. Series A results do not differ substantially from those obtained by assuming that the average annual level of fertility in the 1962-66 period will persist throughout the projection period.)

Source: Department of Commerce, Bureau of the Census: Current Population Reports, Series P-20, Numbers 66, 110, 161, and 162, and unpublished data.

and instructional expenditures could be achieved by using the mass media (ETV) to increase system efficiency, the direct potential benefits for institutes of higher education alone would easily exceed $80 million annually.** And the political mechanism for implementing a national ETV capability is already at hand in the federally funded programs supporting education in educational institutions. The recent history of federal funds for some aspects of education is summarized in Table 12-3. Tie-ins with on-going programs, and utilization of existing agencies, personnel, administrative methods, and policies should facilitate organizing and managing nationwide ETV activities.

Table 12-3. Federal Funds for Selected Education and Related Activities: 1962 to 1966 (in millions of dollars)

	1962	1963	1964	1965	1966
Total for all programs	4,730.4	5,305.2	5,818.1	7,434 2	10,583.5
1) Elementary – Secondary education	554.4	599.8	665.8	892.2	2,410.5
2) Higher education	991.9	1,161.5	1,333.7	1,901.9	2,656.6
3) Adult education	87.8	113.5	203.8	434.4	926.1
4) ETV facilities	-	-	5.2	5.1	15.2
5) Assistance for educationally deprived children	-	-	-	-	959.0

Source: 97, pp 145

The sizeable expenditures for assistance to educationally deprived children (item 5, Table 12-3) are largely associated with the Head Start program. Here again, a one percent increase in efficiency implies an imputed saving of at least $10 million annually if expenditures remain at or above the 1966 level.

**Based on a minimum $800(10^6)/year annual capital expenditures and maintaining the 1964 operating expenditure rate of $7.425 billion. Using maximum 1985 figures, annual benefits would be approximately $0.5 billion.

Table 12-4. Achievement Tests—Median Scores for Students in Grades 1 and 12, by Race or Ethnic Group: 1965

Grade and Type of Test	White	Negro	Puerto Ricans	Indian American	Mexican American	Oriental American
Grade 1						
Nonverbal	54.1	43.4	45.8	53.0	50.1	56.6
Verbal	53.2	45.4	44.9	47.8	46.5	51 6
Grade 12						
Nonverbal	52.0	40.9	43.3	47.1	45.0	51.6
Verbal	52.1	40.9	43.1	43.7	43.8	49.6
Reading	51.9	42.2	42.6	44.3	44.2	48.8
Mathematics	51.8	41.8	43.7	45.9	45.5	51.3
General Information	52.2	40.6	41.7	44.7	43.3	49.0
Five Tests, Average	52.0	41.1	43.1	45.1	44.4	50.1

*(Estimates based on survey of public elementary and secondary schools. Represents results of standard achievement tests of such skills as reading, writing, calculating, and problem solving. Scores on each test were standardized so that the average over the national sample equaled 50 and the standard deviation equaled 10.)

Source: Department of Health, Education, and Welfare, Office of Education; Equality of Educational Opportunity, 1966.

Also, in each group, the nonverbal and verbal test scores for twelfth graders was lower than the comparable test scores of first graders. Assuming that the tests were designed to give equivalent scores, independent of grade levels, the reduction in nonverbal and verbal scores point to an opportunity to improve educational quality. However, since this phenomenon may be a natural "degradation" of intellect or learning ability associated with childhood development, the group differences are probably the most significant manifestations of opportunities to improve or change the quality of education. If the scores of the white group are considered to be desired standards, remedial modifications of the curricula appear desirable for nonwhite students, whether the source of deficiency is social, cultural, ethnic, or physiological.

At the college level, need for improvement in quality is most apparent in those disciplines undergoing rapid expansion and change. In the past 30 years, the mathematics of physics and engineering has expanded to include new algebras and geometries, vector analysis, and

IMPROVEMENT OF EDUCATIONAL QUALITY

Articles in the popular literature have discussed inadequacies in the U.S. educational system which give rise to questions such as, "Why can't Johnny read?" There may in fact be many examples of high school or even college graduates with poor language or computational skills. This study does not enter the controversy of what norms should be, or attempt to establish or discuss optimum curricula. This section discusses the means of improving educational quality in a developed educational system, with only exemplary references to the need for improvements in quality.

In the United States, primary and secondary education is compulsory and free.* The enrollment statistics in Table 12-1 indicate that at the primary level virtually all non-institutionalized children are enrolled in public or private schools. In many states, the minimum age for compulsory attendance is sufficiently low to permit individuals to drop out of school before graduating from high school; consequently, enrollment in secondary schools is somewhat less than in primary schools. However, even where enrollments approach 100 percent, the quality of instruction may vary from region to region. In 1967, current, average, annual expenditures per pupil ranged from $335 in Mississippi to $912 in New York (97, pp 127). The respective, average public school teacher salaries were $4650 and $7900 during the same period in these two states (97, pp 129). Even considering differences in construction costs and costs-of-living, the disparities between per-student expenditures and teacher salaries lead to the inference that educational facilities and teacher qualifications in New York should be superior, generally, to those in Mississippi and, since there is a general variation among all of the states, one may further surmise that the quality of education varies from state to state.

In a survey of public elementary and secondary schools, achievement test scores of different racial or ethnic groups showed significant variation from group to group (Table 12-4).

---

*Here, the term "free" means that students may attend public schools without directly paying tuition; system costs are met by taxation of the general public.

operations research techniques. Economists have extended their working tools to include linear and dynamic programming, game theory, queueing theory, and many of the more common analytical methods. Meanwhile, research journals proliferate as new technology explosively expands. Unless students are willing and capable of greatly extending the length of their studies, new techniques must be used to permit their encompassing the old as well as the new theories and applications in the time period usually allocated to education.

The overlap of disciplines poses even more stringent requirements on the broadening of education. Physicians must know more physics to use lasers, and ultrasonics in their therapies. Sociologists must be more than lay psychologists or economists to understand the impact of their social prescriptions. The examples are many and it can hardly be controverted that at all levels, the quality and quantity of education must be expanded if individuals and society are to reap the benefits of the current and projected expansion of knowledge.

PROBLEMS OF EDUCATION IN DEVELOPING COUNTRIES

By defining a country as "emerging" or "developing," it is explicitly understood that in such countries many resources are far exceeded by the demand for them, and that few development projects can be planned and implemented without constant consideration, in a dynamic sense, of the progress of other critically needed developments. There is little margin for error and great need to view each project and subproject in light of overall goals and plans.

In the area of human resources, emerging countries are often characterized by low labor efficiency, low labor mobility, small numbers of occupational or trade specialists, few entrepreneurs, and social practices and institutions which minimize incentives for economic change. Consequently, a critical requirement in developing countries is the education of the populace in the sciences, technologies, and administrative skills on which desired advances will be based. Without the right numbers and types of trained indigenous personnel, foreigners must be depended upon to staff the industrial and agricultural projects on which economic growth will depend, and this utilization of external manpower may serve more as a deterrent than as a stimulus to development.*

A third and central economic requirement is the ability to produce savings. By foregoing current consumption, a nation can invest part of the national output in new capital, new resources, from which greater production and, hopefully, greater productivity may be derived.

> "and one of the most difficult decisions on economic planning is to get the time cycles of different investments worked out so that the schemes with quick returns come in time to finance the larger projects whose ultimate productivity may be much higher but is much slower to achieve." (115, pp 39)

There must be a balance among competing and complementary investment to achieve optimum growth rates within the existing and projected resourc constraints. Piecemeal investments may help some sectors of a developing economy; however, only when all significant sectors are expanded, industry, agriculture, transportation, electrification, education, and so on, at mutually compatible rates, can an emerging country hope to reach the "take-off" point from whence equilibrium growth may be maintained without large infusions of external assistance. Since each of these sector must utilize trained manpower to expand and be competitively productive, the investment in human capital appears to take top priority.

Primary Education

In the emerging countries, primary education enrollments generally range from approximately 5 to 40 percent of the primary school age population (41, pp 54). These enrollment figures point to a need to expand the primary school systems; however, they do not give the full picture. They do not fully describe the distribution of students by grade or by geographical location. Near urban centers, enrollments may be higher, since teachers are more likely to prefer the relative advantage

*Foreigners generally require higher salaries to work in developing countries than in their own country. This may cause excess costs in producing items for home consumption or for export, thus rendering that portion of the national output less competitive internationally. Further, foreigners' salaries may be sufficiently out of accord with domestic salaries as to cause significant social and political problems (41, pp 60-61).

of living in larger communities where some of the comforts and pleasures of city life are available, rather than in isolated areas where creature comforts are at a minimum. Even with compulsory primary education, the drop-out rates may be very high, with only a small fraction of those who enter the first grade staying to complete the sixth grade. Although data on primary school drop-outs in developing countries is scarce, Table 12-5 gives an indication of the size of the problem.

Table 12-5. Estimated Primary School Drop-Outs in Certain Developing Countries

Country	Grade 1	Grade 2	Grade 3 (percent)	Grade 4	Grade 5
Africa					
Cent. Afr. Rep.	21.8	11.7	9.6	7.1	8.0
Dahomey	24.5	12.8	10.7	11.0	5.7
Madagascar	18.1	10.6	13.6	23.4	9.2
Niger	12.6	4.8	12.0	5.0	11.9
Togo	3.1	1.9	1.0	2.0	10.9
Upper Volta	19.2	17.3	7.3	16.7	8.2
Asia					
Afghanistan	4.0	1.5	2.0	7.0	4.0
Ceylon: Urban	15.6	7.5	9.7	10.6	8.1
Rural	17.4	11.4	11.7	12.8	9.8
Philippines	9.2	6.8	7.6	10.0	8.5
Thailand	12.0	5.0	6.0	--	6.0
Latin America					
Argentina	13.4	5.6	7.6	10.0	10.1
Costa Rica	7.1	10.7	10.6	11.5	10.7

Sources: (Africa): IEDES, Les Rendements de l'enseignement du premier degré en Afrique francophone, III (Paris, 1967); (Asia: Afghanistan and Ceylon): Unesco, "The Problem of Educational Wastage at the First Level of Education in Asia," in Bulletin of the Unesco Regional Office for Education in Asia, Vol. 1, no. 2 (Bangkok, 1967); (Philippines and Thailand): Ministry of Education, Japan, in cooperation with Unesco, Education in Asia (Tokyo, 1964), p. 63; (Latin America: Argentina): Consejo Nacional de Desarrollo, Educación, recursos humanos y desarrollo económico y social (Buenos Aires, 1966), p. 42; (Costa Rica): unpublished data.

These early drop-outs represent a waste of educational funds: frequently, they drop out in the first grade, re-enter, then drop out again, thereby increasing the costs of primary education. Furthermore, early drop-outs tend to lose whatever literacy they may have attained, which actually diminishes the value of their limited education to virtually zero.

The generally poor quality of primary education is as significant as the low enrollments and high drop-out rates. In many developing countries, the primary school teachers are often "unqualified." They may have little more than a primary education themselves, and no special training as teachers. Textbooks and other teaching materials, where used at all, are frequently poor, and curricula consist mostly of memorization of material read by the teacher. As a result of these deficiencies, those who attend may barely achieve sufficient skills in reading and writing to be considered literate, and efforts to rapidly expand the primary school systems may tend to reduce even further the quality of primary education.

Secondary Education

As economic progress is made in developing regions the demand for skilled manpower increases substantially and technicians constitute a strategic group. They are required not only for industrialization, but also to improve the technical quality of the agricultural sector; and where clerks, bookkeepers, secretaries, etc., can be considered technicians, the requirements for business managers, administrators, and general staff adds to the demand for technician level workers.

The supply of technicians arises mainly from secondary education, either academic or vocational. Thus, secondary education is the foundation of the high-level manpower required to achieve increases in the level of technology application and thereby in the level of national output in developing countries. In many areas the second-level graduate is the major source of primary teachers. The critical need for secondary-level personnel is dramatically demonstrated by the induced underemployment of physicians and engineers in India, which is frequently due to the lack of skilled technicians. This underemployment further exacerbates the critical shortage of top level professional personnel.

Many investigators have discussed the requirement to pursue an "unbalanced" educational policy in order to produce, as rapidly as possible, large numbers of secondary school graduates (21, 41 passim). Since most nations are dedicated to universal education, and it is politically difficult to openly adopt a policy of not expanding primary schools, the most likely method of secondary schools expansion in economically constrained countries will be by using new tools and techniques in conjunction with provision of more teachers, more buildings, etc.

As mentioned before, the major demand for secondary-level graduates is in the area of technology and vocational training. This portion of the secondary education system can frequently be handled on a nonformal, nonresident basis. For example, farmers may be taught new agricultural techniques in evening classes, sometimes held outdoors. Given proper audiovisual lecture material, nurses and nurses aides can be trained in the hospitals rather than in institutions specifically constructed as schools.

Higher Education

Higher education is achieved in developing countries in two ways: either by establishing universities within the country or by sending the students to other countries. The establishment of a college or university facility within a country is frequently not an economic decision, but is related to political and social motives. Since most organizations have an optimum size, it is almost axiomatic that, in the beginning, education of nationals at home will be more expensive than providing for their education in established foreign universities. Independent of size, the operations of indigenous universities is also often more expensive, if teaching and administrative staff must be obtained from outside the country. Under normal circumstances these personnel receive higher salaries, by far, than teachers or high government officials within the country. They may also receive a higher salary than they would in their native country. However, once this higher-priced teaching talent is employed, their replacement is difficult. Those students who graduate from the university tend to go on into high government office or, if they remain in the university as faculty, demand the higher wage given the extranational faculty. This latter circumstance tends to distort the salary structure of the country so that it is sometimes inadvisable that they be paid at the equivalent rate of the extranational personnel; this either removes incentive for obtaining the higher education or, if the incentive is maintained, causes the graduate to go into fields other than teaching in order to make as much money as possible. However, the absolute requirement for business managers, physicians, professors, administrators, lawyers, and all those professionally trained persons who make a developing or developed economy function is urgent. Here, again, the new tools and techniques are likely methods for improving the quality and quantity for higher education in a developing nation at minimum cost.

USE OF MASS MEDIA IN EDUCATION

The use of mass communications media for education has greatly expanded the educational process, and can be said to have been a major milestone in man's development. The first truly significant advance in mass communications was the invention of the printing press. Prior to Gutenberg's invention, books were extremely rare and only available to the very rich, or those subsidized by wealthy patrons. As books became more available and less expensive, the accumulation of knowledge became available to anyone with access to a library, and eventually textbooks became the standard source of educational information.

In the late 19th century the newly discovered techniques of photography and phonography permitted the wide dissemination of visual and audio information hitherto only available through in-person attendance at lectures, musical events, and the like. The ensuing developments of motion pictures, sound-on-film, radio broadcasting, and, finally, television broadcasting added not only audiovisual teaching aids, but, as the name implies, the capability of wide distribution of this audio and visual material through broadcasting.

Today, film and record libraries make audio and visual recorded information available in homes and schools possessing projectors or phonographs, almost on demand. Educational television and radio, recorded and live, are increasingly used in formal and informal audiovisual instruction.

12.3 EDUCATIONAL TELEVISION

GENERAL

Educational television (ETV) has, in the last decade, shown great promise as a means of upgrading the quality and quantity of education, both in developed and developing countries. Its advantages have been lauded by educators, communications experts, budget directors, and others interested in cost-effective instruction. It has been the subject of many research and experimental programs, and, in the form of research studies or actual ETV programs, is a line item in the educational budgets of many countries, states, and municipalities. The proponents of ETV sometimes make it appear to be the panacea for education. Its detractors frequently see it as a misuse of scarce resources, a gimmick which may be overemphasized, to the detriment of established systems and goals, or a threat to the tenure of the teachers and administrators in current educational systems. A review of literature in this field suggests there is some merit in both views.

Generically, ETV is the visual display and aural presentation of instructional material, using television receivers as the audiovisual presentation apparatus. It differs from slide or film projection in that many receivers may present the same material, simultaneously, in widely separated locations (and therefore to potentially larger audiences), and permits presentation of many levels and types of educational materials on the same equipment, without maintaining large inventories of films, slides, etc., at each location, or establishing a logistic system for the scheduling and interchange of audiovisual materials.

Educational television (as well as other audiovisual devices) does not provide a complete, self-contained curriculum. It is generally conceded that a "teacher" is required to carry on pre- and post-lecture discussions, answer student questions, and observe student attention, reactions, and so on. This "teacher" need not be fully competent in the disciplines presented by ETV, nor even be a fully qualified educator. However, someone must be on hand to provide supervision of the student group, to monitor the level and quality of student participation, and to coordinate student feedback to the program originators and managers.

As presently conceived, ETV programming for formal education is presented as part of specific courses of study. Serial or individual lectures are fitted into the general classroom work, with the implication that there is related material, whether as textbooks, mimeographed notes, or other textual forms, to be used in conjunction with the audiovisual material. Even in the absence of accompanying textual materials, written tests or written records of oral tests are required to provide student-feedback.

The actual programs may range from straight lecturing to real or animated scenes depicting events or phenomena pertinent to the course work. The skills and techniques which may be brought to bear on preparing the program materials provide the main advantage of ETV audiovisual materials over descriptive classroom lectures, particularly where "master specialist teachers" are used to supplant or support the classroom teacher. An ancillary advantage is that ETV programming helps assure that a uniformly high quality of educational material is available to all students within the system, independent of the qualities of the individual teachers or the peripheral equipment and facilities of the schools or school districts in which they are enrolled.

In view of these statements, ETV as a system may be further defined as an adjunct to an overall educational system, in which students, teacher/monitors, textual materials, audiovisual programming, and receiving and display equipment are combined to provide widespread (and hopefully) high-quality, education.

A REVIEW OF ETV RESEARCH AND PRACTICE

Educational television has been used, at least on an experimental basis, in hundreds of schools, by thousands of students and in many countries.* The data from these programs are predominantly qualitative and subjective, but significant conclusions may be drawn. Chu and

*Some of the more significant studies have been carried out in Hagerstown, Maryland; Chicago, Illinois; The Midwest Program on Airborne Television Instruction (MPATI); American Samoa; Algeria; Australia; Honduras, India; Italy; Ivory Coast; Japan; New Zealand; Niger; Peru; Thailand; and Togo.

Schramm, of the Stanford University Institute for Communication Research, surveyed more than 300 research papers on the use of audio-visual teaching aids, particularly film and television, for the United States Office of Education (17). This comprehensive document may be used as a general guide to the efficacy of TV teaching and to the design of ETV programming and hardware. In their review, Chu and Schramm have drawn a series of general conclusions which may serve as qualitative indicators of the state of knowledge of instructional television. These conclusions are presented in Appendix A.

In another review of research papers, Kanner evaluated the instructional effectiveness of color in television (57). He concluded that color is not significantly superior to black and white as a means of TV teaching. However, the studies reviewed by Kanner were evaluations of color coding of items versus alpha-numerical coding in black and white. It would appear that if an overall color identification is part of the learning process (e. g., soil and water coloration, leaf tints, differentiated animal cells, etc.), then presentations in color should provide superior instructional effectiveness. The overall qualitative conclusion from both reviews cited above is that ETV, either color or black and white, can be an effective educational tool if properly used.

But how effective? How can educational planners justify expenditures on ETV in place of more or better texts, teachers, and classrooms? Unfortunately, very little hard data are available to provide quantitative bases for ETV allocation decisions. In those programs from which quantitative conclusions may be deduced, the applicability of these conclusions to ETV in general is hampered by the unique character of the specific programs. The American Samoa experiment was carried out in a homogeneous society and with essentially unlimited funds. The Hagerstown, Maryland, experiment brought ETV to an existing, relatively modern, unitary educational system. The Midwest Program on Airborne Television Instruction (MPATI) involved many different, and sometimes conflicting, school systems and funding agencies. At best we can observe the results of these experiments and cautiously extrapolate the statistical data derived from them as a guide to potential results in different applications. In the following section, several ETV projects are discussed to point out significant characteristics and experiences in ETV both in developed and developing countries. In addition, the Thai experience in educational radio is described for purposes of comparison. Finally, some statistics on costs and effectiveness are presented.

ETV PROJECTS

American Samoa

American Samoa is a dependency of the U. S., administered by a governor, appointed by the Secretary of the Interior, and by a bicameral legislature. The population is estimated to be 27,000 persons, occupying the islands of Tutila, Tau, Olosega, Ofu, Aunuu, and Swains Island. The total land area is 76 square miles.

In 1961, the governor, Rex Lee, found that students graduated from grade 12 typically scored between grades 5 and 9 on standard achievement tests. Most teachers were indigenous personnel with little more education than the graduating high school students. Though it was desired that instructions would be in English, few teachers were conversationally fluent in English. As a reflection of the generally poor preparation and fluency of the teaching staff, most classroom activity involved rote memorization. Drop-out and absentee rates were very high. It was decided that as soon as possible this educational system would be brought up to the standards of schools in the mainland United States.

