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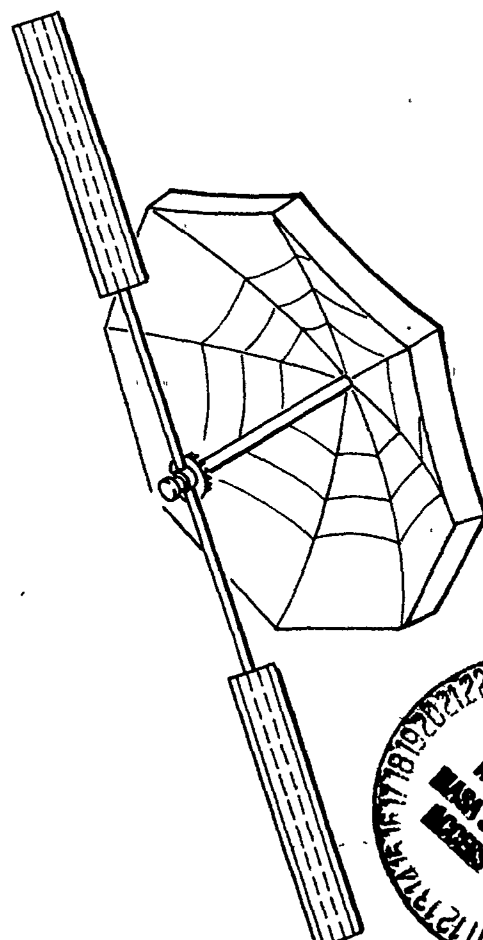
# Satellite Voice Broadcast System Study

## Volume 2 — Technical Report

July 1985





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15 Supplementary Notes

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16 Abstract

This study investigates the feasibility of providing Voice of America (VOA) broadcasts by satellite relay, rather than via terrestrial relay stations. Satellite voice broadcast systems are described for three different frequency bands: HF (26 MHz), VHF (68 MHz), and L-band (1.5 GHz). The geographical areas of interest at HF and L-band include all major land masses worldwide with the exception of the U.S., Canada, and Australia. Geostationary satellite configurations are considered for both frequency bands. In addition, a system of subsynchronous, circular satellites with an orbit period of 8 hours is developed for the HF band. VHF broadcasts, which are confined to the Soviet Union, are provided by a system of Molniya satellites.

Satellites intended for HF or VHF broadcasting are extremely large and heavy. Satellite designs presented here are limited in size and weight to the capability of the STS/Centaur launch vehicle combination. Even so, at HF it would take 47 geostationary satellites or 20 satellites in 8-hour orbits to fully satisfy the voice-channel requirements of the broadcast schedule provided by VOA. On the other hand, three Molniya satellites suffice for the geographically restricted schedule at VHF.

At L-band, only four geostationary satellites are needed to meet the requirements of the complete broadcast schedule. Moreover, these satellites are comparable in size and weight to current satellites designed for direct broadcast of video program material.

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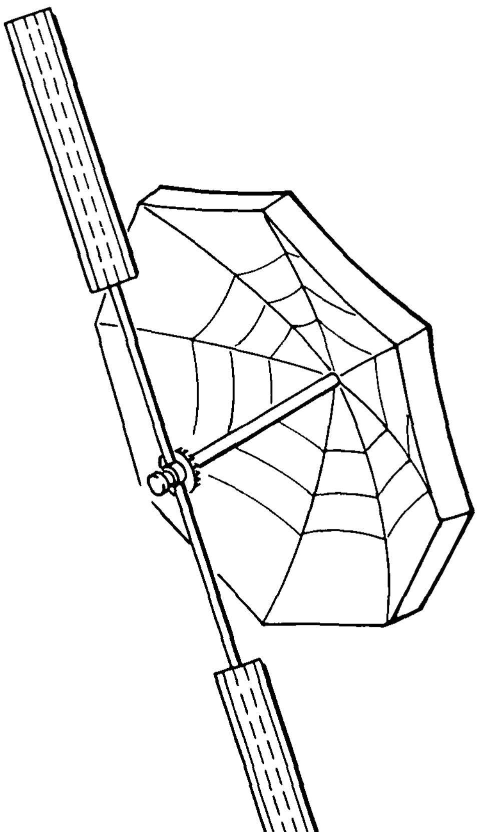

Prepared for
NASA Lewis Research Center

**Federal Systems Division**
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TRW

# Satellite Voice Broadcast System Study

## Volume 2 — Technical Report

## July 1985

Contract No. NAS3-24232

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## PREFACE

This document is the final report of a 1-year study conducted by TRW Federal Systems Division for the NASA Lewis Research Center to determine satellite system designs, and associated life cycle costs, appropriate to Voice of America broadcasting needs.

The report comprises three volumes. Volume 1 is an Executive Summary. Volume 2 contains the technical results of the study, together with a life cycle cost summary. Volume 3, which is labeled proprietary, contains non-recurring and first-unit cost estimates for the various satellite configurations generated during the study.

## CONTRIBUTORS

The following individuals made significant technical contributions in the areas indicated:

| | |
|---|---|
| W. Akle | Satellite Configurations<br>Antenna Structural Analysis<br>Satellite Weight Estimation |
| I. S. Cohen | Transponder Technology |
| S. H. Cushner | Nonsatellite Broadcast Platforms |
| M. Horstein | Link Analysis<br>System Synthesis and Evaluation |
| J. L. Jennings | Orbital Analysis |
| J. D. Phillips | Cost Analysis |
| M. Swerdling | Electrical Power Technology |
| G. G. Wong | RF Antenna Design |
| R. E. Wong | Project Planning |

L'Garde, Inc. of Newport Beach, California, as subcontractor to TRW, provided data on the performance of the inflatable antenna reflector.

The technical study managers for NASA LeRC were Mr. G. H. Stevens and Mr. C. E. Provencher. Their guidance during the course of the study, together with that of Mr. B. E. LeRoy (Head, Satellite Systems Section), is deeply appreciated.

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# 1. INTRODUCTION

The Voice of America (VOA), a division of the U.S. Information Agency (USIA), provides voice broadcasts to most areas of the world. These include, on a daily basis, more than 30 hours of English broadcasts and more than 100 hours of foreign language broadcasts. The dominant broadcast type is news, followed by features, news related material, music, and editorials. News sources include the wire services, domestic and foreign news bureaus, foreign broadcasts, and periodicals.

VOA's technical headquarters are in Washington, DC. VOA programming, which originates in Washington, is transmitted to listeners via relay stations located in the U.S. and in a number of foreign countries, as well as through leased facilities. Most transmissions to U.S. and foreign relay stations are at high frequency (HF), although in some cases satellite links are now used.

Many of the relay station transmission facilities are quite old and/or of lower power than desired. Consequently, VOA has embarked on a $1 billion modernization program to replace antennas at high priority sites, upgrade transmitters at existing relay stations, and begin construction of several new projects.

In conjunction with the modernization effort, VOA is considering the potential application of new technologies. To this end, the USIA has funded NASA to contract with two satellite manufacturers to investigate the role that satellite direct broadcasting might play in VOA's future operations. This report contains the findings of a 1-year study conducted by TRW in answer to this question.

Several previous studies have examined the possibility of satellite voice broadcasting. The earliest studies were conducted for NASA in 1967 (References 1-1 and 1-2). Technology advances in subsequent years have rendered invalid certain conclusions reached in these studies. Report 955 of the XVth Plenary Assembly of the International Radio Consultative Committee (Reference 1-3) considers frequencies between 500 megahertz and 2 gigahertz for sound broadcasting to portable and mobile receivers. The feasibility of the 26-megahertz band for satellite sound broadcasting is examined in Reference 1-4. Central to the feasibility question at

26 megahertz is the matter of ionospheric penetration of the broadcast signals. Results of an analytical investigation to assess ionospheric effects in the HF and VHF bands are reported in Reference 1-5. The latter study served as a precursor to the present effort. Finally, the use of satellite sound broadcasting to aid in the development of Third World countries is considered in Reference 1-6.

To be of value, voice broadcasting must take place at frequencies within the bandwidth of receivers in the hands of the populace. The most widely received shortwave bands are between 6 and 11 megahertz. A considerably smaller percentage of radios can receive frequencies between 20 and 26 megahertz. However, to be reasonably assured that satellite transmissions will penetrate the ionosphere, they should be above 20 megahertz (Appendix A). An additional reason for desiring a higher broadcast frequency is to reduce the size of the satellite antenna, as the antenna diameter needed to produce a given beamwidth varies inversely with frequency.

The array of frequency bands considered in this study is indicated in Figure 1-1. Band 1 comprises four HF subbands for which direct broadcasting allocations exist. Because of the questionable nature of ionospheric penetration at the lower subbands, the Band 1 system designs are described primarily for the top subband.

Band 2, which lies in the VHF band, was considered in this study only for broadcasts to the Soviet Union, in which there exists a significant population of suitably tunable receivers. Because of the inverse relationship between antenna size and frequency, Band 2 systems are assumed to operate at 68 megahertz.

Band 3 receivers are virtually nonexistent today. However, because of the long-range objectives of this study and the attractiveness of the higher frequency bands for direct broadcasting, the characteristics of Band 3 broadcast systems were investigated as well.

The three frequency bands under the Band 4 heading are currently allocated to direct broadcasting in Regions 1, 2, and 3 as defined by the International Telecommunications Union. Operational and contemplated systems designed for this band are generally intended for video broadcasts. However, the Band 4 allocations apply to audio broadcasting as well.

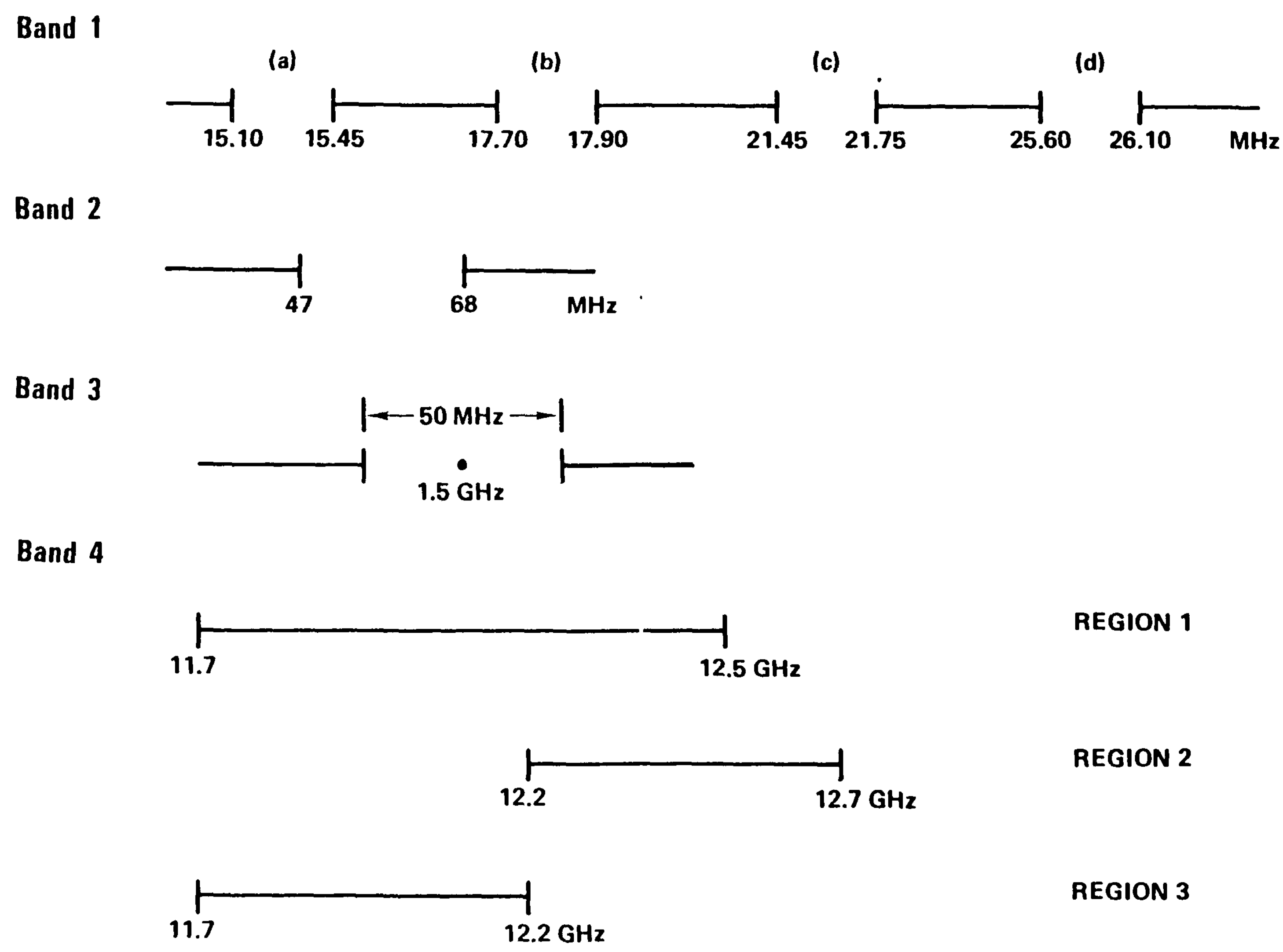


Figure 1-1. Frequency Band Definition

Band 1 transmissions employ double-sideband amplitude modulation (DSB-AM), with a maximum baseband frequency of 5 kilohertz. Broadcasts in Bands 2, 3, and 4 use frequency modulation (FM), with a maximum baseband frequency of 15 kilohertz and a maximum deviation of 75 kilohertz. The RF bandwidths of the DSB-AM and FM transmissions are 10 and 250 kilohertz, respectively.

The present study is confined to developing satellite voice broadcast system concepts for the different frequency bands. A subsequent contract will be awarded by VOA to develop projections of receiver populations worldwide. The results of the latter study will be combined by VOA with the system concepts developed under the present pair of contracts to assess the attractiveness of those system concepts.

Once this assessment has been made, it will be possible to evaluate the merits of satellite broadcast systems as a complement to, or substitute for, terrestrial broadcast facilities. This comparison will be facilitated by life cycle costs developed for each of the satellite systems as part of the present study.

A number of analyses and tradeoffs were performed in the initial phase of this study to help identify the most promising satellite system concepts. These analyses established: coverage afforded by satellites in different orbits, RF power required per broadcast channel in each of the frequency bands, suitable antenna configurations together with antenna weight and stowed dimensions, relative merits of different primary power sources and associated electrical subsystem weight, and the status and weight of different high-power transmitter technologies.

Based on these results, four satellite system concepts were examined in considerable detail. These are identified below by frequency band and satellite orbit.

| System | Band | Orbit |
|---|---|---|
| 1 | 1 | Geostationary |
| 2 | 1 | 8-hour circular |
| 3 | 2 | Molniya |
| 4 | 3 | Geostationary |

Each of the four satellite systems is designed to satisfy the channel requirements of a broadcast schedule provided by VOA. This schedule specifies the number of voice channels to be provided to each of 15 geographical zones at 15-minute intervals throughout the day. (System 3 deals only with the four zones that constitute the Soviet Union.) The required number of satellites is a function of the voice-channel capacity of an individual satellite, which in turn depends on the lift capability to low-earth orbit (LEO) of the Space Transportation System (STS). The latter is taken to be 65,000 pounds; this capability should be available by the end of the decade. A satellite-weight-estimation computer program developed under this contract is used to determine the maximum satellite capacity for all Band 1 and 2 systems. (Band 3 satellites, which are more conventional in design, are sized to accommodate the total voice-channel capacity required at each orbit location.)

Once the satellite capacity is established, it is a simple matter to determine the required number of satellites for a geostationary system, because the satellite coverage pattern is time invariant. The same is true for a Molniya system, because the satellites are nearly stationary during the portion of the orbit (near apogee) when broadcasting takes place.

The satellite requirement for the 8-hour-orbit system (or for any of the other subsynchronous orbits considered in this study) is more difficult to determine because of the continuously varying coverage provided by each satellite. A system design methodology is developed in Section 2 which combines considerations of satellite coverage, broadcast schedule requirements, and satellite voice-channel capacity. This methodology, which has been computerized for the more complex, subsynchronous-orbit cases, is applied in Section 3 to each of the four "baseline" systems.

Feeder-link possibilities for each system are also developed in Section 3. It is shown that, with a few exceptions in the case of the 8-hour-orbit system, it is always possible to provide a real-time feeder link from the U.S., Guam, Western Europe, or Australia.

A number of system variations are developed in Section 4. These are based on:

a) Reductions in coverage and/or voice-channel requirements

b) Reduction in the field-strength requirement (the baseline requirements are 300 and 250 μV/m for Bands 1 and 2, respectively)

c) Use of single-sideband amplitude modulation (SSB-AM) rather than DSB-AM.

Life cycle costs (LCC) are developed for the baseline systems and their variations in Section 5. The LCC, which are normalized to the amount of broadcast service provided, are based on an assumed 20-year program span. Satellite life expectancy is 7 years.

The major technology tradeoffs and analyses that serve to identify the most promising system concepts are discussed in Section 6 and in Appendix B. The results of these analyses are used extensively in the system discussions of Sections 2 through 5. For expository reasons, the system aspects are presented first. However, to make the system discussions more meaningful, it is necessary to first describe the principal technology selections and certain analysis results.

Because of the high field strengths required in Bands 1 and 2, the satellite power requirements are extremely large. This fact, together with the generally irregular shape of the broadcast zones, makes the antenna beamwidth a critical parameter. A beamwidth that is too large inevitably results in large amounts of power being radiated outside zone boundaries. A beamwidth that is too small means that the satellite antenna is unnecessarily large. Examination of the broadcast zones as viewed from geostationary orbit leads to the conclusion that a 3-degree beamwidth represents a good compromise between these two effects. At other altitudes, the beamwidth is modified to illuminate an area equal to that subtended by a 3-degree beam from geostationary orbit. In this way, the power requirements in a given frequency band are made invariant to the choice of orbit.

In Band 1, 10 kilowatts of transmitter power is required to illuminate the area subtended by a 3-degree beam from geostationary orbit with a minimum of 300 μV/m (see Appendix C). This power level is applicable to both geostationary and 8-hour satellites. In Band 2, the transmitter power needed for a minimum field strength of 250 μV/m is 5.5 kilowatts. These two power levels are based on the use of circular polarization (to counteract Faraday rotation) and are valid for a beam centered at the subsatellite point.

The above calculation of RF power requirements ignores a second important ionospheric phenomenon — scintillation. Irregularities in the ionosphere cause amplitude fluctuations which can result in very sizable signal fades. This effect is observed following sunset, primarily at low geomagnetic latitudes and near the poles. Its magnitude varies with the sunspot number and is seasonal in nature. Because of scintillation, there will be times in certain geographical areas when Band 1 broadcasting is not possible. Scintillation is not a problem for the Band 2, Molniya system because the broadcast areas of interest lie outside the scintillation regions.

In computing the amount of broadcast service provided for the purpose of normalizing LCC, scintillation effects are not accounted for. The normalized LCC will therefore be somewhat understated.

Two types of satellite antenna configuration were considered, the parabolic reflector and the phased array. The latter offers greater flexibility in beam steering and is particularly advantageous for multiple-beam transmission. However, the number of radiating elements and the structural weight of the array become prohibitively large above a certain altitude, for an illuminated area corresponding to a 3-degree beamwidth at geostationary altitude. Accordingly, a reflector type of antenna is used for geostationary and Molniya orbits, while the phased array is used for subsynchronous orbits with a period of 8 hours or less. The specific reflector configuration chosen is the cable catenary, which was developed at TRW. Properties of an inflatable reflector, as developed by L'Garde, Inc. under subcontract to TRW, are presented in detail in Reference 1-7.

Three types of primary power source were considered: solar panels, nuclear reactors, and solar dynamic power conversion units. Based on a weight analysis, it was concluded that only solar panels lead to an acceptable electrical power subsystem (EPS) weight for the required power levels. A significant factor in this analysis is the absence of a requirement for eclipse operation. (The absence of broadcast capability during eclipse is also not accounted for in computing the normalized LCC.)

With the antenna types and primary power source specified, it is possible to configure satellites for the various baseline systems. A satellite design for the Band 2, Molniya system is shown in Figure 6-1.

The geostationary Band 1 satellite concept is similar except for the dimensions. The 8-hour Band 1 satellite design is shown in Figure 6-3.

Project planning information for the four baseline systems is presented in Section 7. A discussion of the critical technology items for each baseline satellite design can be found in Section 7.1. System schedules and funding profiles are presented in Section 7.2. The schedule and cost risk associated with each critical technology item is developed in Section 7.3. Finally, a composite schedule and cost risk for each satellite system concept is described in Section 7.4.

In addition to developing a number of satellite system concepts for voice broadcasting, nonsatellite, nonterrestrial broadcasting techniques were investigated. These include both lighter-than-air (LTA) and heavier-than-air (HTA) platforms, all of which are unmanned. The results of this investigation are presented in Appendix D.

The satellites needed to satisfy the broadcast requirements as specified in the original study contract are generally large, heavy, and costly. Consequently, NASA directed TRW to determine satellite characteristics corresponding to single-channel HF broadcasting at field strengths ranging from 300 to 50 μV/m. Six different orbits were examined. Several different second stages were considered, as appropriate, for the lighter satellite designs. The results of this investigation, which include descriptions of satellite visibility periods, are presented in Section 8.

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1-6. J. Chaplin, H. H. Fromm, and C. Rosetti, "Satellite Sound Broadcasting Direct to Portable and Vehicle Receivers," Telecommunications Journal, Vol. 52, No. 1, 1985.

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# 2. SYSTEM DESIGN METHODOLOGY

Design of a satellite voice broadcast system varies considerably in complexity, depending on the class of satellite orbit selected. It is a relatively simple process for a system of geostationary satellites, but much more complex for a system of subsynchronous satellites. Nevertheless, there is a common thread to the system design, regardless of satellite orbit. The common elements are presented in this section and lay the groundwork for the more specific system designs developed in Sections 3 and 4.

## 2.1 SYSTEM REQUIREMENTS

The 15 broadcast zones as defined by NASA are outlined in Figure 2-1. The numbering of the zones tends to run from west to east. Broadcast schedules are stated in terms of universal or Greenwich mean time (GMT). It follows that, as the zone numbers increase, a broadcast occurring at a fixed local time will take place at an increasingly earlier GMT.

As indicated previously, Systems 1, 2, and 4 are intended to operate in all 15 zones. System 3 (i.e., Band 2) broadcasts are directed only at Zones 9, 10, 12, and 14, which are the four Soviet zones.

The broadcast schedule in Figure 2-2 is a slightly modified version of the set of channel requirements specified by NASA. The original schedule was divided into 15-minute intervals. To simplify the system design process, changes in the required number of channels were permitted only at 30-minute intervals. Wherever the original schedules provides for different numbers of channels in the two portions of a 1/2-hour period, the smaller number is assumed to apply throughout the period.

Each channel identified in Figure 2-2 does not necessarily have to be broadcast over the entire zone. This is especially true for large zones and for zones with a multiplicity of channels (reflecting program material in a variety of languages). Advantage will be taken of this fact to reduce the power requirements placed on the satellites.

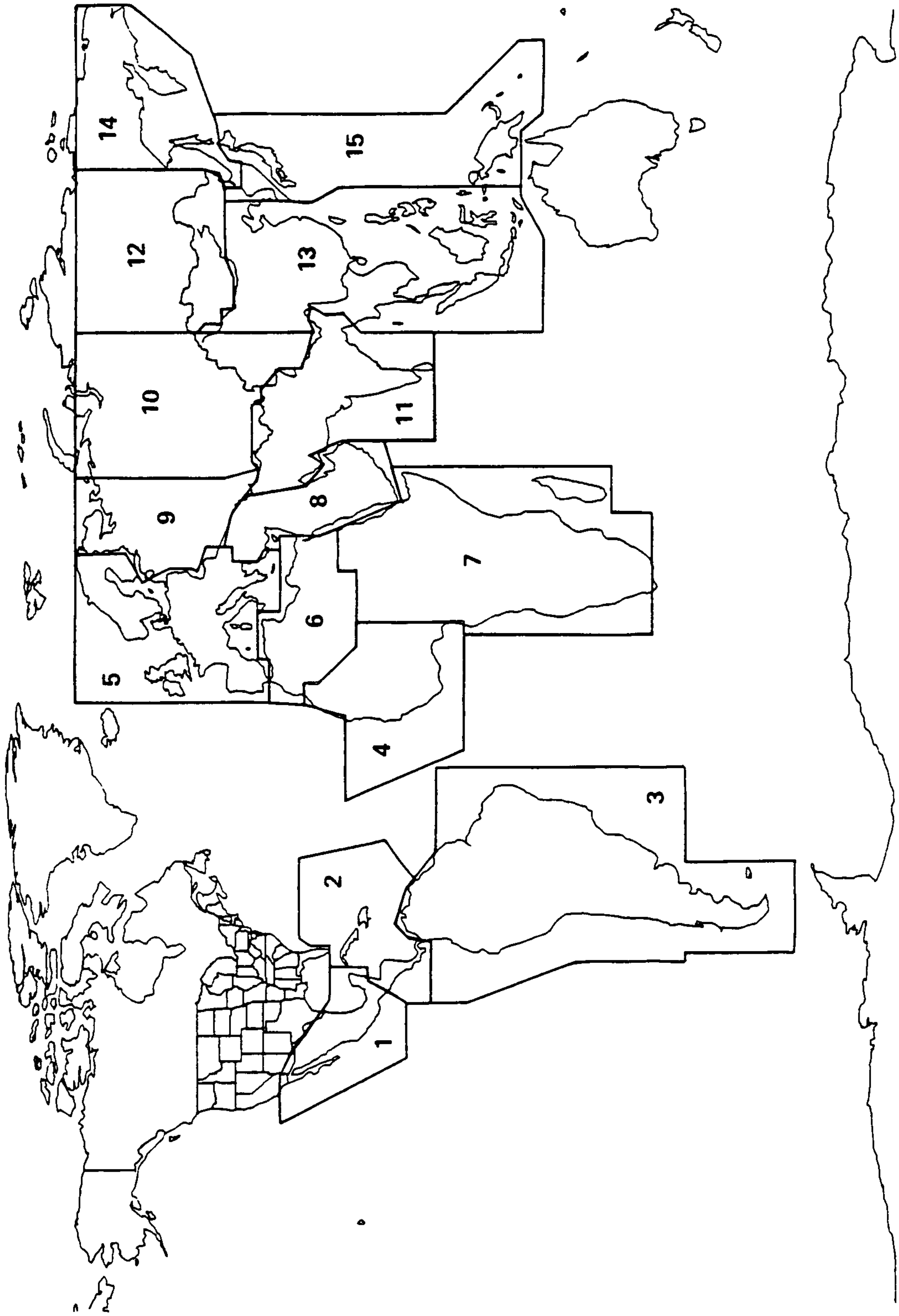


Figure 2-1. Broadcast Zone Definition

- Entries Indicate Number of Voice Channels Per Zone

| Zone | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | | | | | | | | | | | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | | | | | | | | | | | | | | | | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | | | | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | | | | | | | | | | | | | | | | | | 1 | 2 | 2 |
| 3 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | | | | | | | | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | | | | | | | | | | | | | | | | 1 | 1 | 1 | 2 | 2 |
| 4 | | | | | | | | | | | 1 | 2 | 1 | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | 2 | 2 | 1 | 1 | 1 | 1 | | | |
| 5 | | | | | | | 1 | 2 | 8 | 11 | 9 | 6 | 2 | 1 | 1 | 1 | | | | | | | | | | 1 | 1 | 1 | 1 | 1 | | | 2 | 6 | 10 | 11 | 9 | 6 | 4 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | | | | | | | | | | | | | | | | | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| 7 | | | | | | 1 | 2 | 1 | 3 | 3 | 3 | 3 | 2 | 1 | 1 | 2 | | | | | | | | | | | | | | | 1 | 2 | 1 | | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | 1 | 1 |
| 8 | | | | 1 | 1 | 1 | 1 | | 1 | 2 | 2 | 1 | | | | 1 | | | 1 | 1 | 1 | 1 | | | | | | | 1 | 1 | 1 | 2 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | |
| 9 | | | | 1 | 1 | | | 2 | 6 | 1 | | | | | | | | | | | | | | | | | | | 1 | 1 | 1 | 1 | 2 | 5 | 1 | 1 | 1 | | | | | | | | | | | |
| 10 | 1 | 1 | | | 2 | 2 | 2 | 1 | | | | | | | | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | 1 | 1 |
| 11 | | | 2 | 3 | 2 | 2 | 4 | 4 | | | | | | | | | | | | | | | | | | | 2 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | | | | | | | | | | 1 |
| 12 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | 2 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | 1 | 1 | 1 |
| 13 | 2 | 2 | | | | | | | | | | | | | | | | | | | | 2 | 6 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | | | | | | | | | | | 1 | 1 | 2 | 6 | 5 | 4 |
| 14 | | | | | | | | | | | | | | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | | | | |
| 15 | 1 | 1 | | | | | | | | | | | | | | | | | | | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | 1 | 1 | 1 | 1 |

UNIVERSAL TIME – HOURS

Figure 2-2. Broadcast Schedule

## 2.2 BASELINE SYSTEM SELECTION

The salient features of the four baseline systems are given in Table 2-1. While geostationary systems are simplest conceptually, the relatively small satellite weight that can be placed in geostationary orbit, together with the large antenna needed in Band 1 to generate a 3-degree beam, restricts the weight that can be allocated to the remaining subsystems. The satellite broadcast capability is correspondingly limited.

The 8-hour-orbit system was selected as the most promising candidate from the broader class of subsynchronous systems. Because of the relatively large satellite weight that can be placed in 8-hour orbit (exact weight is a function of orbit inclination), the broadcast potential of an individual satellite is large compared with that from geostationary orbit. However, a large number of satellites are required simply to provide coverage of a specified area at the same local time each day.

The broadcast service that can be provided by a satellite in either orbit, as measured by the size of the area illuminated and the number of voice channels transmitted, is a function of the required field strength. For Band 1 broadcasts, the requirement is 300 μV/m.

The Molniya orbit is selected for Band 2 because it is ideally suited for viewing the Soviet zones. If apogee of this 12-hour, highly elliptical orbit is placed at the most northerly latitude attained (63.4 degrees) and at a longitude central to the Soviet Union, the four zones of interest are visible for a period of about 9 hours. Moreover, the satellite position does not vary greatly over this period. Therefore, analysis of the satellite requirements is similar to analysis of a geostationary satellite system. The required field strength in Band 2 is 250 μV/m.

The Band 3 geostationary system is required to reach indoor receivers equipped with small outdoor antennas. The satellite transmit power levels must be chosen accordingly. In this case, a satellite of modest proportions can satisfy all broadcast requirements for areas visible from a given geostationary location.

Table 2-1. Baseline System Concepts

| System | Band | Orbit |
|---|---|---|
| 1 | 1 | Geostationary |
| 2 | 1 | 8-hour |
| 3 | 2 | Molniya |
| 4 | 3 | Geostationary |

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## 2.3 ZONAL BEAM-COVERAGE REQUIREMENTS

The broadcast-channel capability of satellites in the Band 1 and 2 systems is maximized by confining the radiated power, to the extent feasible, within zone boundaries. This is done by choosing the satellite beamwidth small enough (or, equivalently, the satellite antenna large enough) so that a multiple-beam pattern can be constructed to closely match the zone boundaries. A smaller beamwidth than necessary for this purpose would result in a needlessly large antenna structure.

To determine an appropriate beam size, a set of covering ellipses as viewed from geostationary orbit was developed for the 15 broadcast zones (Table 2-2). The ellipses were shaped and oriented to cover, as tightly as possible, the principal land masses in the various zones. Each ellipse is assumed to represent a contour of constant antenna gain, 3 dB below the peak gain.

About half the covering ellipses have dimensions that approximate 3 by 6 degrees. Therefore, a 3-degree beam is about the largest that can be used as a basic building block without "spilling" significant power outside zone boundaries. The right-hand side of Table 2-2 indicates the number of 3-degree beams needed to cover each of the 15 zones from geostationary orbit.

For an 8-hour orbit, the aspect from which a zone is viewed varies with the motion of the satellite. The set of covering beams varies accordingly. To attempt to account for the time-varying nature of the beam-coverage requirements would complicate the problem to an unjustifiable degree. For simplicity, the beam-coverage requirements in Table 2-2 are assumed to apply to the 8-hour orbit as well. The antenna diameter of the 8-hour satellite is adjusted to yield the same subtended beam area as a 3-degree beam from geostationary orbit.

An example of zonal coverage by 3-degree beams is given in Figure 2-3. Zone 3 is one of three zones requiring seven beams. The view shown is from geostationary orbit at a longitude central to Zone 3.

A similar procedure is followed for the Molniya orbit. A 2.7-degree beamwidth is selected because Molniya apogee is 10-percent higher than geostationary altitude. Consequently, the illuminated area for a

Table 2-2. Beam Coverage Requirements for Geostationary and 8-Hour Orbits

• **ELLIPSE AND BEAM DIMENSIONS PERTAIN TO GEOSTATIONARY ORBIT**

| ZONE | COVERAGE ELLIPSE | | NO. OF 3-DEGREE BEAMS FOR ZONAL COVERAGE |
|---|---|---|---|
| | MAJOR AXIS (DEG) | MINOR AXIS (DEG) | |
| 1 | 5.6 | 3.2 | 2 |
| 2 | 5.0 | 3.0 | 2 |
| 3 | 11.2 | 9.0 | 7 |
| 4 | 6 2 | 4.6 | 3 |
| 5 | 6.2 | 4.2 | 2 |
| 6 | 8.0 | 3.0 | 3 |
| 7 | 12.0 | 8.6 | 7 |
| 8 | 6.0 | 4.0 | 2 |
| 9 | 4.4 | 3.2 | 1 |
| 10 | 5.6 | 4.6 | 3 |
| 11 | 8.4 | 6.4 | 4 |
| 12 | 5.2 | 2.6 | 2 |
| 13 | 11.4 | 8.0 | 7 |
| 14 | 6.2 | 2.4 | 2 |
| 15 | 9.4 | 4.6 | 2 |

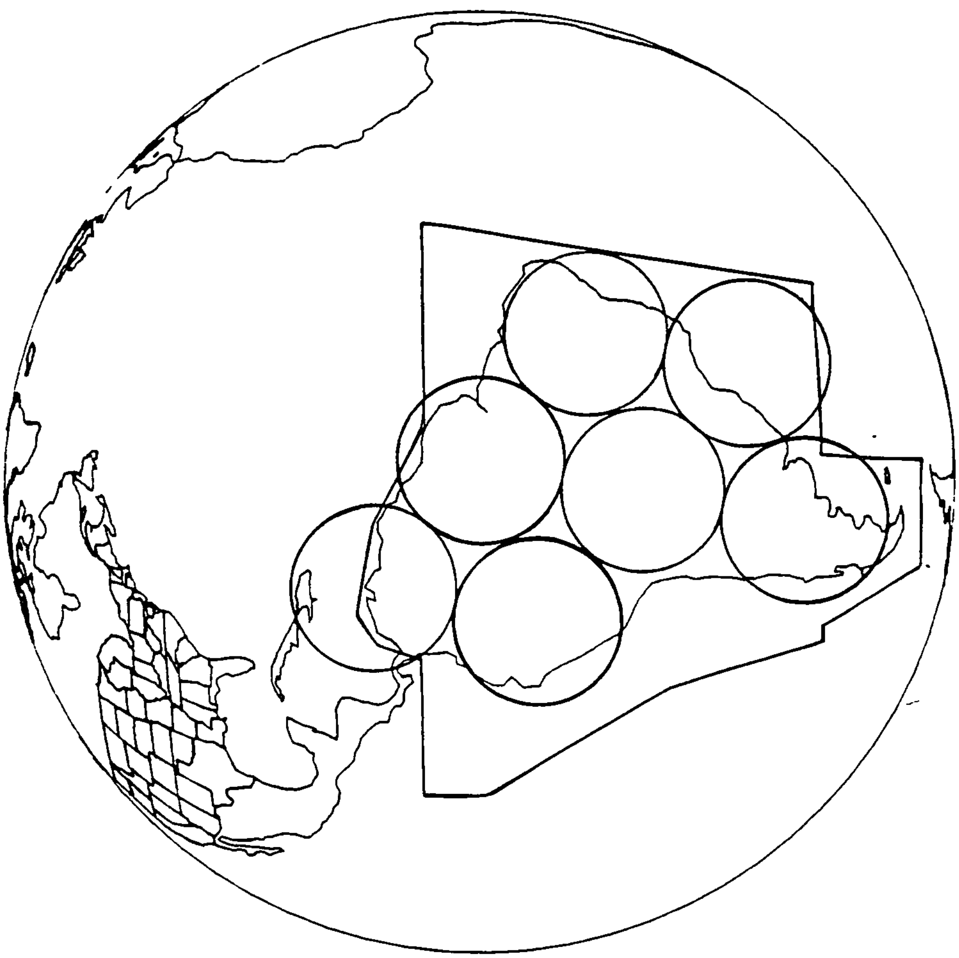


Figure 2-3. Coverage of Zone 3 by 3-Degree Beams

2.7-degree beamwidth is about the same as for a 3-degree beam from geostationary orbit, for a beam centered at the subsatellite point. The ellipse dimensions at Molniya apogee (Table 2-3) are somewhat larger than those from geostationary orbit because the zones are viewed from a more nearly overhead position. The larger ellipse dimensions, coupled with the smaller beamwidth, result in one more beam being required to cover Zones 9, 10, and 12 than is needed from geostationary orbit.

The number of beams required for coverage of each of the four Soviet zones, as indicated in Table 2-3, was determined independently of the other three zones. It will be seen that the complete broadcast requirements for these zones can be provided by a single satellite. (Each of three satellites provides coverage for a different 8-hour period.) It must therefore be verified that the four zones can be covered by the stated number of beams selected from a single pattern of contiguous, 2.7-degree beams (i.e., that four sets of beams, suitably positioned for the four zones, can be generated from a common antenna).

Such a beam pattern is illustrated in Figure 2-4. Note that Zones 10 and 12 have one beam in common. Broadcasts to the two zones in this beam are accomplished on separate frequencies, in the same manner as different channels broadcast to the same zone.

## 2.4 CHANNEL-BEAM CONCEPT

To determine the satellite RF power requirements, it is necessary to know the number of channels transmitted to each of the beam areas. It is assumed that the same number of channels are transmitted to each beam area of a zone (Figure 2-5). Therefore, the transmitter power assigned to Zone i can be written as $C_i N_i P_{CB}$, where $C_i$ is the number of channels required in each beam area of Zone i, $N_i$ is the number of beams needed to cover Zone i, and $P_{CB}$ is the transmitter power assigned to each channel in a given beam (i.e., the transmitter power per channel-beam). Thus, the transmission requirements of a zone are characterized by its C x N product (i.e., the number of channel-beams associated with that zone).

Table 2-3. Beam Coverage Requirements for Molniya Orbit

• ELLIPSE AND BEAM DIMENSIONS PERTAIN TO APOGEE

| ZONE | COVERAGE ELLIPSE | | NO. OF 2.7-DEGREE BEAMS FOR ZONAL COVERAGE |
|---|---|---|---|
| | MAJOR AXIS (DEG) | MINOR AXIS (DEG) | |
| 9 | 5.4 | 3.2 | 2 |
| 10 | 7.2 | 5.4 | 4 |
| 12 | 5.2 | 5.2 | 3 |
| 14 | 6.0 | 3.6 | 2 |

- View from Apogee at Longitude of 90° E
- Antenna Beamwidth = 2.7°

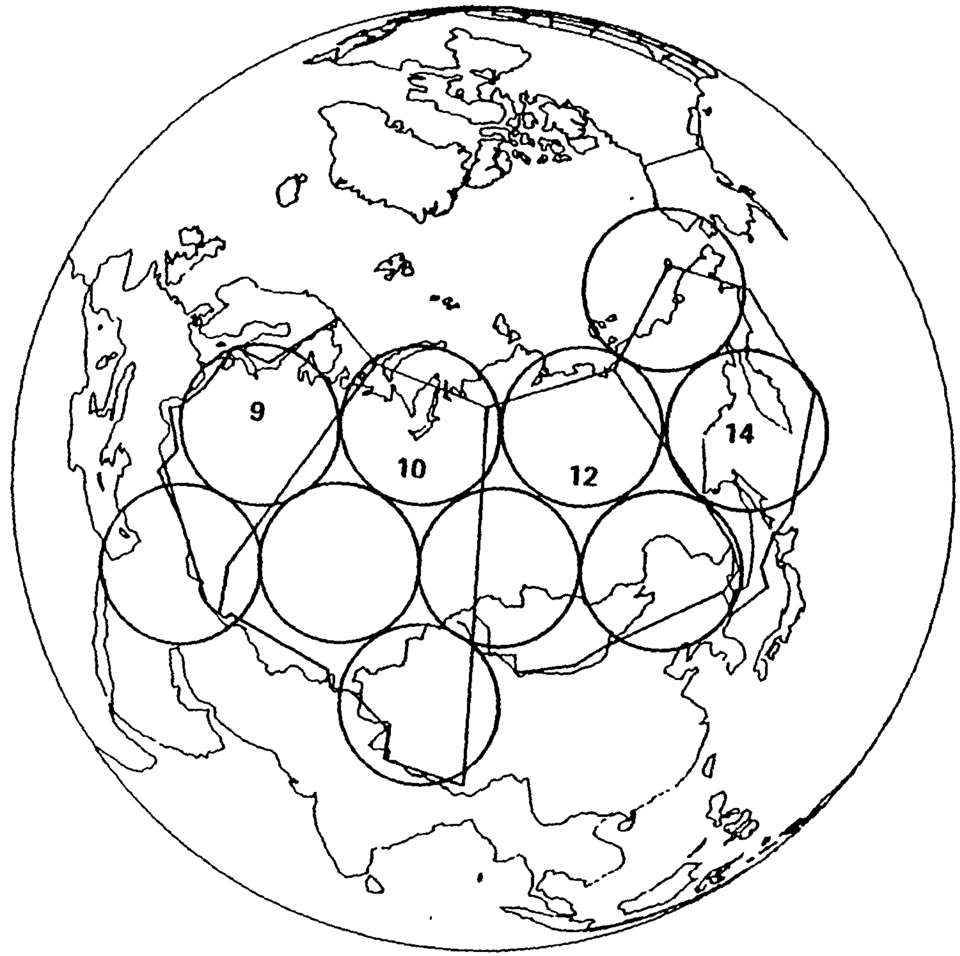
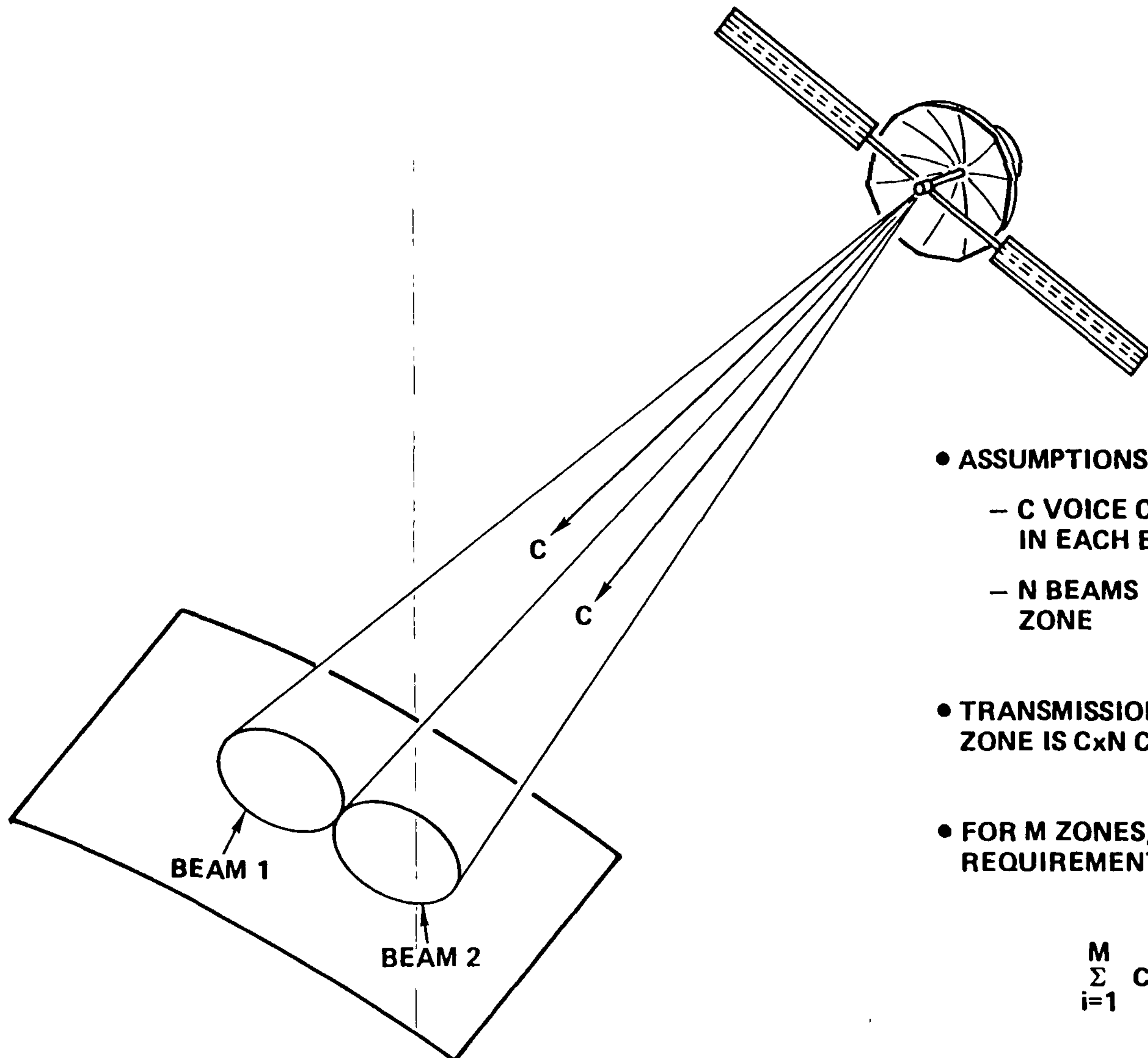



Figure 2-4. Multiple-Beam Coverage from Molniya Orbit




- ASSUMPTIONS
  - C VOICE CHANNELS TRANSMITTED IN EACH BEAM COVERING A ZONE
  - N BEAMS REQUIRED TO COVER A ZONE
- TRANSMISSION REQUIREMENT FOR ZONE IS CxN CHANNEL-BEAMS
- FOR M ZONES, TRANSMISSION REQUIREMENT IS

$$\sum_{i=1}^{M} C_i N_i$$

Figure 2-5. Channel-Beam Concept

To state the RF power requirements in this form, it is first necessary to modify the broadcast schedule of Figure 2-2 to account for the satellite beam structure. This is done in Figure 2-6 for geostationary- and 8-hour-orbit systems. Figure 2-6 accounts for the fact that not all channels must be broadcast over an entire zone. More specifically, the channel requirements of Zone 5 are divided equally between the two beams needed to cover that zone. (If the required number of channels is odd, the beam requirement is rounded upward.) In addition, a maximum of two and three channels, respectively, is required in each of the seven beams of Zones 7 and 13.

The channel-beam demand of each zone, shown in Figure 2-7, is found by multiplying the appropriate entry in Figure 2-6 by the number of beams required to cover the corresponding zone. It is not necessary that a single satellite satisfy the broadcast needs of a particular zone in a given 1/2-hour period. The channel-beam requirement may be divided among any of the satellites from which the zone can be seen. (Variations in beam areas as viewed from different satellite locations are ignored here.)

Similar results for a system of Molniya satellites are shown in Figure 2-8. *In this case, the transmission requirement in each of the two beams* covering Zone 9 is restricted to at most three channels.

The broadcast service provided by a satellite system will be measured by the number of channel-beams transmitted. In other words, the value of a channel-beam is treated as if independent of geographical location, population density, or number of receivers in the hands of the populace. In addition, no distinction is made between a beam wholly contained within the boundaries of a land mass and one which is largely over water (see Figure 2-3).

A subtle distinction should be observed at this point. A larger number of beams is required to cover Zones 9, 10, and 12 from the perspective of Molniya apogee than from geostationary orbit. By the adopted measure of broadcast service, greater value is placed in broadcasting a channel throughout one of these zones from Molniya orbit than from geostationary or 8-hour orbit. This may seem unreasonable at first glance. However, the disparity in receiver population between Band 2 and either

- Geostationary and 8-Hour Orbits
- Entries Indicate Number of Voice Channels Per Beam

UNIVERSAL TIME – HOURS (0–12)

| ZONE | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | | | | | | | | | | | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | | | | | | | | | | 1 | 1 | 2 | 2 |
| 3 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | | | | | | | | 1 | 1 | 1 | 1 | 2 | 2 |
| 4 | | | | | | | | | | | 1 | 2 | 1 | | 1 | 1 | | | | | | | | |
| 5 | | | | | | | 1 | 1 | 4 | 6 | 5 | 3 | 1 | 1 | 1 | 1 | | | | | | | | |
| 6 | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | | | | | | | | |
| 7 | | | | | | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | | | | | | | | |
| 8 | | | | 1 | 1 | 1 | 1 | | 1 | 2 | 2 | 1 | | | | 1 | | | 1 | 1 | 1 | 1 | | |
| 9 | | | | 1 | 1 | | | 2 | 6 | 1 | | | | | | | | | | | | | | |
| 10 | 1 | 1 | | | 2 | 2 | 2 | 1 | | | | | | | | | | | | | | | 1 | 1 |
| 11 | | | 2 | 3 | 2 | 2 | 4 | 4 | | | | | | | | | | | | | | | | |
| 12 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | 2 | 1 |
| 13 | 2 | 2 | | | | | | | | | | | | | | | | | | | | 2 | 3 | 3 |
| 14 | | | | | | | | | | | | | | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | | |
| 15 | 1 | 1 | | | | | | | | | | | | | | | | | | | 1 | | 1 | 1 |

UNIVERSAL TIME – HOURS (12–24)

| ZONE | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | | | | | | | | | | | | | | | | 1 | 1 |
| 2 | 2 | 2 | 2 | 1 | | | | | | | | | | | | | | | | | | 1 | 2 | 2 |
| 3 | 2 | 2 | 1 | 1 | | | | | | | | | | | | | | | | 1 | 1 | 1 | 2 | 2 |
| 4 | | | | | | | | | | | | | 1 | | 1 | 2 | 2 | 1 | 1 | 1 | 1 | | | |
| 5 | | 1 | 1 | 1 | 1 | 1 | | | 1 | 3 | 5 | 6 | 5 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | | | | | | | | | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| 7 | | | | | | | 1 | 2 | 1 | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 |
| 8 | | | | | 1 | 1 | 1 | 2 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | |
| 9 | | | | | 1 | 1 | 1 | 1 | 2 | 5 | 1 | 1 | 1 | | | | | | | | | | | |
| 10 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | 1 | 1 |
| 11 | | | 2 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | | | | | | | | | | 1 |
| 12 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | 1 | 1 | 1 |
| 13 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | | | | | | | | | | | 1 | 1 | 2 | 3 | 3 | 3 |
| 14 | | | | | | | | | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | | | | |
| 15 | 1 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | 1 | 1 | 1 | 1 |

Figure 2-6. Modified Broadcast Schedule to Account for Satellite Beam Structure

- Applies to Geostationary and 8-Hour Orbits
- Total of 894 Channel-Beam-Hours Demanded Daily

UNIVERSAL TIME – HOURS (0–12)

| ZONE | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | | | | | | | | | | | | 2 | 2 |
| 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 2 | 2 | | | | | | | | | | 2 | 2 | 4 | 4 |
| 3 | 14 | 14 | 14 | 14 | 14 | 14 | 7 | 7 | 7 | 7 | 7 | | | | | | | | 7 | 7 | 7 | 7 | 14 | 14 |
| 4 | | | | | | | | | | | 3 | 6 | 3 | | 3 | 3 | | | | | | | | |
| 5 | | | | | | | 2 | 2 | 8 | 12 | 10 | 6 | 2 | 2 | 2 | 2 | | | | | | | | |
| 6 | | | | | | | 3 | 3 | 6 | 6 | 6 | 6 | 3 | 3 | 3 | 6 | | | | | | | | |
| 7 | | | | | | 7 | 14 | 7 | 14 | 14 | 14 | 14 | 14 | 7 | 7 | 14 | | | | | | | | |
| 8 | | | | 2 | 2 | 2 | 2 | | 2 | 4 | 4 | 2 | | | | 2 | | | 2 | 2 | 2 | 2 | | |
| 9 | | | | 1 | 1 | | | 2 | 6 | 1 | | | | | | | | | | | | | | |
| 10 | 3 | 3 | | | 6 | 6 | 6 | 3 | | | | | | | | | | | | | | | 3 | 3 |
| 11 | | | 8 | 12 | 8 | 8 | 16 | 16 | | | | | | | | | | | | | | | | |
| 12 | 2 | 2 | | | | | | | | | | | | | | | | | | | | | 4 | 2 |
| 13 | 14 | 14 | | | | | | | | | | | | | | | | | | | | 14 | 21 | 21 |
| 14 | | | | | | | | | | | | | | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | | |
| 15 | 2 | 2 | | | | | | | | | | | | | | | | | | | 2 | | 2 | 2 |

UNIVERSAL TIME – HOURS (12–24)

| ZONE | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 4 | 4 | 4 | 2 | 2 | 2 | | | | | | | | | | | | | | | | 2 | 2 |
| 2 | 4 | 4 | 4 | 2 | | | | | | | | | | | | | | | | | | 2 | 4 | 4 |
| 3 | 14 | 14 | 7 | 7 | | | | | | | | | | | | | | | | 7 | 7 | 7 | 14 | 14 |
| 4 | | | | | | | | | | | | | 3 | | 3 | 6 | 6 | 3 | 3 | 3 | 3 | | | |
| 5 | | 2 | 2 | 2 | 2 | 2 | | | 2 | 6 | 10 | 12 | 10 | 6 | 4 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 6 | | | | | | | | | | | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 3 | 3 | 3 | 3 |
| 7 | | | | | | | 7 | 14 | 7 | | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 7 | 7 | 7 |
| 8 | | | | | 2 | 2 | 2 | 4 | 2 | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | | | |
| 9 | | | | | 1 | 1 | 1 | 1 | 2 | 5 | 1 | 1 | 1 | | | | | | | | | | | |
| 10 | 3 | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 3 | 3 | | | | | | | | | | | | | 3 | 3 |
| 11 | | | 8 | 16 | 12 | 8 | 12 | 12 | 12 | 12 | 4 | 4 | 4 | 4 | | | | | | | | | | 4 |
| 12 | 2 | 2 | 2 | 2 | | | | | | | | | | | | | | | | | | 2 | 2 | 2 |
| 13 | 21 | 21 | 21 | 21 | 21 | 21 | 14 | 14 | | | | | | | | | | | 7 | 7 | 14 | 21 | 21 | 21 |
| 14 | | | | | | | | | | | | | | | 2 | 2 | 4 | 4 | 4 | 4 | | | | |
| 15 | 2 | 2 | 2 | 2 | 2 | 2 | | | | | | | | | | | | | | | 2 | 2 | 2 | 2 |

Figure 2-7. Channel-Beam Demand of Modified Broadcast Schedule

- Satellite Beamwidth = 2.7°

NUMBER OF CHANNEL-BEAMS

| ZONE | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | | | | 2 | 2 | | | 4 | 6 | 2 | | | | | | | | | | | | | | |
| 10 | 4 | 4 | | | 8 | 8 | 8 | 4 | | | | | | | | | | | | | | | 4 | 4 |
| 12 | 3 | 3 | | | | | | | | | | | | | | | | | | | | | 6 | 3 |
| 14 | | | | | | | | | | | | | | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | | |
| TOTAL | 7 | 7 | | 2 | 10 | 8 | 8 | 8 | 6 | 2 | | | | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 10 | 7 |

UNIVERSAL TIME – HOURS (0–12)

NUMBER OF CHANNEL-BEAMS

| ZONE | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | | | | | 2 | 2 | 2 | 2 | 4 | 6 | 2 | 2 | 2 | | | | | | | | | | | |
| 10 | 4 | 4 | 4 | 4 | 4 | 8 | 4 | 4 | 4 | 4 | | | | | | | | | | | | | 4 | 4 |
| 12 | 3 | 3 | 3 | 3 | | | | | | | | | | | | | | | | | | 3 | 3 | 3 |
| 14 | | | | | | | | | | | | | | | 2 | 2 | 4 | 4 | 4 | 4 | | | | |
| TOTAL | 7 | 7 | 7 | 7 | 6 | 10 | 6 | 6 | 8 | 10 | 2 | 2 | 2 | | 2 | 2 | 4 | 4 | 4 | 4 | | 3 | 7 | 7 |

UNIVERSAL TIME – HOURS (12–24)

Figure 2-8. Band 2 Channel-Beam Demand for Molniya Orbit Coverage

Band 1 or 3 (the latter population being nonexistent, at present) is far more significant than the inconsistency in broadcast service measurement.

## 2.5 SATELLITE CAPACITY

Satellite channel-beam capacity depends on two principal factors:

1) STS/Centaur payload capability

2) Required transmitter power per channel-beam.

The value of these two quantities is shown in Table 2-4 for the three orbits of interest. The same transmitter power per channel-beam is required for the two Band 1 systems, because the satellite beamwidths are chosen to illuminate areas of equal size.

Because the transmitter power requirements are the same for the geostationary and 8-hour systems, the difference in satellite capacity results primarily from the difference in STS/Centaur payload capability. By contrast, the capacity advantage of a satellite in Molniya orbit over one in 8-hour orbit is a reflection of the difference in required transmitter power.

Satellite capacity is determined by dividing the subsystems into two groups, according to whether or not the subsystem weight depends on the number of channel-beams supported (Figure 2-9). Subsystem weight in the channel-beam-independent category (e.g., propulsion) may depend on the total satellite weight. Because satellites for Baseline Systems 1, 2, and 3 are sized to utilize the full STS/Centaur payload capability, the satellite weight is known. Therefore, the weight of the channel-beam-independent subsystems can be computed directly. The remaining weight is allocated to the channel-beam-dependent subsystems. When the latter weight is divided by the subsystem weight required to support each channel-beam, satellite capacity is obtained.

Strictly speaking, the channel-beam capacity is the largest integer less than or equal to the A/B quotient in Figure 2-9. It is more realistic, however, to round this quotient either up or down according to the fractional remainder. The corresponding weight reserve, nominally 20 percent, will be more or less than this value depending on the direction of rounding.

Table 2-4. Satellite Capacity

| Baseline System | Band | Orbit | STS/Centaur Payload Capability (lb) | Transmitter Power per Channel-Beam (kW) | Channel-Beams per Satellite |
|---|---|---|---|---|---|
| 1 | 1 | GEO | 13,846 | 10.0 | 2 |
| 2 | 1 | 8-Hour | 20,764 | 10.0 | 6 |
| 3 | 2 | Molniya | 19,910 | 5.5 | 12 |

Note: System 4 satellites, which operate in Band 3, are sized according to channel-beam demand at each geostationary orbit location

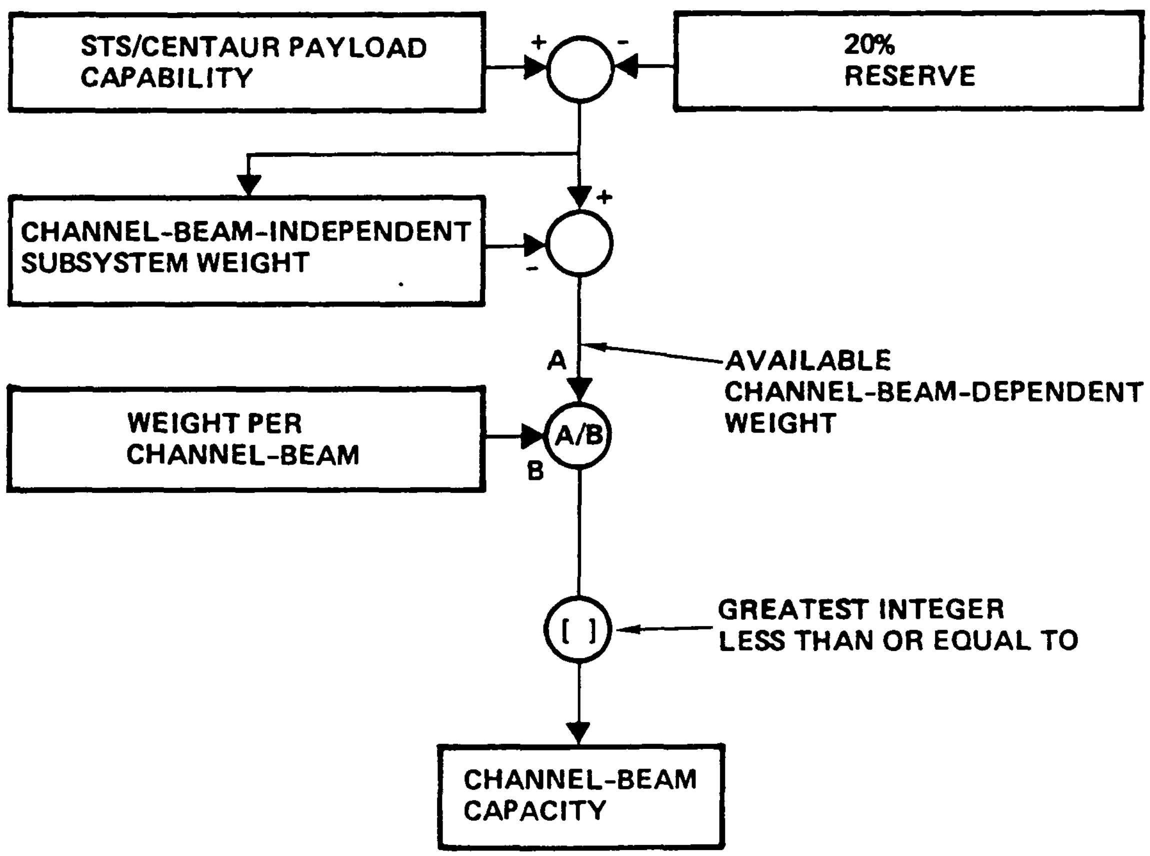



Figure 2-9. Determination of Satellite Channel-Beam Capacity

The process of determining satellite capacity has been computerized. The first of three pages of printout, which provides a satellite weight breakdown by subsystem, is shown in Appendix E for Baseline Systems 1, 2, and 3, as well as for a number of variations on these systems.

## 2.6 SYSTEM DESIGN AND EVALUATION

System design methodology is summarized in Figure 2-10. The broadcast schedule requirements, originally stated in terms of channels/zone, have been converted to channel-beams/zone. The capability of an individual satellite must be viewed from the standpoint of both coverage and capacity. Determination of satellite coverage can be a simple matter, as with geostationary satellites, or quite complex, as is the case with subsynchronous satellites. Coverage is discussed for each orbit type in Section 3. Satellite capacity for Baseline Systems 1, 2, and 3, as indicated in Table 2-4, is the maximum value consistent with the STS/Centaur payload capability. For Baseline System 4, the satellites will be sized according to the channel-beam requirement at each orbit location.

With the broadcast requirements and the satellite capability determined, the satellite constellation can be structured. For geostationary systems, specific orbit locations are selected according to the coverage afforded in relation to the areas represented in the broadcast schedule. To fully meet the demands of the broadcast schedule in the Band 1 geostationary system, the number of satellites at each location must equal the ratio of the maximum number of channel-beams in any 1/2-hour period to the capacity of an individual satellite. A similar procedure can be followed for a system of Molniya satellites, since each satellite is nearly stationary for the period in which it is broadcasting.

For a system of subsynchronous satellites, a certain minimum number of satellites are needed simply to provide daily coverage of the zones of interest at the desired broadcast times. This collection of satellites may have a channel-beam capability either greater or less than the channel-beam demand of the broadcast schedule. In fact, selection of a particular subsynchronous orbit is based, in large measure, on a tradeoff between coverage and capacity. The full range of factors that led to the selection of the 8-hour orbit is shown in Table 2-5.

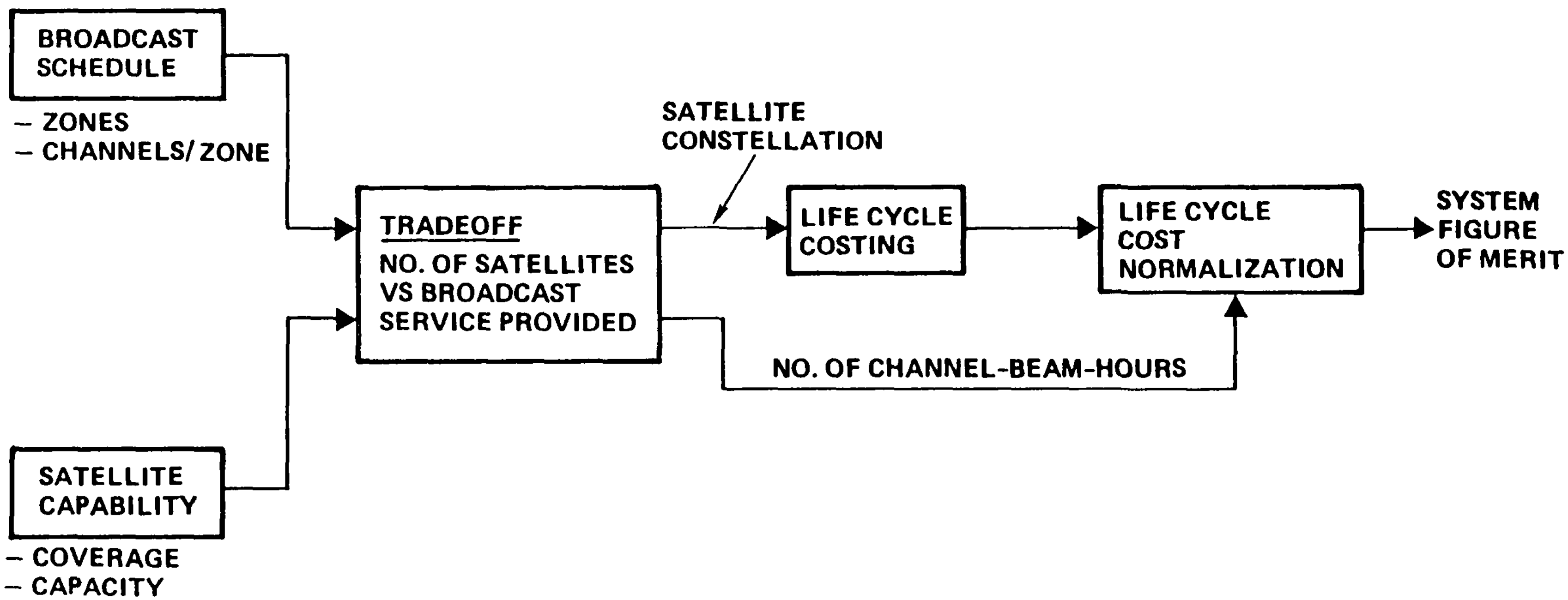



Figure 2-10. System Design Methodology

Table 2-5. Subsynchronous Orbit Selection

- Lower altitude for smaller antenna
- Lower altitude for increased STS/Centaur payload capability
- Twice the solar array area required for 6-hour orbit relative to 8- and 12-hour orbits because of radiation effects
- Higher altitude for better coverage
- Higher altitude for smaller antenna scan angle

---

- 8-hour orbit selected: provides good balance between coverage and payload capability
- Minimum elevation of 20° selected because it
  - Provides adequate single-satellite coverage
  - Avoids dilution of power flux density due to ionospheric refraction in Band 1

From a coverage/capacity standpoint, greater coverage per satellite, and therefore a smaller required number of satellites, results from choice of a higher altitude. On the other hand, a higher altitude implies a lower satellite weight and therefore a smaller channel-beam capacity. The proper choice of altitude is one at which the capacity of an individual satellite is commensurate with its coverage capability in terms of zonal channel-beam demand. Taking into account the multiple-satellite coverage afforded by minimal (from a coverage standpoint) satellite constellations at different altitudes, it was judged that the 8-hour orbit provides the best match between coverage and capacity. This judgment is borne out by the degree to which a minimal 8-hour constellation satisfies the channel-beam demand of the broadcast schedule, as discussed in Section 3.

The LCC for the different satellite systems are found by addition of all development, hardware, and operating costs (in constant, 1984 dollars) for a nominal 20-year program span. It is desirable to be able to compare the costs of satellite systems designed for different broadcast schedules, or systems that satisfy the same broadcast schedule to different degrees. This is done by normalizing the LCC to the number of channel-beam-hours (CBH) provided over the life of the system.*

*A CBH is one channel-beam broadcast for a period of 1 hour.

# 3. BASELINE SYSTEM DEVELOPMENT

The starting point for full system development is the broadcast schedule of Figure 2-7 (or, for System 3, Figure 2-8). Coverage capability is considered for each orbit, in turn, so that a satellite constellation can be matched to the channel-beam requirements of the broadcast schedule.

## 3.1 GEOSTATIONARY SYSTEM DEVELOPMENT

To translate the channel-beam requirements of the broadcast schedule into satellite requirements for the Band 1 and 3 geostationary systems, specific satellite/zone assignments must be made. Three different satellite locations are required to provide coverage of the 15 broadcast zones (Figure 3-1). These locations are 65 degrees west, 30 degrees east, and 115 degrees east longitude. Complete coverage of the five northern zones requires propagation at elevation angles of 10 degrees and below. It is assumed for present purposes that adequate field strength can be provided in Band 1 at these low elevation angles.

In the ensuing analysis, it is assumed that Zones 1, 2, 3, and 4 receive broadcasts from satellites located at 65 degrees west; that Zones 12, 13, 14, and 15 receive broadcasts from satellites located at 115 degrees east; and that the remaining zones are taken care of by satellites located at 30 degrees east.

The results of adding together the channel-beam demand of all zones assigned to each satellite location are shown in Figure 3-2. The number of satellites required at each location for the Band 1 system concept is obtained by dividing the maximum channel-beam demand during the course of a day by the satellite channel-beam capacity. A geostationary satellite operating at 26 megahertz, which is the top subband in Band 1, has a capacity of two channel-beams. A total of 11 such satellites is required just to satisfy the channel-beam demand at 65 degrees west. Similarly, 22 satellites are required at 30 degrees east, and 14 satellites at 115 degrees east. Thus, a total of 47 satellites is required to completely satisfy the demands of the broadcast schedule.

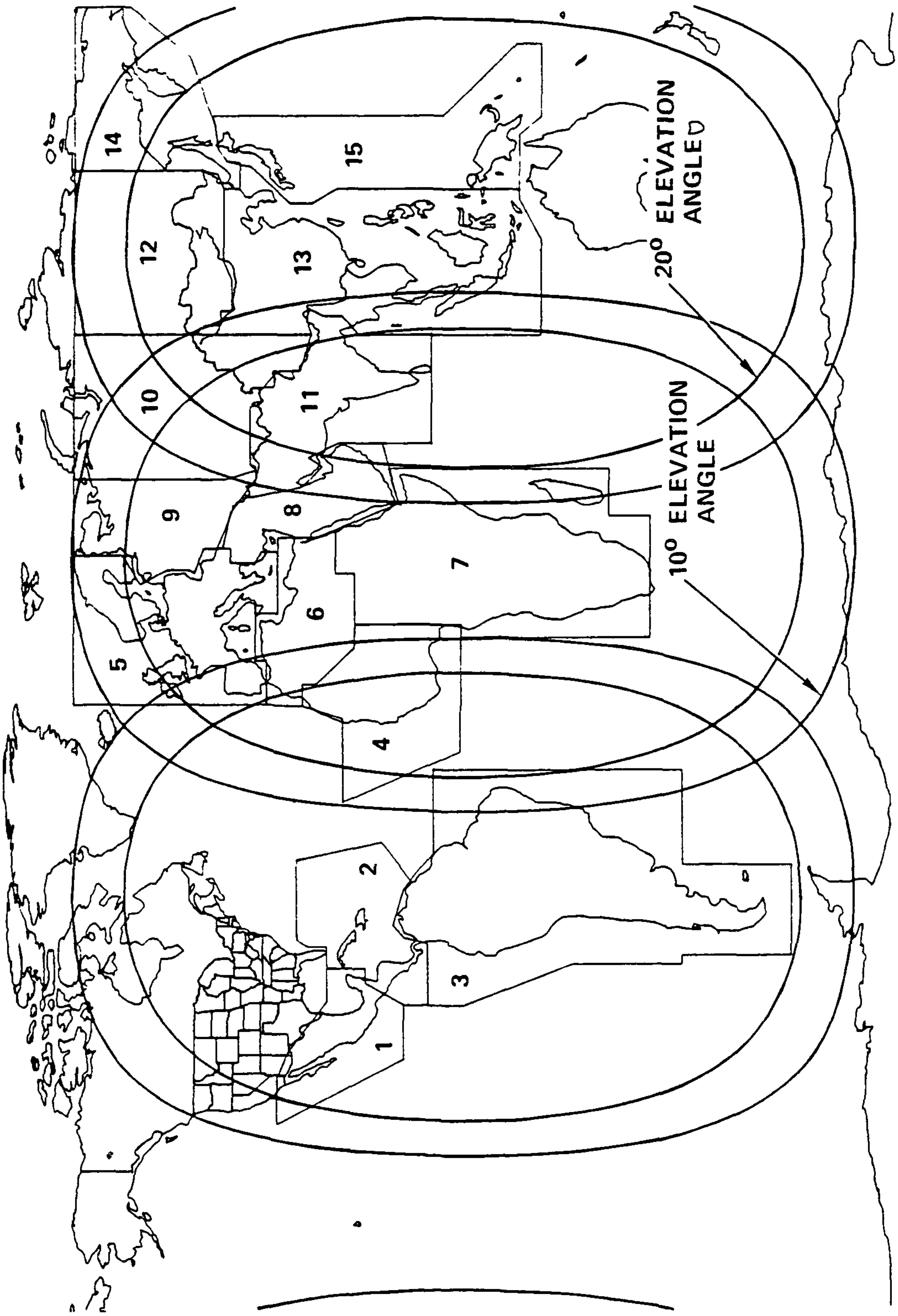



Figure 3-1. Geostationary Satellite Assignment

# NUMBER OF CHANNEL-BEAMS

| SATELLITE POSITION | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65°W | 20 | 20 | 22 | 22 | 22 | 22 | 15 | 13 | 13 | 13 | 16 | 6 | 3 | | 3 | 3 | | | 7 | 7 | 9 | 9 | 20 | 20 |
| 30°E | 3 | 3 | 8 | 15 | 17 | 23 | 43 | 33 | 36 | 37 | 34 | 28 | 19 | 12 | 12 | 24 | | | 2 | 2 | 2 | 2 | 3 | 3 |
| 115°E | 18 | 18 | | | | | | | | | | | | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 4 | 16 | 27 | 25 |

UNIVERSAL TIME – HOURS (0–12)

| SATELLITE POSITION | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65°W | 20 | 22 | 15 | 13 | 2 | 2 | 2 | | | | | | 3 | | 3 | 6 | 6 | 3 | 3 | 10 | 10 | 9 | 20 | 20 |
| 30°E | 3 | 5 | 13 | 21 | 20 | 19 | 25 | 34 | 28 | 26 | 37 | 39 | 37 | 32 | 26 | 24 | 24 | 24 | 24 | 24 | 19 | 12 | 15 | 19 |
| 115°E | 25 | 25 | 25 | 25 | 23 | 23 | 14 | 14 | | | | | | | 2 | 2 | 4 | 4 | 11 | 11 | 16 | 25 | 25 | 25 |

UNIVERSAL TIME – HOURS (12–24)

Figure 3-2. Geostationary Channel-Beam Demand

The channel-beam demand indicated in Figure 3-2 applies equally well to the Band 3 satellite system. It is possible to satisfy the entire channel-beam demand associated with each of the three satellite locations by a spacecraft design which is compatible with a single STS launch. However, the maximum channel-beam demand at 30 degrees east is much larger than the maximum at either 65 degrees west or 115 degrees east. For Band 3, therefore, each satellite is designed to have a capacity of 27 channel-beams. In this way, a single satellite suffices at either 65 degrees west or 115 degrees east, while two satellites are required at 30 degrees east.

The channel-beam requirements of the Band 3 satellites can readily be translated into transponder requirements. These requirements are summarized in Table 3-1.

The required transmitter power per channel-beam, based on a 3-degree beamwidth, is 70 watts (see Appendix C). With a maximum of 27 simultaneously transmitted channel-beams per satellite, the total RF power is 1890 watts. The corresponding dc power is 2900 watts, based on a transmitter efficiency of 65 percent.

The transmitters are sized according to the maximum number of channels per beam. For zones receiving broadcasts from satellites at 65 degrees west and 115 degrees east, the maximum number of channels is three. As many as six channels per beam are required for some of the other zones. However, since two satellites are available to cover these other zones, each satellite need transmit no more than three channels per beam. Therefore, the transmitters are sized for 210 watts of RF power under multi-carrier operation.

The required number of feed elements per satellite (assuming a single element per beam) is determined by the region of responsibility for each satellite. The three beams of Zone 4 have been included in the total for the satellite at 30 degrees east, as well as the total for the satellite at 65 degrees west, since this zone can be covered from either location. Each of the satellites at 30 degrees east is assumed to be capable of broadcasting to any zone covered from that location. If all satellites in the system are regarded as interchangeable, the required number of feed elements is somewhat larger than the maximum value of 25 shown in Table 3-1.

Table 3-1. Transponder Requirements for Band 3 Geostationary System

| Satellite Location | Maximum No. of Channel-Beams | Maximum No. of Channels/Beam | Total No. of Beam Positions | Maximum No. of Activated Beams |
|---|---|---|---|---|
| 65°W | 22 | 2 | 14 | 13 |
| 30°E | 43/2 | 6/2 | 25 | 13 |
| 115°E | 27 | 3 | 13 | 11 |

The required number of transmitters is related to the maximum number of beams that are simultaneously activated. The maximum value of 13 beams is derived from the broadcast schedule. Sixteen transmitters are provided to ensure, with reasonable probability, that 13 will be operable. A switching matrix is required to make the appropriate transmitter/feed-element connections during each broadcast interval.

A weight breakdown by subsystem of the Band 3 geostationary satellite is given in Table 3-2.

## 3.2 MOLNIYA SYSTEM DEVELOPMENT

Satellite coverage contours for one complete Molniya orbit are shown in Figure 3-3. A single satellite has simultaneous and complete visibility of the four Soviet zones for about 9 hours, from 0130 to 1030 hours. Three satellites with the ground track shown suffice, therefore, to provide 24-hour coverage of the Soviet Union. The satellites are spaced at 8-hour intervals along the ground track. To achieve this result, three orbit planes are selected with ascending nodes that differ by 120 degrees. In addition, the times of equatorial crossing differ by 8 hours.

Coverage contours for the complementary orbit, corresponding to the second half of the 24-hour ground track, are shown in Figure 3-4. It is seen that there is a period of 4 hours, from 1600 to 2000 hours, during which a very substantial portion of the Soviet Union is visible. If desired, coverage during this period could supplement the coverage shown in Figure 3-3.

According to the broadcast schedule of Figure 2-8, a maximum total of 10 channel-beams is required by the four Soviet zones. From Table 2-4, on the other hand, a single Molniya satellite can support as many as 12 channel-beams. Consequently, a single satellite can satisfy all broadcast requirements during any 1/2-hour period. It suffices, therefore, to use each satellite only for the 8-hour period centered about apogee.

A small portion of the satellite costs and no launch costs can be saved by sizing the satellites for a capacity of 10 channel-beams. Therefore, system costs will be developed on the basis of a 12-channel-beam satellite.

Table 3-2. Band 3 Geostationary System Satellite Weight Summary

| Subsystem | Weight (lb) | |
|---|---|---|
| Antenna subsystem | | 334 |
| Reflector | 284 | |
| Feeds | 50 | |
| Transponder | | 744 |
| Electrical power subsystem | | 670 |
| Solar array | 170 | |
| NiH2 battery | 240 | |
| Power control unit | 100 | |
| Distribution/integration | 160 | |
| Thermal control subsystem | | 165 |
| Payload | 65 | |
| EPDS | 100 | |
| Structure | | 270 |
| Attitude control subsystem | | 300 |
| Propulsion | | 350 |
| DHS, TT&C, COMM | | 250 |
| Satellite | | 3083 |
| Reserve (20%) | | 616 |
| Total | | 3699 |

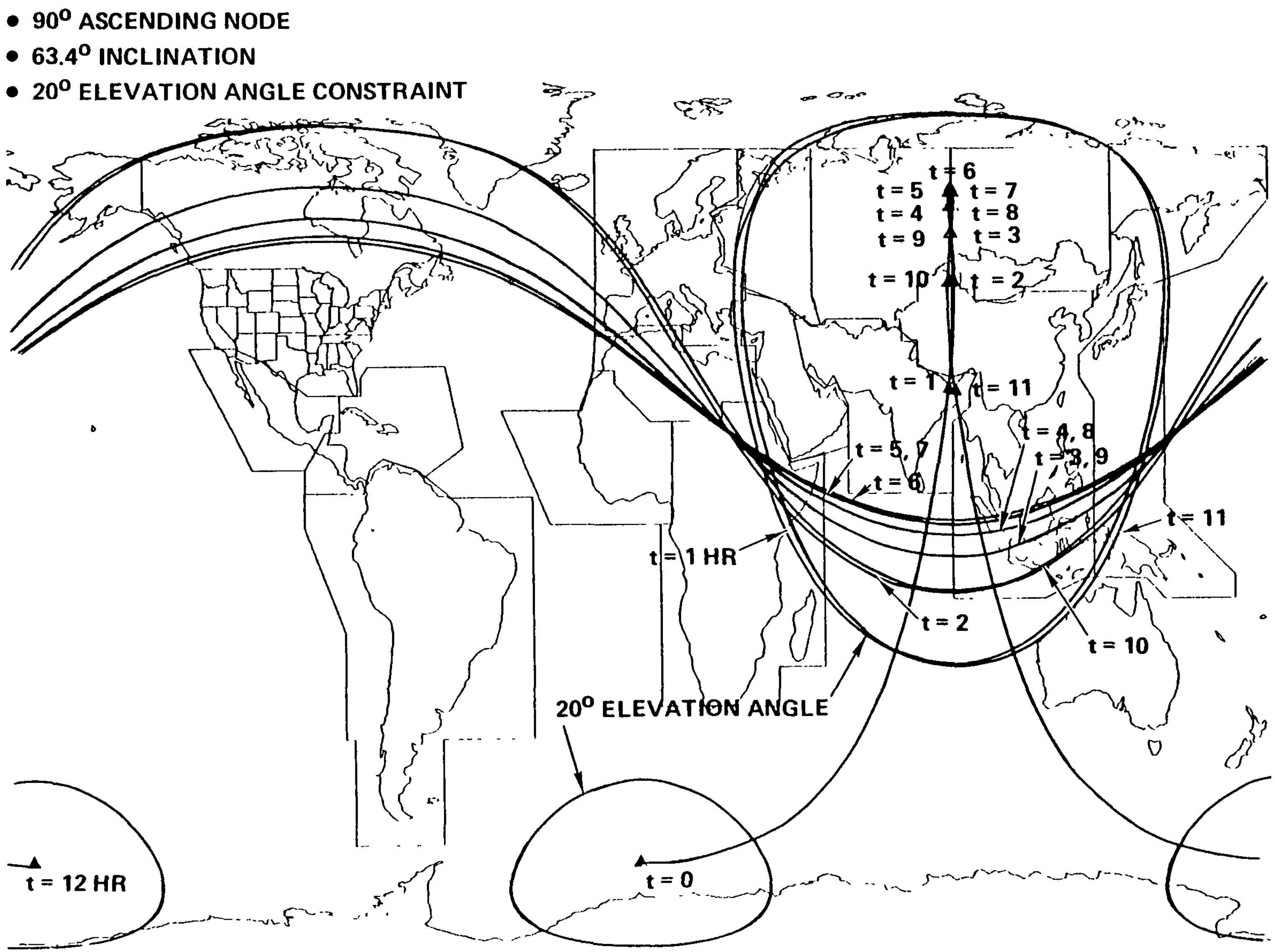



Figure 3-3. Single-Satellite Coverage from Molniya Orbit

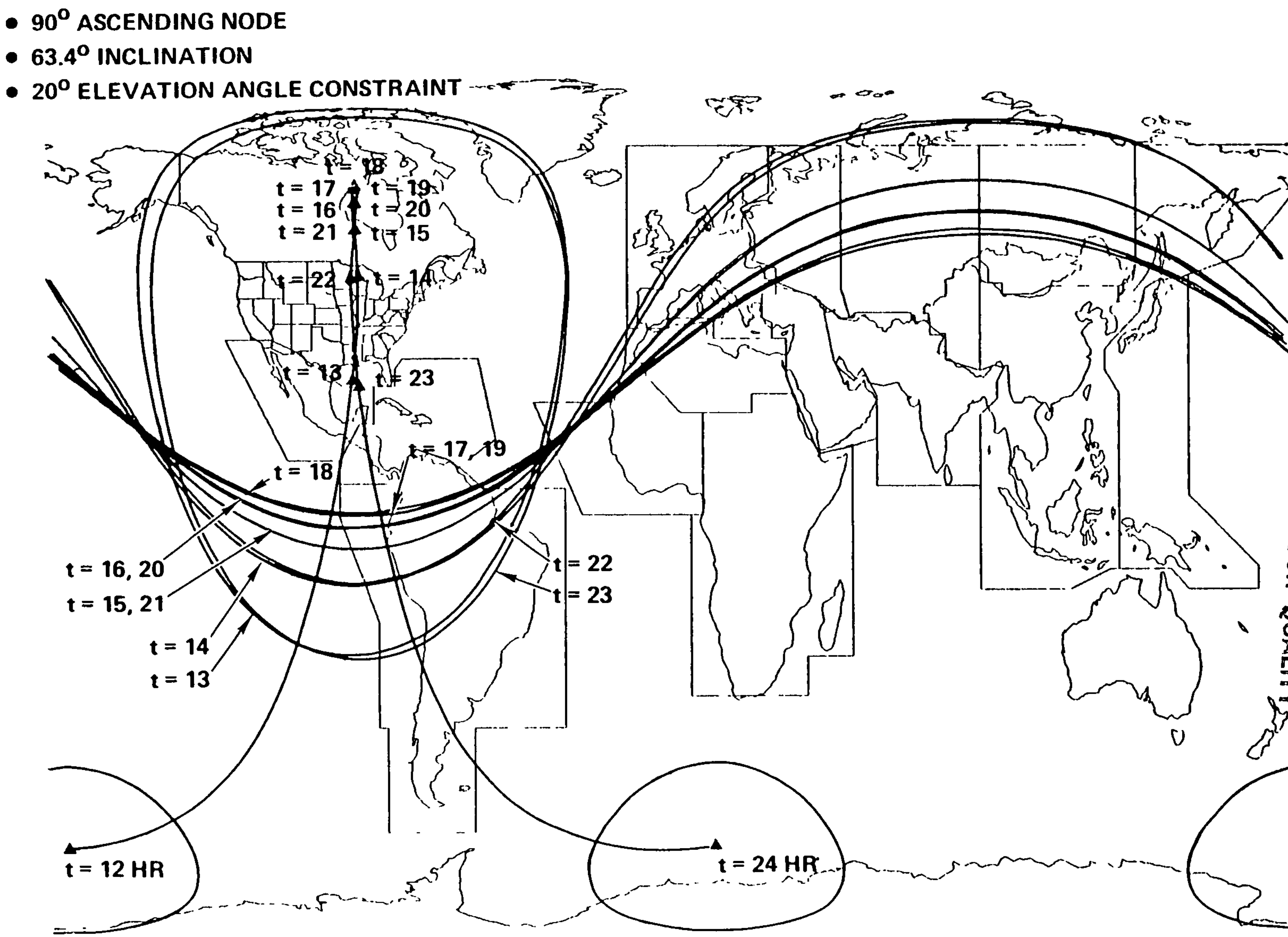



Figure 3-4. Single-Satellite Coverage from Molniya Orbit

## 3.3 8-HOUR-ORBIT SYSTEM DEVELOPMENT

Among subsynchronous orbits, the 8-hour orbit was judged to provide the best match between coverage and capacity, taking into account multiple satellite coverage of the various zones. On the assumption that further analysis will substantiate this judgment, it is reasonable to construct a satellite constellation that provides at least single-satellite coverage of all zones during the specified broadcast periods. The broadcast service provided by such a constellation should then approach the total channel-beam demand of the broadcast schedule.

Because the broadcast schedule is divided into 1/2-hour intervals, the following ground rules are observed:

a) Broadcasts must begin on the hour or 1/2-hour

b) The minimum continuous broadcast period is 1 hour

c) Broadcast periods are constrained to be multiples of 1/2 hour.

Additionally, it is assumed that satellite/zone assignments are not varied during each 1/2-hour period. Therefore, it suffices to describe visibility periods for an individual satellite in 1/2-hour increments.

The ground track for a particular 8-hour orbit, together with instantaneous visibility contours at 1-hour intervals, is shown in Figure 3-5. Visibility is defined by a minimum elevation angle of 20 degrees. An orbit inclination of 28 degrees, which is the latitude of Cape Canaveral, was chosen to maximize the STS/Centaur payload capability (i.e., no plane change is required to place a satellite in an orbit of this inclination). The ascending node of 233 degrees is an arbitrary choice.

Intersections of the areas bounded by successive visibility contours are outlined in bold lines and represent regions of continuous 1-hour visibility. To establish coverage in 1/2-hour increments, a second set of 1-hour visibility regions, interleaved with and midway between those of Figures 3-5, is needed. The two sets of 1-hour visibility regions have been combined to produce the coverage pattern described below.

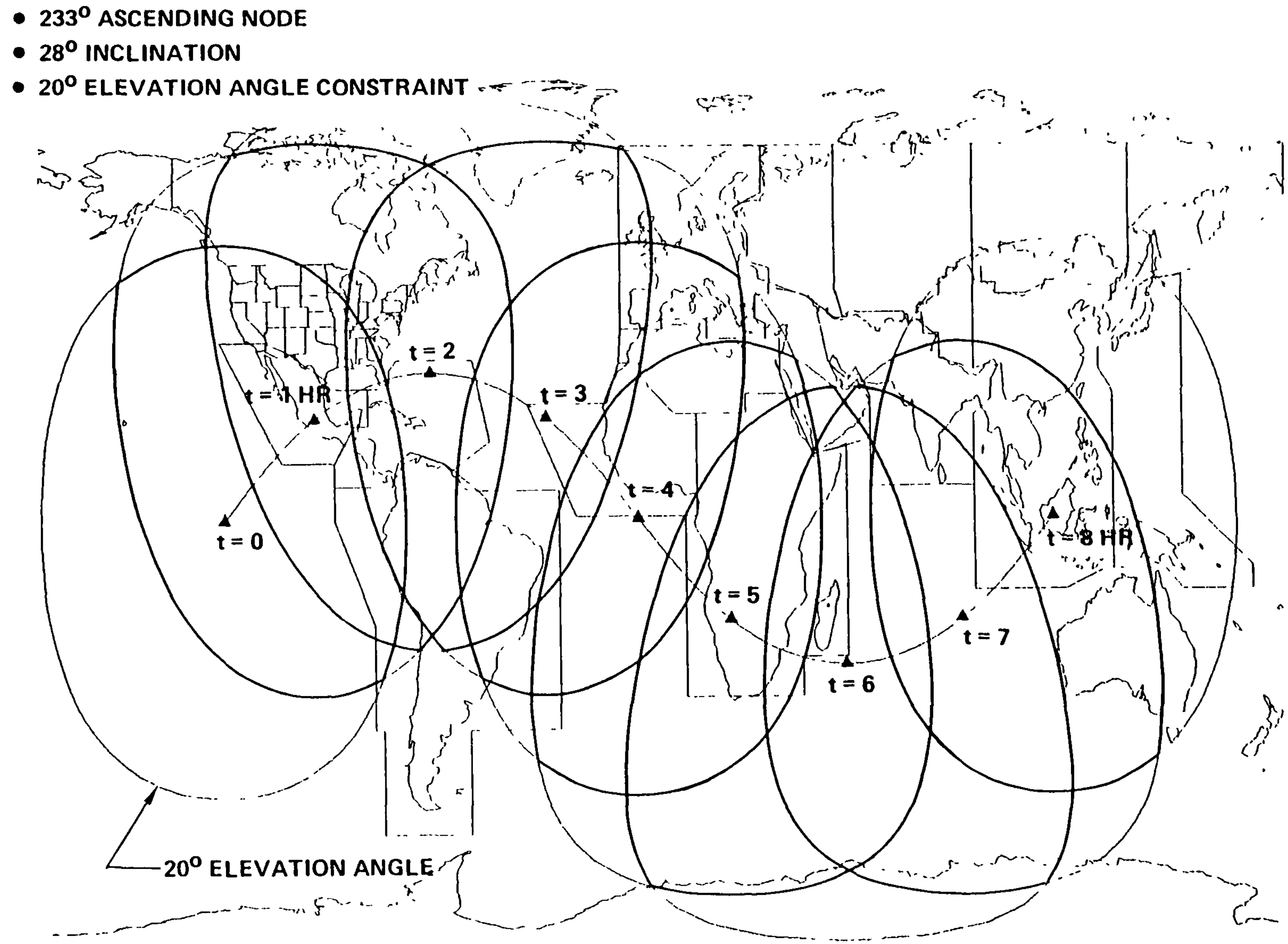



Figure 3-5a. One-Hour Coverage Regions for 8-Hour Circular Orbit

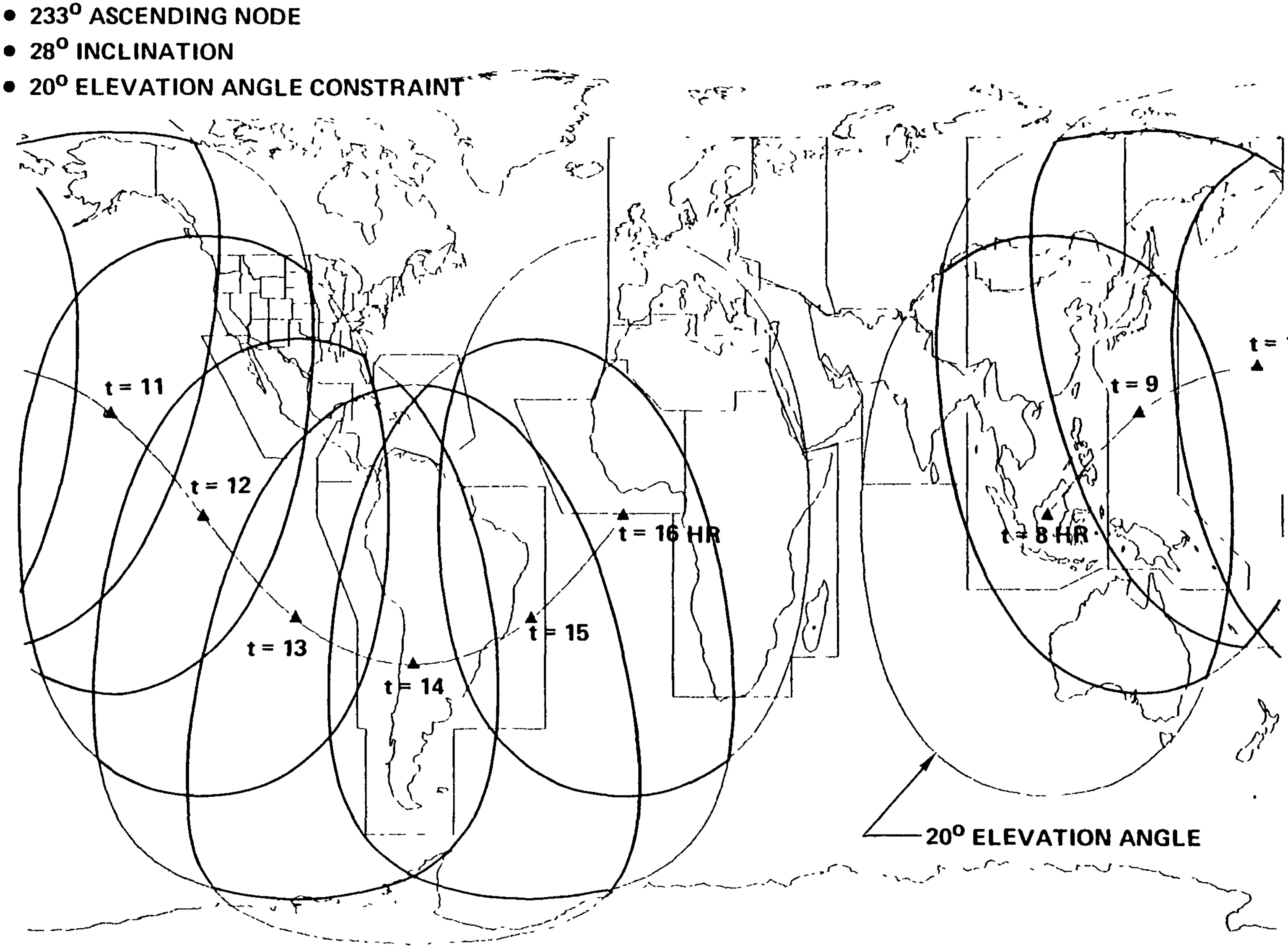



Figure 3-5b. One-Hour Coverage Regions for 8-Hour Circular Orbit

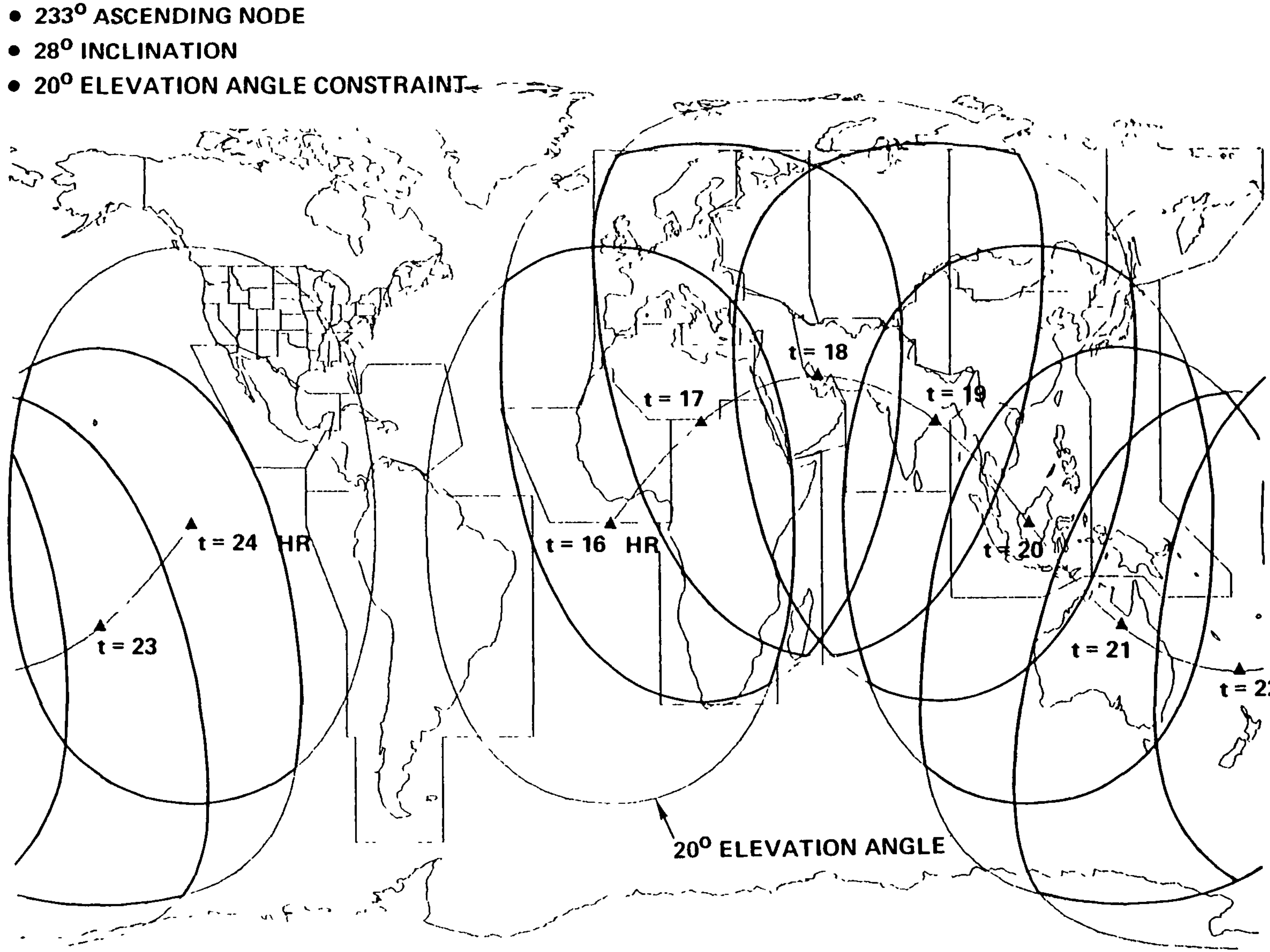



Figure 3-5c. One-Hour Coverage Regions for 8-Hour Circular Orbit

The ground track shown in Figure 3-5 repeats after one sidereal day, or 1436.07 minutes. On the other hand, the standard solar day is 1440 minutes in length. This 4-minute time difference implies that satellite visibility at a given point begins 4 minutes earlier each successive day. (Alternatively, a nonrepeating ground track referenced to a 24-hour day can be constructed such that a given latitude is crossed at the same GMT every day, but with progressively shifting longitude.)

The 4-minute daily shift in satellite visibility, which is incompatible with a fixed broadcast schedule, can be corrected only by a change of orbit plane. If done on a daily basis, this would require a "delta-V" on the order of 150 ft/s per day. Since a correction of this magnitude is impractical, adherence to a fixed broadcast schedule requires 24-hour, continuous coverage of each zone by a constellation of satellites. This is the only means by which satellite visibility can be guaranteed during the same time period each day.

Zonal coverage by a satellite in the orbit described in Figure 3-5 is shown in Figure 3-6, in units of 3-degree beams from geostationary orbit. (The time t=0 marked on the ground track is assumed to correspond to midnight GMT.) Only two or more beams "worth" of coverage is considered, except for Zones 9 and 15. Zone 9 requires only a single beam for complete coverage. Although Zone 15 requires two beams for complete coverage, the two beams cover land masses which are widely separated in a north-south direction. Consequently, coverage of either land mass separately is indicated in Figure 3-6. For the other six zones that require two beams, only complete coverage is shown.

While the coverage pattern may appear exactly as shown in Figure 3-6 on a particular day, it rotates to the left at the rate of 4 minutes per day, or by one column each 7-1/2 days. Thus, the coverage pattern for a single satellite does not repeat for a full year.

Complete coverage of a zone is indicated by a shaded square in Figure 3-6. To determine the number of satellites needed for 24-hour coverage of all zones, only the shaded squares are considered. For the selected orbit, zonal coverage is uneven, with midlatitude zones receiving relatively long periods of coverage and the northern zones (5, 9, 10, 12, and 14) receiving

- Inclination = 28°
- Ascending Node = 233°
- Minimum Elevation Angle = 20°

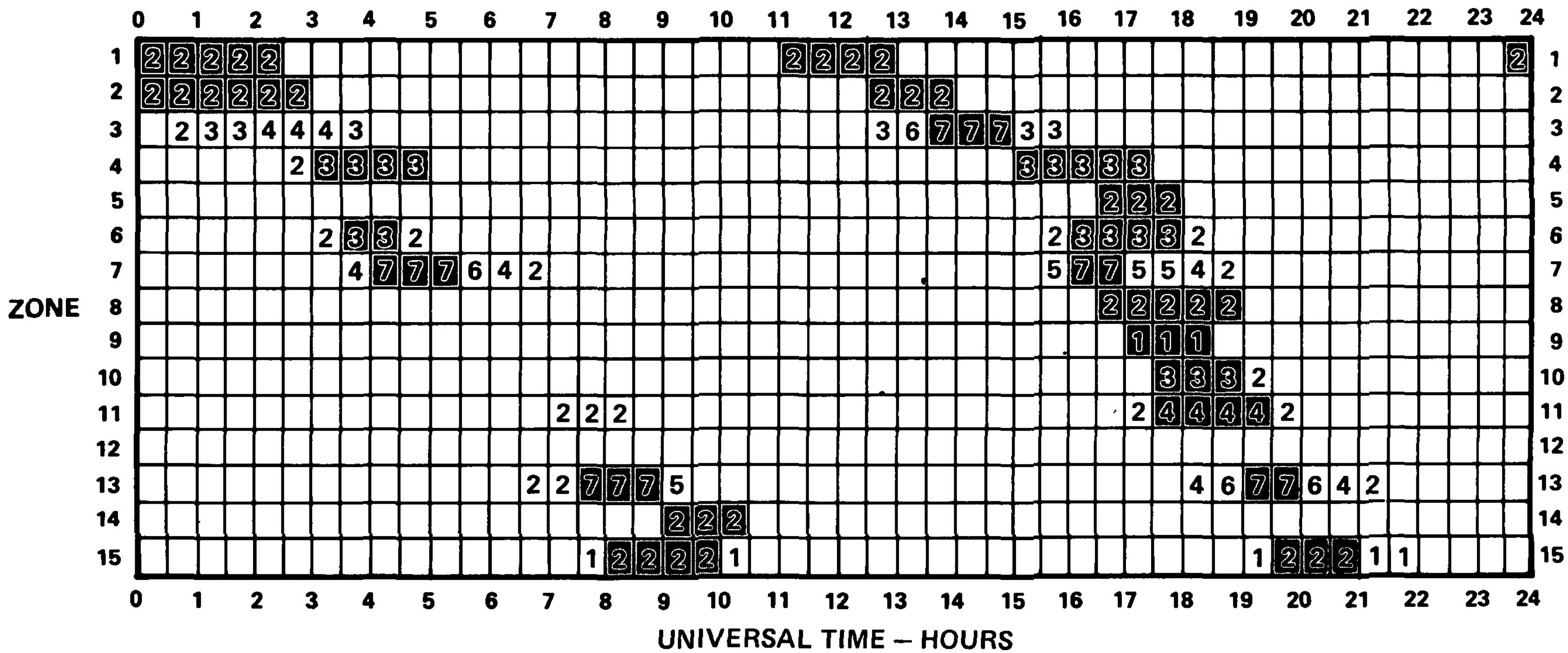



Figure 3-6. Single-Satellite Coverage from 8-Hour Orbit

shorter coverage. In fact, Zone 12, which has an area of two beam units, is shown as receiving no coverage. It is desirable, therefore, to combine the coverage shown with that of a second 8-hour satellite that produces a different ground track.

The south-to-north equatorial crossings of an 8-hour circular orbit are separated by 120 degrees. (This fact can be appreciated by superimposing Figures 3-5a to 3-5c). It is reasonable to expect that two such satellites, with ascending nodes that differ by 60 degrees, will be relatively complementary in their zonal coverage patterns. For this reason, the second 8-hour orbit is chosen to have an ascending node at 293 degrees. Visibility contours for this orbit, and also for representative 6- and 12-hour orbits, are shown in Appendix F.

Coverage provided by an 8-hour orbit with ascending node at 293 degrees is shown in Figure 3-7. It is observed that coverage of Zone 12, which is nonexistent in Figure 3-6, is quite good in Figure 3-7. On the other hand, coverage of Zones 9, 10, and 14 is diminished somewhat. Relatively even coverage of the northern zones can be achieved, therefore, by a combination of the two coverage patterns. More even coverage of the mid-latitude zones also results from combining the two coverage patterns.

A pair of satellites with ground tracks that give rise to the coverage patterns in Figures 3-6 and 3-7 will be used as a building block for the desired satellite constellation. The first satellite is time-phased along its ground track to produce the coverage pattern of Figure 3-7, unshifted in time. The second satellite is time-phased to produce a coverage pattern similar to that of Figure 3-6, but delayed by 7-1/2 hours. The composite coverage pattern, which is designed to produce uninterrupted visibility periods of maximum duration, is shown in Figure 3-8. A shaded square indicates that at least one of the satellites completely covers the zone.

It can be established from an examination of the coverage provided to northern zones that a constellation of 10 satellite pairs, each with a coverage pattern similar to that shown in Figure 3-8, can provide essentially 24-hour, continuous coverage of all zones. The satellite orbits should be chosen so that the coverage pattern provided by each successive satellite pair is delayed by 2-1/2 hours relative to the coverage provided

- Inclination = 28°
- Ascending Node = 293°
- Minimum Elevation Angle = 20°

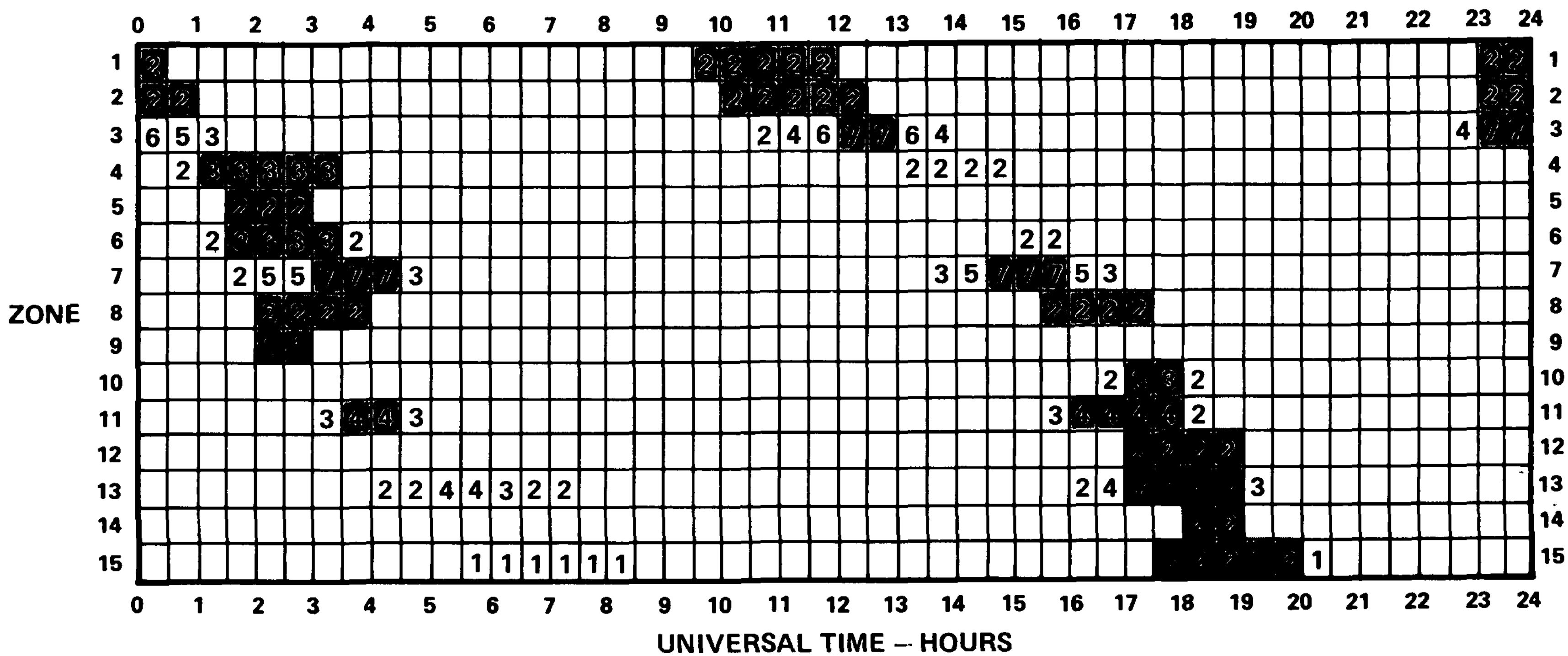



Figure 3-7. Single-Satellite Coverage from 8-Hour Orbit

- Combination of Patterns for Ascending Nodes of 233° (Delayed by 7½ Hrs.) and 293°

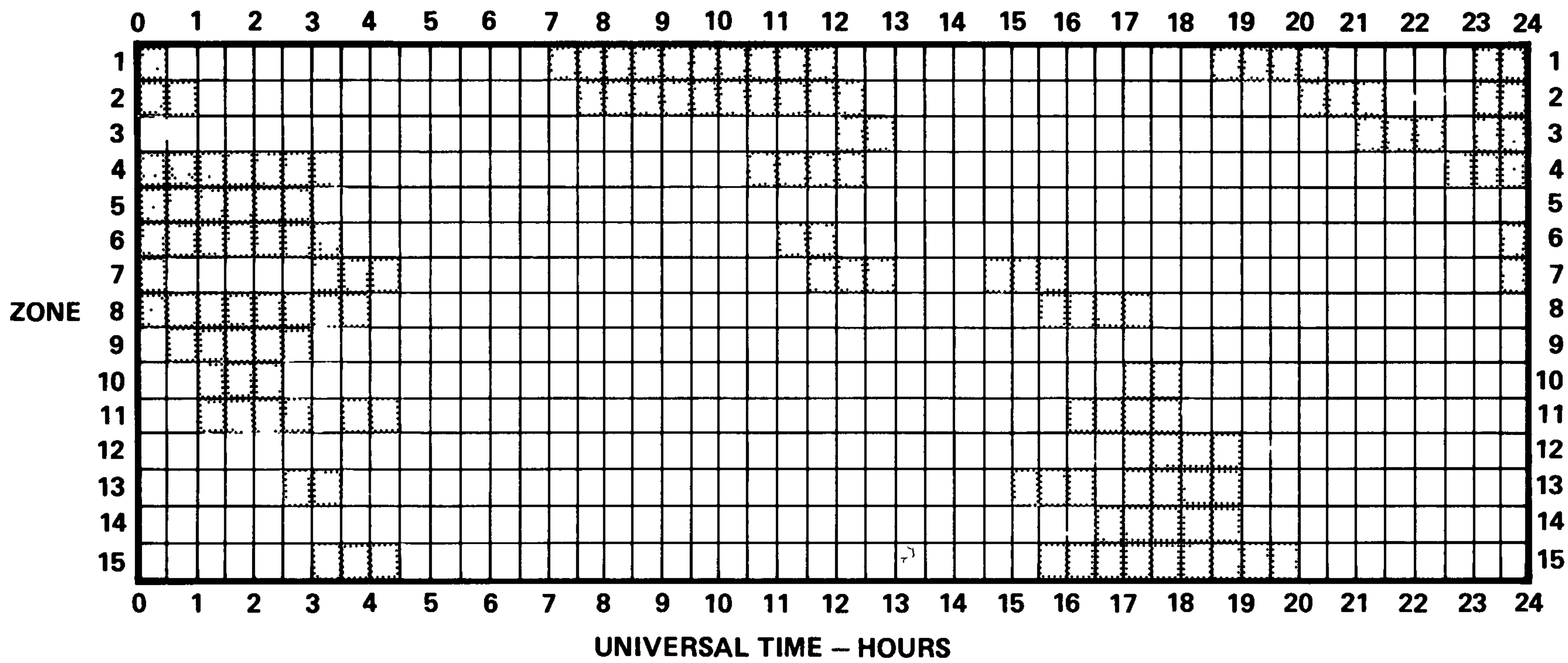



Figure 3-8. Zonal Coverage Provided by a Pair of 8-Hour Satellites

by the immediately preceding pair. This requires that the ascending nodes increase by multiples of 37.5 degrees from those of the initial satellite pair. Equatorial crossing times of satellites producing the same ground track are delayed by the corresponding multiples of 2-1/2 hours. The ascending nodes and equatorial crossing times are summarized below.

- Ground Track No. 1
  - Ascending nodes: -14.5° + 37.5n°, n = 0,1,2, ... 9
  - Equatorial crossing times: 0730 GMT + 2.5n hrs, n = 0,1,2, ... 9
- Ground Track No. 2
  - Ascending nodes: -67° + 37.5n°, n = 0,1,2, ... 9
  - Equatorial crossing times: 0000 GMT + 2.5n hrs, n = 0,1,2, ... 9

The suggested constellation of 20 satellites does not quite provide complete 24-hour coverage of all zones. Figure 3-9 indicates those periods of the day when the various zones are not completely covered. The entries indicate the number of beams of coverage provided to each zone. For example, Zone 3 is not completely covered during three 1/2-hour periods. However, four of the seven beams needed for coverage are provided during each of these periods. Similarly, partial coverage of Zone 10 involves two of three beams; of Zone 11, three of four beams; of Zone 12, one of two beams; and of Zone 13, five of seven beams.

The number of satellites that cover each zone during each 1/2-hour period of the day is indicated in Figure 3-10. It was decided that partial coverage of the three largest zones, each of which requires seven beams for complete coverage, should not be entirely ignored when computing the amount of broadcast service provided. Accordingly, a satellite is considered to provide complete coverage of these zones whenever the actual coverage provided is equivalent to 5 or more beams. The additional coverage provided by this relaxation of the coverage criterion amounts to an average of 1.0 satellite in Zone 3, 1.7 satellites in Zone 7, and 0.6 satellite in Zone 13.

• Entries Indicate Coverage, in Beam Units, Where Less Than Complete Zonal Coverage Is Provided

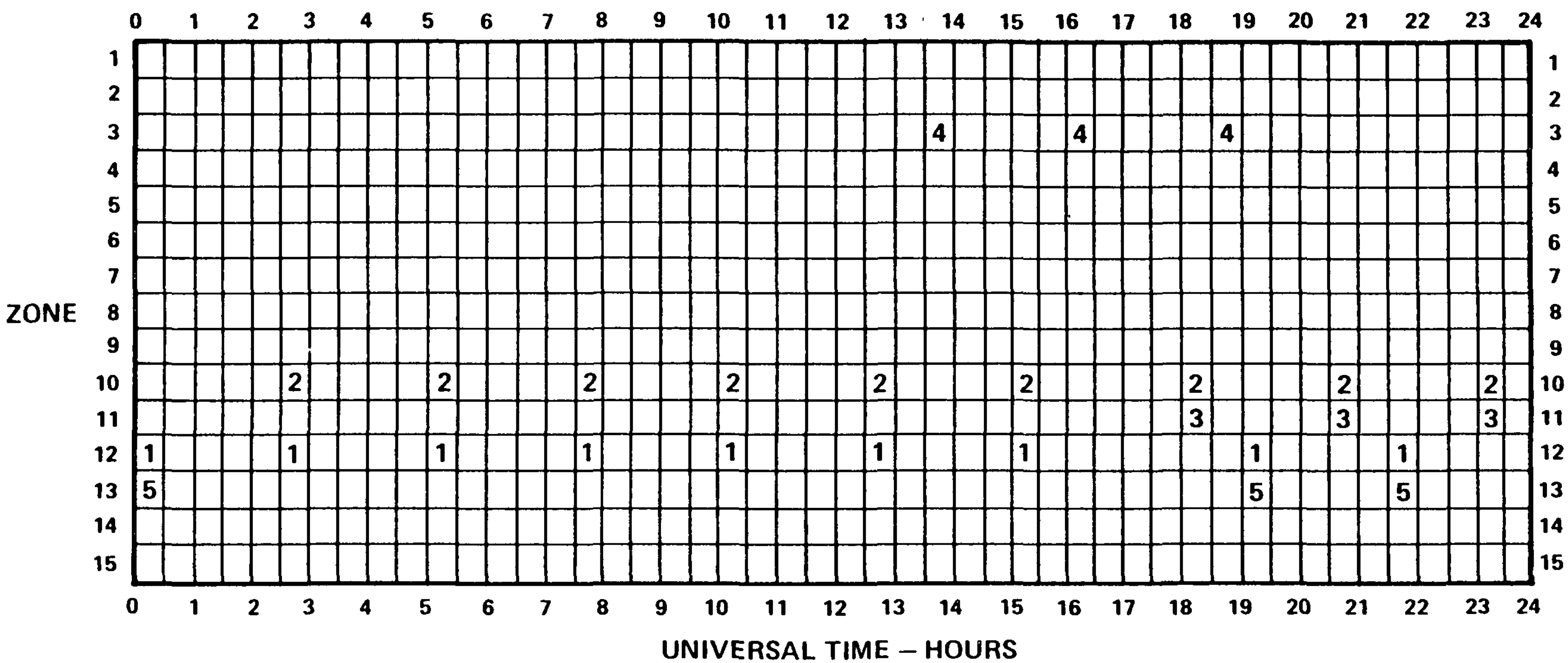



Figure 3-9. Zonal Coverage Provided By Constellation of 20 8-Hour Satellites

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- Entries indicate number of satellites covering each zone
- 735 channel-beam-hours provided daily out of 894 demanded

UNIVERSAL TIME (HOURS) 0–12

| ZONE | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 5 | 5 | 4 | 3 | 3 | 6 | 5 | 3 | 3 | 3 |
| 2 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 3 | 4 |
| 3 | 3 | 3 | 1 | 3 | 2 | 3 | 3 | 1 | 3 | 2 | 3 | 3 | 1 | 3 | 2 | 3 | 3 | 1 | 3 | 2 | 3 | 3 | 1 | 4 |
| 4 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 4 | 3 | 3 |
| 5 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 |
| 6 | 3 | 2 | 2 | 2 | 3 | 3 | 2 | 1 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 3 | 2 | 2 | 2 |
| 7 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 5 |
| 8 | 3 | 4 | 2 | 3 | 4 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 2 | 2 |
| 9 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 10 | 1 | 2 | 2 | 1 | 1 | 0 | 1 | 2 | 1 | 1 | 0 | 1 | 2 | 1 | 1 | 0 | 1 | 2 | 1 | 1 | 0 | 1 | 2 | 1 |
| 11 | 3 | 2 | 3 | 1 | 3 | 3 | 1 | 3 | 2 | 2 | 2 | 1 | 3 | 2 | 2 | 2 | 1 | 3 | 2 | 2 | 2 | 1 | 3 | 2 |
| 12 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 13 | 1 | 2 | 3 | 3 | 4 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 2 |
| 14 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 15 | 3 | 2 | 1 | 3 | 3 | 3 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 3 |

UNIVERSAL TIME (HOURS) 12–24

| ZONE | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5 | 4 | 3 | 3 | 3 | 5 | 4 | 3 | 3 | 3 | 5 | 4 | 3 | 4 | 4 | 5 | 4 | 2 | 3 | 4 | 5 | 4 | 3 | 4 |
| 2 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 5 | 4 | 3 | 3 | 3 | 5 | 5 | 4 |
| 3 | 3 | 3 | 3 | 0 | 3 | 3 | 3 | 3 | 0 | 3 | 3 | 3 | 3 | 0 | 3 | 3 | 3 | 4 | 1 | 3 | 3 | 2 | 4 | 2 |
| 4 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 3 |
| 5 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 |
| 6 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 |
| 7 | 4 | 4 | 4 | 3 | 5 | 5 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 5 | 4 |
| 8 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 4 | 3 | 2 | 3 | 2 | 3 | 3 | 2 | 3 | 2 | 3 | 3 | 2 | 3 | 2 | 3 | 3 |
| 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 10 | 1 | 0 | 1 | 2 | 1 | 1 | 0 | 1 | 2 | 1 | 2 | 1 | 0 | 1 | 1 | 2 | 1 | 0 | 1 | 1 | 2 | 1 | 0 | 1 |
| 11 | 2 | 2 | 1 | 3 | 2 | 2 | 2 | 1 | 4 | 3 | 2 | 2 | 0 | 3 | 3 | 2 | 2 | 0 | 3 | 3 | 2 | 2 | 0 | 3 |
| 12 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 13 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 1 | 2 | 3 | 3 | 3 | 1 | 2 | 3 | 3 | 3 |
| 14 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 15 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 4 | 3 | 3 | 2 | 2 | 4 | 3 | 3 | 2 | 1 | 3 | 3 | 3 | 2 | 1 | 3 | 3 |

Figure 3-10. Zonal Coverage Provided by Constellation of 20 8-Hour Satellites

Comparison of Figures 2-7 and 3-10 permits several observations regarding the degree to which the channel-beam demand of the broadcast schedule can be satisfied by the 20-satellite constellation. For example, Zone 13 frequently requires 21 channel-beams of service. Because a single satellite has a capacity of only six channel-beams, coverage by four satellites is needed to provide this service. With the exception of one 1/2-hour period of the day, Zone 13 receives a maximum of three-satellite coverage. Therefore, no more than 18 channel-beams of service can be provided. Moreover, use of all satellites covering Zone 13 to provide service to that zone precludes simultaneous provision of service by those satellites to other zones.

On the other hand, there are always enough satellites covering Zone 7 to satisfy the maximum demand of 14 channel-beams. Zone 3 represents an intermediate situation, in which the maximum demand of 14 channel-beams can be met only during those 1/2-hour periods (and for those days) when the (appropriated rotated) pattern of Figure 3-10 provides at least three-satellite coverage.

Finally, it is worth observing that the four Soviet zones (9, 10, 12, and 14) have a combined demand that exceeds six channel-beams in only four 1/2-hour periods of the day. With these possible exceptions, the service requirements of the Soviet zones can be satisfied except when a zero entry in Figure 3-10, suitably rotated, coincides with a nonzero entry in Figure 2-7.

To determine the degree to which the demands of the broadcast schedule can be met in each 1/2-hour period, the satellite coverage pattern must be examined in detail. This is done in Figure 3-11 for a particular 1/2-hour period. There are seven zones with a nonzero channel-beam demand. Seven of the 20 satellites cover one or more of these zones. An X in the table denotes zonal coverage. The total service demand is 38 channel-beams, while the total satellite capacity is 42 channel-beams. Nevertheless, only 37 of the 38 channel-beams demanded can be provided for the coverage pattern depicted.

- Satellite Capacity = 6 Channel-Beams

| ZONE | CHANNEL-BEAM DEMAND | ZONAL COVERAGE (SATELLITE NUMBER) 2 | 4 | 8 | 9 | 12 | 13 | 18 |
|---|---|---|---|---|---|---|---|---|
| 4 | 3 | | X | | X | | | X |
| 5 | 2 | | | | | | | X |
| 6 | 6 | | | | X | | | X |
| 7 | 14 | | X | | X | | X | X |
| 8 | 2 | | | X | | X | | X |
| 13 | 7 | | | X | | X | | |
| 14 | 4 | X | | | | | | |

- Total Service Demand = 38 Channel-Beams
- Available Satellite Capacity = 42 Channel-Beams
- Maximum Service Provided = 37 Channel-Beams

Figure 3-11. Satellite/Zone Assignment Problem

To verify this fact, note that Satellite 2 must be assigned to Zone 14, and Satellite 13 to Zone 7. After the latter assignment, 8 of the 14 channel-beams demanded by Zone 7 remain to be provided. Thus, a total of 19 channel-beams remain to be provided to Zones 4, 5, 6, and 7. However, only the 18 channel-beam capacity of Satellites 4, 9, and 18 can be brought to bear on these zones. Therefore, at least one channel-beam of demand must remain unsatisfied. (It is easily verified that 18 channel beams can, in fact, be provided to Zones 4, 5, 6, and 7.) Clearly, Satellites 8 and 12 can provide the required service to Zones 8 and 13. It follows that the combined service provided to the seven zones is 37 channel-beams.

An algorithm has been developed to compute the amount of service that can be provided by an arbitrary satellite constellation relative to a broadcast schedule involving as many as 15 zones. A description of the algorithm is given in Appendix G, together with its application to the example of Figure 3-11. To evaluate the constellation represented by the coverage matrix in Figure 3-10, the algorithm must be applied to each of the 48 1/2-hour periods. The sum of the results (in units of channel-beams), divided by two, is the number of CBH provided daily.

The daily service varies somewhat, depending on the time of year. Forty-eight different versions of the coverage pattern in Figure 3-10 may obtain, as the columns are rotated to account for the difference between the sidereal and solar days. The composite pattern in Figure 3-10 was formed by superimposing 10 patterns like that in Figure 3-8, which are delayed by multiples of 2-1/2 hours. Except for the fact that 2-1/2 hours does not divide evenly into 24 hours, only five of the 48 patterns (corresponding to rotations of 0, 1/2, 1, 1-1/2, and 2 hours) would be different. As it is, rotations of 2-1/2 hours or more produce coverage patterns quite similar to one of these five.

The average daily service provided by these five pattern rotations is 735 CBH. By comparison, the broadcast schedule in Figure 2-7 calls for 894 CBH. Thus, the original judgment that the 8-hour orbit provides the proper balance between satellite coverage and capacity has been borne out.

The daily broadcast service provided by each subsynchronous satellite constellation considered in this study is obtained by exercising a computer program which is constructed around the algorithm in Appendix G.

## 3.4 REAL-TIME FEEDER LINKS

Real-time feeder links can be constructed whenever the broadcast satellite is simultaneously in view of the area that receives the broadcast and an earth station that can originate the broadcast. This situation, which permits the satellite to act as a frequency-translation repeater, is clearly preferable to storage of feeder-link transmissions for later broadcast. Apart from the added complexity of recording and possibly processing the program material onboard the satellite, the latter situation contrasts with current VOA operations, in which terrestrial stations relay broadcasts in real time.

By definition, real-time feeder links require a satellite elevation angle that exceeds 10 degrees at a suitable uplink earth-station location. In order of preference, acceptable earth-station locations include:

1) U.S. (CONUS plus Alaska and Hawaii)

2) U.S. territories

3) Friendly host countries

If none of these possibilities exists, real-time transmission can still be accomplished by satellite relay.

Real-time feeder-link possibilities for the satellite locations used in the Band 1 and 3 geostationary systems are shown in Table 3-3. All broadcasts can be conducted in real time from at least one of the three types of locations listed above. The one U.S. territory considered, Guam, provides an alternative to broadcasts originating in Australia for a satellite located at 115 degrees east.

Real-time feeder-link options for the two 8-hour-orbit ground tracks are shown in Figures 3-12 and 3-13. Entries in these charts correspond to those in Figures 3-6 and 3-7 (i.e., feeder links are considered whenever two or more beams of coverage can be provided to a zone). The broadcast schedule has been ignored in deriving these feeder-link charts. This is appropriate because the 4-minute daily shift of the coverage patterns guarantees that each 1/2-hour of coverage shown will at some point coincide with a broadcast period.

Table 3-3. Feeder Links for Geostationary Satellites

| Satellite Longitude | Zones Covered | Real Time Broadcast From | | | |
|---|---|---|---|---|---|
| | | U.S. | Guam | Australia | Western Europe |
| 65°W | 1, 2, 3, 4 | ● | | | |
| 30°E | 4, 5, 6, 7, 8, 9, 10, 11 | | | | ● |
| 115°E | 10, 11, 12, 13, 14, 15 | | ● | ● | |

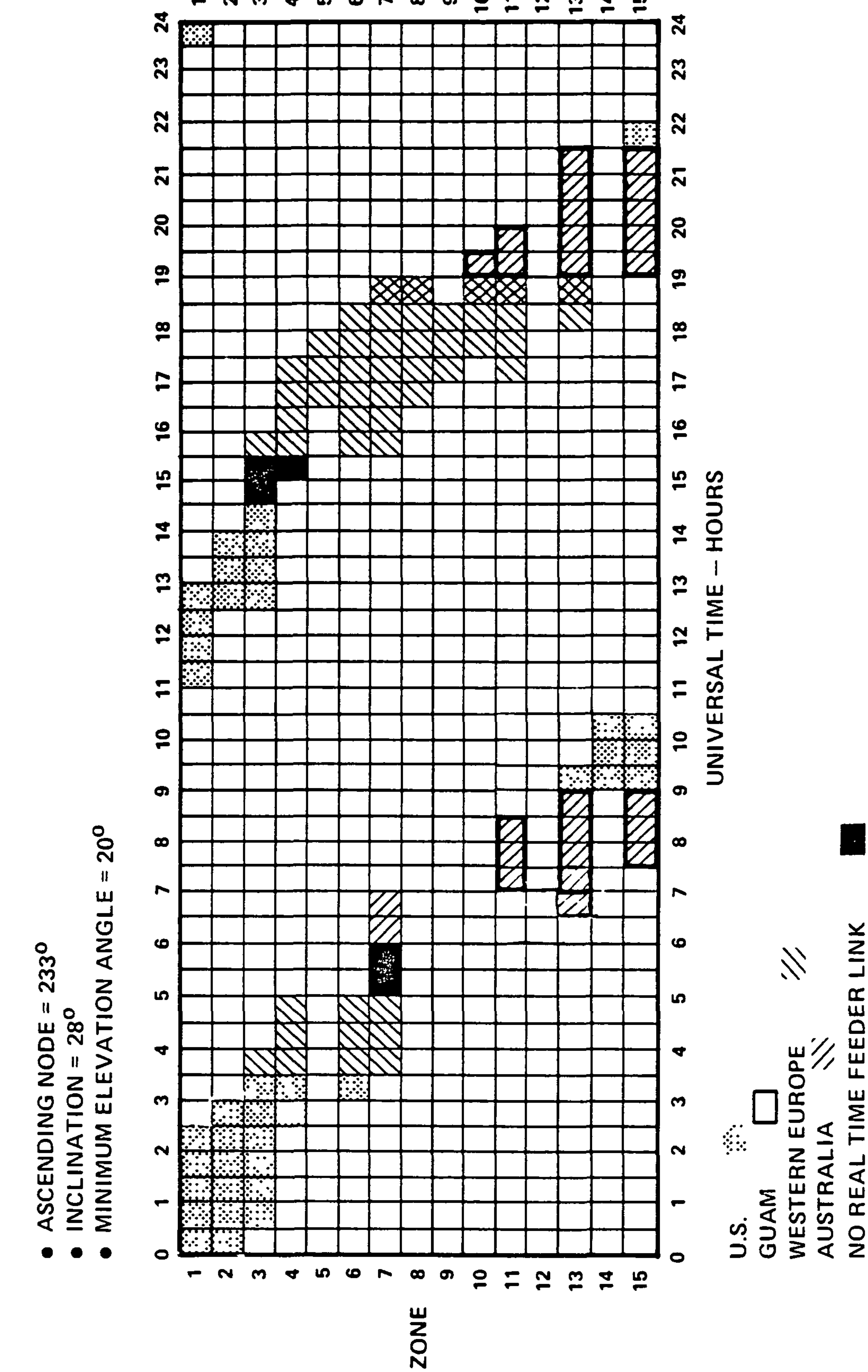


Figure 3-12. Real-Time Feeder Links for 6-Hour Circular Orbit

- ASCENDING NODE = 293°
- INCLINATION = 28°
- MINIMUM ELEVATION ANGLE = 20°

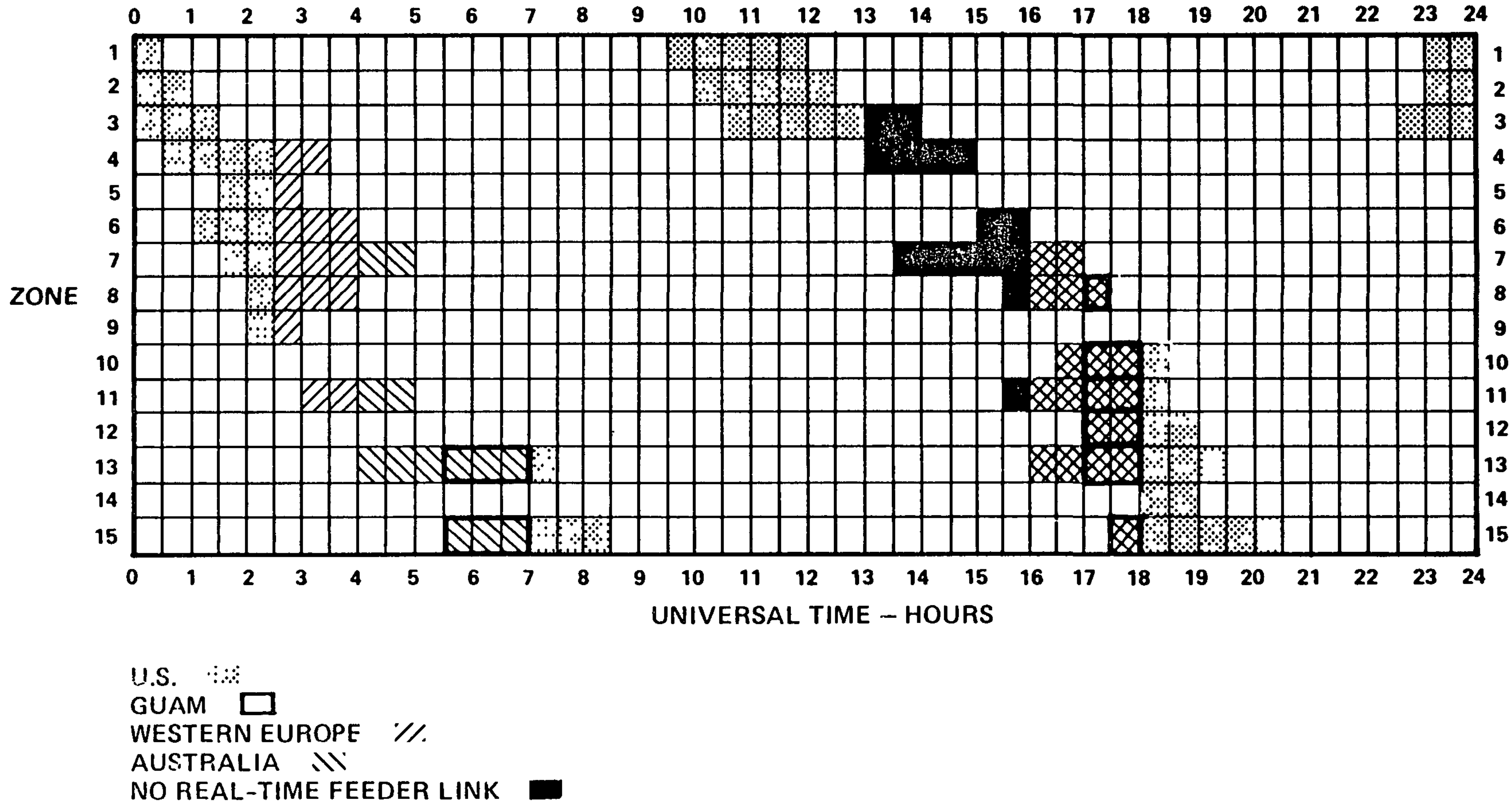


Figure 3-13. Real-Time Feeder Links for 8-Hour Circular Orbit

Following the priorities established for real-time feeder links, when uplink transmission from the U.S. (including Alaska and Hawaii) is possible, alternate earth-station locations are not shown. At other times, all other possibilities are shown.

For the ground track corresponding to Figure 3-12, there are only two 1-hour periods when real-time feeder links cannot be established from the territories considered. The zones affected are 3, 4, and 7. The alternatives in these cases are to:

a) Establish real-time feeder links via satellite relay

b) Store program material on board the satellite based on earlier uplink transmission (from the U.S. for Zones 3 and 4, and from Western Europe for Zone 7).

Only a 1-hour delay is experienced under Alternative b.

A final possibility is to transmit the program material, in real time, from a surface ship (which might, itself, receive the material via satellite). A ship located off the coast of Southwest Africa could serve as an uplink source for the two blacked-out hours shown in Figure 3-12.

A set of earth-station locations sufficient to provide the feeder links indicated in Figure 3-12 includes Florida, Western Alaska, Hawaii, Guam, Southern England, Southwest Germany, and Western Australia.

For the ground track corresponding to Figure 3-13, there is a 3-hour period during which a real-time feeder link cannot be established from the territories considered. The zones affected are 3, 4, 6, 7, 8, and 11. Only for Zone 7 does this 3-hour period include an interval of full zonal coverage, from 1430 to 1600 hours. Program material to be broadcast to Zone 7 during this 1-1/2 hour period can be transmitted from a U.S.-based earth station between 1130 and 1300 hours. (Real-time uplink availability from the U.S. between 1130 and 1300 hours is evident from the indicated Zone 3 coverage.) The broadcast delay in this case would be 3 hours.

To realize the real-time feeder links shown in Figure 3-13, an earth station in Maine must be added to those mentioned previously. In addition, between 1730 and 1800 hours, a site in Sweden must be added to provide a European feeder link, although an uplink from Australia is also possible during this period.

For the Band 2 Molniya orbit, the high altitude and northern latitudes reached near apogee afford an opportunity to provide a real-time feeder link from the U.S. As seen from Figure 3-14, satellite visibility from the U.S. exists for a 9-hour period centered at apogee. In fact, at apogee, visibility exists from points within CONUS (at an elevation angle equal to or greater than 10 degrees). However, if a single U.S. site is to be used for each of three satellites during the 8-hour period centered at apogee, it must be located in Alaska.

Feeder link availability from Guam and Western Europe is shown in Figure 3-14 only when U.S. feeder links cannot be established.

- Ascending node = 90°
- Minimum broadcast elevation angle = 20°
- Minimum feeder-link elevation angle = 10°

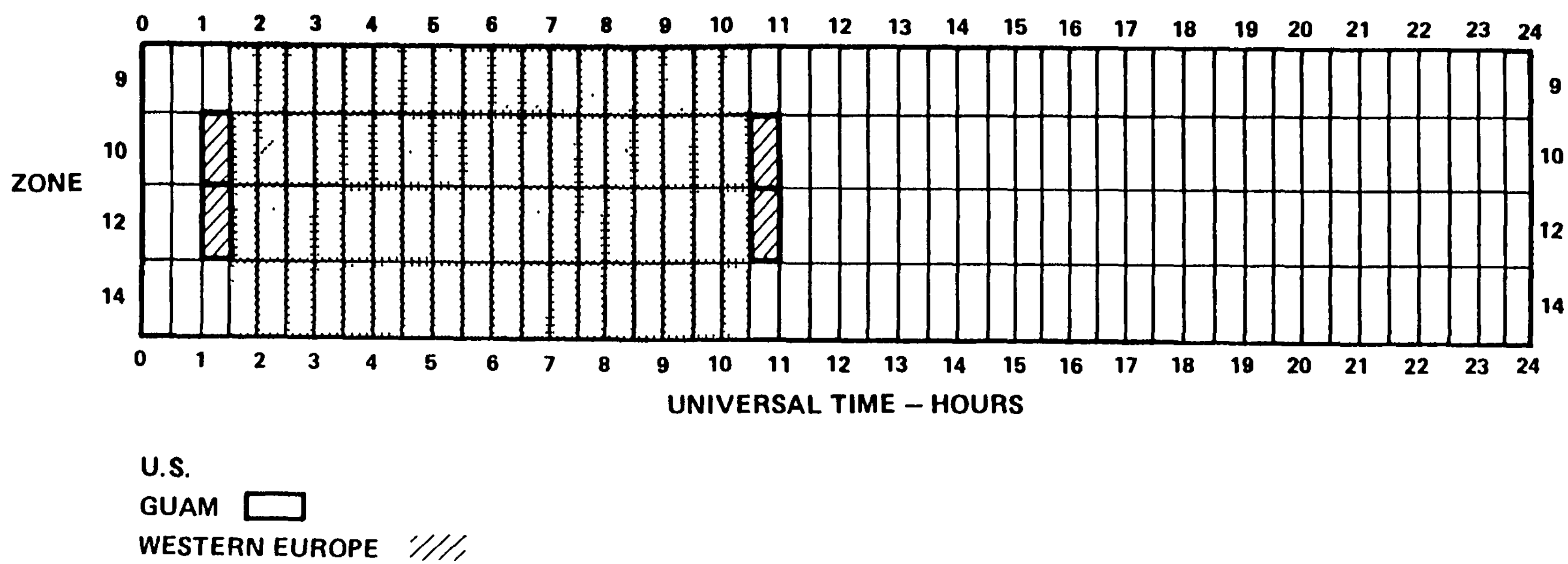


Figure 3-14. Real-Time Feeder Links for Molniya Orbit

# 4. SYSTEM CONCEPT VARIATIONS

The variations on the four baseline system concepts fall into five categories (Table 4-1). The first two categories restrict coverage to middle latitudes or northern and southern latitudes, respectively. Because of uncertainties in propagation to extreme northern latitudes from geostationary orbit in Band 1, only the 8-hour-orbit case is considered for Variation 2. Variations 3 and 4 restrict the channel demand to one channel per zone. While Variation 3 also restricts geographic coverage to the northern and southern zones, Variation 4 applies to all 15 broadcast zones. Variation 3 follows the original broadcast schedule, while Variation 4 provides 2 hours of broadcasting in both morning and evening.

Variations 1 through 4, as they apply to Band 1, require a field strength of 300 μV/m, which is the baseline system requirement. In Variation 5, the field strength requirement is reduced to 150 μV/m. (The Band 2 baseline requirement is 250 μV/m.) Otherwise, the Variation 5 broadcast requirements are exactly as in the baseline systems.

The reduction in field strength to 150 μV/m affords an opportunity either to reduce the number of satellites or to simplify the satellite design. Different approaches will be followed to arrive at the most desirable alternatives to the Band 1 and 2 baseline system designs.

The latitude divisions that define the regions under consideration in Variations 1, 2, and 3 are 40 degrees north and 15 degrees south. The latter division divides two of the larger zones, namely 3 and 7, into two portions. As indicated in Figure 4-1, the northern and southern portions of each zone have been given different designations. Of the seven beams required to cover Zone 3 as seen from geostationary orbit, four are associated with Zone 3' and three with Zone 3". Similarly, of the seven beams required to cover Zone 7, five are associated with Zone 7' and two with Zone 7".

For simplicity, Zones 5, 9, and 10 will be considered to lie entirely to the north of 40 degrees north, and Zones 8, 13, and 15 entirely to the south of 40 degrees north.

Table 4-1. System Concept Variations

| Variation | Applicable To: Band | Applicable To: Orbit |
|---|---|---|
| 1. Restrict broadcasts to latitudes between 40° N and 15° S | 1 | Geostationary, 8-Hour |
| 2. Restrict broadcasts to latitudes above 40° N or below 15° S | 1 | 8-Hour |
| 3. Same as Number 2 above, but with only one channel per zone | 1 | 8-Hour |
| 4. Broadcasts confined to two hours in morning and evening, with one channel per zone (prime-time broadcast system) | 1 | Geostationary, 8-Hour |
| | 3 | Geostationary |
| 5. Field strength requirement reduced to 150 $\mu$V/m | 1 | Geostationary, 8-Hour |
| | 2 | Molniya |

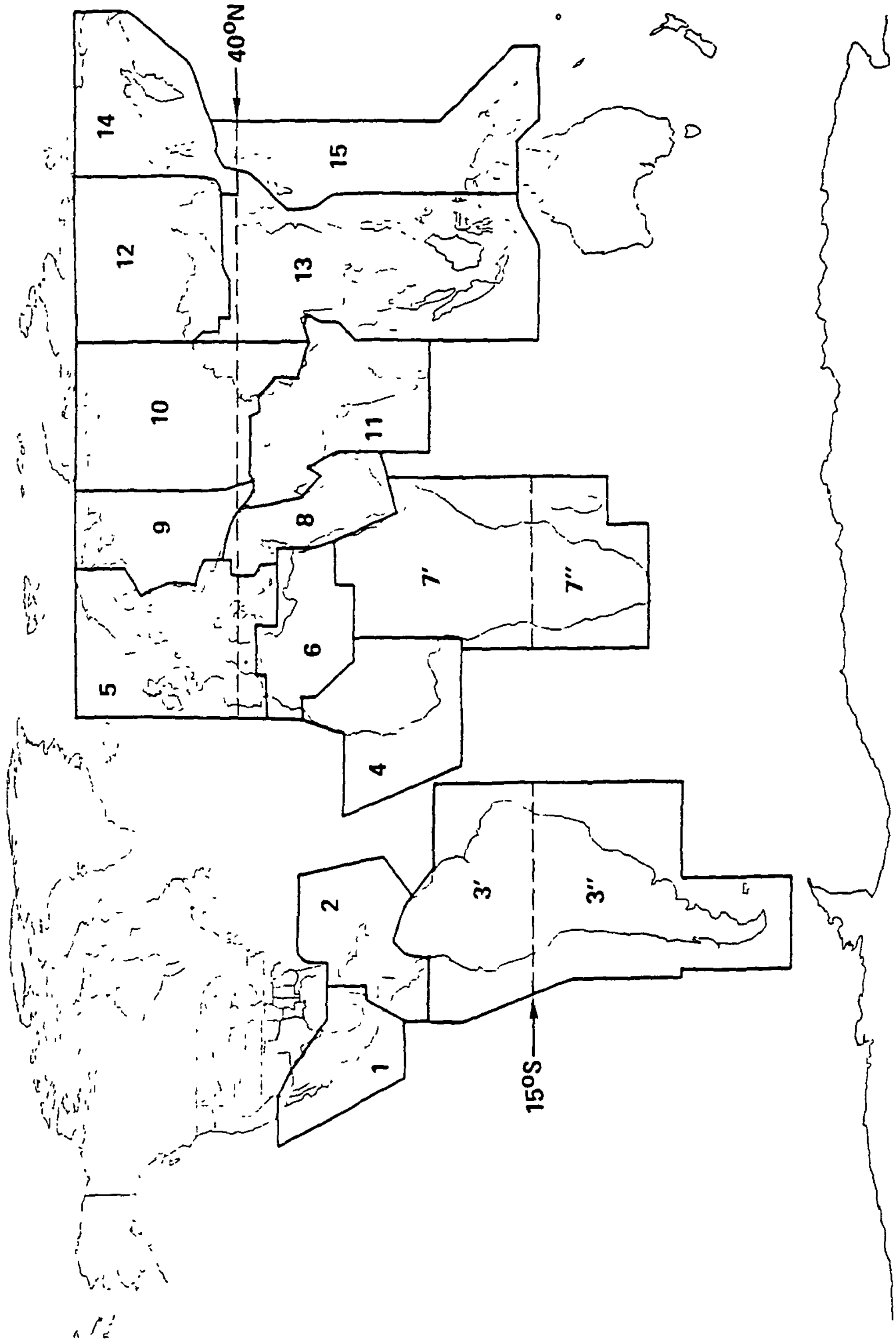


Figure 4-1. Broadcast Zone Redefinition for System Variations 1, 2, and 3

## 4.1 VARIATION 1 - COVERAGE RESTRICTED TO LATITUDES BETWEEN 40 DEGREES NORTH AND 15 DEGREES SOUTH

The broadcast schedule for zones falling between latitudes of 40 degrees north and 15 degrees south is developed in Figure 4-2. The number of voice channels per beam for each zone is the same as that in the broadcast schedule of Figure 2-6. In particular, the numbers of voice channels shown for Zones 3' and 7' are identical to those shown for Zones 3 and 7, respectively.

The required number of channel-beams per zone is obtained by multiplying the number of voice channels per beam by the number of beams per zone. The daily CBH total is 646, compared with 894 CBH in Figure 2-7, from which the baseline systems were derived.

For the Band 1 geostationary system, the same three satellite locations have been selected as in the baseline case. The number of channel-beams that must be provided at each satellite location during each 1/2-hour of the day is indicated in Figure 4-3. Because of the latitude restriction, the channel-beam demand is generally smaller than in the baseline system. Again taking the satellite capacity as two channel-beams, it is easily verified that a total of 36 satellites is required for this system. This compares with a total of 47 in the baseline system.

For the 8-hour system, 24-hour coverage of the zones of interest can be achieved using 12 satellites that generate the same ground track. The coverage pattern for an orbit inclined at 28 degrees, with an ascending node of 293 degrees, is shown in Figure 4-4. Because the extreme northern and southern latitudes are excluded from the region of interest, the minimum coverage per zone is now 2 hours per day. Thus, 12 such patterns, delayed by multiples of 2 hours, provide complete zonal coverage. The corresponding orbit planes have ascending nodes that increase by multiples of 30 degrees. The times of equatorial crossing are delayed by corresponding multiples of 2 hours.

While twelve 8-hour satellites suffice for 24-hour coverage of all zones, the capacity of six channel-beams per satellite limits the broadcast service that can be provided. The daily average is 416 CBH, as compared with 646 CBH called for by the broadcast schedule. Increasing the number

## Number of Voice Channels/Beam

| ZONE | 0 |  | 1 |  | 2 |  | 3 |  | 4 |  | 5 |  | 6 |  | 7 |  | 8 |  | 9 |  | 10 |  | 11 |  | 12 |  | 13 |  | 14 |  | 15 |  | 16 |  | 17 |  | 18 |  | 19 |  | 20 |  | 21 |  | 22 |  | 23 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |  |  |  |  |  |  |  |  |  |  |  | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |  |  |  |  |  |  |  |  |  | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | 2 | 2 |
| 3' | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |  |  |  |  |  |  |  | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | 1 | 1 | 2 | 2 |
| 4 |  |  |  |  |  |  |  |  |  |  | 1 | 2 | 1 |  | 1 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  | 1 | 2 | 2 | 1 | 1 | 1 | 1 |  |  |  |
| 6 |  |  |  |  |  |  | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| 7' |  |  |  |  |  | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | 2 | 1 |  | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 |
| 8 |  |  |  | 1 | 1 | 1 | 1 |  | 1 | 2 | 2 | 1 |  |  |  | 1 |  |  | 1 | 1 | 1 | 1 |  |  |  |  |  |  | 1 | 1 | 1 | 2 | 1 |  | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |  |  |  |  |
| 11 |  |  | 2 | 3 | 2 | 2 | 4 | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |  |  |  |  |  |  |  |  |  | 1 |
| 13 | 2 | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 2 |  |  |  |  |  |  |  |  |  |  | 1 | 1 | 2 | 3 | 3 | 3 |
| 15 | 1 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | 1 | 1 | 1 |

UNIVERSAL TIME – HOURS

## Number of Channel-Beams

| ZONE | 0 |  | 1 |  | 2 |  | 3 |  | 4 |  | 5 |  | 6 |  | 7 |  | 8 |  | 9 |  | 10 |  | 11 |  | 12 |  | 13 |  | 14 |  | 15 |  | 16 |  | 17 |  | 18 |  | 19 |  | 20 |  | 21 |  | 22 |  | 23 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |  |  |  |  |  |  |  |  |  |  |  | 2 | 2 | 2 | 4 | 4 | 4 | 2 | 2 | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 | 2 |
| 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 2 | 2 |  |  |  |  |  |  |  |  |  | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 | 4 | 4 |
| 3' | 8 | 8 | 8 | 8 | 8 | 8 | 4 | 4 | 4 | 4 | 4 |  |  |  |  |  |  |  | 4 | 4 | 4 | 4 | 8 | 8 | 8 | 8 | 4 | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4 | 4 | 4 | 8 | 8 |
| 4 |  |  |  |  |  |  |  |  |  |  | 3 | 6 | 3 |  | 3 | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  | 3 | 6 | 6 | 3 | 3 | 3 | 3 |  |  |  |
| 6 |  |  |  |  |  |  | 3 | 3 | 6 | 6 | 6 | 6 | 3 | 3 | 3 | 6 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 3 | 3 | 3 | 3 |
| 7' |  |  |  |  |  | 5 | 10 | 5 | 10 | 10 | 10 | 10 | 10 | 5 | 5 | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5 | 10 | 5 |  | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 5 | 5 | 5 |
| 8 |  |  |  | 2 | 2 | 2 | 2 |  | 2 | 4 | 4 | 2 |  |  |  | 2 |  |  | 2 | 2 | 2 | 2 |  |  |  |  |  |  | 2 | 2 | 2 | 4 | 2 |  | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |  |  |  |  |
| 11 |  |  | 8 | 12 | 8 | 8 | 16 | 16 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 8 | 16 | 12 | 8 | 12 | 12 | 12 | 12 | 4 | 4 | 4 | 4 |  |  |  |  |  |  |  |  |  | 4 |
| 13 | 14 | 14 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 14 | 21 | 21 | 21 | 14 | 21 | 21 | 21 | 21 | 14 | 14 |  |  |  |  |  |  |  |  |  |  |  | 7 | 7 | 21 | 21 | 21 |
| 15 | 2 | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 | 2 | 2 | 2 |

UNIVERSAL TIME – HOURS

Figure 4-2. Channel-Beam Demand for Latitudes Between 40°N and 15°S

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## Number of Channel Beams

| SATELLITE POSITION | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65°W | 14 | 14 | 16 | 16 | 16 | 16 | 12 | 10 | 10 | 10 | 10 | | | | | | | | 4 | 4 | 6 | 6 | 14 | 14 |
| 30°E | | | 8 | 14 | 10 | 15 | 31 | 24 | 18 | 20 | 23 | 24 | 16 | 8 | 11 | 21 | | | 2 | 2 | 2 | 2 | | |
| 115°E | 16 | 16 | | | | | | | | | | | | | | | | | | | 2 | 14 | 23 | 23 |

UNIVERSAL TIME – HOURS (0–12)

| SATELLITE POSITION | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65°W | 14 | 16 | 12 | 10 | 2 | 2 | 2 | | | | | | | | | | | | | 4 | 4 | 6 | 14 | 14 |
| 30°E | | | 8 | 16 | 14 | 10 | 19 | 26 | 19 | 12 | 22 | 22 | 25 | 22 | 21 | 24 | 24 | 21 | 21 | 21 | 16 | 8 | 8 | 12 |
| 115°E | 23 | 16 | 23 | 23 | 23 | 23 | 14 | 14 | | | | | | | | | | | 7 | 7 | 16 | 23 | 23 | 23 |

UNIVERSAL TIME – HOURS (12–24)

Figure 4-3. Geostationary Channel-Beam Demand for Latitudes Between 40°N and 15°S

- Inclination = 28°
- Ascending Node = 293°
- Minimum Elevation Angle = 20°

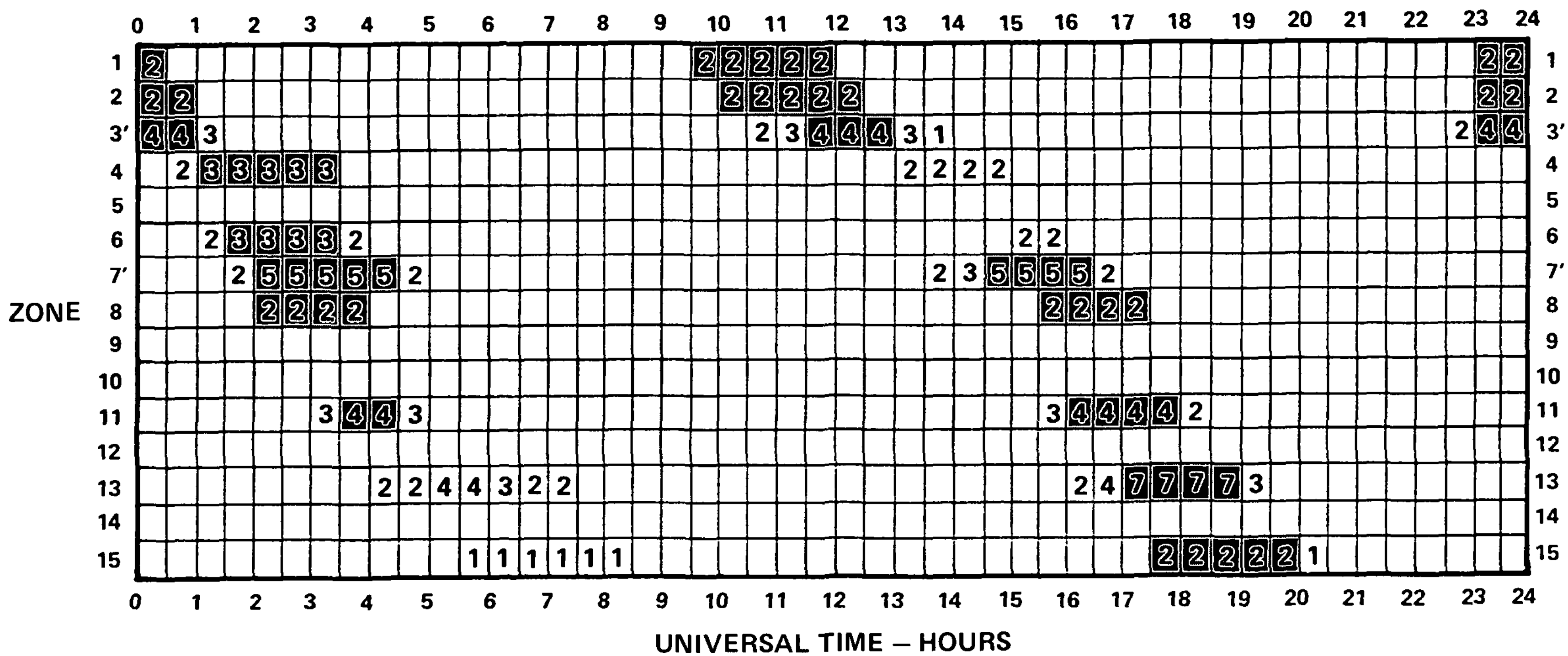



Figure 4-4. Coverage from 8-Hour Orbit for Latitudes Between 40°N and 15°S

of satellites to 16 raises the average number of CBH to 483. This 16 percent increase in service was judged insufficient to justify a 33 percent increase in the number of satellites.

A system summary for Variation 1 is provided in Table 4-2.

## 4.2 VARIATION 2 - COVERAGE RESTRICTED TO LATITUDES ABOVE 40 DEGREES NORTH OR BELOW 15 DEGREES SOUTH

The broadcast schedule for this restricted set of zones is shown in Figure 4-5. The number of voice channels per beam is unchanged from that shown in Figure 2-6, with one exception. For Zone 5, the maximum channel demand per zone has been reduced to six wherever a larger number appears in Figure 2-2. Since the channel demand is assumed to be divided between the two beams required to cover Zone 5, a maximum of three channels per beam is required. For Zones 3" and 7", the number of channels per beam is identical to that for Zones 3 and 7, respectively, as shown in Figure 2-6.

The required number of channel-beams per zone is obtained by multiplying the number of voice channels per beam by the number of beams per zone. The daily CBH total is 234, compared with 894 CBH in the baseline system.

From a coverage standpoint, the required number of 8-hour satellites is the same as for the baseline system, assuming that the orbit inclination is maintained at 28 degrees. Coverage patterns for ascending nodes of 233 and 293 degrees are shown in Figure 4-6. As in the baseline system, the two patterns must be combined (with the top pattern delayed by 7-1/2 hours) to provide substantial coverage of all northern zones. As before, 10 such satellite pairs are required to provide complete and (nearly) continuous coverage of all zones.

It is possible, by choosing an orbit inclination greater than 28 degrees, to provide continuous coverage of the northern zones with only 16 satellites. However, a higher inclination tends to lessen the capacity of an individual satellite because of the reduced STS/Centaur payload capability. Reducing the number of satellites tends to increase the responsibility of an individual satellite with respect to the number of zones to which it must simultaneously provide coverage. It is shown in Figure 4-7 that, even with 20 satellites, the six-channel-beam capacity of a satellite

Table 4-2. Variation 1 System Summary

| Band | Orbit | Number of Satellites | Channel-Beam-Hour Demand | Channel-Beam-Hours Provided |
|---|---|---|---|---|
| 1 | GEO | 36 | 646 | 646 |
| 1 | 8-Hour | 12* | 646 | 416 |
| | | (16) | (646) | (483) |

*Provides 24-hour coverage of all zones

## Number of Voice Channels/Beam

Universal Time – Hours 0–12

| Zone | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3" | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | | | | | | | | 1 | 1 | 1 | 1 | 2 | 2 |
| 5 | | | | | | | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | | | | | | | | |
| 7" | | | | | | 1 | 2 | 1 | 3 | 3 | 3 | 3 | 2 | 1 | 1 | 2 | | | | | | | | |
| 9 | | | | 1 | 1 | | | 2 | 6 | 1 | | | | | | | | | | | | | | |
| 10 | 1 | 1 | | | 2 | 2 | 2 | 1 | | | | | | | | | | | | | | | 1 | 1 |
| 12 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | 2 | 1 |
| 14 | | | | | | | | | | | | | | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | | |

Universal Time – Hours 12–24

| Zone | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3" | 2 | 2 | 1 | 1 | | | | | | | | | | | | | | | | 1 | 1 | 1 | 2 | 2 |
| 5 | | 1 | 1 | 1 | 1 | 1 | | | 1 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7" | | | | | | | 1 | 2 | 1 | | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | 1 | 1 |
| 9 | | | | | 1 | 1 | 1 | 1 | 2 | 5 | 1 | 1 | 1 | | | | | | | | | | | |
| 10 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | 1 | 1 |
| 12 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | 1 | 1 | 1 |
| 14 | | | | | | | | | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | | | | |

## Number of Channel-Beams

Universal Time – Hours 0–12

| Zone | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3" | 6 | 6 | 6 | 6 | 6 | 6 | 3 | 3 | 3 | 3 | 3 | | | | | | | | 3 | 3 | 3 | 3 | 6 | 6 |
| 5 | | | | | | | 2 | 2 | 6 | 6 | 6 | 6 | 2 | 2 | 2 | 2 | | | | | | | | |
| 7" | | | | | | 2 | 4 | 2 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 4 | | | | | | | | |
| 9 | | | | 1 | 1 | | | 2 | 6 | 1 | | | | | | | | | | | | | | |
| 10 | 3 | 3 | | | 6 | 6 | 6 | 3 | | | | | | | | | | | | | | | 3 | 3 |
| 12 | 2 | 2 | | | | | | | | | | | | | | | | | | | | | 4 | 2 |
| 14 | | | | | | | | | | | | | | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | | |

Universal Time – Hours 12–24

| Zone | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3" | 6 | 6 | 3 | 3 | | | | | | | | | | | | | | | | 3 | 3 | 3 | 6 | 6 |
| 5 | | 2 | 2 | 2 | 2 | 2 | | | 2 | 6 | 6 | 6 | 6 | 6 | 4 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 7" | | | | | | | 2 | 4 | 2 | | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 2 |
| 9 | | | | | 1 | 1 | 1 | 1 | 2 | 5 | 1 | 1 | 1 | | | | | | | | | | | |
| 10 | 3 | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 3 | 3 | | | | | | | | | | | | | 3 | 3 |
| 12 | 2 | 2 | 2 | 2 | | | | | | | | | | | | | | | | | | 2 | 2 | 2 |
| 14 | | | | | | | | | | | | | | | 2 | 2 | 4 | 4 | 4 | 4 | | | | |

Figure 4-5. Channel-Beam Demand for Latitudes Above 40°N or Below 15°S

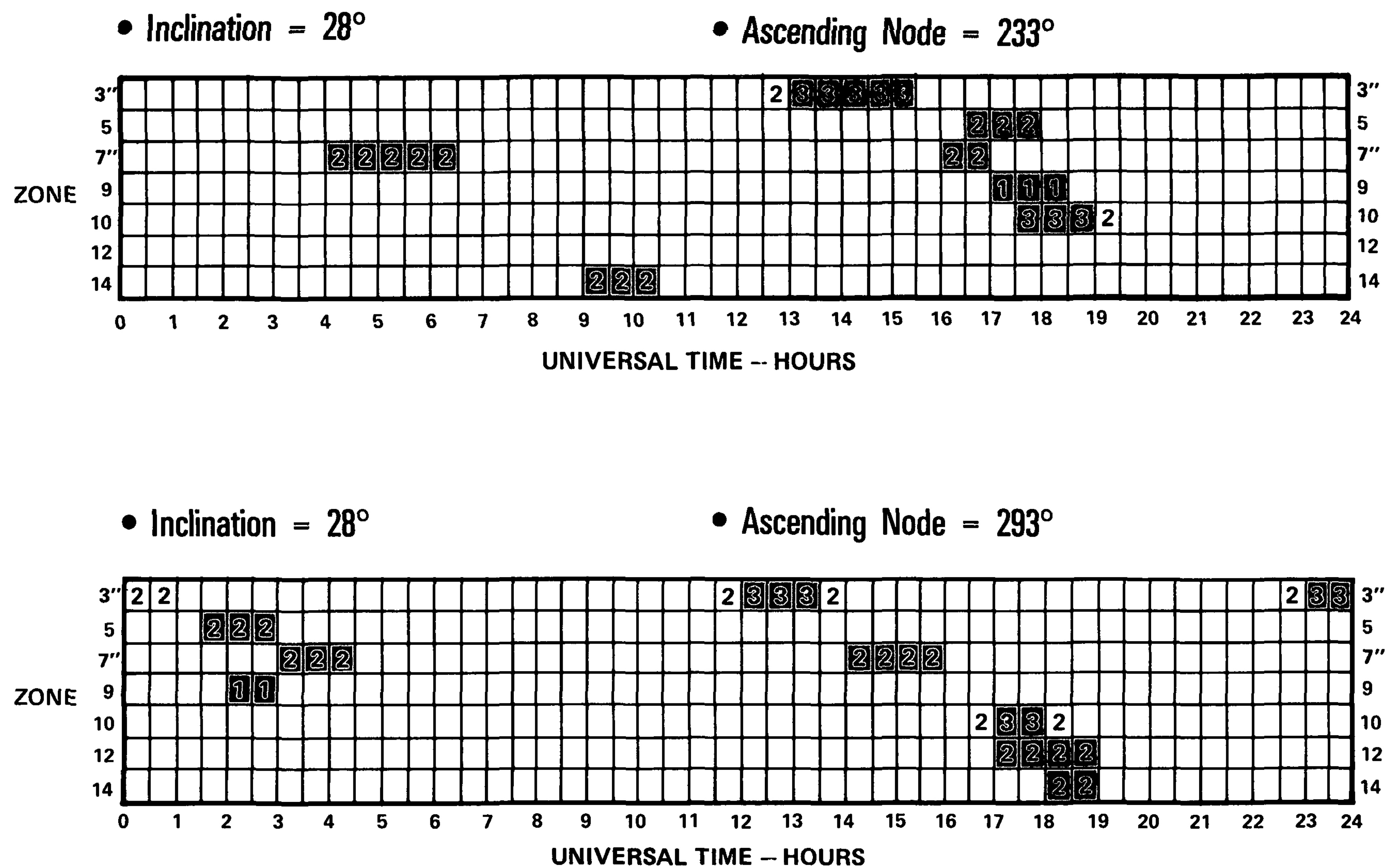



Figure 4-6. Coverage from 8-Hour Orbit for Latitudes Above 40°N or Below 15°S

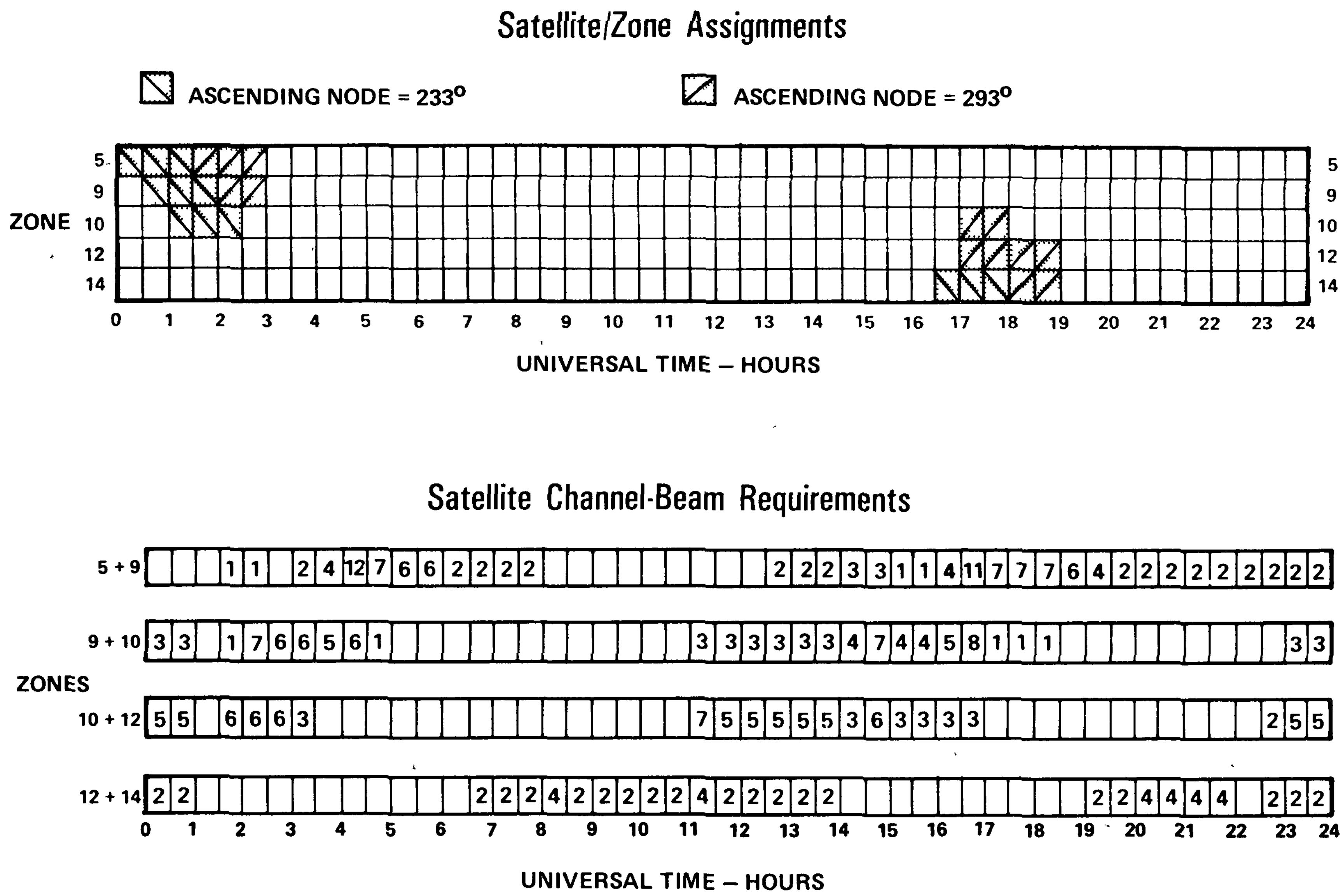



Figure 4-7. Single-Satellite Channel-Beam Requirements for Coverage of Northern Zones

in a 28-degree inclined orbit is insufficient to meet the demands of the broadcast schedule in a number of 1/2-hour periods during the day. Therefore, a 16-satellite constellation was rejected for Variation 2.