> Schramm states:
> "To accelerate the pace of educational development the governor had several alternatives: (a) He could recruit several hundred fully qualified teachers from the United States, and use them to replace Samoan teachers. This would have had very quick results (supposing that the new teachers could have been recruited), but it would have been extremely expensive, and would have required the politically unpalatable dismissal of several hundred Samoan teachers, many of them with long tenure. (b) He could recruit a smaller number of teachers — say, 100 — from the mainland, and place them throughout the school system. This would have been less expensive than the first alternative, and also would have produced a ferment in the system, but it ran counter to a Samoan norm of moving forward together. (c) He could initiate a long-term plan for training future Samoan teachers in the United States, introducing the new trainees into the system as they were ready and as openings appeared. This would indeed have produced well-trained Samoan teachers, and

at less cost than the alternative finally decided upon; but the trainees would have had to receive much of their education beyond primary school, as well as their teacher education, in the United States; and therefore this alternative would have had no effect on the system for ten to fifteen years. (d) He could use television. After two planning surveys, this was the alternative decided upon." (86 pp 18)

Television was to be used as the main core of the teaching program. It was to provide classroom lectures for the students and teacher-training programs to upgrade the Samoan staff capabilities.

The Samoan TV installation comprised six UHF channels, four studios, ten video-tape recorders and other ancillary equipment. Each classroom had one or more television sets, with extra speakers. Highly detailed teaching guides were prepared in conjunction with the curricular programs. Professional teachers, writers, and producers were employed to supervise and prepare the educational materials. The project was formally instituted in 1964.

(It should be noted that early in the project it was found that ETV could not be effectively implemented in the simple premises that had commonly been used for classrooms. Consequently, new and modern classrooms were built to provide appropriate housing, seating, blackboards, lighting, etc.)

To date, no formal, objective evaluation of this project has been published. However, observational appraisals indicate that the goal of high quality education is being achieved, particularly and specifically by means of educational television.

Hagerstown, Maryland

The Hagerstown project is the first instance of television being used as a major part of the educational methodology of an established school system. Actually, the project included the unitary school system in Washington County, Maryland, which is headed by a single superintendent of schools, and therefore could receive vigorous cohesive support by the school administration.

The project was initiated in 1956 as a means of easing the pressures of increased enrollments (and concommittant requirements for additional facilities) and of expanding teacher capabilities, particularly in the elementary grades where science and mathematics were being taught mostly by teachers with no special competence in these fields. A Ford Foundation grant of $1 million and $300,000 of equipment donated by manufacturers were made available for the initial experiment. Washington County classroom teachers, together with various consultants, produced the program material and, in September 1956, the first lessons, in four senior high school subjects, were televised to approximately one-third of the senior high school pupils.

At present, television is used for about 10 percent of the classroom time in grades 1 through 6, about 33 percent for grades 7 and 8, and 17 percent for grades 9 through 12. Additional elective material is also available. Essentially all courses include some television, and advanced mathematics, not ordinarily available in high school, may be taken by qualified students. The total programming is approximately 140 hours per week, 95 percent live. Junior and senior high schools typically use large screen projection to audiences of 100 to 300 students. Elementary schools use one or two sets in each classroom.

The teachers in the Washington County school system feel that the instructional program of a school system is handicapped without the use of television as a resource. Evaluation of the effects on student learning (discussed in the next section), show that ETV has improved the output of the system. The acceptance of ETV in Washington County schools is indicated by the unanimous decision of the school board to take over the entire cost of the project after the Ford Foundation grant expired in 1961.

Midwest Program on Airborne Television Instruction (MPATI)

The MPATI was instituted as an experiment in reducing the per capita costs of education in several contiguous midwestern states. It was felt that by increasing the range of ETV from the normal 50 mile radius of ground-based television, per student costs of programming and broadcasting could be significantly reduced. To this end, an airborne transmitter, flown at 23,000 feet altitude, was used to broadcast ETV over a 150,000 square mile area. The programming was carefully developed and produced, on tape, by professional teachers and television production centers. Ground receivers were installed in participating schools at an average cost of approximately $500 each.

This program, now discontinued, was very expensive (approximately $20 million) and was difficult to administer, since hundreds of independent school districts with different supervisory boards, differing curricula, and disparate sources of funds were included. However, much was learned about program preparation and coordinating educational activities across boundaries of political authority. The major lesson learned was that broad coverage by ETV is best accomplished if there is a central authority managing the project. Additionally, it was found that the instructional effectiveness of the MPATI project was comparable to that of ground-based ETV.

Nigeria

Of the many ETV projects in developing regions, the Nigerian experience is presented here because it points up typical areas of difficulty in implementing effective ETV in developing countries. This does not imply that Nigeria did not attack its educational problems with competence and good judgement. Rather it serves as a case study of the difficulties encountered when new technology is imposed upon an educational system which does not have the availability of resources found in the U. S. programs previously discussed.

In 1965 each of Nigeria's political divisions (Western Nigeria, Northern Nigeria, Eastern Nigeria, and Federal District) had its own ministries and broadcasting organizations. Television instruction had been instituted primarily to upgrade the quality of instruction in the formal school system and to assist in providing teacher training. However, the broadcasting facilities were set up under the Ministries of Information, as commercial stations, and station managers were reluctant to provide daytime ETV, since their revenues derived from evening programs supported by commercial advertisers, and daytime broadcasting involved the expense of an additional crew of technicians. The Ministries of Education were responsible for ETV programming. Consequently, much negotiation and adjustment of budgets between these autonomous ministries was required to assure properly scheduled daytime broadcasting of ETV.

Problems of electrification, power failures, set maintenance and transmitter failures continually plagued the ETV system. Availability of skilled technicians, program personnel, and liaison personnel was far below the minimum required for smooth efficient operation. These problems, complicated by the prevailing philosophy that television was only a frill and not a major means of direct teaching, and lack of strong support from a central authority severly hampered the establishment of effective ETV in Nigeria. By starting with few available programs, sporadically televised, ETV did not command enthusiastic support of classroom teachers. To overcome these difficulties, Nigeria enlisted the aid of experienced ETV personnel from Hagerstown and elsewhere, accelerated technician training programs, and significantly increased the number of program hours.

Peru

Telescuela Popular Americana (ETPA) in Arequipa, Peru was established by a group of teachers, on a voluntary basis, to provide fundamental education by ETV to potential students not formally enrolled in the school system. TV time was donated by the local station and the initial programming was designed to provide literary skills and basic arithmetic. The programs were directed toward viewing in homes by domestic servants and by workers in factories and other business establishments.

With the cooperation of the Ministry of Education the programming was expanded to provide review material for grades 4 and 5, for children who had dropped out of school early, and to provide programming for pre-school children. Subsequently the Ministry of Education provided funds for formal primary instruction and for an adult literacy program.

A significant result of these efforts has been that TEPA has developed an accelerated primary-school program for adolescents, in which material normally requiring a full day of classroom work is presented in a 45-minute TV program, thus permitting students, who through the lack of available time or the lack of nearby schools would otherwise not be able to upgrade their skills, to acquire the training necessary for holding other than menial jobs.

Thailand

Thailand is included here because its Ministry of Education chose to expand education by radio broadcasting rather than by ETV. The Thais carefully developed appropriate educational radio programming, and in 1954 initiated a program of 16 hours of instructional broadcasting to Bangkok children, teachers, and the general public, in their homes. By raising signal strength and adding transmitters, broadcasts were gradually extended to virtually the entire country. The original efforts involved three subjects: English, music, and social studies.

In 1958 school broadcasting was initiated, starting with 286 schools. Now, more than 5,000 schools receive formal instructional radio programs at a cost of approximately one cent an hour per student (86 pp 34). Also, the Ministry of Education has begun an experimental ETV project. As discussed later, the educational radio project did provide measurable improvement to the Thai school system. It was done with very limited means and at a pace commensurate with the availability of funds, teachers, and receiving equipment. Whether greater advances would have been made by starting immediately with TV cannot be readily asserted. Whether other developing countries can afford to proceed at the deliberate pace of the Thai radio project is debatable. However, the Thai's successful project, carried out within severe budget constraints, provides a lesson in how the mass media can be used to accelerate educational development with little or no external assistance, and with no deleterious affects on balances of payments or foreign exchange.

SOME QUANTITATIVE RESULTS FROM ETV PROJECTS

As mentioned before, few data are available on costs or effectiveness of ETV. In most cases it is difficult to identify the residual effect of the TV portion of the curriculum, particularly when it is not the prime method of instruction. Not only do differences in financial and accounting practices prevent direct comparison among projects, but frequently, identification of all cost elements cannot be made. The following data are offered as quantitative indicators of cost and output experiences in some

ETV projects. Hopefully they will be useful in establishing expected values of costs and performance parameters in future systems.

System Effectiveness

The Hagerstown project was carried out in a "standard" U.S. school system in which annual expenditures per student were approximately $450. Taking the national average gain in arithmetical concepts determined by national basic skills and achievement tests to be one year, Hagerstown grade 5 students gained 1.9 years in arithmetic skills during the first year of television (86 pp 68). In four years of educational television:

> "...... in junior high school general mathematics, the average level of urban pupils in Washington country rose...., from the 31st percentile on a standardized test of concepts to the 84th percentile (measured against the national average)....(86 pp 69)

Similar increases in skills and achievement were evidenced by pupils at all grade levels. The following two tables, taken from (86) are further indications of the effectiveness of ETV in the Hagerstown project.

As seen in Table 12-6 students at all levels of ability benefited by televised learning, with increases in growth rate ranging from 25 to 116 percent. The phenomenal doubling of the growth rate for the lowest ability level is of great significance since this group is the one in which drop-outs are most likely to occur and which generally has the most difficulty finding entry-level jobs when their education terminates. In a high-technology society the low-ability group also frequently remains at the bottom of the economic ladder.

Table 12-6. Comparison of Growth of Pupils Taught Conventionally and by Television

Ability Level	Taught Conventionally		Taught by Television		Growth Difference (%)
	Average IQ*	Achievement Growth* (Months)	Average IQ*	Achievement Growth* (Months)	
111-140	117	12	118	15	+25
90-110	100	11	100	14	+27
57-89	83	6	83	13	+117

*IQ and achievement growth are based mostly on the Iowa tests of basic skills and achievement, which are given annually in all parts of the United States.

In Table 12-7 the striking jump in arithmetic test scores after only one year of television is ample evidence of the ability of educational television to provide high-quality teaching on a mass basis. The continued gains in the second and third years of televised teaching reflect not only the effectiveness of television as a teaching medium, but, if one reads along the diagonals, the sustained effect of improvement of early learning.

At higher grade levels, significant gains in mathematical concepts were achieved, but little or no gain was made in problem solving; only small gains were made in social studies and languages at all levels, but good gains were made in history (86 pp 70). The implications are that problem solving and linguistic improvement are more related to the actual work done by students than to the quality of lectures.* The disparity between gains in social studies and history may be related to the quality of presentations in these two disciplines.

Table 12-7. Arithmetic Scores of Rural-Primary Students in Washington County

	Grade 3	Grade 4	Grade 5	Grade 6
National norm in May (1958)*	3.90	4.90	5.90	6.90
1958 (before television)	3.59	4.43	5.26	6.49
1959 (first television year)	4.06	4.97	5.77	6.83
1960	4.18	5.01	6.13	7.17
1961	4.30	5.08	6.19	7.28

*Though not so stated in the reference it is assumed that the norm was measured in May 1958.

In an anonymous questionaire submitted by the Washington County school board to administrators and teachers 72 percent of the 818 eligible persons responded as shown in Table 12-8.

*Language laboratories use oral participation and continuous aural review by the student as a key technique.

Table 12-8. Results of Questionnaire on Opinions of Televised Teaching Respondents

Comments	Administrators	Teachers Primary	Intermediate	Junior High	Senior High
Much or some help in teaching	83.3	76.9	80.9	62.5	40.9
Provides richer experience	98.7	98.4	96.4	90.0	76.3
Enriches and expands curriculum	91.1	94.2	90.7	77.8	76.0
Limits or reduces curriculum	3.8	3.3	6.4	15.3	18.6
Has no effect on curriculum	5.0	2.5	2.8	6.9	5.4
Improves curriculum	91.0	94.0	88.0	81.0	68.0
Improves quality of overall program	97.0	94.0	88.0	81.0	66.0

It can be said that Hagerstown project has achieved the goals it set out to meet. Television enabled the school system to provide high-quality teaching in science, music, and art in grades 1 through 12, modern languages beginning at grade 3, and calculus in high school. This was not possible under the previous system. What is more, measurable gains in student achievement were made.

Data on performance improvements in other ETV projects are sketchy or nonexistent. In Colombia, grade 2 language, grade 5 mathematics, and grade 4 natural science students made noticeable gains with televised instruction. However, other grades did not show significant gains from their television instruction. In Niger, experimental classes using ETV showed improvement in spoken language, reading, writing, and arithmetic over students receiving nontelevised instruction. In Chicago and in Japan, students and teachers accept ETV as a valuable aid to teaching.

In no case has ETV been considered to be detrimental to instruction. However, it is entirely possible that the improvements achieved in many of the ETV projects could have been achieved by some other means. The salient point is that, if used properly and supported properly, both administratively and fincially, ETV can have dramatically beneficial effects on the learning process.

System Costs

To assess the costs of a project, one normally identifies the outlays for wages, salaries, materials, equipment, power, facilities, and so forth, and those charges associated with acquisition of investment capital. In addition, depreciation, or capital consumption allocations, should legitimately be included in long-term cost evaluations, since, eventually, original capital equipment and buildings must be replaced as they wear out or become obsolete. Unfortunately, cost data on ETV projects is rarely reported in sufficient detail to isolate all of the cost elements mentioned above. Generally, available data are limited to gross allocations, and even these may not present the whole picture, since, in many cases, personnel, facilities, or equipment are used jointly with other projects or applications and proration of ETV costs is difficult or debatable.

Comparisons of costs among projects should only be done to indicate orders of magnitude; first, as mentioned before, because financial and accounting practices may vary; second, because the character or quality of the projects being compared may differ considerably; and third, where international comparisons are concerned, exchange rates, wage and price levels, and political or institutional practices may mask the real project costs. Even in comparison of domestic programs, variations in managerial or administrative efficiency may affect the overall costs of otherwise similar systems. In the following discussion of comparative costs, all of these potential variations should be kept in mind.

Cost of ETV and educational radio projects discussed in the previous section are shown in Tables 12-9 and 12-10.

Using the data in Table 12-10 and dividing total current costs by the number of student-hours produced, the data in Table 12-11 were developed.

These tables show that overall and per-student-hour costs of ETV programming may vary considerably, depending upon the characteristics of the project (i. e., how much of the teaching load is carried by ETV, where it is viewed, how many students are in the system), and that radio can be significantly less expensive than ETV. The capital expenditures shown in Table 9 are presented to indicate the size of investment

Table 12-9. Capital Expenditures for Selected ETV and Radio Projects

Project	Production ($\$10^3$)	Transmission ($\$10^3$)	Reception ($\$10^3$)	Total ($\$10^3$)
MPATI	643	4,857	2,250	7,750
American Samoa	1,239	1,045	97	2,381
Hagerstown	463	– 1)	154	617
Ibadan	59	– 1)	90	149
Peru	13	– 1)	25	38
Thailand (radio)	150	20	500	670

1) These costs are not shown because Hagerstown uses closed circuit TV and the other two use hired or donated transmission facilities. More accurate costing would require imputation of these costs.

Source: 88, page 127 and 129

Table 12-10. Annual Current Costs of Selected ETV and Radio Projects

Project	Production ($\$10^3$)	Distribution ($\$10^3$)	Reception ($\$10^3$)	Total ($\$10^3$)
Television in school				
MPATI	192	2,094	800	3,086
American Samoa	908	436	79	1,423
Hagerstown	349	161	53	563
Ibadan	94	68	6	168
Television out of school				
Peru	40	14	17	71
Thailand (radio)	32	11	86	129

Source: 88, page 130

Table 12-11. Annual Cost of Television Per Student-Hour

Project	Student-Hour Output ($\$10^3$)	Cost per Student-Hour (cents)
MPATI	35,200	8.8
American Samoa	2,409	59.0
Hagerstown	3,300	20.0
Ibadan	289	64.0
Peru	163	43.0
Thailand	33,500[1)]	2.0

1) Author's estimate

Source: 88, page 137

experienced in these projects. Obviously, investment size will be related to coverage area, population density, numbers of program hours, and other variables associated with specific projects.

In establishing an ETV project it is advisable that the responsible authorities view ETV as a subcomponent of the overall educational system, and determine what amount and type of programming should go to what audience on what schedule, based on the desired output of the overall system and the various resource constraints affecting the system. For example, if the educational system components are considered to comprise students, teachers, facilities, equipment, teaching aids, researchers, time, financial resources, and the current fund of knowledge, optimum use of ETV as a teaching aid will depend upon the current "configuration" and established goals of the other components. Given the universal constraint of limited funds, only from the systems approach can sub-tradeoffs between such parameters as numbers of sets and numbers of program hours be optimally determined. Conversely, teacher training programs or teacher salaries may be directly influenced by the "configuration" of the teaching-aid subsystem.

Determination of the optimum allocation of resources among the educational subsystems is a problem that should be solved before an ETV project is initiated. Determination of the means of TV broadcasting, whether it should be by terrestrial transmission or by a TV broadcast satellite, is an integral part of that problem.

POTENTIAL EFFECTIVENESS OF SATELLITE-BASED ETV

In the foregoing discussions of education and ETV the need for expansion of the education systems of developed and developing countries has been described and some data on the costs and effects of various ETV projects were presented. In this section an attempt is made to show potential benefits to be derived from space broadcasting of ETV. It is presumed that direct multichannel broadcasting of TV programming is technically feasible and that areas of the order of 10^6 square miles can be illuminated from synchronous altitude. A further presumption is that the requisite quantity and quality of instructional programming can be made available and that diplomacy and statesmanship can overcome problems of frequency allocations and cooperation across political boundaries.

As before, the discussion is divided between developed and developing countries; however, the only developed country considered in detail is the United States. Discussion of developing countries is limited to those non-communist nations on which reliable statistics could be obtained.

Some Potential Benefits of Satellite-Based ETV in the U. S.

It was indicated previously that quantitative expansion of the U. S. education system may be achieved at the preschool, first grade, secondary, and higher levels, and that qualitative changes may be achieved at all levels. Intuitively, one feels that these changes should have pervasive, measurable effects on the entire social and economic structure of the country. But the social scientists have yet to establish the theories and models by which all the possible effects may be measured; consequently, the potential benefits identified here might best be termed "reasonable expectations of some rewards to be gained from a satellite-based ETV system."

Gains in Educational Efficiency

No qualitative data were available to indicate potential gains in education above the secondary level. Though benefits to higher education may possibly be achieved, only primary and secondary levels are discussed.

In the Hagerstown project, from a $450 total annual expenditure per pupil for education, $31, or approximately 7 percent, was spent on television instruction (88 pp 132). The amount of classroom time devoted to television was:

1)	Grades 1 to 6:	10 percent plus 4 percent elective material
2)	Grades 7 and 8:	33 percent
3)	Grades 9 to 12:	17 percent

(88 pp 23).

Using the figures in Table 12-6, it can be deduced that an overall average growth in achievement of 31 percent was obtained with this amount of programming. Of greater importance the lowest ability group gained 117 percent in achievement and the middle and lowest group gained almost 42 percent overall. From Table 12-7 it can be inferred that, after three years of television instruction, efficiency of instruction of rural, primary students in mathematics increased 20 percent in grade 3, 15 percent in grade 4, 18 percent in grade 5, and 12 percent in grade 6.

Using these figures, the cost elasticity* of performance (CEP) as a measure of the sensitivity of educational output to expenditures on ETV was computed (Table 12-12).

The annual current costs for the Hagerstown ETV project are stated to be as follows:

Production	$349,000
Distribution	161,000
Reception	53,000
Total	$563,000**

*The cost elasticity, e, of performance is defined as the absolute value of the rate of percentage change in performance divided by the rate of percentage change in cost; or, where p = performance and c = cost,

$$e = \frac{dp/p}{dc/c} = \frac{c}{p} \cdot \frac{dp}{dc}$$

**In the reference, the total of these numbers is given as $613,000.

Table 12-12. Cost Elasticities of Performance (CEP) of the Hagerstown ETV Project, Based on Achievement Growth and Changes in Rural Primary Arithmetic Scores

Basis	CEP
Achievement Growth	
111-140 ability level	3.6
90-110 ability level	3.9
57-89 ability level	16.7
Overall	4.4
Rural Primary Arithmetic Scores	
Grade 3	2.9
Grade 4	2.1
Grade 5	2.6
Grade 6	1.7

(88 p 130). The major portion of these costs is the 62 percent for program production, this amounts to $19.22 per pupil. But the great advantage of television is that program costs may be shared among all who have receivers in the range of the transmitter. Consequently, if this program production expense were divided among a much larger number of students, the per-pupil costs could be reduced to a negligible amount.