The top portion of Figure 4-7 shows the northern-zone coverage afforded by a pair of satellites in a 28-degree inclined orbit. By considering the coverage provided by nine other satellite pairs that produce patterns delayed by multiples of 2-1/2 hours from the one shown here, the requirements placed on a single satellite can be determined. Each satellite is required to provide simultaneous coverage of at most two zones.

The zonal combinations, together with the associated channel-beam requirements, are shown in the bottom portion of Figure 4-7. It is seen that the capacity required of an individual satellite is frequently seven channel-beams, and occasionally is higher. Thus, even with an inclination of 28 degrees, there will be periods of the day during which the full channel-beam demand is not satisfied.

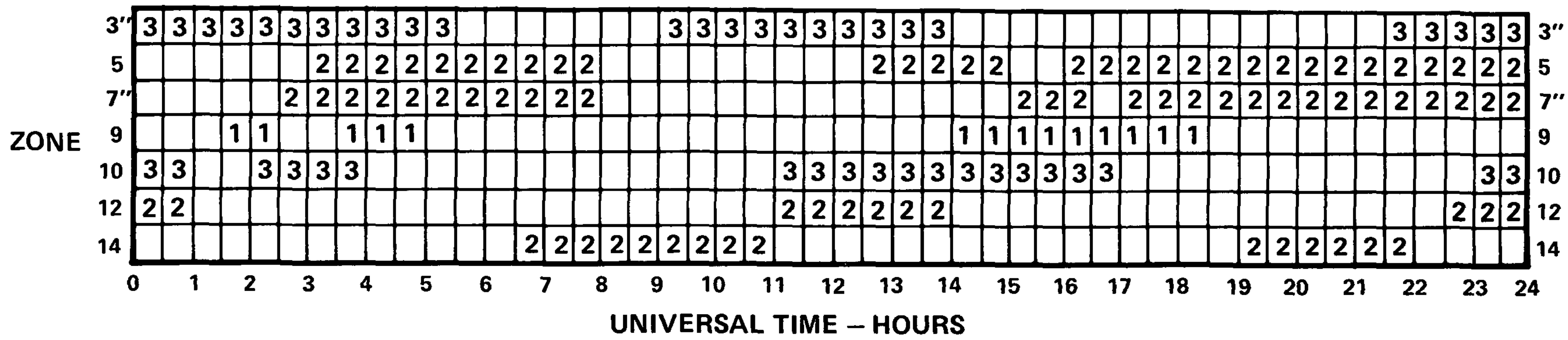
With 20 satellites in 28-degree inclined orbits, an average daily total of 220 CBH can be provided. The difference between this value and the 234 CBH demanded by the broadcast schedule results from lack of complete zonal coverage combined with inadequate satellite capacity.

### 4.3 VARIATION 3 - SINGLE CHANNEL PER ZONE, LATITUDES ABOVE 40 DEGREES NORTH OR BELOW 15 DEGREES SOUTH

In this system variation, the required coverage is the same as in Variation 2. Because of the reduction in channel demand to a single channel per zone, the satellite inclination has been increased to 37 degrees. For an ascending node of 233 degrees, this results in minimum daily coverage of 1-1/2 hours for the zones of interest (see Figure 4-8, bottom half). Therefore, 16 satellites suffice for 24-hour coverage of all zones.

The channel-beam demand of the single-channel-per-zone system is showr in the top half of Figure 4-8. A total of 161 CBH is required daily. On the other hand, the capacity of a satellite in an orbit inclined at 37 degrees is five channel-beams. A constellation of 16 such satellites, wit orbits and equatorial crossing times chosen to produce versions of the coverage pattern in Figure 4-8 delayed by multiples of 1-1/2 hours, can fully satisfy the channel-beam demand of the broadcast schedule.

## Channel-Beam Demand




## Satellite Coverage from 8-Hour Orbit

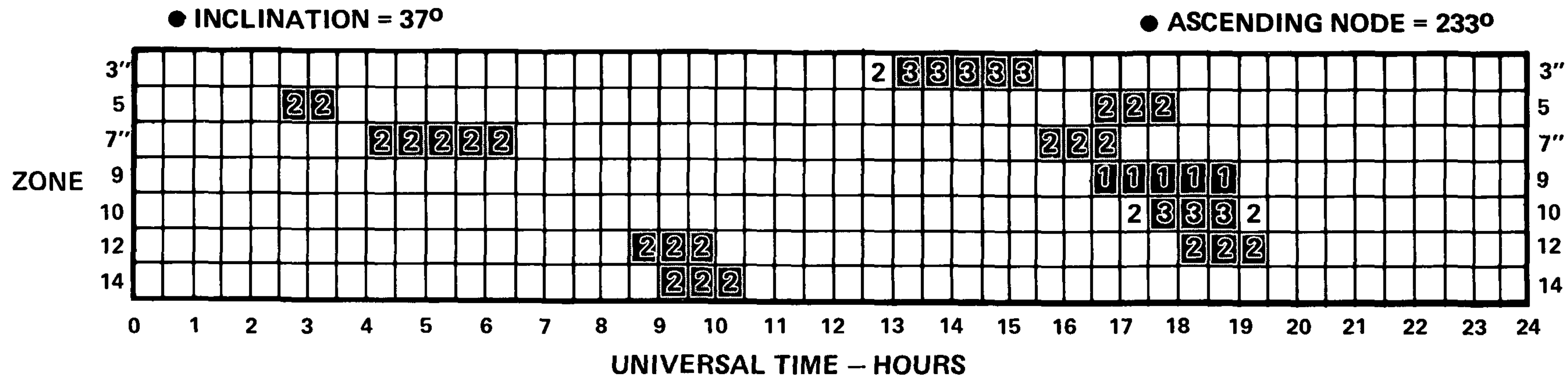



Figure 4-8. Single-Channel-Per-Zone System for Latitudes Above 40°N or Below 15°S

A 25-percent reduction in the number of satellites (i.e., from 16 to 12) reduces the average daily broadcast service to 141 CBH, a drop of 12 percent. However, the smaller number of satellites results in a number of coverage gaps. For this reason, the 16-satellite constellation was chosen for Variation 3.

## 4.4 VARIATION 4 - SINGLE-CHANNEL-PER-ZONE, PRIME-TIME SYSTEM

The objective of this system is to provide a single channel to each of the 15 broadcast zones during a 2-hour prime broadcast period in the morning and in the evening. The number of channel-beams that must be directed at each zone is equal to the number of beams required for complete zonal coverage. To minimize the burden placed on any one satellite, broadcasts to the three largest zones should not be scheduled simultaneously with broadcasts to any other zone that might, on a geographical basis, be provided by the same satellite. A schedule that meets the broadcast requirements, while minimizing the maximum number of channel-beams required of any satellite, is shown in Figure 4-9. The total daily service is 196 CBH.

For a geostationary satellite system and the satellite locations previously selected, the channel-beam requirements corresponding to Figure 4-9 are shown in Figure 4-10. The maximum satellite capacity required at each location is seven channel-beams. With a geostationary satellite capacity of two channel-beams in Band 1, four satellites must be provided at each location to fully satisfy the channel-beam demand. A total of 12 satellites is required for the entire system.

In Band 3, three satellites are required, one at each location with a capacity of seven channel-beams. The corresponding transponder requirements are shown in Table 4-3. As in the baseline system, the required transmitter power per channel-beam is 70 watts. With a maximum simultaneous requirement of seven channel-beams, the RF power requirement is 490 watts. The corresponding dc power requirement is about 800 watts, assuming the availability of MOSFET amplifiers of suitable power.

- Entries Indicate Number of Beams Required for Zonal Coverage
- Total of 196 Channel-Beam-Hours Demanded Daily

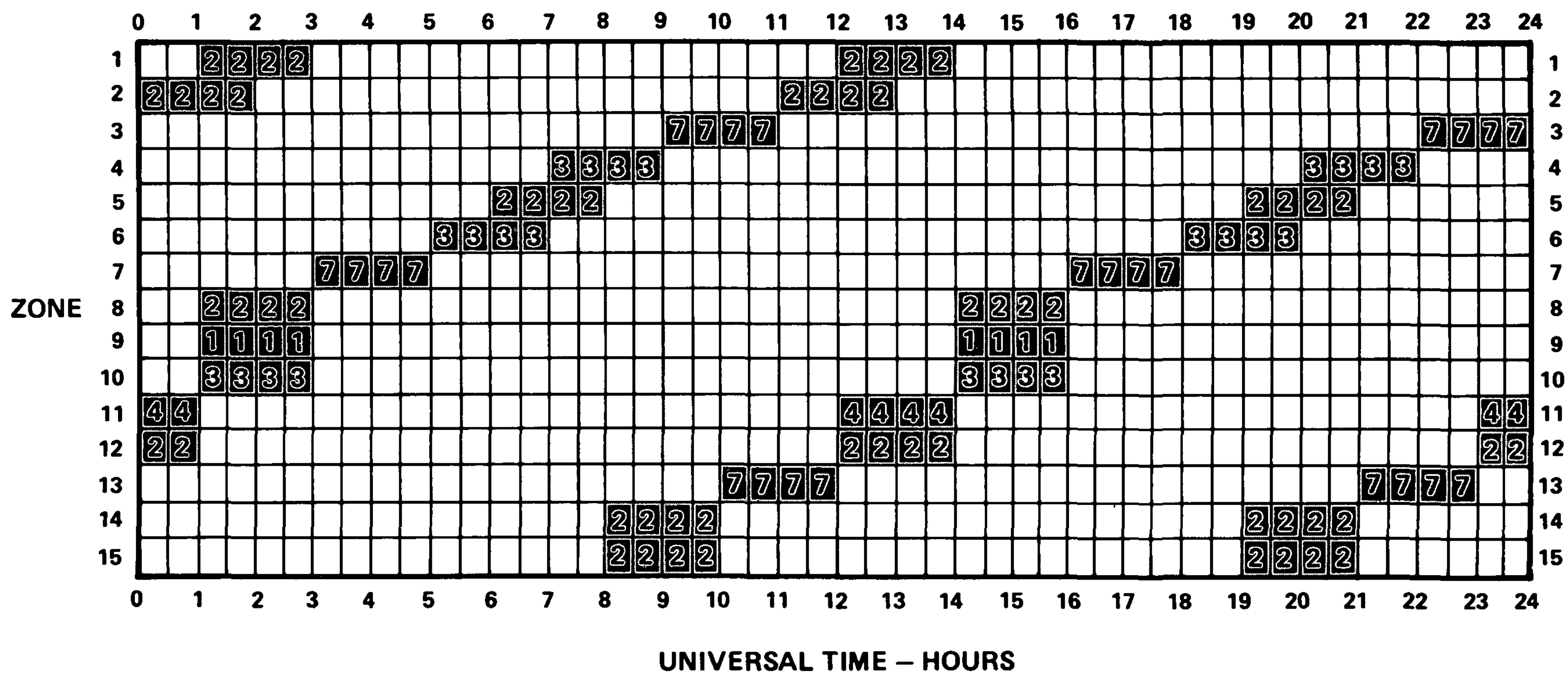



Figure 4-9. Prime-Time Broadcast Schedule Providing One Channel Per Zone

## Number of Channel-Beams

| SATELLITE POSITION | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65°W | 2 | 2 | 4 | 4 | 2 | 2 | | | | | | | | | | | | | 7 | 7 | 7 | 7 | 2 | 2 |
| 30°E | 4 | 4 | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 7 | 3 | 3 | 5 | 5 | 5 | 5 | 3 | 3 | | | | | | |
| 115°E | 2 | 2 | | | | | | | | | | | | | | | 4 | 4 | 4 | 4 | 7 | 7 | 7 | 7 |

UNIVERSAL TIME – HOURS (0–12)

| SATELLITE POSITION | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65°W | 4 | 4 | 2 | 2 | | | | | | | | | | | | | | | | | 7 | 7 | 7 | 7 |
| 30°E | 4 | 4 | 4 | 4 | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 7 | 3 | 3 | 5 | 5 | 5 | 5 | 3 | 3 | | | 4 | 4 |
| 115°E | 2 | 2 | 2 | 2 | | | | | | | | | | | 4 | 4 | 4 | 4 | 7 | 7 | 7 | 7 | 2 | 2 |

UNIVERSAL TIME – HOURS (12–24)

Figure 4-10. Geostationary Channel-Beam Demand with One Channel per Zone During Prime Hours

Table 4-3. Transponder Requirements for Band 3 Prime-Time Broadcasting

| Satellite Location | Maximum No. of Channel-Beams | Maximum No. of Channels/Beam | Total No. of Beam Positions | Maximum No. of Activated Beams |
|---|---|---|---|---|
| 65°W | 7 | 1 | 14 | 7 |
| 30°E | 7 | 1 | 13 | 7 |
| 115°E | 7 | 1 | 13 | 7 |

Since the broadcast schedule calls for only a single channel per zone, there is only one channel transmitted in each beam. The Band 3 transmitters are sized, therefore, for 70-watt, single-carrier operation. Nine such transmitters are provided to give reasonable assurance that seven will be operable.

The number of different beam positions required at each Band 3 satellite location is unaffected by the broadcast schedule and is therefore the same as in the Band 3 baseline system.

A weight breakdown by subsystem of the Band 3 prime-time satellite is given in Table 4-4.

For an 8-hour-orbit, prime-time system, the five-channel-beam capacity of a satellite in a 37-degree inclined orbit is well matched to the demands of the broadcast schedule. The full 15-zone coverage pattern for such an orbit, with an ascending node of 233 degrees, is shown in Figure 4-11. Sixteen such satellites are required for continuous 24-hour coverage of all zones. With 16 satellites, 192 CBH of broadcasting can be provided daily, as compared with 196 CBH called for by the broadcast schedule.

Nearly continuous zonal coverage can be realized with a reduced complement of 12 satellites. Specifically, Zones 5, 10, and 14 experience twelve 1/2-hour periods daily when less than complete coverage is provided. More significantly, however, the 25-percent reduction in the number of satellites results in only a 6-percent drop in the number of CBH provided daily, from 192 to 180. Therefore, the 12-satellite constellation has been selected for prime-time broadcasting.

A summary of the proposed Variation 4 systems is presented in Table 4-5. The smaller channel requirements and scheduling flexibility of the prime-time system reduce the number of Band 1 geostationary satellites to 1/4 that in the baseline system. An identical number of satellites is required in the 8-hour system, while the resulting broadcast service is 8 percent less than that provided by the geostationary system.

Three satellites (rather than four, as in the baseline system) now suffice for the Band 3 geostationary system. Each satellite must support seven channel-beams, as compared with 27 channel-beams in the baseline system.

Table 4-4. Band 3 Prime-Time System Satellite Weight Summary

| Subsystem | Weight (lb) | |
|---|---|---|
| Antenna subsystem | | 334 |
| Reflector | 284 | |
| Feeds | 50 | |
| Transponder | | 340 |
| Electrical power subsystem | | 455 |
| Solar array | 60 | |
| NiH2 battery | 180 | |
| Power control unit | 75 | |
| Distribution/integration | 140 | |
| Thermal control subsystem | | 50 |
| Payload | 20 | |
| EPDS | 30 | |
| Structure | | 200 |
| Attitude control subsystem | | 250 |
| Propulsion | | 300 |
| DHS, TT&C, COMM | | 235 |
| Satellite | | 2164 |
| Reserve (20%) | | 420 |
| Total | | 2584 |

- Inclination = 37°
- Ascending Node = 233°
- Minimum Elevation Angle = 20°

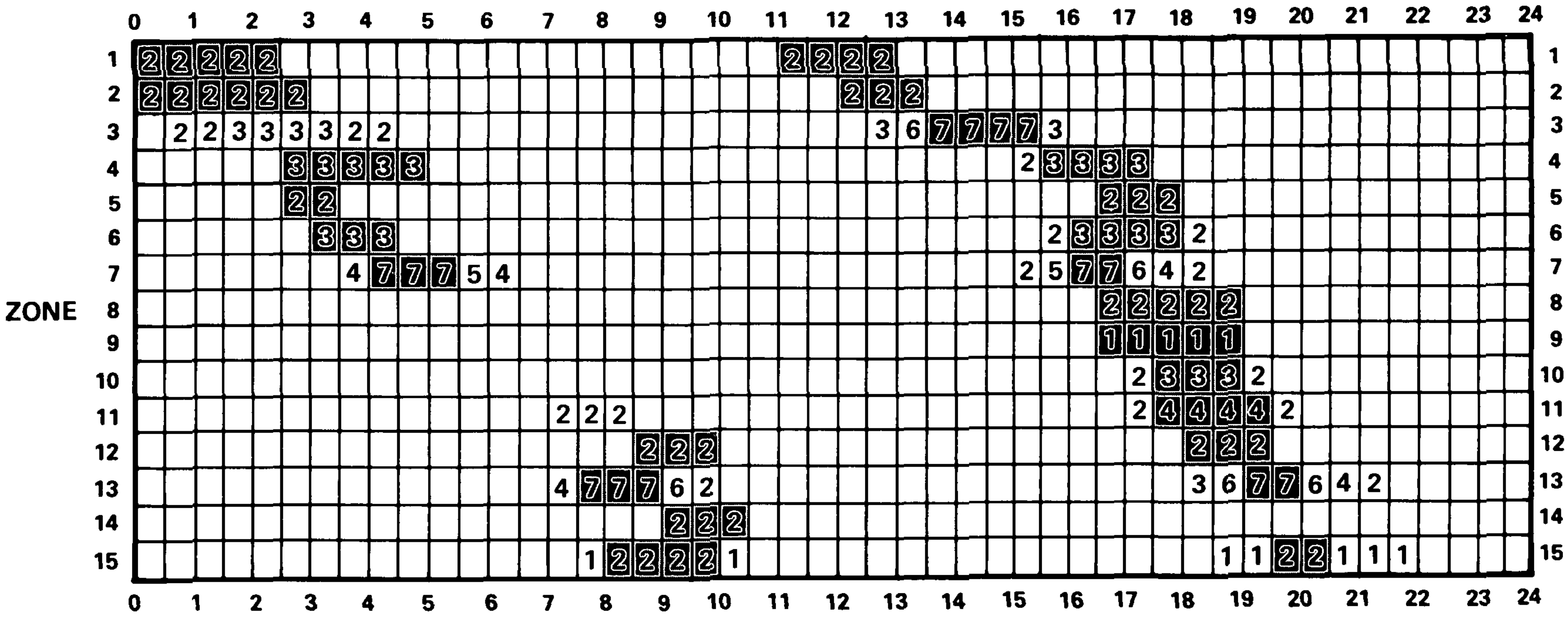



Figure 4-11. Coverage from 8-Hour Orbit for Prime-Time Broadcasting

| Band | Orbit | Number of Satellites | Channel-Beam-Hour Demand | Channel-Beam-Hours Provided |
|---|---|---|---|---|
| 1 | GEO | 12 | 196 | 196 |
| 1 | 8-Hour | 12 | 196 | 180 |
| | | (16)* | (196) | (192) |
| 3 | GEO | 3 | 196 | 196 |

*Provides 24-hour coverage of all zones

## 4.5 SUMMARY OF SYSTEM VARIATIONS FOR BASELINE FIELD STRENGTH REQUIREMENTS

The principal characteristics of each system variation, including number of satellites, satellite capacity, and (for the 8-hour satellite systems) orbit inclination are displayed in Table 4-6. Each system is designed for the baseline field-strength requirement: 300 μV/m in Band 1 and 250 μV/m in Band 2.

Variation 1 restricts service to the midlatitude zones. For the geostationary system, the reduction in number of satellites required is commensurate with the decrease in service provided. For the 8-hour system, elimination of service to the northern zones is largely responsible for a percentage falloff in service that is somewhat larger than the reduction in number of satellites.

It is interesting to note that, despite the large number of satellites in the geostationary system, the total channel-beam capacity of the two systems is the same. However, the 8-hour system provides considerably less broadcast service (416 versus 646 CBH daily). Thus, the 8-hour system is only 64 percent as efficient as the geostationary system in its use of satellite capacity.

In Variation 2, there is no reduction in the number of satellites relative to the baseline system, because of the need to provide coverage of the northern zones. The amount of service is drastically reduced, however, because no credit is taken for coverage of the midlatitude zones. The reduction in the number of satellites from Variation 2 to 3 is comparable to the reduction in service corresponding to a single-channel-per-zone system.

In Variation 4, which provides single-channel-per-zone broadcasting to all 15 zones but limits broadcasts to prime time, only twelve 8-hour satellites are required. The principal beneficiary of prime time broadcasting, however, is the Band 1 geostationary system. Because of the greatly reduced and more nearly uniform channel-beam requirements (see Figure 4-10), the number of satellites needed is reduced by a factor of four from the number required in the baseline system.

The geostationary system is again seen to be more efficient in its use of satellite capacity than the 8-hour system, providing 9 percent more

Table 4-6. Satellite Constellations for System Variations with Baseline Field Strength Requirements

| System Variation | Frequency Band | Satellite Orbit | Number of Satellites | Channel-Beam Capacity Per Satellite |
|---|---|---|---|---|
| 1 | 1 | Geostationary | 36 | 2 |
| 1 | 1 | 8-Hour, 28° Inclination | 12 | 6 |
| 2 | 1 | 8-Hour, 28° Inclination | 20 | 6 |
| 3 | 1 | 8-Hour, 37° Inclination | 16 | 5 |
| 4 | 1 | Geostationary | 12 | 2 |
| 4 | 1 | 8-Hour, 37° Inclination | 12 | 5 |
| 4 | 3 | Geostationary | 3 | 7 |

service with only 40 percent of the channel-beams. More importantly, the two systems require the same number of satellites and, as will be seen, have comparable costs.

For the Band 3 geostationary system, the reduction in number of satellites is only from four to three, but the required capacity per satellite is reduced from 27 to seven channel beams.

## 4.6 VARIATION 5 - 150 μV/m FIELD STRENGTH REQUIREMENT

Reduction of the field strength requirement to 150 μV/m represents a 6 dB power reduction in Band 1 and a 4.4 dB power reduction in Band 2. Advantage can be taken of this power reduction to reduce the number of satellites and/or the satellite complexity.

A simplification that will be considered for the Molniya- and 8-hour-orbit systems is a decrease in antenna size, which is accompanied, of course, by an increase in beamwidth. The channel-beam requirements must be restated, in this case, in units commensurate with the larger beamwidth. To this end, it is necessary to refer to the original broadcast schedule of Figure 2-2, which is stated in terms of the required number of voice channels per zone.

### 4.6.1 Geostationary System

Because of the extremely small (two-channel-beam) capacity of the baseline system satellites, the field strength reduction should be used to maximize satellite capacity. The fourfold reduction in field strength translates into a similar increase in capacity, to eight channel-beams. As a result, only 11 satellites are needed to satisfy the channel-beam demand of the broadcast schedule in Figure 2-7.

### 4.6.2 Molniya System

The baseline Molniya satellite capacity of 12 channel-beams (at a field strength of 250 μV/m) completely satisfied the demands of the broadcast schedule for the four Soviet zones. Nothing would be accomplished, therefore, if the reduced field strength were used to increase the satellite capacity. Instead, the satellite size and weight will be reduced, with an individual satellite still capable of providing the full broadcast service.

If the antenna diameter is halved, for example, the satellite beams are expanded to 5.4 degrees. A single beam of this size is sufficient to cover Zones 9, 12, and 14, and is nearly sufficient to cover Zone 10. Circular beams generated for Zones 10 and 12 from an apogee located at 90 degrees east are shown in Figures 4-12 and 4-13. The view in each case is from directly above beam center.

The channel-beam demand of the Soviet zones, for the beamwidth of 5.4 degrees, is shown in Figure 4-14. Because only a single beam is required to cover each zone, the number of channel-beams is equal to the required number of channels. The maximum value of six channel-beams occurs in only two 1/2-hour periods of the day. By delaying some of these broadcasts by as little as 1 hour, the maximum channel-beam demand can be reduced to three.

On the other hand, the satellite capacity, based on the full STS capability, is nine channel-beams. It is therefore possible to downsize the satellite by using less than the full STS lift capability. A satellite capable of supporting three channel-beams requires only 40,000 pounds of lift capability, as compared with the full STS capability of 65,000 pounds.

It should be recognized that this discussion, in terms of channel-beams, applies only to the power requirements placed on the satellite. It is not appropriate to express the broadcast service provided in terms of the same channel-beam units, since a significant portion of the radiated power falls outside the zone boundaries and is therefore of no value. For comparison with the baseline system, broadcast service should be measured in terms of the smaller channel-beam units (i.e., for a beamwidth of 2.7 degrees). For this purpose, reference should be made to the broadcast schedule of Figure 2-8.

From the standpoint of coverage and capacity, each of three satellites can handle the total Band 2 broadcast requirements during a different 8-hour period of the day. For completeness, it must also be shown that a single antenna subsystem can generate the required beam pattern. It can be seen from Figures 4-12 and 4-13 that the 5.4-degree coverage beams extend well beyond the common boundary of Zones 10 and 12 and therefore overlap to

- View from Directly Above Beam Center (Apogee at Longitude of 90° E)

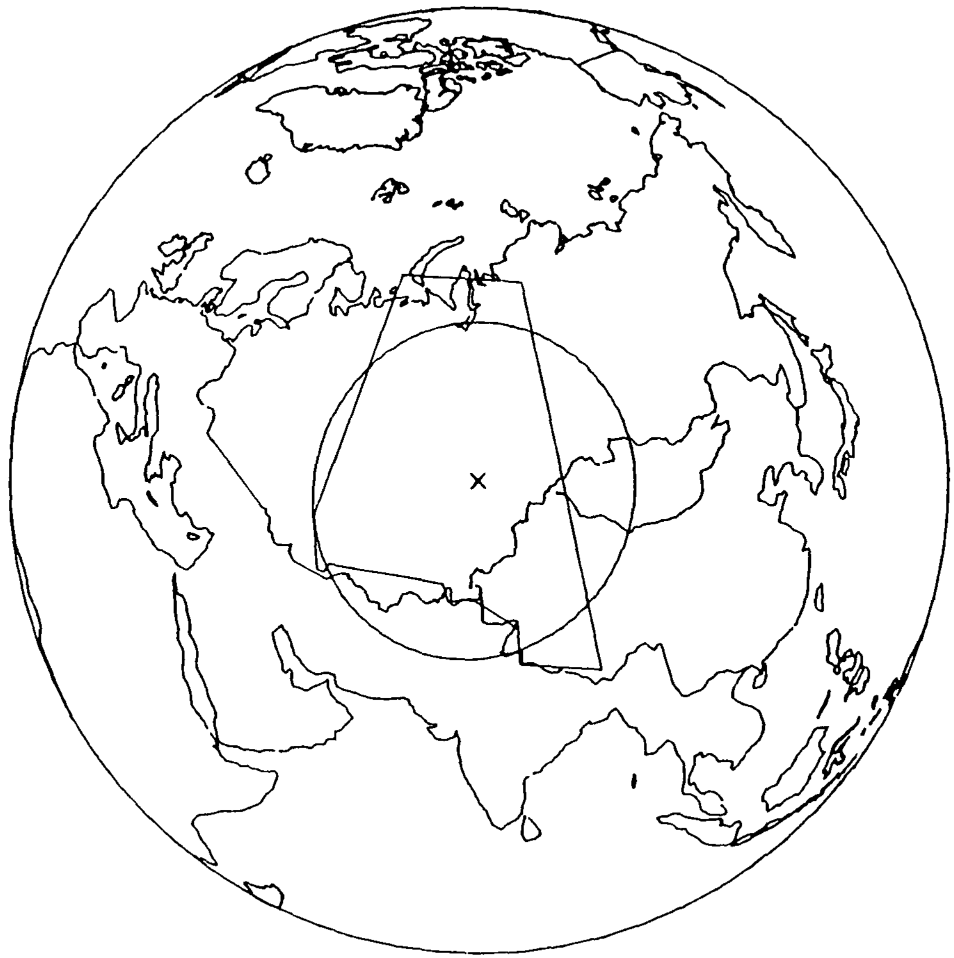


Figure 4-12. Molniya Orbit Coverage of Zone 10 with Beamwidth of 5.4 Degrees

- View from Directly Above Beam Center (Apogee at Longitude of 90° E)

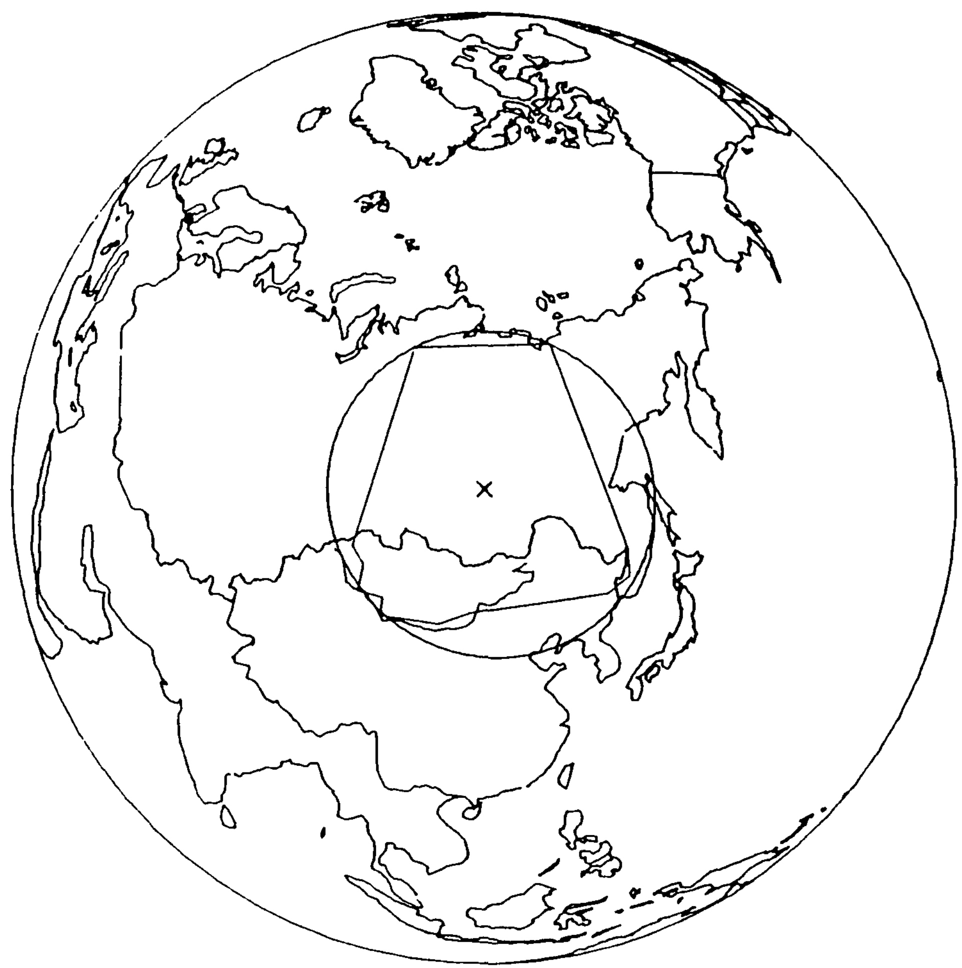


Figure 4-13. Molniya Orbit Coverage of Zone 12 with Beamwidth of 5.4 Degrees

• Satellite Beamwidth = 5.4°

NUMBER OF CHANNEL-BEAMS

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ZONE | 9 | | | | 1 | 1 | | | 2 | 6 | 1 | | | | | | | | | | | | | | |
| | 10 | 1 | 1 | | | 2 | 2 | 2 | 1 | | | | | | | | | | | | | | | 1 | 1 |
| | 12 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | 2 | 1 |
| | 14 | | | | | | | | | | | | | | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | | |
| TOTAL | | 2 | 2 | | 1 | 3 | 2 | 2 | 3 | 6 | 1 | | | | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 3 | 2 |

0 1 2 3 4 5 6 7 8 9 10 11 12

UNIVERSAL TIME -- HOURS

NUMBER OF CHANNEL-BEAMS

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ZONE | 9 | | | | | 1 | 1 | 1 | 1 | 2 | 5 | 1 | 1 | 1 | | | | | | | | | | | |
| | 10 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | 1 | 1 |
| | 12 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | 1 | 1 | 1 |
| | 14 | | | | | | | | | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | | | | |
| TOTAL | | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 6 | 1 | 1 | 1 | | 1 | 1 | 2 | 2 | 2 | 2 | | 1 | 2 | 2 |

12 13 14 15 16 17 18 19 20 21 22 23 24

UNIVERSAL TIME - HOURS

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Figure 4-14. Molniya Orbit Channel-Beam Demand for Expanded Satellite Beams a considerable degree. It is generally not possible, with a single antenna feed element generating each beam, to establish a set of circular, -3 dB gain contours having this relationship.

The simplest solution to this problem is to use a somewhat larger antenna, thereby increasing the peak gain, with beam crossovers occurring at a relative gain no greater than -3 dB. With the antenna size properly chosen, the minimum absolute gain at the zone boundaries can be maintained at the original value.

### 4.6.3 Subsynchronous System

The most straightforward way to take advantage of the reduction in field strength to 150 μV/m is to increase the orbit inclination from the 28-degree value used in the 8-hour baseline system. This lengthens coverage of the northern zones and reduces the number of satellites required for 24-hour coverage of all zones. For an inclination of 37 degrees, 16 8-hour satellites are needed. However, the resulting satellite capacity is 24 channel-beams, which is more than can be applied to the demands of the broadcast schedule. A further reduction in the number of satellites to 12 leaves gaps in the coverage of Zones 5, 10, and 14. Except for these gaps (which lead to a mere 3-percent reduction in the number of CBH provided daily, from 894 to 864), there is sufficient satellite capacity to satisfy the remainder of the broadcast schedule.

A second option is to reduce the satellite antenna size through a doubling of the equivalent geostationary beamwidth to 6 degrees. Because a single beam will now radiate power well outside the boundaries of many zones, the effective capacity of the satellite is reduced by this approach. In other words, the satellite size is decreased at the expense of a reduction in effective radiated power.

The number of channel-beams required for the various zones, relative to an equivalent geostationary beamwidth of 6 degrees, is indicated in Figure 4-15. A single beam suffices to cover all but four of the zones. Zones 3, 7, and 13, which need seven 3-degree beams for complete coverage, require two of the 6-degree beams. Zone 15, which requires two widely separated 3-degree beams to cover the land masses within the zone boundaries, also requires two 6-degree beams.

• 6° Equivalent Beamwidth from Geostationary Orbit

UNIVERSAL TIME – HOURS (0–12)

| ZONE | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | | | | | | | | | | | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | | | | | | | | | | 1 | 1 | 2 | 2 |
| 3 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 2 | 2 | 2 | | | | | | | | 2 | 2 | 2 | 2 | 4 | 4 |
| 4 | | | | | | | | | | | 1 | 2 | 1 | | 1 | 1 | | | | | | | | |
| 5 | | | | | | | 1 | 2 | 8 | 11 | 9 | 6 | 2 | 1 | 1 | 1 | | | | | | | | |
| 6 | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | | | | | | | | |
| 7 | | | | | | 2 | 4 | 2 | 6 | 6 | 6 | 6 | 4 | 2 | 2 | 4 | | | | | | | | |
| 8 | | | | 1 | 1 | 1 | 1 | | 1 | 2 | 2 | 1 | | | | 1 | | | 1 | 1 | 1 | 1 | | |
| 9 | | | | 1 | 1 | | | 2 | 6 | 1 | | | | | | | | | | | | | | |
| 10 | 1 | 1 | | | 2 | 2 | 2 | 1 | | | | | | | | | | | | | | | 1 | 1 |
| 11 | | | 2 | 3 | 2 | 2 | 4 | 4 | | | | | | | | | | | | | | | | |
| 12 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | 2 | 1 |
| 13 | 4 | 4 | | | | | | | | | | | | | | | | | | | | 4 | 8 | 8 |
| 14 | | | | | | | | | | | | | | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | | |
| 15 | 2 | 2 | | | | | | | | | | | | | | | | | | | 2 | | 2 | 2 |

UNIVERSAL TIME – HOURS (12–24)

| ZONE | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | | | | | | | | | | | | | | | | 1 | 1 |
| 2 | 2 | 2 | 2 | 1 | | | | | | | | | | | | | | | | | | 1 | 2 | 2 |
| 3 | 4 | 4 | 2 | 2 | | | | | | | | | | | | | | | | 2 | 2 | 2 | 4 | 4 |
| 4 | | | | | | | | | | | | | 1 | | 1 | 2 | 2 | 1 | 1 | 1 | 1 | | | |
| 5 | | 1 | 1 | 1 | 1 | 1 | | | 2 | 6 | 10 | 11 | 9 | 6 | 4 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | | | | | | | | | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| 7 | | | | | | | 2 | 4 | 2 | | 6 | 4 | 4 | 4 | 6 | 6 | 6 | 6 | 6 | 6 | 4 | 2 | 2 | 2 |
| 8 | | | | | 1 | 1 | 1 | 2 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | | | |
| 9 | | | | | 1 | 1 | 1 | 1 | 2 | 5 | 1 | 1 | 1 | | | | | | | | | | | |
| 10 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | 1 | 1 |
| 11 | | | 2 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | | | | | | | | | | 1 |
| 12 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | 1 | 1 | 1 |
| 13 | 6 | 4 | 6 | 6 | 6 | 6 | 4 | 4 | | | | | | | | | | | 2 | 2 | 4 | 8 | 8 | 8 |
| 14 | | | | | | | | | | | | | | | 1 | 1 | 2 | 2 | 2 | 2 | | | | |
| 15 | 2 | 2 | 2 | 2 | 2 | 2 | | | | | | | | | | | | | | | 2 | 2 | 2 | 2 |

Figure 4-15. Eight-Hour-Orbit Channel-Beam Demand for Expanded Satellite Beams

In the baseline system design, which is based on a 3-degree beamwidth, the maximum number of channels per beam was restricted to two in Zone 7 and three in Zone 13. With a 6-degree beamwidth, these channel limits have been increased to three and four, respectively.

Because a 6-degree beam "spills" power outside zone boundaries in many cases, the required transmitter power per zone is generally greater than with 3-degree beams. The power ratio varies from 4:1 for Zones 9 and 15 to 1:1 for Zone 11.

Single-satellite zonal coverage, in terms of beams which are equivalent to 6-degree beams from geostationary orbit, is shown in Figure 4-16 for an orbit inclination of 37 degrees and an ascending node of 233 degrees. No attempt has been made to show partial coverage of the four zones that require two beams. Since the minimum zonal coverage spans 1-1/2 hours, 16 satellites can provide 24-hour coverage of all zones.

In measuring the broadcast service provided by a constellation of 8-hour satellites with an equivalent antenna beamwidth of 6 degrees, it is necessary, for comparative purposes, to express the results in CBH based on an equivalent 3-degree beamwidth. For consistency with prior analysis, complete coverage of Zones 3, 7, and 13 is assumed whenever visibility extends to five or more 3-degree beams.

In these terms, an average of 884 CBH (out of 894 CBH demanded by the broadcast schedule) can be provided by a constellation of 16 satellites. Decreasing the number of satellites to 12 reduces the average daily service to 845 CBH, a drop of 4 percent. Since this result is achieved with a 25-percent decrease in the number of satellites, a 12-satellite constellation is preferred.

A final system alternative is to increase the orbit altitude to a value corresponding to (for example) a 12-hour period, while maintaining a 3-degree beamwidth. The wider coverage from 12-hour orbit permits a significant reduction in the number of satellites needed for 24-hour coverage of all zones. Because of the increased satellite capacity that accompanies a field strength reduction to 150 μV/m, the broadcast capability of the

- Inclination = 37°
- Ascending Node = 233°
- Minimum Elevation Angle = 20°

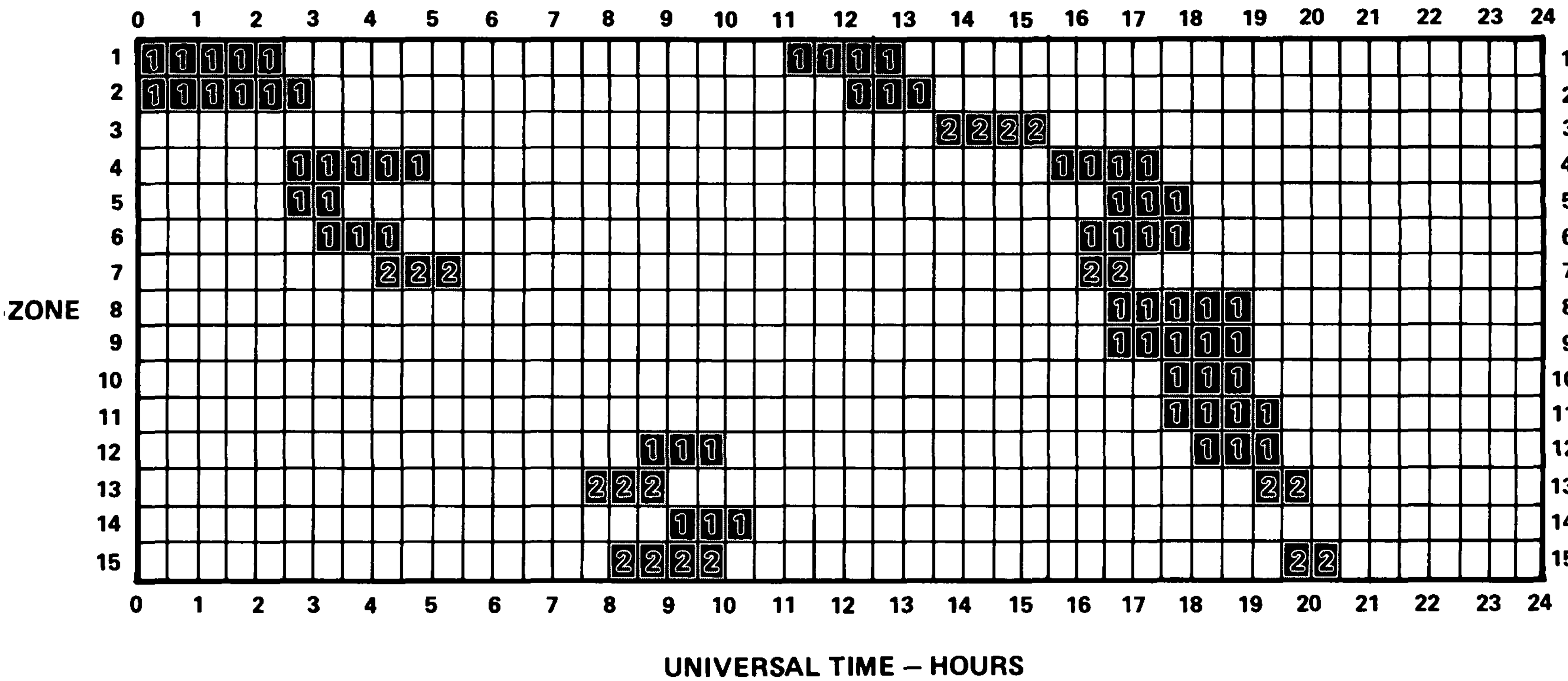


Figure 4-16. Single-Satellite Coverage from 8-Hour Orbit in Terms of Expanded Satellite Beams

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minimum 12-hour constellation is more nearly commensurate with the coverage provided than is the case with the original field strength requirement of 300 μV/m.

The coverage provided by a single satellite in 12-hour orbit is shown in Figure 4-17 for an inclination of 28 degrees and an ascending node of 260 degrees. Although coverage periods of individual zones are typically much longer than those for an 8-hour orbit, for this particular 12-hour orbit no coverage of Zone 9 is provided. Because south-to-north (or north-to-south) equatorial crossings of a 12-hour orbit are spaced by 180 degrees in longitude, a coverage pattern complementary to that shown in this chart results from an ascending node displaced by 90 degrees.

Such a pattern is shown in Figure 4-18. Quite good coverage of Zone 9, which is completely missing in Figure 4-17, is provided. However, there is no coverage of Zone 12. Reference to Figure 4-17 shows that Zone 12 is covered for a total of 3 hours. By pairing the two coverage patterns, fairly even coverage of the northern zones can be achieved.

Figure 4-19 shows the coverage pattern that results from combining the patterns in Figures 4-17 and 4-18, with the first pattern delayed by 1 hour. Minimum zonal coverage of 3 hours occurs for Zone 12. It is conjectured that, if (1) the inclination of each orbit were increased to (for example) 37 degrees and (2) the ascending nodes were suitably adjusted, the minimum zonal coverage could be increased to 4 hours. Should this be the case, a total of 12 satellites would suffice for 24-hour coverage of all zones.

Reducing the number of satellites to fewer than 12 introduces gaps in coverage, particularly in northern zones. However, the reduction in broadcast service provided is initially quite small. This relationship is explored in Table 4-7, which is based on the coverage patterns of Figures 4-17 and 4-18. Each case is based on pairs of satellites in orbits designed to produce suitably delayed versions of the coverage pattern in Figure 4-19. (Actually, the pattern in Figure 4-19 is augmented to show five- or six-beam coverage, rather than just the seven-beam maximum, for Zones 3, 7, and 13.)

- Inclination = 28°
- Ascending Node = 260°
- Minimum Elevation Angle = 20°

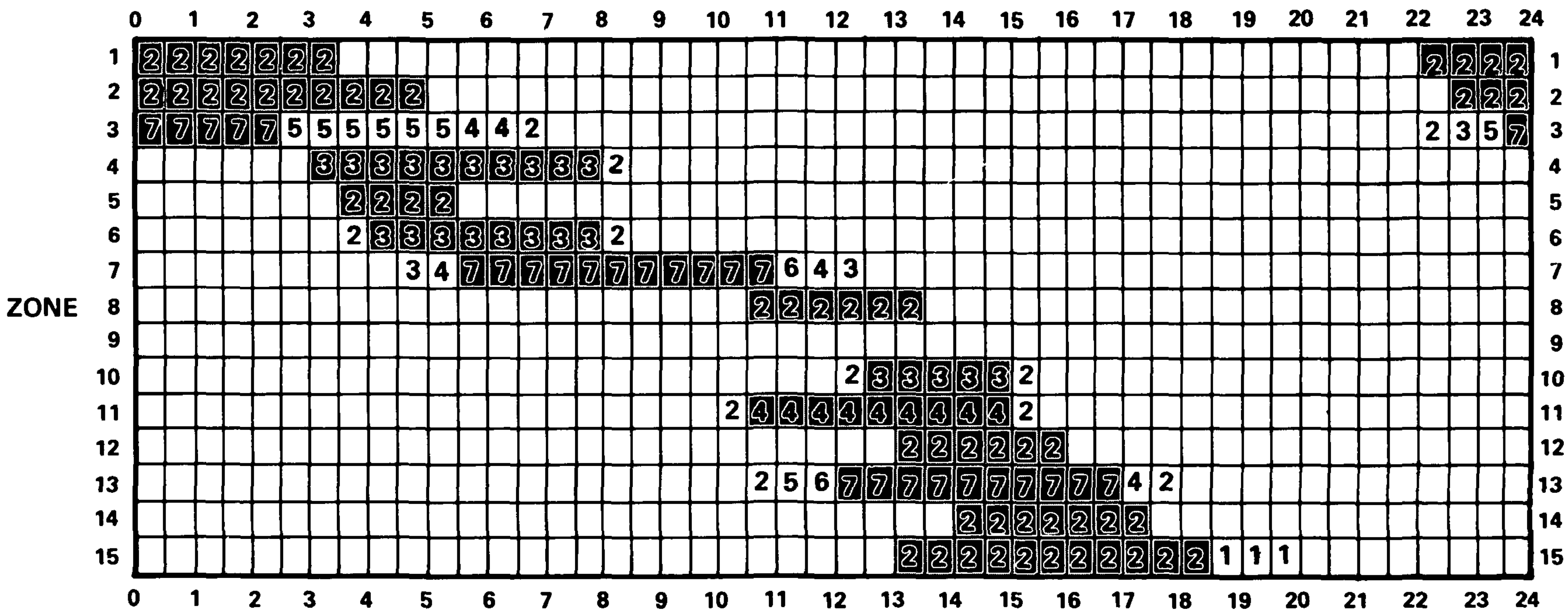



Figure 4-17. Single-Satellite Coverage from 12-Hour Orbit

- Inclination = 28°
- Minimum Elevation Angle = 20°
- Ascending Node = 350°

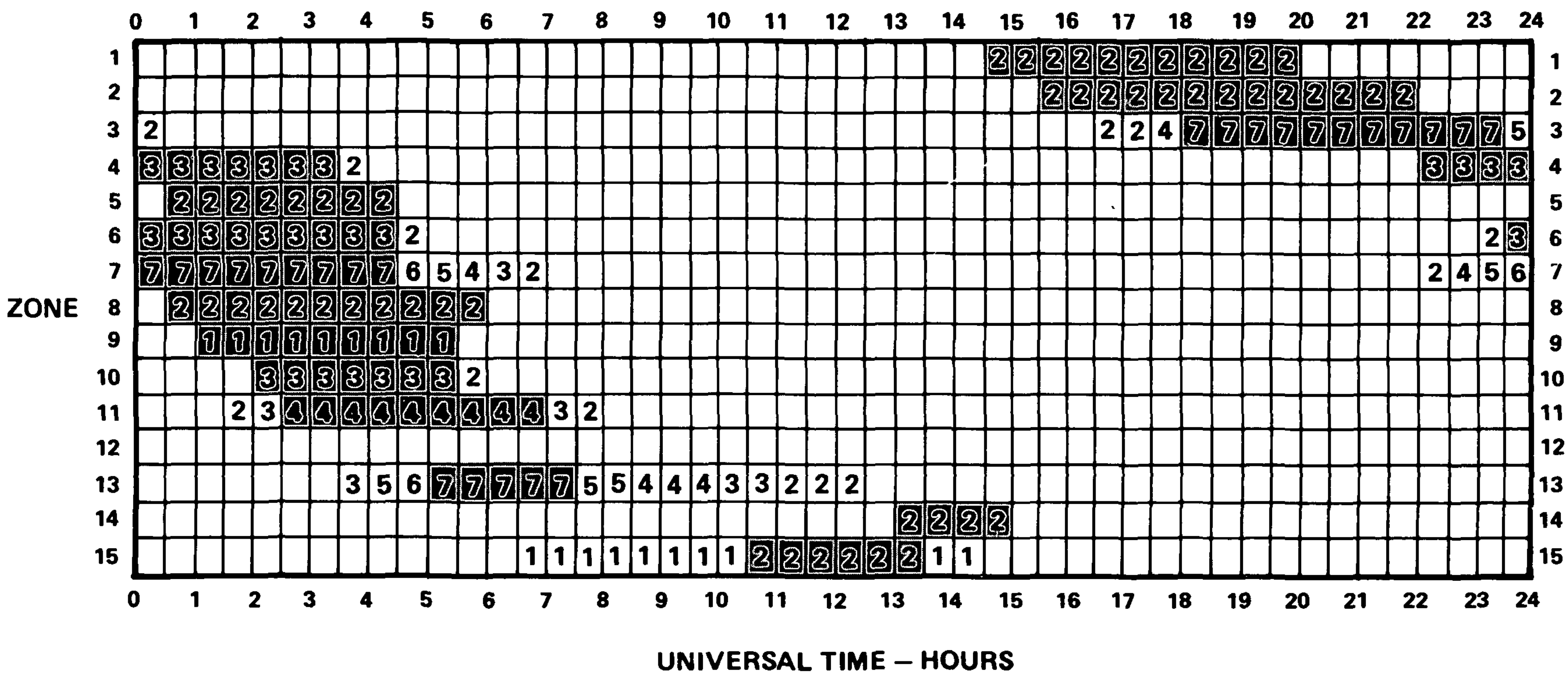



Figure 4-18. Single-Satellite Coverage from 12-Hour Orbit

- Inclination = 28°
- Minimum Elevation Angle = 20°
- Combination of Patterns for Ascending Nodes of 260° (Delayed by 1 Hour) and 350°

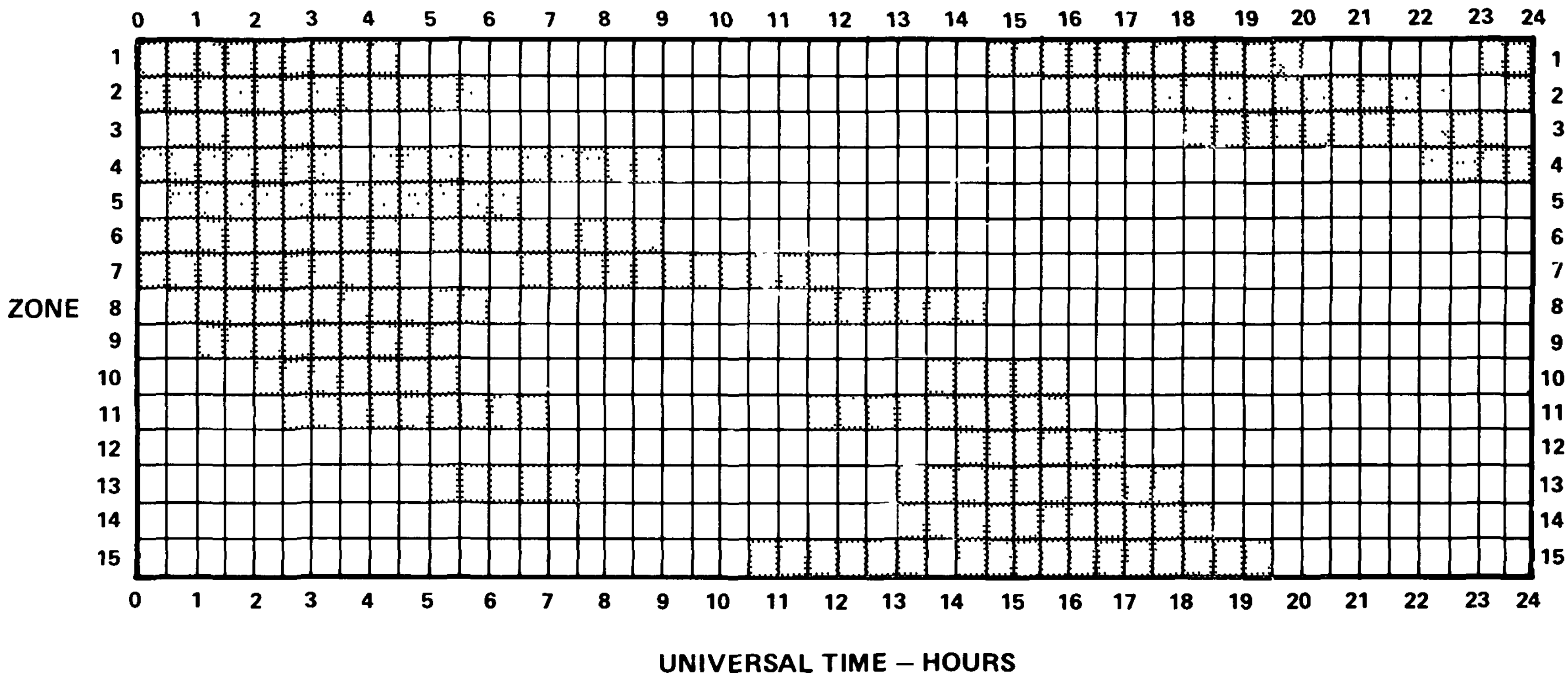



Figure 4-19. Zonal Coverage Provided by a Pair of 12-Hour Satellites

Table 4-7. 12-Hour-Orbit Broadcast Service for 150 μV/m Field Strength Requirement

- Entries indicate average number of channel-beam-hours provided daily
- Broadcast schedule calls for 894 channel-beam-hours

| | Number of Satellites | | | |
|---|---|---|---|---|
| | 12 | 10 | 8 | 6 |
| **Cable-catenary antenna** | 888 | 884 | 851 | 720 |
| **Phased-array antenna** | 887 | 872 | 819 | 683 |

Distinction is made as shown in Table 4-7 between satellites designed with cable-catenary and phased-array antennas. The altitude of the 12-hour orbit is about the largest for which the phased-array antenna is feasible. For this orbit, satellite capacity is 20 channel-beams with the cable-catenary antenna, but only 15 channel-beams with the phased-array antenna.

The small falloff in service as the number of satellites is reduced from 12 to 10 results from lack of complete coverage of the northern zones. A further reduction in the number of satellites produces insufficient capacity for zones with a large channel-beam demand, as well as larger gaps in coverage of the northern zones. (The capacity problem is more severe with the phased-array antenna.) Nevertheless, decreasing the number of satellites from ten to eight reduces the daily service by only 4 percent with a cable-catenary antenna, and by 6 percent with a phased-array antenna. For this reason, an eight-satellite constellation was selected for both antenna types.

A summary of the three subsynchronous systems proposed to take advantage of the field strength reduction is given in Table 4-8.

A summary of all system alternatives considered for a field strength of 150 µV/m is given in Table 4-9. Among the Band 1 systems, the 12-hour system is distinguished by requiring the smallest number of satellites. The reason is the balance struck between satellite coverage and capacity. On the other hand, the structure required to produce the equivalent of a geostationary 3-degree beam from 12-hour orbit is quite large — 115 meters in diameter for the phased array and 178 meters for the cable catenary.

The geostationary system and the two 8-hour systems require about the same number of satellites. The much larger channel-beam capacity of the 3-degree-beamwidth, 8-hour satellites reflects the less efficient utilization of these satellites. The chief advantage the 6-degree-beamwidth, 8-hour satellites is the smaller antenna structure (34 m diameter versus 80 m for a satellite with 3-degree beams).

Finally, the 6-degree-beamwidth Molniya satellites designed for Band 2 operation are substantially reduced in size (57 m versus 114 m antenna) and weight with respect to the baseline satellite design.

Table 4-8. Subsynchronous Satellite System Options with 150 μV/m Field Strength Requirement

| Option | Equivalent Geostationary Beamwidth | Number of Satellites | Channel-Beam-Hours Provided* |
| --- | --- | --- | --- |
| Increase inclination of 8-hour orbit to reduce number of satellites | 3° | 12 | 864 |
| Expand beamwidth of 8-hour satellite to 6° to reduce antenna size | 6° | 12 | 845** |
| Provide 12-hour-orbit system to improve coverage, reduce number of satellites | 3° | 8 | 851, 819*** |

* 894 channel-beam-hours demanded by broadcast schedule

** In terms of 3-degree beams

*** 851 for cable-catenary antenna, 819 for phased-array antenna

Table 4-9. Satellite Constellations for System Variations with 150 μV/m Field Strength Requirement

| Orbit | Frequency Band | Equivalent Geostationary Beamwidth | Number of Satellites | Channel-Beam Capacity Per Satellite |
|---|---|---|---|---|
| Geostationary | 1 | 3° | 11 | 8 |
| 8-Hour | 1 | 3° | 12 | 24 |
| 8-Hour | 1 | 6° | 12 | 7 |
| 12-Hour | 1 | 3° | 8 | 15,20* |
| Molniya | 2 | 6° | 3 | 3 |

* 15 With Phased-Array Antenna,
20 With Cable-Catenary Antenna

## 4.7 SSB-AM BAND 1 SYSTEM

The system variations previously considered are based on reductions in broadcast requirements (i.e., reduction in coverage, number of channels, or field strength). One final variation concerns the use of a different transmission format in Band 1. The possibility of SSB-AM rather than DSB-AM is now considered. The broadcast requirements are those of the schedule in Figure 2-7.

An SSB-AM signal format requires 7.8 dB less transmitter power than DSB-AM. This comparison is based on a 100-percent modulated, double-sideband signal. Comparable performance can be expected if the power in the SSB signal is equal to the power in either sideband of the DSB signal. Each sideband of the DSB signal has 1/4 the carrier power or, equivalently, 1/6 the total power in the signal.

The decrease in transmitter power translates into a field strength requirement of 122 μV/m. Systems designed for this field strength resemble those previously presented for a field strength requirement of 150 μV/m.

Geostationary satellites in this case have a capacity of 12 channel-beams. Seven such satellites can provide a daily average of 882 CBH, compared with 894 CBH called for by the broadcast schedule. Two satellites are located at 65 degrees west, three at 30 degrees east, and two at 115 degrees east.

For an 8-hour-orbit system, 12 satellites in orbits inclined at 37 degrees provide nearly complete zonal coverage. At a field strength of 122 μV/m, maximum satellite capacity consistent with the STS/Centaur payload capability is 10 channel-beams. It was shown in Variation 5, however, that a similar constellation with a satellite capacity of seven channel-beams can provide a daily average of 845 CBH. A similar satellite requirement will be adopted here. Because of the lower field strength requirement (122 versus 150 μV/m), the resulting satellite is lighter than in Variation 5.

# 5. LIFE CYCLE COST SUMMARY

To develop LCC for the various systems, a nominal 20-year program span was adopted. In addition, the satellite life was assumed to be 7 years. Schedules containing the satellite development period and the cumulative launch profile are shown for the four baseline systems in Table 5-1.

Systems 1 and 3 are assumed to require the longest development period because of the large cable-catenary antenna. The phased-array antenna of System 2 leads to a 1-year shorter or 4-year development period. The 3-year development period for System 4 is comparable to that for today's commercial communication satellites.

Two complete sets of satellites are required for a 20-year program. For satellites that require the full STS launch capability, it is felt that four launches per year is a reasonable assumption. Twice that number has been assumed for System 1 simply to allow the system to achieve its required complement of 47 satellites.

Because of the linear buildup with time of each satellite constellation, the amount of service provided is also assumed to increase linearly in the period preceding full operational capability. The full-capacity period, which varies with the required number of satellites, is followed by a period of service decay equal in length to the buildup period. Although the full-service period varies from system to system, all four systems provide the equivalent of 14 years of full operational service.

The development and launch schedule in Table 4-1 is introduced at this point primarily to establish the amount of service provided by each system. The satellite nonrecurring and recurring costs, as well as other LCC components (except for O&M costs), have been computed independently of the indicated schedule (see Appendix H). For the purpose of "spreading" LCC in Section 6, a modified launch schedule is introduced which accounts for the spare satellites, which are assumed to be 10 percent of the total operational quantity.

Table 5-1. Baseline System Development and Launch Schedule

| | Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baseline System 1 | DDT&E | X | X | X | X | X | | | | | | | | | | | | | | | |
| | Cumulative Launch Qty | | | | | | 8 | 16 | 24 | 32 | 40 | 47 | | 55 | 63 | 71 | 79 | 87 | 94 | | |
| Baseline System 2 | DDT&E | X | X | X | X | | | | | | | | | | | | | | | | |
| | Cumulative Launch Qty | | | | | 4 | 8 | 12 | 16 | 20 | | | 24 | 28 | 32 | 36 | 40 | | | | |
| Baseline System 3 | DDT&E | X | X | X | X | X | | | | | | | | | | | | | | | |
| | Cumulative Launch Qty | | | | | | 1 | 3 | | | | | | 4 | 6 | | | | | | |
| Baseline System 4 | DDT&E | X | X | X | | | | | | | | | | | | | | | | | |
| | Cumulative Launch Qty | | | | 2 | 4 | | | | | | 6 | 8 | | | | | | | | |

## 5.1 BASELINE SYSTEM LIFE CYCLE COSTS

Life cycle costs for the four baseline systems are given in Table 5-2. In addition to the satellite costs, the LCC include launch costs of $100 million for a full STS load and $58 million for a Centaur class upper stage. Additionally, there are earth stations for satellite control and feeder-link transmission. There are two such stations in System 3, four in Systems 1 and 4, and seven in System 2. The cost per station is taken as $10 million. Finally, there are operations and maintenance costs of $12.5 million/station/year.

To provide a measure of system effectiveness, the LCC are normalized to the broadcast service provided. The average number of CBH provided daily by the full complement of satellites in each system is given in Section 3. This value is multiplied by 5110, the number of days in 14 years, to obtain the service provided over the life of the system. The entries in the last column of Table 5-2 provide the normalized LCC for the four baseline systems.

The high cost of the geostationary system is attributable to the small satellite capacity, which is two channel-beams. By contrast, the capacity of a satellite in 8-hour orbit is six channel-beams. The average traffic per satellite is approximately the same for the Molniya and 8-hour systems; however, the 8-hour system benefits from considerably more "learning" and also has the nonrecurring satellite cost spread over a larger number of satellites. Hence the smaller LCC/CBH for the 8-hour system.

System 4 has by far the smallest LCC/CBH. The satellites in this system are not very different from some current commercial satellites. Operations and maintenance costs, which are minor for the other three systems, are estimated to approach 50 percent of the System 4 LCC.

Measures of system cost other than the normalization of LCC with respect to CBH may be of interest. For example, the system cost per year of (full) operation is found by dividing the LCC by 14. In round numbers, the annual costs of Systems 2 and 4, which provide comparable amounts of programming (735 versus 894 CBH daily), are $1 billion and $140 million, respectively.

Table 5-2. Baseline System Life Cycle Costs (LCC)

| System | Band | Orbit | Fleet Qty | LCC Qty | LCC ($Billion)* | Channel-Beam Hours (x $10^6$)† | LCC/CBH** ($000)* |
|---|---|---|---|---|---|---|---|
| 1 | 1 | GEO | 47 | 104 | 31.7 | 4.57 | 6.93 |
| 2 | 1 | 8-Hr | 20 | 44 | 14.2 | 3.76 | 3.78 |
| 3 | 2 | Molniya | 3 | 7 | 2.9 | 0.54 | 5.54 |
| 4 | 3 | GEO | 4 | 9 | 1.9 | 4.57 | 0.41 |

*Constant (1984) dollars

†Delivered service over 14 effective years of life

**CBH = channel-beam-hour

All Band 1 systems considered thus far have been designed to operate at 26 megahertz. There are, in fact, four distinct subbands that constitute Band 1. The capacity of a satellite sized to the limit of the STS/Centaur capability for each subband is shown in Table 5-3, for both a geostationary and an 8-hour satellite system. The reduction in capacity as the frequency decreases is attributable to the increased size of the satellite antenna. It is evident that, at the baseline field strength requirement of 300 µV/m, only a system of 8-hour satellites is worthy of further consideration.

Life cycle costs for the lower-subband versions of the 8-hour system are presented in Table 5-4. The LCC are nearly identical, primarily because the fleet size is the same for all four systems. Fleet size is selected on the basis of geographical coverage considerations, which are independent of frequency. Additionally, the satellites are sized for the largest number of channel-beams that can be supported by a single STS launch. Therefore, the satellite weights in the four cases differ only because the capacity varies in discrete steps.

The daily broadcast service provided is a function of satellite capacity. At the two middle subbands, where the satellite capacity is five channel-beams, the loss of service with respect to the top subband is fairly small. The loss of service at the bottom subband, where the satellite capacity is four channel-beams, is somewhat more significant and gives rise to substantially higher LCC than in the top subband.

## 5.2 VARIATIONAL SYSTEM LIFE CYCLE COSTS

A number of variations on the baseline system concepts were presented in Section 4. The five categories of system variations are repeated in Table 5-5. The LCC for these systems are summarized in Table 5-6.

Restricting coverage to midlatitude zones (Variation 1) has little effect on LCC/CBH for either the 8-hour or the geostationary system, because the reduction in service is commensurate with the decrease in number of satellites. However, the reduction in service for the 8-hour system is greater than that for the geostationary system, because the minimum number of satellites needed for 24-hour zonal coverage was chosen.

Table 5-3. Band 1 Baseline System Satellite Capacities

| Sub-Band (MHz) | Orbit | Number of Channel-Beams |
|---|---|---|
| 26.1 | Geostationary | 2 |
| | 8-hour | 6 |
| 21.8 | Geostationary | 1 |
| | 8-hour | 5 |
| 17.9 | Geostationary | 1 |
| | 8-hour | 5 |
| 15.5 | Geostationary | 0 |
| | 8-hour | 4 |

Table 5-4. Life Cycle Costs for Baseline 8-Orbit-Hour Systems

| Sub-Band (MHz) | Fleet Qty | LCC Qty | LCC ($ Billion)* | Channel-Beam Hours (x $10^6$) | LCC/CBH ($ 000)* |
|---|---|---|---|---|---|
| 26.1 | 20 | 44 | 14.2 | 3.76 | 3.78 |
| 21.8 | 20 | 44 | 14.1 | 3.44 | 4.09. |
| 17.9 | 20 | 44 | 14.4 | 3.44 | 4.18 |
| 15.5 | 20 | 44 | 14.3 | 3.04 | 4.70 |

*Constant (1984) dollars

Table 5-5. System Concept Variations

| Variation | Applicable To: Band | Applicable To: Orbit |
|---|---|---|
| 1. Restrict broadcasts to latitudes between 40° N and 15° S | 1 | Geostationary, 8-Hour |
| 2. Restrict broadcasts to latitudes above 40° N or below 15° S | 1 | 8-Hour |
| 3. Same as Number 2 above, but with *only one* channel per zone | 1 | 8-Hour |
| 4. Broadcasts confined to two hours in morning and evening, with one channel per zone (prime-time broadcast system) | 1 | Geostationary, 8-Hour |
| | 3 | Geostationary |
| 5. Field strength requirement reduced to 150 $\mu$V/m | 1 | Geostationary, 8-Hour |
| | 2 | Molniya |

Table 5-6. Variational System Life Cycle Costs (LCC)

| Variation | Band | Orbit | Fleet Qty | LCC Qty | LCC ($Billion)* | Channel-Beam Hours (x $10^6$) | LCC/CBH ($000)* |
|---|---|---|---|---|---|---|---|
| 1 | 1 | GEO | 36 | 79 | 24.8 | 3.30 | 7.51 |
| 1 | 1 | 8-Hr | 12 | 26 | 9.4 | 2.13 | 4.39 |
| 2 | 1 | 8-Hr | 20 | 44 | 14.2 | 1.12 | 12.68 |
| 3 | 1 | 8-Hr | 16 | 35 | 11.5 | 0.82 | 13.98 |
| 4 | 1 | GEO | 12 | 26 | 9.5 | 1.00 | 9.54 |
| 4 | 1 | 8-Hr | 12 | 26 | 9.1 | 0.92 | 9.88 |
| 4 | 3 | GEO | 3 | 7 | 1.6 | 1.00 | 1.61 |
| 5 | 1 | GEO | 11 | 24 | 8.5 | 4.57 | 1.86 |
| 5 | 1 | 8-Hr | 12 | 26 | 9.1 | 4.42 | 2.06 |
| | | | | | 8.9 | 4.32 | 2.05 |
| 5 | 1 | 12-Hr | 8 | 18 | 7.4 | 4.35 | 1.70 |
| | | | | | 7.2 | 4.19 | 1.72 |
| 5 | 2 | Molniya | 3 | 7 | 2.2 | 0.54 | 4.03 |

*Constant (1984) dollars

Were the number of satellites in the 8-hour system increased to provide service comparable to that of the geostationary system, the LCC/CBH would be significantly higher.

Restriction of coverage to extreme northern and southern latitudes (Variations 2 and 3) leads to very large values of LCC/CBH, because the duty cycle of the satellites is low. As in the baseline system, the number of satellites is determined by coverage requirements of the northernmost zones. However, no credit is taken for the capability of these satellites to broadcast to midlatitude zones.

The 8-hour-orbit, prime-time system is much less effective (as measured by LCC/CBH) than the corresponding baseline system because the satellites are underutilized, particularly over the midlatitude zones. The effectiveness of the Band 1 geostationary, prime-time system is comparable to that of the 8-hour system, because both require the same number of satellites. The LCC/CBH of the Band 3 geostationary, prime-time system is four times that of the baseline system, because the service provided is five times smaller while the life-cycle number of satellites is only reduced from nine to seven.

Variation 5 permits a transmitter power reduction in Band 1 by a factor of four. For the geostationary system, the number of satellites is reduced by a similar factor, as is the LCC/CBH. A system of 8-hour satellites requires one more satellite than the geostationary system and has a slightly higher LCC/CBH. The 12-hour system shows to best advantage from a cost standpoint because of the smaller number of satellites required for zonal coverage. The LCC/CBH of the Band 2 Molniya system is only slightly less than in the baseline case, because the satellites are smaller in size but not in number.

Two Variation 5 systems are shown for 8-hour and 12-hour orbits. The first 8-hour system is designed with 3-degree satellite beams; the second, with 6-degree beams. In the first 12-hour system, a cable-catenary antenna is used; in the second, a phased-array antenna. The specific satellite design clearly has little effect on LCC/CBH.

## 5.3 LIFE CYCLE COSTS FOR SSB-AM BAND 1 SYSTEMS

Life cycle costs for the two SSB-AM Band 1 systems are given in Table 5-7. The LCC difference between the two systems is attributable to the greater launch costs of the 8-hour-orbit system. Total satellite costs are essentially the same, despite the larger number of 8-hour satellites. The much higher per-satellite cost of the geostationary system is attributable to the 267-meter cable-catenary antenna. By contrast, the 8-hour satellites have phased-array antennas that measure only 34 meters on a side.

Table 5-7. Life Cycle Costs for SSB-AM Band 1 Systems

| Orbit | Fleet Qty | LCC Qty | LCC ($ Billion)* | Channel-Beam Hours (x $10^6$) | LCC/CBH ($ 000)* |
|---|---|---|---|---|---|
| GEO | 7 | 15 | 5.9 | 4.51 | 1.30 |
| 8-hr | 12 | 26 | 8.1 | 4.32 | 1.88 |

Constant (1984) dollars

# 6. KEY SATELLITE TECHNOLOGIES

A satellite designed for voice broadcasting is constrained by the STS weight and volume limitations. Analysis of several key technologies is necessary, first, to establish whether a particular satellite configuration is feasible and, secondly, to determine the maximum number of channel-beams consistent with the STS constraints. Among these are the antenna, electrical power subsystem (EPS), and high-power transmitter technologies.

Before discussing each of these technologies in detail, the two principal satellite configurations will be described. The satellite concept for the geostationary and Molniya orbits is shown in Figure 6-1. The dimensions shown pertain to the Molniya orbit.

The antenna aperture dominates the satellite, which is shown in its deployed configuration. The antenna is of the deployable mesh, cable-catenary design. To minimize both solar shadowing of, and RF blockage by, the solar array, the array wings are deployed on extendable booms beyond the aperture. The main spacecraft bus, including the feed array, is positioned by a mast extending from the cable catenary. With the bus located "ahead" of the feed array, RF beam interference is minimized.

Details of the feed array, bus, and stowage concept are shown in Figure 6-2. The number of feeds in the array is determined by the number of distinct broadcast areas to be served. The feed cross-arms and the flexible-mesh ground plane stow parallel to the feed center post, which is fixed. The center reflector mast is made of dielectric material to limit RF interference. The extensive radiator area required is provided by pivoting radiator panels. The panels utilize advanced heat-pipe technology.

With the radiators folded on the main bus body and the cable catenary retracted, the stowed satellite occupies approximately one-half the Orbiter cargo bay. The Centaur-class OTV measures about 22 feet in length. Thus, the combination is a full Orbiter load.

The satellite concept for the 8-hour-orbit Band 1 system is shown in Figure 6-3. Beams generated by the 8 by 8 phased array are equivalent, in terms of illuminated area, to 3-degree beams from geostationary orbit. The cross-beam structure provides intersections at the feed elements and has a

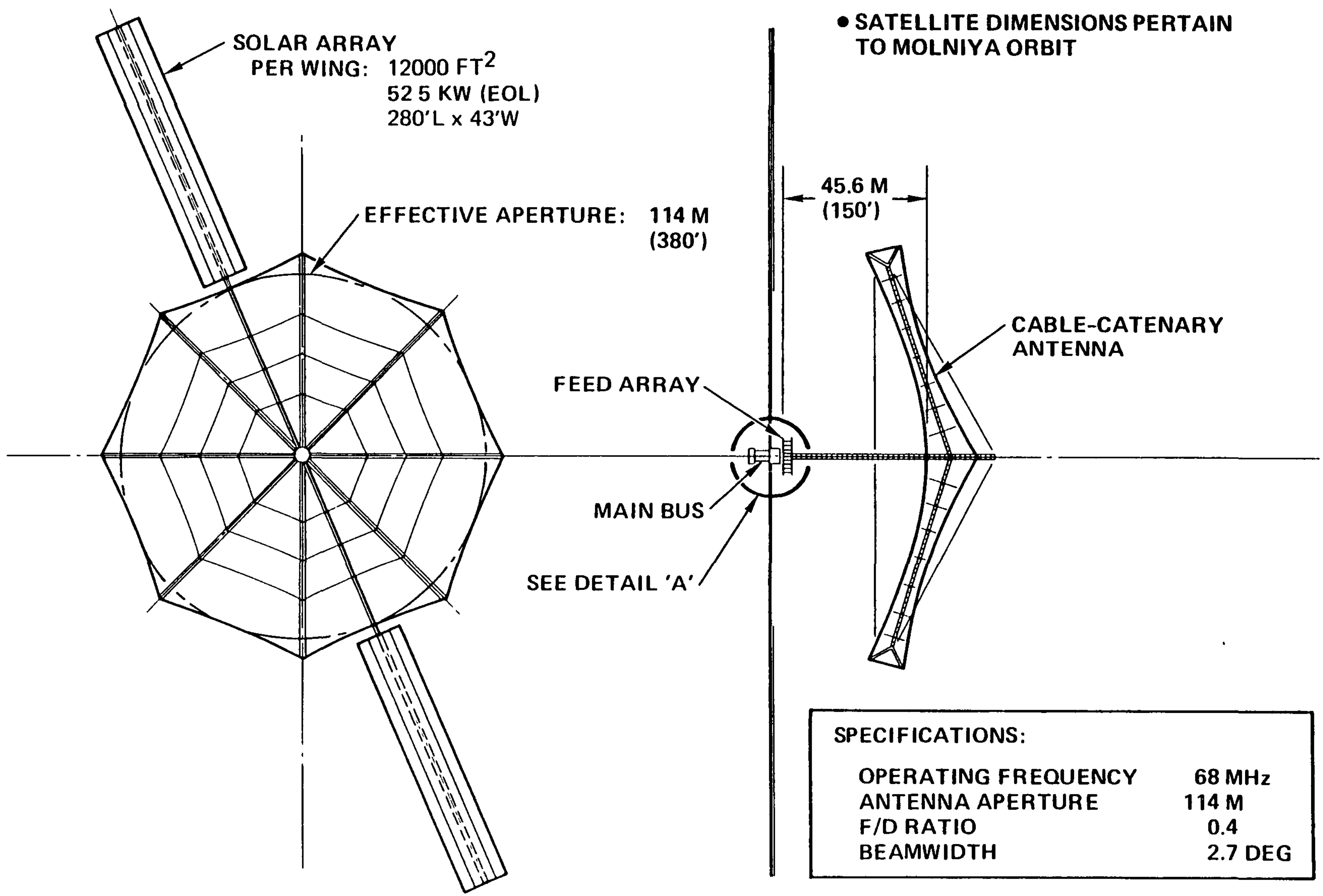



Figure 6-1. Molniya and Band 1 Geostationary Satellite Concept

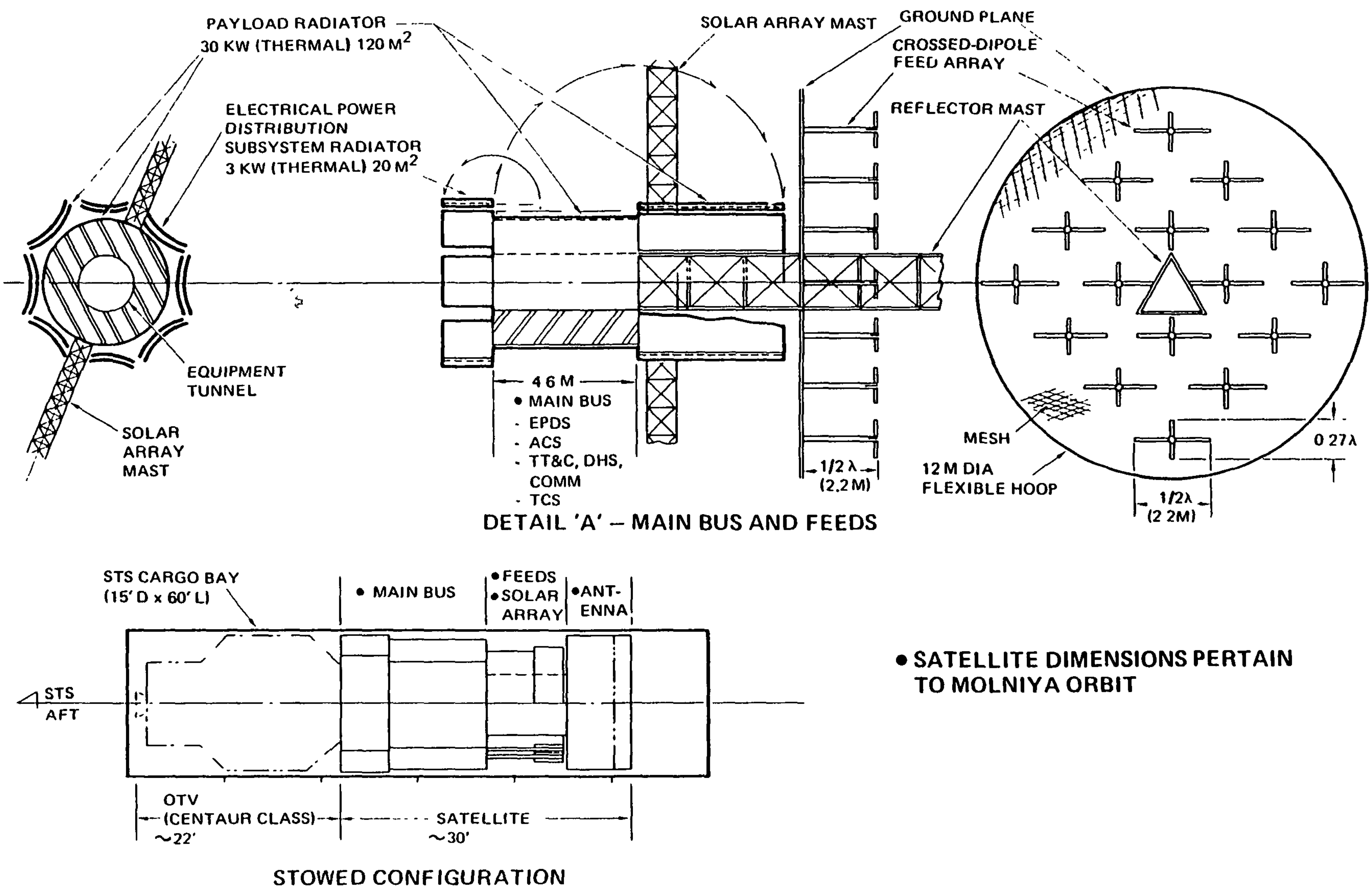



Figure 6-2. Molniya and Band 1 Geostationary Satellite Concept

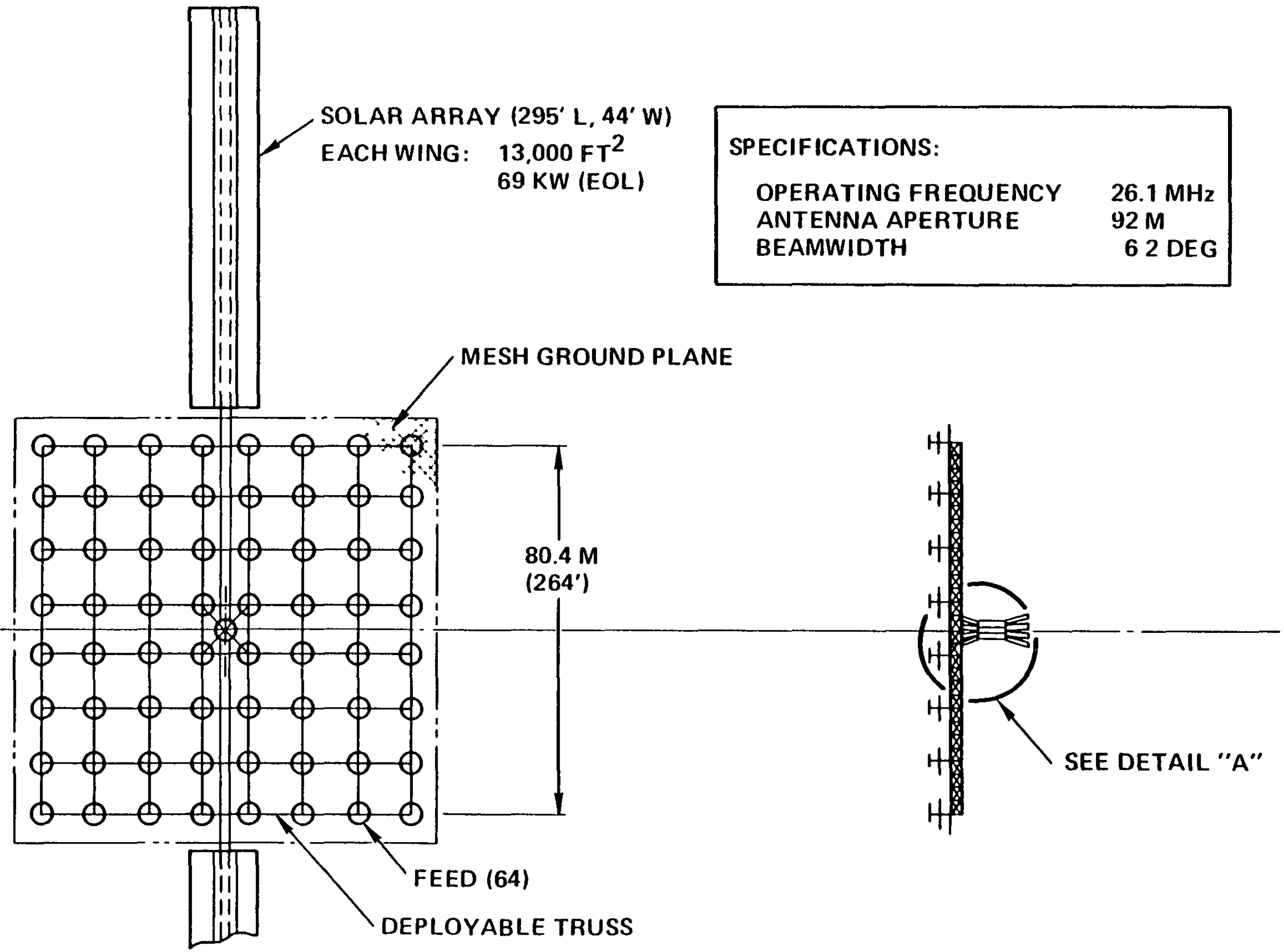



Figure 6-3. Satellite Concept for 8-Hour Orbit

depth of 1.8 meters. A flexible mesh is extended to provide the ground plane. The solar array is deployed outboard of the aperture to preclude solar shadowing and RF blockage. The spacecraft main bus is shown with its radiators extended.

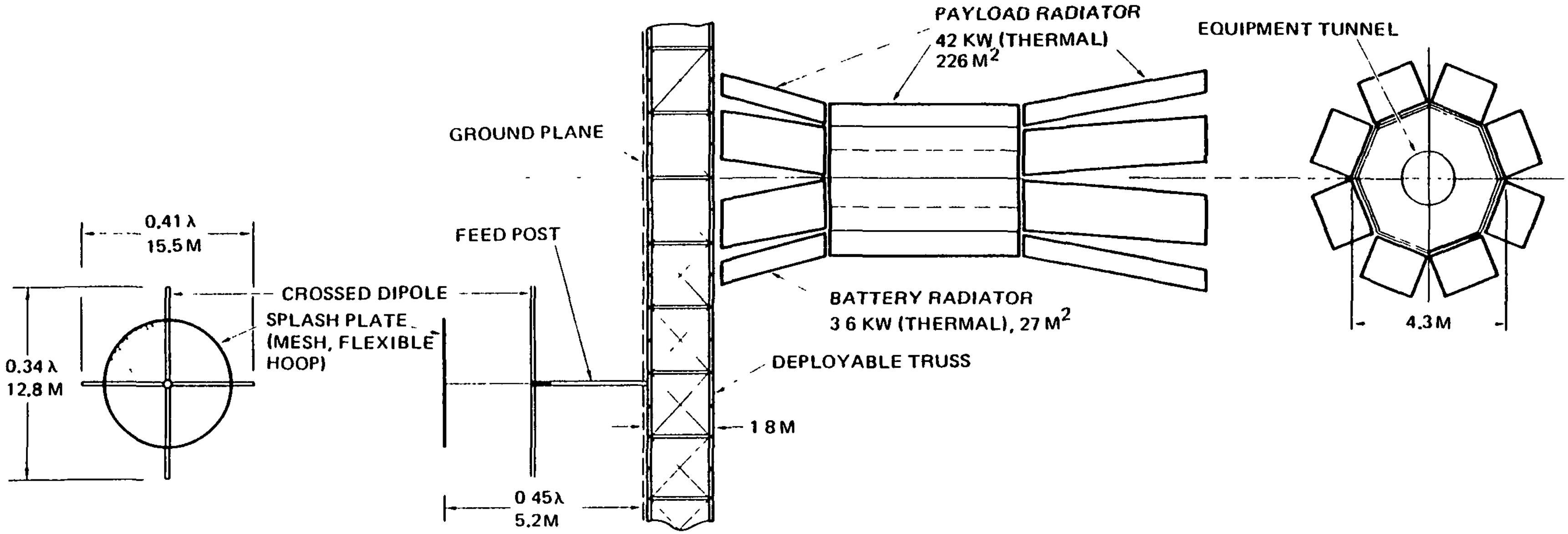
Details of this concept are shown in Figure 6-4. The feed dipoles and flexible-mesh splash plates stow parallel to the fixed center mast. The cross-beam structure stows compactly; with hinge points as shown, its stowed length is limited to the 1.8-meter depth of the structure. The extensive radiator area required is achieved by hinged panels that stow against the spacecraft main bus. The stowed satellite (~34 feet), together with the Centaur class OTV (~22 feet), completely fills the Orbiter cargo bay.

## 6.1 ANTENNA TECHNOLOGY

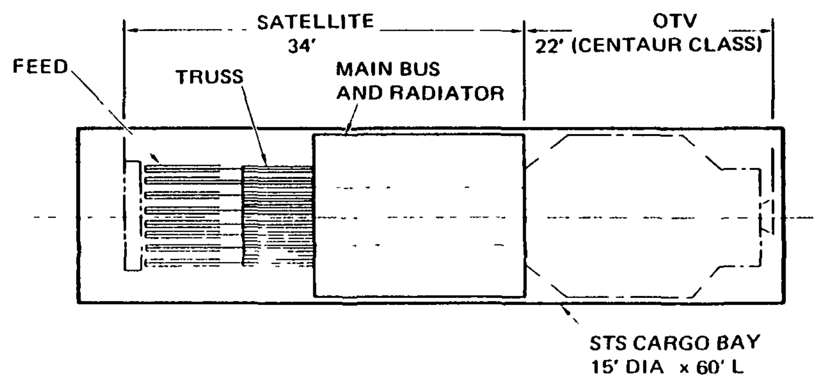
For purposes of antenna design, the orbits of interest can be divided into two groups: those for which transmission takes place at geosynchronous altitude or above, and subsynchronous orbits from which transmission takes place at much lower altitude. The first category includes the Molniya orbit, for which all broadcasting is done near apogee.

An antenna beamwidth of 3 degrees has been selected from geostationary orbit, because it tends to minimize antenna size while keeping transmitter power close to the minimum possible value for the various broadcast zones. The relatively high gain associated with a 3-degree beam is most readily achieved with a reflector type of antenna. The required reflector diameter is on the order of 20 wavelengths.

Illumination of a similar size area from altitudes substantially below synchronous is accomplished with a larger antenna beam. This permits use of a phased-array antenna. The phased array has the advantage of being planar and somewhat simpler structurally. However, the number of radiating elements varies inversely with the square of the beamwidth. Below a certain beamwidth, the phased array becomes too complex and too heavy. The crossover point corresponds roughly to a 12-hour orbit. For the lower subsynchronous orbits considered (i.e., for 6- and 8-hour periods), the phased array is preferred to the reflector antenna.




DETAIL A – MAIN BUS AND FEEDS




STOWED CONFIGURATION

Figure 6-4. Satellite Concept for 8-Hour Orbit (Continued)

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Analysis of the two antenna types will be divided into RF and structural aspects. In particular, attributes of different reflector configurations will be considered under the structural heading.

### 6.1.1 RF Aspects of Antenna Design

#### 6.1.1.1 Geostationary and Molniya Orbits

Major aspects of reflector antenna design include selection of: f/D (focal length-to-diameter ratio), feed element type, illumination taper, and maximum beam offset from boresight. The value of f/D should be selected for effective reflector illumination to achieve high antenna efficiency. Maximum antenna gain will be achieved if the feed illumination has a -10 dB edge illumination taper. The beam offset is a consideration because of the scan loss that occurs when the beam is pointed off boresight.

A single-feed-per-beam approach will be adopted in conjunction with a parabolic reflector. The feed corresponding to a specific beam may be selected from a fixed array of elements, or it may be one of a small number of (laterally) movable feeds. The latter design feature permits a better matching of the area illuminated by a beam to a specified broadcast zone.

Use of movable feeds should be restricted to systems in which the number of simultaneously transmitted beams per satellite is small. This approach is useful, therefore, for the Band 1 geostationary system, where the satellite capacity is two channel-beams. For a Molniya satellite, which has a 12-channel-beam capacity, an array of fixed feeds is preferred.

The specific feed element proposed is the crossed dipole, which consists of two orthogonal, unequal-length dipole arms (Figure 6-5). The relative dipole lengths are adjusted to obtain the phase quadrature required for generating circular polarization. The dipoles are fed by a split balun, with impedance matching achieved by a quarter-wavelength transformer. The bandwidth of the proposed design is typically 3 percent, which is adequate for the present application. The dipole arms are designed to fold during launch. By operating the crossed-dipole feed over a metallic mesh ground plane, the dipole weight can be kept quite small.

The feed element configuration shown in Figure 6-5 consists of a group of triangularly arranged crossed-dipole feeds. The feeds are spaced a

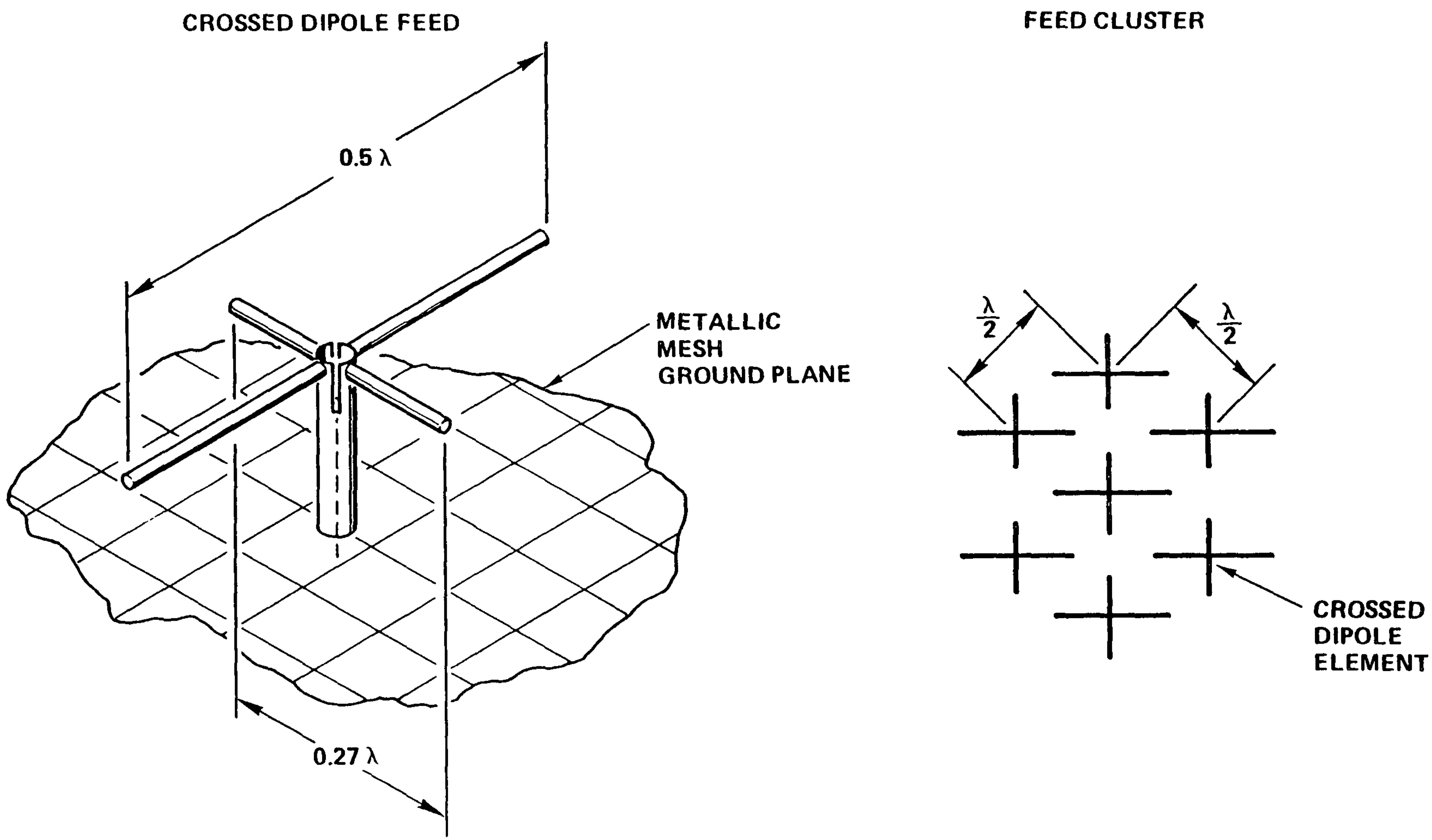



Figure 6-5. Feed Geometry for Reflector Antenna

half-wavelength apart to provide contiguous coverage (i.e., -3 dB cross-overs) between beams where needed. One or more feeds may be excited to satisfy the coverage needs of individual zones. The individual dipole feeds can easily be designed to handle 10 kilowatts of power.

### 6.1.1.2 Subsynchronous Orbits

The required antenna beamwidth at subsynchronous orbit typically varies between 6 and 10 degrees, depending on the altitude and the minimum satellite elevation angle for which the system is designed. While a reflector aperture can be used with this class of orbits, certain operational problems arise. Each satellite is responsible for coverage of specified geographical areas during definite broadcast intervals. Because of the satellite motion, the various beams must be steered in a more or less continuous manner to maintain coverage of the specified areas. This is difficult to accomplish with a single-feed-per-beam approach and a fixed set of elements. If movable feeds are considered, the number must be kept reasonably small and may be insufficient to fully utilize the satellite channel-beam capacity.

Other factors affecting the selection of antenna type for subsynchronous orbits are listed in Table 6-1. The weight and stowed dimensions pertain to the 8-hour orbit. While the weight factor favors the reflector design, the reflector diameter for an 8-hour orbit is 130 meters as compared with an array dimension of 92 meters for the same antenna beamwidth. Neither design presents a stowage problem, although the stowed length of the phased array is considerably greater. Deployment of the phased array is relatively simple in comparison with the cable catenary.

Both types of antenna require a considerable development effort. For the phased array, this principally involves the RF aspects of the beamformer network. However, the dynamics of the structure must also be understood. For the reflector, technology development involves deployment, mesh management, and structural dynamics and its impact on control system design.

A key aspect of the antenna selection involves the power amplifiers. Power requirements for the reflector design are extremely large. On a per-amplifier basis, the required per-carrier power for an 8 by 8 phased array,

Table 6-1. Comparison of Reflector and Phased-Array Antennas

| Factor | Reflector | Phased Array |
|---|---|---|
| Weight (for 8-Hr Orbit) | 1940 Lb | 2815 Lb |
| Stowed Volume (for 8-Hr Orbit) | 6 Ft Long, 13 Ft Diam | 16 Ft Long, 10 Ft Diam |
| Deployment | Moderate Complexity | Relatively Simple |
| Power Amplifier Requirements | Small Number of Large Amplifiers | Large Number of Small Amplifiers |
| Beamforming Network | Not Required | Required |
| Scan Loss | Moderate | Moderate |
| Reliability | Fairly High | High (Graceful Degradation) |
| Development Required | Mechanical Aspects | Electronic Aspects |

corresponding to an 8-hour orbit, is only 1/64 as large. Each amplifier may have to support as many as six separate carriers, corresponding to the satellite channel-beam capacity. Nevertheless, the amplifier rating required with a phased array designed for an 8-hour orbit is typically an order of magnitude smaller than that needed with a reflector antenna. Additionally, transmission of several carriers through a common amplifier would reduce the peak-to-average power ratio the amplifier has to accommodate.

From the above considerations, the phased array has been selected as the preferred configuration for all but the 12-hour subsynchronous orbit. For the 12-hour orbit, which is considered only as a system variation with a reduced field strength of 150 μV/m, both the phased array and the reflector antenna have been examined (see Section 4.6.3).

To maintain a fixed transmitter power requirement per channel-beam, irrespective of orbit, the antenna beamwidth must be sized for the maximum slant range to the target area. This occurs at the minimum satellite elevation angle, which corresponds to the start or finish of the coverage period. For an 8-hour orbit, the appropriate beamwidth for a 20-degree minimum elevation angle is 6 degrees.

For simplicity of satellite attitude control, the antenna boresight is assumed to be pointed toward nadir. In general, a lower satellite altitude requires larger scan angles off boresight. The maximum scan angle should be kept as small as possible to minimize associated losses. For example, for an 8-hour orbit with coverage provided to a 20-degree elevation angle limit, visibility extends to 17 degrees off boresight. The maximum scan angle, which is less than this amount by half the antenna beamwidth, is therefore 14 degrees.

For a phased array, scan loss is minimized by (1) proper selection of the element pattern, which must be relatively flat over the scan angle, and (2) careful spacing of the antenna elements. A balance must be struck between mutual coupling, which is reduced by larger spacing, and grating loss, which is introduced if the spacing is too large. For the element type and spacing described below, the maximum scan loss for an 8-hour orbit is about 0.5 dB.

For a parabolic reflector (considered only for the 12-hour orbit), as the feed is positioned farther from the focal point in the focal plane, the comalobe increases and the antenna gain decreases. This scan loss can be reduced by employing a larger f/D. However, this implies a higher feed element gain and a correspondingly larger element size. For Band 1, especially, any increase in feed element size is highly undesirable. An f/D of 0.4 has been adopted for the reflector antenna. This results in a scan loss comparable to that for the phased array.

Feed Element Selection. Two array elements have been considered for the phased-array antenna. The short-backfire dipole (Figure 6-6) is a design which has been studied in depth by TRW for the Aerosat program. The element is short, mechanically rigid, self supporting, and has a "flat-top" pattern. A high edge-coverage gain is provided when the array is phased to form a beam off boresight, a desirable feature for minimizing scan loss. The peak element gain has been measured at 11.2 dB in the array environment. Mutual coupling isolation between adjacent elements is greater than 37 dB.

The short-backfire element measures 0.45λ in both height and width. Circular polarization is conveniently obtained by unequal-length dipoles. High gain is achieved by the pumping action of the splash plate and the cavity formed by the surrounding elements. The antenna is very compact and lightweight, and can be designed to fold during launch.

The helical element (Figure 6-6) inherently provides circular polarization, of a sense determined by the direction of its winding. The single-element gain ranges from 10 to 17 dB, depending on the element diameter and axial length. For the equivalent gain of the short backfire element, the height of the helical element is 1.5λ as opposed to 0.45λ. The cross section is approximately $\lambda/\pi$ in diameter, which is about 30 percent smaller than the short-backfire element. The helical design requires a support mast and is not easily designed mechanically for folding during launch.

The major features of the two candidate elements are summarized in Table 6-2. The short-backfire element is clearly the preferred candidate. The bandwidth, although narrow, is adequate for this application.

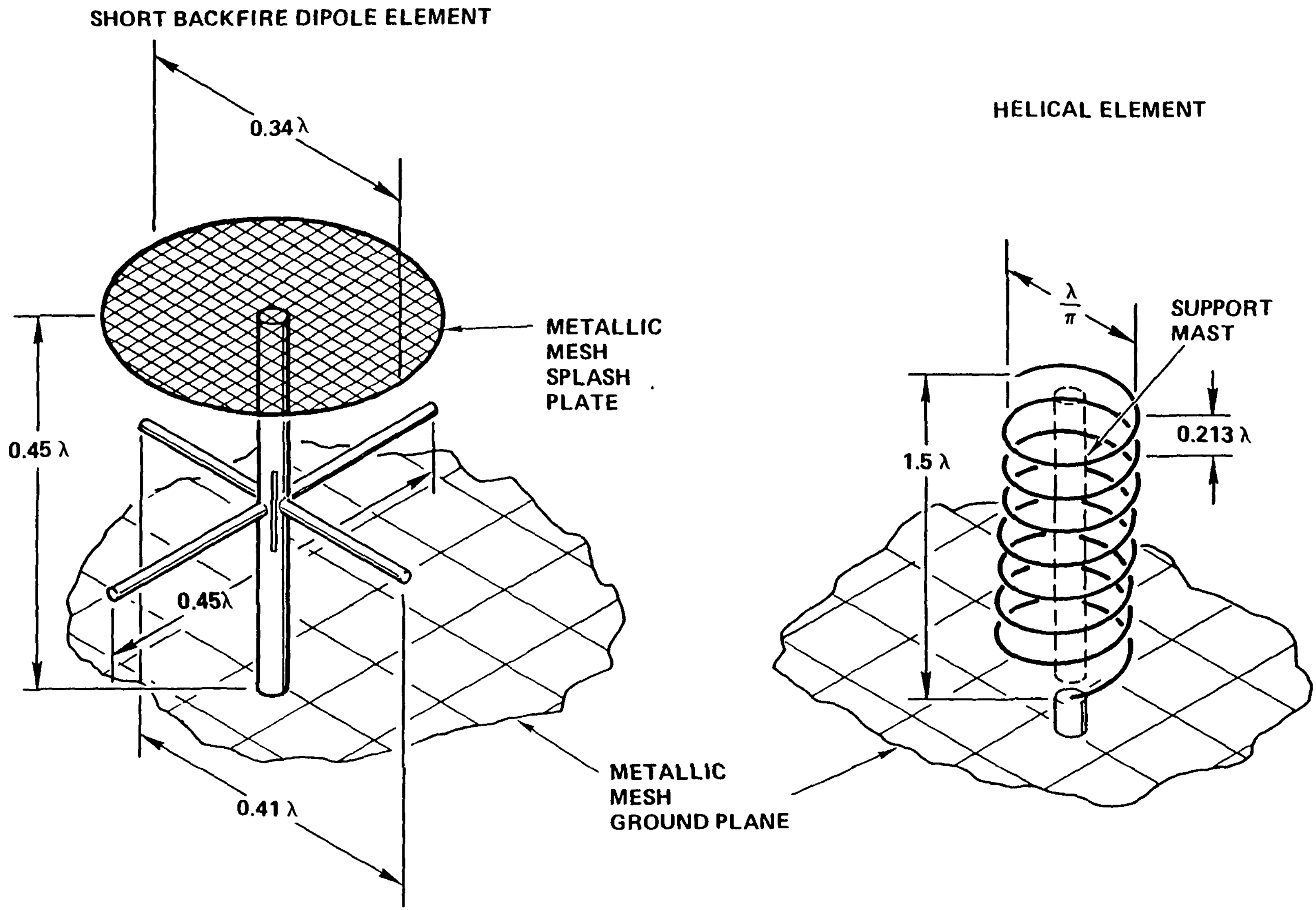



Figure 6-6. Candidate Array Elements

Table 6-2. Phased-Array Element Comparison

| Antenna Element | Gain | Bandwidth | Storage Volume | Pattern Characteristics | Weight | Support Structure |
|---|---|---|---|---|---|---|
| Short Backfire | Excellent | Narrow | Excellent | Excellent | Very Light | Self-Supporting |
| Short Helix | Good | Broad | Poor | Good | Light | Requires Center Mast |

The short-backfire element pattern shown in Figure 6-7 was measured in an array environment with a rotating linear source. The axial ratio over a 28-degree coverage angle (corresponding to an 8-hour circular orbit with a 20-degree elevation angle constraint) is very small. Also, the antenna pattern has the desirable "flat-top" characteristic for minimizing scan loss.

Array Geometry and Beamformer Network. The array characteristics will be described for an 8-hour orbit. An 8 by 8 element array is required (Figure 6-8). Each element, of the short-backfire type, provides a gain of 11 dB. To this is added the array factor of 18 dB, corresponding to 64 elements, making the total gain 29 dB. The latter value corresponds to a 3-dB beamwidth of 6 degrees.

Because of the array size in Band 1 ($8\lambda$ = 92 meters at 26 megahertz), the elements should be arranged for minimum stowage complexity. This objective is accomplished by the rectangular array shown. The stowage concept for this configuration is shown in Figure 6-18.

The beamformer network shown in Figure 6-8 for illustrative purposes can support the formation of (1) four simultaneous beams, each with a single carrier, (2) a single beam with four carriers, or (3) some intermediate combination of beams and carriers. In the first case, the four phase-shifter settings for a given amplifier would generally be different from one another; in the second case, they would be the same.

### 6.1.2 Structural Aspects of Antenna Design

#### 6.1.2.1 Parabolic Reflector Antennas

The required antenna diameters, particularly in Band 1, are well beyond anything presently contemplated by the large space structure community. A number of different reflector configurations have been proposed in the past for applications requiring smaller diameters. In a number of cases prototype antennas have been built, typically at diameters smaller than required for the motivating applications.

The results of a preliminary assessment of candidate reflector antennas are shown in Figure 6-9. While the STS/Centaur limitation placed on satellite weight depends on the broadcast orbit selected (e.g., 14,000 pounds for geostationary orbit, but 20,000 pounds for Molniya orbit), a

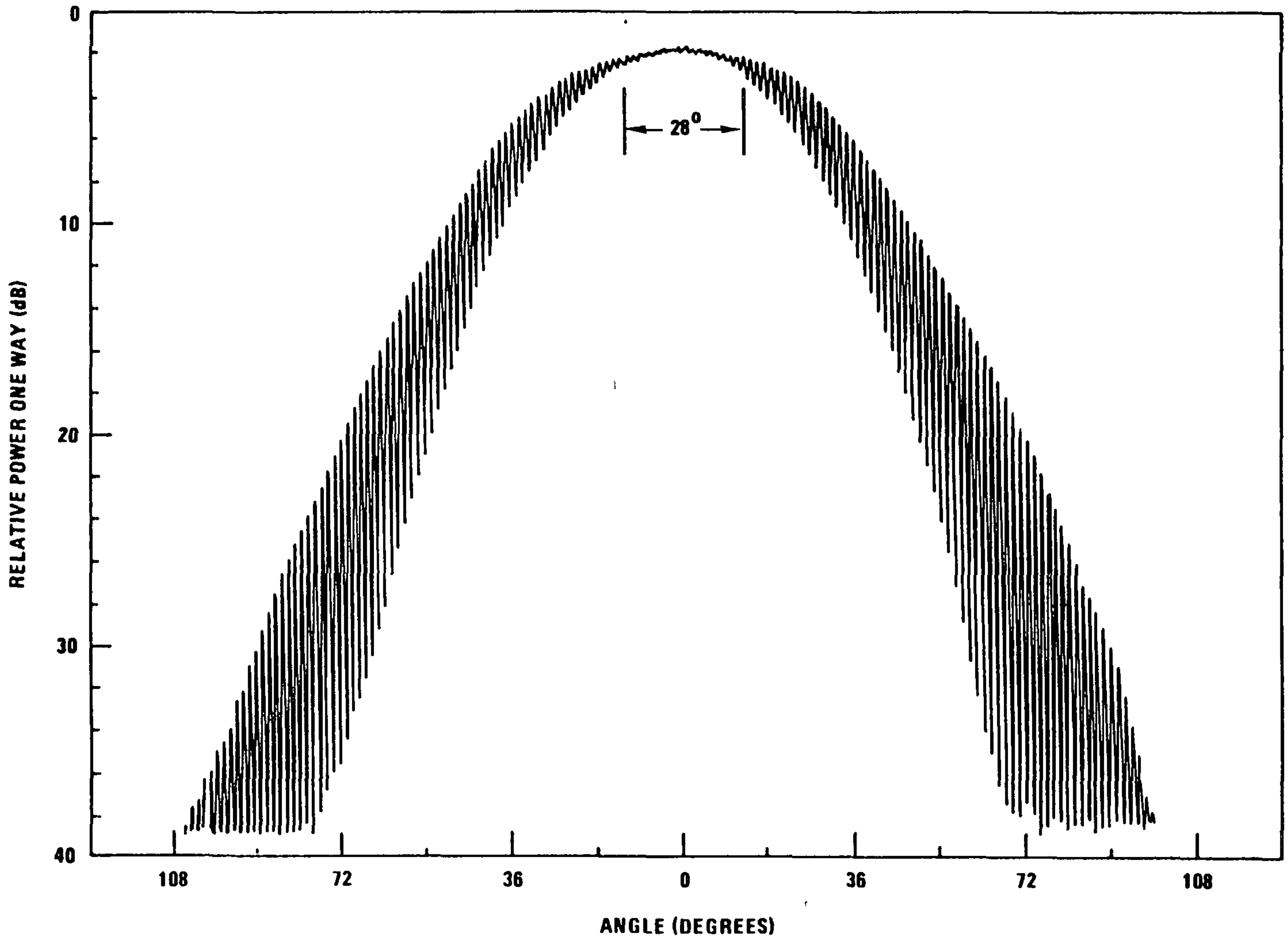



Figure 6-7. Short-Backfire Element Pattern (In Array Environment)

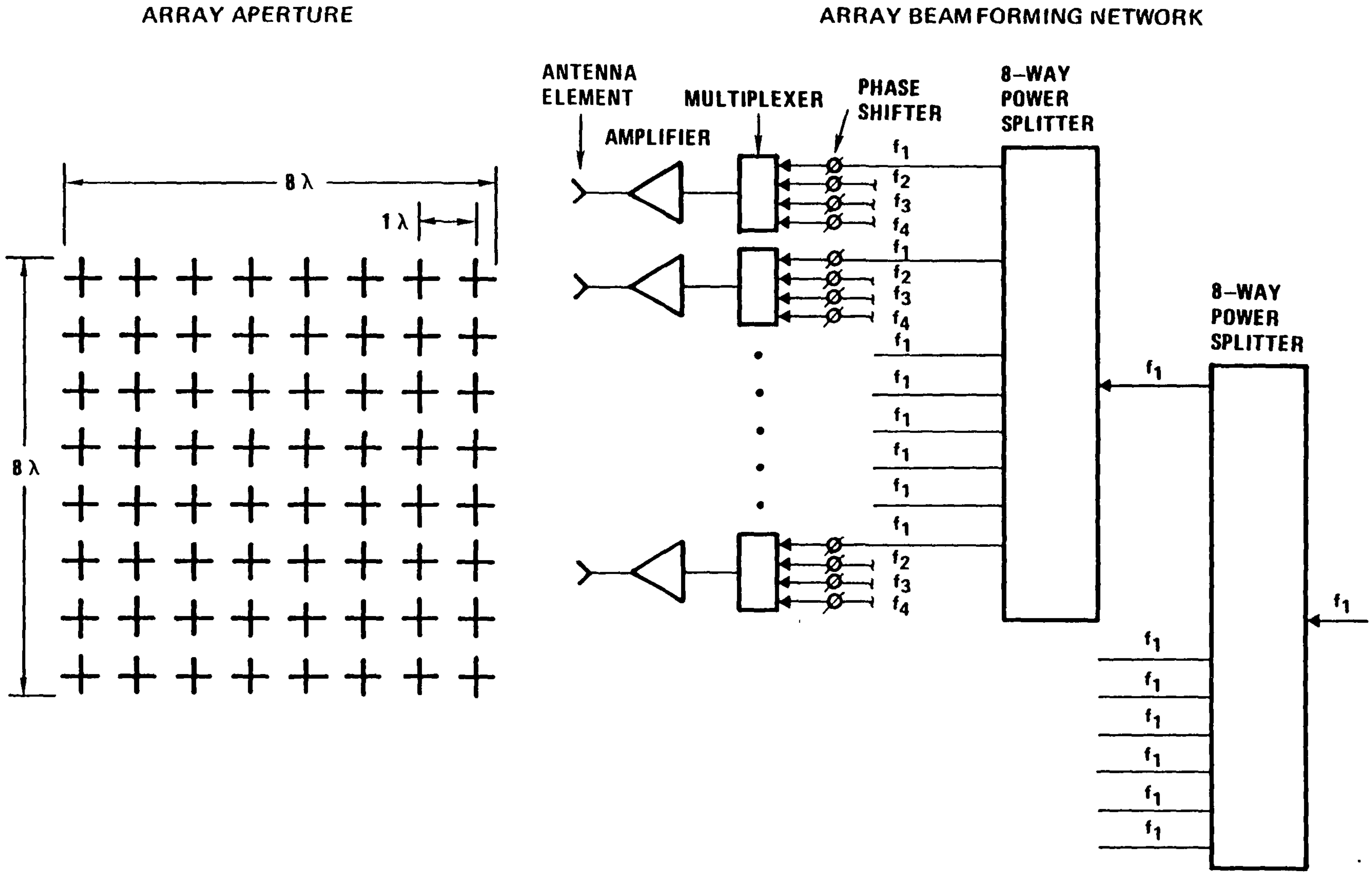



Figure 6-8. Array Geometry and Electronics

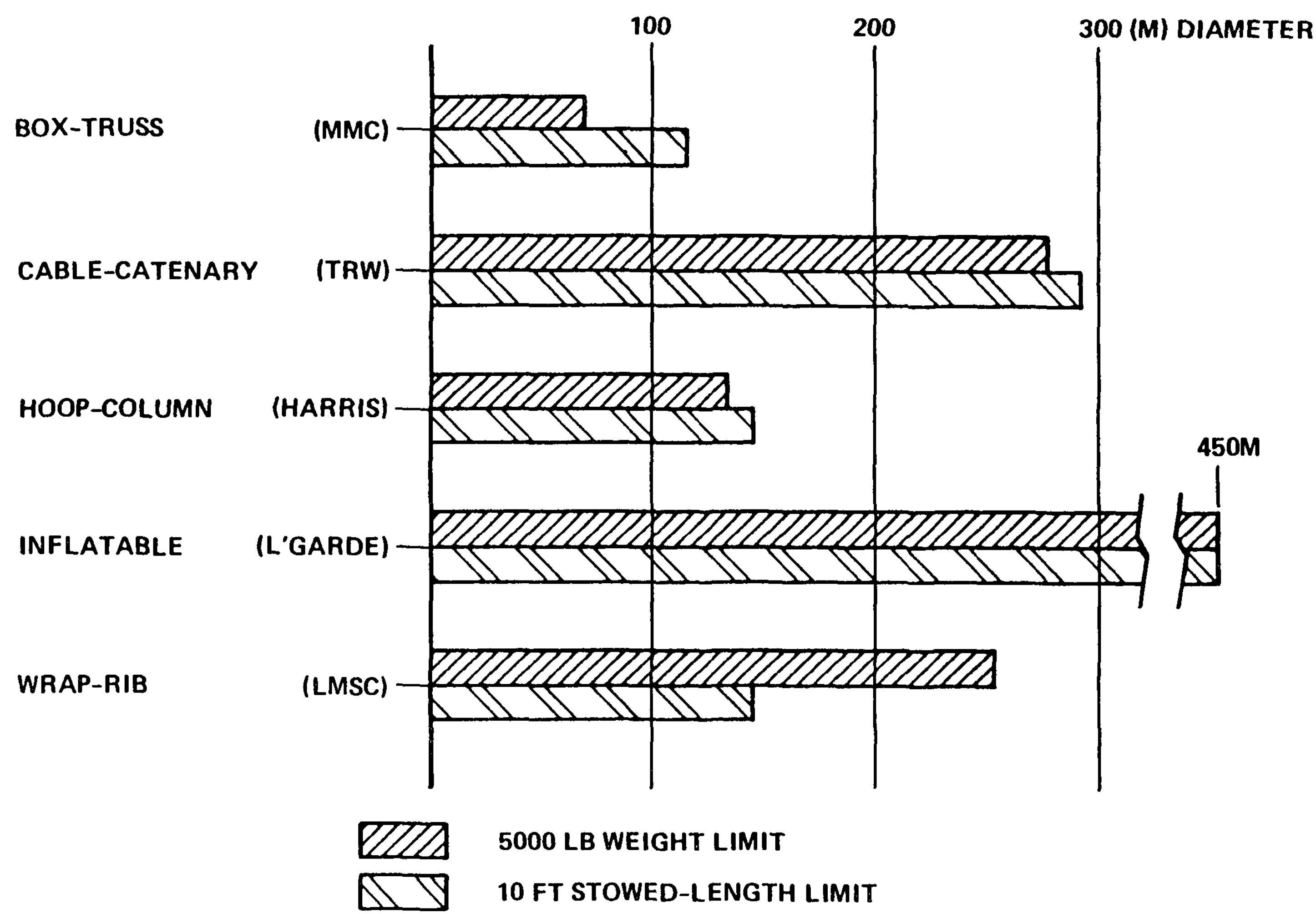



Figure 6-9. Initial Assessment of Reflector Candidates

nominal 5000-pound limit is placed on the reflector weight. The stowed-length limitation is taken as 10 feet. The corresponding limitations on the diameter of each antenna type are shown in the figure. Because an antenna diameter of 267 meters is required at geostationary orbit for the Band 1 baseline system, only the cable-catenary and inflatable antennas are viable candidates. While the hoop-column and wrap-rib antennas could be considered for the Band 2 Molniya satellites, which have a 114-meter antenna diameter, these two configurations would be considerably heavier than a satellite based on either the cable-catenary or the inflatable design.

The inflatable antenna does have weight and stowage advantages over the cable-catenary antenna, according to Figure 6-9. The inflatable antenna (Figure 6-10) has been investigated by NASA as an alternative to mesh antennas. The antenna diameter is maintained by a self-rigidizing torus at the intersection of the parabolic and conic sections. The shape is maintained by pressurizing the cavity to $1 \times 10^{-7}$ psi, or 0.001 $P_a$, which is nevertheless a couple of magnitudes above the collapsing solar pressure. Inflatant make-up to compensate for leaks and meteorite punctures is done by a stored liquid system. The weight of an inflatable antenna is shown as a function of diameter in Figure 6-11.

Despite its weight and stowage advantages, there are several environmental and operational questions about the inflatable antenna that must be satisfactorily resolved before it can be considered a preferred reflector candidate. For this reason, all reflector configurations in this report are based on the cable-catenary design.

The cable-catenary antenna has been under development at TRW since the late 1960s. It is adaptable to very large diameters (over 300 meters) and yet is compatible with an integrated STS satellite launch. Additionally, there is no interfering cabling within the RF beam, and the design exhibits considerable torsional rigidity. Figure 6-12 shows a 10-foot working model of the cable catenary. Its main elements are (Figure 6-13):

a) Eight radial deployable boom masts. These booms (as well as the feed mast) are triangular articulated masts, having full torsional as well as axial rigidity.

b) Deployable feed and hub masts.

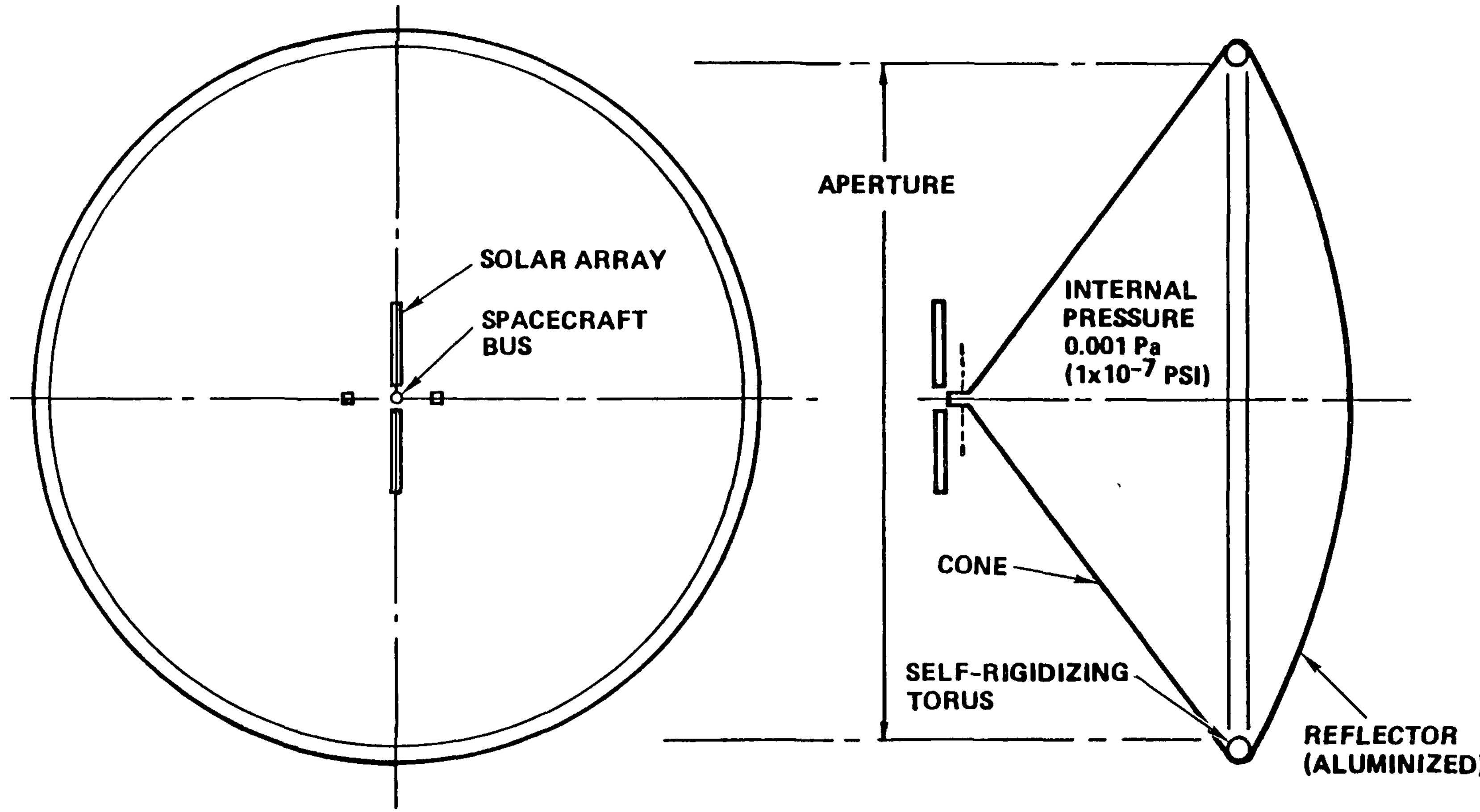



Figure 6-10. Inflatable Parabolic Antenna Configuration

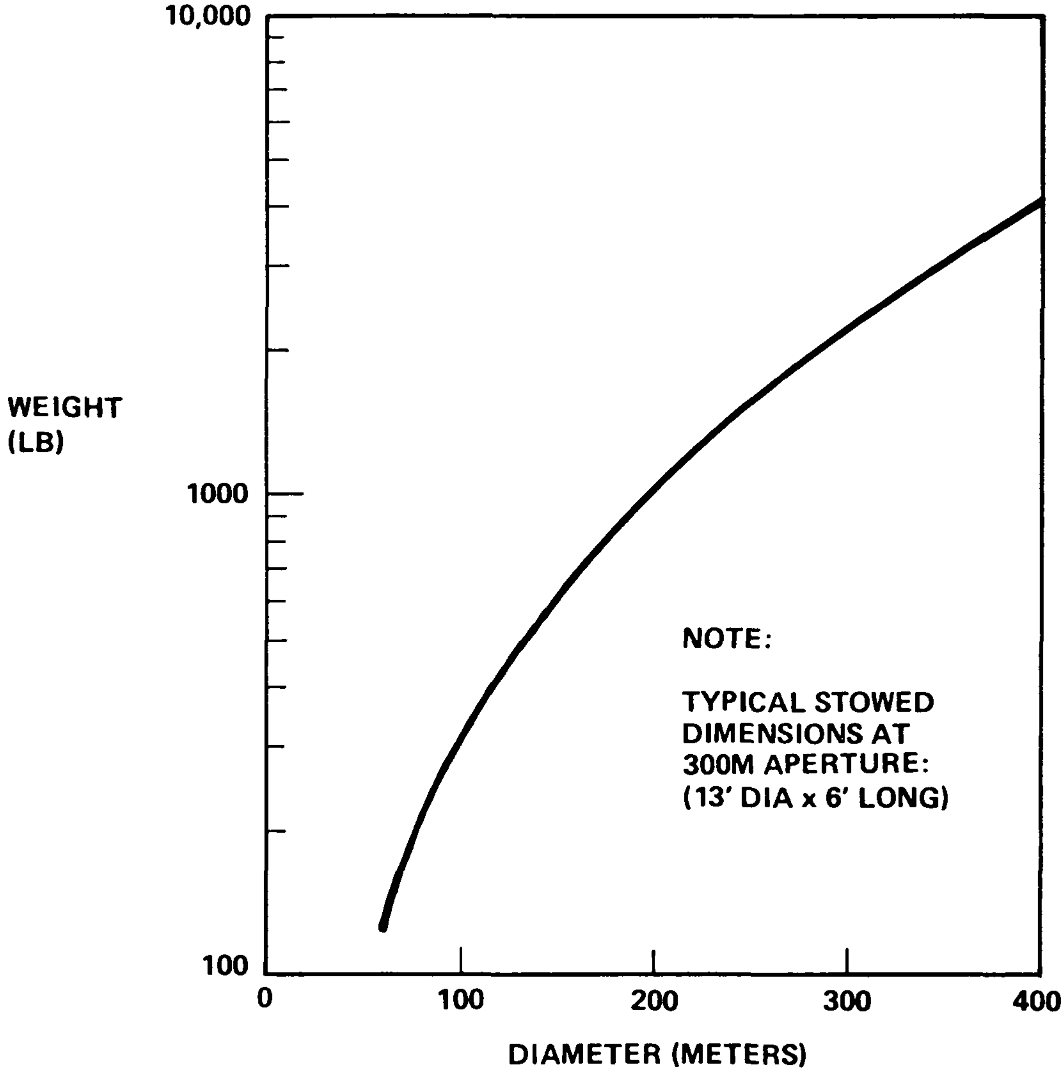



Figure 6-11. Inflatable Parabolic Antenna Weight

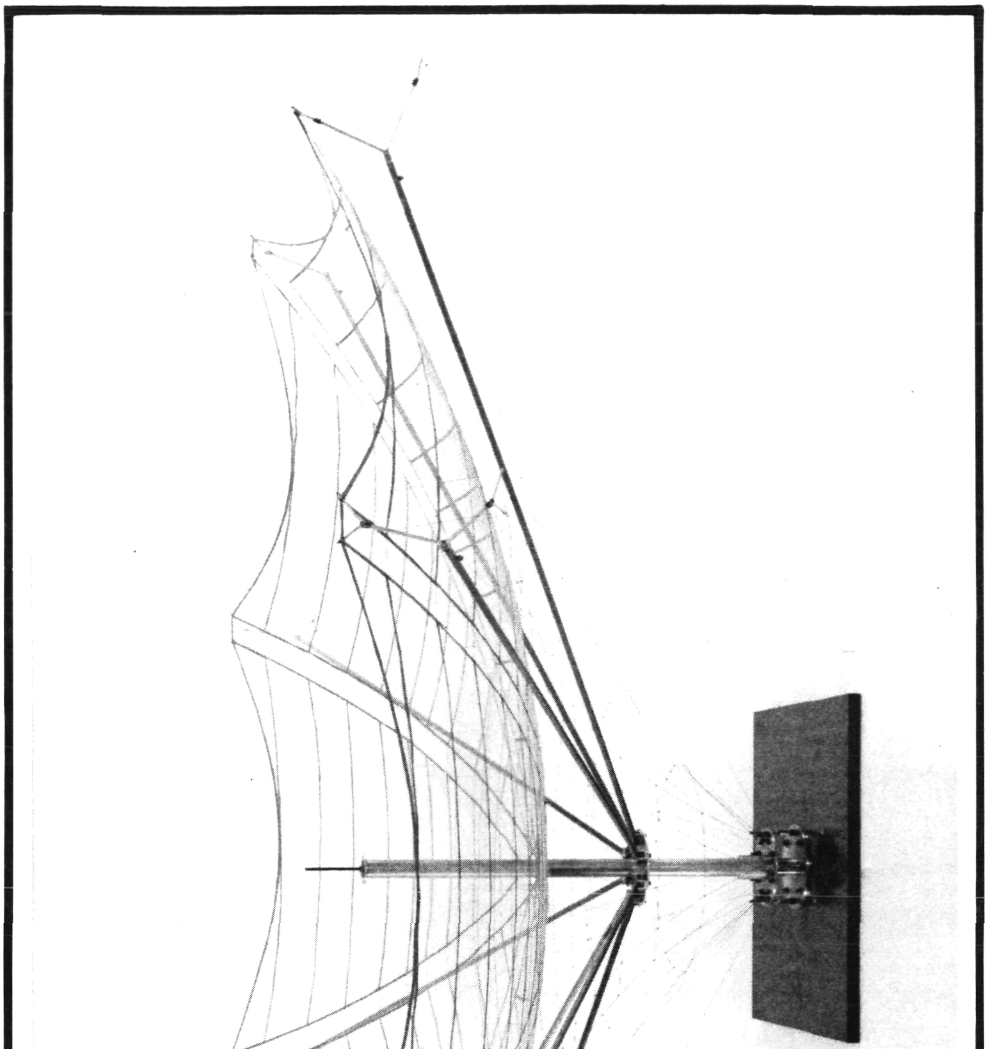


Figure 6-12. Cable-Catenary Antenna, 10-Foot Scale Model

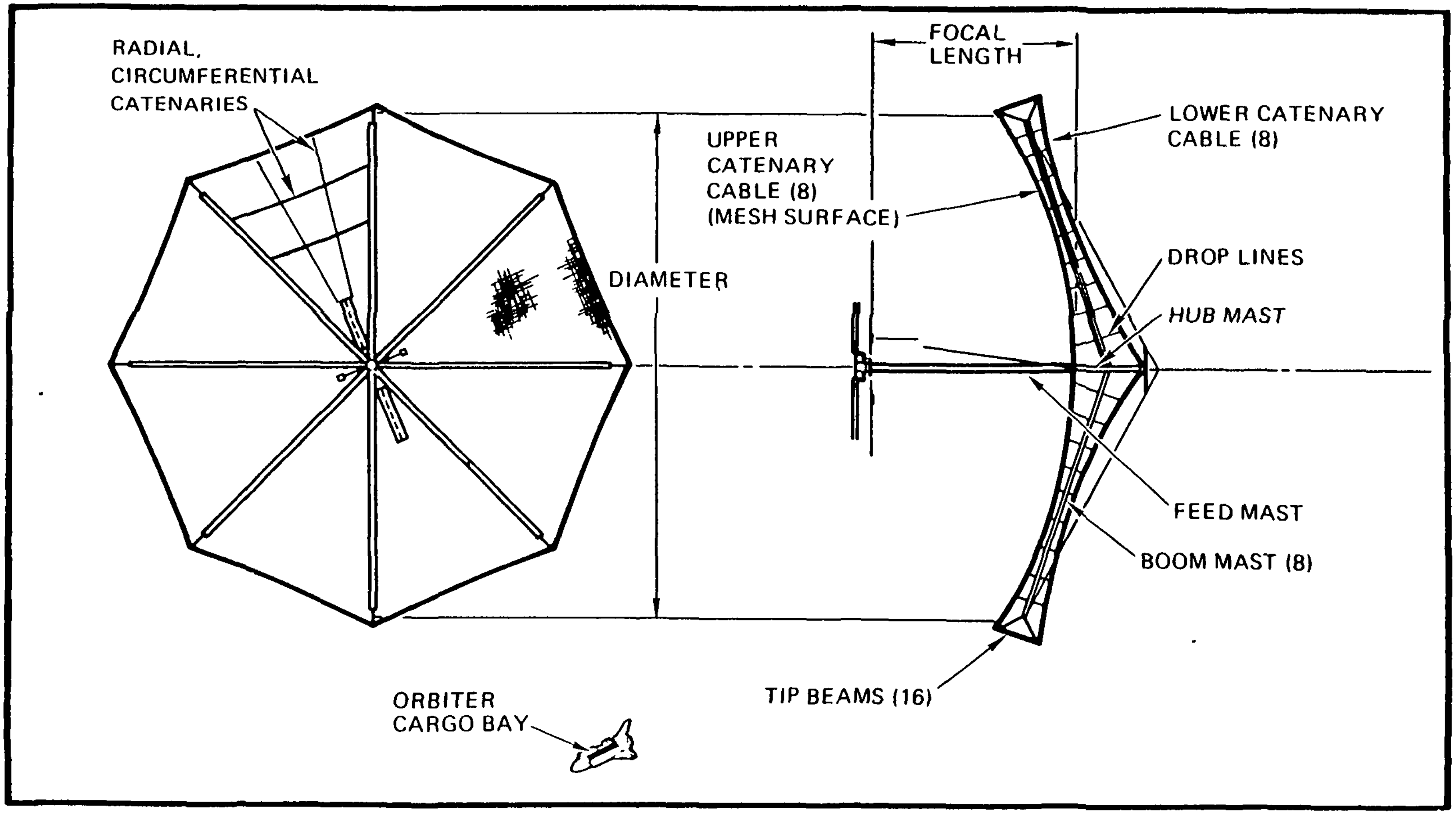



Figure 6-13. Cable-Catenary Antenna - Deployed Configuration

c) Balanced (front and back) radial and circumferential lightweight cabling, which forms the parabolic surface by catenary tensioning of the cables. This is accomplished by the drop lines between the two cabling surfaces.

d) An RF reflecting mesh mounted to the front surface to provide the reflector surface.

Figure 6-14 shows the deployment sequence of the cable-catenary antenna. In the stowed condition, the radial-mast canisters are rotated against, and clustered around, the center-mast canisters. The mesh management system is stowed between and around the mast canisters.

Deployment starts by rotation of the radial-mast canisters into position, with the mesh system following this motion. The tip booms are then extended radially from their stowed position in the canisters. The feed mast is deployed first. Following this, the radial masts are deployed, with the mesh playout controlled by the mesh management system. The mesh management also lends itself to surface accuracy adjustments after the antenna is deployed.

The cable-catenary weight is shown as a function of antenna diameter in Figure 6-15. The stowed length is shown in Figure 6-16. The boom and feed-mast cluster occupy most of the length, with the balance taken by the mesh, catenary cabling, and reflector deployment management. The cable catenary occupies the full STS cargo bay diameter of 14 feet.

6.1.2.2 Phased Array Antenna

The TRW crossbeam phased-array antenna concept (Figure 6-17) provides an efficient and lightweight feed support structure, which integrates well with the spacecraft and the STS. The articulated, deployable beams operate similarly to the articulated masts of the cable-catenary antenna, as previously described.

Figure 6-18 shows the deployment sequence for four bays of the phased array. The feed dipoles and splash plates are initially folded back on the feed center tube. The articulated beams fold at the beam-caps/struts intersection, as well as midspan between them. After the satellite orbit is achieved, the beam expands and locks in place. The dipole cross-arms and splash plates are released to complete the deployment sequence.

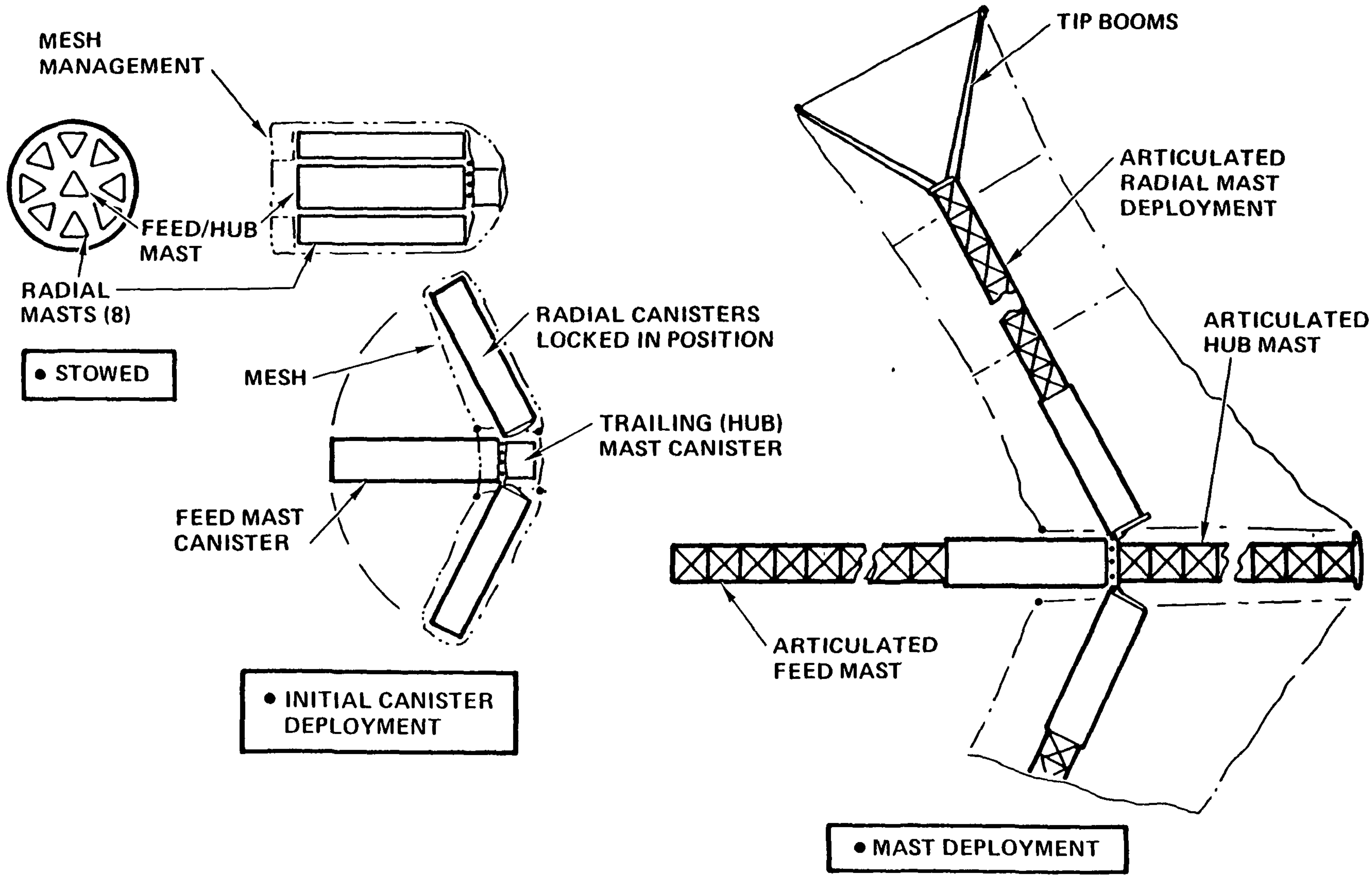



Figure 6-14. Cable-Catenary Antenna - Deployment Sequence

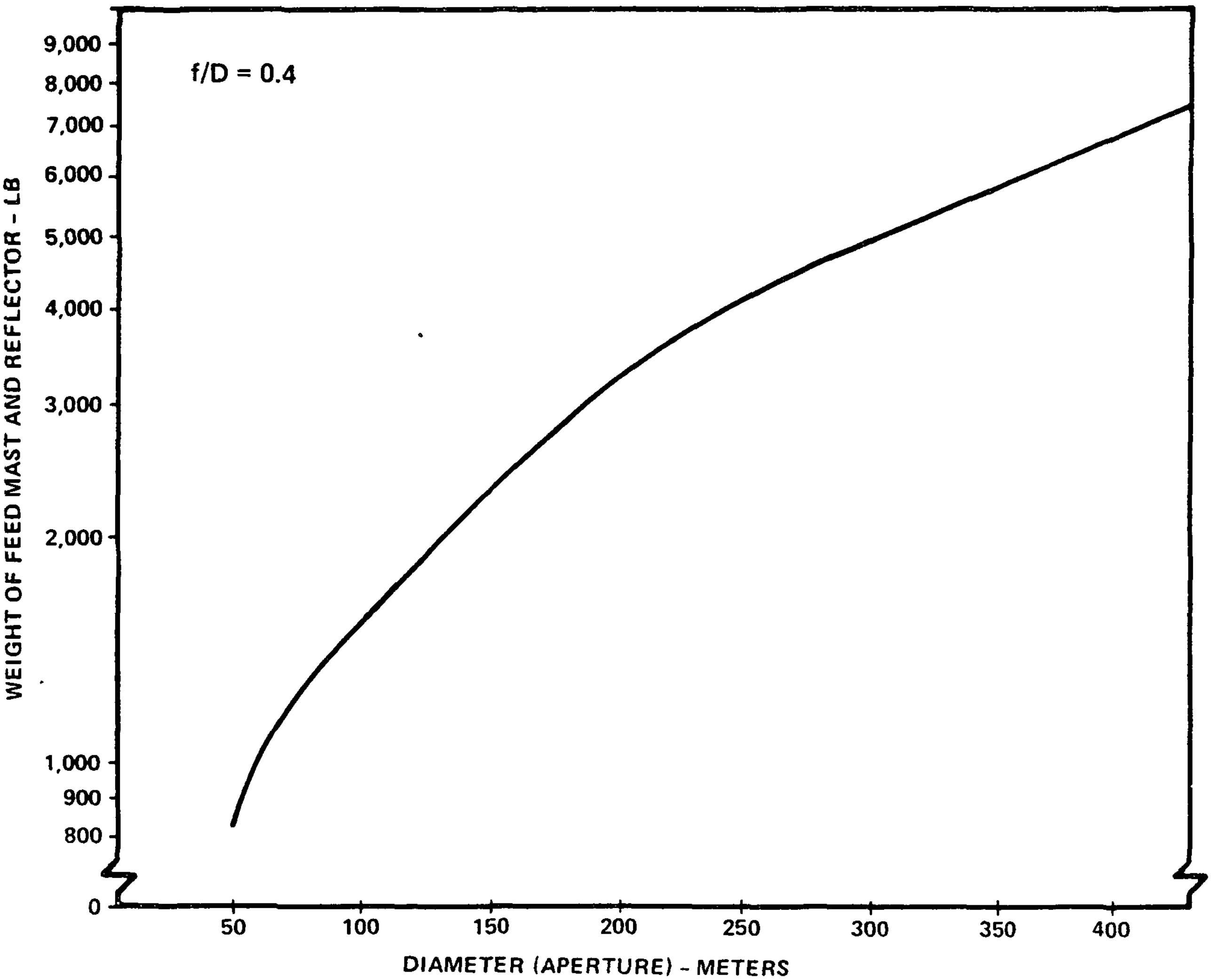



Figure 6-15. Cable-Catenary Antenna Weight

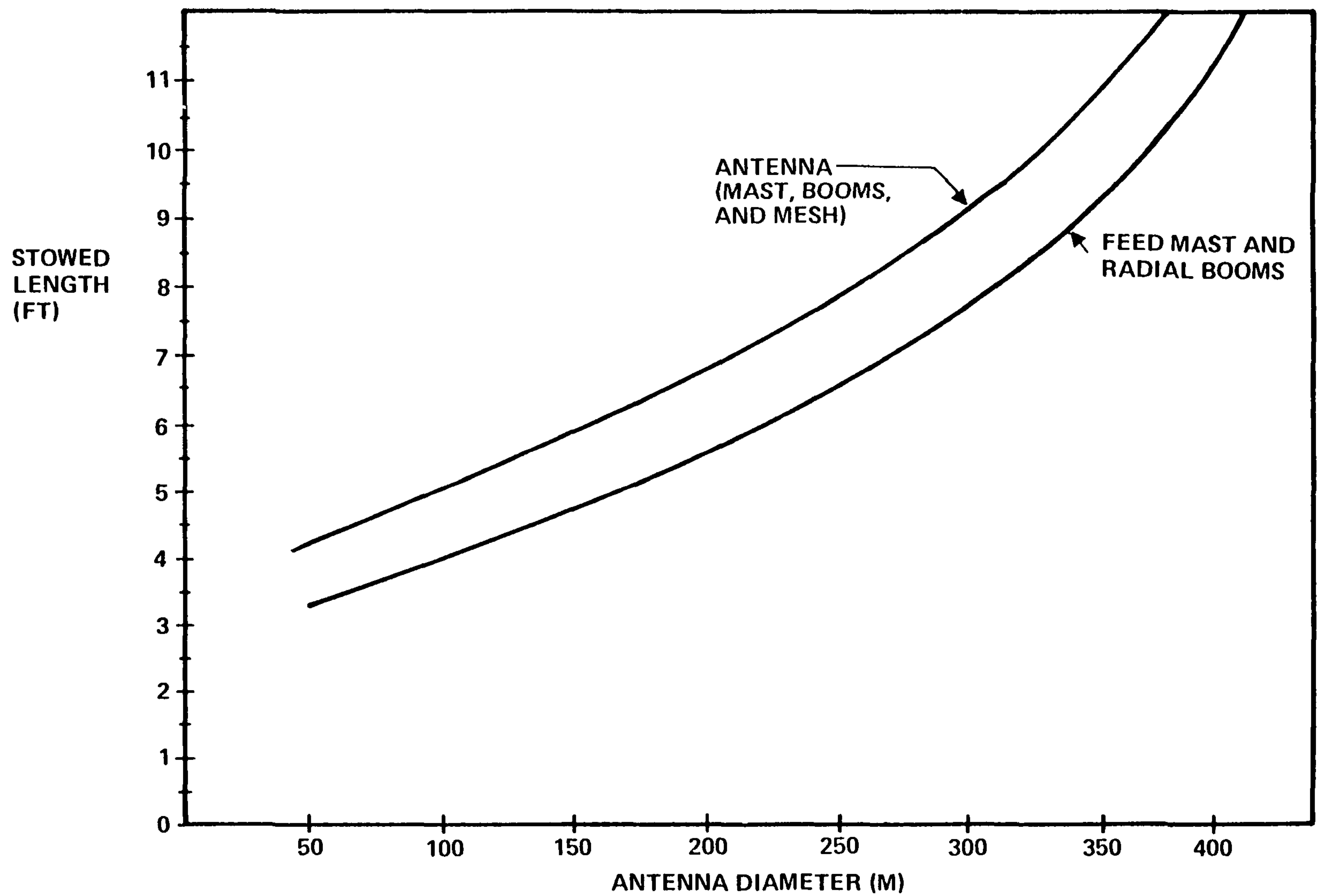



Figure 6-16. Cable-Catenary Antenna Stowed Length

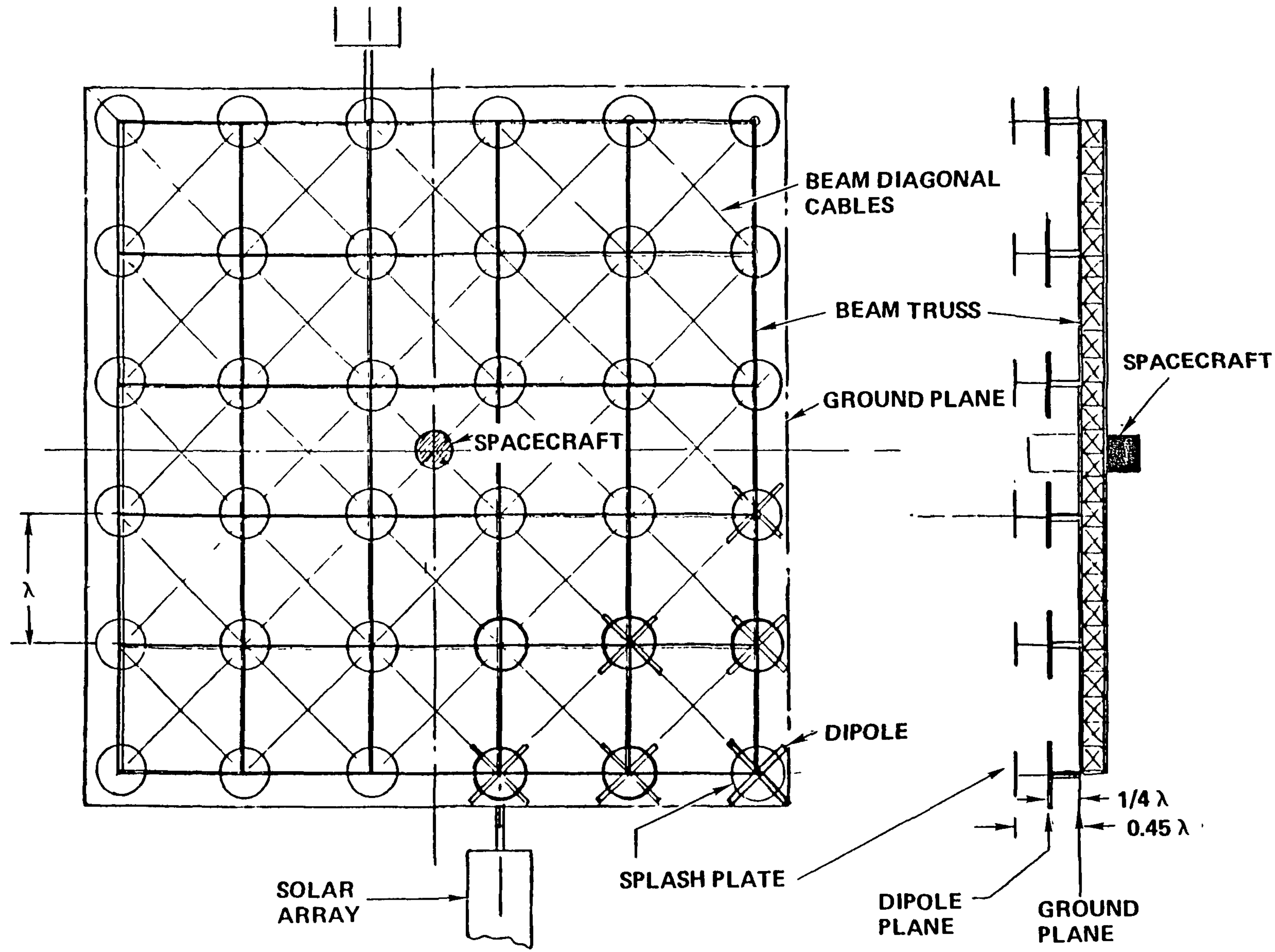



Figure 6-17. Dipole Phased-Array Antenna

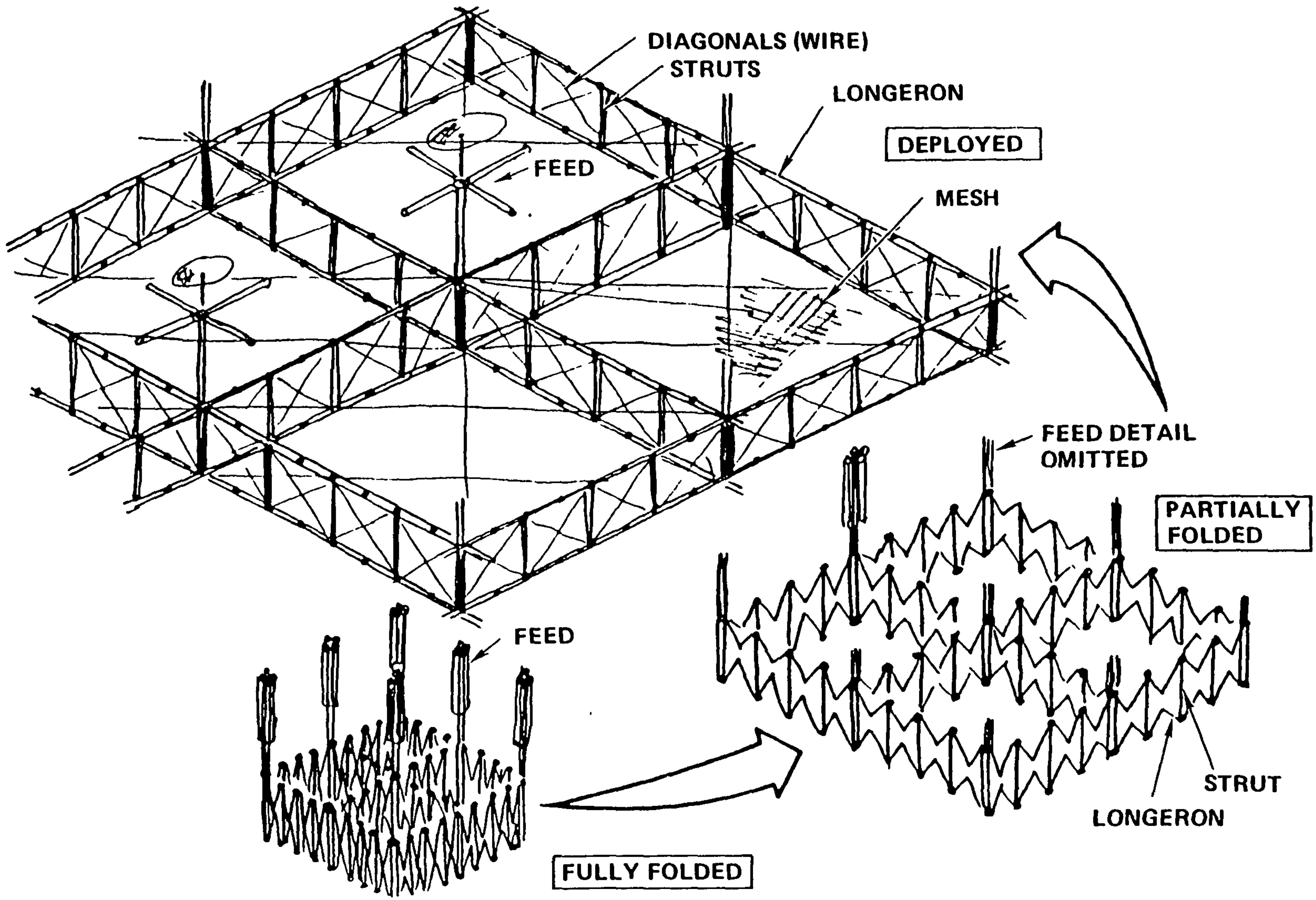



Figure 6-18. Crossbeam Structure Stowage and Deployment

The weight of the crossbeam structure and associated feeds is shown as a function of the number of feeds in Figure 6-19. The feed spacing is assumed to be one wavelength. The stowed diameter and length are shown in Figure 6-20. The crossbeam structure determines the stowed diameter, while the length is driven by the feed center tube. The STS cargo bay diameter limits the array size as shown.

## 6.2 ELECTRICAL POWER SUBSYSTEM (EPS)

There are two principal issues associated with the design of the EPS:

1) Selection of the primary power source

2) Provision of eclipse capability.

### 6.2.1 Primary Power Source Selection

Primary power source candidates include solar panels, nuclear reactors, and solar dynamic power conversion. Power source selection is based primarily on the resulting EPS weight, because of the difficulty in placing a satellite with significant broadcast capability into suitable orbit with a single STS launch. An EPS weight comparison depends on whether or not eclipse capability is required. If it is, solar panels must be combined with a secondary power source of substantial weight. By contrast, no additional weight penalty is incurred with a nuclear reactor, and only a slight weight penalty results from adding thermal storage to a solar dynamic power conversion unit.

Primary power source comparison will be based on the requirements in 8-hour orbit. With no eclipse capability, the weight attributable to a solar-panel-based EPS capable of providing 100-kilowatt load power is 3700 pounds (see Table 6-4). Based on results of the SP-100 nuclear reactor program (a tri-agency effort involving Defense Department, NASA, and Energy Department), a nuclear reactor of similar capability would weigh 3000 kilograms or 6600 pounds. Two examples of EPS design based on solar dynamic power conversion are:

1) 40-kilowatt Brayton engine, which weighs 3800 kilograms

2) 40-kilowatt Sterling engine, which weighs 2980 kilograms.

Clearly, in the absence of a requirement for eclipse capability, solar panels are the preferred source of primary power.

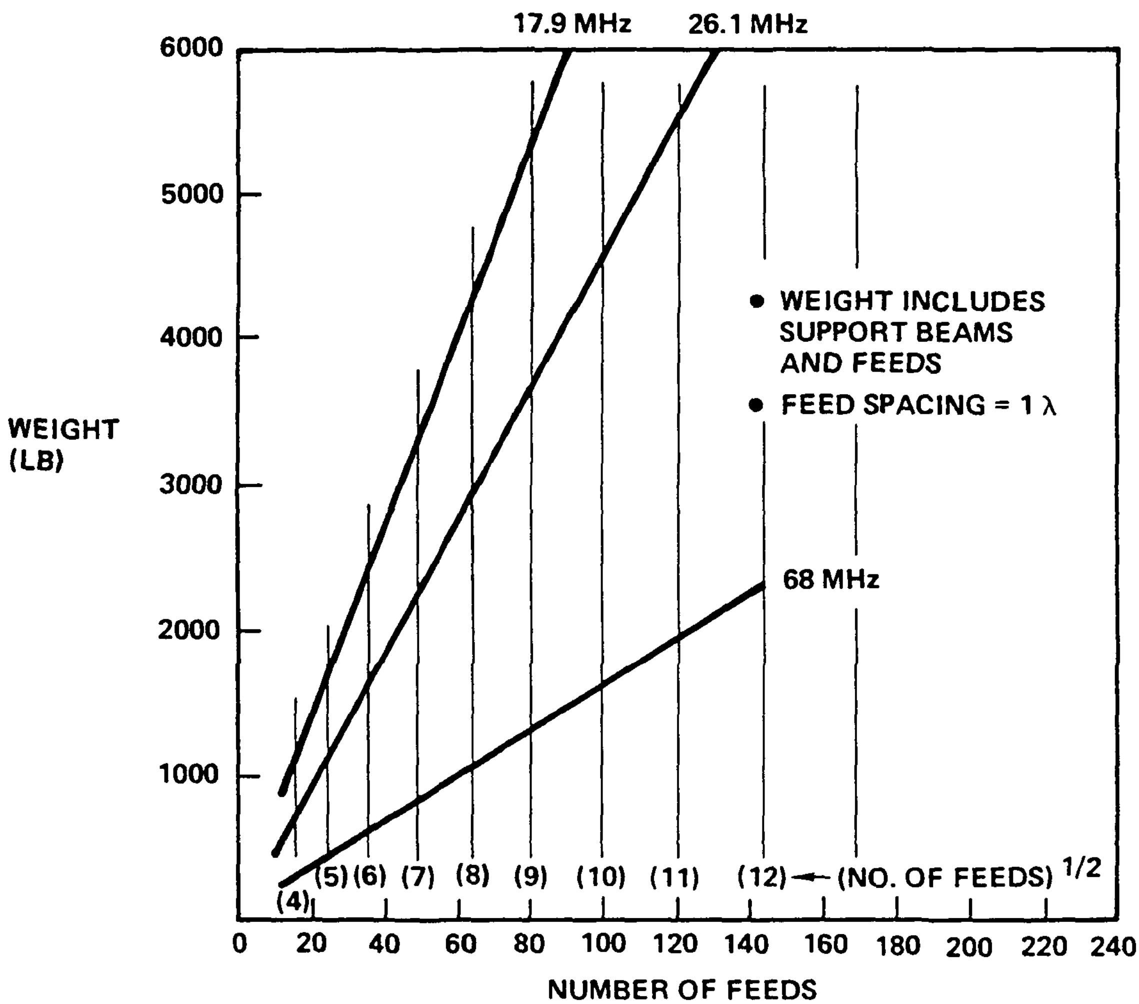



Figure 6-19. Phased-Array Antenna Weight

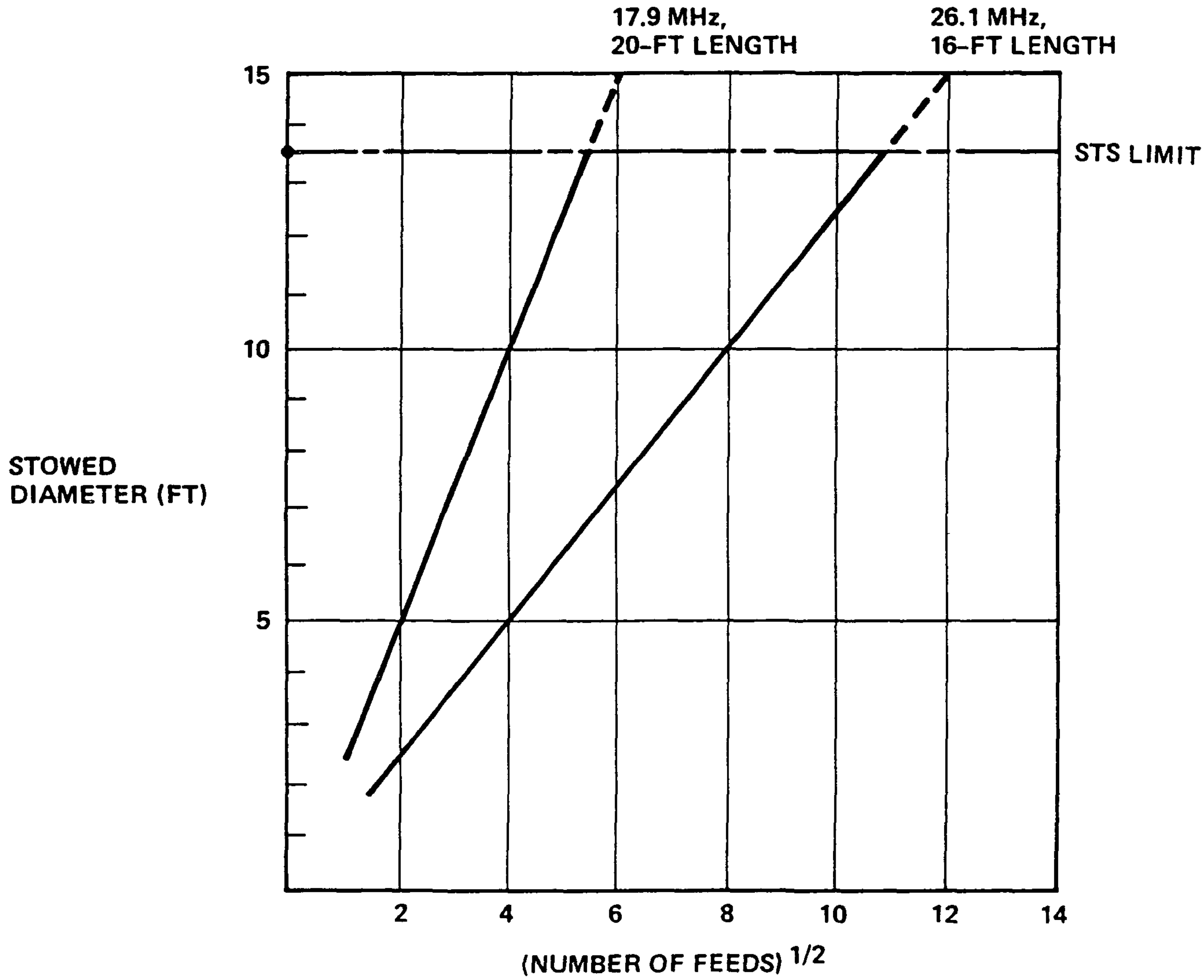



Figure 6-20. Phased-Array Antenna Stowed Dimensions

If eclipse capability is required, the weight of an EPS based on the use of solar panels depends on the choice of secondary power source. The lightest of these sources is the high-energy-density rechargeable battery. A sodium sulfur embodiment of this technology is presently under development. The corresponding EPS weight for 100-kilowatt average load power is 4700 pounds. Approximate EPS weights with more traditional secondary power sources are:

1) 10,000 pounds with regenerative fuel cell (RFC)

2) 13,000 pounds with $NiH_2$ batteries.

These figures include the radiator weight associated with the secondary power source, which is very substantial in the case of the RFC. The EPS weight based on use of sodium sulfur batteries has a 2000-pound advantage over a nuclear-reactor-based EPS and a much larger advantage over solar dynamic power conversion units.

Thus, only if sodium sulfur batteries are not available by the 1990s would a nuclear reactor provide eclipse capability at the lowest EPS weight. However, the weight penalty attributable to provision of eclipse capability in this case would be 3000 pounds. This penalty cannot be tolerated in the context of a single STS launch. For this reason, only a solar-panel-based EPS is considered in the following.

### 6.2.2 Solar Array Area and Weight

Parametric solar array data are based on the use of 2-mil silicon cells embedded in a lightweight blanket. Solar array area is shown as a function of array output power in Figure 6-21, for four different orbits and for satellite lifetimes of 7 and 10 years. Differences in array area at similar power levels result from different levels of fluences (dose rates). For the 6-hour orbit, the lightweight blanket provides relatively little shielding; as a result, the array area is twice that required for either an 8-hour or a 12-hour orbit. Solar array performance is based on technology expected in 1994.

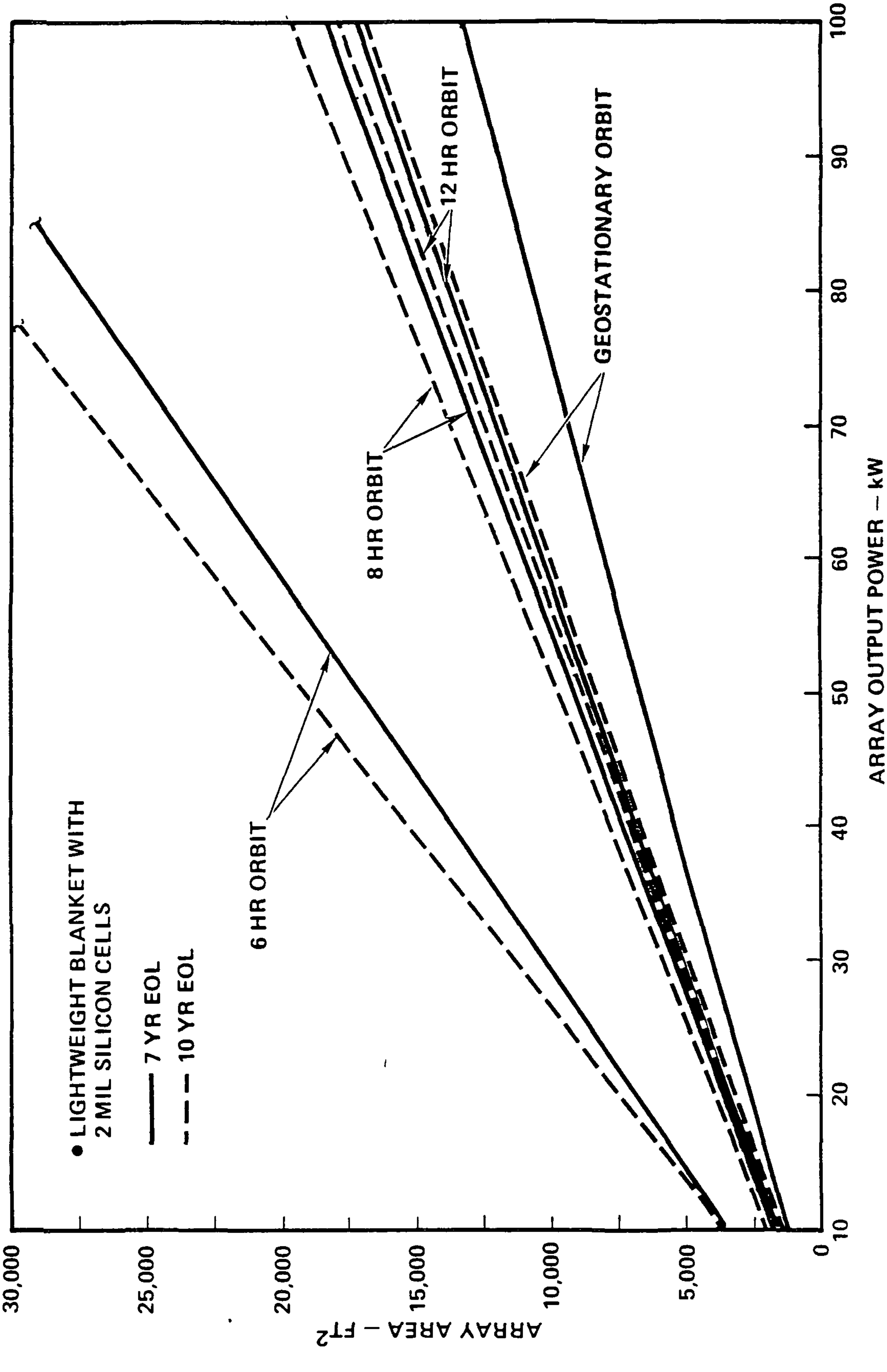



Figure 6-21. Solar Array Area

The specific end-of-life (EOL) performance assumed for each case is indicated below:

| Orbit | 7-Year EOL | 10-Year EOL |
|---|---|---|
| 6-hour | 3.0 $W/ft^2$ | 2.6 $W/ft^2$ |
| 8-hour | 5.6 $W/ft^2$ | 5.2 $W/ft^2$ |
| 12-hour | 5.8 $W/ft^2$ | 5.4 $W/ft^2$ |
| Geostationary | 7.0 $W/ft^2$ | 5.9 $W/ft^2$ |

The conversion coefficient of 0.084 $lb/ft^2$ relates solar array weight to solar array area. The array weight for the four orbits, for 7- and 10-year satellite lifetimes, are shown in Figure 6-22.