Now consider the possible effectiveness of a TV-broadcast satellite as a national tool for upgrading the entire U.S. education system, assuming that the program quality and quantity used at Hagerstown would achieve Hagerstown results if used nationally.

Program Production and Reception

The Ford Foundation grant to Hagerstown was $1 million. This amount was spent in preparing for and in preparation of the programs used through 1961; it may have covered additional nonprogram-related expenses, but it can be accepted that program production did not exceed $1 million. For this amount, 2,530 hours of program material were produced (88 pp 134). For the sake of discussion assume that for the entire U. S., diseconomies of scale would cause program production costs to be an order of magnitude greater, or $10 million. Further, assume that to continually upgrade program material an annual expenditure of $10 million would be required.

In 1967, the U. S. public elementary and secondary school system consisted of approximately 44 million students in 1.7 million classrooms in 100,000 schools. The investment costs for reception equipment for the entire system should then be the sum of the number of classrooms times the cost of one receiver per classroom, and the number of schools times the cost of equipment required to bring the appropriate signal to the classroom receiver.

In the 1972 era it seems reasonable to expect that 23-inch color receivers, having a useful life of 10 years, may be manufactured in mass quantities for no more than $250 each. Assuming that the antenna and the required electronic accessories, also with a 10-year life would cost no more than $1,000 per unit, installed, investment in reception equipment would be $525 ($10^6$) as follows:

Receivers: 1.7 (10^6) at $250 each	$425 ($10^6$)
Antennas and associated electronics, installed: 100,000 at $1,000 each	$100 ($10^6$)
Total	$525 ($10^6$)

The reception equipment need not be installed in all classrooms simultaneously, but could be gradually introduced in areas of greatest need or of greatest benefit.

The operating costs of the reception equipment would be mainly incurred for maintenance and repair, and for power. The maintenance and repair costs for reception equipment are arbitrarily considered to be 10 percent of the original equipment costs, annually. Power costs are taken as $15 annually per receiver set* and $7.50 per converter unit.**

---

*Based on a 200-watt set operating 5 hours a day, 250 days a year at $0.03 per kilowatt-hour

**Based on 100 watts per unit, times 10 hr/day, 250 days/yr at $0.03 per kilowatt-hour

As an approximation then, the "start-up" reception costs for one receiver per classroom in every public elementary and secondary school in the U. S. would be:

Initial investment costs:	$525 ($10^6$)
Annual operating costs:	
Maintenance and repair	$ 52.6 (10^6)
Power (sets)	12.8
Power (converters)	.8
	$ 66.2 (10^6)

These projected figures are probably higher than would be actually experienced, but are presented to help provide conservative estimates of potential system effectiveness.

Distribution

Satellite costs used here are for purposes of estimation only, and can be refined to more accurately reflect total system costs when a specific system is under consideration.

To provide ETV for grades 1 through 12, at least six TV channels will be required (88 pp 22). Considering the time variations across the country and the projected 10^6 square mile illumination capability of the satellite antennas, at least three sets of telecasts would be needed. This could be accomplished by various satellite/antenna configurations, including three separate six-TV channel satellites, each dedicated to one-third of the country. This latter configuration will be considered here. Depending on the broadcast frequency and the receiver antenna gain, in-orbit costs of a six-channel satellite may range from $15 to $20 million. Thus, using the higher number, in-orbit costs for a system of three satellites would be $60 million, with an additional $20 million for a spare. Expected in-orbit life would be 5 years.

In a national, space-based ETV system, programs may originate from one location. As with the satellite, the cost of an earth transmission station will depend upon the operating characteristics of the earth-space system; additionally, the location and personnel accommodations will influence transmission station costs. For this analysis, earth station costs are assumed to be $\$10^7$. This figure may be high by a factor of two; however, as with the satellite costs, the high figure is used to provide a conservative estimate of the system effectiveness.

Costs and Benefits of a Hypothetical National Satellite-Based ETV System for Public Elementary and Secondary Schools

First, suppose that the Federal Government wished to implement national, space-based ETV in support of the public elementary and secondary school system. The establishment of a national program of education would not be a radical departure from current practice. The fact that students, today, may readily transfer from state to state, and that graduate record examinations to qualify for college entrance are given nationally, imply a de facto national standard curriculum. Suppose also that funding begins in FY 1970; three six-TV channel satellites are placed in synchronous orbit in 1972; and their expected operating lives are 5 years. The hypothetical current expenditures for this system are shown in Table 12-13.

Current total expenditures on public elementary and secondary schools represent a significant portion of the gross national product, and Federal expenditures for the same purposes represent a significant portion of the Federal budget. Further, a large portion of the Federal outlay for education is specifically directed toward improving the quality of education for disadvantaged children. Table 12-14 is a compilation of Federal funds for education and training programs in which ETV may be effectively used. Table 12-15 is a summary of public elementary and secondary education expenditures for 1967, 1968, and 1969, together with other pertinent national statistics.

From these tables it may be concluded that expenditures on public elementary and secondary education in general, and on special educational assistance programs for elementary and secondary students, will increase in dollar value while maintaining a fairly constant relationship with each other and with the gross national product.

It is difficult to define precisely the output of the school system. Over a one-year period, students attend classes and produce (or consume) a certain number of student-hours; tests are given nationally, and student achievement is measured by test scores. National and state median levels of education are measured in school years, and on a long-term basis, national productivity, mean individual income, and other parameters are

Table 13. Current Expenditures for a Hypothetical National Satellite-Based ETV System for Public Elementary and Secondary Schools ($$10^6$)

Expenditure Component	1970	1971	1972	1973	1974	1975	1976	Total
Investment								
Program procurement	10	10	10	10	10	10	10	70
Procurement and installation of receiving equipment (1/3 of 1968 total in three consecutive years)		175	175	175	50 [1)]	50 [1)]	50 [1)]	675
Procurement and installation of ground station equipment		10						10
Procurement and launch of three satellites plus allowance for procurement and launch of spare		40 [2)]	40					80
Total investment	10	235	225	185	60	60	60	835
Maintenance and repair [3)]		19	36	54	59	64	69	291
Operating Expenditures								
Receiver power		5	9	14	16	18	20	82
Ground station [4)]		1	1	1	1	1	1	6
Total costs	10	260	271	254	136	143	150	1224

1) Expenditures to accommodate the maximum projected enrollment growth shown in Table 2.
2) Progress payment.
3) Costs taken as 10 percent of cumulative earth-hardware expenditures
4) Arbitrary assumption of 100 persons plus miscellaneous.

Table 12-14. Some Federal Funds for Education and Training for Which ETV May Be Used

	Estimated Outlays 1967	1968	1969
Department, Agency and Program			
Office of Economic Opportunity			
Head start	295	310	345
Adult training, remedial education, etc.	85	99	108
Job Corps	268	286	275
Subtotal	648	695	728
Department of HEW			
Office of Education			
Elementary and secondary education of children from low income families and drop-out prevention	1,057	1,070	1,089
Aid to federally impacted schools (operations)	400	341	384
Teacher training			
Elementary	76	85	107
College	54	86	90
Expansion and improvement of vocational education	253	287	286
Education R & D	71	88	104
Public Health Service			
Health professions training	101	102	136
Subtotal	2,012	2,059	2,196
Department of Interior			
Indian education and related programs	112	114	153
Total	2,772	2,868	3,077
All Federal Education Outlays	9,218	10,753	11,570

(96, Table H.-3)

Table 12-15. Current U. S. Expenditures for Public Elementary and Secondary Education and other Funding Data ($$10^6$)

	Category		1967	1968	1969
(1)	Special current HEW and OEO funds from Table 14		2,772	2,868	3,077
(2)	All federal education outlays		9,218	10,753	11,570
(3)	Total U S. current education expenditures		22,623	25,361	28,000[1]
	(1) ÷ (2) x 100	(Percent)	30	27	27
	(1) ÷ (3) x 100	(Percent)	12	11	11
(4)	Federal budget outlays		158,414	175,635	186,062
(5)	Gross national product		785,000	871,000[2)]	945,000[1)]
	(1) ÷ (4) x 100	(Percent)	1.7	1.6	1.7
	(2) ÷ (4) x 100	(Percent)	5.8	6.1	6.2
	(3) ÷ (5) x 100	(Percent)	2.9	2.9	3.0

1) Author's estimate.
2) Federal Reserve, Third Quarter, seasonally adjusted to annual rate. (34 pp A-67)

associated with the output of the education system. Since student-hours are the most immediate and direct results of educational expenditures, they are used as a measure of output in this analysis.

Achievement tests, given nationally, are used to establish a national standard of development or achievement of elementary and secondary school students. This norm, together with the total number of student-hours, reflects the efficiency of the system (i. e., a certain number of student-hours per student, at a certain quality-level of instruction, produces a measured level of achievement). When the scores of the individual achievement tests and the associated student-hours per student are averaged over the sample population, the resulting statistics can be compared with those from other periods or other samples of interest to derive relative efficiencies of different teaching methods, or the effects of other variables on system performance.

The number of school days in a school year and school hours per day are set by the boards of education of the various states or school districts and remain virtually constant. The average number of days attended per enrolled pupil varies to some minor extent because of student absentee rates, but also may be considered virtually constant.

To estimate the benefits of national ETV for public elementary and secondary schools, it is necessary to project the number of student-hours and the comparative efficiencies of the system, with and without ETV. To project the number of student-hours in 1975, enrollments and their distribution in 1966 were tabulated and the distribution of student-hours by age group was estimated (Table 12-16). From the 1967 annual, average, per-student expenditure of $623 for elementary and secondary education (1968 Statistical Abstract) and the student-hours estimated in Table 12-16, an average per-student-hour cost of $0.81 was derived for 1967. Although annual, average, per student expenditures have continually increased, both in absolute and real* terms during this century, the $0.81 figure will be assumed constant over the period under analysis. This assumption will undoubtedly result in considerable understatement of per-student-hour and overall costs of elementary and secondary education; however, as may be seen from the subsequent analysis, such understatement will tend to make the benefits estimates even more conservative. This is not to say that future annual expenditure figures cannot be more accurately projected, but that the scope of this study does not permit detailed, refined projections of this parameter.

*"Real" is used in the economics sense and is defined as the absolute dollar value deflated by a price index.

Table 12-16. Estimates of Annual Student-Hours in Public and Private Elementary and Secondary Schools

Age (years)	Enrollments[1] (000)	Percent of Total	Average[2] Student-Hours/Day	Annual[3] Student-Hours (000)	Average Annual Student Hours per Student
5	3,087	6.4	2.5	1,273,387	412.5
6	4,069	8.4	3.3	2,215,571	544.5
7 to 9	12,283	25.4	4.3	8,714,789	709.5
10 to 13	15,612	32.3	4.7	12,107,106	775.5
14 to 17	13,293	27.5	5.3	11,624,729	874.5
Total	48,344	100.0		35,935,582	743.3
6 to 17	45,257			34,662,195	765.9

[1] 1966 enrollment figures

[2] Author's estimate

[3] Assuming average of 165 days attendance

Source: 2, pp. 112

The apparent gains in student performance shown in Tables 6 and 7 ranged from 12 percent to 117 percent. It is not clear at what point in the project the data in Table 12-6 were developed. However, we assume that both the comparisons were made after three years of operation, and, in the analysis, we assume that no gains will be made prior to completion of three years of operation. Two levels of potential performance increase were examined: the 31 percent overall increase in achievement growth indicated in Table 12-6 and the 12 percent "efficiency" growth exhibited by grade 6 in Table 12-7. In the third year of hypothetical operation, these changes in system performance are assumed to take place in one jump. Since the national norm is based on average student performance throughout the country, the projected higher test performance is then the national norm. No further growth in performance due to ETV is projected. System performance in the third year and afterward is considered to be a constant 12 percent or 31 percent better than second year and previous performance.

The educational or social effects of an increase in achievement growth are many and complex. In his educational career, a slow learner may lag further and further behind his original peer group, until he becomes overwhelmed by the gap and drops out; or, if he stays through the twelfth grade, he may graduate with skills far below the twelfth grade level. For example, if the conventionally taught lower ability group of Table 6 maintained the same growth rate through all 12 grades, its final achievement scores would be closer to the sixth grade level than to the twelfth grade level. Raising the achievement rate to 12 months instead of 6 would effectively add 6 school-years to the group's 12-year career or, viewed another way, would eliminate 6 ineffective school years. In addition, reduction of the drop-out rate and the attendant decreased probability of delinquency and criminality and increased probability of employment and higher earnings, from which tax revenues would derive, are some other potential benefits which might be obtained if achievement growth is stimulated by new teaching methods.

The only quantitative benefits to public elementary and secondary schools treated in this study are the effective student-hours added by increasing achievement growth rates, and the imputed monetary value of these added student-hours.

Since the "standard" number and quality of student-hours produces a "standard" advance in grade level achievement (as defined by the nationally derived norm), an increase in grade-level achievement can be equated to a comparable increase in "standard" student-hours at the "standard" quality of teaching. That is, if a student advances 1-1/2 grade levels in an ETV system when he would have advanced only one grade level in the "standard" system, the extra half-year of achievement was gained at a saving of one-half year of school hours. Using this rationale, and the previously assumed per student-hour cost of $0.81, the effective student-hour increase and imputed monetary benefits were projected from the third year of operation of the hypothetical ETV system. These figures and their present values, calculated at 4 and 6 percent discount rates, starting at the initiation of the ETV project and continuing through 15 years, are compiled in Table 12-17. For comparison, the estimated costs and present values of initiating and operating the hypothetical ETV satellite system are shown in the same table. The 4 and 6 percent discount rates used in these calculations were chosen to reflect the probable cost to the U.S. government of money. Generally, Federal outlays are treated as current expenditures, whether they are for long-life capital equipment or for goods and services consumed in the current year. However, since the government's public debt is serviced at some composite rate of interest (approximately 4.2 percent in FY 1969, 96 pp 10 and 54) the selected discount rates may be used to evaluate the long-term effects of the outlays and imputed benefits to be derived from the hypothetical project.

Comparison of the costs and benefits of Table 12-17 shows that after the hypothetical ETV project has been in operation three years, the cumulative benefits far exceed the cumulative costs, both in absolute terms and in discounted present value terms. The average annual discounted expenditures are $177 million through 1976, and $227 million through 1984. (Compare these expenditures with the 1969 Federal expenditures of $345 million for the Head Start Project alone, which serves only 731,000 children.) (96 pp 105). These cost-benefit comparisons are

Table 12-17. Comparison of Undiscounted and Discounted Costs and Benefits of a Hypothetical National Satellite ETV Project

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
Costs ($ million)															
Program production	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Receiver installation		175	175	175	50	50	50	50	50	50	50	225	225	225	100
Ground station		10										10			
Satellites in orbit and spares		40	40				40	40				40	40		
Maintenance and repair		19	31	49	59	64	69	74	79	84	89	94	99	104	109
Operating expense. Power		5	9	14	16	18	20	22	24	26	28	30	32	34	36
Ground Station		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Total outlays	10	260	271	254	136	143	190	197	164	171	178	410	407	374	256
Cumulative	10	270	541	795	931	1,074	1,264	1,461	1,625	1,796	1,974	2,384	2,791	3,165	3,421
• Present value of future outlays:															
i = 4%	9.6	240 5	240 9	217.2	111 8	113.0	144 4	144.0	115 3	115.6	115 7	256.3	244 6	215.8	142.1
Cumulative	9.6	250.1	491.0	708 2	820 0	933 0	1,077.4	1,221.4	1,336.7	1,452.3	1,568.0	1,824.3	2,068 9	2,284 7	2,426.8
i - 6%	9.4	231.4	227 6	201.2	101 6	100 8	126.4	123.5	97 1	95.4	93 8	203.8	190 9	163.3	106 8
Cumulative	9.4	240.8	468.4	669.6	771.2	872 0	998.4	1,121 9	1,219.0	1,314 4	1,408.2	1,612.0	1,802 9	1,966.2	2,073.0
Benefits															
Effective increase in student hours[1] (million)															
• @12% improvement						2,842	4,263	4,263	4,263	4,263	4,263	4,263	4,263	4,263	4,263
• @31% improvement						7,342	11,014	11,014	11,014	11,014	11,014	11,014	11,014	11,014	11,014
Imputed Monetary Benefits[2] ($ million)															
• @12% improvement						2,302	3,453	3,453	3,453	3,453	3,453	3,453	3,453	3,453	3,453
Cumulative						2,302	5,755	9,208	12,661	16,114	19,567	23,020	26,473	29,926	33,379
• 1970 present value															
i = 4%						1,818	2,624	2,524	2,427	2,334	2,245	2,158	2,075	1,993	1,916
Cumulative						1,818	4,442	6,966	9,393	11,727	13,972	16,130	18,205	20,198	22,114
i = 6%						1,623	2,296	2,165	2,044	1,927	1,820	1,716	1,619	1,526	1,440
Cumulative						1,623	3,919	6,084	8,128	10,055	11,875	13,591	15,210	16,736	18,176
• @ 31% improvement						5,947	8,921	8,921	8,921	8,921	8,921	8,921	8,921	8,921	8,921
Cumulative						5,947	14,868	23,789	32,710	41,631	50,552	59,473	68,394	77,315	86,236
• 1970 present value:															
i = 4%						4,698	6,780	6,521	6,271	6,031	5,799	5,576	5,361	5,147	4,951
Cumulative						4,698	11,478	17,999	24,270	30,301	36,100	41,676	47,037	52,184	57,135
i = 6%						4,193	5,932	5,593	5,281	4,978	4,701	4,434	4,184	3,943	3,720
Cumulative						4,193	10,125	15,718	20,999	25,977	30,678	35,112	39,296	43,239	46,959

1) Based on 35,528 (10^6) student hours in 1975
2) Computed at $0.81 per student hour

considered to be very conservative since high estimates were used in projecting future benefits.*

In a private enterprise, the desirability of different investment opportunities may be ranked by comparing the differences between the present values of the flow of investment outlays and expected revenues over the life of the individual project, for each investment opportunity, discounted at an interest rate identified by the firm's managers as its cost of capital.** Only those opportunities having net present values greater than zero are considered in the rankings. The net present value concept may be applied to government projects, but cautiously. Most government investment is for projects businessmen would deem unprofitable, but which are socially worthwhile. The benefits to be gained from government-sponsored projects are difficult to quantify. As Dorfman has aptly stated:

> "The practioners (of cost-benefit analyses) were very skeptical and inclined to doubt whether the most important social effects of government investments could ever be appraised quantitatively by cost-benefit analysis or any other formalized method. One of them likened the problem to appraising the quality of a horse-and-rabbit stew, the rabbit being cast as the consequences that can be measured and evaluated numerically, and the horse as the amalgam of external effects, social, emotional, and psychological impacts, and historical and aesthetic considerations that can be adjudged only roughly and subjectively. Since the horse was bound to dominate the flavor of the stew, meticulous evaluation of the rabbit would hardly seem worthwhile." (66 pp 2).

It may be impossible to rank the comparative benefits or net present values of a national educational television project with urban redevelopment, air traffic control, national scientific research, national defense, and other Federally funded projects. The basic premise of this analysis

---

*Note that cost figures for 1981 through 1984 include $665 million for replacement of equipment which would then have operating life past the period of analysis.

**The cost of capital may be interpreted in many ways; it is seldom the simple cost of borrowing money. For a detailed discussion of the cost of capital concept, see 5 Part II and III; 59, Chapter 8; and 40, Chapter 2.

is that large quantities of Federal, state, and municipal funds have been, and continue to be, allocated to education, specifically for the purpose of improving the quality and quantity of education offered to the citizenry. This study is thus concerned with the efficient application of those funds.

Following the net present value concept, the data in Table 12-17 were examined to determine the net benefits which might be obtained if a satellite-based national ETV project were implemented for public elementary and secondary schools. Also, calculations were made to determine what level of improvement of the education system would provide a net present value of zero if the hypothetical ETV project were instituted. The results of these calculations are shown in Table 12-18.

Depending upon the discount rate used and the assumed level of improvement of the education system, net present values of the fully operational system range from $2.9 billion in 1976 to $55 billion in 1984. That is, if the project is terminated in the year indicated in the table, the cumulative net present value is the figure shown in the appropriate column and row. Even if the project is terminated in 1975, after all of the initial costs have been incurred but the system is only two thirds operational, the minimum net present value is $769 million, with no consideration of the scrap value of 1.7 million, 3-year old 23-inch color television sets and other valuable equipment and programming.

If the added efficiency of television teaching is viewed pessimistically, and 12 or 31 percent improvement appears to be too much to expect, procurement of programming, satellites, and receiving equipment for the project can be rationally approved if only a 3 percent improvement in efficiency is gained in the one year (1976 in our hypothesis) in which the system has been fully operational for three years; the project may be terminated at that point with a net present value of zero. For longer project durations, the efficiency required for a zero net present value reduces to 1.3 or 1.4 percent by 1984.

In addition to the educational benefits imputed for national elementary and secondary school ETV, the same facilities and equipment may be used for adult education programs, and elementary and secondary teacher training, which were included in the 1969 Federal budget at $108 million and $107 million, respectively (96 pp 110).

Table 12-18. 1970 Present Values and Net Present Values of a Hypothetical Satellite-Based ETV System at Various Educational Improvement Levels and Discount Rates ($ million)

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
Present values of system costs										
at i = 4% cumulative	933.0	1,077.4	1,221.4	1,336.7	1,452.3	1,568.0	1,824.3	2,068.9	2,284.7	2,426.8
at i = 6% cumulative	872.0	998.4	1,121.9	1,219.0	1,314.4	1,408.2	1,612.0	1,802.9	1,966.2	2,073.0
Imputed benefits at 12% improvement										
i = 4% cumulative	1,818.0	4,442.0	6,966.0	9,393.0	11,727.0	13,972.0	16,130.0	18,205.0	20,198.0	22,114.0
i = 6% cumulative	1,623.0	3,919.0	6,084.0	8,128.0	10,055.0	11,875.0	13,591.0	15,210.0	16,736.0	18,176.0
Imputed benefits at 31% improvement										
i = 4% cumulative	4,698.0	11,478.0	17,999.0	24,270.0	30,301.0	36,100.0	41,676.0	47,037.0	52,184.0	57,135.0
i = 6% cumulative	4,193.0	10,125.0	15,718.0	20,999.0	25,977.0	30,678.0	35,112.0	39,296.0	43,239.0	46,959.0
Net present values at 12% improvement										
i = 4% cumulative	885.0	3,364.6	5,744.6	8,056.3	10,274.7	12,404.0	14,305.7	16,136.1	17,913.3	19,687.2
i = 6% cumulative	751.0	2,920.6	4,962.1	6,909.0	8,740.6	10,466.8	11,979.0	13,407.1	14,769.8	16,103.0
Net present values at 31% improvement										
i = 4% cumulative	3,765.0	10,400.6	16,777.6	22,933.3	28,848.7	34,532.0	39,851.7	44,968.1	49,899.3	54,708.2
i = 6% cumulative	3,321.0	9,126.6	14,596.1	19,780.0	24,662.6	29,269.8	33,500.0	37,493.1	41,272.8	44,886.0
Percent improvement* required for net present value = 0										
i = 4%	6.19	2.91	2.10	1.71	1.49	1.35	1.36	1.37	1.36	1.32
i = 6%	6.34	3.04	2.20	1.79	1.56	1.42	1.42	1.42	1.41	1.36

*In 1975 only two-thirds of the system is considered to have accrued imputed benefits

Detailed estimation of potential indirect effects on the national economy or other government programs were considered far beyond the scope of this study. However, the following statistics on the California Criminal Justice System indicate another area in which improved elementary and secondary education may increase government revenues, reduce government expenditures, or have measurable effects on the social welfare of the nation.

Effects on Crime and Losses Due to Criminal Activity

There has been considerable recent concern about increases in crime and maintenance of law and order. In 1965, the total economic cost of crime was estimated to be $20,980 million, of which $4,212 million were for enforcement and justice (96 pp 155). During the same period, a total of 5,031,393 arrests were made, of which 2,124,100 or 42 percent involved persons 24 years old or younger (96 pp 154). In a study of the California system of justice (70) it was shown that in California the crime rate was increasing only in the younger age groups. For the older age groups, the crime rate was actually decreasing. A summary of these data is shown in Table 12-19.

In the California study, the age group from 14 to 29 years was considered to be the "crime susceptible" group and it was projected that the population in this age group is increasing at almost twice the rate of increase of the population in the 1960-1975 period (71 pp 8). The concept of "career costs," defined as "the operating cost of the complete (criminal justice) system required for dealing with an average offender and accrued over the lifetime of the offender," was introduced. Results of career cost calculations for various categories are shown in Table 12-20.

The educational achievement levels of institutionalized California adults are shown in Table 12-21.

These California data are not necessarily directly applicable to all of the 50 states. However, they do serve to indicate the order of magnitude of law enforcement and justice system savings which could be achieved if the crime rate could be reduced, and that some relationship between educational achievement level and criminal convictions exists. It would be specious to assume that if all adults achieved a grade 12 achievement level the prison population would be reduced by 90 percent.

Table 12-19. 1960-1964 Average Trends

Item	Age Group	Average Annual Rate per 100 Age Group Population	Average Annual Rate Change*	Percent Change of Annual Rate
Reported felonies				
Seven major offense groups	10 to 64	2.45	+0.099	+4.04
Violent crimes only	14 to 29	1.15	-0.006	-0.52
Juvenile arrests				
All delinquency.	10 to 17	9.12	+0.298	+3 27
Major law violations only	14 to 17	3.39	+0.019	+0.56
Violent crimes only	14 to 17	0.372	+0.006	+1.61
Adult felony arrests				
All	18 to 64	1.071	-0 036	-3.36
Violent crimes only	18 to 29	0.959	-0 035	-3.65
Commitments to institutions				
Juvenile Court commitments to CYA	10 to 17	0.163	-0.001	-0.61
Adult commitments to CDC	18 to 64	0.061	-0.005	-8.20
Supervised population**				
Based on 10 to 64 population	10 to 64	1.53	+0.028	+1 83
Based on 14 to 29 population	14 to 29	4 95	-0.052	-1 50

*Computed by linear least-square curve fit

**1961-1964 only. Includes parole, probation, and institution caseloads

Table 12-20. Per Capita Career Costs

Offense	Per Capita Costs of Institutionalized Persons ($)		Per Capita System Costs ($)	
	Cost of New Arrival from Court	Career Cost of First Arrival	Cost per Arrestee	Career Cost of New Offender
All adult felons	6,500	8,300	3,600	4,000
All juveniles	6,000	9,000	680	800
Adult homicide	12,000	12,300	6,300	5,800
Adult robbery	12,000	15,800	3,700	3,700
Adult assault	9,400	12,300	2,000	2,700
Adult burglary and theft	9,100	11,900	3,000	3,800
Adult forgery and checks	6,900	10,900	5,300	16,900
Adult narcotics	10,200	17,100	4,500	10,900

Table 12-21. Percent of Institutionalized Adult California Criminals by Crime Category and Educational Achievement Levels*

Crime Category	Educational Achievement				Total Percent
	Illiterate	Grade 3 to 8	Grade 9 to 11	Grade 12 and More	
Homicide	4	64	30	2	100
Robbery	1	57	39	3	100
Assault	5	62	32	1	100
Burglary	2	59	36	3	100
Theft	3	50	44	3	100
Automobile theft	3	61	35	1	100
Forgery	1	45	50	4	100
Rape	3	60	36	1	100
Narcotics	3	66	29	2	100
Lewd and other sex	3	55	39	3	100

*1963 data

Source: 71, page 213

Yet one could infer that by reducing the number of school drop-outs, fewer juveniles would become "career cost" statistics and the national total economic costs of crime might be significantly reduced. It should be noted that a reduction of 1.5 percent in annual total economic costs of crime would more than meet the annual average cost of the hypothetical ETV project.

In sum, implementation of a satellite-based national ETV project for public elementary and secondary education appears to be highly desirable on a monetary basis. System costs are far exceeded by system benefits at the assumed levels of improvement, and even at very low levels of improvement the hypothetical system exhibits a positive net present value. Further benefits such as reducing the economic costs of crime and producing more wage earners and fewer welfare recipents may be obtained, however, no analysis of these potential benefits was made.

A list of other potential benefits arising from increased educational achievement levels includes:

- Reducation of welfare expenditures
- Increase in tax revenues due to more productive employment
- Increased national productivity and output
- Improvements in trade balances
- Improvements in balance of payments
- Increased consumer demand
- Increased worker mobility
- Decrease in economic cost of crime.

SOME POTENTIAL BENEFITS OF SATELLITE ETV IN DEVELOPING COUNTRIES

In developing nations there is a great drive to increase individual and national social welfare. The economic development plans of these countries generally call for large infusions of capital in the industrial and agricultural sectors, and as much investment in infrastructure development and health and education projects as can be afforded. Most of these funds are derived from the domestic economies and are limited by the gross domestic products and the degree of austerity that can be practiced to divert funds from consumption to private or government investment. The developed countries provide economic assistance, either through international organizations or on individual bases; but even with the investment of domestic and foreign funds, the income gap between poor and rich countries tends to grow with time.

In Appendix 12B, a theoretical model linking growth in national output to improvement in education is discussed. The model is neither detailed nor comprehensive; it is presented to show formally what is felt intuitively: that expenditures on improving or expanding the education systems of developing nations are important factors in economic growth. Expansion of the student body and improvement of educational quality or efficiency are the keys to increased productivity.

To investigate the need for improvement of education systems, economic and education statistics of 97 countries were examined (Table 12-22. The selection of countries was dictated by the availability of reliable statistical data, which is less than desired, and certainly less than is needed for a comprehensive comparative analysis of developed and developing countries. However, the magnitude of the discrepancy between education expenditures and characteristics of developed and developing countries can be observed, and some potential effects of reducing these discrepancies can be estimated.

To delineate between developed and developing countries, it was arbitrarily assumed that countries with annual per capita gross domestic products greater than $750 may be categorized as developed; all others are considered to be developing. In Table 12-22, the first 26 countries (ranked in descending order of per capita GDP) are in the developed category.

Although social, economic, and political differences among the developed countries prohibit direct comparison of their education systems, it may be accepted that each of these nations attempts to maintain an education system compatible with its need for educated citizens and its ability and desire to pay for all socially beneficial institutions and projects. To the degree that education may be associated with economic parameters, the characteristics of education systems in developed countries should serve as models for developing countries to emulate. That is, if developed countries typically maintain certain student-teacher ratios or typically expend a certain fraction of their gross domestic products on education, developing countries seeking to establish industrial, agricultural and social conditions comparable and competitive with the developed countries must also establish comparable education systems.

From the data in Table 12-22, "typical" statistics for developed and developing countries were calculated. The results of these calculations are shown in Table 12-23.

From the data in Table 12-23, it may be concluded that, compared to developed countries, developing countries typically are not educating a sufficient percentage of their populations, and even with this smaller

Table 12-22. Economic and Educational Statistics for 97 Countries

	Country	Gross Domestic Product per Capita $	Annual per Student Expenditures $	Student/ Population	Students/ Teachers	Education Budget/GDP
1.	Kuwait	4,289	334.91	0.186	18.3	0.015
2.	U.S.A.	3,509	506.78	0.286	23.5	0.041
3.	Sweden	2,517	513.39	0.183	19.7	0.037
4.	Canada	2,459	395.80	0.272	22.2	0.044
5.	Denmark	2,120	431.00	0.184	NA*	0.037
6.	Switzerland	2,119	437.13	0.150	NA	0.031
7.	Australia	2,014	122.87	0.236	25.5	0.014
8.	Luxembourg	1,954	338.70	0.168	24.7	0.029
9.	France	1,920	180.00	0.227	24.1	0.021
10.	Norway	1,896	494.96	0.188	15.0	0.049
11.	Germany (W)	1,891	234.40	0.180	33.5	0.022
12.	New Zealand	1,844	174.78	0.260	26.5	0.012
13.	United Kingdom	1,797	303.24	0.176	23.0	0.030
14.	Finland	1,759	310.15	0.201	18.7	0.036
15.	Belgium	1,636	200.90	0.240	17.1	0.029
16.	Iceland	1,633	NA	0.211	32.6	NA
17.	Netherlands	1,521	81.96	0.255	34.8	0.014
18.	Israel	1,393	113.64	0.266	16.9	0.022
19.	Austria	1,285	161.24	0.159	18.6	0.020
20.	Puerto Rico	1,179	191.39	0.276	31.8	0.045
21.	Italy	1,089	266.15	0.177	17.7	0.043
22.	Venezuela	939	112.46	0.206	28.8	0.025
23.	U.S.S.R.	921	202.91	0.245	22.7	0.054
24.	Ireland	886	139.77	0.235	24.8	0.037
25.	Japan	856	102.74	0.234	23.4	0.028
26.	Argentina	759	125.91	0.191	14.9	0.032
27.	Libya	713	NA	0.124	25.3	NA
28.	Cyprus	653	82.34	0.176	29.6	0.023
29.	Trinidad-Tobago	645	56.20	0.243	33.0	0.021
30.	Uruguay	611	50.89	0.183	34.0	0.015
31.	Greece	597	NA	0.174	42.4	NA
32.	Chile	591	65.14	0.225	43.7	0.025
33.	Netherlands Antilles	589	15.35	0.295	32.6	0.008
34.	Spain	556	15.61	0.164	38.7	0.005
35.	Jamaica	498	43.91	0.203	49.7	0.018
36.	Panama	453	53.98	0.201	27.3	0.024
37.	Mexico	446	29.46	0.188	45.8	0.012
38.	Gabon	440	NA	0.184	35.3	0.003
39.	Malta	435	70.48	0.228	20.4	0.037
40.	South Africa	408	NA	0.151	36.8	NA
41.	Costa Rica	408	NA	0.234	26.2	NA
42.	Barbados	392	NA	0.225	30.5	NA
43	Portugal	360	29.29	0.134	27.2	0.011
44.	Lebanon	331	37.48	0.187	21.2	0.021
45.	Guyana	323	34.29	0.274	32.0	0.043
46.	Guatemala	312	NA	0.109	25.0	NA
47.	Nicaragua	308	34.61	0.143	30.1	0.016
48.	Malaysia	303	19.97	0.192	26.6	0.013
49.	Peru	301	NA	0.191	30.0	NA

*Not Available

Source Reference

Table 12-22. Economic and Educational Statistics for 97 Countries (Continued)

	Country	Gross Domestic Product per Capita $	Annual per Student Expenditures $	Student/ Population	Students/ Teachers	Education Budget/GDP
50.	Iraq	293	63.30	0.151	24.0	0.032
51.	El Salvador	265	34.28	0.156	29.7	0.020
52.	Turkey	257	NA	0.139	39.3	NA
53.	Ivory Coast	254	NA	0.090	41.7	NA
54.	Iran	250	NA	0.120	NA	NA
55.	Mauritius	246	29.21	0.234	29.9	0.028
56.	Dominican Republic	244	25.78	0.182	NA	0.019
57.	Rhodesia	241	NA	0.147	37.7	NA
58.	Ghana	236	8.25	0.190	30.6	0.007
59.	Colombia	234	29.77	0.242	26.7	0.019
60.	Zambia	233	17.05	0.111	47.0	0.008
61.	Surinam	229	16.77	0.316	30.7	0.023
62.	Jordan	228	27.97	0.202	32.6	0.025
63.	China (T)	221	19.33	0.241	33.1	0.021
64.	Honduras	221	NA	0.133	31.5	NA
65.	Tunisia	217	48.38	0.169	58.4	0.038
66.	Ecuador	215	28.00	0.178	28.8	0.023
67.	Paraguay	211	14.89	0.192	32.2	0.014
68.	Algeria	193	3.42	0.124	49.0	0.002
69.	Morocco	190	63.76	0.096	36.4	0.032
70.	Senegal	189	59.20	0.070	40.0	0.022
71.	U.A.R.	179	49.38	0.154	33.7	0.043
72.	Brazil	167	NA	0.147	27.8	NA
73.	Philippines	165	21.26	0.212	31.9	0.027
74.	Sierra Leone	152	20.23	0.058	28.9	0.007
75.	Bolivia	146	NA	0.178	27.4	NA
76.	Viet-Nam (S)	143	20.23	0.127	51.8	0.018
77.	Ceylon	142	24.31	0.230	27.4	0.039
78.	Cameroon	135	16.50	0.145	45.7	0.018
79.	Thailand	125	15.90	0.147	29.8	0.019
80.	Cambodia	124	33.09	0.141	44.4	0.038
81.	Malagasy Republic	109	NA	0.121	60.3	NA
82.	Cent. African Rep.	108	31.56	0.095	50.7	0.028
83.	Togo	105	21.52	0.102	47.1	0.021
84.	Kenya	105	29.52	0.111	31.8	0.031
85.	Korea (S)	101	7.70	0.217	51.7	0.017
86.	India	101	6.88	0.127	32.6	0.009
87.	Pakistan	99	9.65	0.094	34.7	0.009
88.	Sudan	98	62.04	0.043	35.9	0.027
89.	Uganda	81	NA	0.078	33.8	NA
90.	Nigeria	76	21.76	0.054	31.1	0.016
91.	Haiti	74	13.12	0.069	39.4	0.012
92.	Dahomey	73	36.52	0.059	39.5	0.030
93.	Burma	64	39.75	0.095	39.8	0.020
94.	Ethiopia	61	27.67	0.019	37 9	0.009
95.	Lesotho	61	10.26	0.199	56.9	0.034
96.	Tanzania	58	NA	0.062	48.9	NA
97.	Malawi	44	25.77	0.073	31.2	0.043

*Not Available

Source Reference

Table 12-23. Typical Education and Economic Statistics of 97 Developed and Developing Countries*

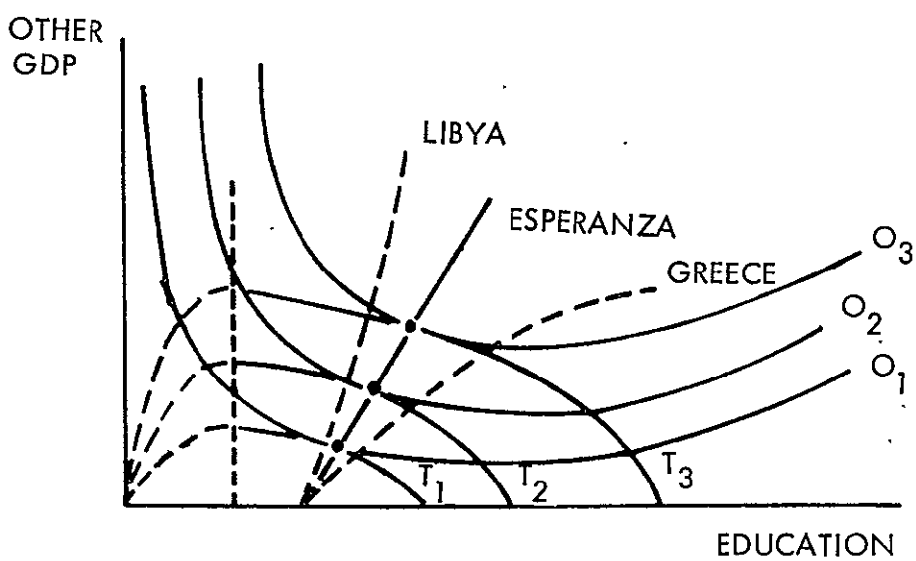
	26 Developed Countries	71 Developing Countries	Total Sample
Typical annual education budget per student	$259	$32	$104
Typical student/population ratio	0.215	0.156	0.172
Typical student/teacher ratio	23	36	32
Typical education budget/GDP ratio	0.031	0.021	0.027

*These data are statistical means of the country data in Table 12-22. Because of variations among the countries in population, gross domestic product, etc., the term "typical" is used to preclude unwarranted statistical inferences.

proportion of students, too few teachers are available and per student budgets are an order of magnitude too low. The comparatively low education budget-to-gross domestic product ratio of developing countries undoubtedly reflects the severe competition among industrial, agricultural, infrastructure and social welfare projects for limited financial resources.

If unlimited funds were available, it would be possible for developing countries to duplicate, or even improve upon the education systems of developed countries; that is, teachers, educational software and school facilities can be purchased, either indigenously or extranationally. However, with severely constrained funds, financial and education planners must carefully consider each new allocation for both short- and long-term effects.

Higgins (47, Chapter 19) has presented some of the problems in optimal expansion of education systems in developing countries. Considering the opportunity costs of allocating labor (including students who might be in the labor force if they were not students) and capital to education or other activities which contribute to the gross domestic product, different countries may, ideally, allocate these factors in different proportions, depending upon the existing qualities of their education systems and the availability of opportunities for expanding national output by conversion of natural resources or utilization of special national capabilities. Thus, given increasing levels of national output, an "expansion path" for a particular country's education system may be derived. The figure below graphically illustrates this concept.