Radiation effects are significant not only for the 6-hour orbit, which is just above the radiation belt extending from 1000 to 5000 nmi, but also for a Molniya satellite, which passes completely through this belt. The area and weight of a solar array based on 2-mil silicon cells are shown in Figure 6-23. These curves fall between those of the 6-hour orbit in Figures 6-21 and 6-22 and those for 8-hour and 12-hour orbits.

An alternative to silicon solar cells is the use of concentrator arrays with GaAs cells. The latter technology is expected to be available in the early 1990s. GaAs cells provide considerably greater power per-unit-area at beginning of life. Furthermore, they are relatively impervious to radiation. Therefore, the EOL area requirements are considerably less than those for 2-mil silicon (see Figure 6-23). For this reason, the GaAs array would be considerably less costly. EOL performance for the two types of cells is given below.

| Solar Cell | 7-Year EOL | 10-Year EOL |
|---|---|---|
| 2-mil silicon | 4.7 $W/ft^2$ | 3.9 $W/ft^2$ |
| GaAs concentrator | 16.0 $W/ft^2$ | 15.7 $W/ft^2$ |

On the other hand, for a given output power level, a GaAs concentrator array is considerably heavier than a 2-mil silicon array (see Figure 6-23). Because STS weight limitations severely constrain the number of voice channels that can be supported by a single satellite, EPS weight estimates are based on the use of 2-mil silicon cells. Similar arguments can be applied to reject the use of GaAs concentrator arrays for the 6-hour circular orbit.

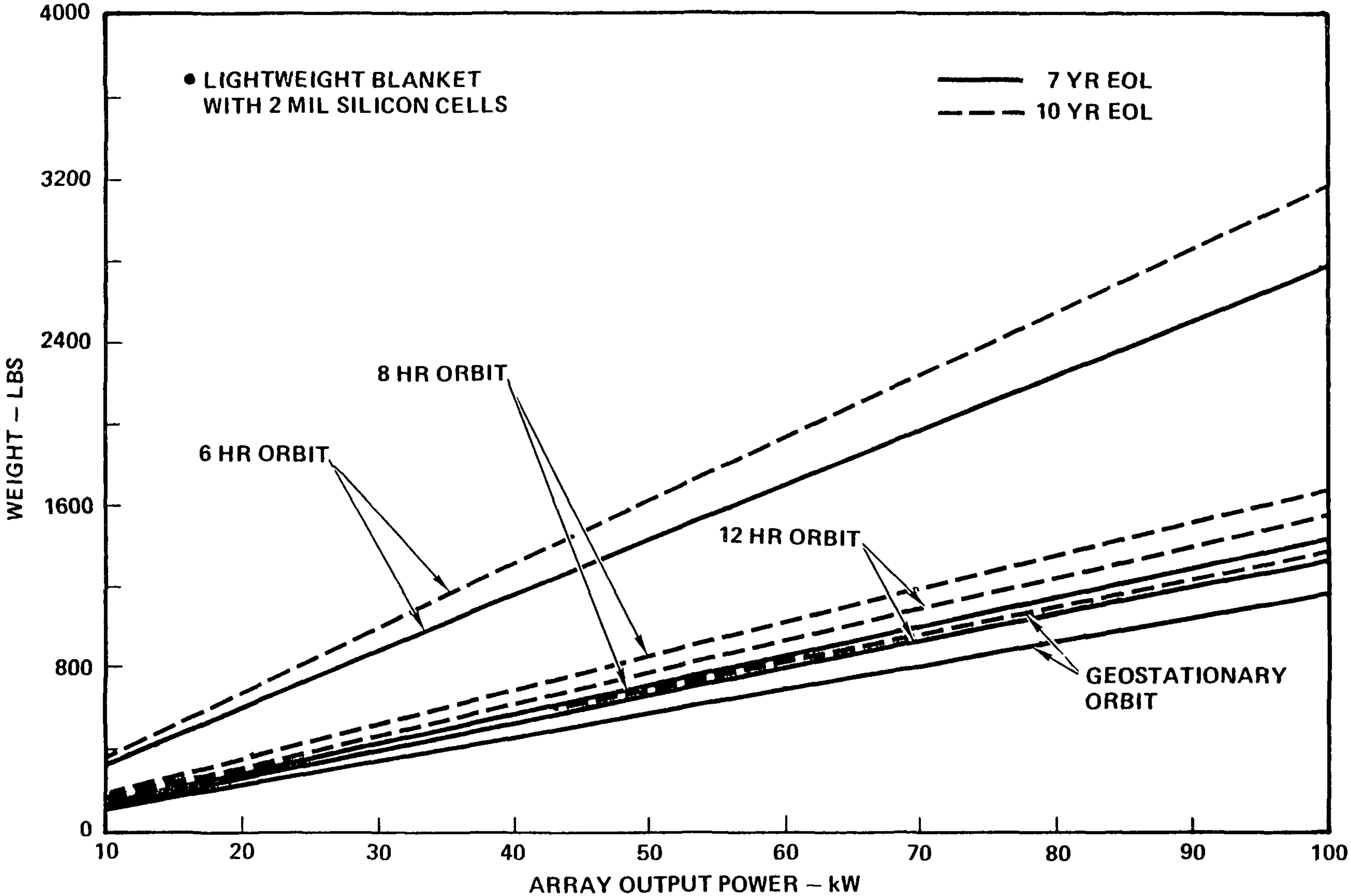



Figure 6-22. Solar Array Weight

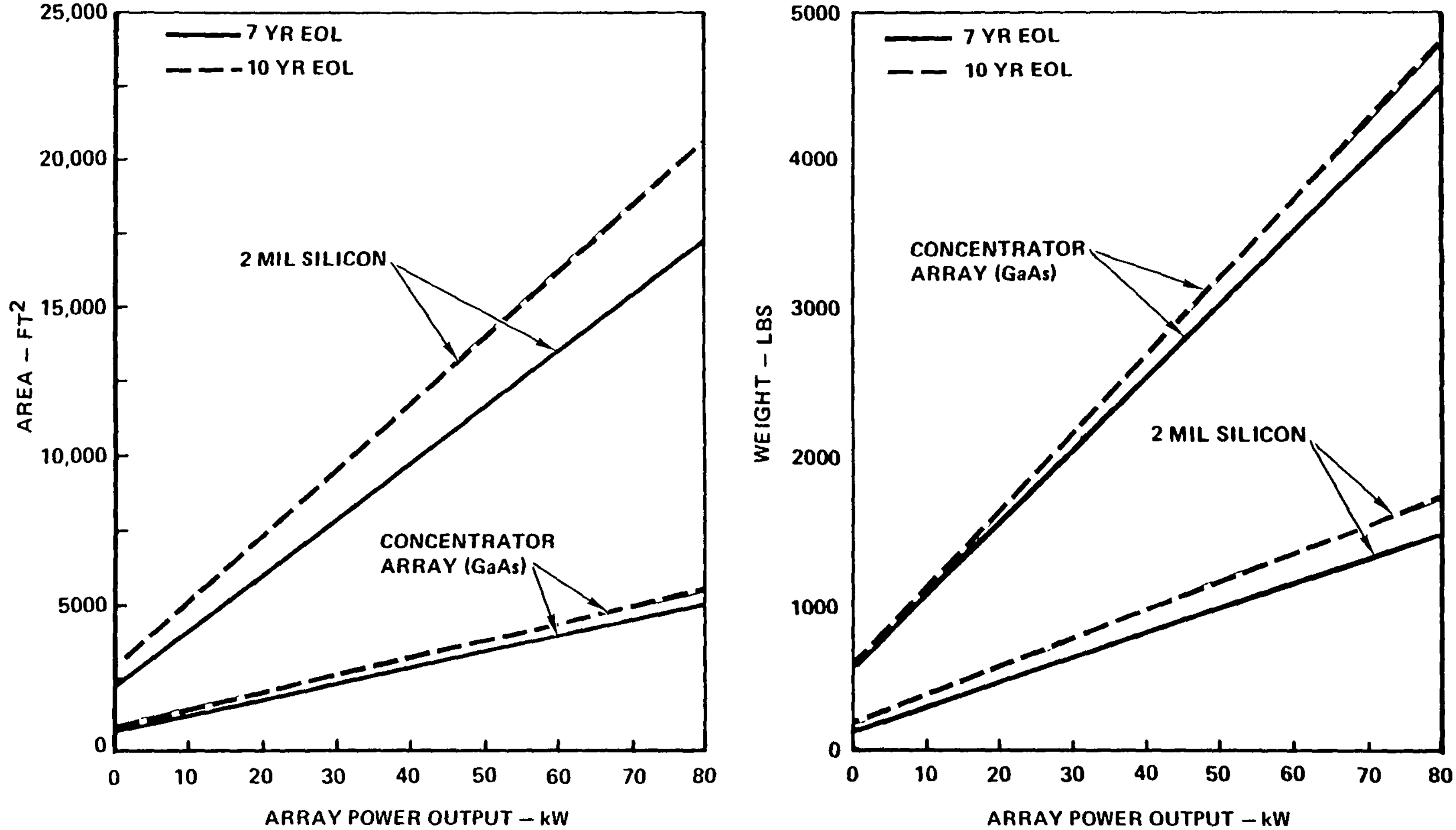



Figure 6-23. Solar Array Area and Weight for Molniya Orbit

### 6.2.3 Secondary Power Sources

Two different secondary power source technologies are expected, with high confidence, to be available in the 1990s: advanced $NiH_2$ batteries and RFC. A third candidate technology, that of high-energy-density rechargeable sodium-sulfur batteries, is in an earlier stage of development but gives promise of substantial weight reduction over the other two.

$NiH_2$ battery weight and volume is shown in Figure 6-24 as a function of load power for several orbits. Differences in battery weight result from different eclipse duration, together with differences in permissible depth of discharge. A geostationary satellite experiences a single eclipse per day (during eclipse season), a 12-hour satellite undergoes two eclipses per day, etc. Comparable battery lifetimes require that a smaller depth of discharge be associated with a greater eclipse frequency, and hence with an orbit of shorter period. On the other hand, satellites in higher orbit experience somewhat longer eclipse periods. The net effect of these two factors is that more battery capacity (i.e., greater weight) is required at lower orbits.

The RFC is an extension of technology presently planned for Space Station. Significant weight savings are expected over other secondary energy sources (e.g., the $NiH_2$ battery). However, because of the low thermal efficiency (50 to 55 percent) of the RFC, a larger radiator is required than is needed with secondary batteries.

RFC weight is shown in Figure 6-25 as a function of load power. Also shown is the required RFC capacity for geostationary and midaltitude (i.e., subsynchronous) orbits. The RFC capacity is proportional to eclipse duration. Because the specific energy density for the two orbit types is in roughly the same proportion as the eclipse periods, the RFC weight for a given load power is essentially independent of orbit. Therefore, only a single weight curve is shown.

Specific energy density ratings of 150 to 200 WH/kg for sodium sulfur batteries have been achieved in the laboratory on a cell basis. This is a factor of 2-1/2 to 3 times better than the advanced $NiH_2$ battery. It is expected that, by 1994, a complete battery will be developed to operate at a 100-percent depth of discharge with a specific energy density of 75 to

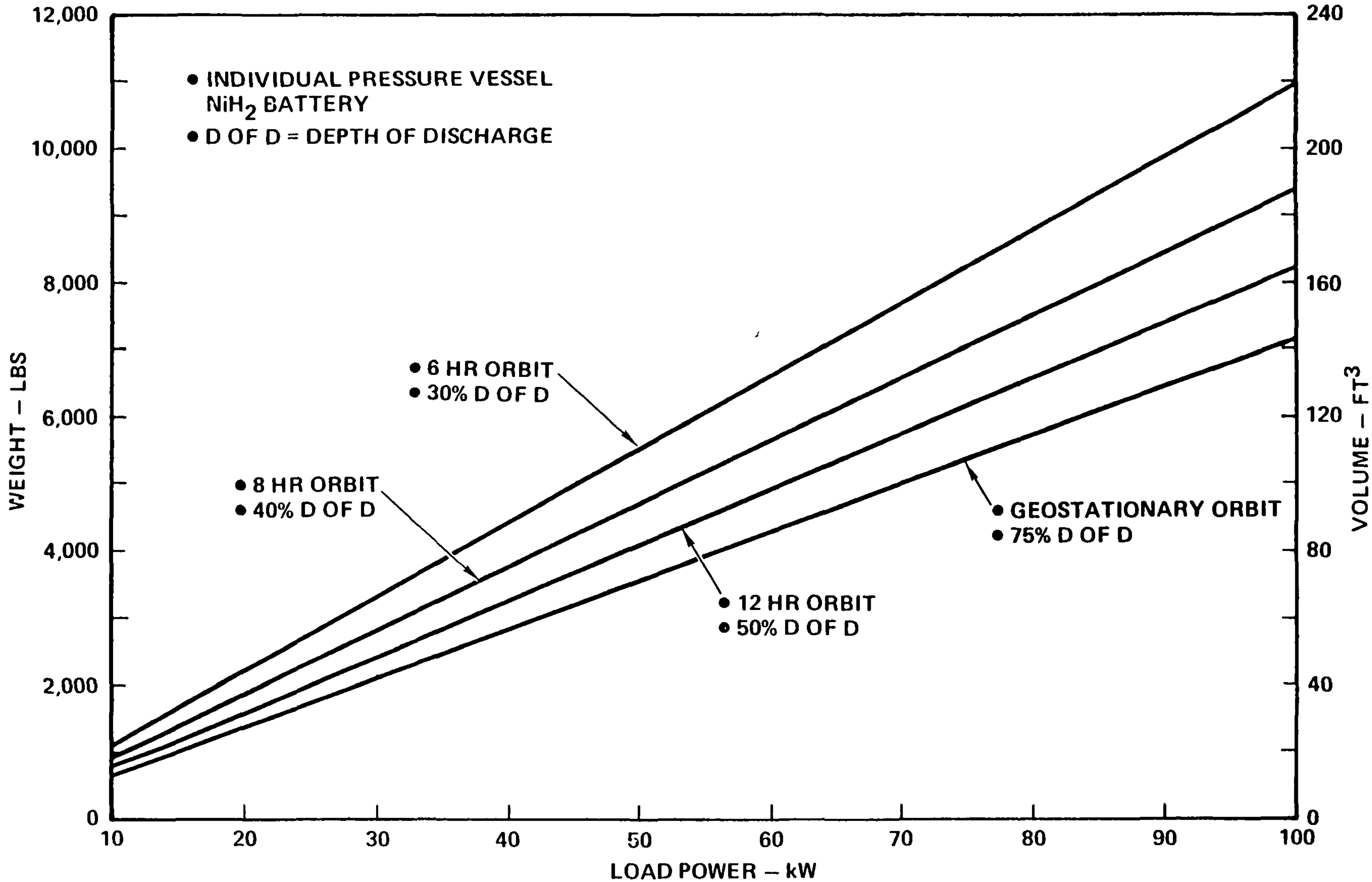



Figure 6-24. Nickel Hydrogen Battery Weight and Volume

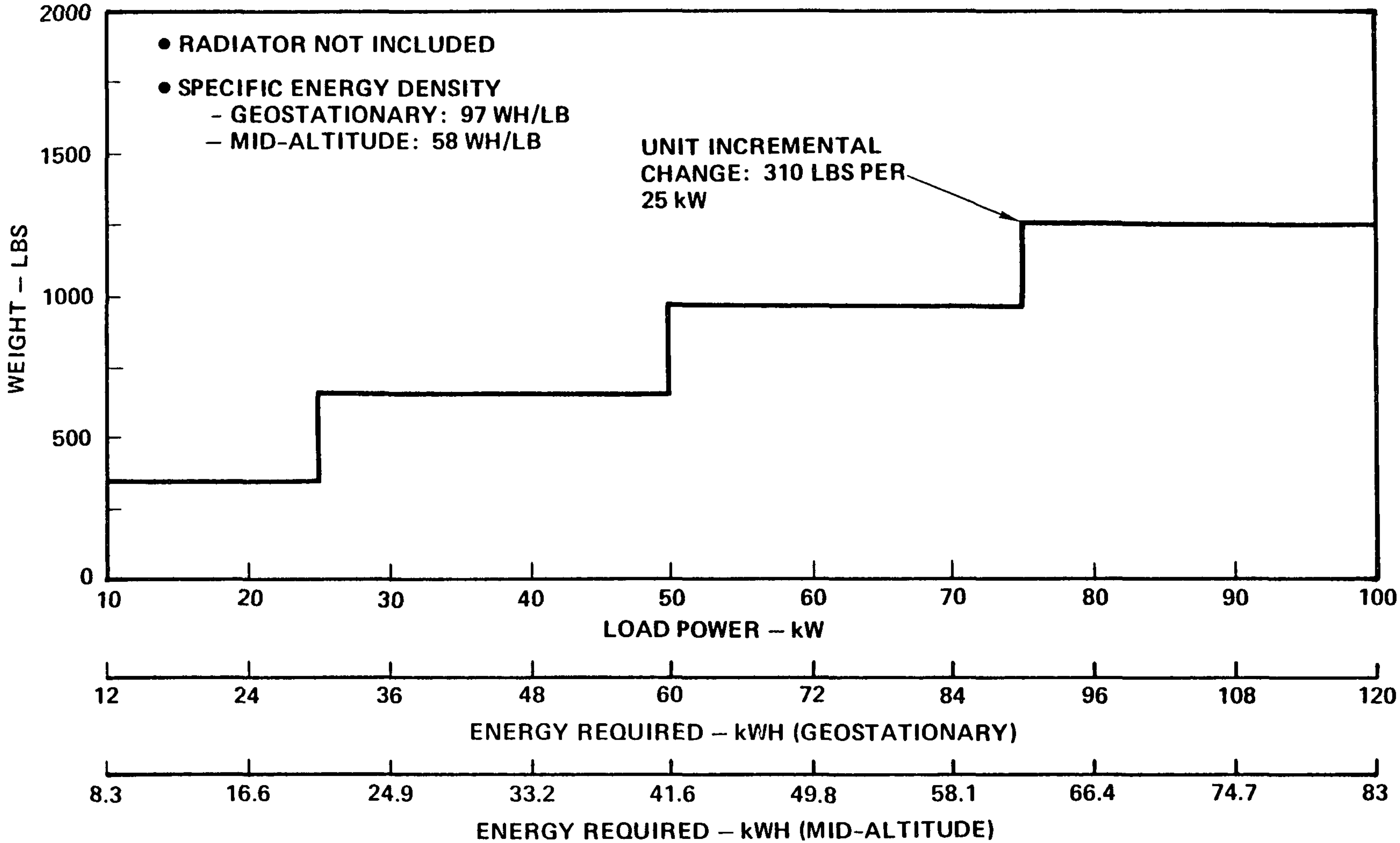



Figure 6-25. Lightweight Regenerative Fuel Cell System

80 WH/kg. Provided the required cycle life can be demonstrated, this type of battery would be very competitive on a weight basis with the RFC. Moreover, the thermal efficiency of the sodium sulfur battery is about 85 percent. It therefore requires a much smaller radiator for thermal control.

The projected weight of the sodium sulfur battery is shown as a function of load power in Figure 6-26. A conservative 75-percent value for depth of discharge has been assumed for all orbits. Because the depth of discharge is not orbit dependent, the required battery size and weight increase with eclipse duration. For this reason, battery weight is greatest at the highest altitude.

### 6.2.4 Electrical Power Subsystem Weight

The principal elements of the EPS, in the absence of eclipse operation, are: solar array, power control unit (PCU), cabling and harnesses within the spacecraft bus, and batteries for housekeeping purposes. (Weight of cabling between solar array and bus, which depends on the placement of the solar arrays, is not included). Solar array weight with 2-mil silicon cells has been given previously. The PCU weight in pounds is taken as 8.3 times the load power ($P_L$) in kilowatts. Cabling and harness weight is 145 + 3 $P_L$ pounds. Finally, the housekeeping power requirement is assumed to be 3 kilowatts. To maintain these functions during eclipse takes about 200 pounds of $NiH_2$ batteries. EPS weight is shown as a function of load power for the orbits of interest in Figure 6-27.

The weight of an EPS that does provide eclipse capability is shown in Figures 6-28 to 6-30 for the various secondary power sources. It should be emphasized that the weight associated with thermal control of the secondary power source is not included in these figures. The solar panels must now be sized to provide recharging power for the batteries between eclipses, in addition to providing the normal load power. Apart from the 6-hour orbit case, in which the solar panels suffer substantial radiation damage, EPS weight differences between orbits are attributable to the shallower depth of discharge and the shorter interval between eclipses associated with the orbits of shorter period.

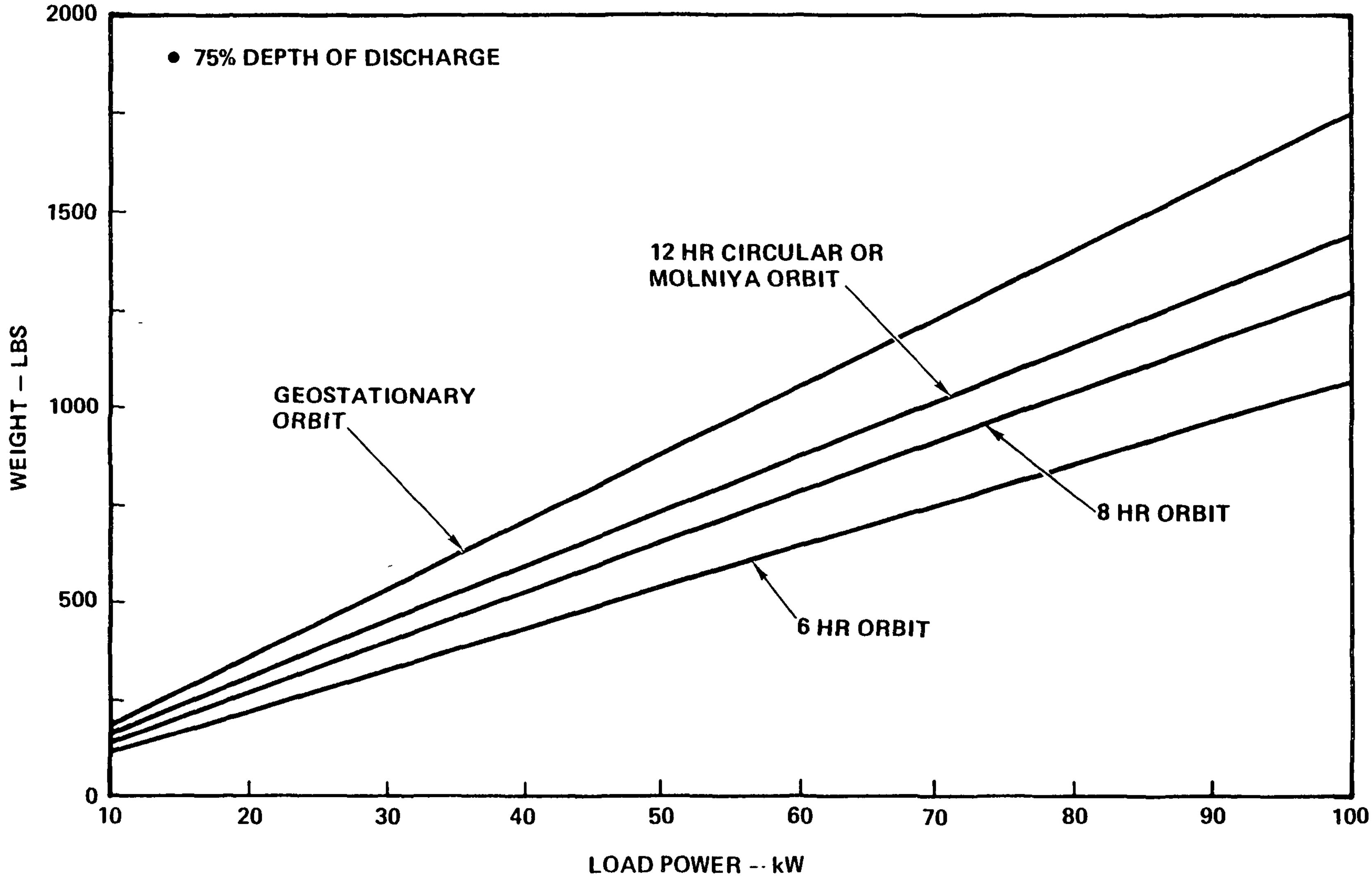



Figure 6-26. Sodium Sulfur Battery Weight

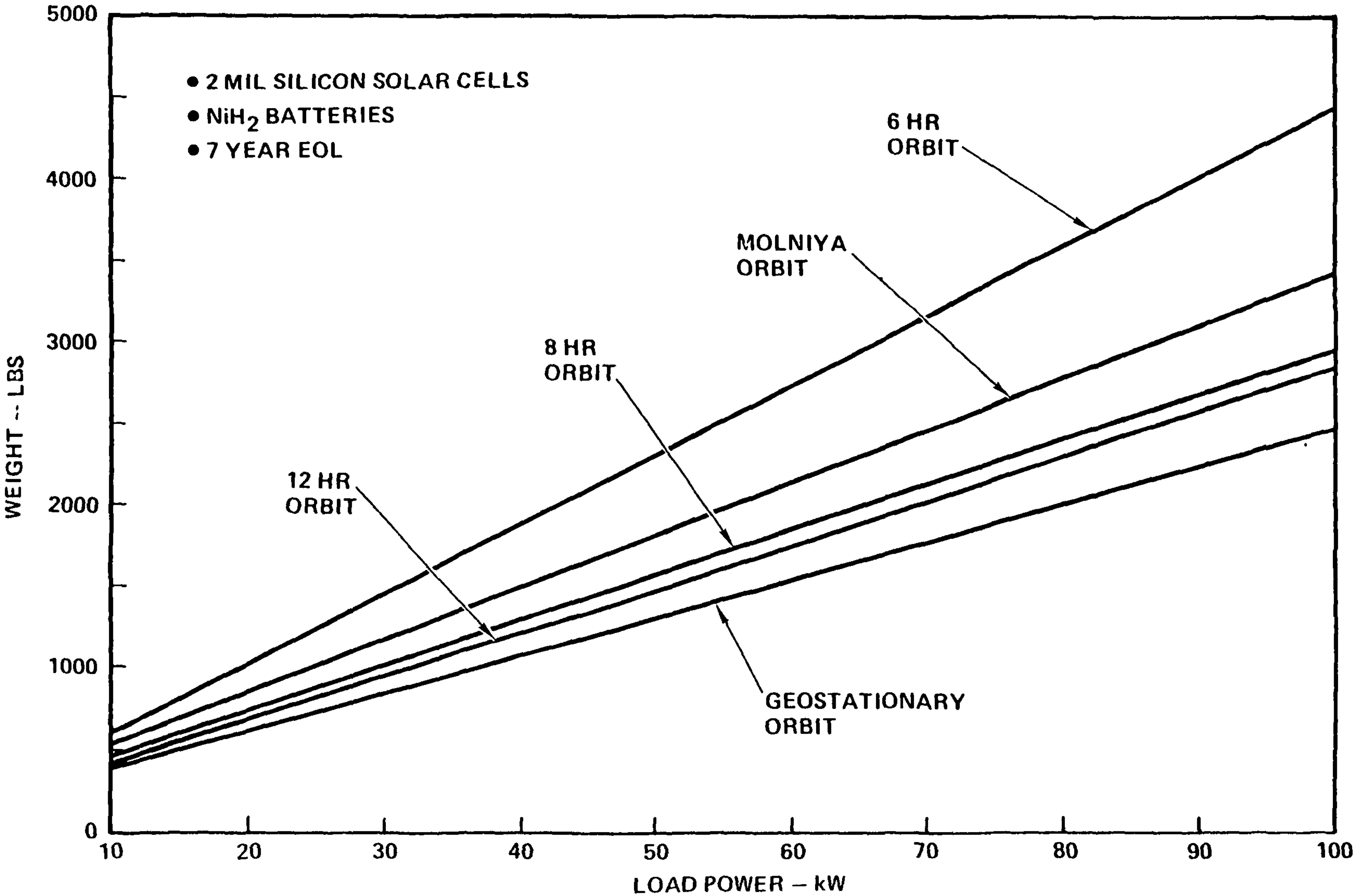



Figure 6-27. Electrical Power Subsystem Weight (No Eclipse Operation)

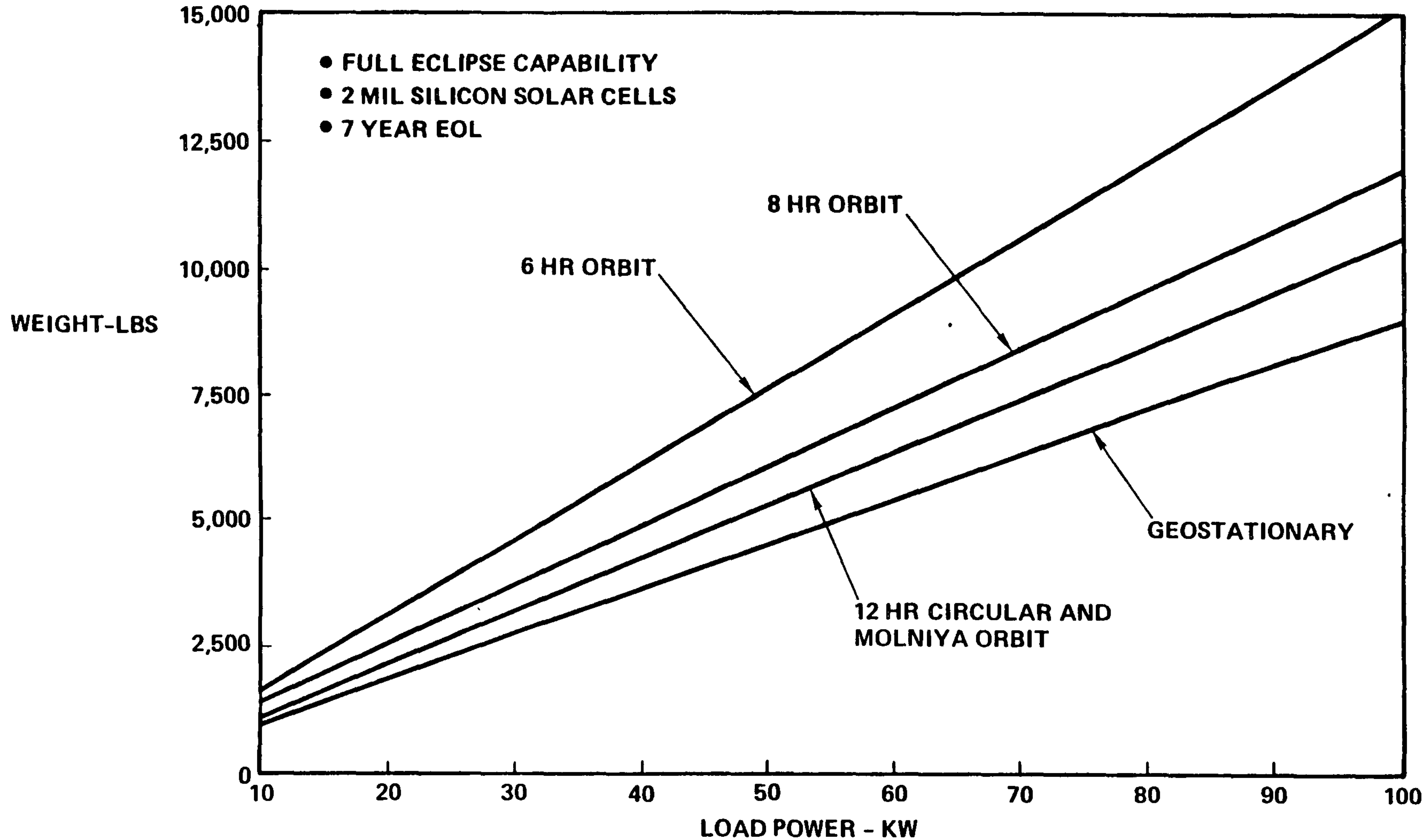



Figure 6-28. Electrical Power Subsystem Weight with $NiH_2$ Batteries

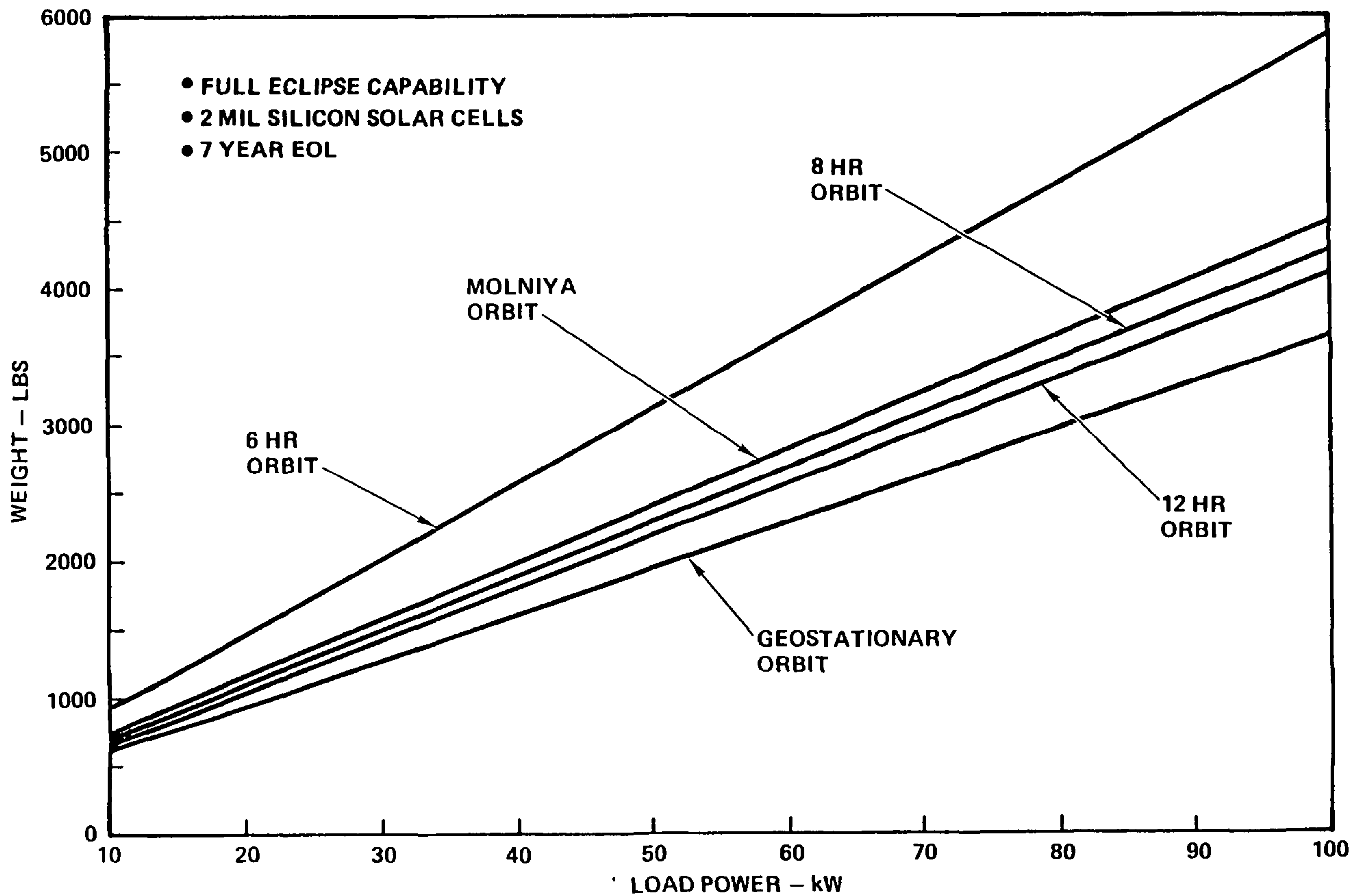



Figure 6-29. Electrical Power Subsystem Weight with Regenerative Fuel Cell

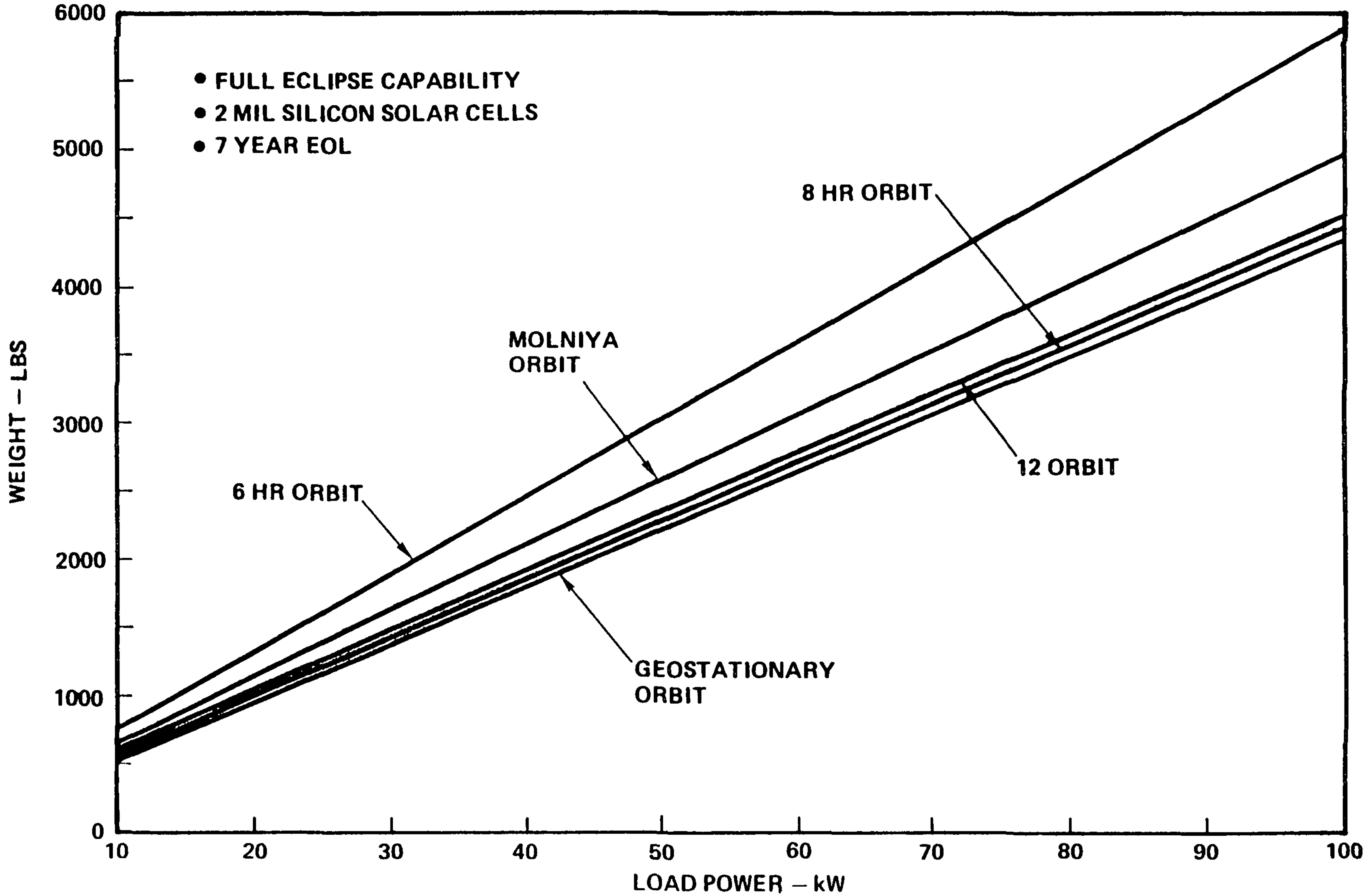



Figure 6-30. Electrical Power Subsystem Weight with High-Energy Density Batteries

The thermal efficiency of $NiH_2$ batteries is 85 percent. Therefore, the associated radiator weight is relatively small. However, as is evident from Figure 6-28, the weight of the batteries themselves makes them inappropriate as a power source for eclipse operation.

Based on a comparison of Figures 6-29 and 6-30, it would appear that the RFC is competitive, from a weight standpoint, with sodium sulfur batteries. This is not the case, however, because of the weight required for thermal control of the RFC.

The total weight attributable to an EPS designed for 60-kilowatt load power, for each of the secondary power sources and for three different orbits, is shown in Table 6-3. Also shown for comparison is the weight of an EPS that provides no eclipse capability. Provision of eclipse capability through the use of sodium sulfur batteries involves a weight penalty of about 1000 pounds. On the other hand, use of $NiH_2$ batteries or an RFC results in a prohibitive weight penalty.

All of the foregoing weight relationships are based on a steady (i.e., nonfluctuating) load power requirement. Because the transmitted carriers in Band 1 are amplitude modulated, the instantaneous power drawn by the transmitters fluctuates with changes in voice amplitude. The ratio of peak-to-average power associated with an individual channel depends on the modulation index. If a statistical criterion is applied to define peak power (e.g., a level exceeded no more than 5 percent of the time), the peak-to-average power ratio for the satellite as a whole decreases with the number of carriers transmitted simultaneously.

For purposes of illustration, 100-kilowatts average load power and 150-kilowatts peak power are considered in conjunction with an 8-hour circular orbit in Table 6-4. In a system designed for broadcast during eclipse, any of the three storage devices can provide the necessary power surges without additional capacity. When no eclipse capability is provided, however, extra solar panels must be included. From a weight standpoint, only "no eclipse" and sodium sulfur battery systems are competitive. The weight penalty associated with eclipse capability is again seen to be 1000 pounds, in this case for 100-kilowatts load power.

Table 6-3. EPS Weight Comparison for Different Secondary Storage Devices

- **Load Power = 60 kW**
- **EPS Weight Includes**
  - Solar Array
  - Storage Device Plus Thermal Control
  - Power Control Plus Cabling Within Spacecraft

| | Satellite Orbit | | | |
|---|---|---|---|---|
| **Storage Device** | **Geosynchronous** | **Molniya** | **8-Hr Circular** | |
| **$NiH_2$** | 6620 lb | 7800 lb | 8220 lb | Full Eclipse Capability |
| **RFC** | 5690 lb | 6290 lb | 6100 lb | Full Eclipse Capability |
| **Sodium Sulfur** | 2910 lb | 3210 lb | 2900 lb | Full Eclipse Capability |
| | 1720 lb | 2080 lb | 1800 lb | No Eclipse Capability |

Table 6-4. Accommodation of Power Fluctuations in Frequency Band 1

- **Instantaneous Power Requirements Fluctuate with Amplitude Modulation**
- **Example**
  - 8 Hour Circular Orbit
  - 100 kW Average Load Power
  - 50 Percent Peak-to-Average Power Ratio
- **Total Weight Attributable to Electrical Power Subsystem**

| Case | Without Power Fluctuations | With Power Fluctuations | Difference Attributable to |
|---|---|---|---|
| No Eclipse Capability | 2900 lb | 3710 lb | Added Solar Cells |
| Eclipse Capability with RFC | 10,080 lb | 10,080 lb | – |
| Eclipse Capability with Sodium Sulfur Batteries | 4730 lb | 4730 lb | – |
| Eclipse Capability with $NiH_2$ Batteries | 13,610 lb | 13,610 lb | – |

## 6.3 TRANSPONDER TECHNOLOGY

Principal transponder design considerations include reliability, weight, and power conversion efficiency.

Higher reliability can generally be achieved through use of solid-state devices, rather than TWTs. Reliability is also enhanced by the introduction of active, rather than standby, redundancy. However, this involves fully powering the redundant unit; if there is M for N redundancy, power consumption is increased by the factor M/N. Standby redundancy minimizes power consumption, but introduces switching complexity.

Power efficiency is always reduced by the requirement to combine the outputs of individual amplifiers. It is desirable, therefore, to match wherever possible the output of a single device to the transmitter requirement. If the power required per carrier or for multiple carriers that must be transmitted through a common amplifier exceeds the single device capability, high-efficiency multiple-port power and channel combiners should be used.

Power combiners at Band 1 and 2 frequencies tend to be rather heavy, in addition to resulting in loss of transmitter efficiency. Their use should therefore be minimized from this standpoint as well. Transponder weight is further minimized by the use of high-frequency feeder links and VLSI in the receiver, modulator, and exciter stages.

Band 1 is unique in that the frequency-modulated feeder-link signals must be demodulated prior to amplitude modulation of the broadcast carrier (Figure 6-31). If multiple carriers per beam are required, they are amplified by separate exciter amplifiers to a level of about 10 watts, and then filtered and gain equalized prior to power amplification. On the other hand, if the power available from a single amplifier stage is less than that required for an individual channel, multiple power amplifier outputs have to be combined prior to exciting the appropriate antenna feed element.

### 6.3.1 Power Amplifier Requirements

Projections of power amplifier technology can be assessed only by reference to power amplifier requirements. These requirements are related to the per-channel-beam RF power requirements. In Band 1, the required RF power per channel-beam exceeds 10 kilowatts for both the geostationary and

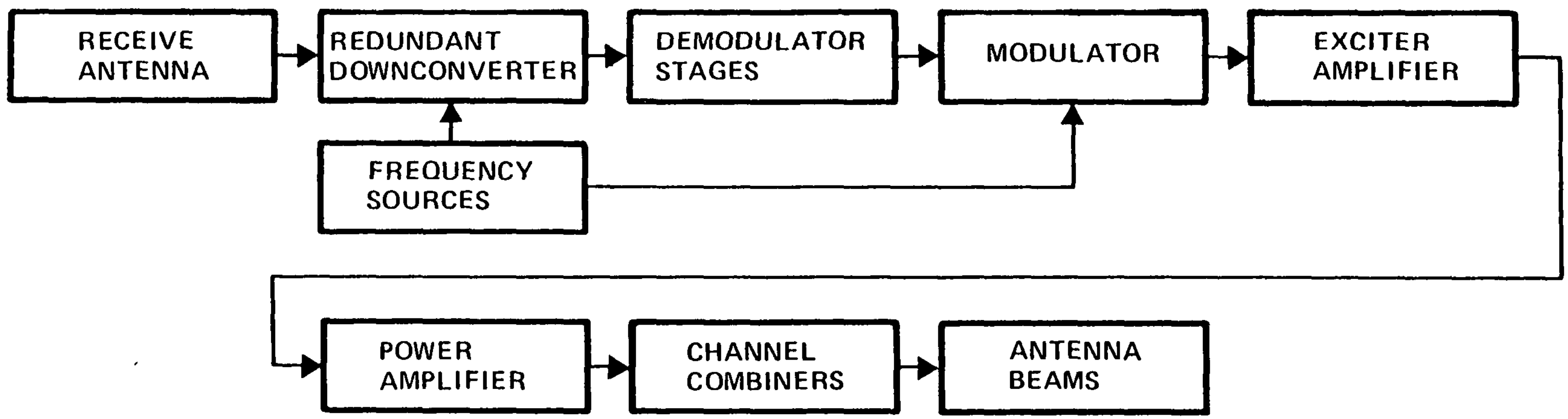



Figure 6-31. Simplified Transponder Block Diagram for Band 1

8-hour orbits. In Band 2, it exceeds 5 kilowatts for the Molniya orbit. The required power amplifier rating also depends on (1) whether the satellite antenna is of the reflector or phased-array type, and (2) the number of carriers transmitted through each feed element and, consequently, supported by each power amplifier.

For a geostationary satellite, which has a reflector antenna, it may safely be assumed that there is but one carrier per feed element, because of the low satellite capacity. (A given broadcast zone can be provided with multiple channels through the transmissions of separate satellites.) Therefore, the amplifier rating must exceed 10 kilowatts.

For the Band 2 Molniya system, a single satellite accounts for all transmissions. With the exception of two half-hour periods in Zone 9, the broadcast schedule calls for no more than two voice channels per zone. Therefore, the amplifier rating must be about 10 kilowatts.

The satellites in the 8-hour-orbit system are equipped with a phased-array antenna having 64 elements. The baseline system satellites have a capacity of six channel-beams. If it is assumed that no element radiates more than twice the average power per element, the amplifiers must have a rating on the order of 2 kilowatts. Thus, the phased array leads to a significant reduction in the individual transmitter power requirements.

### 6.3.2 Power Amplifier Projections

Toshiba currently markets a 5-kilowatt AM broadcast transmitter for use at Band 1 frequencies. These transmitters incorporate MOSFETs because of their wide operating range, high gain, and high efficiency. The power amplifier is based on 120-watt devices, which are first combined into a 600-watt amplifier, then into 3000-watt amplifiers, and finally into a 5.5-kilowatt amplifier. The 120-watt device was developed using VLSI technology with a channel length of 2 microns. With multiple gates, an effective channel width of 22 centimeters, equivalent to 10,000 transistors, is achieved.

VLSI technology projections, referenced to this 1982 development, make it reasonable to anticipate an equivalence of several hundred thousand transistors and therefore a 2500-watt device, provided there is appropriate motivation for enhanced technology development. Correspondingly, power amplifier projections of 10 kilowatts or more, based on MOSFETs with VLSI technology, are not unreasonable.

Although the efficiency of an individual power amplifying transistor is more than 90 percent, power regulation and conversion losses, together with combining inefficiencies, reduce the overall efficiency to between 65 and 75 percent. As shown in Figure 6-32, achieving this level of efficiency depends on selection of an appropriate device power level.

Band 2 power amplifier projections are similar to those for Band 1. Power levels up to 3 kilowatts are currently achieved using MOSFETs. Projections in this band also exceed 10 kilowatts.

Solid-state amplifiers are in use today at 2.2 gigahertz, which is slightly above Band 3. In these amplifiers, the outputs of several 10-watt bipolar transistors are combined. Bipolar transistors are significantly less efficient than MOSFETs, but production versions of the latter have been operated only to 250 megahertz. Use of MOSFETs in Band 3 will require technology enhancement and motivation to develop transistors with channel lengths less than 0.4 micron. Based on the 10-watt range available today in power transistors, 150 watts is a likely limit for the 1990s. This value is consistent with the Band 3 baseline system requirements.

MOSFETs for use in Band 3 are capable of 90-percent efficiency. If lower efficiency can be accepted, TWTs may be used instead. Typical TWT efficiency is 50 percent. Output power levels of 450 watts are achievable with TWTs today, while projections extend beyond 1 kilowatt.

### 6.3.3 Transponder Weight

The transponder weight is dominated by the weight of the exciter/power amplifier. The amplifier weight was calculated by assuming a typical structure and heat sink weight equal to 33 percent of the total weight of the exciter/power amplifier. The structural, heat sink, and electronic board/carrier weight was scaled, assuming that technology enhancement would permit increased output power without significant increase of electronic piece-part count. Weight calculations include an allowance for redundant elements and switching devices, as well as for voltage converters and voltage regulators.

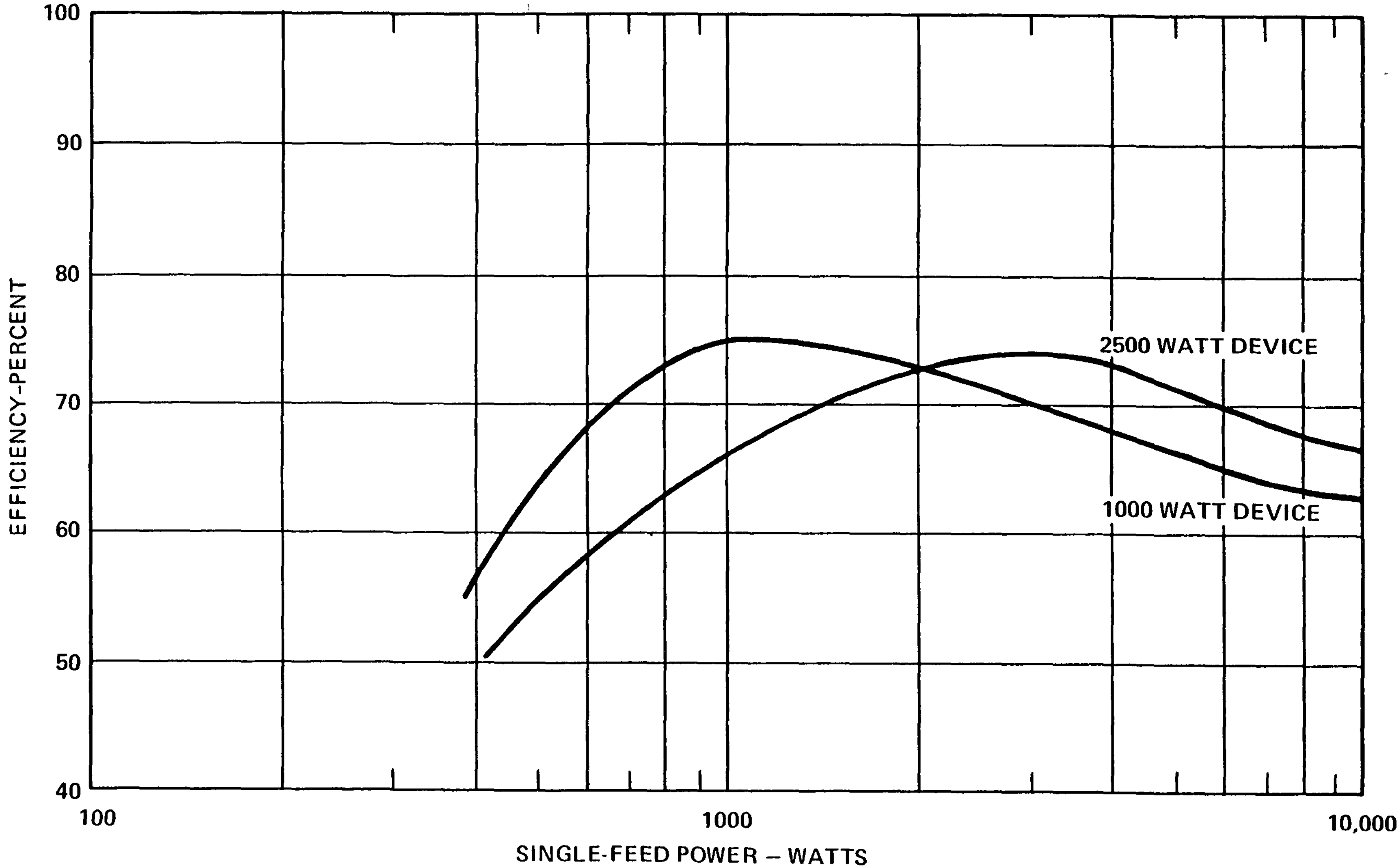



Figure 6-32. Transponder Efficiency for Band 1

Band 1 and 2 amplifier weights are similar, for the same required output power (Figure 6-33). For high reliability, it is assumed that derated components will be used in both cases. Accordingly, the peak power requirements for the amplitude modulated signals in Band 1 should be satisfied by an amplifier whose weight is a function of the average power requirement.

Although the per-transmitter power requirements are different for the geostationary and 8-hour systems in Band 1, the power per-channel-beam is about the same. Because the curve of weight versus output power is linear and directed toward the origin, the transmitter weight per-channel-beam is also the same. Therefore, the single curve in Figure 6-33 is appropriate for both the reflector and the phased-array configurations. If the abscissa in each case is regarded as the total satellite RF power, the ordinate is the weight of the total transmitter complement.

Band 3 weight and power (Figure 6-34) are derived from TRW fabricated S-band transponder data. However, availability of a 150-watt transistor with 90-percent efficiency was assumed rather than the 40-percent-efficient bipolar device in the S-band transponder.

Low-power transponder weight is dominated by receiver and redundant (two-for-one) amplifier weight. High-power transponder weight is affected by combining losses, while redundancy is decreased to five-for-four.

Low-power transponder input power is significantly affected by receiver and exciter amplifier power consumption, while high-power transponder input power shows the effects of combining losses.

### 6.3.4 Power or Channel Combining

Carrier combining may be necessary for either of two reasons:

1) For multichannel broadcasting to a given region

2) To achieve the required individual-channel power level.

A certain amount of loss is unavoidable in carrier combining. Therefore, high-power combining should be avoided whenever possible. This requires matching the output level of the power devices used to the required feed power. Because of the lower power levels required with a phased array than with a reflector antenna, a lesser degree of power combining is needed with former.

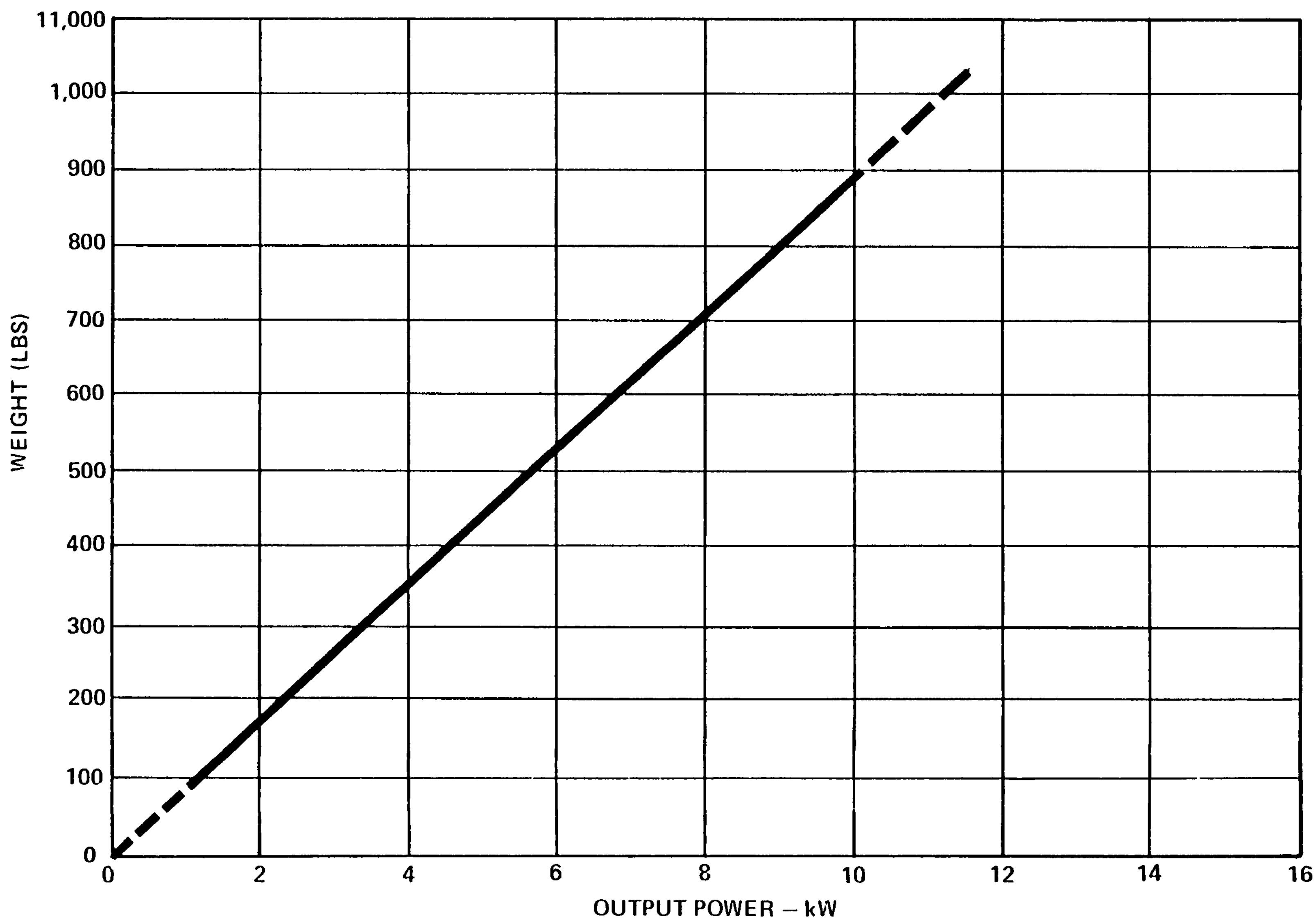



Figure 6-33. Transponder Weight for Bands 1 and 2

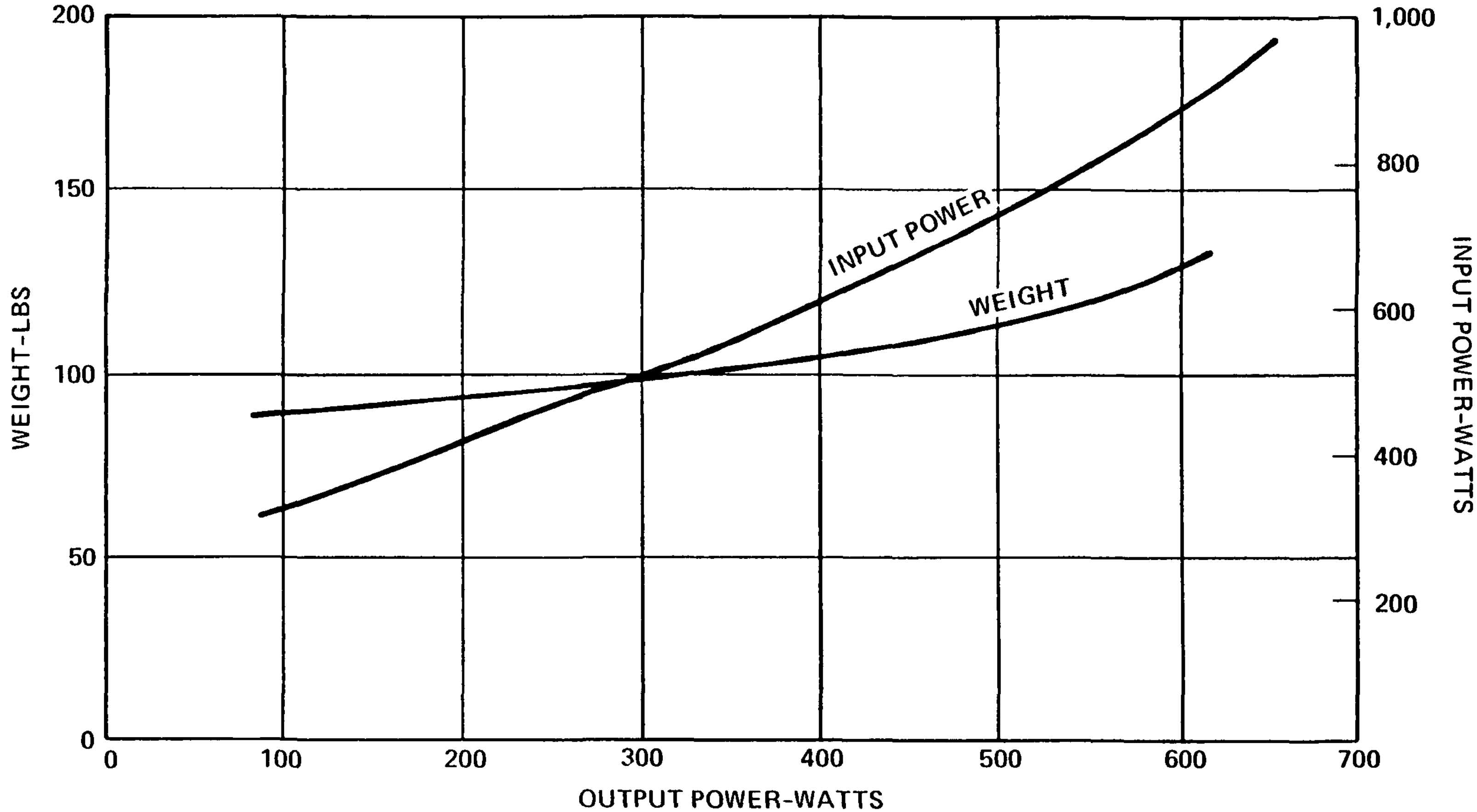



Figure 6-34. Transponder Characteristics for Band 3

In Bands 1 and 2, carrier combining can be performed by either a hybrid transformer or a Wilkinson circuit equivalent L-C combiner. The former provides a wider bandwidth, but is more lossy. Bandwidths of 10 to 15 percent can be achieved. The combining loss is about 5 percent per combining stage.

In Band 3, a slabline combiner is preferred. This is a higher frequency, distributed-circuit-element equivalent of lumped circuit combiners planned for lower frequency bands. The combining loss is approximately 3 percent per combining stage. N-way combiners ($N > 8$) with bandwidths as high as 20 percent have been developed by both Stanford and TRW. Recent TRW breakthroughs have achieved very high efficiencies with a large number of ports. The inputs are self-isolating.

For efficient combining, the gain and phase length of modules must be identical. If channel combining is attempted at the amplifier inputs to reduce high-power conversion losses, some inefficiencies will still result because of inclusion of unwanted intermodulation products and losses resulting from the difficulty in keeping gain and phase uniform.

# 7. PLANNING SUPPORT

The project planning activity described in this section has four parts. In Section 7.1, the critical technology items needed for development of one or more baseline system satellites are identified. A schedule for each baseline system, together with a "spreading" of LCC over the 20-year project span, is developed in Section 7.2. Cost and schedule risk for critical technology items are presented in Section 7.3. Finally, satellite nonrecurring and first-unit cost and schedule risk are found in Section 7.4.

## 7.1 CRITICAL TECHNOLOGY

Critical technology items for each baseline system are defined as those subsystems, or portions thereof, where the uncertainty in performance is sufficient to justify an R&D effort to produce test models. The only technology that might be considered critical for the Band 3 system is that of the high-power transmitters. However, alternatives for the baseline MOSFET amplifier selection exist which would result in some loss of performance, but would not invalidate the system concept.

In Bands 1 and 2, the subsystems containing critical technology are:

- o Antenna — cable-catenary and phased-array
- o Electrical power — solar array and power distribution
- o Transponder — high-power transmitter
- o Thermal control.

In addition, the technology involved in the attitude control subsystem perhaps should be labeled critical.

### 7.1.1 Large Deployable Antenna Technology

The three baseline systems intended for Band 1 or 2 operation require extremely large antenna apertures. These range from 80 meters for the 8-hour-orbit, Band 1 phased array to the 267-meter cable catenary for the Band 1 geostationary system. By contrast, the largest known antenna yet deployed in space, on the ATS-6, is 10 meters in diameter.

Current NASA-directed, large-space-structure technology efforts include:

- 15-meter antenna ground-test models
- Large antenna conceptual studies
- Space Station assembly conceptual studies.

Antenna development has been confined to parabolic reflector concepts such as the LMSC wrap-rib and the Harris hoop-column. These configurations are applicable only for diameters up to 100 meters or so. There is no NASA funding at present for development of large phased-array antennas.

The main technology issues surrounding development of a large cable-catenary type of antenna are identified in Table 7-1. All are related to the size of the antenna and its inability to withstand even a fraction of the earth's gravity. Several of these issues will be addressed in greater detail to demonstrate the nature of the technological problems involved.

A parabolic antenna spanning (say) 120 meters will have a depth of about 50 meters. A building must be found in which to assemble such an antenna. Since the antenna cannot support its own weight, an extensive support system is required. Air currents and thermal gradients must be minimized.

Additionally, a way must be found to deal with the very fine mesh. Once the antenna is assembled, retraction for storage must be resolved. When verification and testing are considered, the magnitude of the problem becomes apparent.

On the other hand, assembly of (say, 1/8 pie) segments can take place on the ground, followed by full assembly on Space Station. This procedure minimizes the size structure that must be dealt with on the ground, but it poses several different problems. Joining the segments in space may require new antenna techniques. Astronaut handling of lightweight mesh and complex cabling raises safety and feasibility questions.

Moreover, the system is still not testable on the ground. Inability to perform ground tests requires development of analytical and verification methods to qualify the system.

Table 7-1. Large-Antenna Technology Issues

**Principal Issue: Development of Large Zero-g System in 1g Environment**

- Design and Analysis — Lack of Test Data or Comparable Structures
- Assembly — Size and Strength Preclude Use of Any Present Methodology
- Test — Untestable as a Unit on the Ground
  — Component Tests in 1g Very Questionable
- Mesh Management — Ability to Handle Lightweight Mesh in the Size Required
- Dynamic Response — Structural Flexibility Poses Severe Control Problem
- Deployment — Ability to Deploy Masts and Mesh Without Hang-Ups or Damage
- Space Station Impact — Largely Unknown – Is Space-Aided Assembly a Feasible Alternative?

For a selected satellite orbit, the phased-array antenna is somewhat smaller than the parabolic antenna. More importantly, it is flat and is constructed of squares. Nevertheless, most of the technology issues identified in Table 7-1 apply, although in lesser degree, to this configuration as well.

A logical structure for the required technology development is shown in Figure 7-1. A corresponding schedule is given in Figure 7-2. Parallel antenna technology and system conceptual studies constitute the first step. These studies interact and result in realistic system requirements and definition of key technology issues.

In-depth studies are then required to address key issues in the areas of analysis, design, assembly, and integration. Critical elements must be tested before proceeding further. Full technology development, leading to flight-configured concepts, can then follow.

### 7.1.2 Electrical Power Subsystem

#### Solar Panels

The Band 1 and 2 baseline systems have extremely large power requirements. The Band 1 geostationary satellites require a solar panel output of 68 kilowatts (for two channel-beams); the Band 1 8-hour satellites, 160 kilowatts (for six channel-beams); and the Band 2 Molniya satellites, 95 kilowatts (for 12 channel-beams).

The satellite weight estimates in this report are based on the development of 2-mil silicon solar cells. This is a reasonable assumption for the 1990s. However, the cells presently under development measure 2 by 4 centimeters. For power production in the multiple tens of kilowatts, large cells are required for reasons of economy. A 3 by 6 centimeter silicon cell is expected to be developed for Space Station. However, these cells will have a thickness of 8 mils, since solar panel weight is not as critical for this application. There is no anticipated program that will make use of 2-mil, 3 by 6 centimeter silicon cells.

The period required for development of such a cell depends on the number of thermal cycles the satellite undergoes during its lifetime. For the orbits of interest here, a 2- to 3-year development period is projected. The cost of such a development would be about $500,000.

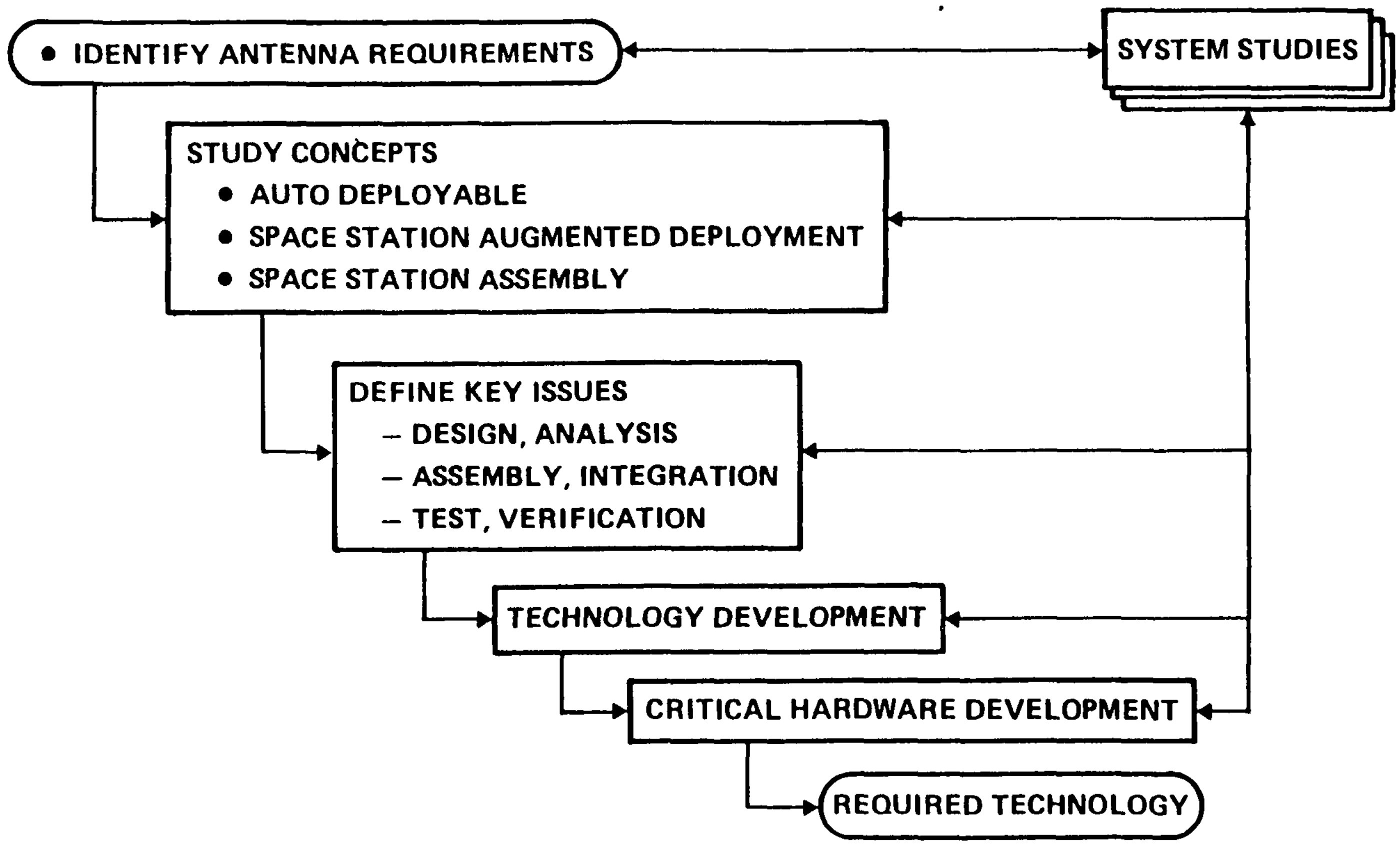



Figure 7-1. Large-Antenna Technology Development Logic

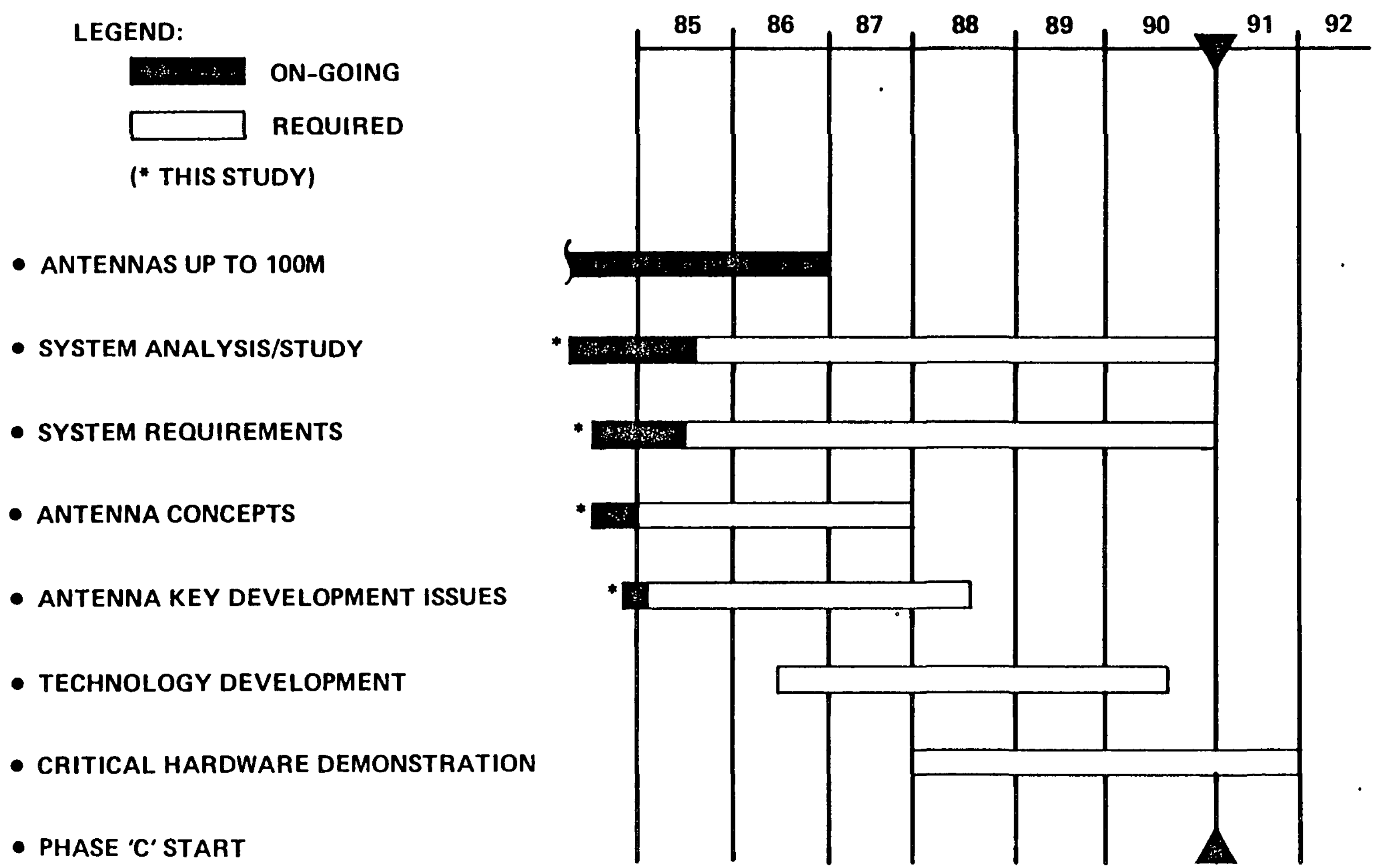



Figure 7-2. Large-Antenna Technology Development Plan

In addition to development of solar cells, a "blanket" mechanism is needed for deployment of the solar arrays. It is expected that the Jet Propulsion Laboratory will issue an RFP in 1985 for development of a high-performance, 2-mil lightweight blanket. (In all likelihood, the individual cells will measure 2 by 4 centimeters.)

Electrical Power Distribution

Because of the physical dimensions of the baseline satellite designs for Bands 1 and 2 and the extremely large transmitter power requirements, the weight of the distribution cabling can be very significant. The weight of copper wiring required to transfer several tens of kilowatts, first within the solar array, then to the spacecraft bus, and finally to the payload would be prohibitive, especially at the current 30-volt bus technology. Consequently, aluminum wiring and a higher distribution voltage have both been incorporated in the baseline satellite designs.

Aluminum wiring, because of its low density, is required to minimize cabling weight. This technology exists for fixed bus configurations. However, as currently available, aluminum is not sufficiently flexible to serve as cabling in a configuration in which the solar panels and elements of the payload are folded prior to launch. New techniques (e.g., coating, winding, or flat cabling) are needed if the satellite designs are to benefit from the low weight of aluminum cabling.

Cabling weight is also strongly dependent on the distribution voltage. A 200-volt distribution system is assumed for the Band 1 and 2 satellite designs. A range of 100 to 200 volts is being considered for the Space Station distribution system. If the higher voltage should be selected, it may be assumed that the needed technology will be available for the present application. If, instead, a 100-volt distribution system should be developed for Space Station, a higher voltage system would be required to avoid a substantial distribution system weight penalty.

### 7.1.3 High-Power Transmitters

Individual power amplifier requirements exceed 10 kilowatts for the Band 1 geostationary system and the Band 2 Molniya system, and are about 2 kilowatts for the Band 1 8-hour system. The Band 3 baseline system requires 210 watts per amplifier. The high reliability of MOSFET devices makes them the preferred power amplifier technology, provided the indicated power levels can be achieved.

The emphasis of the Japanese government on solid-state devices for commercial broadcasting indicates that MOSFET development will continue to be pursued for the broadcast bands. Frequency extension for mobile communication and wideband FM broadcasting would be the next logical steps in commercial development. The higher reliability exhibited by these devices accounts for the continuing Japanese transition to solid-state transmitters, although their cost in 1984 was triple that of comparable tube transmitters.

Interest in commercial broadcast transmitters extends from 1 to at least 25 kilowatts. VLSIC and VHSIC technologies are heading toward the equivalent of several millions of transistors on a single chip. As these technologies advance, they will provide the techniques for developing MOSFETs with 10 to 20 times the power handling capability of those in use today.

It is therefore expected that commercial requirements will propel MOSFET development to the power levels needed for Bands 1 and 2. The remaining task of space qualifying these high-power, highly efficient MOSFETs is estimated to require $1,000,000 of advanced development effort. It is also anticipated that, prior to space qualification, three or four man-months per year will be needed to maintain familiarity with progress in commercial MOSFET development.

The evolutionary expectations for solid-state devices usable in Bands 1 and 2 are overly optimistic for Band 3. There is no apparent commercial impetus for development of MOSFETs or other devices more efficient than current bipolar transistors. Unless the low (30 percent) efficiency of these transistors or the lower reliability of TWTs is acceptable, technology enhancement will be necessary. It is estimated that $4,000,000 would be required to develop and space qualify an efficient solid-state device for 100-watt operation at 1.5 gigahertz.

### 7.1.4 Thermal Control

Transmitter RF power requirements exceed 10 kilowatts per channel-beam in Band 1 and are about 5 kilowatts in Band 2. Even with high efficiency transmitters, power dissipation due to dc/RF conversion loss will exceed 5 kilowatts per channel-beam in Band 1 and 2.5 kilowatts in Band 2. Total dissipation is obtained by multiplying these values by the maximum number of channel-beams transmitted, which is two for the geostationary Band 1 system, six for the 8-hour Band 1 system, and ten for the Molniya Band 2 system.

Present trends in thermal control technology are dominated by Space Station, a system that can be maintained by astronauts. Therefore, active high-efficiency systems (i.e., heat pumps) can be considered for large heat rejection. Broadcast satellites, on the other hand, presumably should be designed to survive without repair, thus making active systems less appealing. Consequently, despite the weight saving afforded by an active system, a passive thermal control system has been assumed.

To keep the weight of the thermal control subsystem manageable, a sizable advance over present, passive radiator technology has been assumed. This would take the form of an advance in variable-conductance, heat-pipe technology. There are no current efforts in this direction, however.

The radiator orientation must be fixed, since a sun-tracking joint would require an active pumping system. Because of the fixed orientation, the radiator efficiency varies with the sun direction relative to the satellite attitude. Careful selection of the radiator orientation could improve the radiator efficiency and make the assumed thermal control subsystem weight more realistic.

### 7.1.5 Attitude Control

The Band 1 and 2 baseline satellites are very large, highly flexible structures. The technology for controlling such structures is evolving slowly. The first relevant test took place in late 1984 with the Orbiter deployment of a 150-foot solar array wing.

There are two options for dealing with the attitude control problem in the baseline systems:

1) Accept the structural modal response without resorting to active control procedures.

2) Provide active attitude control.

Currently available analytical techniques are not capable of choosing between these two alternatives.

There are several factors that favor the first option. Fine pointing control is not required, since the precise geographic area illuminated is not critical. Also, the spacecraft modal response is expected to be below the attitude control subsystem (ACS) control bandwidth, thereby providing a degree of isolation between structure and ACS. Furthermore, advances in attitude control should lead to robust, modal discriminating control technology in a reasonable period of time. Finally, acceptance of the structural modal response leads to lower implementation cost.

Selection of the second option would positively eliminate modal interaction between structure and ACS. It also guarantees control of pointing errors. Lastly, it results in lower technical risk.

Option 1 has been selected because it is judged that the technical risk is within acceptable limits. Careful monitoring of large space structure developments will reveal whether this is the proper choice.

## 7.2 PROJECT PLAN

In Section 5, LCC were developed for the four baseline systems, as well as for a number of variations on those systems. A LCC summary for the baseline systems is given in Figure 7-3. Division of the LCC among DDT&E (design, development, test, and engineering), production, launch, and O&M (operations and maintenance) is shown in Figures 7-4 to 7-7. Also shown in these figures is a breakdown of satellite costs among antenna subsystem, other hardware, AI&T (assembly, integration, and test), and system level costs.

A project schedule has been developed for the baseline systems, and the LCC have been spread over the years spanned by this schedule. The schedule for each system is shown in Figure 7-8. The DDT&E periods shown, with the exception of System 4, are governed by the time needed to develop the antenna subsystem. Other satellite hardware costs are generally spread over a shorter period. There is no break in satellite production for Systems 1 and 2, so that maximum advantage can be taken of the "learning" experience. A 3-year production break is assumed for Systems 3 and 4.