In the sketch, O_1, O_2, and O_3 are national indifference curves: loci of combinations of education system output and other national output which provide equal social welfare at a given level of gross domestic product. T_1, T_2, and T_3 are transformation curves: loci of combinations of resource inputs to the education system or to other GDP producing activities which can be made at a given budget level. The dotted portions of the transformation curves may be ignored since

> "...it would be senseless to stop expansion of the education industry before reaching the point where output of 'everything else' declines as a result.
>
> In most developing countries the income elasticity of demand for education is presumably above unity; in any case, countries do in fact tend to spend a larger share of income on education as income rises. On the other hand the opportunity costs of education, in terms of other income, probably rise once a certain level of education has been reached. (More empirical

> research could usefully be done on this question.) The expansion path will be the outcome of these two opposing tendencies. For any particular country as we move from now into the future, moving through time as we proceed along the path, the shape of the expansion path will also depend on the initial position regarding level of per capita income and education. On resource-rich and education-poor countries like Libya the expansion path may be concave upward; it may simply be impossible to expand the education industry as fast as income rises—at least without more technical assistance than is politically acceptable. In education-rich but resource-poor countries like Greece it may be concave downward, while in a 'normal' developing country like the mythical Esperanza (and probably only mythical developing countries are normal) the path may approximate a straight line." (47, pp 443 and 444)

A satellite-based ETV project in a developing country or region must be considered as part of the overall education system. Not only must the country be financially and administratively capable of implementing the space and terrestrial portions of the ETV communication system, but it must also be able to provide the proper environment and peripheral equipment required to permit effective use of ETV. In American Samoa, it was found that grass huts previously used as school buildings were inadequate as ETV classrooms. Therefore, along with the expense of installing transmitters and receivers, and producing programming, it was necessary to provide for modern classrooms, complete with blackboards, desks, proper lighting, and so on (35). Even in areas of cheapest labor, the costs of a modern schoolroom will undoubtedly exceed by far the cost of a television receiver and antenna. If textbooks, work books, and similar software are required to support ETV programs, these items too may have aggregate costs which equal or exceed the reception, transmission and program production costs. Thus, cost analyses which deal only with specific ETV hardware and program production do not provide adequate information for planning the expansion of a developing country's educational system. Granted the efficacy of ETV as a teaching tool, how large an ETV system can a country afford in a given period? Despite the technical feasibility of complete coverage of a nation or region by satellite ETV transmission, can this ubiquitous signal be effectively used? These questions can only be answered by thorough analyses, on a country-by-country or region-by-region basis.

Since the satellite system under study will have a 10^6 square mile coverage capability, selected countries and regions of the world were appraised for their potential as audiences for satellite, direct-TV broadcasting. The main purpose of this appraisal was to identify those countries or regions where, in view of areal dimensions, population densities, linguistic characteristics, and ethnic homogeneities, satellite broadcasting is a potential alternative to terrestrial approaches. The countries of Europe, the Soviet bloc, and the Peoples Republic of China were not included.

Table 12-24 is a list of candidate countries outside of North America, identified by region, including statistics on their areas, income, and population. The regional groupings are based on general similarities in ethnology such as racial stock, common languages, religious and social practices, and, of course, geographic location. Except where a state of war exists between interregional countries, it is assumed that, despite problems of differing political policies and nationalism within a region, international cooperation, at least of the quality existing in current United Nations organizations, particularly UNESCO, may be obtained for educational programming (and possibly also for entertainment programming).

In North Africa and the Middle East, a common thread of Arabic language and customs links all of the countries of that region, except Niger and Mali, which use French as their official language. In Central Africa, the ex-colonial black nations use French or English as first or second official languages. With the exception of Portuguese-speaking Brazil, Spanish is virtually the universal language of Central and South America.

The Asian countries have almost no useful common linguistic ties. Though English is increasingly used in commerce, literacy in the national language is a prime goal of the various Asian educational systems which, when combined with other ethnographic differences, would tend to make common TV programming impractical or impossible.

Without discussing the characteristics of the countries in each region in further detail, the following selections appear to be likely candidate audiences:

Table 12-24. Statistical Data on Selected Countries Outside of North America

	Population[1] (000)	Area (km^2)	Area (mi^2, U.S.)	Population Density per Square Mile	Per Capita[2] Gross Domestic Product ($)	Number of Students (10^6)	Per Student[3] Budget ($)	Official Languages
1. Africa and the Middle East								
North								
• Western								
Algeria	12,150	2,381,741	919,500	13.21	228	1.511	3.42	Arabic, French
Chad	1,437	1,284,000	495,752	6.77	75[4]	-	-	French, Arabic
Libya	1,677	1,759,540	679,358	2.47	713	0.208	-	Arabic, English
Mali	4,654	1,240,000	478,764	9.72	70[4]	-	-	French
Mauretania	1,070	1,030,700	397,953	2.69	138[4]	0.208	-	French, Arabic
Morocco	13,725	445,050	171,833	79.87	190	1.318	63.76	Arabic, French
Niger	3,433	1,267,000	489,189	6.95	75	0.065	55.29	French, Hausa
Spanish Sahara	48	266,000	102,703	0.47	-	-	-	Arabic, Spanish, French
Tunisia	4,460	164,150	63,378	70.37	217	0.752	48.38	Arabic, French
Total	42,654	9,838,181	3,798,520	Mean density: 11.23		4.062		
• Eastern								
Iraq	8,338	434,724	167,847	49.68	293	1.262	63.30	Arabic
Jordan	2,059	97,740	37,737	54.56	228	0.415	27.97	Arabic
Kuwait	491	16,000	6,178	79.48	4,289	0.091	334.91	Arabic, English
Muscat and Oman	565	212,379	82,000	6.89	-	-	-	Arabic, Hindi
Saudi Arabia	6,870	2,149,690	829,995	8.28	380[4]	-	-	Arabic
Sudan	13,940	2,505,813	967,494	14.41	98	0.602	62.04	Arabic, English
Syria	5,400	185,180	71,498	75.53	200	0.942	-	Arabic
United Arab Republic	30,145	1,001,449	386,659	77.97	179[4]	4.647	49.38	Arabic
Yemen	5,000	195,000	75,290	66.41	125[4]	-	-	Arabic
Total	72,810	6,797,975	2,624,698	Mean density: 27.74		7.959		
South of Sahara								
• Western								
Cameroon	5,350	475,442	183,568	29.14	135	0.776	16.50	French, English
Dahomey	2,410	112,622	43,483	55.42	73	0.143	36.52	French
Gabon	468	267,667	103,346	4.53	440	0.086	-	French
Ghana	7,945	238,537	92,099	86.26	236	1,507	8 25	English, Twi
Guinea	3,608	245,857	94,925	38.01	80[4]	-	-	French, English
Ivory Coast	3,920	322.463	124,503	31.49	253	0.354	-	French, Agni
Liberia	1,090	111,369	43,000	25.35	207[4]	0.124	-	English
Nigeria	58,600	923,768	356,667	164.30	125[4]	3.172	21.76	English, Hausa
Portuguese Guinea	529	36,125	13,948	37.93	-	-	-	Portuguese
Senegal	3,580	196,192	75,750	47.26	189	0.252	59.20	French, Wolof
Sierra Leone	2,403	71,740	27,699	86.75	152	0.140	20 23	English

Table 12-24. Statistical Data on Selected Countries Outside of North America (Continued)

	Population[1] (000)	Area (km^2)	Area (mi^2, U.S.)	Population Density per Square Mile	Per Capita[2] Gross Domestic Product ($)	Number of Students (10^6)	Per Student[3] Budget ($)	Official Languages
1. Africa and the Middle East (Continued)								
South of Sahara (Continued)								
• Western (Continued)								
Spanish Guinea	272	28,051	10,830	25.12	-	-	-	Spanish
Tago	1,680	56,000	21,622	77.70	105[4]	0.172	21.52	French
Upper Volta	4,955	274,200	105,868	46.80	55[4]	-	-	French
Total	96,810	3,360,033	1,297,308			6.726		
			Mean density:	74.64				
• Eastern								
Central African Republic	1,437	622,984	240,534	4.97	108[4]	0.136	31.56	French, Sangho
Congo	850	342,000	132,046	6.44	145[4]	-	-	French, Bantu
Ethiopia	23,000	1,221,900	471,776	48.75	61	0.440	27.67	Amharic, Arabic
Kenya	9,643	582,644	224,959	42.87	105[4]	1.068	29.52	Swahili, English
Republic of Congo	15,986	2,345,409	905,562	17.64	111[4]	-	-	French, Swahili
Rwanda	3,204	26,338	10,169	315.08	50	-	-	French, Kinyarwanda
Somali	2,580	637,657	246,199	10.48	60	-	-	English, Italian, Arabic
Tanzania	11,833	939,701	362,819	32.61	58[4]	0.739	-	English, Swahili, Bantu
Uganda	7,740	236,036	91,133	84.93	92[4]	-	-	English, Kiswahili, Bantu
Zambia	3,881	752,614	290,584	13.35	233	0.431	17.05	English, Bantu, Afrikaans
Total	80,154	7,707,283	2,975,781			2.814		
			Mean density:	26.93				
2. Latin America								
Central America								
British Honduras	109	22,965	8,867	12.29	385	-	-	English, Spanish
Costa Rica	1,486	50,700	19,575	29.31	408	0.348	-	Spanish
El Salvador	3,037	21,393	8,260	367.67	265	0.474	34.28	Spanish
Guatemala	4,575	108,889	42,042	108.82	312	0.498	-	Spanish
Honduras	2,363	112,088	43,277	54.60	221	0.314	-	Spanish
Mexico	44,145	1,972,546	761,600	57.96	446	8.299	29.46	Spanish
Nicaragua	1,715	130,000	50,193	34.17	308	0.245	34.61	Spanish
Panama	1,287	75,650	29,208	44.06	453	0.258	53.98	English, Spanish
Total	58,717	2,494,231	963,022			10.436		
			Mean density:	60.97				
South America								
• Western								
Bolivia	3,748	1,098,581	424,162	8.84	146	0.667	-	Spanish
Colombia	18,596	1,138,914	439,735	42.29	234	2.780	29.77	Spanish
Ecuador	5,326	283,561	109,483	48.65	215	0.948	28.00	Spanish
Peru	12,012	1,285,216	496,222	24.21	301	2.291	-	Spanish
Venezuela	8,921	912,050	352,143	25.33	939	1.835	112.46	Spanish
Chile	8,750	756,945	292,256	29.94	591	1.972	65.14	Spanish
Total	57,353	5,475,267	2,114,001			10.493		
			Mean density:	27.13				

Table 12-24. Statistical Data on Selected Countries Outside of North America (Continued)

	Population[1] (000)	Area (km^2)	Area (mi^2, U.S.)	Population Density per Square Mile	Per Capita[2] Gross Domestic Product ($)	Number of Students (10^6)	Per Student[3] Budget ($)	Official Languages
2. Latin America (Continued)								
South America (Continued)								
Eastern								
Argentina	22,691	2,776,655	1,072,067	21.17	759	4.325	125.91	Spanish
Brazil	83,175	8,511,965	3,286,470	25.31	167	12.233	-	Portuguese
French Guiana	37	91,000	35,135	1.05	-	-	-	Spanish
Guyana	662	214,969	83,000	7.98	323	0.181	34.29	Spanish
Paraguay	2,094	406,752	157,047	13.33	211	0.403	14.89	Spanish
Surinam	350	163,265	63,037	5.55	229[4]	0.102	16.77	Spanish
Uruguay	2,749	186,926	72,172	38.09	569[4]	0.502	50.89	Spanish
Total	111,758	12,351,533	4,768,928			17.746		
			Mean density: 23.43					
3. Central Asia								
Afghanistan	15,397	647,497	249,999	61.59	85[4]	-	-	Persian, Pushtu
Ceylon	11,491	65,610	25,332	453.62	142	2.648	24.31	Sinhalese
Indonesia	107,000	1,491,564	575,893	185.80	100	13.146	-	English, Bahara, Indonesia
India	498,680	3,268,090	1,261,810	395.21	101	58.888	6.88	English, Hindi
Malaysia	9,725	332,633	128,429	75.72	303	1.866	25.77	Malay, English
Nepal	10,294	140,797	54,362	189.36	75	-	-	Nepali, English
Pakistan	105,044	946,716	365,527	287.38	99	9.824	9.65	Urdu, Bengali, English
Total	757,631	6,892,907	2,661,352			86.372		
			Mean density: 284.72					
4. Pacific Ocean Area								
Australia	11,541	7,686,810	2,967,877	3.89	2,014	2.726	122.87	English
New Guinea	1,582	238,693	92,159	17.17	-	-	-	French, English
New Hebrides	76	14,763	5,700	13.33	-	-	-	French
New Zealand	2,676	268,676	103,736	25.80	1,844	0.695	174.78	English, Maori
Philippines	32,345	299,404	115,600	279.81	165	7.097	21.26	English, Tagalog
Total	48,220	8,508,346	3,285,072			10 518		
			Mean density: 14.68					

[1] 1966 U.N. estimates

[2] 1966 U.N. estimates at 1966 U N. estimated exchange rates

[3] Recurrent expenditures only

[4] Advertising Age 1966-estimates based on AID statistics

Latin America

Central America

British Honduras	Costa Rica	El Salvador
Guatemala	Honduras	Mexico
Nicaragua	Panama	

South America

Western

Bolivia	Colombia	Ecuador
Peru	Venezuela	Chile

Brazil

Argentina	Uruguay	Paraguay

Africa

South of the Sahara

Western

Cameroon	Ivory Coast	Togo
Guinea	Sierra Leone	Ghana
Senegal	Gabon	Nigeria
Dahomey	Liberia	Upper Volta

Eastern

Central African Republic	Congo	Somali
Republic of Congo	Rwanda	Kenya
Uganda	Zambia	Tanzania
	Ethiopia	

Central Asia

India

Pakistan

Pacific Ocean Area

Australia

Philippines

The expected regional benefits cannot be readily ranked in social or economic priorities. Three potential audience areas of feasible geographic size are clearly within stated interests of U. S. domestic or foreign policies and commitments. They are:

Central America

Brazil

India

The two candidate Latin American regions (as well as the rest of Latin America) are so closely associated with United States economic and political interests that social and economic benefits which may arise from their establishing satellite-based ETV would undoubtedly include benefits to the United States as well as to the regions themselves. However, with the exception of the ASCEND report (1), literature on Latin American ETV tends to be qualitative, general statements (23, 29, 44, 54, 85, 106) rather than analytical, cost-benefit studies. (It is hoped and recommended that detailed cost-benefit studies of satellite-based ETV in Latin America will be initiated in the near future.)

Considerable attention has been given by the U.N., the U.S., and the Indian Government to the potential use of satellite-based ETV in India. Unfortunately, currently available reports and papers deal primarily with spacecraft and receiver costs, with some allusions to program production costs and almost no quantitative statement of other facilities and software costs. Development of detailed cost and benefit data for an Indian ETV system will require development of much more comprehensive data on the characteristics of the current and planned Indian education system and reliable projections of specific demographic data related to school-age population and other educational statistics. To the extent that such data are currently available, a truncated view of some of the benefits and costs of an Indian satellite-based ETV system can be presented.

In a report on the "Delhi Project" (113) the use of TV to provide agricultural information to some villages in the vicinity of Delhi was discussed. The subject matter of the TV programs was:

1) Practices for raising high-yielding varieties of wheat

2) Weed control in wheat

3) Methods of irrigating rabi crops

4) Cultivation of tomato, cauliflower and cabbage

5) Foliar application of fertilizers

6) Raising of vegetables on saline soils

7) Control of field rats

Tests were given to 100 randomly selected farmers who had seen the programs (experimental group) and 100 farmers selected from villages that did not have TV. The test results, shown in Tables 12-25, 12-26 and 12-27 show that in the India context dissemination of agricultural information by TV is significantly superior to ordinary, in-person lectures for providing knowledge, changing attitudes and encouraging adoption of new practices. This form of instructional television can obviously improve the level of agricultural output and help make India self-sufficient in food production; other social, cultural and technological goals may also be achieved by appropriate use of ETV. However, the quantitative benefits to the country as a whole are difficult to estimate without extensive investigation of the specific sectors of interest and specific regions of India.

Table 12-25. Mean Knowledge Scores

	Topic of Program	Experimental Group (n = 100)	Standard Deviation	Control Group (n = 100)	Standard Deviation	"t" Value	x^2 Value
1)	Package of practices for high yielding varieties of wheat (18)	14.11	1.9	8.57	2.8	15.99*	123.45*
2)	Weed control in wheat (22)	12.45	3.4	6.87	3.1	11.90*	67.04*
3)	Methods of irrigating rabi crops (5)	4.12	0.45	3.65	0.50	6.27*	Not applicable
4)	Cultivation of tomato, cauliflower, and cabbage (23)	14.56	4.2	7.51	5.1	10.50*	31.64*
5)	Foliar application of fertilizers (10)	5.70	2.6	1.11	1.20	16.00*	91.85*
6)	Raising of vegetables on saline soils (12)	3.02	3.6	0.58	1.30	6.20*	28.44*
7)	Control of field rats (13)	8.67	2.3	7.97	2.30	1.60	5.73
8)	Total knowledge score (113)	62.86	13.8	35.88	10.70	15.32*	117.21*

Note: *Significant at one percent level

Figures in the brackets are the total knowledge scores obtainable for that practice

The "t" and x^2 values indicate that except for the program on the control of field rats, the differences in the knowledge scores of the two groups are significant at one percent level

Table 12-26. Mean Attitude Scores

Topic of Program	Experimental Group (n = 100)	Standard Deviation	Control Group (n = 100)	Standard Deviation	"t" Value	x^2 Value
1) Chemical control of weeds (12)	11.16	1.3	6.11	4.7	10.52*	65.26*
2) Chemical fertilizers (12)	11.84	0.6	11.48	1.4	1.6	1.51
3) High yielding varieties of wheat (12)	9.37	2.9	7.90	3.4	3.26*	7.69**
4) Foliar application of fertilizers (12)	9.22	1.8	1.53	3.2	21.36*	132.88*

Note: *Significant at one percent level

Figures in the brackets are the total obtainable attitude score for that practice

The "t" and x^2 values indicate that except for the program on chemical fertilizers, the difference in the attitude scores of the two groups are significant at one percent level

Table 12-27. Number of Adopters of Improved Practices

Topic of Program	Experimental Group A	Experimental Group NA	Control Group A	Control Group NA	x^2 Value
1) Chemical control of weeds	42	58	11	89	24.6*
2) Chemical fertilizers	99	1	92	8	3.01
3) High yielding varieties of wheat	82	18	55	45	16.9*
4) Foliar application of fertilizers	16	84	2	98	11.9*

Note: A - adopters of the practice

NA - non-adopters of the practice

*Significant at one percent level

Except for the practice of chemical fertilizers, the number of adopters in the experimental group is significantly more compared to the number in the control group for the rest of the practices

Educational television projects for general academic use in the Indian education system have not been well documented. Broad allusions to potential benefits were reported by a UNESCO Expert Mission, which in December 1967 studied the implementation of a satellite ETV pilot project (70). Because of the very small mileage of currently installed microwave relays and the time and money required to establish a country-wide microwave network, the U.N. mission strongly recommended establishment of a satellite broadcasting capability, particularly for educational television.

> "According to the information given to the Mission the needs for extended telecommunication facilities are so great that new facilities are fully utilized within ... a short period of time. Any additional telecommunications facilities through a satellite system could be put to immediate use." (70, pp 15)

Potential benefits were seen to be:

1) To train teachers—in 1965-66 only 50 percent of the teachers in lower primary schools had completed secondary school.

2) To expand enrollments in primary and secondary schools—1965-66 enrollment statistics were:

	Percent of Age-Group Not Enrolled
Primary grades 1-4	31
Primary grades 5-7	64
Secondary grades 8-10	81
Secondary grades 11-12	91

3) To provide agricultural information to India's 50,000,000 farmers

4) To disseminate information on and encourage birth control

5) To provide mass communications for other beneficial social projects

India's solutions to problems of population growth, food production, illiteracy, and other social conditions are of great importance to the political stability of Asia and to the economies of many countries, including the United States. The possibilities of using a TV broadcast satellite for alleviating these problems and for assisting India to reduce negative balances of trade and payments and to achieve a stable, growing economy requiring little or no external economic aid, appear sufficiently attractive to warrant a thorough systems study of the costs and benefits associated with an Indian TV broadcast satellite: not a one-channel, one-year experiment, but a satellite configured to fit India's specific needs and capabilities.