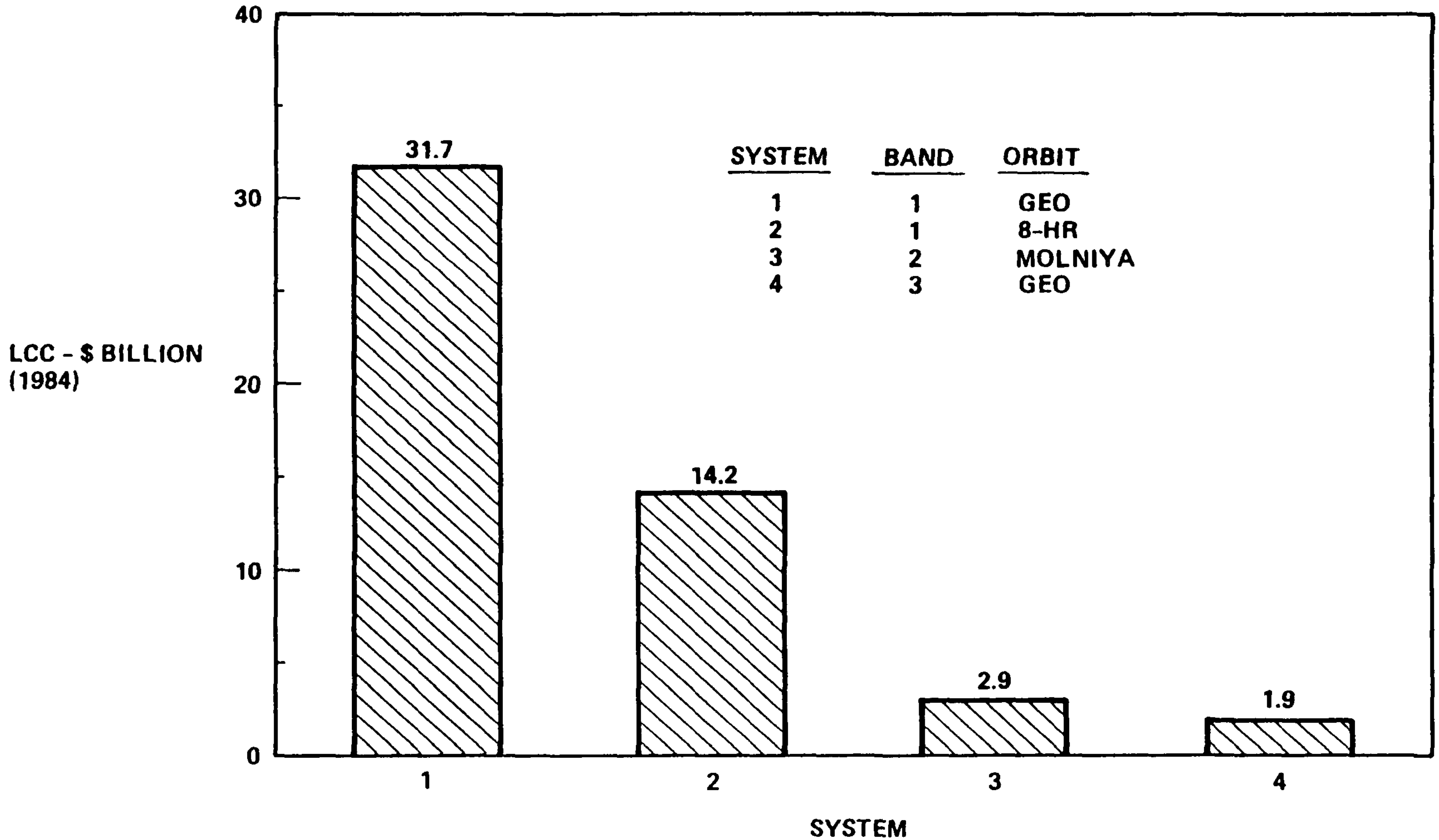



Figure 7-3. System Life Cycle Cost Comparison

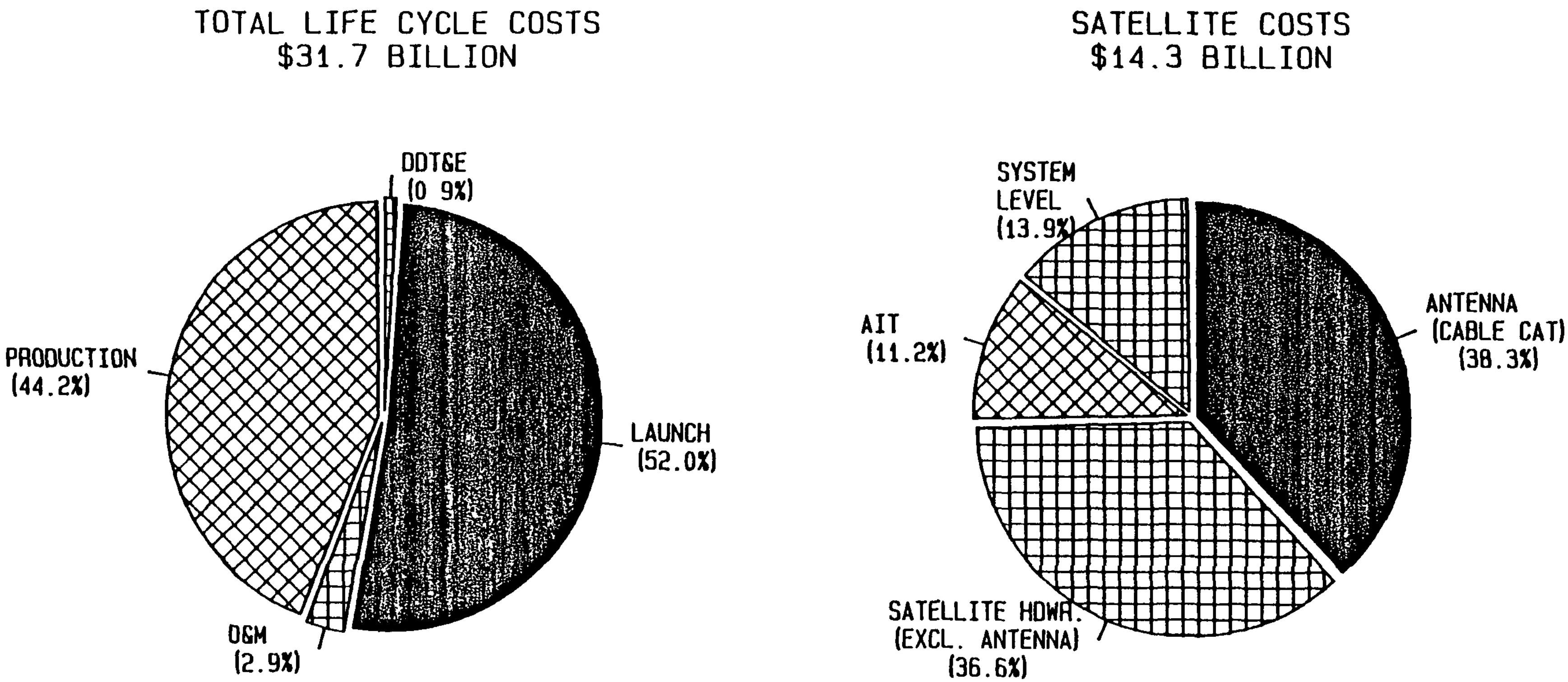



Figure 7-4. Baseline System 1 Life Cycle and Satellite Cost Distribution

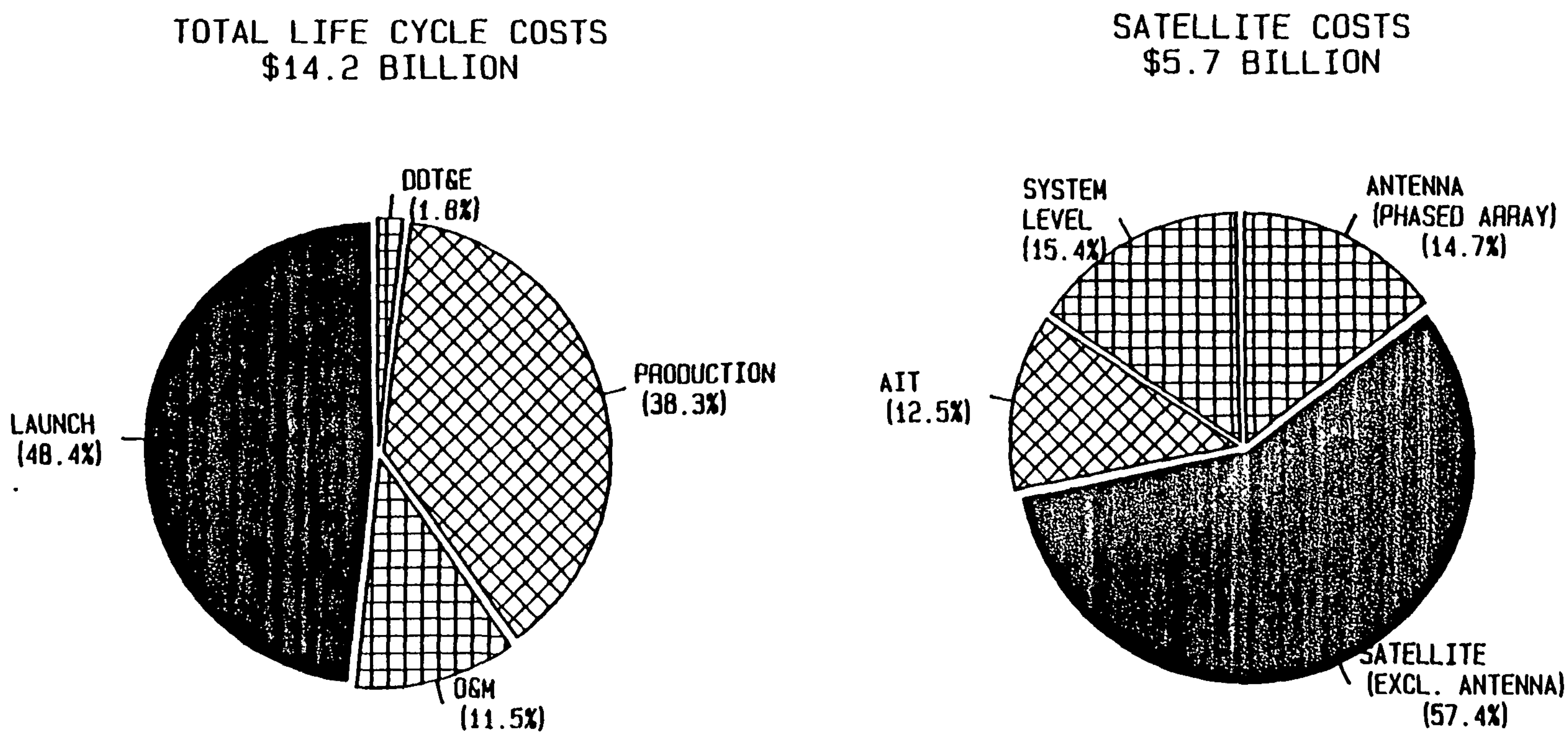



Figure 7-5. Baseline System 2 Life Cycle and Satellite Cost Distribution

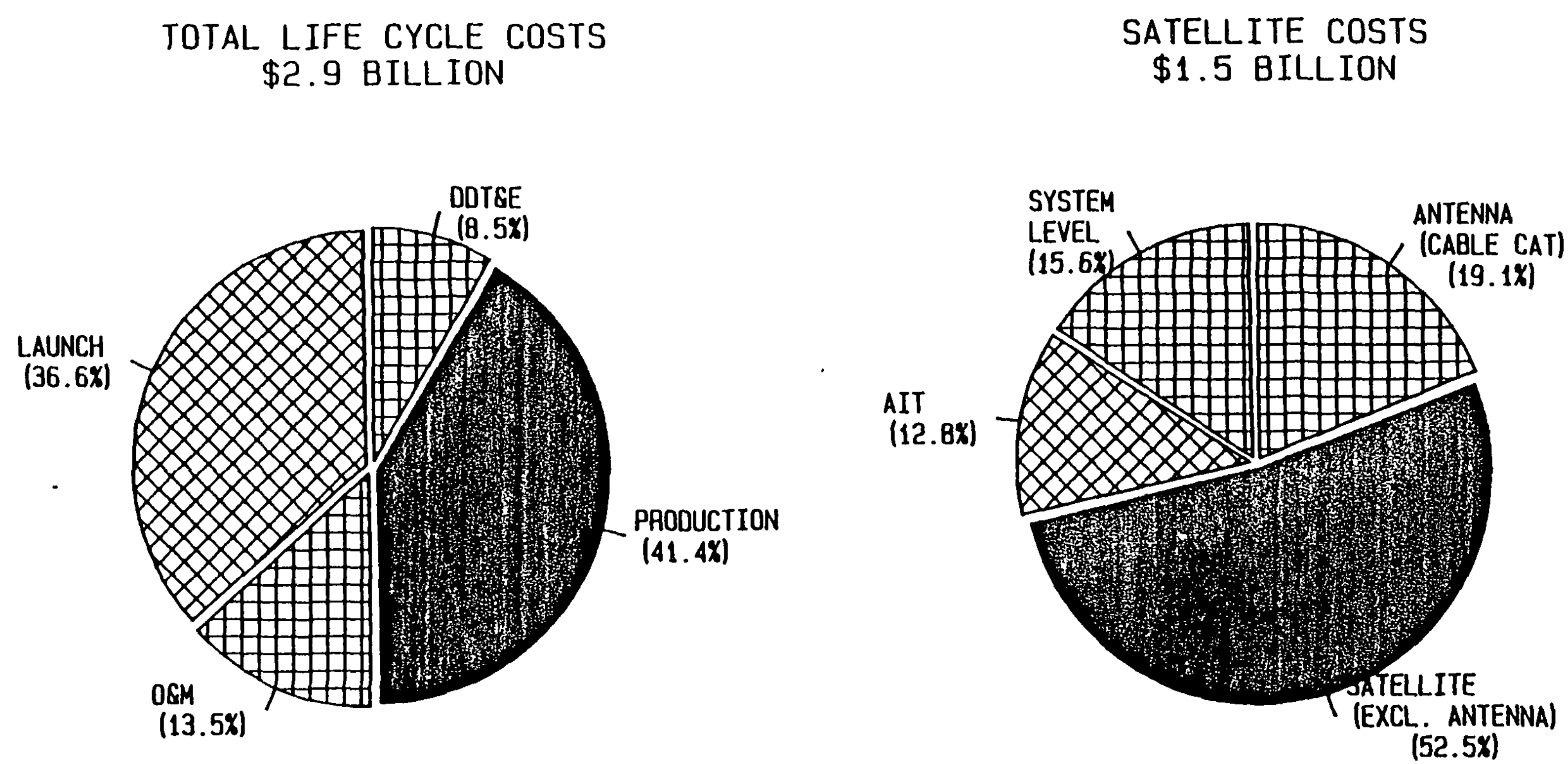



Figure 7-6. Baseline System 3 Life Cycle and Satellite Cost Distribution

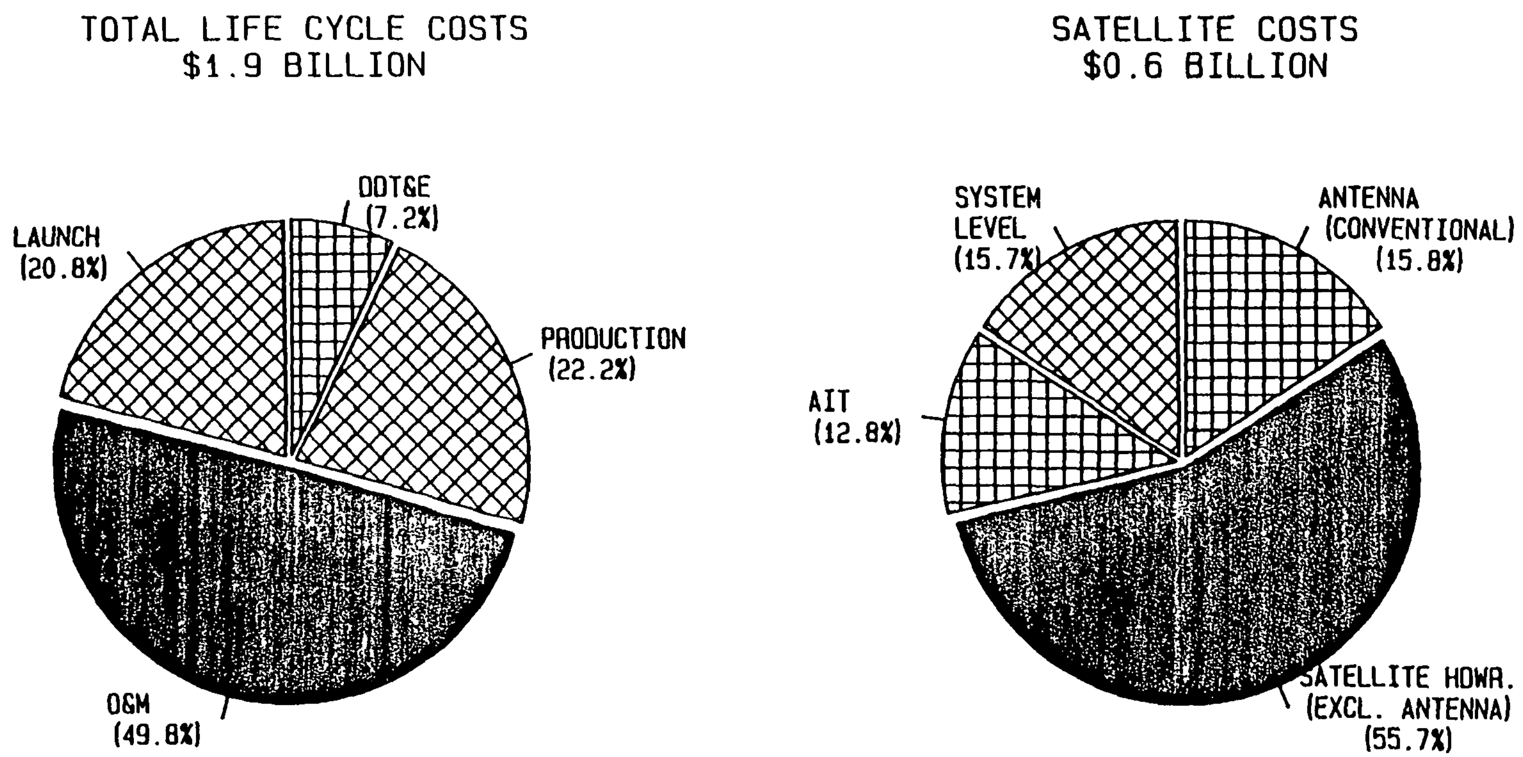



Figure 7-7. Baseline System 4 Life Cycle and Satellite Cost Distribution

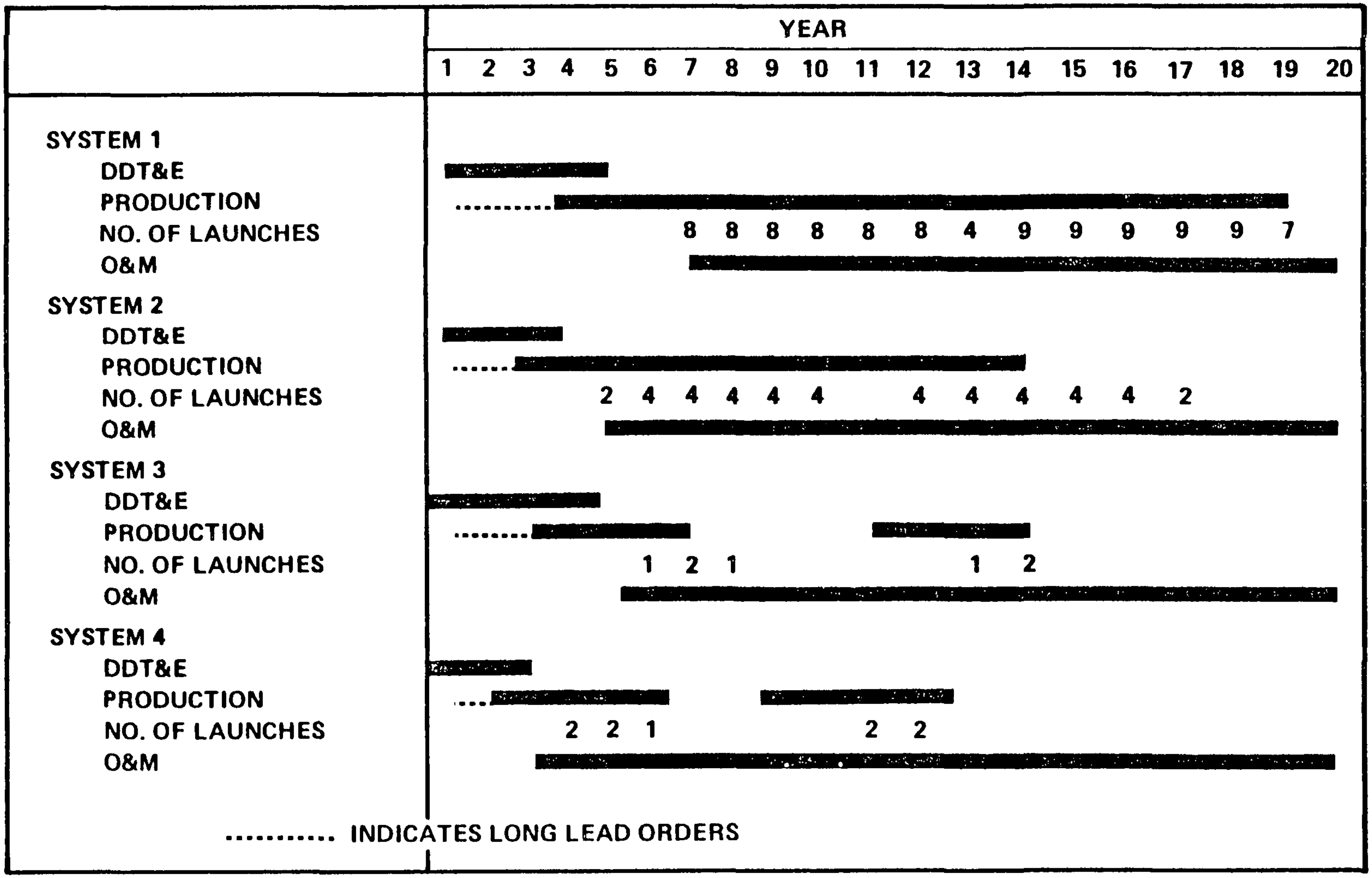



Figure 7-8. Baseline System Schedule

Launch years for the spare units are chosen in accordance with the nominal satellite launch profile. In System 1, for example, the full operational system comprises 47 satellites. The first spare is assumed to be launched as the eighth satellite in Year 12; four more spares are launched in Year 13, which is nominally devoid of launches; and the remaining five spares are launched, one per year, in Years 14 through 18. (The second or replacement set of satellites are launched beginning in Year 14.) In System 2, the last two satellites launched in Year 10 and the two satellites launched in Year 17 are regarded as spares. In System 3 and 4, the single spare satellite follows the initial set of scheduled satellites.

Launch costs are assumed to be paid over a 3-year period, at 10, 30, and 50 percent of total cost. This apportionment corresponds to the payment schedule in the STS Reimbursement Guide.

Operation and maintenance costs are assumed constant at:

| System | Cost Per Year ($M) |
|---|---|
| 1 | 60 |
| 2 | 105 |
| 3 | 30 |
| 4 | 60 |

These costs are based on the number of feeder links required for each system, and are at the rate of $12.5 million/year for each feeder-link station.

Funding profiles for the four baseline systems are shown in Figures 7-9 to 7-12. Satellite acquisition costs are broken out separately in each case. The time spread of the latter costs is based on analogy with prior TRW satellite projects, such as TDRS, and on discussion with the Manufacturing staff. The O&M costs are shown only through Year 20 although, except for System 4, one or more satellites have a lifetime that extends beyond Year 20.

## 7.3 CRITICAL TECHNOLOGY COST AND SCHEDULE RISK

The methodology employed to identify cost and schedule risk associated with critical technology items is outlined in Figure 7-13. First, the

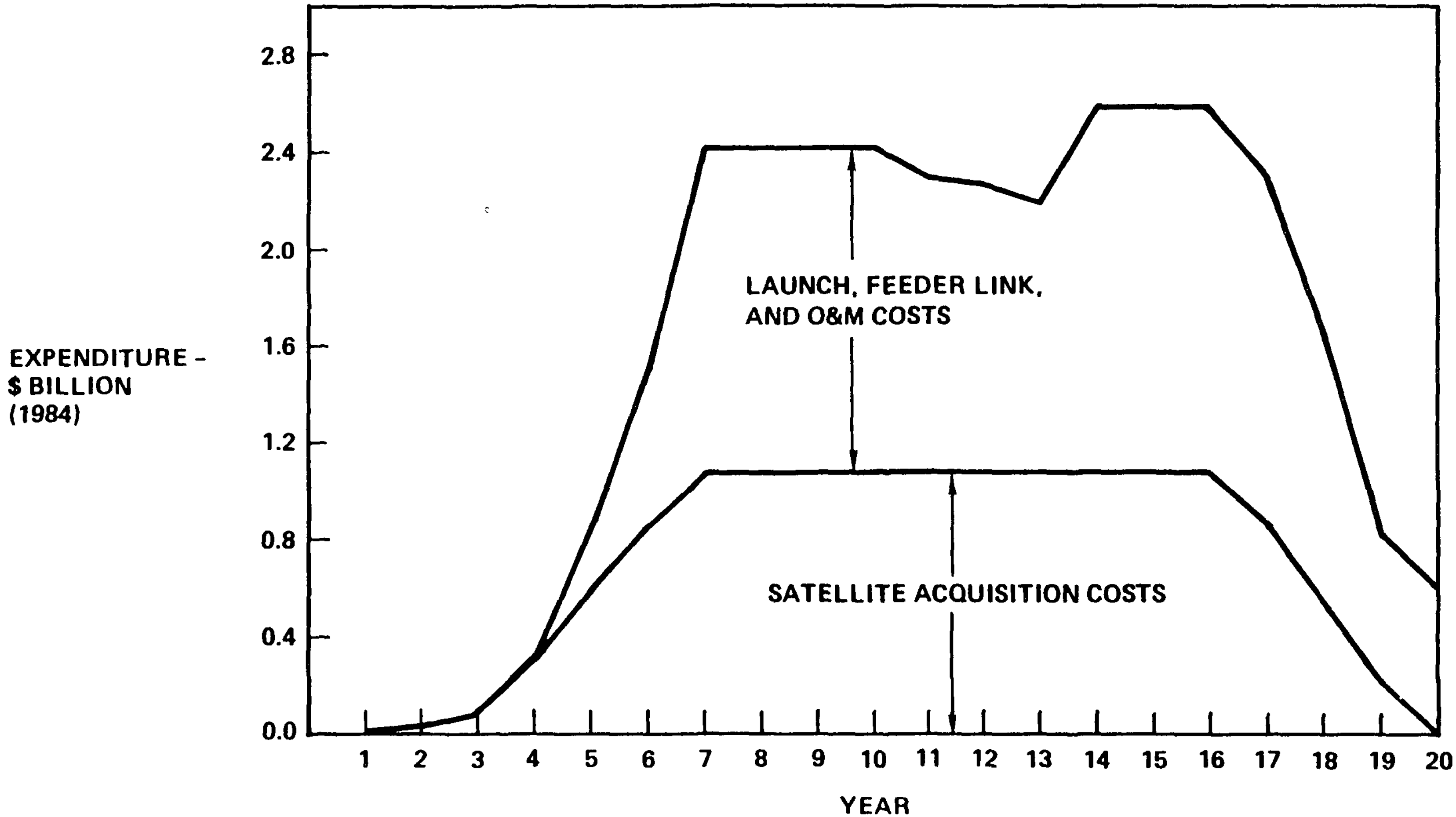



Figure 7-9. Baseline System 1 Funding Profile

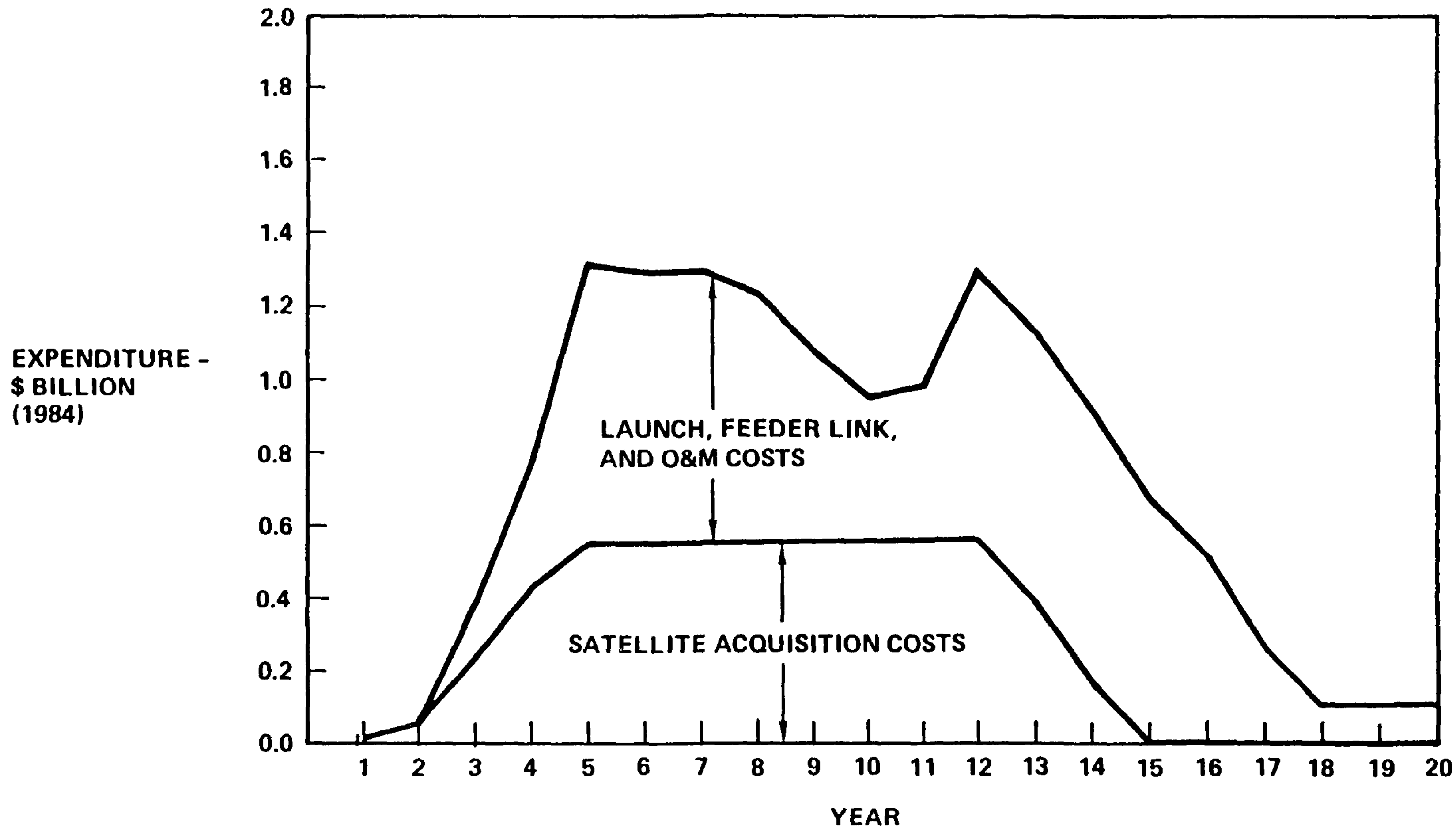



Figure 7-10. Baseline System 2 Funding Profile

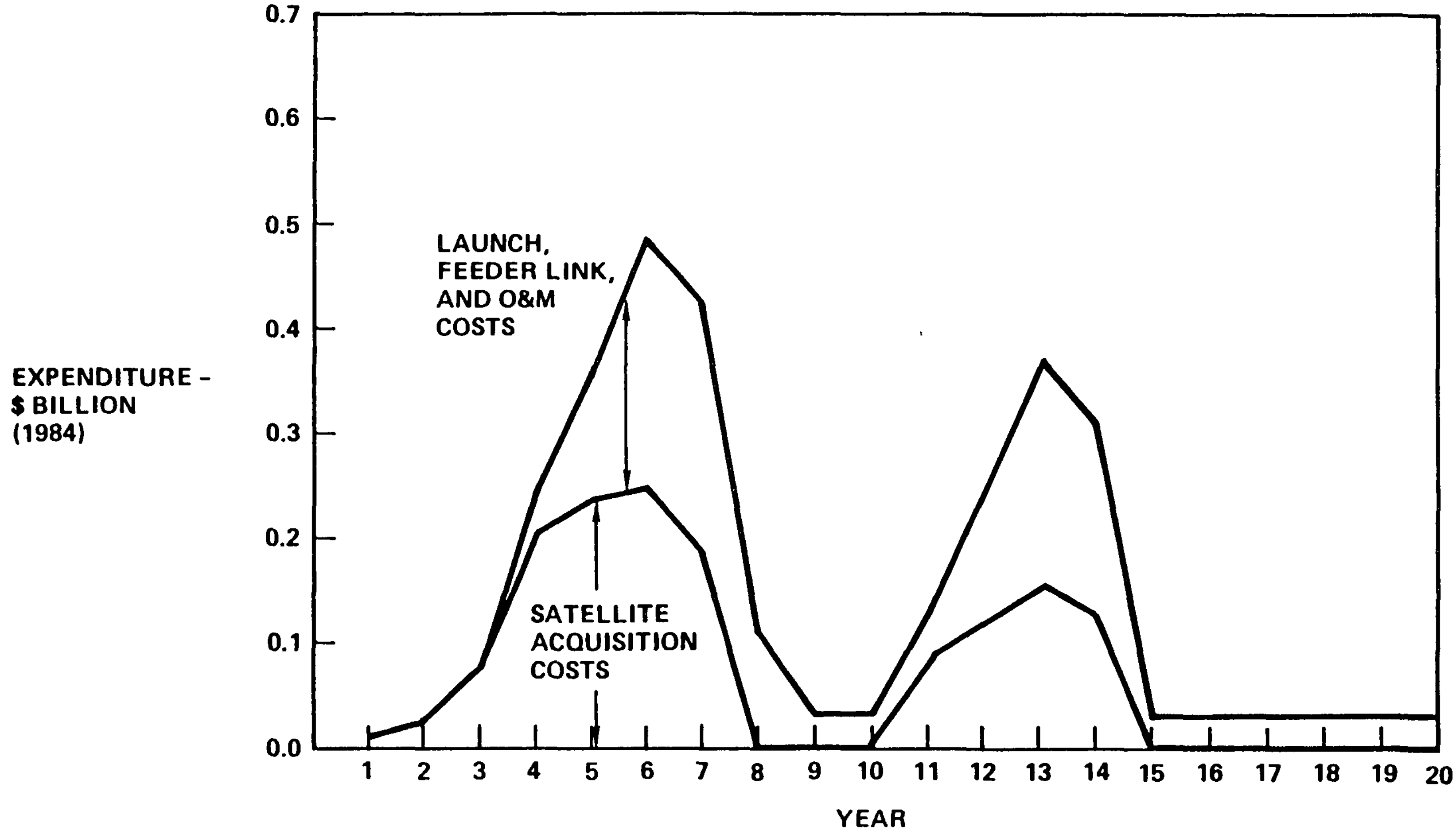



Figure 7-11. Baseline System 3 Funding Profile

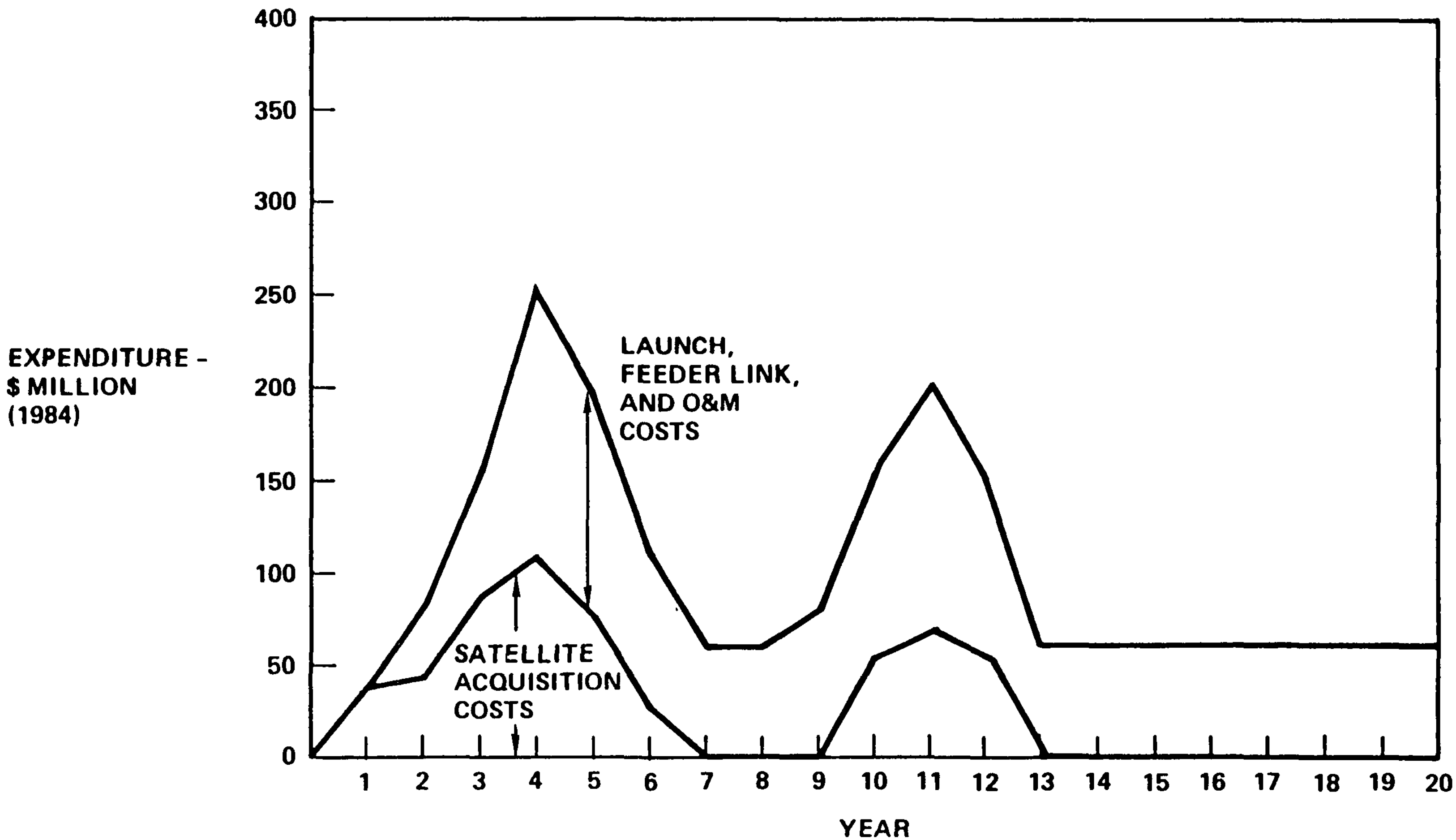



Figure 7-12. Baseline System 4 Funding Profile

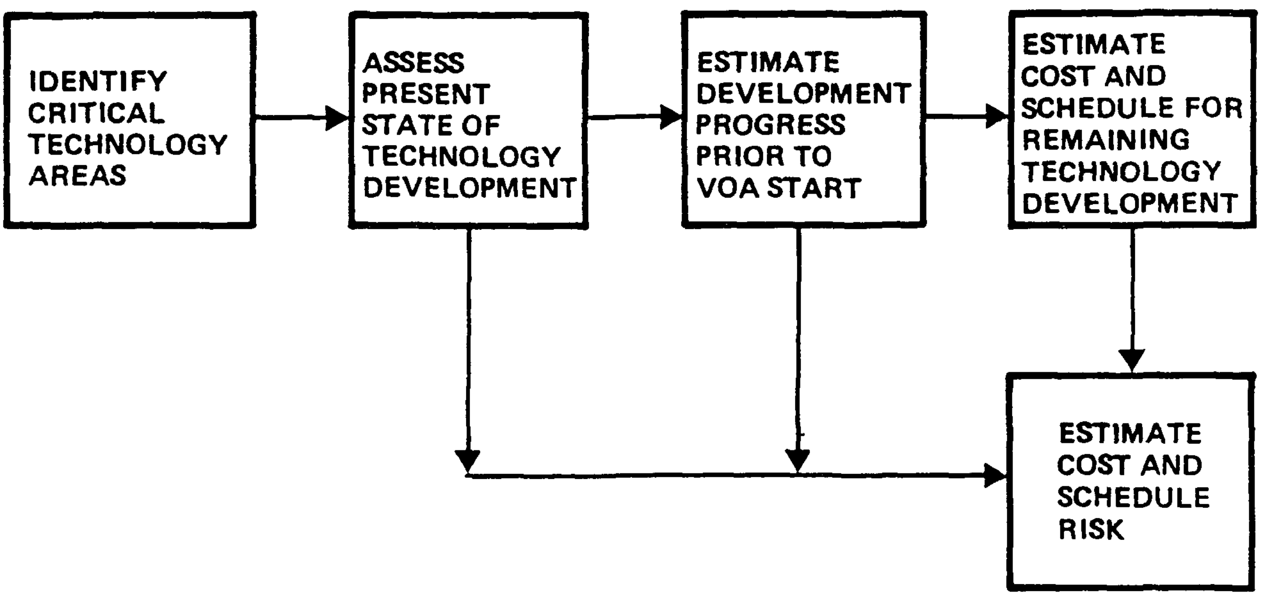



Figure 7-13. Methodology for Critical Technology Risk Assessment

critical technology areas, which are identified in Section 7.1, are delineated for each of the baseline systems (Figure 7-14). This figure is based on an assessment of the current state of technology development. The NASA classification scheme for technology readiness shown below is introduced for this purpose (Reference 7-1). A technology is considered critical unless Level 6 has been reached.

| Technology Readiness Level | Definition |
|---|---|
| 1 | Basic principles observed and reported |
| 2 | Conceptual design formulated |
| 3 | Conceptual design tested analytically or experimentally |
| 4 | Critical function/characteristic demonstration |
| 5 | Component/breadboard tested in relevant environment |
| 6 | Prototype/engineering model tested in relevant environment |
| 7 | Engineering model tested in space |
| 8 | Full operational capability (baselined into production design). |

Several of the entries in Figure 7-14 require further explanation. As indicated in Section 7.1, it is uncertain at present whether current ACS technology is adequate for the (cable-catenary) satellite designs of Systems 1 and 3. This issue can be resolved by analysis. Until this is done, the ACS will be considered a critical technology area.

The half-shaded circle for the thermal subsystem in System 2 indicates that, if a weight reduction in heat-pipe technology is not forthcoming, satellite capability will suffer somewhat. The system concept would not be rendered infeasible, however. Current thermal control technology is adequate for System 1 because the two-channel-beam satellite capacity results in a smaller amount of dissipated power. It is also adequate for System 3 because the satellite design corresponding to the maximum STS lift capability has excess capacity (12 channel-beams versus 10 required).

Aluminum may or may not turn out to be suitable cabling material. The impact of having to resort to copper cabling varies according to the amount of cabling required. For System 1, the additional weight would be prohibitive because of the satellite dimensions. For System 2, some reduction in

| SUBSYSTEM OR TECHNOLOGY | SYSTEM | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| ANTENNA | | | | ○ |
| CABLE CATENARY | ● | | ● | |
| PHASE ARRAY | | ● | | |
| TT&C | ○ | ○ | ○ | ○ |
| ACS | ● | ○ | ● | ○ |
| RCS | ○ | ○ | ○ | ○ |
| STRUCTURE | ○ | ○ | ○ | ○ |
| THERMAL | ○ | ◒ | ○ | ○ |
| EPS | | | | ○ |
| SOLAR CELLS | ● | ● | ● | |
| 200 V DISTRIBUTION | ● | ● | ● | |
| ALUMINUM CABLING | ● | ◒ | ○ | |
| PAYLOAD | | | | |
| TRANSMITTER | ● | ● | ● | ◒ |

● CRITICAL TECHNOLOGY DEVELOPMENT REQUIRED

◒ TECHNOLOGY DEVELOPMENT DESIRABLE, BUT NOT ESSENTIAL (PERFORMANCE DEGRADATION MAY RESULT)

○ TECHNOLOGY EXISTS

Figure 7-14. Critical Technology Identification capacity would result. For System 3, on the other hand, the impact is minimal because of the excess satellite capacity.

If the desired MOSFET amplifier technology for System 4 (i.e., at 1.5 gigahertz) should not be available, there are two possible alternatives:

1) Bipolar transistors, which operate at lower efficiency

2) TWTs, which provide lower reliability.

Estimates of both the present level of critical technology readiness and the projected level of readiness in 1990 are shown in Figure 7-15. The taper of either the solid bar (present level) or the dotted bar (projected level) indicates the degree of uncertainty in the estimate. All estimates of technology readiness, as well as uncertainties in these estimates, represent judgments based on discussions with appropriate TRW subsystem engineers.

The small horizontal span of the dotted bars for the two antenna types implies that advances beyond the present state-of-art will be largely the result of R&D funds related to a VOA satellite system. On the other hand, significant advances in solar cell technology and high-voltage distribution systems can be expected in the absence of VOA-directed efforts. Solar cells measuring 3 by 6 centimeters will be developed for Space Station, but at 8-mil thickness. In addition, there is a high probability that Space Station requirements will propel development of 200-volt distribution technology. Space Station start is expected in 1987, with initial operational capability in 1992. The only uncertainty associated with this activity is whether or not the distribution system voltage will be as high as 200 volts. In the case of aluminum cabling, the high degree of uncertainty in the present level of readiness relates to the possible inadequacy of aluminum as a cable material.

The length of the empty bar to the left of Readiness Level 6 for each technology is a measure of the R&D effort that must be specifically directed at a VOA satellite program. There are two types of uncertainty associated with this R&D effort. The first type concerns the projected level of technology readiness and is reflected by the taper at the left end of the empty bar. Secondly, for any given level of readiness, the time and dollar amount needed to reach Readiness Level 6 is uncertain.

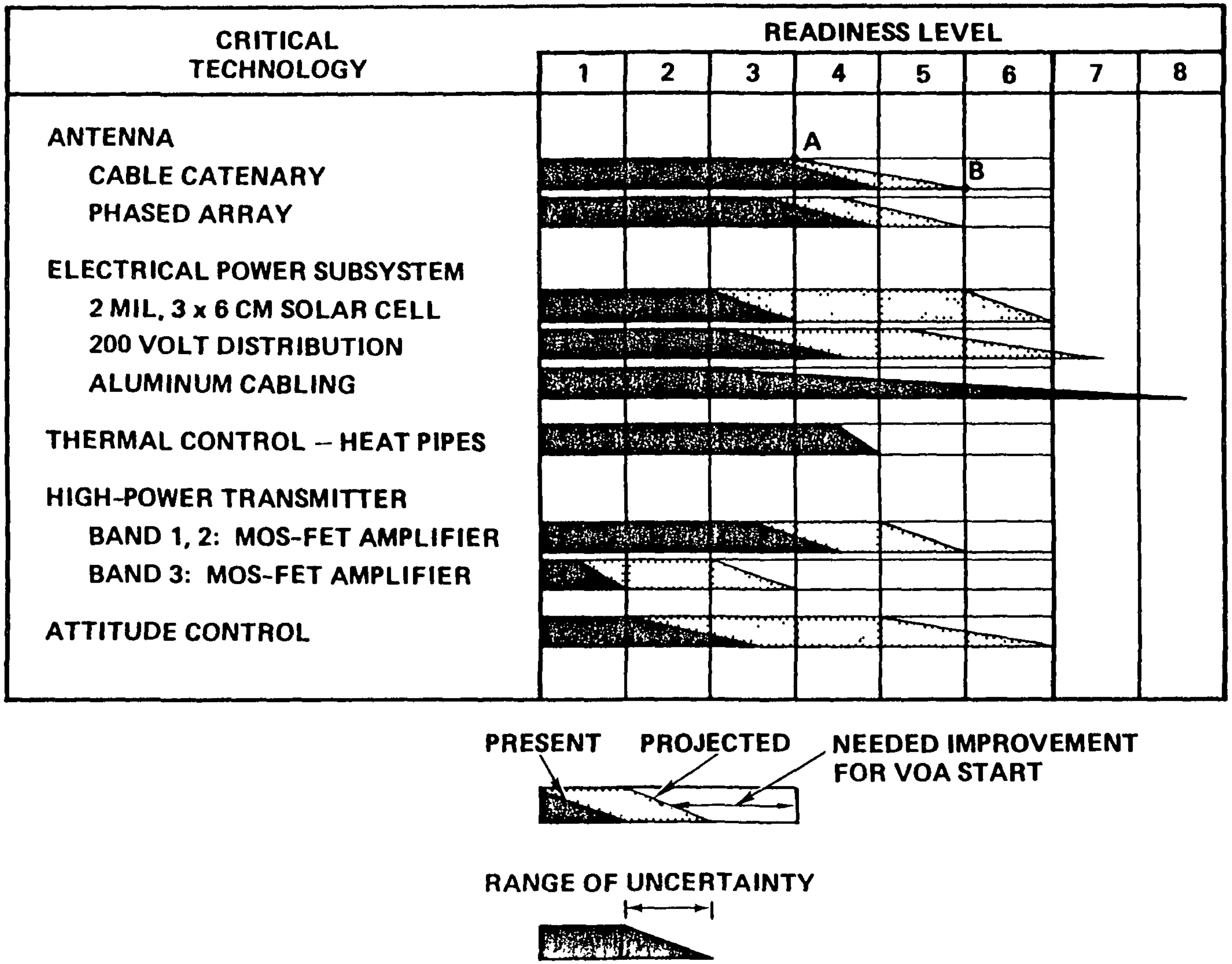



Figure 7-15. Assessment of Technology Readiness

Nominal cost and schedule estimates for each technology should be interpreted as corresponding roughly to the midpoint of the taper, together with the best estimate of cost and time needed to reach Readiness Level 6. Nominal cost and schedule values for each critical technology are listed in Table 7-2.

To bound the period and funding level of the R&D effort for any technology item, the two types of uncertainty described above must be combined. The period or cost that has a 10-percent chance of being exceeded may be obtained by taking the maximum estimated value for a readiness level corresponding to the leftmost point on the taper (e.g., point A in Figure 7-15). Similarly, the period or cost that has a 90 percent chance of being exceeded is found by taking the minimum estimated value for a readiness level corresponding to the rightmost point on the taper (e.g., point B in Figure 7-15).

The major cost- and time-consuming technologies are the cable-catenary and phased-array antenna development. Cost and schedule estimates for the cable-catenary antenna are based on analogy with the detailed cost estimates developed by TRW in performing the Mobile Communications Satellite System Study for NASA LeRC. The phased array is a simpler structure and therefore requires less R&D funding.

Cost and schedule estimates for the remaining critical technologies are based on analogy with other programs and estimates of manpower needed to perform the advanced development.

Ranges of cost and schedule estimates corresponding to 90- and 10-percent exceedance levels are shown in Table 7-3 for each critical technology. The 90-percent exceedance level is zero in those cases where the projected readiness is shown in Figure 7-15 to have a chance of reaching Level 6 or beyond. Certain technologies (e.g., heat pipes for thermal control) exhibit large percentage cost and schedule uncertainties despite a small uncertainty in the readiness level at the start of the R&D effort. In these cases, there is a large uncertainty in the funding required to realize the needed technology improvement.

Table 7-2. Critical-Technology-Development Cost and Schedule Estimates

| CRITICAL TECHNOLOGY | SCHEDULE (YRS) | COST ($M 1984) |
|---|---|---|
| ANTENNA | | |
| CABLE CATENARY (SYSTEM 1) | 5 | 39 |
| CABLE CATENARY (SYSTEM 3) | 4 | 31 |
| PHASED ARRAY | 2.5 | 14 |
| ELECTRICAL POWER SUBSYSTEM | | |
| 2 MIL, 3 x 6 CM SOLAR CELLS | 2 | 0.5 |
| 200 VOLT DISTRIBUTION | 2 | 2 |
| ALUMINUM CABLING | 1.5 | 0.5 |
| THERMAL CONTROL – HEAT PIPES | 2 | 1 |
| HIGH-POWER TRANSMITTERS | | |
| BAND 1, 2: MOS-FET AMPLIFIERS | 1.5 | 1 |
| BAND 3: MOS-FET AMPLIFIERS | 3 | 4 |
| ATTITUDE CONTROL* | | |
| SYSTEM 1 | 5 | 5 |
| SYSTEM 3 | 4 | 4 |

*PERFORMED IN CONJUNCTION WITH CABLE CATENARY DEVELOPMENT

Table 7-3. Critical-Technology-Development Cost and Schedule Risk

| CRITICAL TECHNOLOGY | SCHEDULE (YRS) | | COST ($M 1984) | |
|---|---|---|---|---|
| EXCEEDANCE LEVELS | 90% | 10% | 90% | 10% |
| ANTENNA | | | | |
| CABLE CATENARY (SYSTEM 1) | 4 | 6 | 22 | 49 |
| CABLE CATENARY (SYSTEM 3) | 3 | 5 | 18 | 39 |
| PHASE ARRAY | 2 | 3 | 8 | 17 |
| ELECTRICAL POWER SUBSYSTEM | | | | |
| 2 MIL, 3 x 6 CM SOLAR CELLS | 0 | 3 | 0 | 0.8 |
| 200 VOLT DISTRIBUTION | 0 | 3 | 0 | 5 |
| ALUMINUM CABLING | 0 | 1.5 | 0 | 0.8 |
| THERMAL CONTROL - HEAT PIPES | 1 | 3 | 0.5 | 1.6 |
| HIGH-POWER TRANSMITTERS | | | | |
| BAND 1, 2: MOS-FET AMPLIFIERS | 1.0 | 1.5 | 0.8 | 1.1 |
| BAND 3: MOS-FET AMPLIFIERS | 2.5 | 4 | 3.5 | 5.5 |
| ATTITUDE CONTROL* | | | | |
| SYSTEM 1 | 0 | 6 | 0 | 6 |
| SYSTEM 3 | 0 | 5 | 0 | 4.8 |

*PERFORMED IN CONJUNCTION WITH CABLE CATENARY DEVELOPMENT

## 7.4 Satellite Cost and Schedule Risk

The approach to calculating satellite cost and schedule risk is indicated in Figure 7-16. Satellite risk is developed separately for the nonrecurring development activity and for production of the first unit.

The first step is to compute subsystem cost and schedule probability distributions. These distributions are based, in part, on cost and schedule distributions for past projects, with the nominal cost and schedule values interpreted as most likely values.

Figure 7-17 shows some of the factors considered in developing the subsystem distribution functions. These profiles are obtained through discussions with subsystem engineers, who are asked to assess the probabilities of certain specific events. Where a subsystem incorporates new technology, the distribution is modified accordingly.

The system level or satellite distributions are obtained through use of TRW's Stochastic Planning Model (SPM). Elements of this model are shown in Figure 7-18. The subsystem probability distributions are approximated by triangular distributions for use in the SPM. In those cases where distributions cannot be derived from past programs (i.e., where there is significant new technology), the triangular distribution is based on the estimated degree of risk, as shown below. In choosing specific values in these ranges, consideration is given to the magnitude of the subsystem cost. The minimum value on the triangular distribution is always chosen to be at least 50 percent of the nominal value.

| Risk Level | Maximum Value (% Above Nominal) |
|---|---|
| High | 50 - 80 |
| Moderate | 30 - 50 |
| Low | Below 30 |

The Monte Carlo technique is used to combine the subsystem distributions. Five hundred iterations are performed in which the cost and schedule distributions are randomly sampled. Since cost and schedule for a given subsystem are normally correlated, the same random number is used to sample the two distributions.

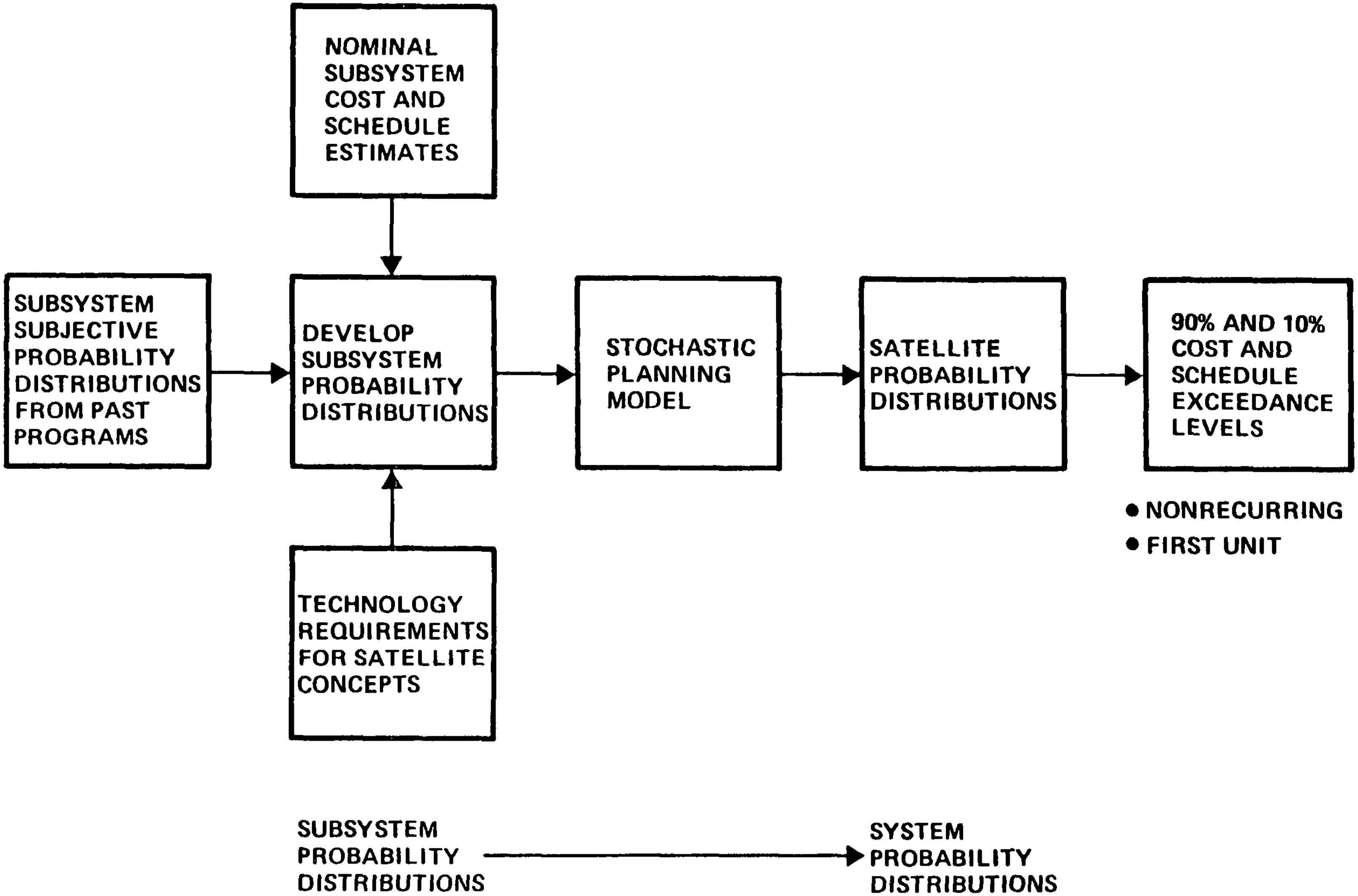



Figure 7-16. Methodology for Satellite Risk Assessment

- Start with a "normal" doing-business cost and eliminate activities, assessing Δ probabilities as this is done

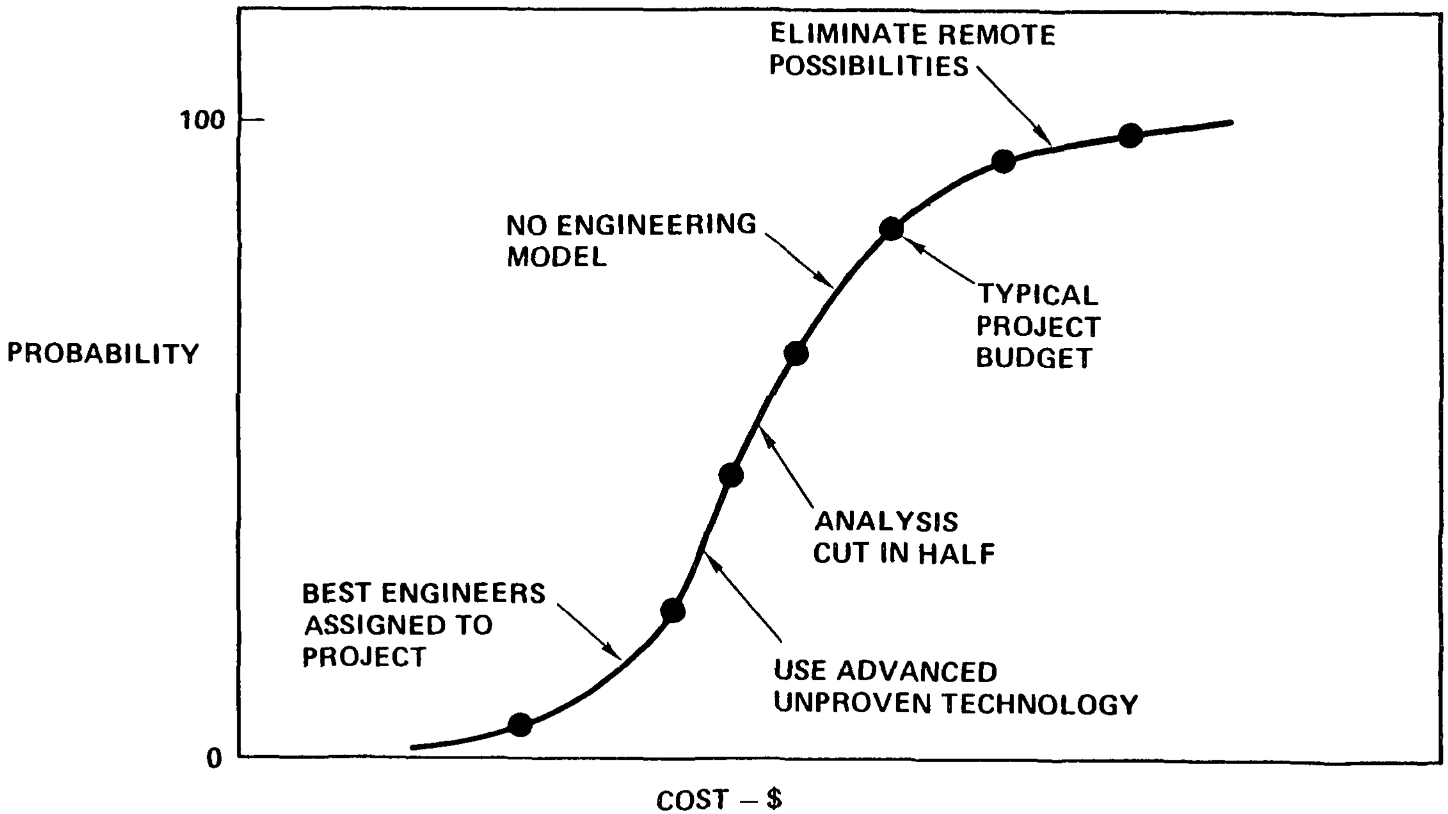



Figure 7-17. Typical Subsystem Cost Distribution

Model Characteristics

- Individual subsystem cost and schedule probability distributions estimated by engineers
- Logic network for activities
- Monte Carlo simulation to combine probability distributions

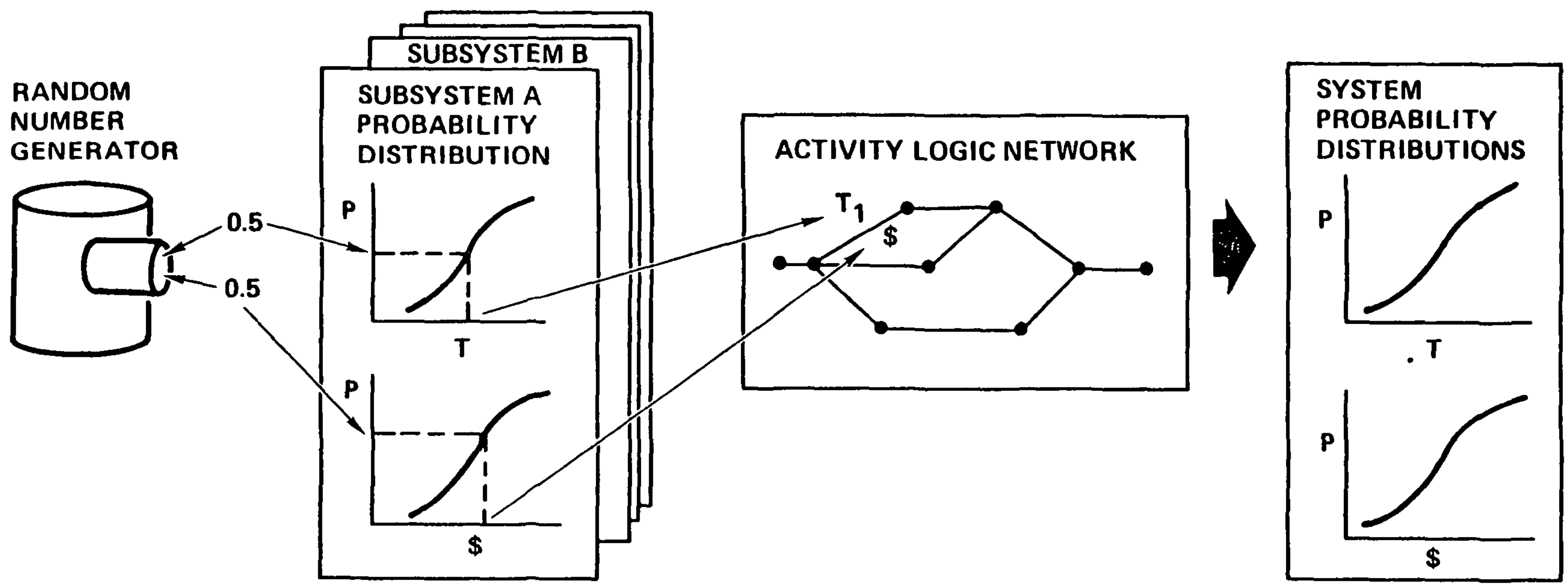



Figure 7-18. Stochastic Planning Model

The schedule samples generated by the SPM are fed into a PERT network, so that dependencies between activities are properly accounted for. In this particular case, there is only one link in the PERT network for the development activity and two (manufacture and AI&T) for production of the first unit).

Satellite cost and schedule exceedance levels of 90 and 10 percent are shown in Table 7-4 for the four baseline satellites. The sizable difference between the 90- and 10-percent values for Systems 1 and 3 are largely the result of development and production risks associated with the cable-catenary antenna. The System 4 nonrecurring cost range is also relatively large, because of the potential for reduced costs due to mature technologies and designs.

Reference

7-1. "NASA Space System Technology Model, Vol. 2A — Space Technology Trends and Forecasts," January 1984.

Table 7-4. Satellite Cost and Schedule Risk

| CONCEPT | SCHEDULE (YRS) | | COST ($M 1984)* | |
|---|---|---|---|---|
| EXCEEDANCE LEVELS | 90% | 10% | 90% | 10% |
| SYSTEM 1 | | | | |
| NONRECURRING | 3.0 | 6.0 | 193 | 289 |
| FIRST UNIT | 2.5 | 3.5 | 188 | 274 |
| SYSTEM 2 | | | | |
| NONRECURRING | 3.0 | 5.0 | 151 | 210 |
| FIRST UNIT | 2.0 | 3.5 | 181 | 242 |
| SYSTEM 3 | | | | |
| NONRECURRING | 3.0 | 6.0 | 188 | 258 |
| FIRST UNIT | 2.5 | 3.5 | 195 | 256 |
| SYSTEM 4 | | | | |
| NONRECURRING | 2.0 | 4.5 | 86 | 123 |
| FIRST UNIT | 1.5 | 2.5 | 55 | 74 |

*THESE COSTS EXCLUDE PROFIT, WHICH IS ASSUMED TO BE 12% IN PRIOR ESTIMATES

# 8. SINGLE-CHANNEL SATELLITE BROADCASTING SYSTEMS

The originally specified set of broadcast requirements (as embodied in the broadcast schedule of Figure 2-2) led to Band 1 satellite systems comprising many satellites of extremely large physical dimensions, with very large costs. As a result, TRW was directed to perform an additional task to determine the broadcasting capability that can be derived from a single satellite with sufficient power to broadcast just one voice channel. Three values of field strength — 300 μV/m (the baseline value), 150 μV/m, and 50 μV/m — were to be considered.

Six different orbits were examined. These include geostationary and Molniya orbits, as well as subsynchronous orbits with (approximately) 6-, 8-, and 12-hour periods. (The precise period is selected to produce synchronization with the sidereal day so as to yield a repetitive ground track.) The inclination of the 6- and 8-hour orbits is 28.5 degrees, while that of the 12-hour orbit is 37 degrees.

The sixth orbit is referred to as a "triply-sync" orbit. It is highly elliptical, with apogee of 7843 kilometers, perigee of 521 kilometers, and inclination of 116.6 degrees. The orbit period is exactly 3 hours, which makes it synchronous with the solar day. Hence apogee occurs at the same local time each day. This avoids the 4-minute sidereal shift inherent to the other five orbits. In addition, gravitational perturbations cause the orbit major axis to drift in such a way as to bring about synchronization with the earth's rotation. Therefore, this orbit is synchronous with both the sun and the earth, and it also appears each day at the same local time — hence the name "triply synchronous." The coverage afforded specific geographical areas depends on the placement of apogee. The latitude selected is 63.4 degrees, which is the maximum value attained.

## 8.1 SATELLITE VISIBILITY

Visibility for a geostationary satellite is simply described. The visible region is shown in Figure 8-1 as a function of latitude and longitudinal offset, for a minimum elevation angle of 20 degrees.

Visibility periods for a satellite in Molniya orbit are immediately evident from a set of instantaneous visibility contours. Visibility

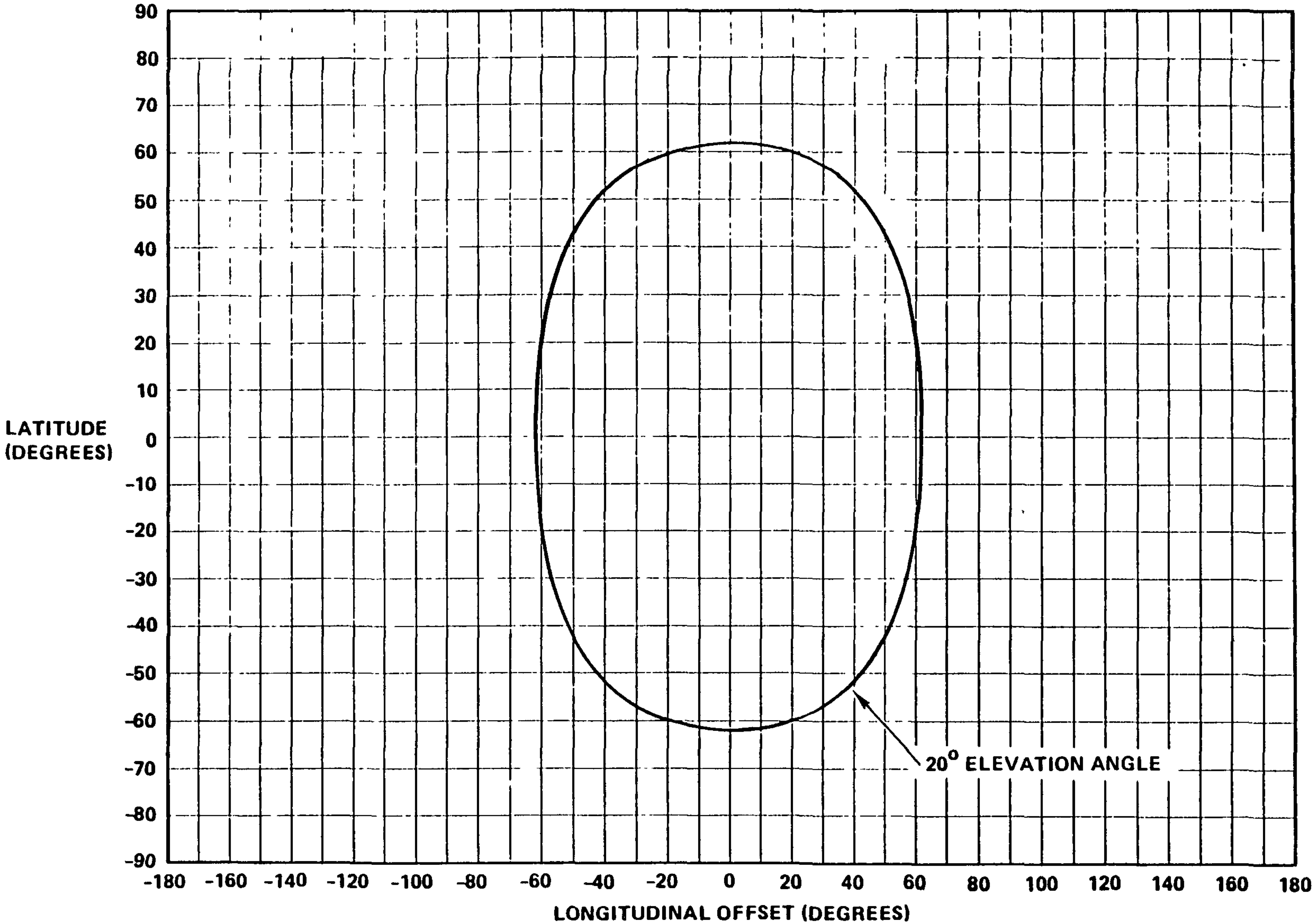



Figure 8-1. Geostationary Satellite Visibility

contours valid for either of two consecutive 12-hour orbits are shown in Figure 8-2. The only distinction between the two orbital passes is that the longitudinal reference (i.e., the longitude of apogee) is shifted by 180 degrees.

Satellite visibility for each open contour in Figure 8-2 (e.g., for t = 2 hr) extends to all points above that contour. Visibility for the closed contours (e.g., t = 1 hr) is restricted to those points within the contour. Continuous satellite visibility for the period $(t_1, t_2)$ requires that the observer be located above or within all open or closed contours, respectively, for times between $t_1$ and $t_2$.

For a given value of $|t_2 - t_1|$, the greatest region of visibility results from setting $t_2 = -t_1$, $t_1 < 0$. In other words, the maximum region of visibility results from choosing a period that is centered at apogee passage. The visibility regions for a number of such periods are indicated in Figure 8-2.

The triply-sync orbit offers the possibility of several significant (from a broadcasting standpoint) visibility periods per day. The ground track of the triply-sync orbit is shown in Figure 8-3. Because of the 3-hour orbit period, a given latitude is crossed, in either the north-south or south-north direction, at a longitudinal separation of 45 degrees on successive orbits. At latitudes above 20 degrees, the span of observer longitudes over which the satellite is visible for 30 minutes or more is several times 45 degrees. It follows that a fixed observer at a latitude above 20 degrees will have satellite visibility exceeding 30 minutes on several successive orbits.

Figure 8-4 shows the period of visibility for three different latitudes as a function of displacement from the longitude of apogee. In each case the visibility period shows remarkably little variation over a wide range of longitudes, before falling off rapidly. Dividing the longitudinal span over which the visibility period is approximately constant by 45 degrees gives the number of successive orbits on which this degree of visibility is realized. Satellite visibility is summarized below for three values of observer latitude. For a latitude of 20 degrees, visibility during one pass in the middle of the sequence will be less than 30 minutes.

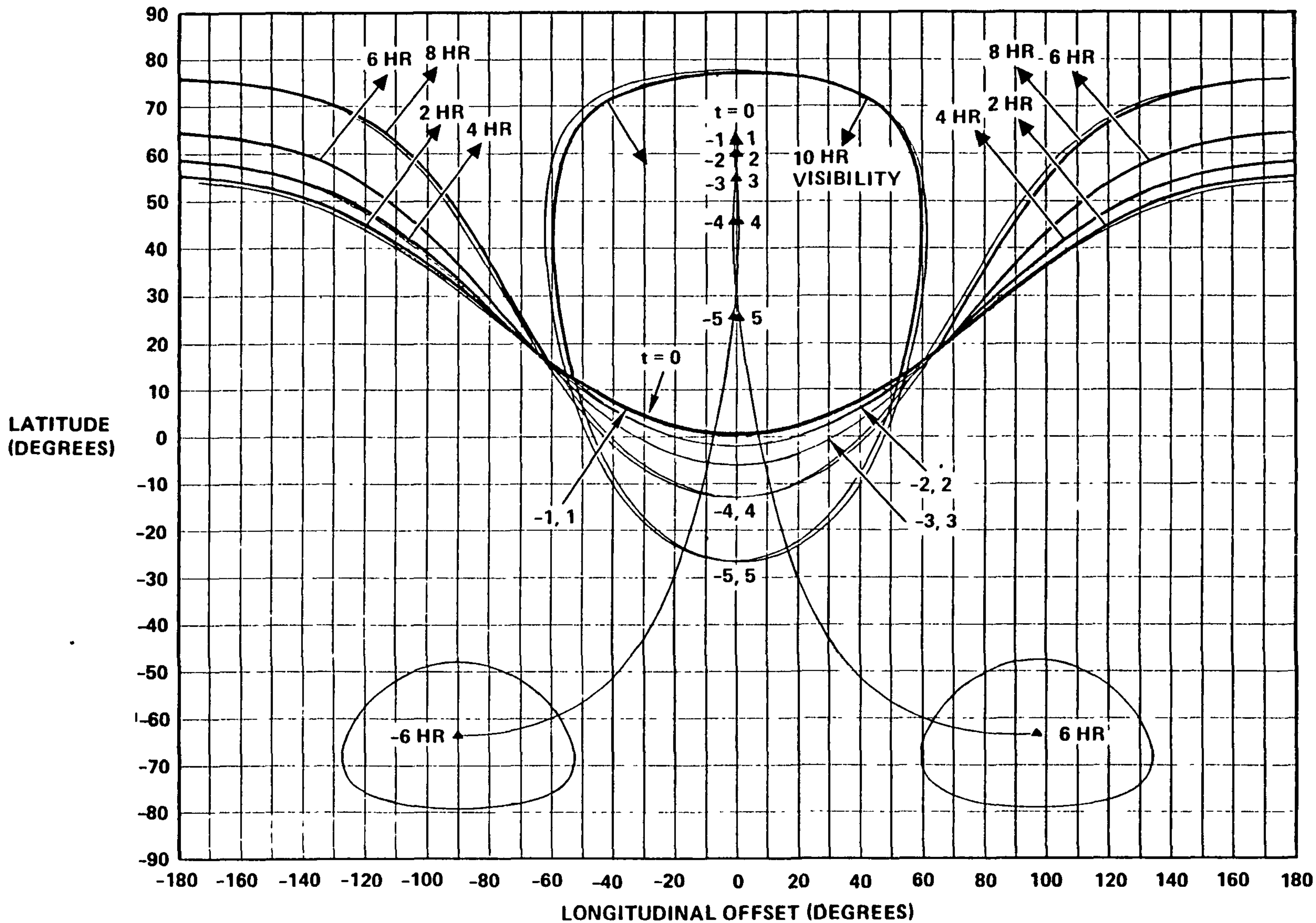



Figure 8-2. Satellite Visibility Periods for Molniya Orbit

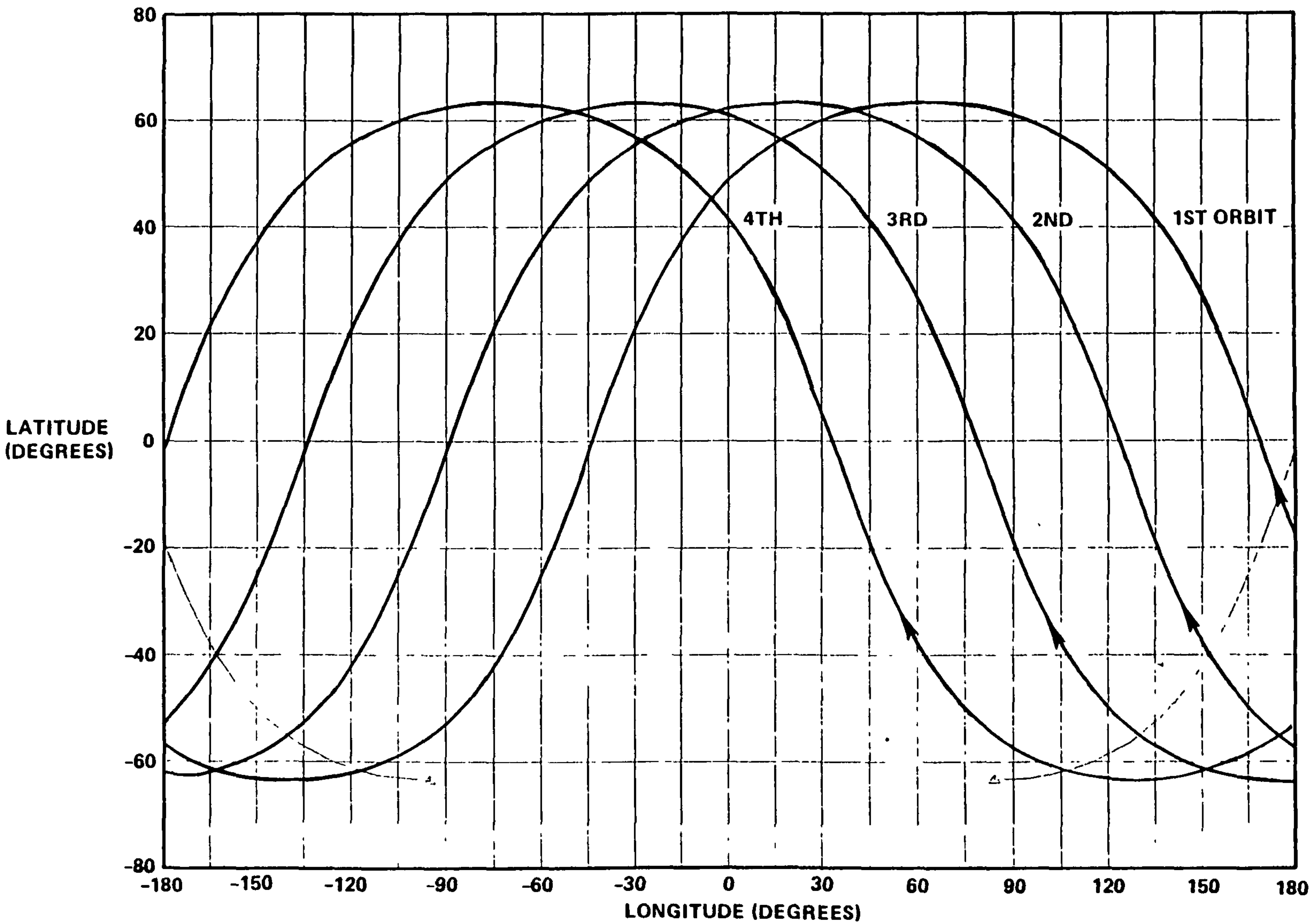



Figure 8-3. Triply-Sync Orbit Ground Track

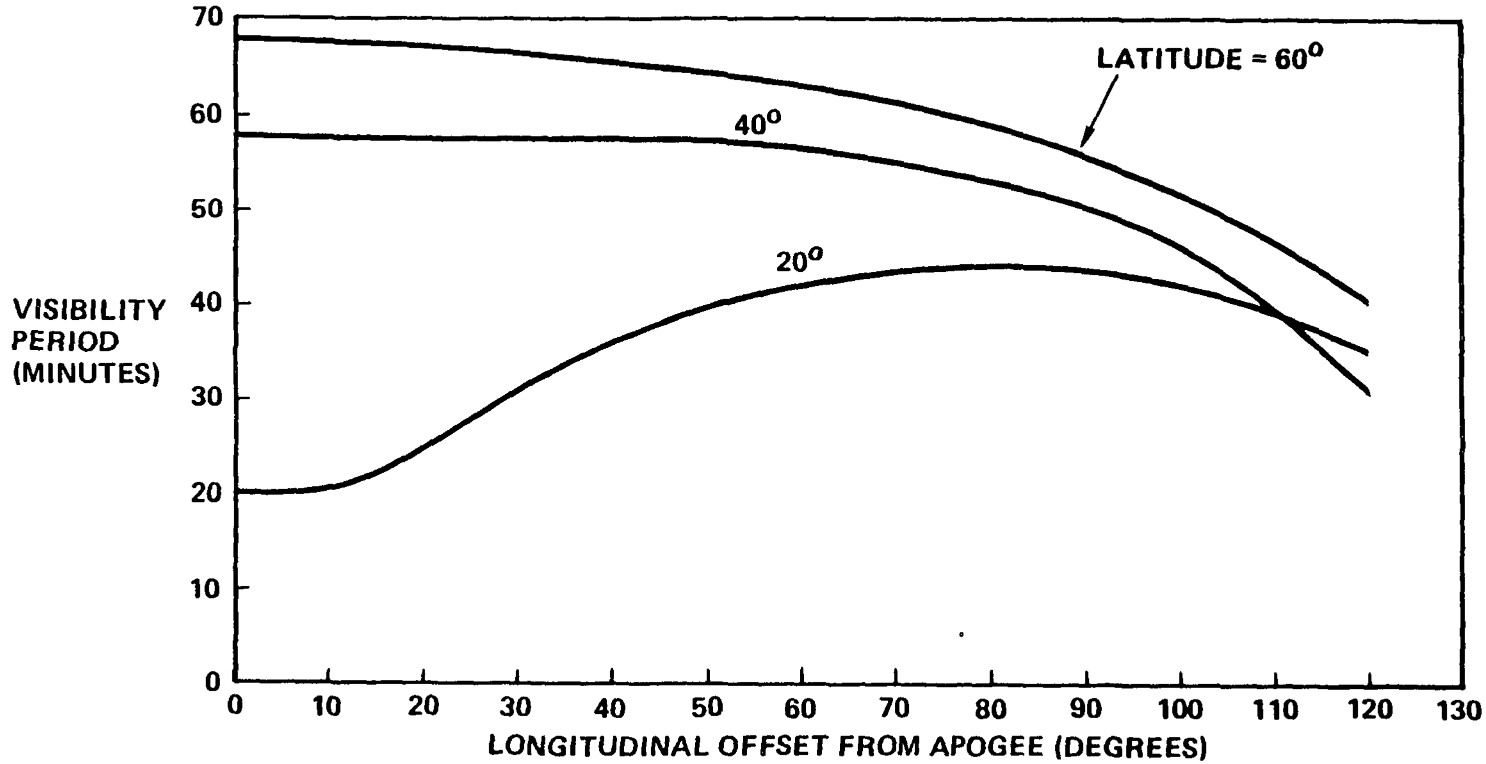



Figure 8-4. Visibility Period for Triply-Sync Orbit

The exact number of satellite passes on which the selected period of visibility is realized depends on the longitudinal offset from the closest satellite pass.

| Latitude (Degrees) | Period of Visibility (Min) | Number of passes |
|---|---|---|
| 60 | 50 | 5 |
| 40 | 50 | 4 |
| 20 | 30 | 6 |

Visibility of a satellite in subsynchronous orbit will be described next, as a function of observer latitude and longitudinal separation from the satellite ascending node.

The ground track for a 6-hour circular orbit of 28.5 degrees inclination is shown in Figure 8-5. Passage through the ascending node is assumed to occur at t=0. Although four complete orbits (i.e., 24 hours) are required before the ground track repeats, because of the earth's rotation there are only three distinct satellite passes. In other words, depending on the observer coordinates, there can be as many as three separate visibility periods daily.