12.4 COSTS OF ALTERNATE SYSTEMS

In addition to direct broadcasting from a TV satellite, nationwide distribution of television signals may currently be achieved by microwave or cable networks, or by satellite-microwave-cable combinations. In the future, use of laser "light pipes" or other yet-to-be-discovered advanced techniques may prove to be efficient means for signal distribution. Projection of costs of optimum combinations of microwave, cable, and satellite broadcasting would require engineering and operations analyses at least comparable to the engineering portion of this study. However, a rough estimate of alternate costs can be made to permit order of magnitude comparisons.

First, consider the primary capability of satellite-based TV: complete coverage of the entire nation with acceptable-grade TV signals. If one assumes that the three million square miles of the conterminous United States were geometrically square and could be completely illuminated by a square array of evenly spaced transmitters, each with a 50-mile radius of coverage, approximately 370 transmitters would be required. In this square-square array all 370 transmitters may be connected to one properly located point of origin by a minimum of 38,000 route-miles of microwave relay. The assumptions of squareness permit a least estimate of the number of stations and route-miles necessary for complete coverage of the United States. The estimates are not exact because of expected variations in actual coverage due to terrain characteristics and the assumption of full coverage by nonoverlapping circularly illuminated areas. However, the resulting minimum estimates provide bases for very conservative estimates of alternate system costs.

Costs of transmitters and microwave relays vary, depending on the local topography, noise environment, signal quality, and tradeoffs between ease of access for maintenance and repair purposes and optimum location for minimizing hop-lengths or maximizing coverage area. Precise costing would require an exact engineering analysis of the system under consideration. However, it is informative to compare a hypothetical terrestrial system which can provide the same services as the previously hypothesized satellite ETV system for United States public and elementary schools.

For the hypothetical terrestrial system, the following assumptions are made:

1. 370 transmitters, evenly spaced in a square array, can cover the entire conterminous United States. Each transmitter providing six channels of color TV costs $500,000, including land and buildings. Useful life is 10 years for the equipment and 30 years for buildings.

2. All transmitters can be connected to one point of program origin by 38,000 route-miles of microwave relay at $2500 per route mile. Useful life of the relay system is 15 years.

3. Annual operating and maintenance costs of each transmitter are $38,000.

4. Annual operating costs of the microwave relay system per route-mile are $474.

5. Each of the 1.7 million classrooms will have one 23-inch color TV receiver at $250 each.

6. Annual receiver repair and maintenance expense is 10 percent of installed receiver costs.

7. Annual operation cost of receivers is $15 each.

8. Costs of programming are equal for both systems (and therefore not included in the calculations).

Comparison of costs for a hypothetical microwave connected transmitter system and the previously hypothesized satellite system providing six channels of color ETV to all United States public elementary and secondary schools is shown Table 12-28. Set requirements and other costs are based on a constant (no growth) 44-million enrollment in 1.7 million classrooms in 100,000 schools. Investment and operating costs of the microwave system are considered to be low but reasonable estimates based on the wide range of costs of single-channel systems reported in the literature (vide 73). The effects of adding five channels have been neglected, to render the comparison even more conservative. The bases for the satellite system costs are the same as those associated with Table 12-17. Considering that high estimates are used for the satellite system and very low estimates for the microwave system, it is significant that the cumulative outlays and 1970 present values of the microwave system exceed those of the satellite system in every analyzed year from 1970

Table 12-28. Comparisons of System Costs for Microwave or Satellite-Distributed Six-Channel Color ETV for the United States Public Elementary and Secondary School Systems

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
Cost Elements															
Microwave System															
Investment															
• Transmitters 370 stations at $500,000 each[a]	61.7	61.7	61.6								49.3[a]	49.3[a]	49.4[a]		
• Microwave relay 38,000 route-miles at $2,500 each	31.7	31.7	31.6												
• Receivers: 1.7 (10^6) at $250 each	141.7	141.7	141.6								141.7	141.7	141.6		
Operation & Maintenance															
• Transmitters at $38,000 per year each	4.7	9.4	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1
• Microwave relay at $474 per-route-mile-year	6.6	12.1	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
• Receivers repair and maintenance at 10 percent of costs	14.2	28.4	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5
• Power at $15 per set-year	8.5	17.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Total Outlays	269.1	302.0	334.4	99.6	99.6	99.6	99.6	99.6	99.6	99.6	290.6	290.6	290.6	99.6	99.6
Cumulative	269.1	571.1	905.5	1,005.1	1,104.7	1,204.3	1,303.9	1,403.5	1,503.1	1,602.7	1,893.3	2,183.9	2,474.5	2,574.1	2,673.7
Present value at i = 6%	253.8	268.9	280.9	78.9	74.4	70.2	66.2	62.4	59.0	55.6	153.1	144.4	136.3	44.0	41.5
Cumulative	253.8	522.7	803.6	882.5	956.9	1,027.1	1,093.3	1,155.7	1,214.7	1,270.3	1,423.4	1,567.8	1,704.1	1,748.1	1,789.6
Satellite System															
Investment															
• Reception	175.0	175.0	175.0								175.0	175.0	175.0		
• Ground station	10.0										10.0				
• Satellites	40.0	40.0				40.0	40.0				40.0	40.0			
Operation & Maintenance															
• Reception: Repair, etc.	18.5	36.0	53.5	53.5	53.5	53.5	53.5	53.5	53.5	53.5	53.5	53.5	53.5	53.5	53.5
Power	8.5	17.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
• Ground station	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Total Outlays	252.1	269.0	254.5	79.5	79.5	119.5	119.5	79.5	79.5	79.5	304.5	294.5	254.5	79.5	79.5
Cumulative	252.1	521.1	775.6	855.1	934.6	1,054.1	1,173.6	1,253.1	1,332.6	1,412.1	1,716.6	2,011.1	2,265.6	2,345.1	2,424.6
Present value at i = 6%	237.7	239.4	213.8	63.0	59.4	84.2	79.5	49.8	47.1	44.4	160.5	146.4	119.4	35.1	33.2
Cumulative	237.7	477.1	690.9	753.9	813.3	897.5	977.0	1,026.8	1,073.9	1,118.3	1,278.8	1,425.2	1,544.6	1,579.7	1,612.9

(a) Calculated at $120,000 for land and buildings and $380,000 for transmitter equipment to 1984. It may be concluded, then, that a national six-channel, color, ETV system for public elementary and secondary schools has a net positive present value when its costs are compared to imputed potential benefits (Table 18), and that a satellite system is more cost-effective than a microwave system for providing this service.

Alternate costs for providing an additional commercial TV network would depend on the number and location of markets to be included in the network. If the satellite coverage capability is to be duplicated by a terrestrial system, at least all of the current 251 markets must be covered. Analysis of the incremental and total costs of covering these markets has not been performed in this study. It is expected that, because of the uneven distribution of market "centroids" assumptions of square areas and arrays would not be applicable, and a detailed operations analysis would be required.

BIBLIOGRAPHY

1. "Advanced System for Communications and Education in National Development," Final Report, School of Engineering, Stanford University, Stanford, Calif., June 1967.

2. Al-Samarrie, Ahmad and Herman P. Miller, "State Differentials in Income Concentration," the American Economic Review, March 1967.

3. "An Asian Model of Educational Development—Perspectives for 1965-80," published by the United Nations Educational, Scientific and Cultural Organization, Place de Fontenoy, Paris-7e, 1966.

4. Andelić, Tatomir, "Applications of Artificial Satellites to the Education and Instruction of People in Developing Countries," presented at United Nations Conference on the Exploration and Peaceful Uses of Outer Space, Thematic Session VIII, Yugoslavia, A/Conf. 34/Viii.28, 28 May 1968.

5. Archer, Stephen H. and Charles A. D'Ambrosio, The Theory of Business Finance: A Book of Readings, The MacMillan Company, New York, 1967.

6. Barnett, H. J. and E. Greenberg, "On the Economics of Wired City Television," The American Economic Review. (Original published in the Washington University Law Quarterly, Fall 1967 and Winter 1968.)

7. Beideman, Elliot F., "Systems Analysis and Public Problems, the California Experiment," dissertation presented to the Faculty of the Graduate School of Business Administration, University of Southern California, June 1966.

8. Blamont, Jacque, "Space Means at the Service of Education and Mass Information," paper presented at United Nations Conference on the Exploration and Peace Uses of Outer Space, Paris, 16 July 1968.

9. Blank, David M., "Request for Quantity and Diversity in TV Programming," American Economic Review, Vol. 56, No. 2, May 1966.

10. Borden, Neil H., "The Economic Effects of Advertising," a summary from The Economic Effects of Advertising, published by Richard D. Irwin, 1947; from Mass Communications, Wilbur Schramm, ed., University of Illinois Press, Urbana, Ill., 1960.

BIBLIOGRAPHY (Continued)

11. Briskman, Robert D., "Domestic Communications Services via Satellites—Comsat Pilot Program," No. 68-412, presented at AIAA 2nd Communications Satellite Systems Conference, San Francisco, California, April 8-10, 1968.

12. Bryce, Murray D., Industrial Development, McGraw-Hill Book Company, Inc., New York, 1960.

13. Burns, R. F., et al., "An Econometric Analysis of an Educational TV Distribution System," No. 66-321, presented at AIAA Communications Satellite Systems Conference, Washington, D. C., May 2-4, 1966.

14. Bushnell, David S. and Arnold Mitchell, Technology in Education, Long Range Planning Service, Stanford Research Institute, 1963.

15. Cassirer, Henry R., "Television Extends Higher Education: A Pilot Project in Poland," reprinted from Unesco Chronicle, Vol. XII (1966), No. 9.

16. Chansky, Norman N., Untapped Good, Charles C. Thomas, Publisher, Springfield, Illinois, 1966.

17. Chu, Godwin C. and Wilbur Schramm, "Learning from Television: What the Research Says," ERIC at Stanford, ERIC Clearinghouse on Educational Media and Technology at the Institute for Communication Research, Stanford University, Stanford, Calif., August 1968.

18. "Close-Up on India, Fifteen Year Survey," reprinted by Information Service of India, Embassy of India, Washington, D. C. Courtsey: Indian Investment Center, New York, N. Y.

19. Colino, Richard R., "Intelsat: Doint Business in Outer Space," the Columbia Journal of Transnational Law, published by The Columbia Society of International Law, 1967.

20. Collins, J. A., "Considerations for a Canadian Domestic Satellite System," No. 68-413, presented at AIAA 2nd Communications Satellite Conference, San Francisco, Calif., April 8-10, 1968.

21. Coombs, Philip H., The World Educational Crisis, Oxford University Press, New York, 1968.

22. de Lipski, Vladimir, "The Content of General Education," Tor Gjisdal, "Mass Media in Adult Education and Literacy," Unesco Chronicle, Vol. XIV, No. 3, Unesco House, Place de Fontenoy, Paris 7e, March 1968.

23. de Mendonca, Fernando, "Some Practical Applications of Space Age Programs for Developing Nations," A/Conf. 34/IV.7, Themalic Session IV, Brazil, United Nations Conference on the Exploration and Peaceful Uses of Outer Space, 23 July 1968.

24. Dennison, Edward F., "Education, Economic Growth, and Gaps in Information," Journal of Political Economy (Supplement), Vol. 70, No. 5, Part 2, Octover 1962, pp 124-128.

25. Dlugatch, Irving, "A Low Cost Communications Satellite Educational System," SP-2493, written to be presented at the XVII International Astronautical Congress, Madrid, Spain, October 1966.

26. Doan, Richard K., "Global Television... When?" TV Guide, January 27, 1968.

27. Economic Report of the President, transmitted to the Congress, February 1968.

28. Educational Television - The Next Ten Years, OE-34036, U. S. Department of Health, Education, and Welfare, Office of Educatio U.S. Government Printing Office, Washington, D. C., 1965.

29. "Educational Television Via Satellite," Communications Satellite Corporation, Washington, D. C., Rev. April 1967.

30. "Estimated Annual U.S. Advertising Expenditures: 1947-1967, Allocations," Advertising Age, April 8, 1968, p 56.

31. Evans, H. W., "Technical Background, AT and T Domestic Satellite Proposal," No. 68-411, presented at AIAA 2nd Communications Satellite Systems Conference, San Francisco, Calif., April 8-10, 1968.

32. "Factbook" published by National Association of Commercial Broadcasters in Japan, Bungei Shunji Bldg., Tokyo, Japan, 1968.

33. "Federal Interagency Requirements for Day Care," U. S. Dept. of Health, Education, and Welfare, Office of Economic Opportunit Dept. of Labor, May 25, 1968.

34. "Federal Reserve Bulletin," No. 12, Vol. 54, Dec. 1968.

35. Feedler, Martha L., "ETV Goes Way Out and Brings the World to Samoa...," American Education 3:14-17, March 1967.

36. Fein, Rashi, "An Economic and Social Profile of the American Negro," Reprint 110, The Brookings Institution, Washington, D. C January 1966.

37. "Financial Statistics of Institutions of Higher Education," Dept. of Health, Education, and Welfare, Office of Education, 1963-1964.

38. Firestone, O. J., The Economic Implications of Advertising, commissioned by the Institute of Canadian Advertising, Methuen Publications, Toronto and London, 1967.

39. Fougeyrollas, Pierre, "Television and Social Education of Women," a first report on the Unesco-Senegal Pilot Project at Dakar, printed in the workshops of the United Nations Educational, Scientific and Cultural Organization, Place de Fontenoy, Paris 7[e], 1967.

40. Friedland, Seymour, The Economics of Corporate Finance, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1966.

41. Harbison, Frederick and Charles A. Myers, Education, Manpower, and Economic Growth, McGraw-Hill Book Company, New York, 1964.

42. Haviland, R. P., "Broadcast Satellites: Their Applications and Implementation Impediments," No. 68-1064, presented at AIAA 5th Annual Meeting and Technical Display, Philadelphia, Pa., October 21-24, 1968.

43. Haviland, R. P., "Space Broadcasting - How, When, and Why," unpublished paper.

44. Haviland, R. P., "Why Space Broadcasting?" No. 68-422, presented at AIAA 2nd Communications Satellite Systems Conference, San Francisco, Calif., April 8-10, 1968.

45. Hesselbacher, R. W., "An Evaluation of Voice Broadcast Satellite Systems," No. 68-423, presented at AIAA 2nd Communications Satellite Systems Conference, San Francisco, Calif., April 8-10, 1968.

46. Hesselbacher, R. W. (Manager - Broadcast Satellite Systems, General Electric Company, Missile and Space Division, Valley Forge, Pa.), "Satellites for Television Instruction," unpublished paper.

47. Higgins, Benjamin, Economic Development Problems, Principles, and Policies, W. W. Norton and Company, Inc., New York.

48. Housley, C. B. E., "Application of Satellites to the Telecommunications Scene," presented at United Nations Conference on the Exploration and Peaceful Uses of Outer Space, Thematic Session I, Australia, A/Conf. 34/I-13, 31 May 1968.

49. "India, Bulwark of Democracy," Information Service of India, Embassy of India, Washington, D. C. (no date).

50. "India in Perspective," designed and produced by the Directorate of Advertising and Visual Publicity, Minister of Information and Broadcasting, Government of India, for the Ministry of External Affairs; printed by the National Printing Works, Delhi-6, 1967.

51. "India, Pocket Book of Economic Information 1966," Government of India, Ministry of Finance, Dept. of Economic Affairs.

52. "India the World's Largest Democracy," Information Service of India, Embassy of India, Washington, D. C.

53. Jacobs, George, "Satellite Target: 1970," Television Age, July 1968.

54. Jamison, Dean, "Optimal Utilization of Communication Satellites for Educational Purposes," No. 68-421, presented at AIAA 2nd Communications Satellite Systems Conference, San Francisco, Calif., April 8-10, 1968.

55. Jansen, John, "Communication Satellites for Educational Television," presented at the 18th International Astronautical Congres Belgrade, Yugoslavia, 24-30 Sept. 1967.

56. Japan Economic Yearbook 1967, The Oriental Economist.

57. Kanner, Joseph H., "The Instructional Effectiveness of Color in Television: A Review of the Evidence," ERIC Clearinghouse on Educational Media and Technology, Stanford University, Stanford, Calif., January 1968.

58. Kiesling, John D., "Spaceborne Transmitter for Direct Color Television Transmission from Satellites," IEEE Transactions on Broadcast and Television Receivers, V. BTR-12, No. 2, May 1966.

59. Lerner, Eugene M. and Willard T. Carleton, A Theory of Financ Analysis, Wm. J. Baumol, Princeton Press, ed., Harcourt, Bra and World, Inc., New York, 1968.

60. Lessing, Lawrence, "Cinderella in the Sky," Fortune, October 1

61. Liu, Bangnee, Alfred, "Estimating Future School Enrolment in Developing Countries," No. 40 in series "Population Studies," United Nations Educational, Scientific and Cultural Organization, Place de Fontenoy, Paris-7e.

62. Machlup, Fritz, The Production and Distribution of Knowledge in the U.S., Princeton University Press, Princeton, N. J., 1962, Chapter IV.

63. Martin, Brian V. and Charles B. Warden, "Transportation Planning in Developing Countries," reprint 121, The Brookings Institution, Washington, D. C.

64. Martin, Louise G., "Around the World by Microwave for Half a Billion Dollars," the Microwave Journal, March 1965.

65. "Measurement of Advertising Effectiveness," No. 297, Long Range Planning Service, Stanford Research Institute, Menlo Park, Calif., p 22.

66. Measuring Benefits of Government Investments, Robert Dorfman, ed., The Brookings Institution, Library of Congress Card No. 65-18313, 1965.

67. Meier, Gerald M., Leading Issues in Development Economics, Oxford Press, New York, 1964.

68. Morgan, James, "The Anatomy of Income Distribution," Review of Econ. Stat., V. 44, pp 270-283, August 1962.

69. Nelson, Richard R. and Edmond S. Phelps, "Investment in Humans, Technological Diffusion, and Economic Growth," American Economic Association, May 1966.

70. "Preparatory Study of a Pilot Project in the Use of Satellite Communication for National Development Purposes in India," prepared for United Nations Educational, Scientific and Cultural Organization by a Unesco Expert Mission in cooperation with a national counterpart team appointed by the Government of India, 18 Nov. to 7 Dec. 1967.

71. "Prevention and Control of Crime and Delinquency," Final Report PCCD-7, prepared for Youth and Adult Corrections Agency, State of California, by Space General Corporation, El Monte, Calif. July 29, 1965.

72. "Public Broadcasting Act of 1967," U. S. Senate, 90th Congress, 1st Session, Calendar No. 213, Report No. 222.

73. Public Television: A Program for Action, Carnegie Commission on Educational Television, Bantam Books, New York, 1967.

74. Radius, Walter A., "Comments on Broadcast Satellite Systems," presented to Panel on Broadcast Satellite Applications, IEEE International Conference on Communication, Philadelphia, 12 June 1968.

75. Rao, B. S., et al., "Satellite Television: A System Proposal for India," presented at United Nations Conference on the Exploration and Peaceful Uses of Outer Space, Thematic Session I/India, A/Conf. 34/I. 1, 24 June 1968.

76. "Recommendations Concerning the Setting Up of a European Regional Telecommunication Satellite System," Eurospace, 10 Rue Cognacq-Jay, 75-Paris 7 eme, October 1967.

77. Rivlin, Alice M., "Critical Issues in the Development of Vocational Education," Unemployment in a Prosperous Economy, A Report of the Princeton Manpower Symposium, May 13-14, 1965, pp 161-162.

78. Robinson, Richard D., "High-Level Manpower in Economic Development, The Turkish Case," Harvard Middle Eastern Monographs XVII, Harvard University Press, Cambridge, Mass., 1967.

79. Rosen, Harold A., "Satellite System for Educational Television," A/Conf. 34/1.5, Thematic Session II, United Nations Conference on the Exploration and Peaceful Uses of Outer Space, United States, 20 June 1968.

80. Rosenberg, Laurence C., "On Costs and Benefits of a National Television System for India," The Indian Economic Journal, Vol. XIV, No. 1, July-September 1966.

81. Rubin, Philip A., "Information Distribution Systems for Developing Nations," presented at IEEE Winter Convention on Aerospace and Electronics Systems, Los Angeles, February 14, 1968.

82. Rubin, Philip A., "Satellites for Education," presented at XIXth Congress of the International Astronautical Federation, New York City, October 13-19, 1968.

83. Sava, Samuel G., "When Learning Comes Easy," Saturday Review, November 16, 1968.

84. Schramm, Wilbur, et al., "Communication in the Space Age," published by the United Nations Educational, Scientific and Cultural Organization, Place de Fontenoy, Paris 7e, 1968.

85. Schramm, Wilbur, "Communication Satellites for Education, Science and Culture," No. 53, printed in the Workshops of the United Nations Educational, Scientific and Cultural Organization, Place de Fontenoy, Paris 7e, 1968.

86. Schramm, Wilbur, Mass Media and National Development, Stanford University Press, 1964.

87. Schramm, Wilbur, "Satellites for Education: Lessons from a Decade of Experience with Educational Television," presented at United Nations Conference on the Exploration and Peaceful Uses of Outer Space, Thematic Session I, United States, A/Conf. 34/I. 6, 3 June 1968.

88. Schramm, Wilbur, et al., "The New Media: Memo to Educational Planners," published by the United Nations Educational, Scientific and Cultural Organization, Place de Fontenoy 75 Paris 7e, 1967.

89. Schultz, Theodore W., "Capital Formation by Education," Journal of Political Economy, pp 571-583, December 1960.

90. Schultz, Theodore W., "Social Forces Influencing American Education," The Sixtieth Yearbook of the National Society for the Study of Education, Part 2, Nelson B. Henry, ed., University of Chicago Press, Chicago, 1961, pp 60 and 73.

91. Seiden, Martin H., "An Economic Analysis of Community Antenna Television Systems and the Television Broadcasting Industry," Report to the Federal Communications Commission, U. S. Government Printing Office, Washington, D. C., February 12, 1965.

92. Smith, Adam, An Inquiry into the Nature and Causes of the Wealth of Nations, Canaan, ed. (reissued by Modern Library), Random House, Inc., 1937, Book II, pp 265-266.

93. Social Forces Influencing American Education, Nelson B. Henry, ed., The National Society for the Study of Education, Chicago, Ill., 1961.

94. Solow, Robert M., "Technical Change and the Aggregate Production Function," Review of Economics and Statistics, Vol. 39, No. 3, August 1957, pp 312-330.

95. Solow, Robert M., "Technical Progress, Capital Formation, and Economic Growth," American Economic Review, Vol. 52, No. 2, May 1962, pp 76-86.

96. "Special Analyses, Budget of the United States, Fiscal Year 1969," U. S. Government Printing Office, Washington, D. C.

97. "Statistical Abstract of the United States," United States Dept. of Commerce, Bureau of the Census, 1967.

98. Steinmayer, A. G., "A Low Cost Communication System for a Developing Nation," Telecommunications, General Electric Company, Valley Forge Space Technology, Philadelphia, Pa., January 1968.

99. Steiner, G. A., The People Look at TV: A Study of Audience Attitudes, Alfred A. Knopf Inc., 1963, New York, N.Y.

100. Surveys of Economic Theory, Vol. II, St. Martin's Press, New York, 1967.

101. Swensen, R. D., "Economic Comparisons of Domestic Satellite Television Distribution Systems," No. 68-410, presented at AIAA 2nd Communications Satellite Systems Conference, San Francisco, Calif., April 8-10, 1968.

102. Telser, Lester G., "Supply and Demand for Advertising Messages," American Economic Review, Vol. 56, May 1966.

103. Television Factbook, No. 38, Television Digest, Inc., Washington, D. C., 1968.

104. The Cost of Acquiring and Owning a Private Microwave System, Arthur D. Little, Inc., January 1965.

105. The Economics of Underdevelopment, A. N. Agarwala and S. P. Singh, eds., A Galaxy Book, New York, Oxford University Press, 1963.

106. "The Potentialities of Space Communication for Promoting the Free Flow of Information and Greater Cultural Exchange and the Related International Arrangements Needed," A/Conf. 34/I.20, Thematic Session I, United Nations Conference on the Exploration and Peaceful Uses of Outer Space, 3 July 1968.

107. "TV Broadcast Financial Data - 1966," Federal Communications Commission, Public Notice 5317, August 25, 1967.

108. Unesco Chronicle, Vol. XIV, No. 7-8, Unesco House, Place de Fontenoy, Paris 7e, July-August 1968, pp 267-284, 298.

109. Unesco Chronicle, Vol. XIV, No. 6, Unesco House, Place de Fontenoy, Paris 7e, June 1968, pp 217-239, 247, 255.

110. United Nations Statistical Yearbook - 1967, Statistical Office of the United Nations Department of Economic and Social Affairs, New York, 1968.

111. "Use of Communication Satellites by the United Nations," paper presented by the Secretary-General of the United Nations at the United Nations Conference on the Exploration and Peaceful Uses of Outer Space, A/Conf. 34/I.27, 10 June 1968.

112. "Use of the Spectrum by Satellite Systems Through 1980," Office of Telecommunications Management, February 1968.

113. Vepa, Prasad L., "Opportunities Available for Developing Nations through the use of Communication Satellites: The Delhi Project," presented at United Nations Conference on the Exploration and Peaceful Uses of Outer Space, Thematic Session VII, India, A/Conf. 34/VII. 2, 2 June 1968.

114. "Video Research Service," Video Research, Ltd., Tokyo, Japan. (no date).

115. Ward, Barbara, The Lopsided World, W. W. Norton and Company, Inc., New York, 1968.

116. Ward, Barbara, The Rich Nations and the Poor Nations, W. W. Norton and Company, Inc., New York, 1962.

117. Readings in the Applied Economics of Africa, Whetham, Edith H., and Jean I. Currie, eds., Vol. I: Micro-Economics, Cambridge University Press, 1967.

118. Readings in the Applied Economics of Africa, Whetham, Edith H., and Jean I. Currie, eds., Vol. 2: Macro-Economics, Cambridge University Press, 1967.

119. Woodward, Eliot G., "Community Antenna Television Systems," Long Range Planning Service, Stanford Research Institute, Menlo Park, Calif., 1966.

120. "World Estimates of Gross National Product," Advertising Age, June 17, 1968, p 88.

121. Yoshida, Todashi, "Possibility of, and Profit to be Gained by, Using Satellites for Educational Purposes," A/Conf. 34/I. 2, Thematic Session I, United Nations Conference on the Exploration and Peaceful Uses of Outer Space, Japan, 29 May 1968.

APPENDIX 12A

QUALITATIVE CONCLUSIONS CONCERNING INSTRUCTIONAL TELEVISION*

1. Given favorable conditions, children learn efficiently from instructional television.

2. By and large, instructional television can more easily be used effectively for primary and secondary school students than for college students.

3. So far as we can tell from present evidence, television can be used efficiently to teach any subject matter where one-way communication will contribute to learning.

4. Television is most effective as a tool for learning when used in a suitable context of learning activities at the receiving end.

5. Television is more likely to be an efficient part of an educational system when it is applied to an educational problem of sufficient magnitude to call forth broad support.

6. Television is more likely to be an efficient tool of learning if it is planned and organized efficiently.

7. There is no evidence to suggest that either visual magnification or large-size screens will improve learning from television in general.

8. There is insufficient evidence to suggest that color will improve learning from film or television.

9. Where learning of perceptual-motor skills is required, a subjective angle presentation on television will tend to be more effective than an objective angle presentation.

10. There is no clear evidence on the kind of variations in production techniques that significantly contribute to learning from instructional television. However, students will learn better when the visuals are presented in a continuous order and carefully planned both by the television team and the studio teacher.

11. Attention-gaining cues that are irrevelant to the subject matter will most probably have a negative effect on learning from instructional television.

---

*Chu, Godwin C. and Wilbur Schramm, "Learning from Television: What the Research Says," ERIC at Stanford, Clearinghouse, On Educational Media and Technology at the Institute for Communication Research, Stanford University, Stanford, California, August 1968.

12. There is no consistent evidence to suggest that either humor or animation significantly contribute to learning from instructional television.

13. Subtitles tend to improve learning from instructional television, particularly when the original program is not well organized.

14. There is insufficient evidence to suggest that dramatic presentation will result in more learning than will expository presentation in instructional television.

15. Inserting questions in a television program does not seem to improve learning, but giving the students a rest pause does.

16. Whether a television program is used to begin or to end a daily lesson by the classroom teacher makes no difference in learning.

17. Repeated showings of a television program will result in more learning, up to a point. But teacher-directed follow-up, where available, is more effective than a second showing of the same program.

18. If saving time is important, a television program can probably be shortened and still achieve the minimum requirement of teaching.

19. There is not clear evidence to suggest whether eye-contact in television instruction will affect the amount of learning.

20. Problem-solving instruction on television is more effective than lecturing where the materials taught involve the solving of a problem.

21. The students are likely to acquire the same amount of learning from instructional television whether the materials are presented as a lecture, or in an interview, or in a panel discussion.

22. Where accurate perception of images is an important part of learning, wide viewing angle and long distance will interfere with learning from instructional television.

23. Adequate attention provided by the classroom teacher will, in most cases at least, remedy the adverse effect due to a wide viewing angle.

24. Noise will reduce the effectiveness of learning from film and television so far as part of the learning comes from the auditory medium.

25. Instructional television appears to be equally effective with small and large viewing groups.

26. Instructional television may or may not be more effective with homogeneously grouped students, depending on other factors in the learning situation.

27. Whether instructional television can teach students who view at home as effectively as students in the classroom seems to depend on other conditions.

28. At the college level, permissive attendance does not seem, by itself, to reduce the effectiveness of instructional television.

29. Students will learn more from instructional television under motivated conditions than under unmotivated conditions.

30. Learning from television by the students does not seem necessarily to be handicapped by the lack of prompt feedback to the instructor.

31. Showing, testing and revising an instructional television program will help substitute for lack of live feedback to the teacher, and make for more learning by the students.

32. The lack of opportunity for students to raise questions and participate in free discussion would seem to reduce the effectiveness of learning from instructional television, particularly if the students are fairly advanced or the material is relatively complicated.

33. If a student being taught by instructional television can be given immediate knowledge of whether he has responded correctly, he will learn more.

34. Students taught by television tend to miss the personal teacher-student contact, but there is insufficient evidence to suggest that the lack of such contact will impair learning from instructional television.

35. Practice, whether by overt or covert response, will improve learning from instructional television if the practice is appropriate to the learning task, and if the practice does not constitute an interference.

36. Note-taking while viewing instructional television is likely to interfere with learning if time for it is not provided in the telecast.

37. Teachers and pupils are more favorable toward the use of instructional television in elementary school than in secondary school and college.

38. Administrators are more likely to be favorable toward instructional television than are teachers.

39. Voluntary home students of televised college classes tend to be more favorable toward learning by television than are the students who take these same televised courses in the classroom.

40. At the college level, students tend to prefer small discussion classes to television classes and television classes to large lecture classes.

41. There is evidence of a Hawthorne effect among students beginning to use instructional television, but no firm evidence that attitudes toward the medium necessarily improve or worsen with time.

42. Favorable attitudes are distributed widely enough among different televised courses to cast doubt on the assumption that some academic subjects, per se, may be disliked as material for instructional television.

43. Liking instructional television is not always correlated with learning from it.

44. Among the factors that determine teachers' attitudes toward instructional television are a) how they perceive the degree of threat to the classroom teacher; b) how they estimate the likelihood of mechanized instruction replacing direct contact with students; c) how they estimate the effectiveness of instructional television; d) the difficulties they see in the way of using modern techniques; e) how conservative they are, and whether they trust or distrust educational experimentation.

45. Among the factors that determine pupils' attitudes toward instructional television are a) how much contact they think they will have with a teacher; b) how they compare the relative abilities of the studio and classroom teachers; c) whether they find instructional television boring or interesting; d) the nature of the televised programs they have seen; e) the conditions of viewing.

46. There is no evidence to lead us to believe that children learn any less efficiently from television in developing countries than elsewhere.

47. Under suitable conditions, television has been shown to be capable of highly motivating learning in developing regions.

48. Illiterate people need to learn certain pictorial conventions. There is some evidence suggesting that these conventions are not hard to learn.

49. When media are introduced for upgrading the level of instruction, then it has proved very important to train teachers in their proper use and to keep in close touch with them.

50. Resistance to television and other media is likely to be no less in developing countries, but the size and urgency of the problems are likely to provide greater incentive for overcoming it.

51. Feedback from the classroom teacher to the studio teacher will be helpful to effective use of the media.

52. There is ample evidence that the new media, particularly television, are effective for in-service training of teachers for developing regions.

53. Given favorable conditions, pupils can learn from any instructional media that are now available.

54. There appears to be little if any difference between learning from television and learning from film, if the two media are used the same way.

55. Television and radio have certain advantages over films in flexibility and deliverability.

56. Radio is less expensive than television; economies of scale usually govern cost comparisons of television and film.

57. More complete control of film by the classroom teacher gives it a potential advantage over television.

58. The use of visual images will improve learning of manual tasks, as well as other learning where visual images can facilitate the association process. Otherwise, visual images may cause distraction and interfere with learning.

59. There is some evidence to suggest that moving visual images will improve learning if the continuity of action is an essential part of the learning task.

60. Student response is effectively controlled by programmed methods, regardless of the instructional medium.

APPENDIX 12B

A THEORETICAL MODEL RELATING EDUCATION TO ECONOMIC GROWTH IN DEVELOPING COUNTRIES

To understand the potential effects of new educational techniques on a developing economy, we will first examine a Harrod-Domar-type* growth model. The term Harrod-Domar-type is used because we will introduce a modification of the commonly accepted concept of population growth.

Key assumptions in the Harrod-Domar model are:

1) A constant proportion, s, of income, Y, is devoted to savings

2) The amounts of labor and capital required to produce a unit of output is uniquely given

3) The labor force grows at a constant rate, n, due to social conditions unrelated to economics.

Because of the assumed fixed relations of capital and labor, the rate of growth, g, of Y is constrained by n, which implies that in equilibrium, $g \leq n$. If $g < n$ there will be a continuing increase in unemployment over time. If it is assumed that increasing unemployment would affect the labor market in a manner to prevent equilibrium growth, then the necessary condition for long-term, steady-state economic growth is that $g = n$. Harrod calls this the "natural" growth rate.

The production function for the economy may be written

$$Y = f(K, L) \tag{1}$$

where K is the stock of capital, expressed in value terms, and L is the

*The literature on economic growth theory is very extensive and includes numerous models. The main differences among them are their basic assumptions regarding saving, consumption and production functions, capital-output ratios, and the roles of wages, prices and interest rates. A Harrod-Domar-type model is used here as a point of departure mainly because the basic assumptions are not incompatible with the realities of developing countries and our subsequent analyses of the effect of education on a developing economy. For a comprehensive review of growth theory see Reference 100 Survey V.

labor supply. In a closed economy, in equilibrium, and with a fixed capital-output ratio (K/Y), Y can only grow if K grows, and the rate of increase in K will be given by the amount of savings developed in the economy. Savings can only arise from profits of entrepreneurs or from foregone consumption of wage earners. If hoarding is excluded, the rate of savings,

$$s = \frac{\Delta K}{K} = \frac{\Delta Y}{Y}.$$

But with fixed relations between K and L to produce Y, this can only occur if L increases proportionately, thus s will be limited by n, and, where population expansion is socially undesirable, each new birth control technique would serve to reduce s and thereby g.

In a world of technological advance output may be increased by increasing the productivity of capital or labor or both. To express the effect of technological change on output, the production function may be rewritten

$$Y = A(t)\, f(K, L) \tag{2}$$

where A(t) is a measure of efficiency derived by applying new technology. The t refers to a specific time period. Technological advance may be either labor-augmenting or capital-augmenting; its net effect will be to increase Y, given a stock of capital and labor. Obviously, such an increase in output may increase s, by either increasing profits on capital or real wages to labor. We shall not explore the demand conditions which would permit a ΔY, or the behavioral aspects of savings or consumption. Our purpose is to show that, at least on a short-term basis, or in disequilibrium, output may be increased by technological advance.

By differentiating (2) with respect to time we find

$$\frac{dY}{dt} = \frac{d\,A(t)}{dt}\left[f(K, L)\right] + A(t)\frac{d f(K, L)}{dt} \tag{3}$$

but from assumptions 2 and 3 and by differentiating (1) with respect to time

$$\frac{dY}{dt} = g = \frac{df(K, L)}{dt} = n$$

Thus

$$\frac{dY}{dt} = \frac{d\,A(t)}{dt}\left[f\,(K,\ L)\right] + n\,A(t) \tag{4}$$

The implications of (4) are that the time-rate of increase of national output will depend upon the rate of change of technology which permits more efficient production, and upon the rate of growth of the labor force at the current level of production efficiency.

A commonly found characteristic of developing nations is that the level of productivity of the labor force is significantly less than that found in developed nations. This indicates that A(t) is low. Of equal importance, there may be a sizeable portion of the population existing outside of the money economy and therefore not technically considered to be part of the labor force. In such cases, the labor force can be made to grow at a very much greater rate than the population growth rate, at least for some short period, merely by bringing these "outsiders" into the labor force. This requires educating and training the new entrants in the techniques of production.

Nelson and Phelps* express the rate of change of the level of application of technology in a given period as

$$\dot{A}(t) = \phi(h)\left[T(t) - A(t)\right] \tag{5}$$

where (h) is a function of the average level of education, $T(t) = T_o e^{\lambda t}$, denotes the current theoretical level of technology associated with some exponential growth factor, λ, over a period t, and A(t) is the actual level of technology applied in period t. They assume that h is constant, or essentially so, over a short period. This assumption is reasonable for industrialized, developed countries with relatively high average levels of education. But for the developing countries, those which have low average

*Richard R. Nelson and Edmund S. Phelps, "Investment in Humans, Technological Diffusion and Economic Growth," American Economic Review, May 1966, pp. 69-75. It has been suggested by Mr. R. Alexovitch of the NASA Lewis Laboratories that this function should be more generally stated as $\dot{A}(t) = \phi(h)\,F\left[T(t),\ A(t)\right]$. However, since our analysis is only concerned with the $\phi(h)$ term, we have used the expression, as presented in the original paper.

educational levels, one might expect that h is not only not constant, but may be growing at a sufficient rate to significantly affect $\dot{A}(t)$.

In simple form, the average educational level, h, of a country at any instant may be given by

$$h = \frac{\sum_{j=0}^{P} (py)_j}{P} \qquad j = 0, 1, 2, 3 \ldots P-1, P \tag{6}$$

where the (py) are the student-years of formal schooling of the j^{th} person of the population, P. However, considering the emerging nations, a simple statement of student-years neglects the quality of the educational programs. Even when differences in wage rates and living costs are taken into consideration, an expenditure of $500 per student-year in one country versus $50 per student-year in another, implies a difference in the quality of school years. Introduction of improved teaching methods, teaching materials, or teacher-training programs can significantly improve the output of the educational system, quite possibly at the same per-student expenditure rate.

In the United States, average achievement of students, at various grade levels, varies from locale to locale. Students transferring from one school system to another frequently require remedial or enrichment attention, or are shifted from their previously assigned grade level, up or down, to the suitable grade level in the new school system. Performance on national tests also shows variations in achievement among students from different locales. If we assume that these differences have some correlation with per-student school expenditure, then we can establish a "standard" expenditure, per-student, associated with the national average achievement, and, given uniform pedagogy, the effective achievement level in a given system may be related to the disparity between the standard expenditure and the actual expenditure in that system such that:

$$h = \frac{\sum_{t=n}^{m} \frac{a_t}{\beta_t}}{(m-n)} \cdot \frac{\sum_{j=0}^{P} (py)_j}{P_m} \qquad \begin{array}{l} j=0, 1, 2, 3, \ldots P-1, P \\ t=n, n+1, n+2, \ldots m-1, m \end{array} \tag{7}$$

where a_t is the actual per-student budget in year t, β_t is the standard expenditure in year t, and m and n are the boundaries of the period under investigation. Generally, m and n should be chosen to reflect the realities of the system.

If living conditions were uniform in all regions and all teachers and administrators were perfectly mobile, one might expect that in market economies, above some threshold level of per-student expenditure, teaching materials, methods, and efficiencies would be uniform. Unfortunately this is not the case. Wealthy school systems may attract especially qualified teachers and have high teacher-student ratios; they may use the most advanced audio-visual aids and otherwise employ the latest tools of educational technology. Poor systems may not even have books and paper, or teachers with four-year college degrees. Clearly, then, in computing national, average levels of education, the school years must be factored by some quantity which reflects the differences in quality among systems. Again, assuming a "standard" quality for a "standard" system (which might be measured by average level of teacher training, numbers of books per student, numbers of hours of audio-visual teaching, teacher-student ratios, and so forth), Equation (3) may be modified by an efficiency factor, $\epsilon = \frac{r}{\rho}$, where r is the quality of practiced pedagogy and ρ is the "standard" quality, to arrive at an expression of the effective average level of education, $\overset{*}{h}$, at a point in time.

$$\overset{*}{h} = \frac{\sum_{\tau=n}^{m} \epsilon_\tau}{(m-n)} \cdot \frac{\sum_{\tau=n}^{m} \frac{\alpha_\tau}{\beta_\tau}}{(m-n)} \cdot \frac{\sum_{j=0}^{m} (py)_{j_m}}{P_m} \qquad \begin{matrix} j=0,\ 1,\ 2,\ \ldots\ P-1,\ P \\ \tau=n,\ n+1,\ \ldots\ m-1,\ m \end{matrix} \tag{8}$$

In Equation (5), $\dot{A}(t)$ implies a potential for change in the level of technology being practiced in some region or nation. If Equation (5) is rewritten as a difference equation:

$$\Delta\dot{A}(t) = \Delta\left[\phi(\overset{*}{h})\ [T(t) - A(t)]\right] \tag{9}$$

and $\overset{*}{h}$ is a time related variable, we must also express its rate of change in order to properly evaluate $\Delta\dot{A}(t)$.