Satellite visibility for the 6-hour orbit, based on a minimum elevation angle of 20 degrees, is shown for longitudinal separations from the ascending node of 0, 30, 60, 75, and 115 degrees in Figures 8-6 to 8-10. Visibility is shown only for discrete values of latitude that are multiples of $\pm10$ degrees. Visibility is considered for 1/2-hour periods beginning on the hour or 1/2-hour. The shaded areas correspond to complete 1/2-hour periods of visibility. Actual visibility, therefore, can exceed that shown by an amount approaching 1 hour (1/2 hour for satellite ascent plus 1/2 hour for satellite descent) in extreme cases.

Visibility data for longitudinal offsets in the range (0°, 135°) can be simply manipulated to obtain visibility for the range (135°, 270°). Note that the ground track for the latter interval in Figure 8-1 is identical to the ground track for the former interval reflected about the 0-degree latitude line. Therefore, the shaded regions in each of Figures 8-6 to 8-10, if shifted to the right by 3 hours and reflected about the 0-degree latitude line, apply to a longitude that is higher by 135 degrees than that indicated.

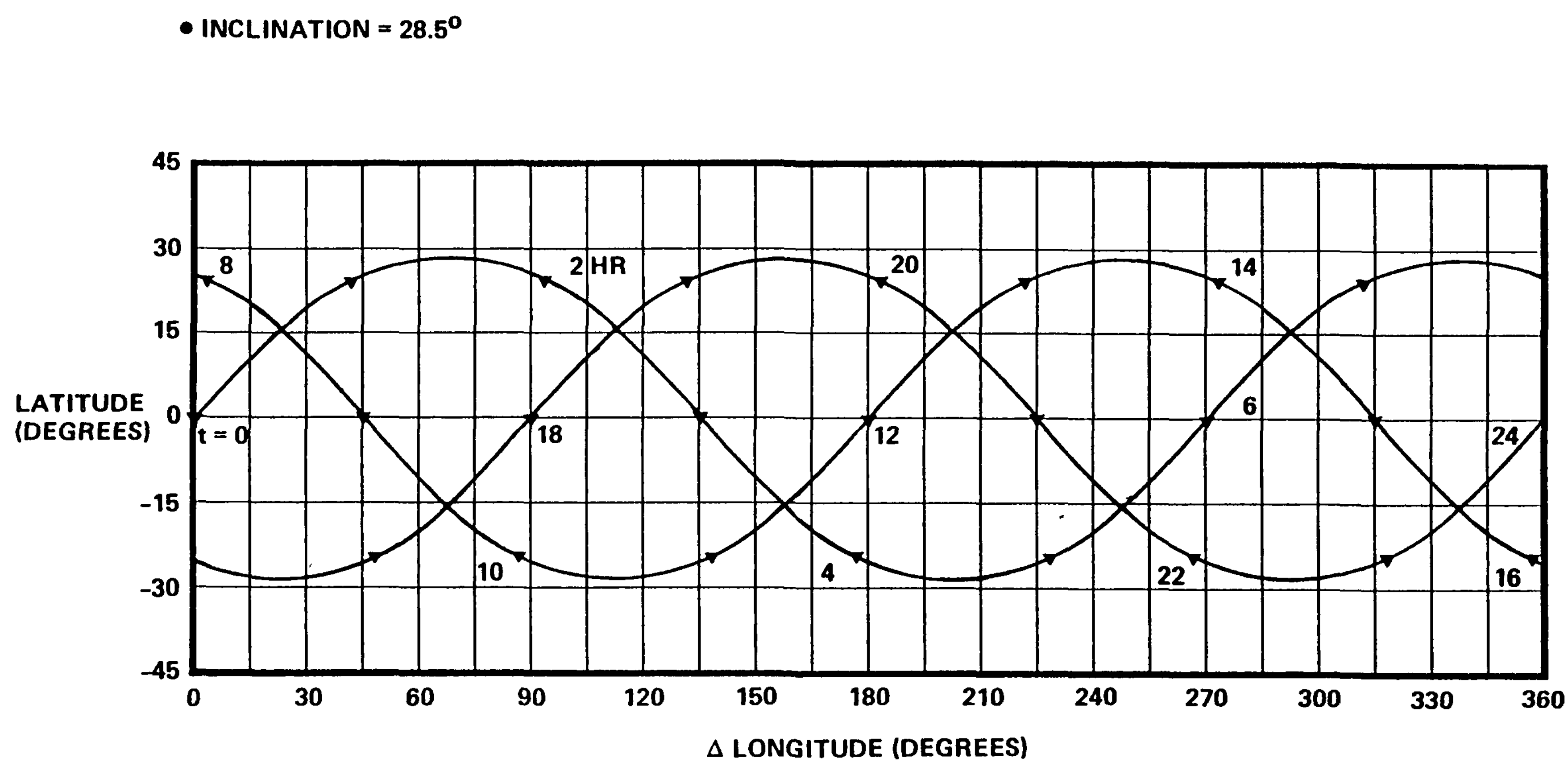



Figure 8-5. Ground Track for 6-Hour Circular Orbit

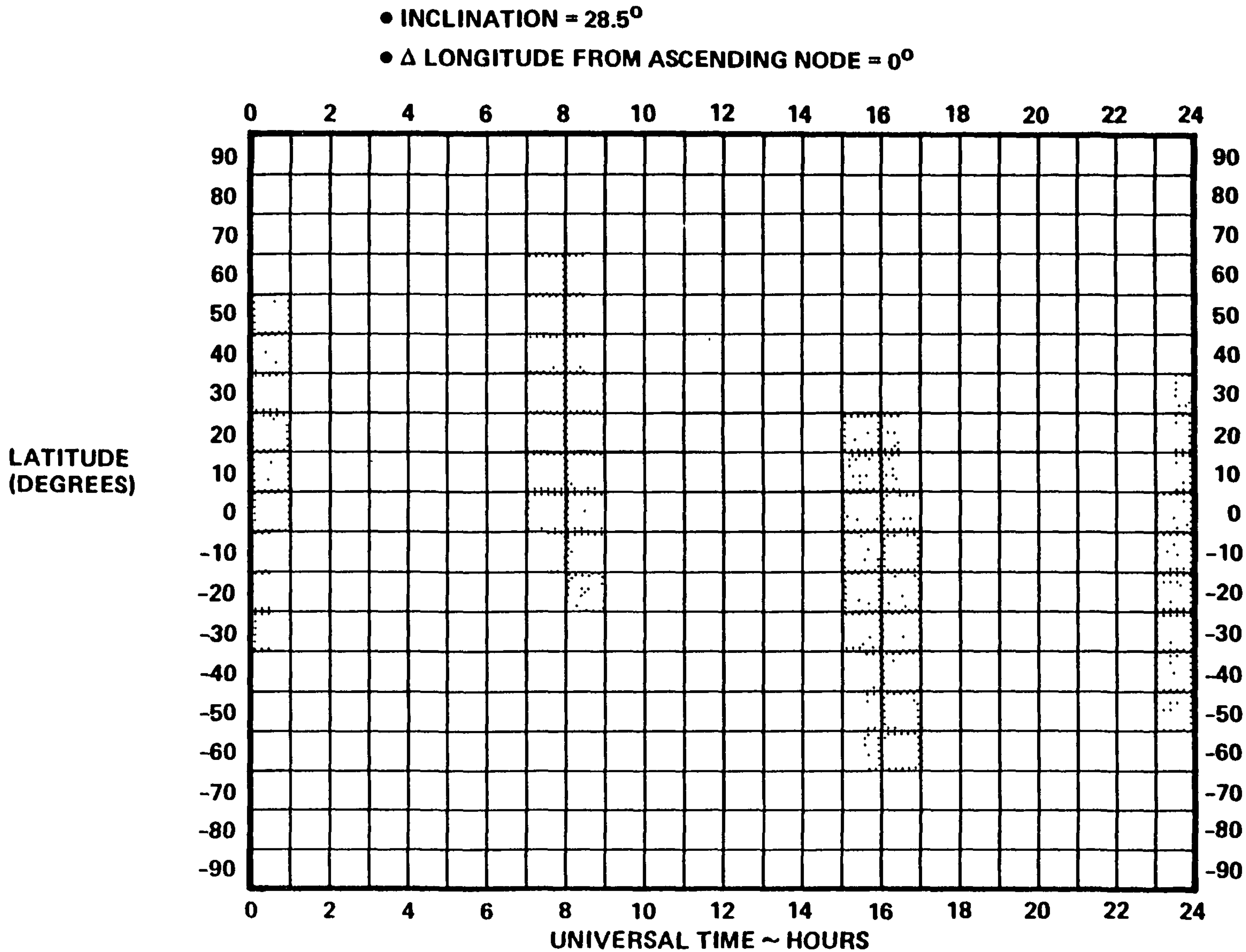



Figure 8-6. Single-Satellite Visibility for 6-Hour Circular Orbit

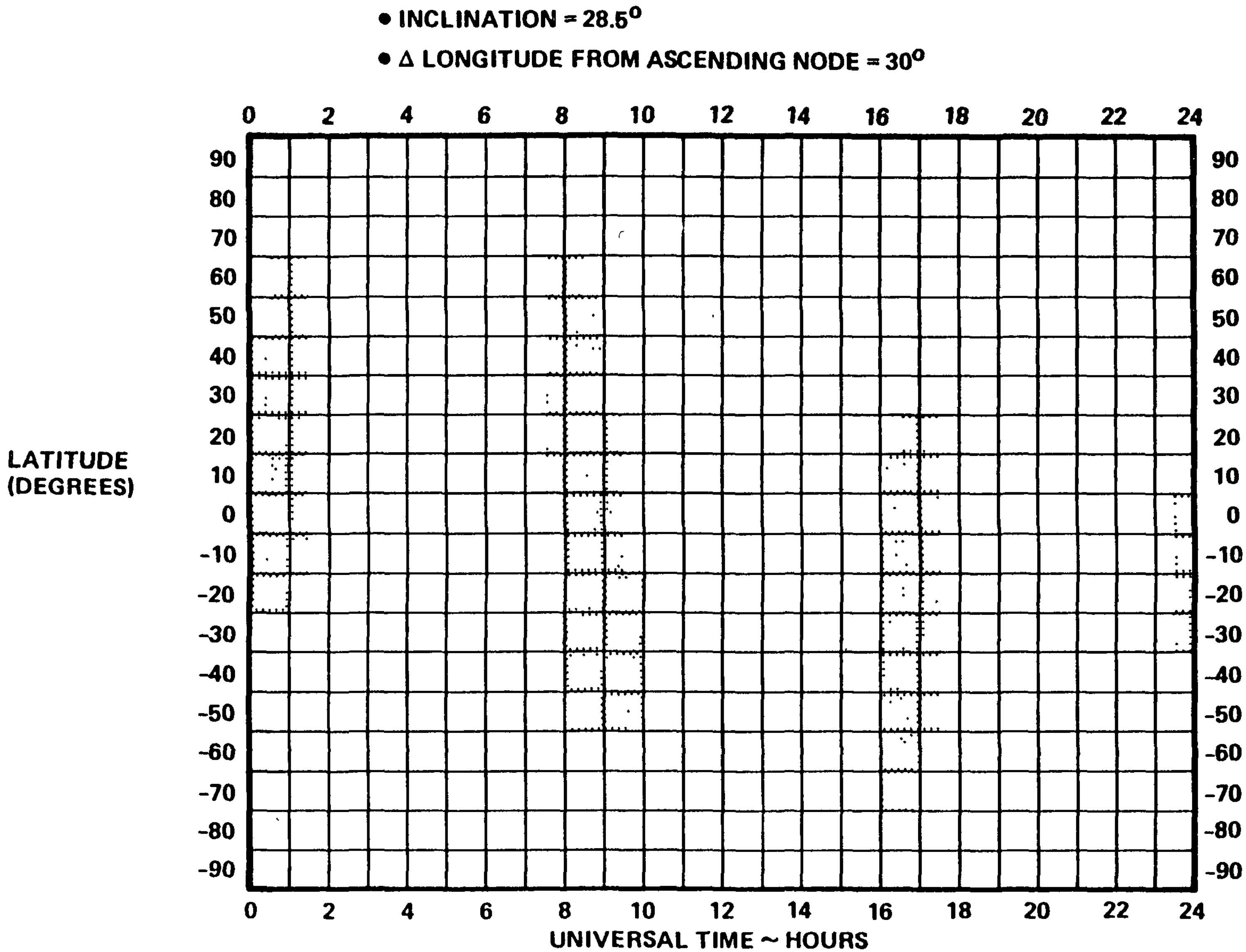



Figure 8-7. Single-Satellite Visibility for 6-Hour Circular Orbit

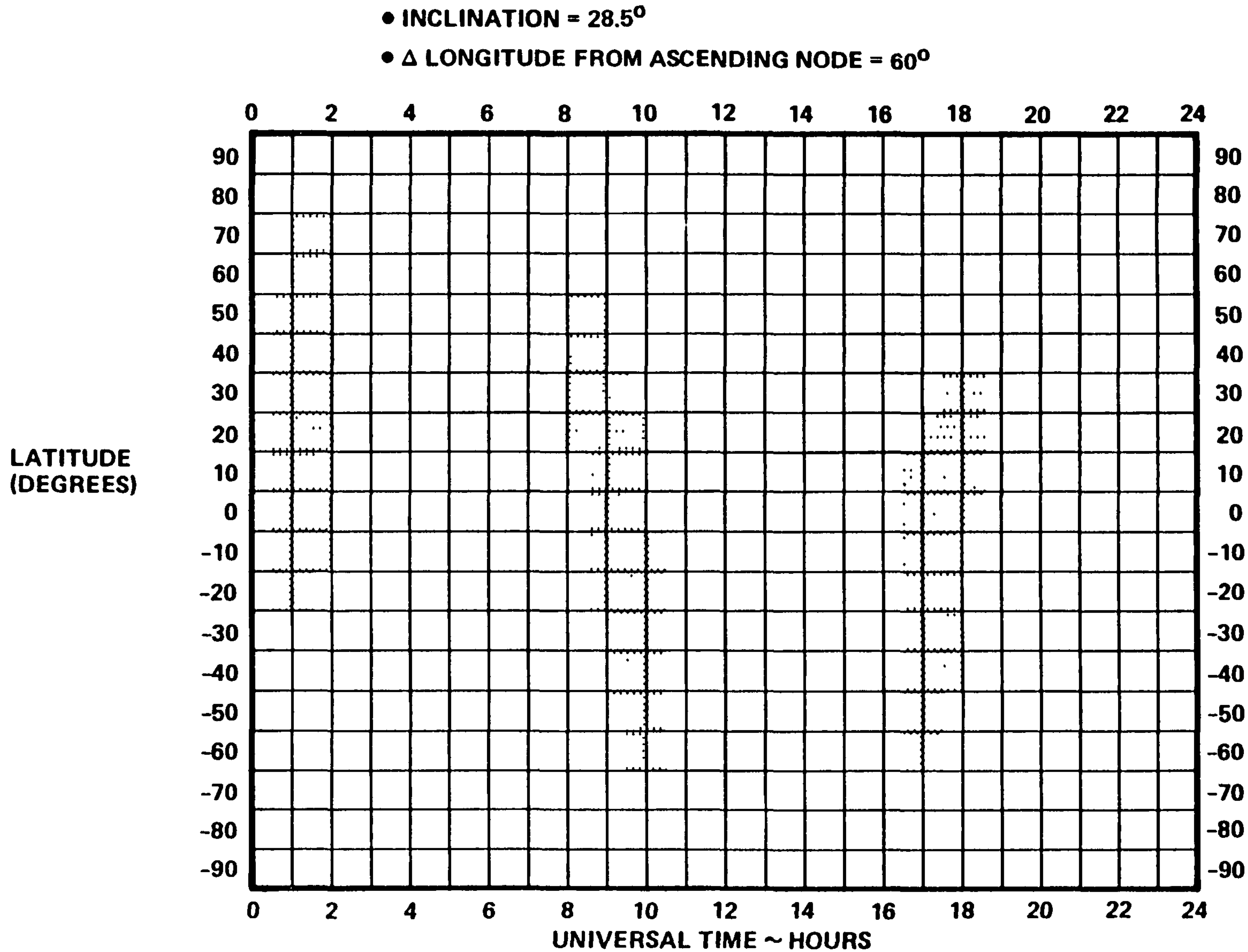



Figure 8-8. Single-Satellite Visibility for 6-Hour Circular Orbit

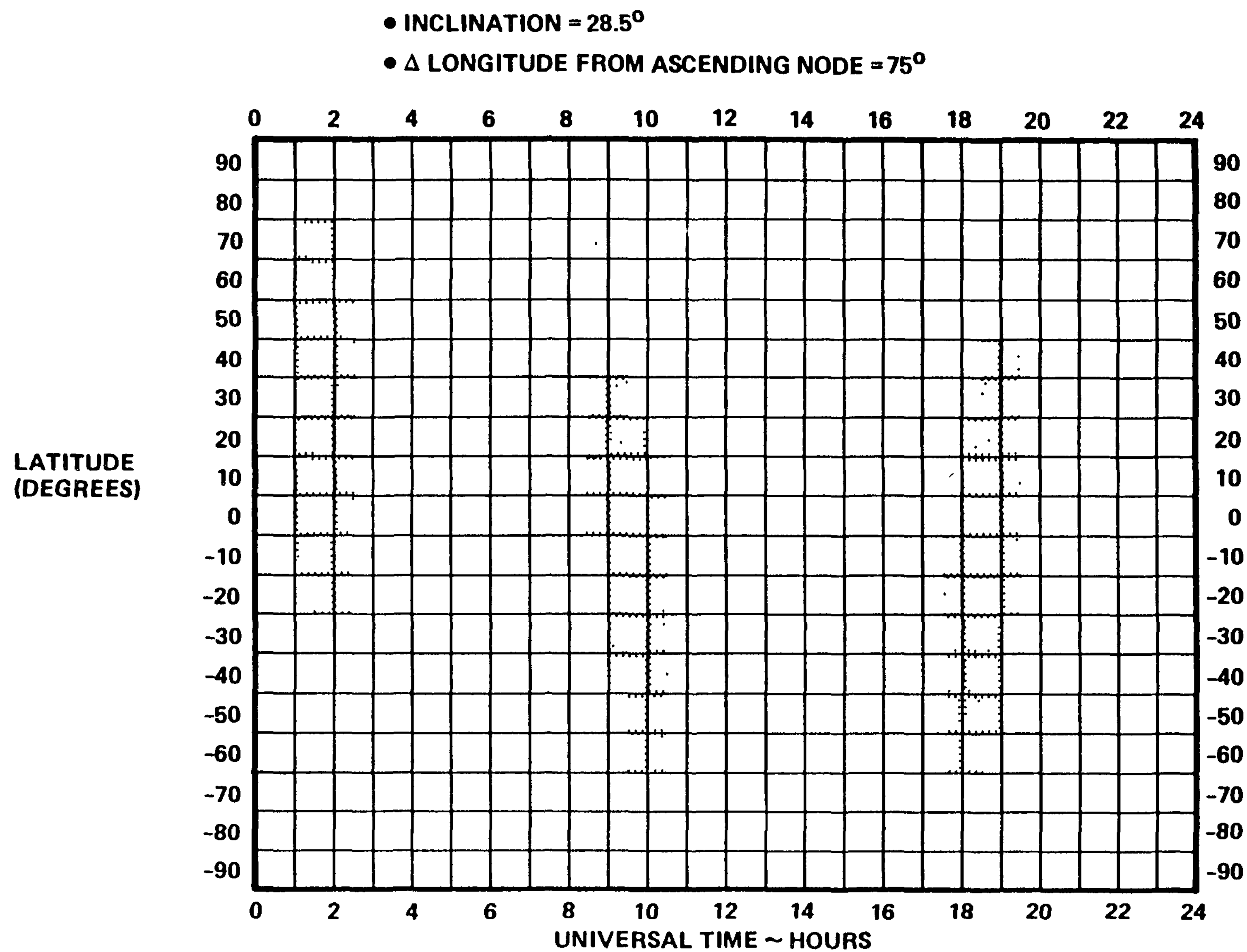



Figure 8-9. Single-Satellite Visibility for 6-Hour Circular Orbit

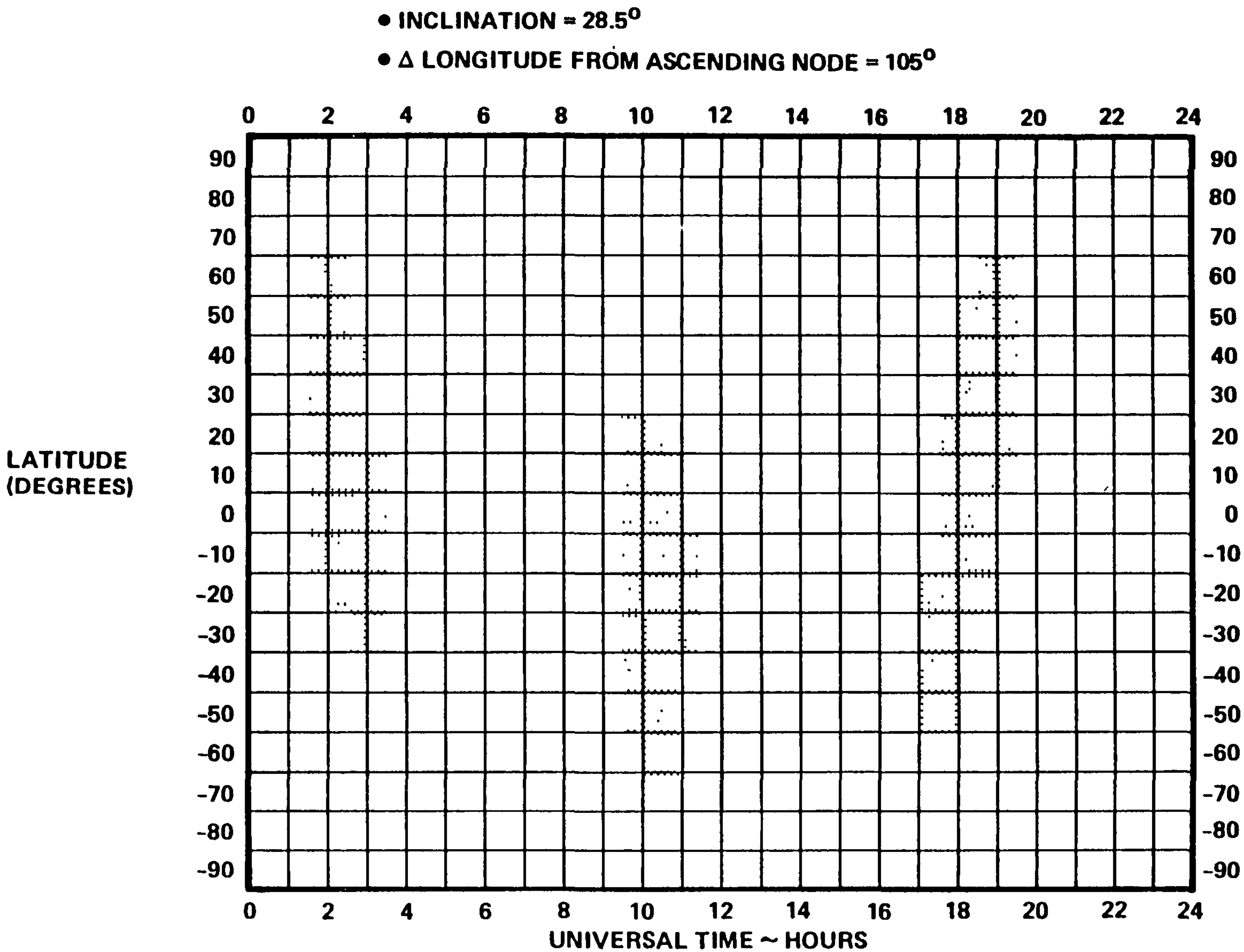



Figure 8-10. Single-Satellite Visibility for 6-Hour Circular Orbit

Satellite visibility for the longitude range (270°, 360°) is identical to that for the range (0°, 90°), except for a 6-hour delay.

The ground track for an 8-hour circular orbit of 28.5 degrees inclination is shown in Figure 8-11. In this case there are two distinct satellite passes, leading to the possibility of two separate visibility periods daily. Satellite visibility for longitudinal offsets of 0, 30, 60, and 90 degrees is shown in Figures 8-12 to 8-15. Visibility for a longitudinal offset in the range (120°, 240°) can be found from that for an offset which is smaller by 120 degrees, through a 4-hour delay and a reflection about the 0-degree latitude line. Visibility for longitudinal offsets in the range (240°, 360°) is identical to that for offsets in the range (0°, 120°), except for an 8-hour time delay.

Finally, the 12-hour ground track is shown in Figure 8-16. In this case there is but a single satellite pass each day. Satellite visibility for longitudinal offsets of 0, 30, 45, and 60 degrees is shown in Figures 8-17 to 8-20. Visibility for the offset range (180°, 270°) is the same as that for the range (0°, 90°), except for a 12-hour delay. Visibility for the longitudinal ranges (90°, 180°) and (270°, 360°) is obtained from the pattern for the range (0°, 90°) by a delay of 6 or 18 hours, respectively, and a reflection about the 0-degree latitude line.

In applying visibility data for the various orbits to specific geographic locations, it should be remembered that the satellite will appear at a given point on the ground track 4 minutes earlier each day. The visibility patterns, as related to universal time or GMT, are therefore valid only for a single time of year. Relative to that time of year, the patterns rotate to the left at the rate of 4 minutes per day.

## 8.2 REPRESENTATIVE OTV/SATELLITE CHARACTERISTICS

Because the required field strength covers such a wide range (from 300 to 50 μV/m), the satellite transmitter power for a selected orbit and given beamwidth can vary by a ratio of 36:1. It would make little sense, however, to maintain a fixed beamwidth (equal, say, to the baseline geostationary equivalent of 3 degrees) in the face of a reduction in required field strength to 50 μV/m. Instead, the antenna size and RF power requirement have been traded off to maintain a reasonable balance between the two parameter values.

• INCLINATION = 28.5°

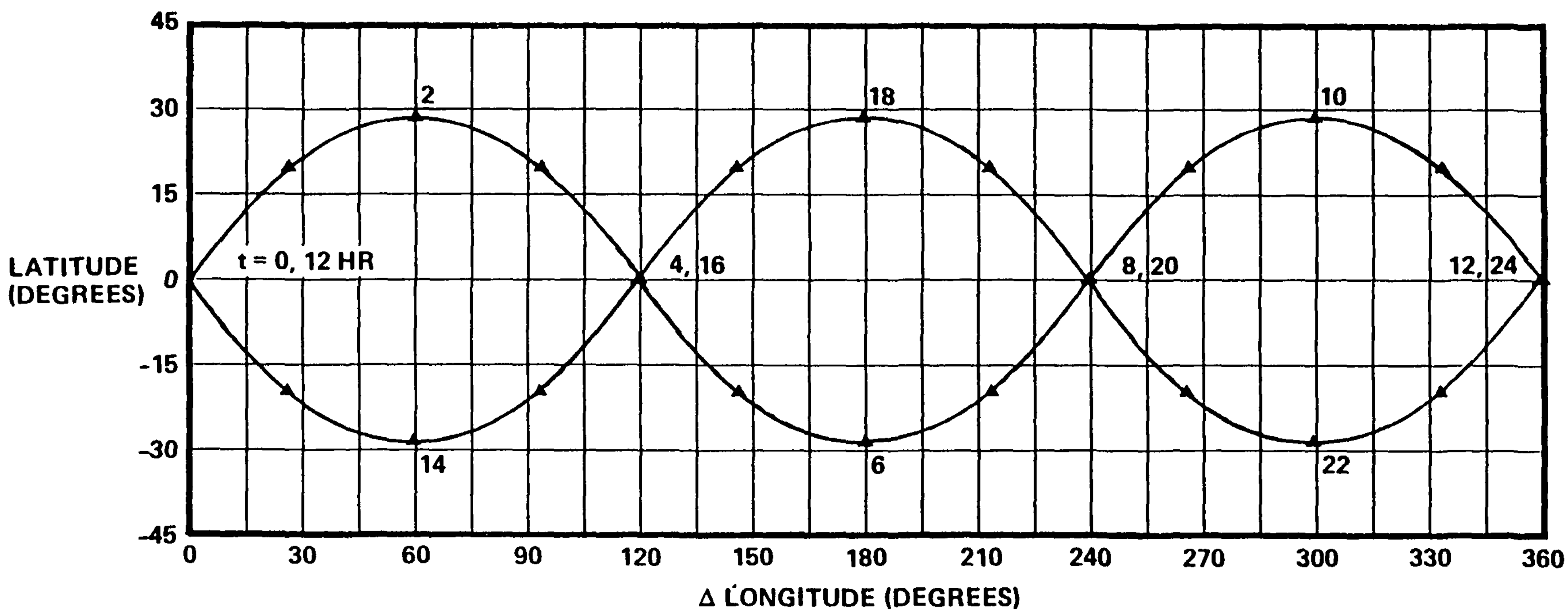



Figure 8-11. Ground Track for 8-Hour Circular Orbit

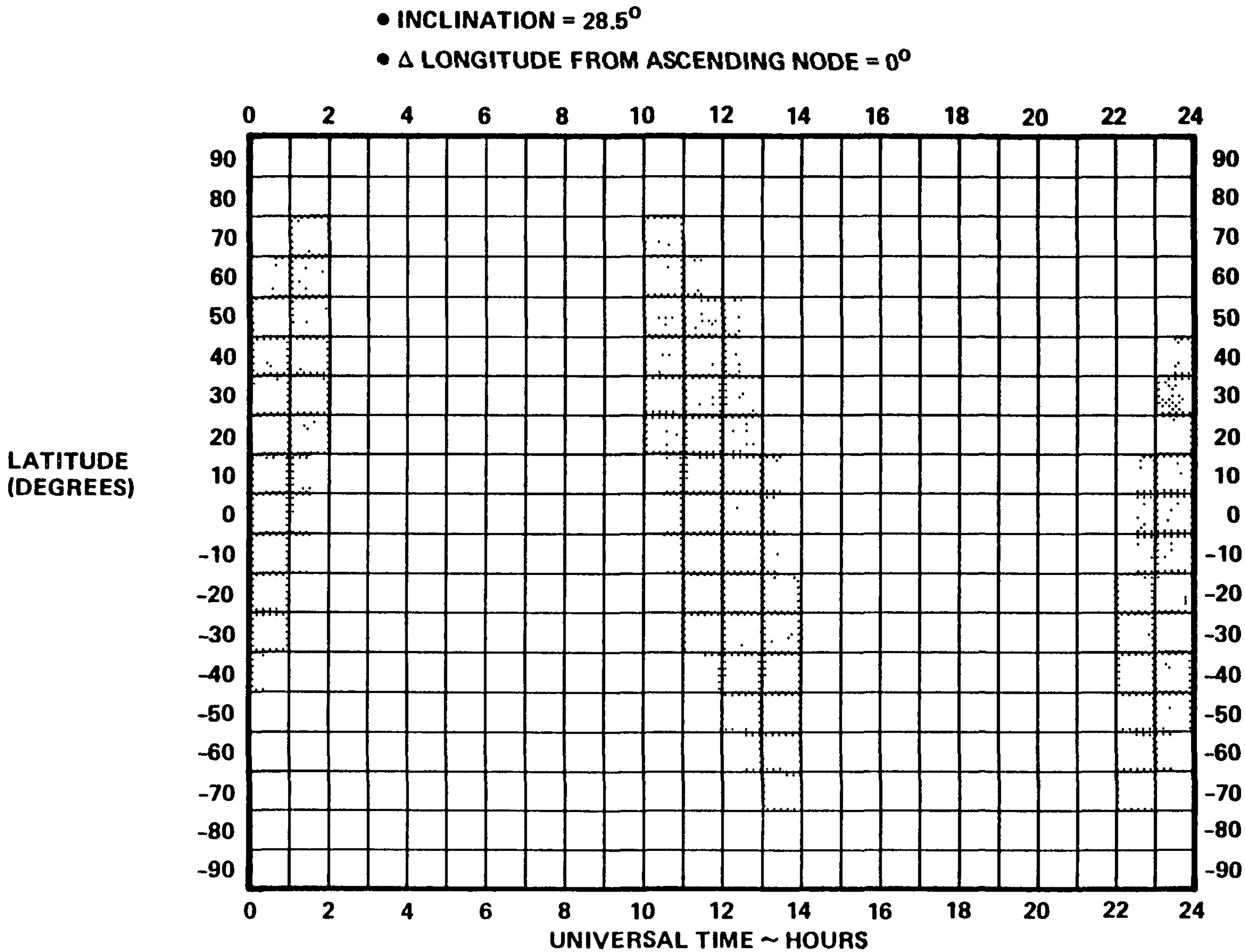



Figure 8-12. Single-Satellite Visibility for 8-Hour Circular Orbit

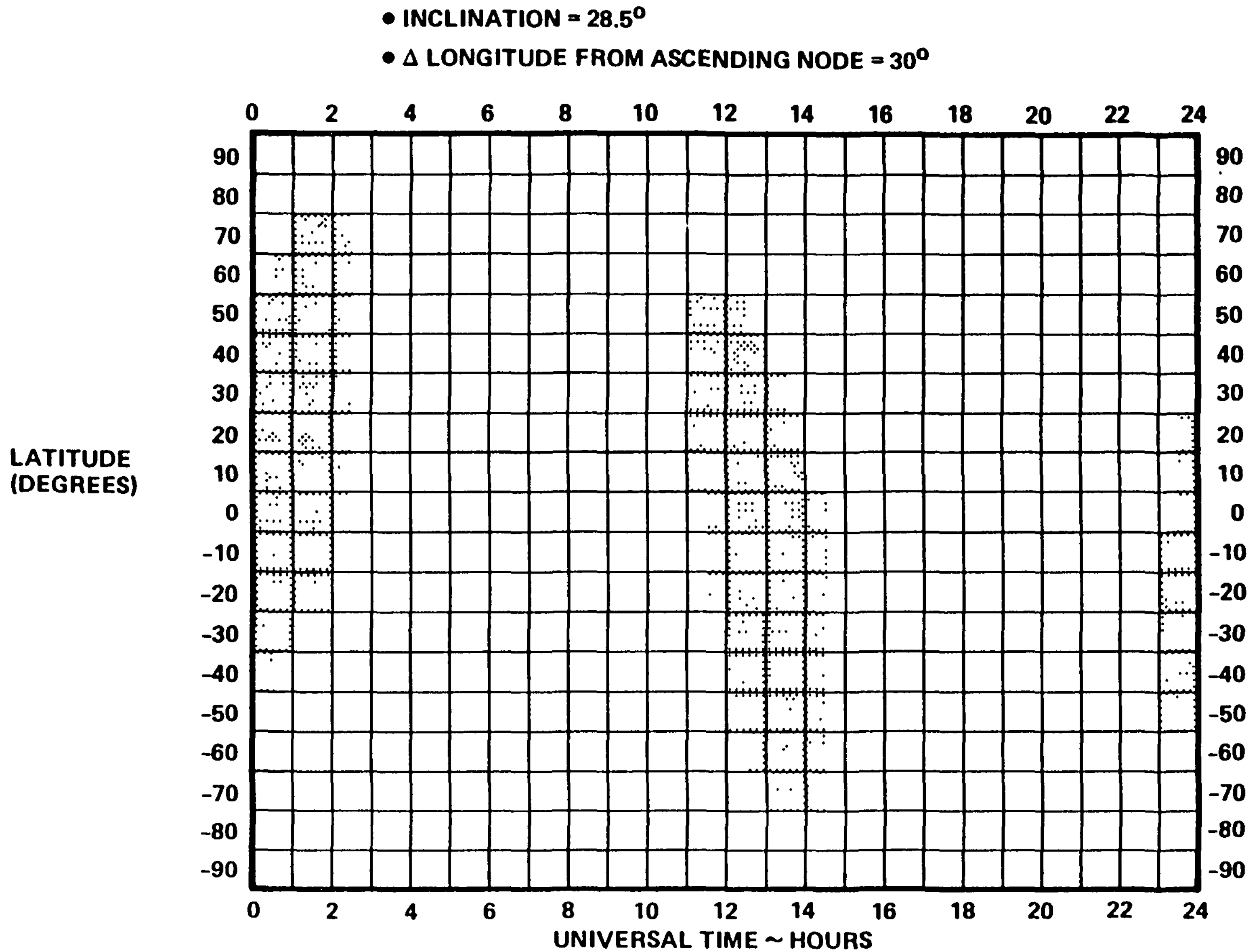



Figure 8-13. Single-Satellite Visibility for 8-Hour Circular Orbit

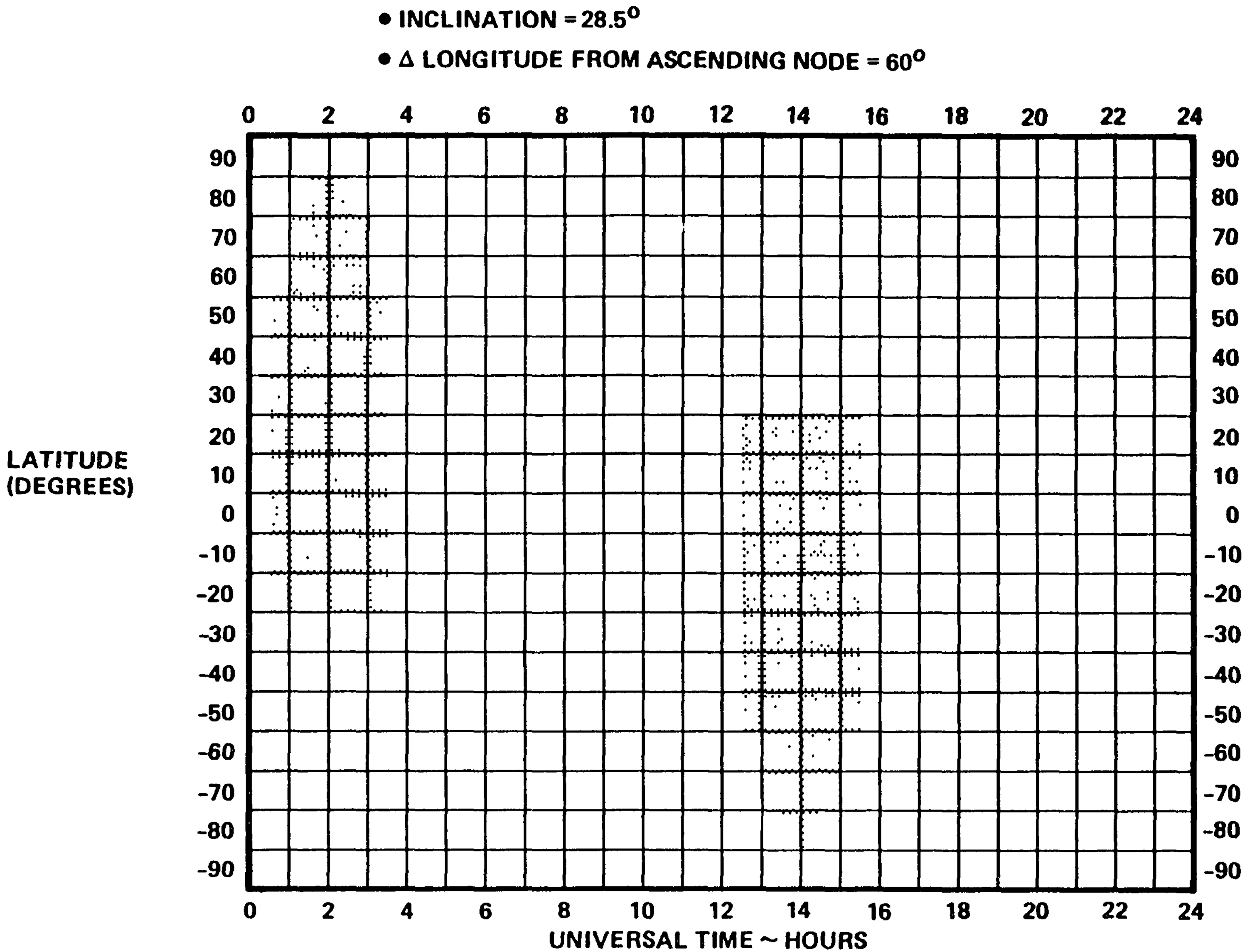
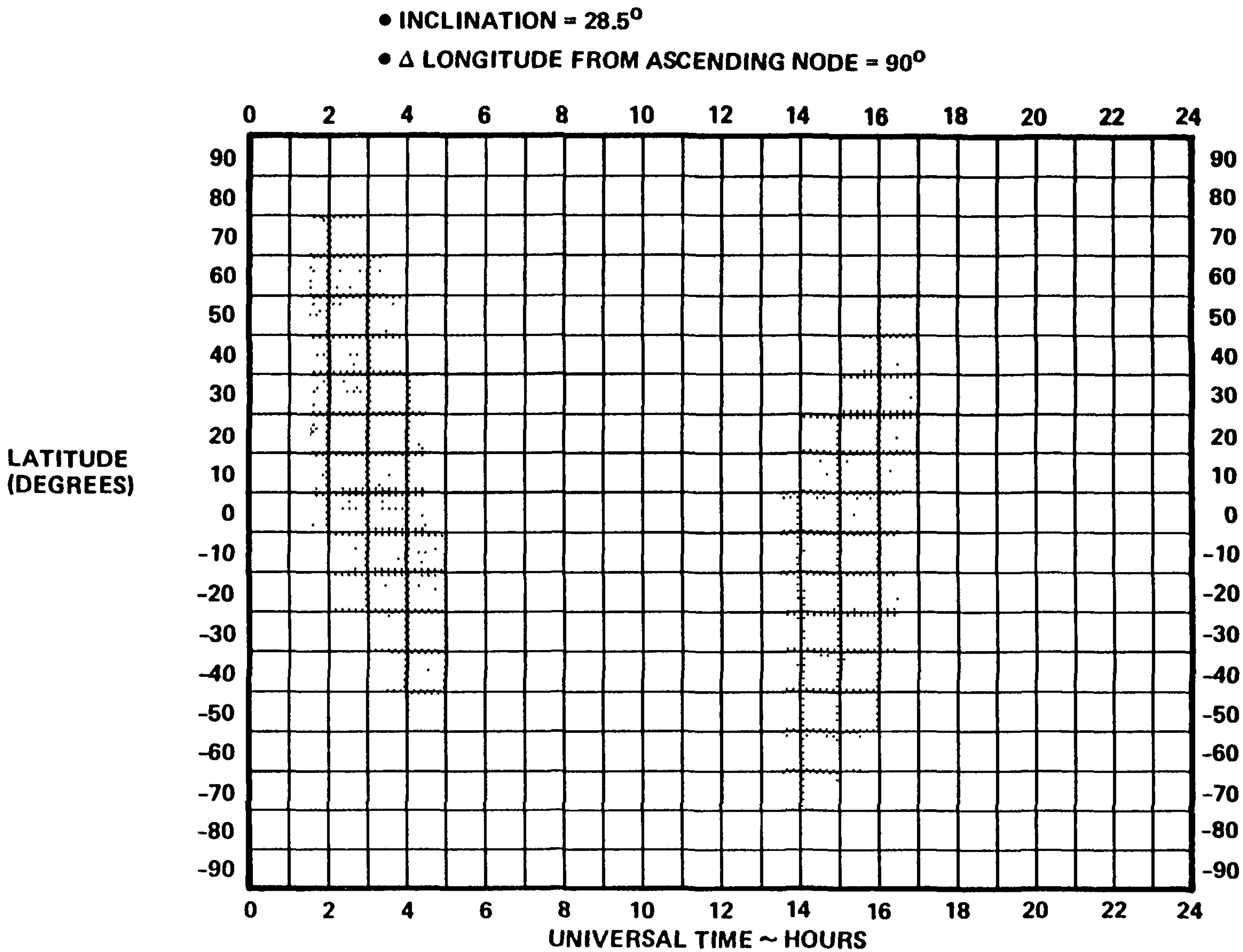



Figure 8-14. Single-Satellite Visibility for 8-Hour Circular Orbit




ORIGINAL PAGE IS OF POOR QUALITY

Figure 8-15. Single-Satellite Visibility for 8-Hour Circular Orbit

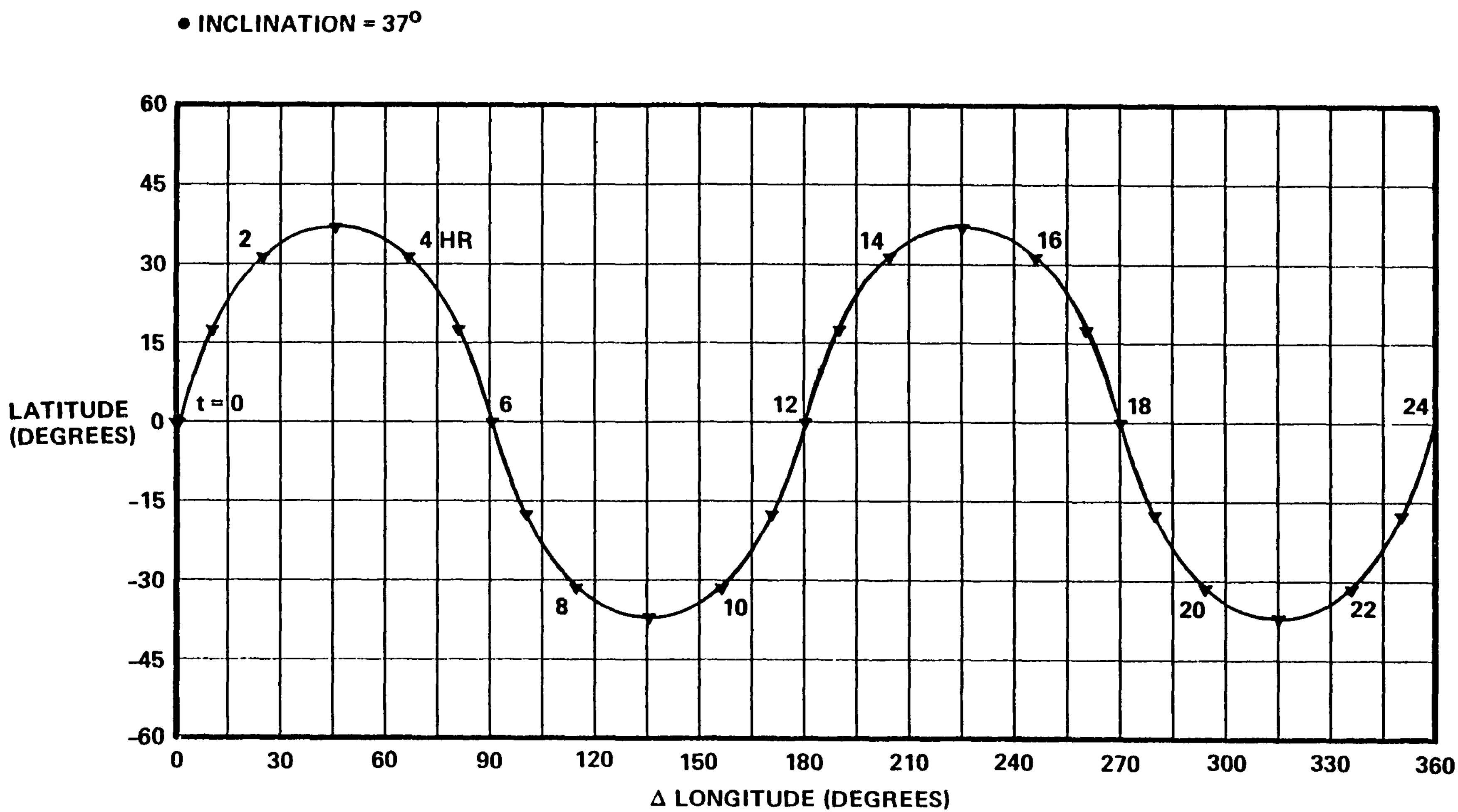



Figure 8-16. Ground Track for 12-Hour Circular Orbit

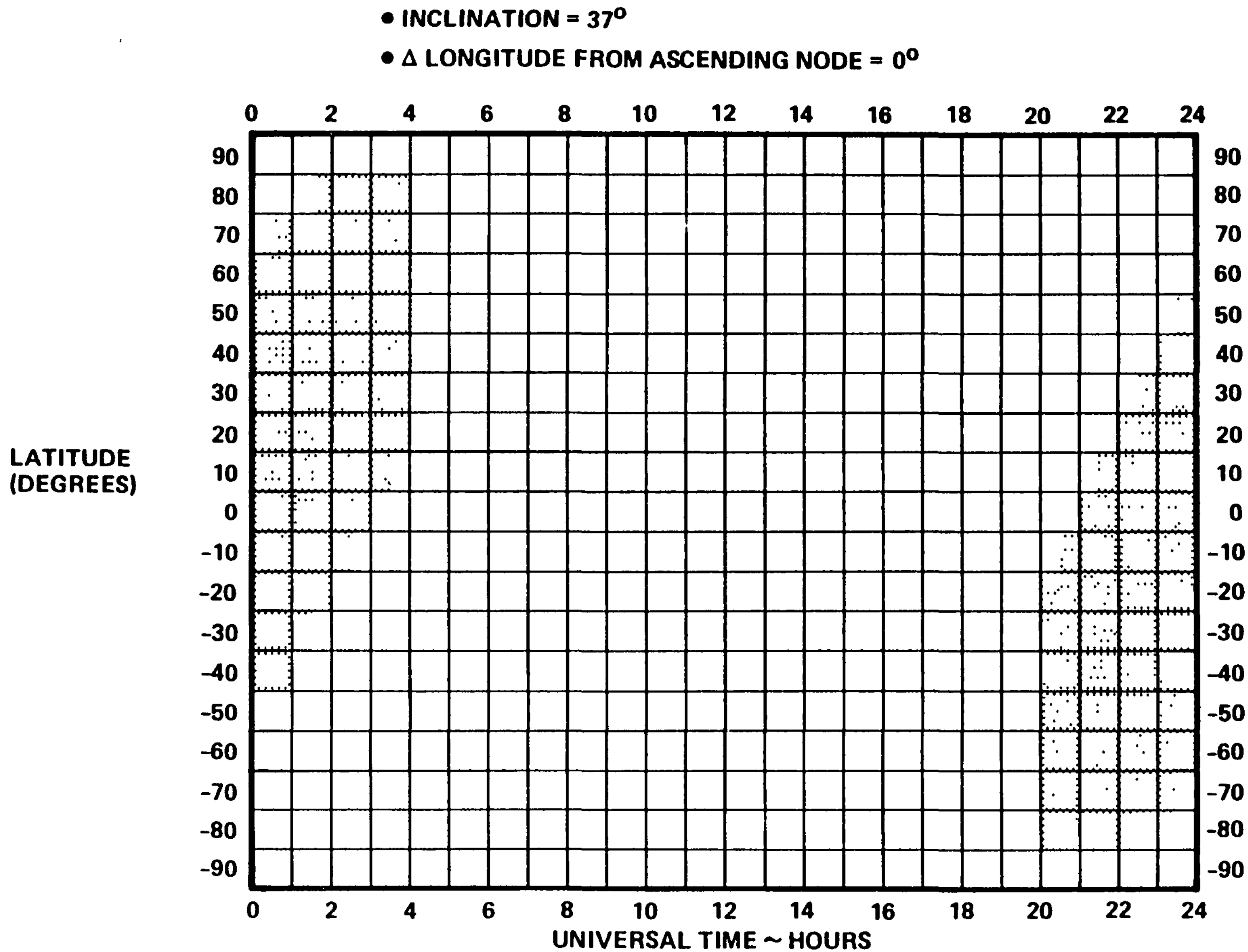



Figure 8-17. Single-Satellite Visibility for 12-Hour Circular Orbit

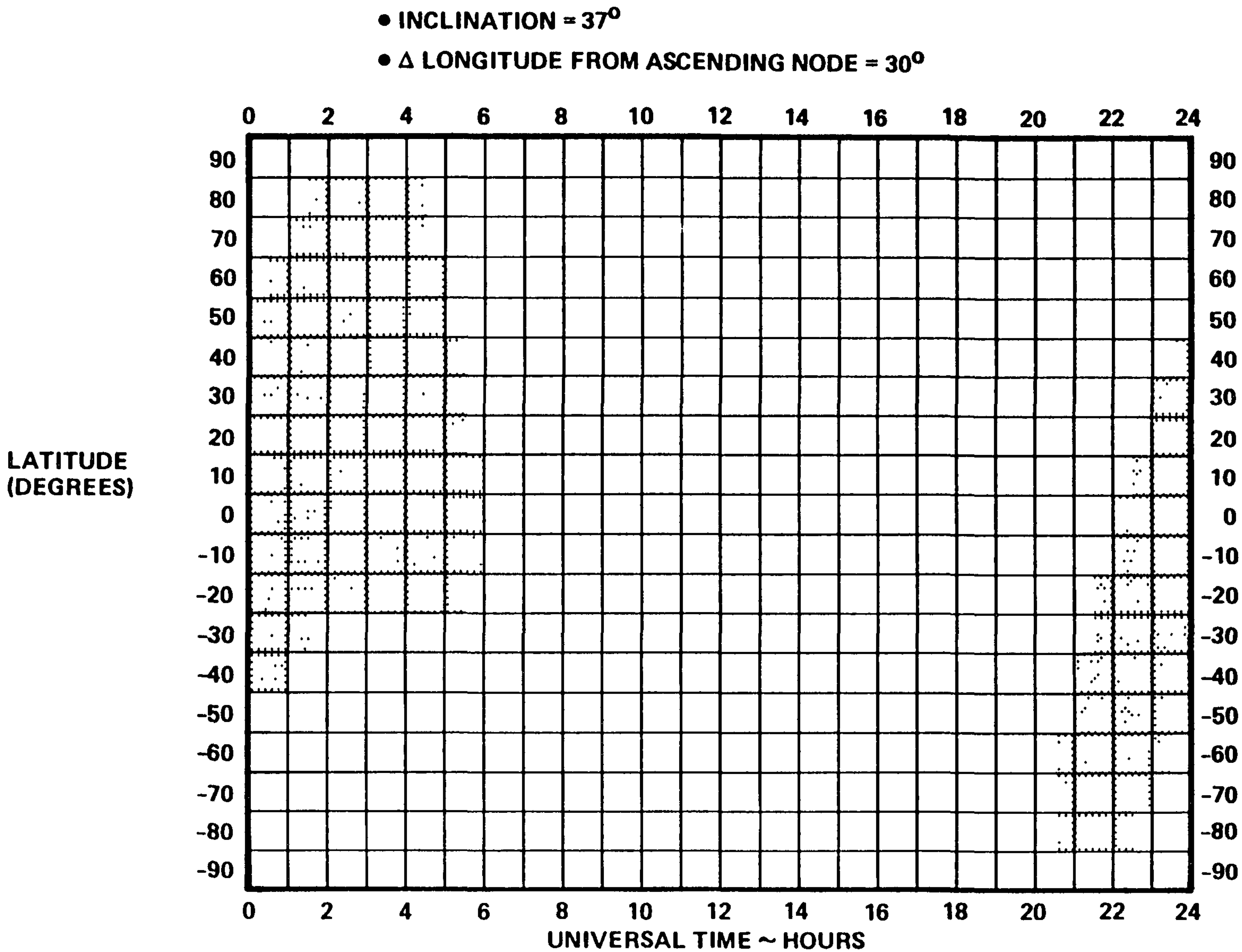



Figure 8-18. Single-Satellite Visibility for 12-Hour Circular Orbit

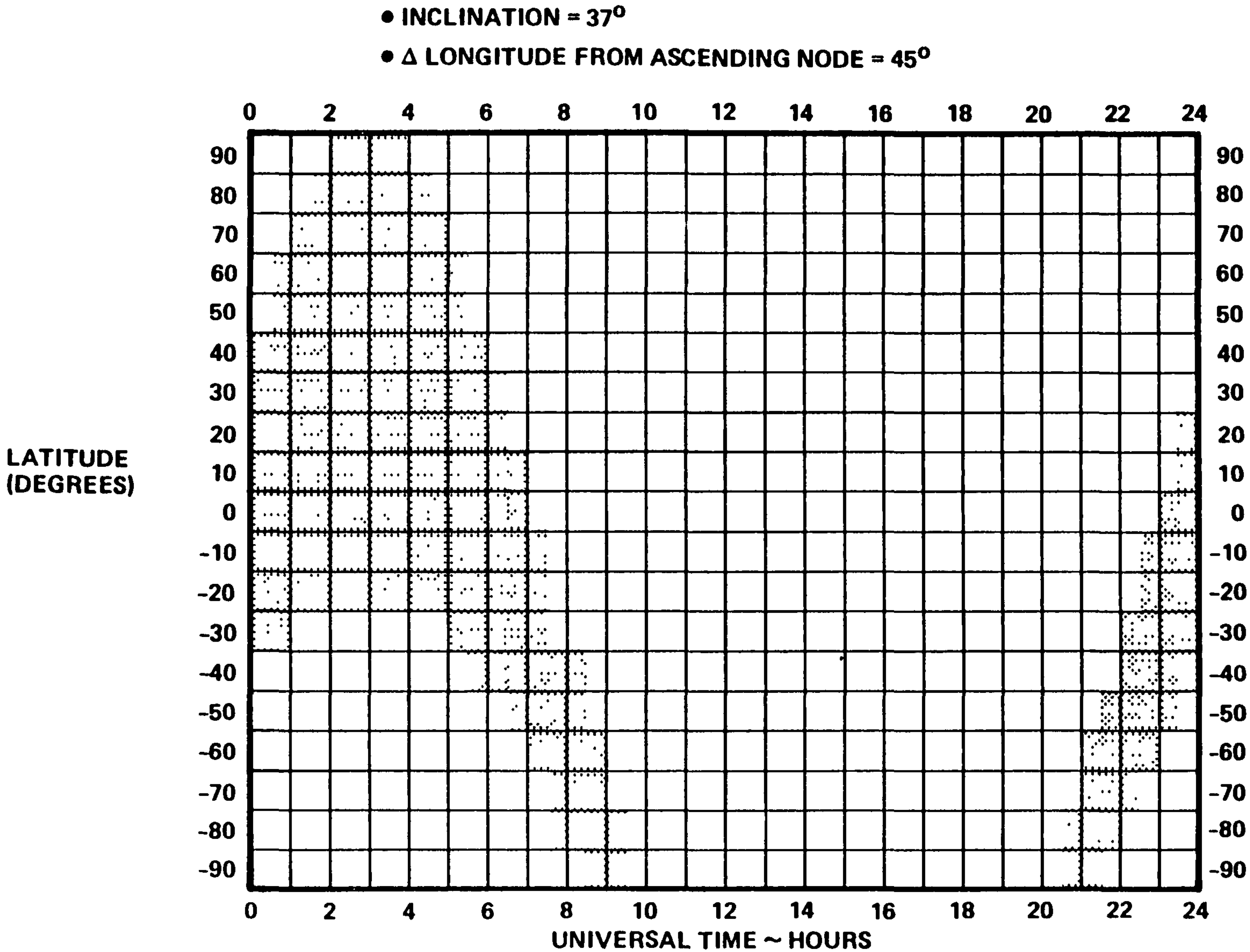



Figure 8-19. Single-Satellite Visibility for 12-Hour Circular Orbit

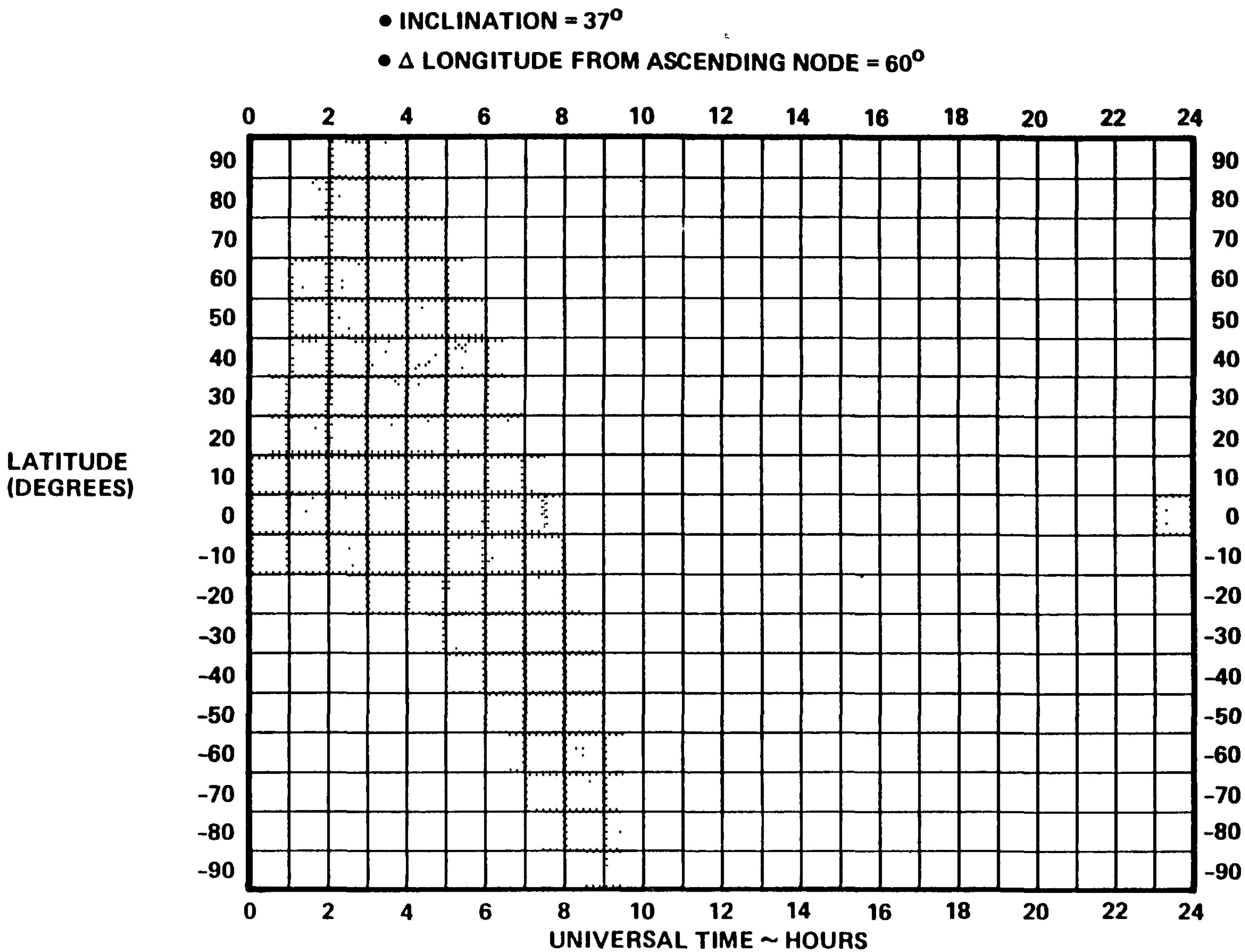



Figure 8-20. Single-Satellite Visibility for 12-Hour Circular Orbit

To accommodate the widely varying system requirements, a stable of OTVs with comparably varying payload capability to broadcast orbit must be considered. The selected OTVs are indicated in Table 8-1.

The custom cryogenic OTV is the Centaur-class vehicle that has been used throughout the study to this point. Fuel loading is determined, in conjunction with the STS lift capability of 65,000 pounds to LEO, to maximize the payload weight to broadcast orbit. This OTV is needed at the higher field strengths for both the geostationary and the Molniya orbits. (The satellite weight requirements for the Molniya orbit are considerably greater in Band 1 than they would be in Band 2.)

The PAM-A is the preferred OTV at very low values of field strength for 6- and 8-hour circular orbits and for the triply-sync orbit.

A custom bipropellant OTV has been selected to fill the wide gap between the PAM-A and the custom cryogenic OTV. The needed payload flexibility is obtained by allowing the portion of the STS lift capability actually used to vary. For the selected value, the OTV fuel loading is varied to maximize the payload weight to broadcast orbit. The custom bipropellant OTV is similar to the Aerojet HPPM. The latter has an ISP of 328 seconds; a conservative value of 300 seconds has been assumed for the former.

Representative satellite parameter values for the six orbits, for each of the three field strengths, are given in Table 8-2. (Except for the three cases noted below, in which current rather than advanced technology is assumed, satellite sizing is accomplished through use of the satellite weight estimation software developed under this contract.) Because of the generally large equivalent geostationary beamwidths, either a cable-catenary or a phased-array antenna is physically feasible in most cases. The former is selected for the geostationary, Molniya, and triply-sync orbits because the requirements call for a single, essentially fixed beam. (Broadcasting from Molniya orbit takes place during the near-stationary portion of the orbit centered at apogee, while the triply-sync antenna beam is assumed to be directed toward the center of the earth.) The phased array is retained for the three circular, subsynchronous orbits because of the need to continuously repoint the beam to compensate for satellite motion.

Table 8-1. Candidate Orbital Transfer Vehicles

| Orbital Transfer Vehicle | ISP (sec) | Fuel Capacity (lb) |
|---|---|---|
| Custom Cryogenic | 450 | Variable |
| Custom Bipropellant | 300 | Variable |
| PAM-A | 276 | 7751 |

Table 8-2. Representative OTV/Satellite Characteristics for Single-Channel Capability at 26 MHz

| ORBIT | FIELD STRENGTH (μV/m) | ORBITAL TRANSFER VEHICLE | STS PAYLOAD TO LEO (LB) | EQUIVALENT GEO BEAMWIDTH (DEG) | ANTENNA APERTURE (M) | AVERAGE RF POWER (kW) | SATELLITE WEIGHT (LB) |
|---|---|---|---|---|---|---|---|
| GEO | 300 | CENTAUR | 65,000 | 5.5 | 146 | 40 | 11,108 |
| GEO | 150 | CENTAUR | 65,000 | 12.2 | 66 | 50 | 11,051 |
| GEO | 50 | CUSTOM BIPROP | 40,000 | 20.0 | 40 | 15 | 4,209 |
| MOLNIYA | 300 | CENTAUR | 65,000 | 6.8 | 130 | 59 | 16,192 |
| MOLNIYA | 150 | CENTAUR | 65,000 | 14.4 | 62 | 66 | 16,143 |
| MOLNIYA | 50 | CUSTOM BIPROP | 40,000 | 28.0 | 32 | 28 | 7,302 |
| TRIPLY SYNC | 300 | CUSTOM BIPROP | 30,000 | 3.4 | 71 | 15 | 9,564 |
| TRIPLY SYNC | 150 | CUSTOM BIPROP | 30,000 | 7.2 | 33 | 17 | 9,629 |
| TRIPLY SYNC | 50 | PAM-A | 20,700 | 16.6 | 14 | 10 | 5,861 |

Table 8-2. Representative OTV/Satellite Characteristics for Single-Channel Capability at 26 MHz (Continued)

| ORBIT | FIELD STRENGTH ($\mu$V/m) | ORBITAL TRANSFER VEHICLE | STS PAYLOAD TO LEO (LB) | EQUIVALENT GEO BEAMWIDTH (DEG) | ANTENNA APERTURE (M) | AVERAGE RF POWER (kW) | SATELLITE WEIGHT (LB) |
|---|---|---|---|---|---|---|---|
| 6 HR | 300 | CUSTOM BIPROP | 40,000 | 5.0 | 34 | 32 | 9,313 |
| 6 HR | 150 | CUSTOM BIPROP | 38,000 | 10.0 | 11 | 32 | 8,526 |
| 6 HR | 50 | PAM-A | 13,000 | 10.0 | 11 | 3 5 | 4,070* |
| 8 HR | 300 | CUSTOM BIPROP | 42,000 | 5.0 | 46 | 31 | 8,302 |
| 8 HR | 150 | CUSTOM BIPROP | 38,000 | 10.0 | 17 | 31 | 7,109 |
| 8 HR | 50 | PAM-A | 14,500 | 12.0 | 11 | 5.0 | 4,950* |
| 12 HR | 300 | CUSTOM BIPROP | 56,000 | 5.0 | 65 | 31 | 10,082 |
| 12 HR | 150 | CUSTOM BIPROP | 48,000 | 10.0 | 28 | 31 | 8,222 |
| 12 HR | 50 | CUSTOM BIPROP | 21,000 | 13.0 | 19 | 5.7 | 5,860* |

*BASED ON CURRENT TECHNOLOGY

In general, the antenna aperture shown is the smallest value consistent with the indicated STS payload capability. This does not necessarily mean that the antenna/RF-power combination shown leads to the most attractive satellite design. Nevertheless, it is felt that the selected designs represent a reasonable balance between the antenna and RF power requirements.

Because the antenna size is minimized in all cases, no control is exercised over the antenna beamwidth. In many cases, the illuminated region is larger than is meaningful for a single-language broadcast. In fact, in some cases the required field strength is maintained over the entire visible surface of the earth.

The 40,000-pound STS payload to LEO in the geostationary and Molniya, 50 μV/m cases is an arbitrary choice. The antenna size could be reduced further by using the full 65,000 pounds STS lift capability. The 30,000-pound payload to LEO for the triply-sync orbit represents the maximum STS capability.

The STS payload to LEO for the 6-, 8-, and 12-hour orbits was chosen to achieve a reasonable balance between antenna size and RF power. For the 300 μV/m field strength requirement, the equivalent geostationary beamwidth is 5 degrees for all three orbits. Advantage is taken of the field strength reduction to 150 μV/m to reduce the antenna size through a doubling of the beamwidth. For the 6-hour orbit, the further field strength reduction to 50 μV/m is converted into an equivalent decrease in RF power. For the 8- and 12-hour orbits, the same field strength reduction is used to decrease both the antenna size and the RF power.

Among the subsynchronous, circular orbits, it is possible to use the PAM-A only for the 6- and 8-hour, 50 μV/m cases. In both instances, the antenna aperture is fixed at 11 meters, which corresponds to a 2 by 2 phased array. The PAM-A is then off-loaded to the point where a single channel can just be supported.

For most of the cases presented in Table 8-2, the RF power levels are too large to be produced by a single amplifier. For the subsynchronous, circular orbits, where a phased-array antenna is used, the RF power is naturally divided among a number of amplifiers, each of which feeds a separate radiating element. For the other orbits, where a reflector type of antenna is used, separate amplifier/feed-element combinations are also employed. In the latter cases, the elements are clustered to form the equivalent of a single feed to maintain the circular beam structure.

An alternative is to use a phased array instead of a reflector antenna for the second group of orbits. This possibility is more attractive at the lower field strengths of 150 and 50 μV/m because of the wider beamwidths in these cases. The antenna/RF-power tradeoff would have to be repeated for the phased array to find combinations that are appropriate for the assumed OTV.

With several significant exceptions, the satellite weights in Table 8-2 reflect the same set of advanced technologies as was assumed to be available for the baseline system satellites. Because the triply-sync satellite spends much of its time within the lower of two radiation belts surrounding the earth, 2-mil silicon solar cells cannot be used. A GaAs concentration array, which is relatively impervious to radiation, is selected instead. The specific weight (in lb/W) of this type of solar cell, however, is seven times that of 2-mil silicon. As a result, half the satellite weight indicated for this orbit (for all three field strengths) is attributable to the electrical power subsystem.

GaAs concentrator arrays have the disadvantage that the normal to the array must be kept pointed within 1 degree of the sun. A dual solar-array drive is therefore required. A GaAs planar array could be used in place of the concentrator array. However, the eventual cost of the planar array is expected to be considerably higher than that of the concentrator array.

Present-day technology in the form of 8-mil silicon cells could also be used. However, the specific weight of these cells is twice that of the GaAs concentrator material. For this reason, 8-mil silicon was not considered.

The weight estimates for the 6-, 8-, and 12-hour satellites designed for a field strength of 50 μV/m, based on advanced technology, range from 1600 to 2200 pounds. The validity of the weight estimation model is questionable for satellites this small. More importantly, the antenna sizes and RF power levels in these three cases are well within the capability of today's technology. For this reason, the weight of these satellites was estimated using present-day or near-term technology.

A satellite weight breakdown by subsystem for each of the satellites in Table 8-2 is given in Appendix I.

# 9. CONCLUSIONS

Because of the low broadcast frequencies and high RF power levels, satellite voice broadcasting at HF or VHF requires extremely large and heavy space structures. Satellites considered in this study were restricted in weight and stowed dimensions to designs that are consistent with a single STS launch. The resulting capacity for a geostationary satellite broadcasting at HF is two channel-beams, while a satellite in 8-hour orbit has a capacity of six channel-beams. A satellite in Molniya orbit broadcasting at VHF has a capacity of 12 channel-beams. (The unit of capacity is based on a 3-degree beam from geostationary orbit, which covers about 1 million square miles on the earth's surface.)

Four baseline systems have been developed to satisfy the requirements of a broadcast schedule provided by NASA. This schedule calls for one or more voice channels to be broadcast to most areas of the world, at specified times of day, at both HF and L-band (1.5 GHz). To satisfy these requirements at HF, a fleet of 47 geostationary satellites or 20 8-hour satellites is needed. At L-band, four geostationary satellites of modest size (comparable to those designed for direct broadcast of video signals) can fully comply with the broadcast schedule requirements.

At VHF, broadcasting is of interest only to the Soviet Union. A single satellite in Molniya orbit can satisfy the broadcast needs for an 8-hour period centered at apogee. Thus, three such satellites in suitably chosen orbits can provide 24-hour broadcast coverage.

Real-time satellite feeder links are desirable from the U.S., its territories, or from friendly host countries. For a Molniya satellite system, only U.S. earth stations are needed. For a geostationary satellite system, real-time uplink transmission requires earth stations in the U.S., Guam, Australia, and Western Europe. For an 8-hour satellite system, which involves two different satellite ground tracks, real-time feeder links can be established for all but one hour with one satellite ground track and for all but 2-1/2 hours with the second ground track.

A measure of system effectiveness is provided by the life cycle cost per channel-beam-hour (LCC/CBH) of broadcast service. These costs, in 1984 dollars, are summarized below for the four baseline systems.

| Band | Orbit | LCC/CBH ($000) |
|---|---|---|
| HF (26 MHz) | Geostationary | 6.9 |
| HF (26 MHz) | 8-Hour | 3.8 |
| VHF (68 MHz) | Molniya | 5.5 |
| L-Band (1.5 GHz) | Geostationary | 0.4 |

A number of system variations were examined, based on reductions in coverage, number of broadcast channels, or required field strength. Systems providing reduced broadcast capability, in terms of coverage or channel complement, naturally involve a smaller number of satellites than the corresponding baseline systems. However, the LCC/CBH is generally higher for the system variations, because of lower satellite utilization.

A reduction in the field strength requirement, on the other hand, significantly reduces life cycle costs. The LCC/CBH for a geostationary or 8-hour HF satellite system is about $2000 for a field strength of 150 μV/m (The baseline field strength is 300 μV/m.) For a system of Molniya satellites operating at VHF, the LCC/CBH is $4000 at 150 μV/m. (The baseline field strength is 250 μV/m.)

A number of critical technology items must be developed before a satellite voice broadcast project at HF or VHF can be undertaken. Primary among these are the structural aspects of the cable-catenary antenna for geostationary or Molniya orbit, or the phased-array antenna for the 8-hour or other subsynchronous orbit. In the electrical power subsystem, 2-mil silicon solar cell technology is required in cell sizes measuring 3 by 6 cm and in sufficient quantity to generate on the order of 100 kW of dc power. In addition, high-voltage (~200 V) distribution systems are needed with aluminum or other lightweight cabling flexible enough to accommodate the stowed satellite configuration. Finally, high-power (~10 kW) transmitters are required for the cable-catenary satellites, although a lesser power level (~2 kW) suffices for the phased-array design.

Because of the large, heavy, and costly satellites associated with the HF systems investigated under the original contract, TRW was directed to determine satellite characteristics corresponding to single-channel broadcasting at field strengths ranging from 300 μV/m to 50 μV/m (a ratio of 36:1 in RF power). In addition to the orbits already considered, a "triply-sync" orbit, which is highly elliptical and sun-synchronous with a period of three hours, was introduced. Apogee for this orbit was placed at a latitude of 63.4 degrees, the highest value attained. The PAM-A second stage was considered for the lightest satellites, and a custom bipropellant OTV filled the gap between the PAM-A and the Centaur-class vehicles considered previously.

It was found that, even at 50 μV/m field strength, fairly large antennas and/or sizable RF power levels are needed for satellites in geostationary or Molniya orbit. The requirements are quite modest (11 m antenna and 5 kW RF power) for an 8-hour orbit and 50 μV/m field strength. At 150 μV/m, these requirements increase to 17 m and 31 kW. The corresponding "equivalent" geostationary beamwidths are 12 and 10 degrees, respectively. A PAM-A second stage suffices in the first case, but a custom bipropellant OTV is needed in the second case.

There can be up to two distinct visibility periods per day for an 8-hour orbit, depending on the observer location. Over a wide range of latitudes, these periods last for three hours or more.

For the triply-sync orbit, visibility periods at latitudes of 40 and 60 degrees exceed 50 minutes on four and five successive orbits, respectively. Even at a latitude of 20 degrees, there are several successive visibility periods exceeding 30 minutes.

For the triply-sync orbit and a field strength of 50 μV/m, an earth-coverage beam is generated with a 14-m antenna and 20-kW RF power, using the PAM-A second stage. At 150 μV/m, these requirements grow to 33 m and 17 kW for an equivalent geostationary beamwidth of 7 degrees. A custom bipropellant OTV is needed in this case.

# APPENDIX A
# IONOSPHERIC PROPAGATION EFFECTS

Signals transmitted at HF and VHF (Bands 1 and 2), and even those at L-band (Band 3), undergo significant transformations on encountering the ionosphere. The major question, for purposes of this study, is whether the signal penetrates the ionosphere or is reflected from it. If ionospheric penetration does occur, at the lower bands there is generally some signal attenuation which must be accounted for in selecting the satellite transmitter power. The question of ionospheric penetration is discussed in detail below.

A second effect is Faraday rotation, which is a rotation of the plane of polarization of linearly polarized waves. It is much more pronounced at the lower frequency bands. At HF it has been measured in the hundreds of radians; at VHF, in the tens of radians. Receiving antennas not aligned with the orientation of the received plane of polarization will suffer signal loss because of this nonalignment.

A simple and effective solution to the problem of Faraday rotation is to transmit circularly polarized waves. The price paid to eliminate this problem is a 3-dB loss in received signal strength, which requires an offsetting increase in satellite transmitter power.

The Faraday effect is quite small at L-band. Nevertheless, the amount of rotation does vary during the course of a day. Therefore, no fixed receive antenna alignment will avoid signal loss. The solution, for this band as well, is to take a fixed 3-dB loss by adopting circular polarization.

The final ionospheric effect of significance is scintillation, which results in both increases and decreases (i.e., fading) in signal level because of ionospheric irregularities. The magnitude of the effect varies with frequency, time of day, magnetic and solar activity, season, and latitude. It is most pronounced at low latitudes in the hours following sunset, and therefore can be quite disruptive to prime-time broadcasting.

Scintillation magnitudes generally increase with decreasing frequency. Observations of scintillation effects at HF are minimal. However, long-term measurements of scintillation at 136 megahertz made in Peru and Ghana indicate that peak-to-peak signal fluctuations exceeding 9 dB (or, equivalently, fades exceeding 5.6 dB) typically occur 15 percent of the time at night (Reference A-1). Fades of this magnitude would severely disrupt voice broadcasts. Moreover, at HF, significantly larger fade magnitudes can be expected. (Scintillation at VHF need not be considered because only the Soviet broadcast zones are of interest in this band.)

It is not feasible to try to overcome the effects of scintillation through an increase in transmitter power. In fact, the large power demands in the absence of scintillation severely limit the broadcast capability of an individual satellite at HF. In this report, the effects of scintillation are ignored in computing the amount of broadcast service provided by a given satellite system. Because scintillation is of concern only at low latitudes (polar effects, which are also sizable, are not relevant), the average reduction in broadcast service on a systemwide basis is relatively small. More significantly, however, it will be very difficult to broadcast to certain geographic regions in the evening hours for prolonged periods of time.

Ionospheric Penetration

The utility of satellites for voice broadcasting, at HF in particular, depends on the selected frequency being high enough to penetrate the ionosphere. The shielding effect of the ionosphere is determined by the critical frequency of the F layer, which is the highest frequency at which normally incident waves are reflected. If the critical frequency is denoted by $f_c$, the broadcast frequency by f, and the angle of incidence (measured with respect to vertical) at the F layer by i, penetration will take place if $f > f_c/\cos i$.

The critical frequency is a function of sunspot number, season, and local time. Analysis of the ionospheric penetration phenomenon for transmission at 26 megahertz, for a limited number of sunspot-number/time-of-day combinations, has been performed by Phillips and Knight (Reference A-2). A more extensive investigation of this phenomenon, together with other ionospheric effects, has been done by Rush, et. al. (Reference A-1). The balance of this discussion is based on the latter work.

Minimum penetration frequencies were determined for broadcasts emanating from a geostationary satellite and directed at various geographical zones. (Zone definitions were different from those used in this study, but spanned essentially the same geographical areas.) These minimum frequencies are 90-percent values (i.e., they are exceeded only 10 percent of the time for the specified month and level of solar activity). The satellite longitude was generally chosen to be central to the zone in question.

Attention was focused on the two prime broadcast periods, one in the morning and the other in the evening. In general, the highest minimum penetration frequency was found to correspond to the evening hours and to the equinox periods (i.e., April and October) during periods of maximum sunspot number. This minimum penetration frequency tends to be about 20 megahertz in midlatitude zones and 26 megahertz in high-latitude zones. Based on these values, the 21.6 and 25.9 megahertz subbands of Band 1 are available in midlatitude zones, but ionospheric penetration is only possible at the higher subband in the northern zones.

The 90-percent value of the ionospheric loss associated with the minimum penetration frequency varies from 1 to 3 dB. In general, the loss decreases as the transmission frequency is increased relative to the minimum penetration frequency. In most cases, broadcasting at 26 megahertz will lead to an ionospheric loss less than the maximum value. For this reason, a 2-dB loss has been used in determining the required transmitter power.

The minimum penetration frequency is largely dependent on the angle of incidence or, equivalently, the elevation angle of the satellite as seen by the listener. The high minimum penetration frequencies cited for northern latitudes (i.e., for latitudes as high as 70 degrees north) correspond to elevation angles as low as 10 degrees. Were the satellite offset in longitude rather than being central to the zone in question, the minimum elevation angle would be lower yet and the minimum penetration frequency even higher.

Minimum penetration frequencies for a satellite in subsynchronous orbit can be inferred from those for a geostationary satellite by concentrating on the minimum elevation angle. For a subsynchronous orbit, the aspect from which a particular broadcast zone is viewed is continuously changing in accordance with the satellite motion. A ground rule adopted for all subsynchronous orbits is that satellite visibility will be considered only for elevation angles greater than 20 degrees. By comparison with the geostationary case, it may be concluded that, under the worst set of conditions (i.e., maximum sunspot number and fall or spring equinox), the minimum penetration frequency will be no greater than 20 megahertz, 90 percent of the time. Thus, the upper two subbands of Band 1 will be available in all broadcast zones.

It should be emphasized that, even during periods of maximum sunspot activity, many months will exhibit lower minimum penetration frequencies than those prevailing during the equinox months. Of course, during periods of lower sunspot activity, minimum penetration frequencies will generally be lower than those cited above. Therefore, there will be considerable periods of time when one or both of the lower Band 1 subbands (i.e., at 15.4 and 17.7 megahertz) will also be available. This is especially true for subsynchronous orbits, where the 20-degree elevation angle constraint leads to lower minimum penetration frequencies.

The above discussion pertains to the HF band, and therefore to the geostationary and 8-hour-orbit systems only. The Molniya satellite system is intended for operation at VHF; consequently, there is no ionospheric penetration problem. The loss of signal strength in passing through the ionosphere at VHF is no more than 1 dB.

References

A-1. "Study of Factors Affecting an HF/VHF Direct Broadcasting Satellite Service," National Telecommunications and Information Administration, Report 84-158, September 1984.

A-2. G. J. Phillips and P. Knight, "Use of the 26-MHz Band for Satellite Broadcasting," EBU Technical Review, No. 170, August 1978, pp. 173-178.

## APPENDIX B
## TECHNOLOGY TRADEOFFS

In specifying the four baseline systems, it is necessary to identify the technologies involved in each of the satellite subsystems. Important technology choices are involved only in the three Band 1 and 2 systems. Moreover, except for the antenna design, the same choice is made in each case. The baseline technology choices are indicated in Table B-1. Rejected technology alternatives, where such exist, are also identified.

The OTV alternatives (Item 1) would result in either (1) greater payload weight (and therefore more broadcast capability) coupled with lower cost, or (2) lower risk. However, a groundrule for this study was to consider only OTVs for which definite development plans exist. For this reason, the STS lift capability was restricted to 65,000 pounds, while only tankage variations were permitted of the Centaur.

The choice of a cable-catenary antenna (Item 2) is restricted to geostationary and Molniya satellite systems. A reflector type of antenna is required at these altitudes. The cable catenary is the only known reflector design, other than the inflatable antenna, for which the weight is not prohibitive at the required diameters.

Another study groundrule is that eclipse capability is not required (Item 4). The batteries are therefore sized to perform only housekeeping functions. A relatively conservative technology, $NiH_2$ batteries, suffices for this purpose. If eclipse capability were desired, only NaS batteries (a very advanced technology) could provide this capability without a prohibitive weight penalty.

A third study groundrule is that each satellite require only a single STS launch (Item 12). Therefore, Space Station assembly was ruled out at the start.

In addition, no refurbishment or repair capability was assumed. Were this not the case, active thermal control (Item 11) could have been chosen in place of heat-pipe technology for weight reduction.