The change in $\overset{*}{h}$ from one period to the next will be related to the original state, the average change in $\overset{*}{h}$ induced by effective student-years added in the next period, either through the educational system or by immigration, and the decrease in $\overset{*}{h}$ related to mortality or emigration. This may be expressed as

$$\Delta\overset{*}{h}(t) = \overset{*}{h}(t+1) - \overset{*}{h}(t) = E\overset{*}{h}(t) - \overset{*}{h}(t) \tag{10}$$

where Δ and E are difference operators and the t's denote the time period.

Considering the effects of continued education, emigration and mortality,

$$\overset{*}{h}(t+1) = \frac{\sum\limits_{\tau=n}^{m} \frac{r_\tau}{\rho_\tau}}{(m-n)} \cdot \frac{\sum\limits_{\tau=n}^{m} \frac{\alpha_\tau}{\beta_\tau}}{(m-n)} \cdot \frac{\sum\limits_{j=0}^{P_t} (py)_j}{P_t} + \frac{r_{t+1}}{\rho_{t+1}} \frac{\alpha_{t+1}}{\beta_{t+1}} \frac{\sum\limits_{i=0}^{S} (sy)_i}{P_{t+1}}$$

$$+ \frac{\sum\limits_{k=0}^{Q} (qy)_k}{P_{t+1}} - \frac{\sum\limits_{\tau=n}^{m} \frac{r_\tau}{\rho_\tau} \sum\limits_{\tau=n}^{m} \frac{\alpha_\tau}{\beta_\tau}}{(m-n)^2} \cdot \frac{\sum\limits_{\ell=0}^{U} (uy)_\ell}{P_{t+1}} \tag{11}$$

and

$$\Delta\overset{*}{h}(t) = \frac{r_{t+1}}{\rho_{t+1}} \frac{\alpha_{t+1}}{\beta_{t+1}} \frac{\sum\limits_{i=0}^{S} (sy)_i}{P_{t+1}} + \frac{\sum\limits_{k=0}^{Q} (qy)_k}{P_{t+1}} - \frac{\sum\limits_{\tau=n}^{m} \frac{r_\tau}{\rho_\tau} \sum\limits_{\tau=n}^{m} \frac{\alpha_\tau}{\beta_\tau}}{(m-n)^2} \cdot \frac{\sum\limits_{\ell=0}^{U} (uy)_\ell}{P_{t+1}} \tag{12}$$

where the $(sy)_i$ represent the additional formal student-years of education of the i^{th} person in the indicated period, the $(qy)_k$ represent the educational levels of the k^{th} immigrant during that period, and the $(uy)_\ell$ denote the educational level of the ℓ^{th} decedent or emigrant from the population in the indicated period. Then

$$\Delta \dot{A}(t) = E\phi(\overset{*}{h})\, \Delta \left[T(t) - A(t)\right] + \Delta\phi(\overset{*}{h}) \left[T(t) - A(t)\right] \tag{13}$$

If we let

$$\frac{\sum_{\tau=n}^{m} \frac{r_\tau}{\rho_\tau}}{(m-n)} = \bar{\epsilon},$$

an average system efficiency factor and

$$\frac{\sum_{\tau=n}^{m} \frac{a_\tau}{\beta_\tau}}{(m-n)} = B,$$

an average budget factor, and

$$\epsilon = \frac{r}{\rho} \text{ and } b = \frac{a}{\beta}$$

Then (13) can be rewritten

$$\Delta \dot{A}(t) = \left[B\bar{\epsilon} \frac{\sum_{j=0}^{P_t} (py)_j}{P_t} + \epsilon_{t+1}\, b_{t+1} \frac{\sum_{i=0}^{S} (sy)_i}{P_{t+1}} + \frac{\sum_{k=0}^{Q} (qy)_k}{P_{t+1}} - B\bar{\epsilon} \frac{\sum_{\ell=0}^{U} (uy)_\ell}{P_{t+1}} \right]$$

$$\left[T_o e^{\lambda t} \left[e - 1\right] - \Delta A(t) \right] \tag{14}$$

$$+ \left[T_o e^{\lambda t} - A(t) \right] \left[\epsilon_{t+1}\, b_{t+1} \frac{\sum_{i=0}^{S} (sy)_i}{P_{t+1}} + \frac{\sum_{k=0}^{Q} (qy)_k}{P_{t+1}} - B\bar{\epsilon} \frac{\sum_{\ell=0}^{U} (uy)_\ell}{P_{t+1}} \right]$$

Further, if

$$\hat{P}_t = \frac{\sum_{j=0}^{P} (py)_j}{P_t}; \quad \hat{S}_{t+1} = \frac{\sum_{i=0}^{S} (sy)_i}{P_{t+1}}; \quad \hat{Q}_{t+1} = \frac{\sum_{k=0}^{Q} (qy)_k}{P_{t+1}};$$

and

$$\hat{U}_{t+1} = \frac{\sum_{\ell=0}^{U} (uy)_\ell}{P_{t+1}};$$

then (14) can be written

$$\Delta\dot{A}(t) = \left[B\bar{\epsilon}\hat{P}_t + \epsilon_{t+1} b_{t+1} \hat{S}_{t+1} + \hat{Q}_{t+1} - B\bar{\epsilon}\hat{U}_{t+1}\right]\left[T_o e^{\lambda t}[e - 1] - \Delta A(t)\right]$$

$$+ \left[T_o e^{\lambda t} - A(t)\right]\left[\epsilon_{t+1} b_{t+1} \hat{S}_{t+1} + \hat{Q}_{t+1} - B\bar{\epsilon}\hat{U}_{t+1}\right] \qquad (15)$$

In most countries the annual number of deaths is less than one percent of the existing population. Also, since average education levels are, and for a long time have been, rising virtually everywhere, those who die probably have a lower average level of education than the general population. Although emigrants generally have comparatively high educational levels, they are relatively few in number. Consequently, if we delete the U term, the size of the error in average educational level introduced by this deletion should be less than one percent. Similarly, deletion of the Q term should not introduce an error greater than one percent (except in countries such as Australia, which have small populations and very high immigration rates). Since these two potential small errors are of opposite sign, the combined effect of neglecting the U and Q terms should introduce a negligible error.

By eliminating the immigration, emigration and mortality terms and rearranging Equation (15) we arrive at

$$\Delta\dot{A}(t) = \dot{A}(t+1) - \dot{A}(t) = \left(B_1\bar{\epsilon}_1\hat{P}_1 + \epsilon_2 b_2 \hat{S}_2\right)\left[T(t+1) - A(t+1)\right]$$

$$- B_1\bar{\epsilon}_1\hat{P}_1\left[T(t) - A(t)\right] \qquad (16)$$

where subscript 1 denotes t' and subscript 2 denotes $t+1$; and finally we have:

$$\dot{A}(t+1) = \left[B_1\bar{\epsilon}_1\hat{P}_1 + \epsilon_2 b_2 \hat{S}_2\right]\left[T(t+1) - A(t+1)\right] \quad . \qquad (17)$$

But when (17) is substituted for $\frac{dA(t)}{dt}$ in (4) we see that, independent of the gap between theoretical and applied technology, the rate of change of application of technology, and therefore the rate of change of economic growth, is not only related to the average effective level of education ($B_1\bar{\epsilon}_1\hat{P}_1$) in some base period, but also to the rate at which effective student-years are being added in the current period ($\epsilon_2 b_2 \hat{S}_2$). In emerging countries, where $B_1\bar{\epsilon}_1\hat{P}_1$ is small, changes in $\epsilon_2 b_2 \hat{S}_2$ will dominate $\dot{A}(t+1)$. Also, since in emerging countries b_2 is highly constrained by competition among other projects (e.g., agricultural, industrial and infrastructural development, health, and housing programs) for budget allocations, ϵ_2 and $\hat{S}_2$ are more likely parameters for affecting A(t+1). The added efficiency of audio-visual techniques, together with the immediate and rapid expansion of the student body by wide dissemination of satellite ETV, should therefore play a major role in promoting economic growth. This effect may well be far greater than simple cost savings over competing systems which cannot be made operational as rapidly.

13. TECHNOLOGY EVALUATION

13.1 COMMUNICATIONS SUBSYSTEM

Except for high-power transmitter output amplifiers, communication subsystems for television broadcast satellites can be built with the technology used in communication satellites presently in operation.

The present state-of-the-art in spaceborne RF power amplifiers reaches to output powers of a few hundred watts. For output power levels above 0.5 kilowatt, further development is necessary. Technological advances are absolutely required to achieve a 5-year life with adequate reliability (>0.7) and to provide adequate and reliable cooling commensurate with the 5-year life requirement. Improved transmitter efficiency relaxes the cooling requirements, to a theoretical limit, and therefore is as important for feasibility as cooling capacity.

Enhancement of efficiency further relaxes requirements on the design of large solar arrays and when developed, will yield savings in satellite costs or earth receiver costs.

Recent studies (References 3-1 through 3-5) of multi-kilowatt RF amplifiers resulted in analytical designs (Table 3-1). In these studies, primary emphasis was on achieving high overall efficiency. All these designs feature multi-stage depressed collectors as the method yielding the largest efficiency improvement. Heat-pipe configurations for cooling were presented in all studies, while life was approached primarily from the viewpoint of cathode design and loading. Amplitude linearity for AM/VSB and phase linearity (group delay) were examined in varying degree.

Clearly, experimental verification of efficiency, thermal design, life, and linearity are required. Experiments in simulated environment and considerable hardware development are required before operational spaceborne amplifiers with output levels above 1 kilowatt can be produced.

Development of lightweight RF circuit components (including) diplexers and filters) capable of handling high average power (up to 10 kw) in space environment, is required. The critical issues are multipaction and cooling.

Local oscillators with adequate frequency stability ($2 \cdot 10^{6}$) are within the present state-of-the-art. The use of advanced solid-state devices such as avalanche diodes, Gunn and LSA mode devices, is not strictly necessary for feasibility, but will most likely offer simpler and more reliable circuits. In view of the present rapid development of these devices, separate activity for the Television Broadcast Satellite Mission is not recommended.

Overall subsystem development will be required for specific designs, with emphasis on linearity and stability of high-gain amplification, isolation between transmitter and receiver, and thermal isolation.

13.2 ANTENNAS

13.2.1 Reflector Antennas

A fundamental requirement on antennas for television broadcast satellites will be concentration of the total radiated power on a limited area. At the lowest frequency of interest, 0.9 GHz, this requirement dictates the use of satellite antennas as large as 30 feet (9 m) to cover an area with a diameter of 1000 miles, or 60 feet for a 500 mile coverage.

The critical issues are weight, deployment reliability, and the geometric accuracy of the surface when subjected to dynamic and thermal distortion in space environment. The surface accuracy requirements are set primarily by the acceptable limits on sidelobe levels and pointing accuracy (Sections 2.6.2, 4.2.1.2, and 4.4.3).

Substantial efforts have been spent on the design of unfurlable antennas with wire-mesh surfaces (Appendix 4A). To date, space flight experience has not been obtained with antennas larger than 10 feet (3 m).

Further full-scale model development and testing are required to obtain the level of confidence in reliability and performance which is required to commit a 30 foot deployable antenna to a space mission.

Feed configurations for large reflector antennas capable of handling multi-kilowatt power levels, are not state-of-the-art. Development is required to achieve illumination patterns for low sidelobe levels and power handling capability up to an average of 10 kilowatts. The critical issues of the latter objective are multipaction and thermal control.

Shroud limitations on spacecraft dimensions will, in general, prohibit the use of more than one large deployable reflector antenna. Multiple beam transmission by reflector antenna can then be achieved only with a multiple-feed arrangement. The main problems with this approach are geometric conflicts at the feed and the feasibility of low-level sidelobes. Coma caused by off-axis location of feed radiation centers and coupling between feeds, have adverse effects on the sidelobe level. An array-type of feed is a potential solution. Further development is required if multiple-beam transmission by a single reflector is an actual requirement. Any decisions on such development should be made only after consideration of the potential capabilities of phased arrays.

13.2.2 Phased Arrays

The potential advantages of phased arrays are:

- Beam pointing without attitude disturbance torques.
- More freedom in aperture distribution design than possible with reflector antenna feeds, permits achievement of lower sidelobe levels.
- Multiple-beam capability without adverse effects on sidelobe level.
- With active arrays, distributed power dissipation facilitates thermal control.

Phased arrays fed by a single transmitter compare unfavorably with reflector antennas, because of the large weight of a phased corporate feed network with full RF output power capability and the heavy power losses in such a network. Only active arrays, with final amplification at each element (or small group of elements), are potentially competitive and only at the lower frequencies, 0.9 GHz and 2.5 GHz.

Active arrays for the present application are not within the existing state-of-the-art. With the rapid development of solid-state devices for microwave power generation, it appears that active arrays at 0.9 GHz and 2.5 GHz become competitive for missions in the 1975-1980 time period. This would require development in the following areas:

- Design elements such as a strain energy deployable reflector with a complementary pair feed or a strain energy deployable helix.
- Power capability and efficiency of transmit modules.
- Deployment of array with feed network.
- For multiple-beam capability, feed network development.

13.2.3 RF Rotary Joints

The critical issues of RF rotary joint design for the present application are multipaction and thermal control. Apparently, there is not sufficient evidence of feasibility from tests in simulated space environment. RF rotary joints for power levels above 1 kilowatt can, therefore, not yet be considered state-of-the-art.

In the present application, the use of RF rotary joints is warranted only when the spacecraft body is sun-oriented. Since earth-oriented antennas are indicated for both downlink and uplink (Section 2.9), the RF rotary joint must handle both the high transmitter output power and the considerably lower received RF signal power. Thus, at least two channels are required and isolation between these channels is a severe design criterion.

Additional development and testing of RF rotary joints are required, before a spacecraft having a sun-oriented body can be built with RF output level over 1 kilowatt.

13.3 ELECTRICAL POWER

Silicon solar cell arrays are within the present state-of-the-art. Development is required for adaption to bus voltages of at least 100 volts.

In the areas of array deployment, structural design, and orientation considerable development efforts are in progress. The Pegasus mission has shown the feasibility of deployment. The structural development required for the television broadcast mission will be primarily adaption of existing technology to the particular spacecraft dynamics and attitude control performance.

DC sliprings are within the present state-of-the-art. Additional development is required for adaption to bus voltage of at least 100 volts. Consideration should also be given to possible outgassing problems, brush redundancy requirements, and the risk of cold welding associated with high current density at contacts with low slip velocity.

Efficient conditioning of multi-kilowatt power is not within the present state-of-the-art. Additional development is required in the following areas:

- Modular, high-power, multi-kilowatt, self-protecting collector power supplies, regulated for input line and load variations.
- Converters for recovery of energy from collectors and feedback to input bus.
- Output filters to supply synchronizing power and provide low output impedance for amplitude modulation induced load variations.
- High power solid-state inverters operating from input voltages, 200 to 500 volts for improved conversion efficiency.

13.4 ATTITUDE CONTROL AND STATIONKEEPING

The control system analyses performed in the present study resulted in the recommendation of a three axis control using colloid engines for attitude control and stationkeeping during normal operational conditions. Also, it was recommended that hydrazine be used for trim maneuvers after orbit injection and initial orientation and for reacquisition maneuvers in case of loss of control. This approach is within the present state-of-the-art, except for 5-year life of colloid engines. Life tests in simulated space environment are being performed. Further development may be required to achieve 5-year life.

With a transmit antenna beam width of 3 degrees, beam pointing to an accuracy of 0.1 degree is required to keep pointing error losses within 0.5 db. With interferometer techniques using sensors mounted on the transmit antenna, control of the sensor mount orientation within ± 0.1 degree is feasible with state-of-the-art techniques. However, dynamic and thermal distortions of the transmit antenna cause an unknown offset between the actual beam direction and the sensed direction. This error would be removed if the interferometer signals use the transmit antenna reflector. Development of such a system is recommended.

The dynamic interactions of structural flexibility, primarily in large antennas and large solar arrays with the attitude control, require development of accurate models to represent the flexible systems and of hybrid computer software to examine the dynamic interactions. Several studies are required to clarify various aspects of the interaction simulation which heretofore received only scant attention. These are:

- Development of more realistic nonviscous models for structural damping.
- Investigation of the modal coupling effect through damping.
- Effect of discrete dampers on the motion of a flexible spacecraft:
  - Viscous dampers
  - Impact dampers
  - Eddy current dampers
  - Magnetic hysteresis dampers
- Development of analytical models to describe the characteristics of interconnections of structural members (joint interface, backlash, etc.).
- Study of dynamic isolation of spacecraft components; for example, isolation of a 22 foot boom from the control system of the OGO spacecraft.
- Improved control configurations:
  - Type, number, and location of sensors which will provide accuracies of better than ± 0.1 degree.
  - Auxiliary control systems designed to maintain the shape of sensitive spacecraft components (large dish antenna).
  - Improved actuators in control system design.

Hardware development will be required to shape the frequency response of the solar array drive servo. system for dynamic isolation of the array from the spacecraft body. Also, active elastic oscillation damping sensors and dampers need to be developed.

13.5 THERMAL CONTROL

Two specific areas need significant development before a satisfactory thermal control system can be designed. Large, deployable antennas require an integrated thermal structural analysis with a high degree of sophistication. The high heat density sources present another difficult design problem which has not been encountered previously in spacecraft.

13.5.1 Deployable Antenna Thermal Analysis

The preservation of satisfactory RF performance in large parabolic antennas in space, requires that during flight the reflecting surfaces be maintained close to their original geometry. External thermal inputs in space, such as solar heating, tend to produce gradients which may result in distortions of the antenna surfaces. Thus, an essential part of the required analysis is the prediction of the temperature and distortion profiles and resultant effects on antenna performance. This analysis must have a high degree of sophistication as satisfactory thermal vacuum testing of these large antennas is beyond the capabilities of existing environmental simulation facilities.

An integrated thermo/structural analysis procedure is required to determine temperature distributions and distortions. Clearly, this could only be done through computer simulation. The effect of various hole patterns in the antenna must be included. Resultant differential shading of the antenna for various solar inclination angles must be simulated in the computer program. Conduction and radiation interchange between the antenna and support structures must be included. A program capable of describing highly redundant structures must then be integrated with the thermal analysis.

13.5.2 High Density Cooling

Cooling of the rf tube presents a difficult problem because of the high heat densities expected at the source. The density is high enough, in most cases, to preclude heat removal by radiation. Thus, an active system must be designed for transfer of heat from the source to a radiator surface of sufficient area for rejection at a suitable temperature. Two systems have been identified in this study: heat pipe system and circulating liquid system.

Considerable development would be required to apply either system. The long lifetime requirements on TV broadcast satellites impose severe reliability constraints on the motor-pump combination of any active system. Since the system does not operate during eclipse periods, control of the system to prevent undercooling would be required. The fluid must be capable of withstanding both heat during operation and cold during eclipse. The development of heat pipe system must include both system configuration and fluid for high heat transfer density.

13.5.3 Low Density Cooling

The low density cooling of all power conditioning equipment and, low power, internal equipment is controlled by louvers. This method is within the state-of-the-art. Warping of louvers under sunlit condition may require some application development.

13.6 USER EQUIPMENT

The user equipment consists of a space-oriented antenna and electronic equipment to adapt a regular television receiver to satellite transmission. Development of the adapter is currently being pursued by General Electric under contract with NASA. The results of these efforts should lead to indication of further development requirements.

System cost and performance would benefit from development of low cost, circularly polarized antennas. Low sidelobes and backlobes are desirable for rejection of man-made noise and earth radiation noise.

13.7 PRIORITY

First priority should be given to the development objectives required for feasibility of an experimental mission. These include:

- RF output power amplifiers with high efficiency.
- Thermal control of transmitters.
- Power conditioning for transmitters.
- Solar array deployment.
- Dynamic interaction of flexible structures.

Large deployable antennas are necessary for feasibility only for broadcasting at 0.9 GHz.

Items of second priority are those required for feasibility of a 5-year operational mission and ones with potentially significant impact on performance or cost. These items are:

- Antenna feed design for low sidelobes.
- Multiple-beam transmission by single-reflector antenna.
- Active phased arrays.
- RF rotary joints.
- Adaption of solar array technology to bus voltages over 100 volts.
- DC slipring design to bus voltages over 100 volts and 5-year life.
- Colloid engines for 5-year life.
- RF techniques for sensing of the true direction of the transmit beam.