Table B-1. Technology Tradeoffs for Band 1 and Band 2 Systems

| ITEM | BASELINE | TECHNOLOGY *ALTERNATIVES* | COMMENTS |
|---|---|---|---|
| 1. ORBITAL TRANSFER VEHICLE (OTV) | MODIFIED CENTAUR | REUSABLE OTV, SPACE STATION BASED | ENABLES MORE PAYLOAD TO ORBIT. LOWER COST |
| | | LOW THRUST OTV | DEPLOY, CHECKOUT SATELLITE PRIOR TO ORBITAL TRANSFER. LOWER RISK |
| 2. LARGE DEPLOYABLE ANTENNA | CABLE-CATENARY | INFLATABLE | ADVANCED TECHNOLOGY |
| 3. TRANSMITTERS | SOLID-STATE MOS-FET DEVICES | BIPOLAR, TWT | ADVANCED TECHNOLOGY. PROVIDES HIGH EFFICIENCY AND RELIABILITY |
| 4. BATTERIES | $NiH_2$ BATTERIES | NaS BATTERIES | NaS BATTERIES REQUIRED FOR ECLIPSE CAPABILITY |
| 5. SOLAR ARRAYS | 2 MIL SILICON | CONCENTRATOR (GaAs) | 2 MIL SILICON IS ADVANCED TECH-NOLOGY WITH LOWER WEIGHT. CON-CENTRATOR REQUIRES LESS AREA |
| 6. ELECTRICAL DISTRI-BUTION CABLING | ALUMINUM WIRING | NONE | ADVANCED LOW-WEIGHT TECHNOL-OGY. PROVIDES WEIGHT/SIZE REDUCTION |
| 7. ELECTRICAL SWITCHING AND CONTROL | HI-VOLTAGE (200V+) | NONE | ADVANCED TECHNOLOGY. PROVIDES WEIGHT/SIZE REDUCTION AND REDUCES LOSSES. |

Table B-1. Technology Tradeoffs for Band 1 and Band 2 Systems (Continued)

| ITEM | BASELINE | TECHNOLOGY ALTERNATIVES | COMMENTS |
|---|---|---|---|
| 8. POWER DISTRIBUTION | DC DISTRIBUTION | AC DISTRIBUTION | WEIGHT SAVING. REQUIRES DISTRIBUTION GEAR AND CONVERTER DEVELOPMENT |
| 9. ATTITUDE CONTROL | PASSIVE CONTROL (0.25-0.50 DEGREE POINTING ACCURACY) | ACTIVE, DISTRIBUTED CONTROL (LESS THAN 0.25 DEGREE) | LARGE FLEXIBLE STRUCTURE. HOWEVER, EXTREME POINTING ACCURACY NOT REQUIRED |
| 10. PROPULSION | BI-PROPELLANT (300 SEC ISP) | ELECTRICAL PROPULSION | ELECTRICAL PROPULSION AFFORDS LOWER WEIGHT. BI-PROPELLANT WEIGHT IS ONLY ABOUT 1/20 OF SATELLITE WEIGHT, HOWEVER |
| 11. THERMAL CONTROL | ADVANCED HEAT PIPE TECHNOLOGY | ACTIVE CONTROL (HEAT PUMPS) | PASSIVE TECHNIQUE CHOSEN FOR RELIABILITY |
| 12. SATELLITE ASSEMBLY | GROUND ASSEMBLY | SPACE STATION ASSEMBLY | ADVANCED TECHNOLOGY. COST? RISK? |
| 13. REFURBISHMENT/ REPAIR | NONE | ORBITAL MANEUVERING VEHICLE (OMV) | ADVANCED TECHNOLOGY. LOWER INITIAL AND LIFETIME COST |
| 14. GROUND STATION AUTONOMY | HIGHLY AUTONOMOUS. MINIMIZES CREW AT REMOTE STATIONS | NONE | ADVANCED TECHNOLOGY. CRITICAL COST FACTOR OVER SYSTEM LIFE |

## APPENDIX C
## SATELLITE RF POWER REQUIREMENTS

The RF power requirements in Bands 1 and 2 are driven by the specified electric field strength: 300 μV/m in Band 1 and 250 μV/m in Band 2. In Band 3, the RF power level is chosen to achieve a demodulated signal-to-noise ratio of 49 dB with an indoor receiver and an outdoor antenna.

Link power budgets for the three bands are shown in Tables C-1 to C-3. In each case the computation is made for a listener located at the edge of a circular area, centered at the subsatellite point, that would be subtended by a 3-degree beam from geosynchronous altitude. In other words, the size of the area illuminated is independent of satellite altitude. For the Molniya orbit, the required beamwidth from apogee, which is 10-percent higher than geosynchronous altitude, is 2.7 degrees.

Because the illuminated area is the same in all cases, differences in transmitter power requirements result only from differences in propagation factors or received signal requirements. In particular, the transmitter requirements for a Band 1 satellite in 8-hour orbit are the same as those for a Band 1 geostationary satellite. Thus, Table C-1 may be regarded as the power budget for an 8-hour orbit as well.

In Band 3, a 2-foot antenna is assumed to be mounted on the exterior of a dwelling, with a clear view of the satellite. The 3-dB beamwidth of such an antenna is 25 degrees at 1.5 gigahertz, so the pointing requirements are not severe. The antenna gain shown in Table C-3 is the -3 dB value. The 3 dB line loss on the ground accounts for the distance (~30 feet) between antenna and receiver. The receive system noise temperature includes the effects of a background noise temperature of 300 K and a dual-gate FET front end. The latter device has a 1 dB noise figure; however, the noise figure of a receiver based on this device is about 3 dB.*

*T. Sate, et al, "High Performance UHF Varactor Tuner with a Dual Gate GaAs MESFET and GaAs Varactor Diodes," IEEE Transactions on Consumer Electronics, Vol. CE-26, August 1980, pp. 423-430

Table C-1. Band 1 Broadcast Link Power Budget (Geostationary Orbit, 3-Degree Beamwidth)

| | |
|---|---|
| Transmitter output, dBW | 40.0 (10 kW) |
| Line loss, dB | -0.5 |
| Antenna gain, dB | 31.4 |
| EIRP, dBW | 70.9 |
| Spreading factor ($1/4\pi r^2$), dB | -162.1 |
| Ionospheric loss, dB | -2.0 |
| Polarization loss, dB | -3.0 |
| Power flux density, dBW/$m^2$ | -96.2 |
| Electric field strength, μV/m | 300.0 |

Table C-2. Band 2 Broadcast Link Power Budget (Molniya Apogee, 2.7-Degree Beamwidth)

| | |
|---|---|
| Transmitter output, dBW | 37.4 (5.5 kW) |
| Line loss, dB | -0.5 |
| Antenna gain, dB | 32.2 |
| EIRP, dBW | 69.1 |
| Spreading factor ($1/4\pi r^2$), dB | -162.9 |
| Ionospheric loss, dB | -1.0 |
| Polarization loss, dB | -3.0 |
| Power flux density, dBW/$m^2$ | -97.8 |
| Electric field strength, μV/m | 250.0 |

Table C-3. Band 3 Broadcast Link Power Budget (Geostationary Orbit, 3-Degree Beamwidth)

| | |
|---|---|
| Transmitter output, dBW | 18.5 (71 kW) |
| Line loss, dB | -1.5 |
| Antenna gain, dB | 31.7 |
| EIRP, dBW | 48.7 |
| Path loss, dB | -187.8 |
| Polarization loss, dB | -3.0 |
| Receive antenna gain, dB | 14.4 |
| Line loss, dB | -3.0 |
| Receiver carrier power, dBW | -130.7 |
| Receive system noise temperature, dB-K | 27.7 |
| Boltzmann's constant, W/K-Hz | -228.6 |
| Carrier noise bandwidth, dB-Hz | 54.0 |
| Received noise power, dBW | -146.9 |
| Carrier-to-noise ratio (C/N), dB | 16.2 |
| Demodulator gain, dB | 26.5 |
| Pre-emphasis gain, dB | 6.3 |
| Signal-to-noise ratio (S/N), dB | 49.0 |

The RF power requirements in Tables C-1 to C-3 are computed for a half-power beamwidth of 3 degrees as viewed from geosynchronous altitude. The required RF power perchannel-beam in Bands 1 and 2 is shown as a function of equivalent geosynchronous beamwidth, with field strength as a parameter, in Figures C-1 and C-2. The selected beamwidth is highlighted in each case.

The required antenna diameter is shown as a function of beamwidth for Bands 1 and 2 in Figure C-3. The frequencies identifying the curves correspond to the four broadcast subbands in Band 1 and the highest and lowest frequencies in Band 2.

Signals in beams directed other than at the subsatellite point incur both an additional path loss and an antenna scan loss. For the geostationary and Molniya orbits, transmitter power requirements are increased by typical values for these losses. For the 8-hour orbit, transmitter power is increased to account for scan loss. However, the additional path loss is offset by an increase in antenna size. For this purpose, the path loss is computed at the limit of visibility (i.e., at a point where the satellite elevation angle is 20 degrees).

The Band 1 field strength requirement of 300 μV/m is interpreted as an average value. Because amplitude modulation is used in Band 1, the instantaneous field strength must fluctuate above and below 300 μV/m to maintain this average value. Similarly, the transmitter RF output will fluctuate above and below the 10 kilowatt value indicated in Table C-1. The rate of power fluctuation will typically be several times a second, corresponding to the fluctuations in human speech. The instantaneous dc power requirement fluctuates in an identical manner.

In a satellite designed to provide eclipse operation, a power storage device designed for the average power requirement would normally have sufficient reserve to accommodate the power fluctuations. In the absence of eclipse capability, the solar panel area must be sized for the peak power requirement.

The peak-to-average power ratio ($P_P/P_{AV}$) for the satellite as a whole depends on the corresponding ratio for a single voice channel, as well as on the number of voice channels transmitted simultaneously. The number of

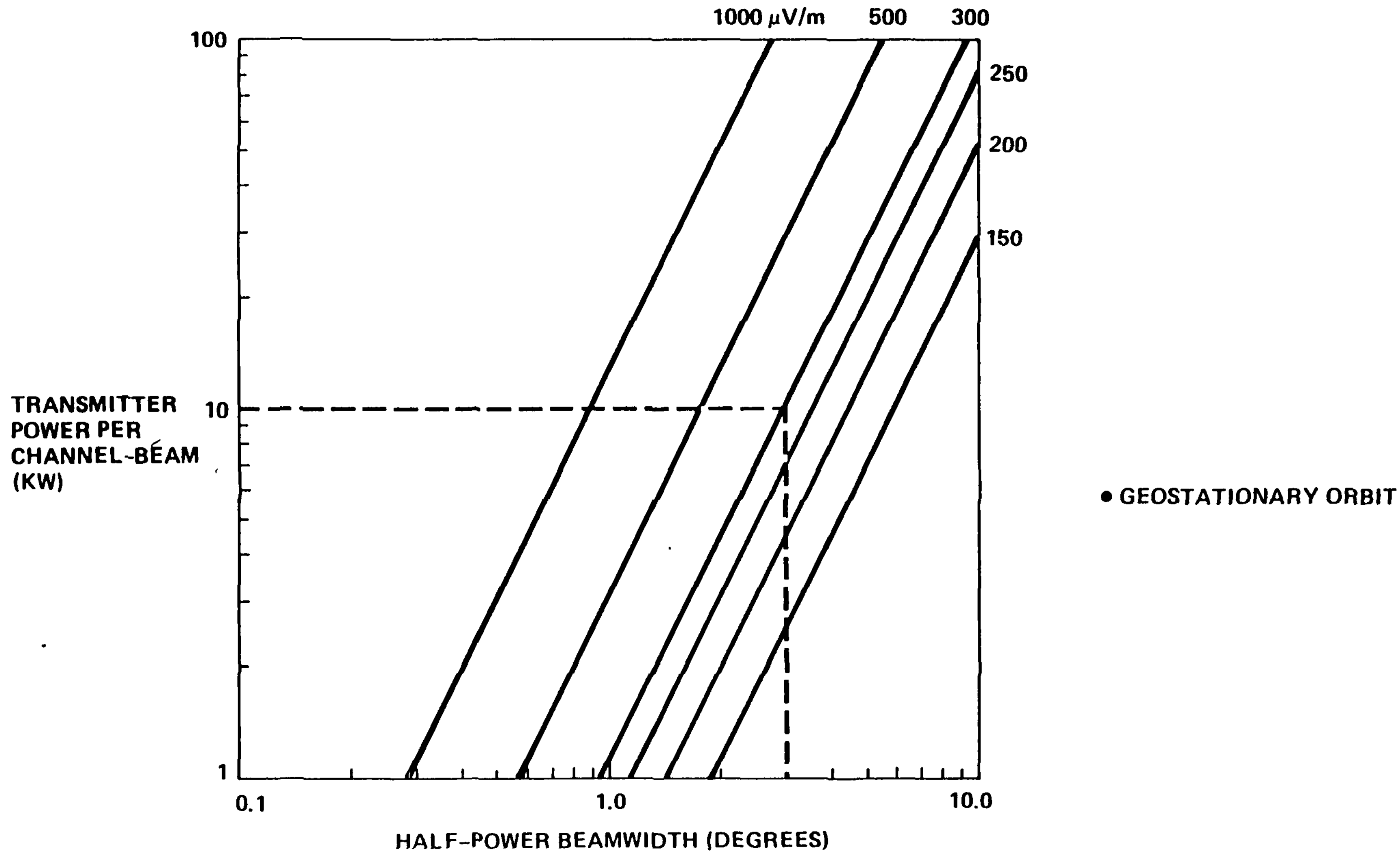



Figure C-1. Band 1 Transmitter Power Requirements

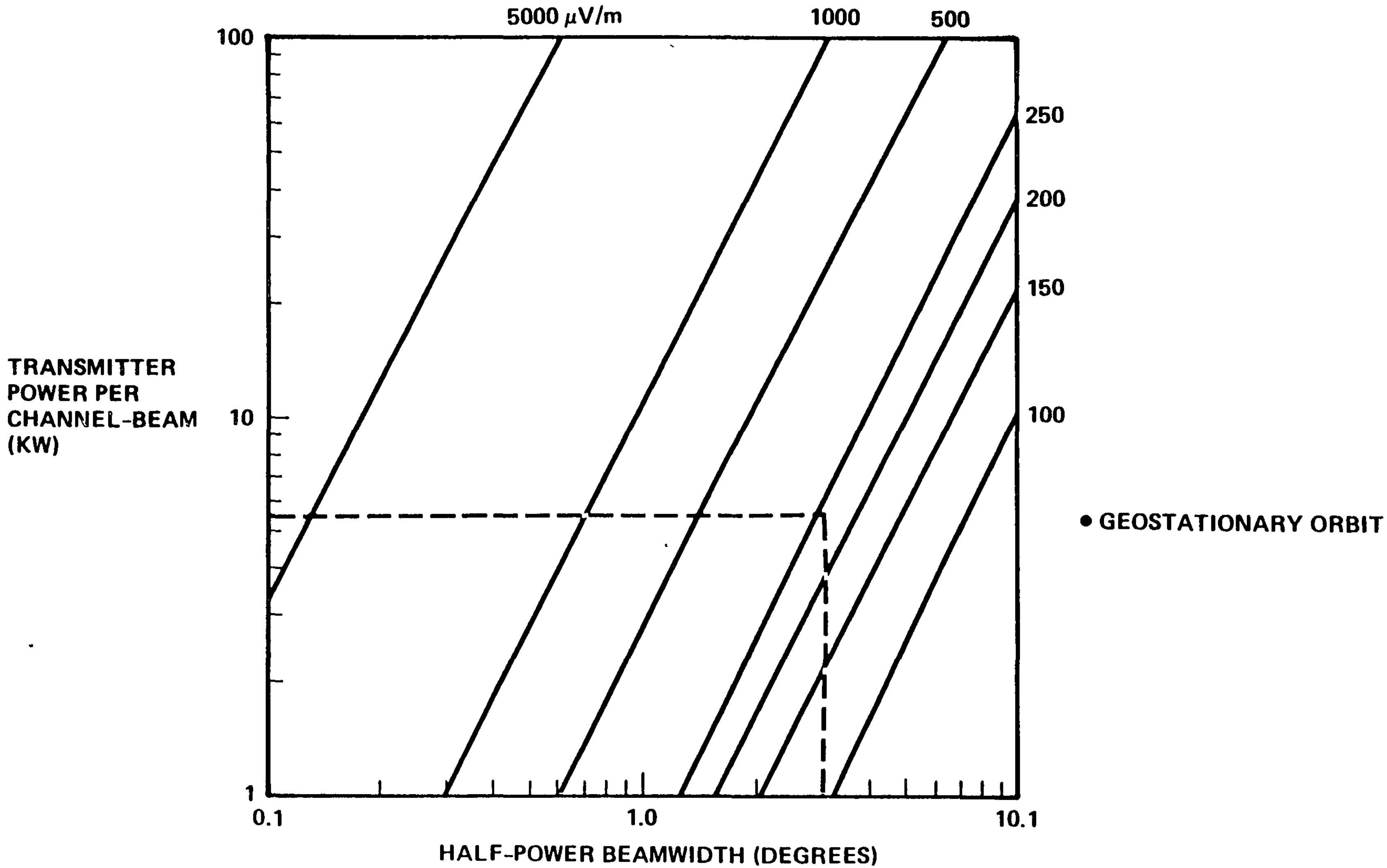



Figure C-2. Band 2 Transmitter Power Requirements

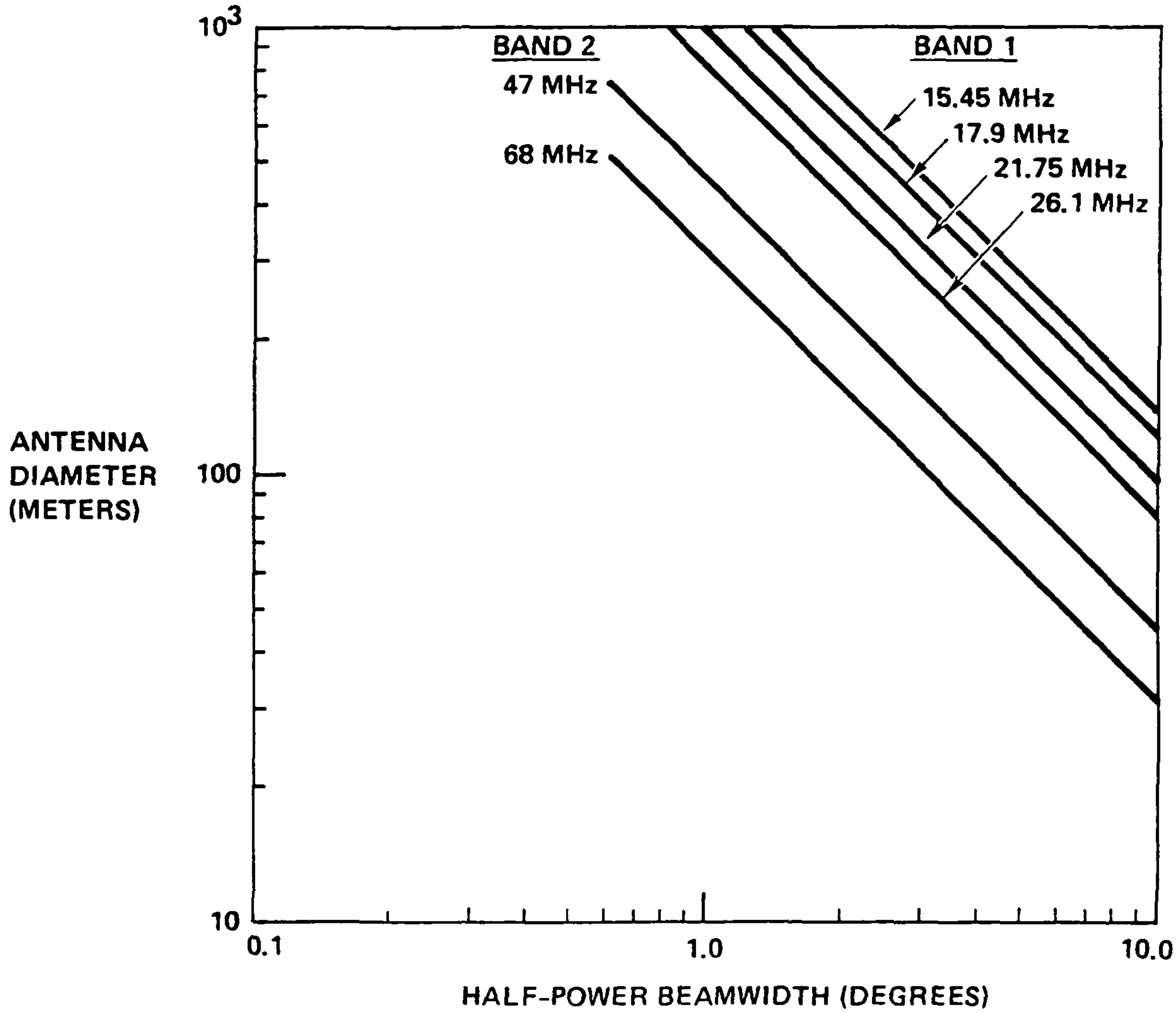



Figure C-3. Spot-Beam Coverage Versus Antenna Diameter channels is assumed equal to the satellite channel-beam capacity. $P_p/P_{AV}$ for an individual channel depends on the modulation factor (which is chosen in conjunction with the degree of linear compression to be applied at the transmitter). For a modulation factor between 70 and 100 percent, $P_p/P_{AV}$ varies between 2.9 and 4.0 for an individual channel. Based on this range of values, $P_p/P_{AV}$ for the satellite is assumed to have the following values: 1.7 for 2 or 3 channels, 1.4 for 4 to 12 channels, and 1.2 for 13 or more channels.

The per-channel-beam peak and average transmitter power levels for the baseline and variational system satellites described in Sections 3 and 4 are listed in the computer printouts of Appendix E. In particular, the average power levels for the baseline systems are: 12.0 kilowatts for the Band 1 geostationary satellite, 11.2 kilowatts for the Band 1 8-hour satellite, and 6.3 kilowatts for the Band 2 Molniya satellite. The corresponding peak power levels are 20.4, 15.7, and 6.3 kilowatts.

# APPENDIX D
# SURVEY OF OTHER SOUND BROADCASTING ALTERNATIVES

Sound broadcasting systems discussed in the main text are confined to satellite systems designed around three specific orbit types: geostationary, Molniya, and subsynchronous circular orbits. In this appendix, nonsatellite techniques for sound broadcasting will be examined. In addition, the coverage afforded by several other orbit types will be presented.

## D.1 NONSATELLITE BROADCASTING TECHNIQUES

Nonsatellite platforms may be classified as either lighter than air (LTA) or heavier than air (HTA). The former category may be subdivided into tethered and free platforms. All of the LTA and HTA platforms considered are unmanned.

There may be situations where an LTA or HTA platform could be used in conjunction with a satellite. The satellite/platform downlink would be at a fixed-satellite frequency such as L-band or Ku-band. Since the number of potential listeners with receivers at these frequencies is small, the platform would rebroadcast in Band 1.

Climatology in the deployment area is a major factor in determining the utility of LTA platforms. Wind patterns strongly affect launch, ascent, endurance, and recovery of both tethered and free LTA platforms. For free flying LTA and HTA platforms, there is the option of remote launch at a "good" location and then navigation to the desired station within an altitude regime where winds are less critical, e.g., above 50 kft in many locations. Platform recovery is similar. This approach requires the expenditure of fuel which would otherwise be used for mission operation.

### Lighter-Than-Air Systems

Lighter-than-air systems can operate at altitudes ranging from 10,000 to 100,000 feet with endurance up to several months. There are three categories of LTA systems: free balloons, airships (i.e., blimps — some with active stationkeeping), and tethered balloons or aerostats. Representatives of the free balloon class with no stationkeeping assets are not likely to be very useful for broadcasting.

A design for a large, high-altitude blimp with stationkeeping capability was developed by Lockheed Missiles and Space Co. under the DoD High Altitude Surveillance Platform for Over-The-Horizon Targeting (HISPOT) program. (This program, which dates from the early 1970s, is no longer active.) The blimp measures 500 feet in length and 150 feet in diameter. The service altitude is 50,000 to 70,000 feet, with a 600-mile-diameter, line-of-sight coverage area. An internal combustine engine/propeller combination provides stationkeeping and payload power. Payload capability is 5000 pounds. The wind-dependent endurance is about 20 days.

One realization of a tethered balloon or aerostat is the system operated by TCOM (Tethered Communications, Inc., a Westinghouse subsidiary). Operating altitude is 10,000 to 15,000 feet, while the diameter of the coverage area is 250 to 300 miles. The TCOM aerostat is 175 feet long, 57 feet in diameter, and has a tail span of 82 feet. It has an internal-combustion-driven generator with a 5-kilowatt output at altitude and can operate in a 100-kn wind at altitude. Its endurance is limited by a 200-gallon fuel tank.

In a typical TCOM deployment, considerable tether is laid out horizontally, depending on local winds. The total payload weight of 4000 pounds includes the weight of the tether. The payload minus tether is about 1000 pounds.

TCOM systems are in operation in the Bahamas and in Nigeria. A typical payload includes VHF/UHF transponders for both data relay and direct subscriber broadcast. The TCOM system is manufactured by Raven Industries.

Other manufacturers of tethered balloons include Sheldahl Corp., Winzen Research, and ILC. (Sheldahl quotes a price of $800,000 for tethered balloons in quantities of 10 or more.) Sheldahl had been the primary source of large, very high altitude, untethered balloons used to carry scientific (manned and unmanned) payloads. At present, the demand for such vehicles is met mostly by Winzen Research.

Heavier-Than-Air Systems

The Teledyne Ryan unmanned aircraft is a HISPOT development in the HTA category. It cruises at 50,000 to 80,000 feet with an air speed of 100 to 150 kn. The coverage area diameter is typically 600 miles. The aircraft has a gross weight of 4500 pounds and requires 2000 to 3000 feet for takeoff and landing.

The Ryan aircraft has two propulsion options. First is an RTG/alternator/electric-motor combination, which can support a 100-pound payload for a period up to 30 days. The second option is a turbo-charged, liquid-cooled, piston engine, which can support a 300-pound payload at 50,000 feet for 80 hours.

The purchase price of this vehicle (without payload) is $2 million (1983) in quantities of two or more. Operating costs are $300/hr.

NASA Langley has performed and sponsored a number of studies of high-altitude, long-endurance HTA platforms. Power sources include: solar/fuel cells, RTG/electric, and microwave beamed power.

A current investigation by Lockheed Missiles and Space Co. of a solar-powered, high-altitude unmanned aircraft is funded in part by NASA Langley (Aviation Week, November 26, 1984). Operation for at least a year at altitudes of about 65,000 feet is intended. The wingspan is several hundred feet. The payload, carried in an underslung pod, could weigh up to 200 pounds (Figure D-1).

The propeller, about 40 feet in diameter, is expected to operate at more than 90 percent efficiency. Solar-power-generated thrust would be sufficient for the aircraft to hold its position. Surplus electric energy collected during daylight from solar cells mounted on wingtips and vertical stabilizers would separate water into oxygen and hydrogen for use at night by a fuel cell to generate electric energy.

## D.2 OTHER SATELLITE ORBITS

A variation on geostationary satellite coverage is provided by satellites at geosynchronous altitude in orbits inclined to the equator. Figure D-2 provides an example of the coverage achieved by four satellites inclined at 64 degrees. Care must be taken in selecting the inertial

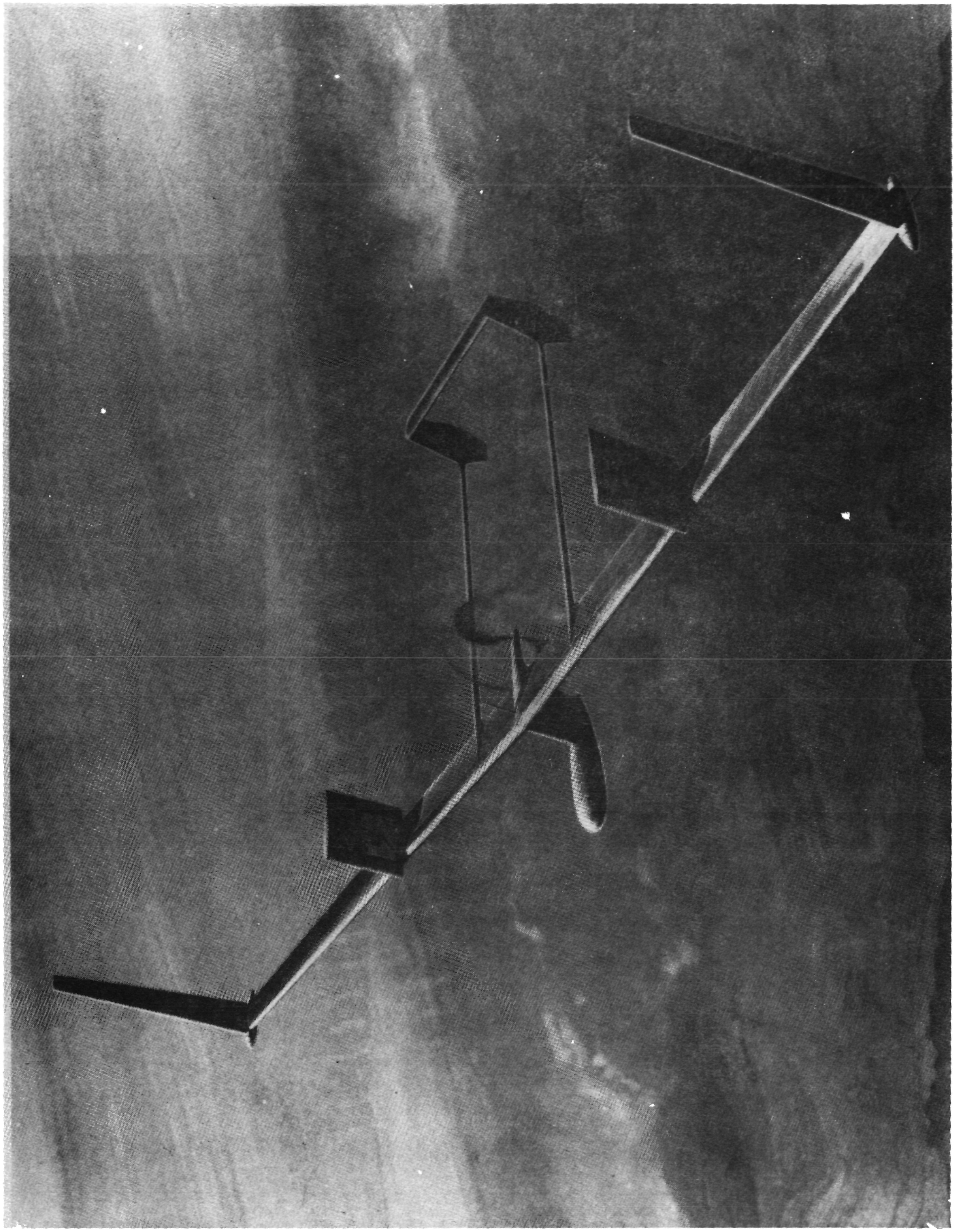


Figure D-1. LMSC Solar-Powered Aircraft

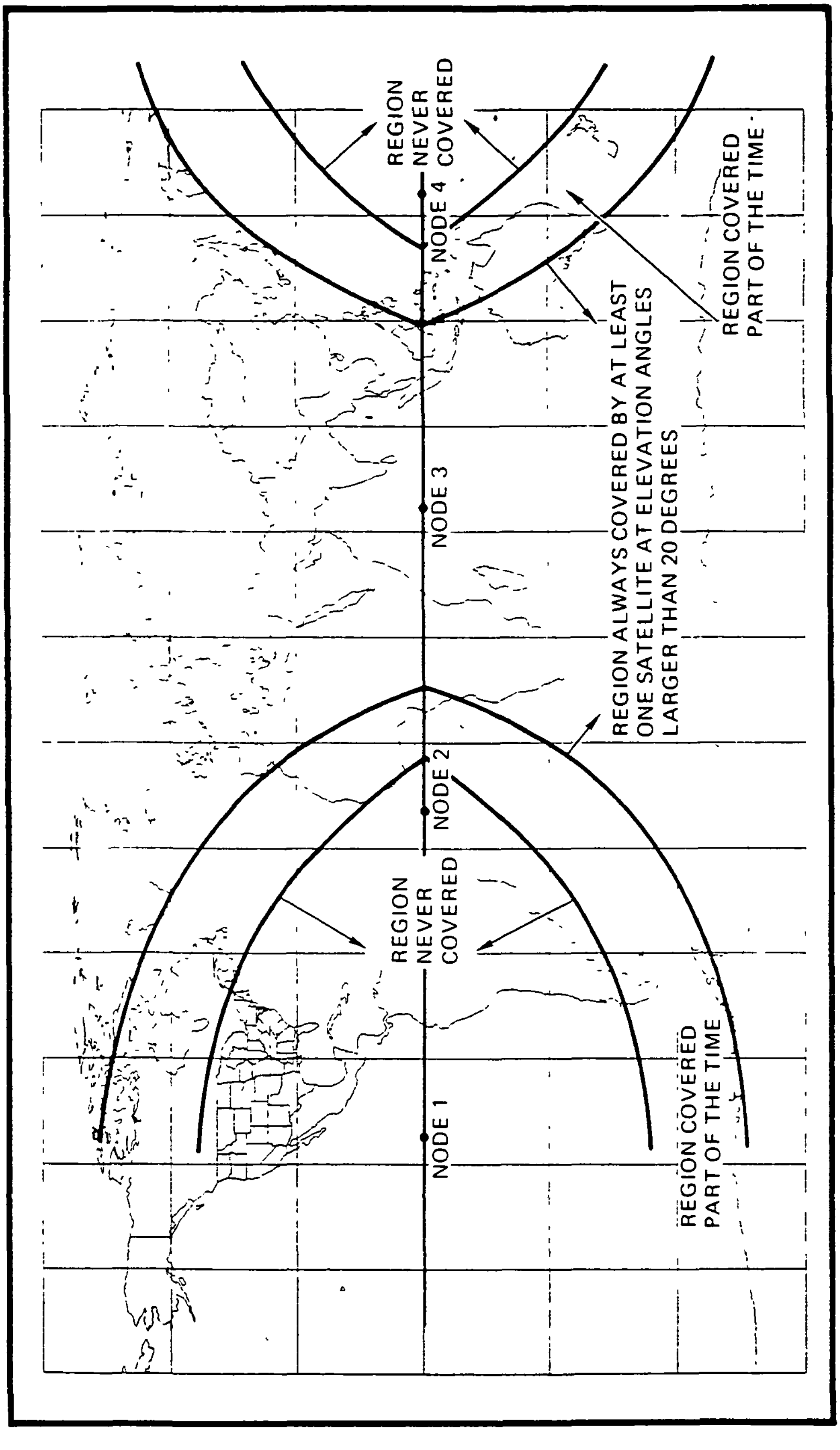



Figure D-2. Coverage from Four 64-Degree-Inclined Geosynchronous Satellites ascending nodes and satellite in-orbit positioning so that the resulting constellation will provide the desired coverage.

There is nothing unique about the 64-degree inclination. Inclination is introduced to provide northern and southern coverage at higher elevation angles than is afforded by geostationary satellites. Figure D-2 is based on a minimum elevation angle of 20 degrees. As inclination is reduced, so also is the amount of northern and southern coverage.

To complete the discussion of geosynchronous satellites, single-satellite coverage from polar orbit (i.e., 90-degree inclination) is provided in Figure D-3, based on a 10-degree elevation angle limit. The ground track completely describes the 24-hour motion of the satellite in 1-hour time ticks. Contours describing the first 6 hours of visibility are shown and vary from the equatorial to the polar view. A complete coverage description can be obtained by phase shifting the visibility contours for the next 6 hours and then inverting the entire family of contours for the remaining 12 hours.

A sun-synchronous orbit is so inclined that its inertial ascending node drifts eastward at the apparent solar rate, approximately 0.99 degree per day. This results in the satellite crossing any given latitude at the same local time during each orbit. The ground track is virtually north-south or south-north, thereby providing coverage at nearly the same local time during the entire transit.

Continuous-coverage regions for a sun-synchronous orbit of 600 nmi altitude are shown in Figures D-4 and D-5 for elevation angle limits of 10 and 25 degrees. A given satellite is seen continuously from a point on the ground track for periods of only 6 and 4 minutes, respectively. It therefore takes five satellites in the first case, and seven in the second, to provide 1/2 hour of continuous broadcasting.

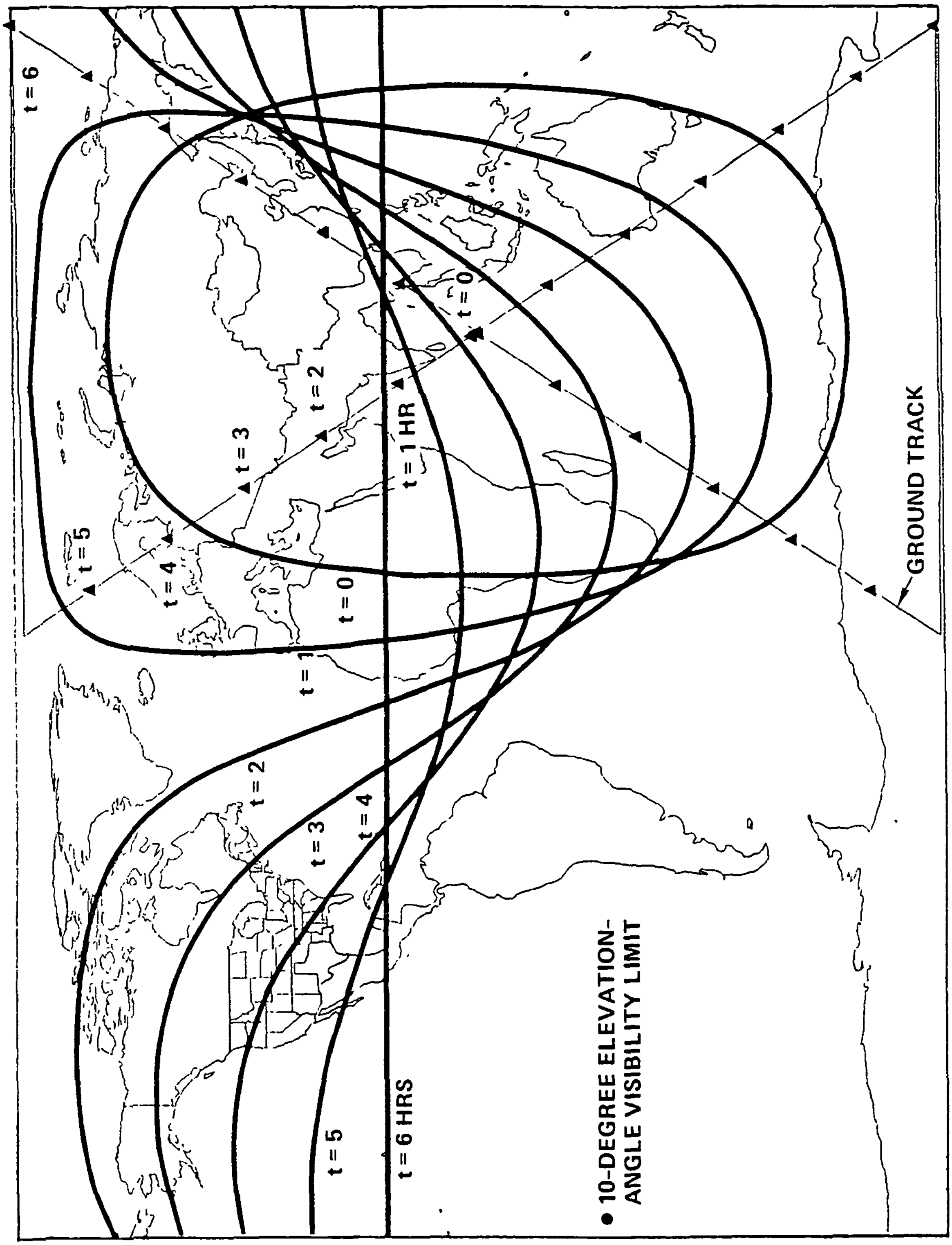



Figure D-3. Coverage from Geosynchronous Polar Orbit

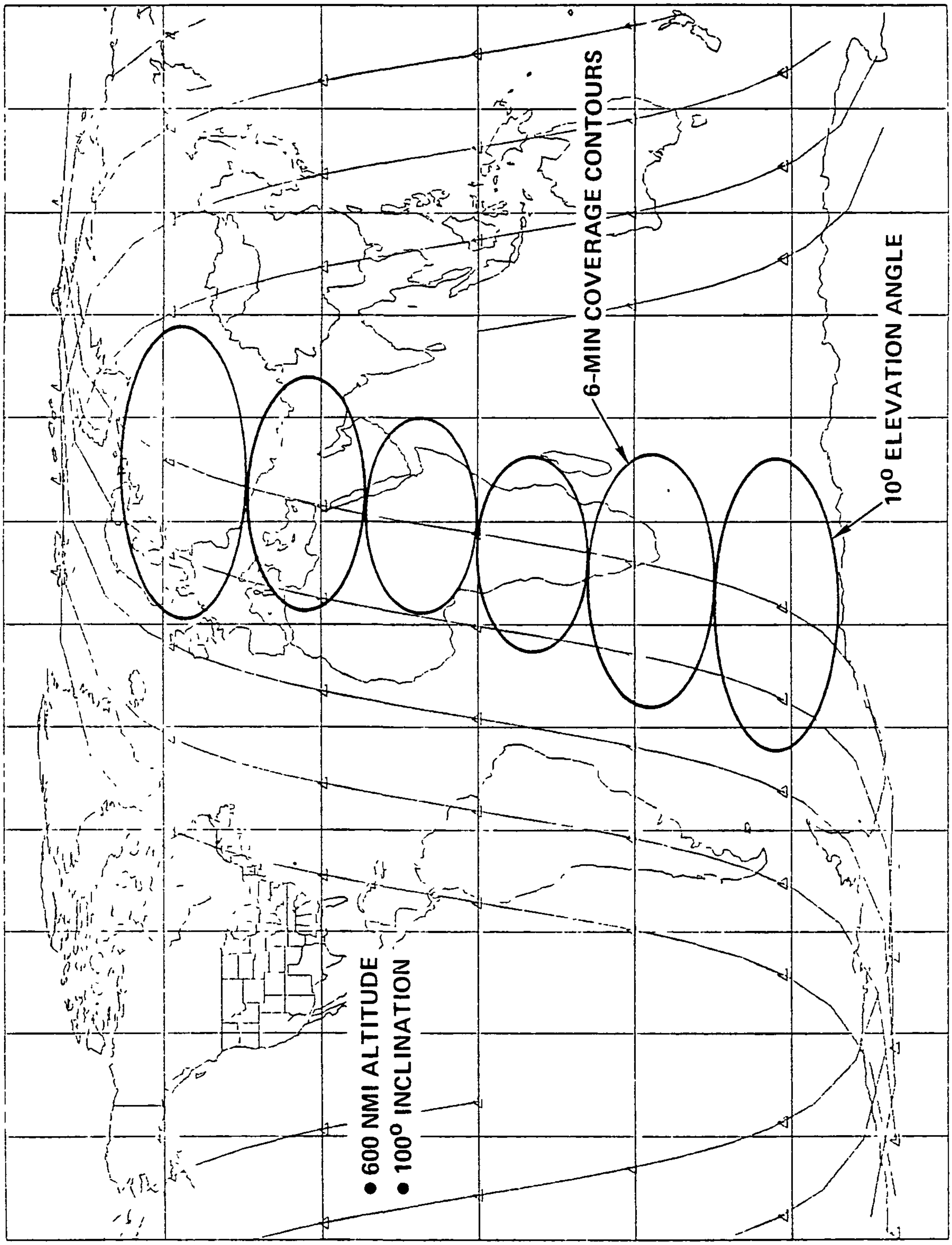



Figure D-4. Sun-Synchronous Orbital Coverage

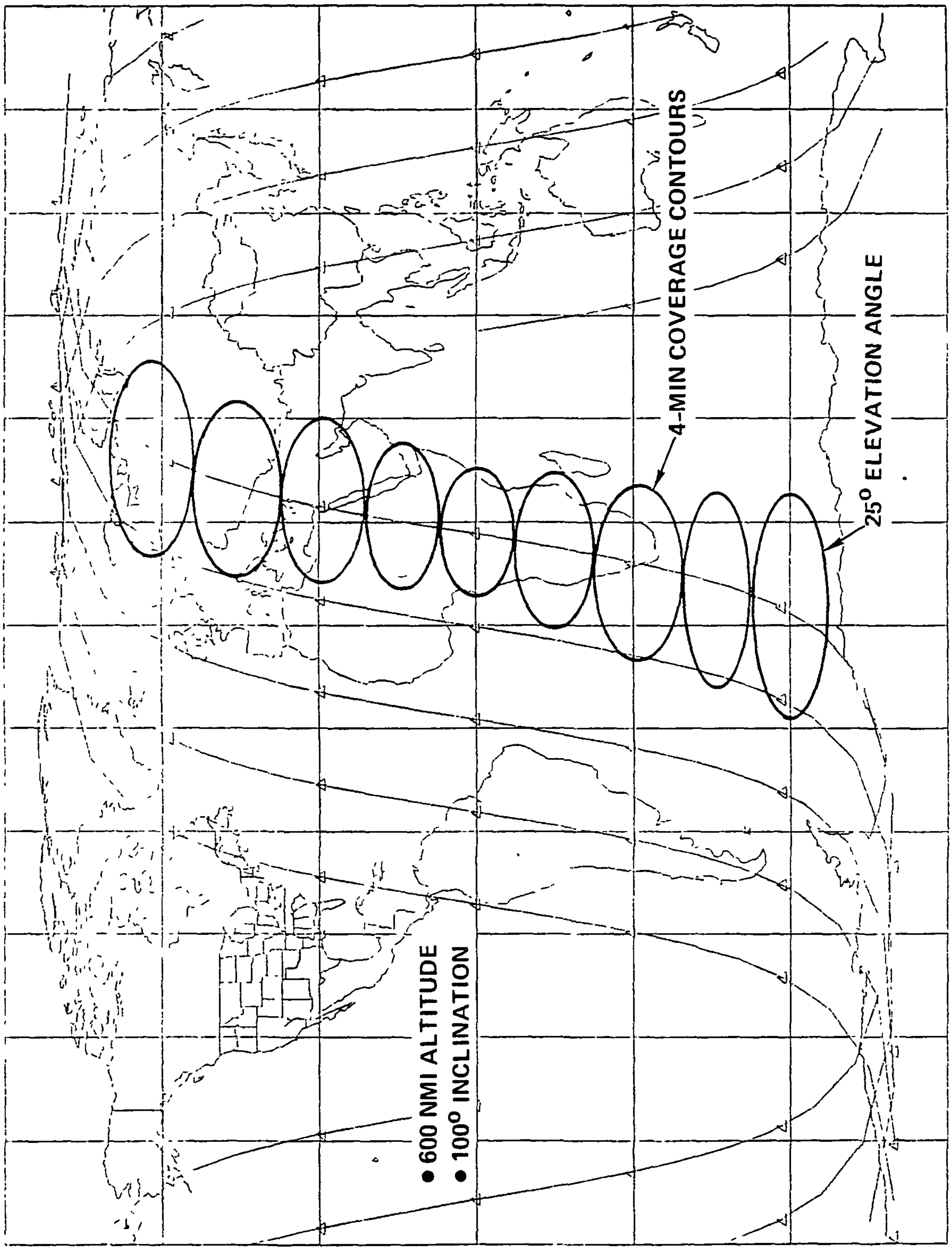



Figure D-5. Sun-Synchronous Orbital Coverage

# APPENDIX E

## SATELLITE WEIGHT AND CAPACITY ESTIMATION

Except in certain cases, the satellites in Bands 1 and 2 are designed to fully utilize the assumed 65,000-pound STS delivery capability to low earth orbit. The allowable satellite weight is determined by an iterative procedure (Figure E-1) in which the Centaur tankage capacity is varied until the combined weight of the Centaur, satellite, and ASE is 65,000 pounds. The weight of a Centaur-class vehicle is based on Centaur G data.

The procedure followed to obtain the satellite channel-beam capacity is outlined in Figure E-2. The first step is to create a 20-percent weight reserve by subtracting 1/6 of the STS/Centaur payload capability. The result is the maximum permissible satellite design weight. Those subsystem weights which are channel-beam-independent (e.g., attitude control, propulsion) are subtracted from this satellite weight. The remainder is the weight available for the channel-beam-dependent elements. When the latter weight is divided by the weight attributable to each channel-beam (e.g., solar panel, radiator), the channel-beam capacity is obtained.

The procedure described, including determination of the maximum satellite weight, has been automated on an IBM personal computer. Printouts providing the principal subsystem parameter values for the Band 1 and 2 baseline and variational systems are given at the end of this appendix.

Nominal channel-beam RF power requirements of 10 kilowatts for Band 1 and 5.5 kilowatts for Band 2 are derived in Appendix C. These values pertain to a boresight beam (i.e., a beam centered at the subsatellite point). Additional path loss associated with beams directed off-boresight is accounted for in two different ways, depending on the satellite orbit. For geostationary and Molniya orbits, the transmitter power requirements are increased by an amount corresponding to a typical northern zone. For subsynchronous orbits, the additional path loss is offset by an increase in antenna size. The diameter is chosen so that the beamwidth matches the area to be illuminated (i.e., equivalent to a 3-degree beam from geosynchronous orbit) in the crossrange direction, at the minimum satellite

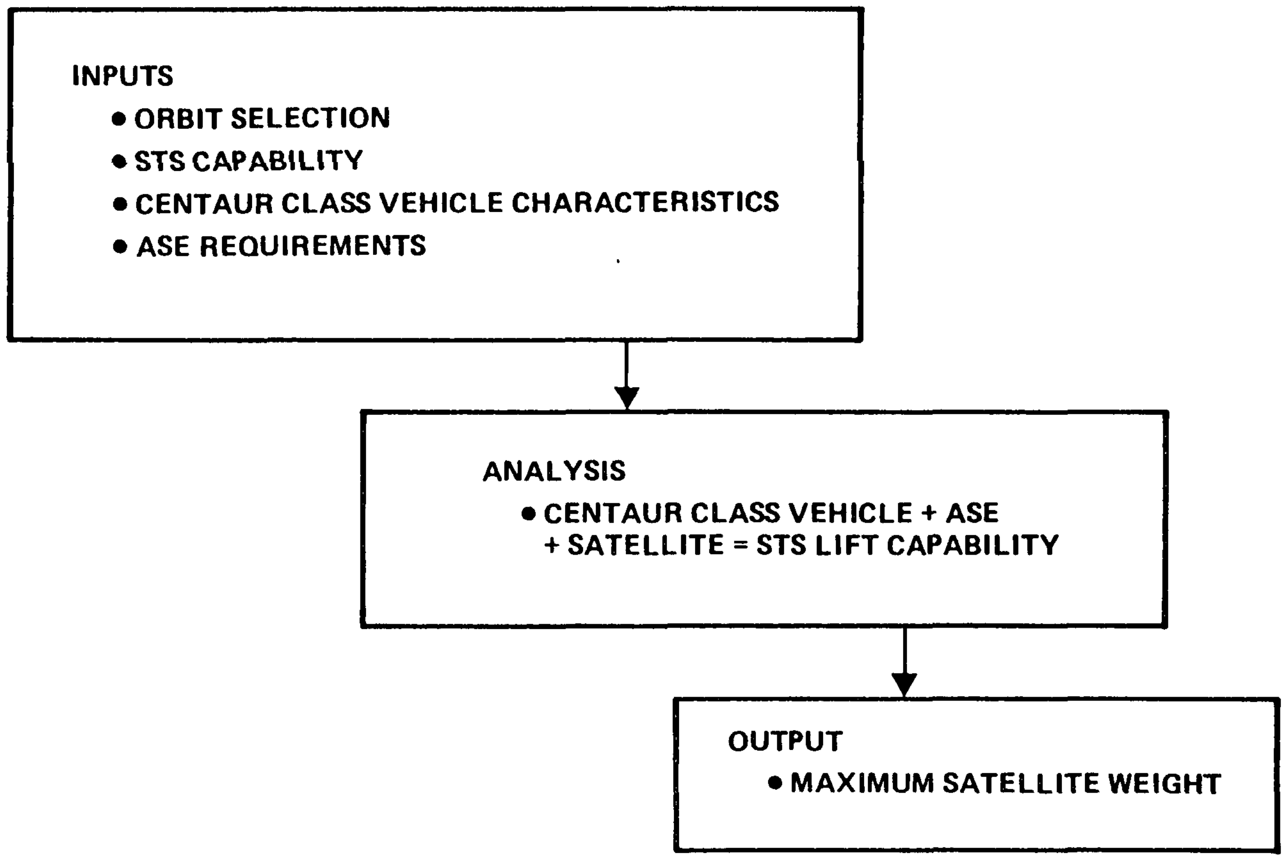



Figure E-1. STS/Centaur Payload Capability

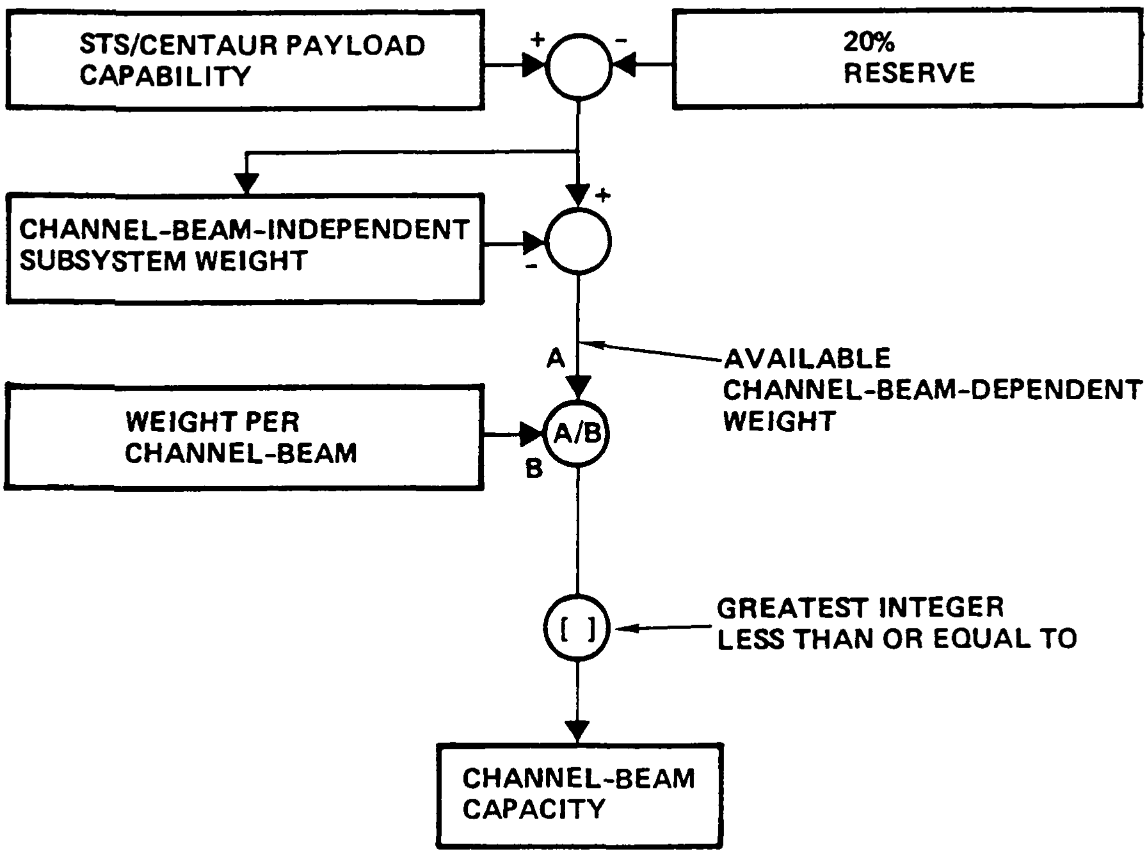



Figure E-2. Determination of Satellite Channel-Beam Capacity elevation angle. In addition to the path loss increment, a scan loss contribution is included in the required RF power to account for off-axis beams.

With the transmitter output power determined, electrical power and thermal subsystem requirements can be derived from the system power diagram (Figure E-3). The load power demanded by the satellite payload is equal to the RF power requirement plus the indicated losses. A thermal radiator is required to dissipate these losses.

For the PCU, two additional considerations (other than losses) must be addressed. The first is battery sizing, which depends on whether or not eclipse operation is required. In either case, the solar array is sized to provide full battery charging during sunlight.

The second consideration is the load-power fluctuation in Band 1. If operation during eclipse is required, there will be adequate battery power to accommodate these power fluctuations. If the battery system is sized only for housekeeping power (no eclipse operation), the solar array capacity must be sized for peak, rather than average, power demand.

The thermal radiator required for PCU temperature control is sized to meet the PCU electronics and battery discharge losses simultaneously. Thermal subsystem weight contributions for both payload and PCU (battery) temperature control are shown in Figure E-4. The larger weight coefficient associated with the PCU is attributable to the lower temperature requirement of the batteries as compared with the payload.

Solar array cabling losses are added to the power budget, as the solar arrays are separated from the PCU by half the antenna aperture to avoid shadowing.

Analysis leading to the attitude control and propulsion subsystem weight is diagrammed in Figure E-5. Subsystem weight depends on the satellite weight, inertias, and projected area with respect to the solar wind direction. The antenna and solar array dominate the projected area. For mesh deployable antennas, a conservative 95 percent permeability (open area) is assumed. For the continuous-membrane, inflatable antenna, 70 percent permeability is assumed, based on vendor transparent-film data at end-of-life.

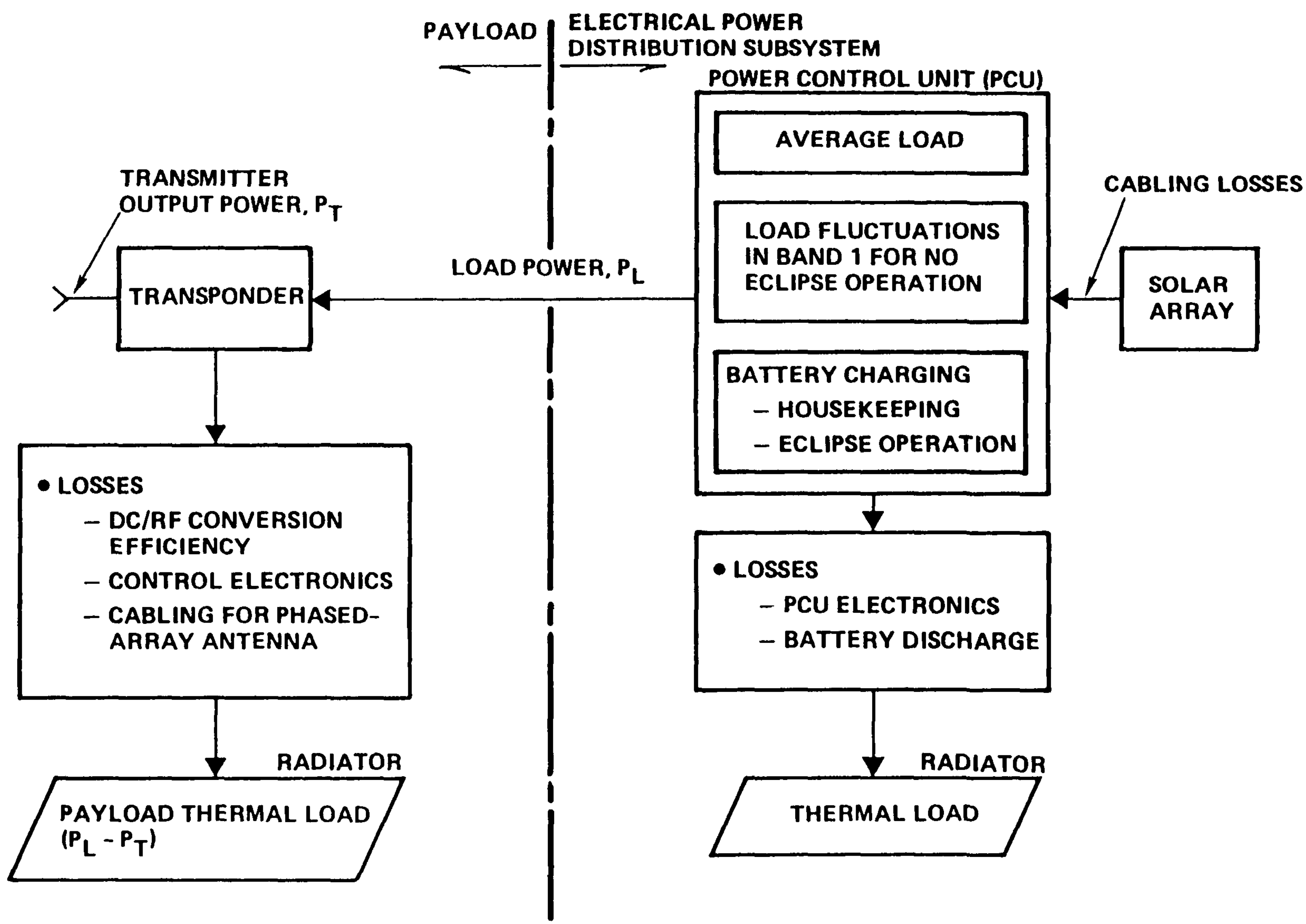



Figure E-3. Electrical Power and Thermal Subsystem Requirements

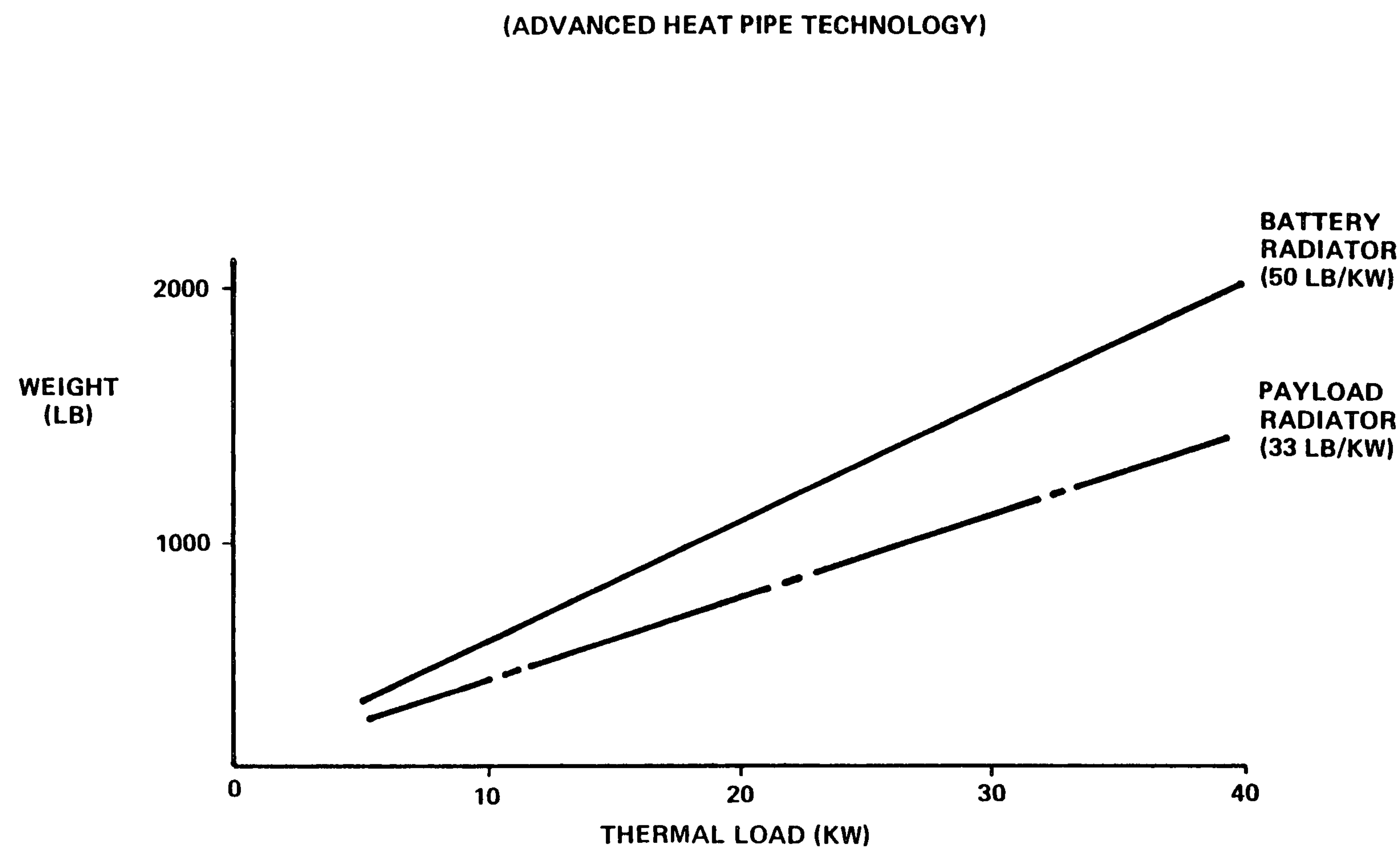



Figure E-4. Thermal Subsystem Weight

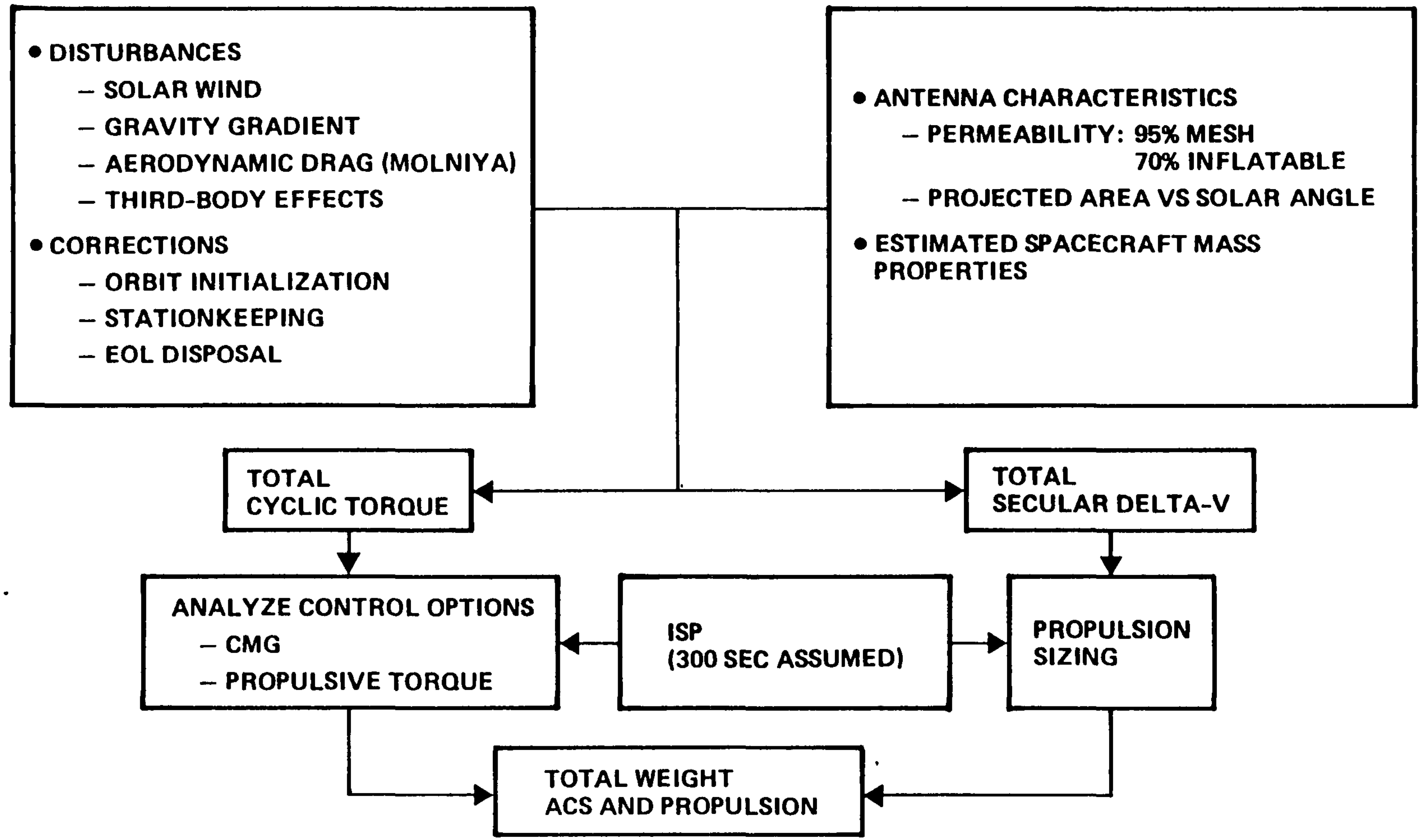



Figure E-5. Attitude Control and Propulsion

Disturbances acting on the satellite are divided into two categories. The first consists of cyclic torques, for which energy can be stored in and recovered from control-moment gyros (CMGs). Cyclic disturbances can also be managed by propulsive means. Both methods are analyzed for each system and the one leading to the lower subsystem weight is selected. CMG weight versus momentum buildup is shown in Figure E-6. These data are based on Space Station work and represent extensions of present large CMGs.

Secular, or one-way, disturbances must be counteracted by propulsive means. Advanced bipropellants (ISP = 300 sec) are assumed for this analysis.

Twenty-two satellite systems have been developed in the course of this study. Seven of these are identified as baseline systems (including four 8-hour-orbit systems designed for different Band 1 frequencies) and 15 are variations on these systems. Sixteen different satellite designs are involved in these 22 systems.

Tables E-1 and E-2 identify, by number, the 14 satellites associated with the Band 1 and 2 systems designs. (Satellites 10 and 11 are associated with Band 3 systems.) Computer printouts showing subsystem level contributions to the satellite weight estimates are shown in Table E-3. The circled numbers at the top of the tables identify the satellites. The number of channel-beams each satellite is capable of supporting is shown near the bottom of the table. In those cases where the residual or unused weight is close to the incremental weight per channel-beam, the capacity has been taken as the next higher integer.

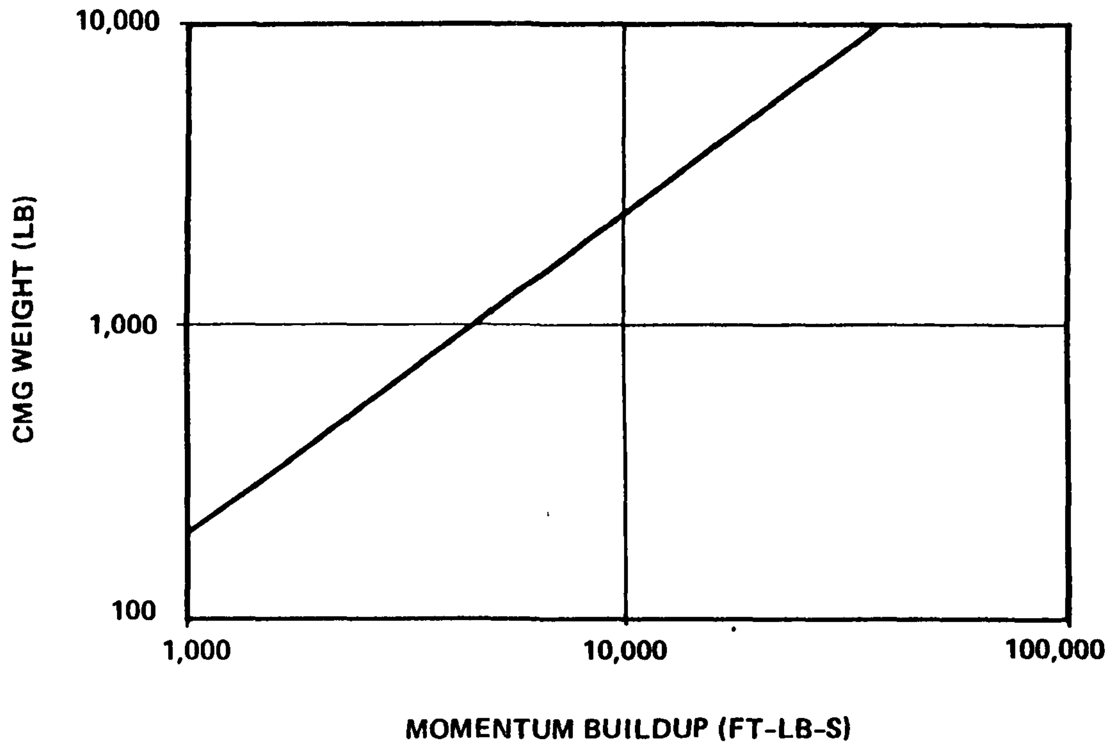



Figure E-6. CMG Weight Versus Momentum

Table E-1. Satellite Identification for Baseline Systems

| SYSTEM | BAND | FREQUENCY (MHz) | ORBIT | ANTENNA TYPE | SATELLITE NUMBER |
|---|---|---|---|---|---|
| BASE 1 | 1a | 26.1 | GEO | CC | 1 |
| BASE 2 | 1a | 26.1 | 8-HR | PA | 5 |
| | 1b | 21.8 | 8-HR | PA | 12 |
| | 1c | 17.9 | 8-HR | PA | 13 |
| | 1d | 15.5 | 8-HR | PA | 14 |
| BASE 3 | 2 | 68 | MOLNIYA | CC | 3 |
| BASE 4 | 3 | 1500 | GEO | — | 10 |

Table E-2. Satellite Identification for System Variations

| SYSTEM VARIATION | BAND | ORBIT | ANTENNA TYPE | EQUIVALENT GEO BEAMWIDTH (DEG) | SATELLITE NUMBER |
|---|---|---|---|---|---|
| 1 | 1 | GEO | CC | 3 | 1 |
| 1 | 1 | 8-HR | PA | 3 | 5 |
| 2 | 1 | 8-HR | PA | 3 | 5 |
| 3 | 1 | 8-HR | PA | 3 | 6 |
| 4 | 1 | GEO | CC | 3 | 1 |
| 4 | 1 | 8-HR | PA | 3 | 6 |
| 4 | 3 | GEO | – | 3 | 11 |
| 5 | 1 | GEO | CC | 3 | 2 |
| 5 | 1 | 8-HR | PA | 3 | 6 |
| 5 | 1 | 8-HR | PA | 6 | 7 |
| 5 | 1 | 12-HR | CC | 3 | 9 |
| 5 | 1 | 12-HR | PA | 3 | 8 |
| 5 | 2 | MOLNIYA | CC | 6 | 4 |
| SSB-AM-1 | 1 | GEO | CC | 3 | 15 |
| SSB-AM-2 | 1 | 8-HR | PA | 6 | 16 |

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# Table E-3. Satellite Weight and Capacity Estimates

| System Analysis Parameters: | (1) System 1 | (5) System 2 | (3) System 3 |
|---|---|---|---|
| Orbit choice | Geosync | 8 hr | Molniya |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cable-catn | Cross-beam | Cable-catn |
| Operate during eclipse | No | No | No |
| STS lift capability (Lb) | 65000.0 | 65000.0 | 65000.0 |
| Field strength (micro-V/M) | 300.0 | 300.0 | 250.0 |
| Ref GEO beamwidth (Deg) | 3.0 | 3.0 | 3.0 |
| Elevation angle (Deg) | 20.0 | 20.0 | 20.0 |
| Operating frequency (MHz) | 26.1 | 26.1 | 68.0 |
| Ratio aperture/thrusters spacing | 1.0 | 1.0 | 1.0 |
| Ratio of SA spacing/aperture | 1.0 | 1.0 | 1.0 |
| Peak/Avg solar array power ratio | 1.7 | 1.4 | 1.0 |
| ***** System Analysis output ****** | | | |
| Orbit inclination (Deg) | 0.0 | 28.0 | 63.4 |
| Beamwidth (Deg) | 3.0 | 6.2 | 2.7 |
| RF power/channel-beam: Peak (kW) | 20.4 | 15.7 | 6.3 |
| RF power/channel-beam: Average (kW) | 12.0 | 11.2 | 6.3 |
| Wavelength (Ft) | 38 | 38 | 14 |
| STS/Centaur orbit capability (Lb) | 13846 | 20764 | 19910 |
| STS ASE (Lb) | 1000 | 1000 | 1000 |
| Weight reserve (Lb) | 2308 | 3461 | 3318 |
| Antenna aperture (M) | 267 | 80 | 114 |
| Antenna weight (Lb) | 4453 | 2816 | 1631 |
| TT&C, DHS, Comm subsystems (Lb) | 303 | 261 | 272 |
| Attitude control (Lb) | 418 | 256 | 302 |
| Propulsion (Lb) | 464 | 995 | 1228 |
| Structures (Excl Antenna) (Lb) | 609 | 1440 | 1396 |
| Thermal control weight (Lb) | 427 | 984 | 1243 |
| Total weight/channel-beam (Lb) | 189 | 187 | 99 |
| EDI total weight (Lb) | 996 | 632 | 714 |
| Total EDI weight/channel-beam (Lb) | 425 | 97 | 47 |
| EPDS total weight (Lb) | 1874 | 3027 | 3471 |
| Total weight/channel beam (Lb) | 692 | 583 | 270 |
| Power storage/channel beam (Lb) | 0 | 0 | 0 |
| PAYLOAD weight/channel-beam (Lb) | 920 | 1006 | 506 |
| Maximum number of channel-beams: | 2 | 5 | 12 |
| Residual weight (Lb): | 149 | 1859 | 250 |
| Total weight/channel-beam (Lb) | 2226 | 1873 | 924 |
| Available payload weight (Lb) | 4601 | 11224 | 11338 |
| Non-beam-related weight (Lb) | 6937 | 6079 | 5254 |

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Table E-3. Satellite Weight and Capacity Estimates (Cont)

| System Analysis Parameters: | (12) System 1 | (13) System 2 | (14) System 3 |
|---|---|---|---|
| Orbit choice | 8 hr | 8 hr | 8 hr |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cross-beam | Cross-beam | Cross-beam |
| Operate during eclipse | No | No | No |
| STS lift capability (Lb): | 65000.0 | 65000.0 | 65000.0 |
| Field strength (micro-V/M): | 300.0 | 300.0 | 300.0 |
| Ref GEO beamwidth (Deg): | 3.0 | 3.0 | 3.0 |
| Elevation angle (Deg): | 20.0 | 20.0 | 20.0 |
| Operating frequency (MHz): | 21.8 | 17.9 | 15.5 |
| Ratio aperture/thrusters spacing - : | 1.0 | 1.0 | 1.0 |
| Ratio of SA spacing/aperture : | 1.0 | 1.0 | 1.0 |
| Peak/Avg solar array power ratio : | 1.4 | 1.4 | 1.4 |

***** System Analysis output ******

| System Analysis output | System 1 | System 2 | System 3 |
|---|---|---|---|
| Orbit inclination (Deg): | 28.0 | 28.0 | 28.0 |
| Beamwidth (Deg): | 6.2 | 6.2 | 6.2 |
| RF power/channel-beam: Peak (kW): | 15.7 | 15.7 | 15.7 |
| RF power/channel-beam: Average (kW): | 11.2 | 11.2 | 11.2 |
| Wavelength (Ft): | 45 | 55 | 64 |
| STS/Centaur orbit capability - (Lb): | 20764 | 20764 | 20764 |
| STS ASE (Lb): | 1000 | 1000 | 1000 |
| Weight reserve (Lb): | 3461 | 3461 | 3461 |
| Antenna aperture (M): | 96 | 117 | 136. |
| Antenna weight (Lb): | 3379 | 4106 | 4757 |
| TT&C, DHS, Comm subsystems - (Lb): | 267 | 274 | 279 |
| Attitude control (Lb): | 270 | 286 | 299 |
| Propulsion (Lb): | 1001 | 1010 | 1019 |
| Structures (Excl Antenna) (Lb): | 1402 | 1353 | 1309 |
| Thermal control weight (Lb): | 984 | 798 | 797 |
| Total weight/channel-beam (Lb): | 187 | 187 | 187 |
| EDI total weight (Lb): | 684 | 642 | 711 |
| Total EDI weight/channel-beam (Lb): | 108 | 124 | 142 |
| EPDS total weight (Lb): | 3044 | 2485 | 2503 |
| Total weight/channel beam (Lb): | 583 | 583 | 583 |
| Power storage/channel beam - (Lb): | 0 | 0 | 0 |
| PAYLOAD weight/channel-beam (Lb): | 1053 | 1126 | 1203 |
| Maximum number of channel-beams: | 5 | 4 | 4 |
| Residual weight (Lb): | 1005 | 1843 | 812 |
| Total weight/channel-beam (Lb): | 1930 | 2020 | 2114 |
| Available payload weight (Lb): | 10655 | 9923 | 9268 |
| Non-beam-related weight (Lb): | 6648 | 7381 | 8036 |

Table E-3. Satellite Weight and Capacity Estimates (Cont)

| System Analysis Parameters: | (6) System 1 | (2) System 2 | (7) System 3 |
|---|---|---|---|
| Orbit choice | 8hr 37 | Geosync | 8hr 37 |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cross-beam | Cable-catn | Cross-beam |
| Operate during eclipse | No | No | No |
| STS lift capability (Lb): | 65000.0 | 65000.0 | 65000.0 |
| Field strength (micro-V/M): | 300.0 | 150.0 | 150.0 |
| Ref GEO beamwidth (Deg): | 3.0 | 3.0 | 6.0 |
| Elevation angle (Deg): | 20.0 | 20.0 | 20.0 |
| Operating frequency (MHz): | 26.1 | 26.1 | 26.1 |
| Ratio aperture/thrusters spacing | 1.0 | 1.0 | 1.0 |
| Ratio of SA spacing/aperture | 1.0 | 1.0 | 1.0 |
| Peak/Avg solar array power ratio | 1.4 | 1.4 | 1.4 |
| ***** System Analysis output ****** | | | |
| Orbit inclination (Deg): | 37.0 | 0.0 | 37.0 |
| Beamwidth (Deg): | 6.2 | 3.0 | 12.5 |
| RF power/channel-beam: Peak (kW): | 15.7 | 4.2 | 15.7 |
| RF power/channel-beam: Average (kW): | 11.2 | 3.0 | 11.2 |
| Wavelength (Ft): | 38 | 38 | 38 |
| STS/Centaur orbit capability (Lb): | 19951 | 13846 | 19951 |
| STS ASE (Lb): | 1000 | 1000 | 1000 |
| Weight reserve (Lb): | 3325 | 2308 | 3325 |
| Antenna aperture (M): | 80 | 267 | 34 |
| Antenna weight (Lb): | 2816 | 4453 | 636 |
| TT&C, DHS, Comm subsystems (Lb): | 261 | 303 | 235 |
| Attitude control (Lb): | 256 | 418 | 202 |
| Propulsion (Lb): | 956 | 464 | 945 |
| Structures (Excl Antenna) (Lb): | 1373 | 609 | 1522 |
| Thermal control weight (Lb): | 984 | 427 | 1358 |
| Total weight/channel-beam (Lb): | 187 | 47 | 187 |
| EDI total weight (Lb): | 632 | 845 | 690 |
| Total EDI weight/channel-beam (Lb): | 97 | 88 | 78 |
| EPDS total weight (Lb): | 3027 | 1629 | 4140 |
| Total weight/channel beam (Lb): | 583 | 142 | 583 |
| Power storage/channel beam (Lb): | 0 | 0 | 0 |
| PAYLOAD weight/channel-beam (Lb): | 1006 | 245 | 926 |
| Maximum number of channel-beams: | 5 | 8 | 7 |
| Residual weight (Lb): | 1288 | 425 | 416 |
| Total weight/channel-beam (Lb): | 1873 | 522 | 1773 |
| Available payload weight (Lb): | 10653 | 4601 | 12827 |
| Non-beam-related weight (Lb): | 5973 | 6937 | 3799 |

Table E-3. Satellite Weight and Capacity Estimates (Cont)

| System Analysis Parameters: | (9) System 1 | (8) System 2 | (4) System 3 |
|---|---|---|---|
| * Orbit choice | 12 hr | 12 hr | Molniya |
| * Power storage choice | NiH2 | NiH2 | NiH2 |
| * Antenna choice | Cable-catn | Cross-beam | Cable-catn |
| * Operate during eclipse | No | No | No |
| * STS lift capability (Lb): | 65000.0 | 65000.0 | 40000.0 |
| * Field strength (micro-V/M): | 150.0 | 150.0 | 150.0 |
| * Ref GEO beamwidth (Deg): | 3.0 | 3.0 | 6.0 |
| * Elevation angle (Deg): | 20.0 | 20.0 | 20.0 |
| * Operating frequency (MHz): | 26.1 | 26.1 | 68.0 |
| * Ratio aperture/thrusters spacing : | 1.0 | 1.0 | 1.0 |
| * Ratio of SA spacing/aperture : | 1.0 | 1.0 | 1.0 |
| * Peak/Avg solar array power ratio : | 1.2 | 1.2 | 1.0 |

***** System Analysis output ******

| | System 1 | System 2 | System 3 |
|---|---|---|---|
| Orbit inclination (Deg): | 28.0 | 28.0 | 63.4 |
| Beamwidth (Deg): | 4.5 | 4.5 | 5.4 |
| RF power/channel-beam: Peak (kW): | 3.4 | 3.3 | 9.1 |
| RF power/channel-beam: Average (kW): | 2.9 | 2.7 | 9.1 |
| Wavelength (Ft): | 38 | 38 | 14 |
| STS/Centaur orbit capability - (Lb): | 18374 | 18374 | 8106 |
| STS ASE (Lb): | 1000 | 1000 | 1000 |
| Weight reserve (Lb): | 3062 | 3062 | 1351 |
| Antenna aperture (M): | 178 | 115 | 57 |
| Antenna weight (Lb): | 2812 | 5464 | 995 |
| TT&C, DHS, Comm subsystems - (Lb): | 288 | 273 | 250 |
| Attitude control (Lb): | 356 | 284 | 241 |
| Propulsion (Lb): | 816 | 782 | 488 |
| Structures (Excl Antenna) (Lb): | 1150 | 1058 | 476 |
| Thermal control weight (Lb): | 953 | 731 | 479 |
| Total weight/channel-beam (Lb): | 45 | 45 | 143 |
| EDI total weight (Lb): | 958 | 527 | 289 |
| Total EDI weight/channel-beam (Lb): | 41 | 25 | 48 |
| EPDS total weight (Lb): | 2761 | 1916 | 1289 |
| Total weight/channel beam (Lb): | 121 | 118 | 389 |
| Power storage/channel beam - (Lb): | 0 | 0 | 0 |
| PAYLOAD weight/channel-beam (Lb): | 245 | 267 | 724 |
| Maximum number of channel-beams: | 20 | 15 | 3 |
| Residual weight (Lb): | 310 | 268 | 72 |
| Total weight/channel-beam (Lb): | 452 | 456 | 1305 |
| Available payload weight (Lb): | 9350 | 7108 | 3987 |
| Non-beam-related weight (Lb): | 5962 | 8204 | 2768 |



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Table E-3. Satellite Weight and Capacity Estimates (Cont)

| System Analysis Parameters: | | (15) System 1 | (16) System 2 |
|---|---|---|---|
| Orbit choice | | Geosync | 8hr 37 |
| Power storage choice | | NiH2 | NiH2 |
| Antenna choice | | Cable-catn | Cross-beam |
| Operate during eclipse | | No | No |
| STS lift capability | (Lb) | 65000.0 | 65000.0 |
| Field strength | (micro-V/M) | 122.0 | 122.0 |
| Ref GEO beamwidth | (Deg) | 3.0 | 6.0 |
| Elevation angle | (Deg) | 20.0 | 20.0 |
| Operating frequency | (MHz) | 26.1 | 26.1 |
| Ratio aperture/thrusters spacing | | 1.0 | 1.0 |
| Ratio of SA spacing/aperture | | 1.0 | 1.0 |
| Peak/Avg solar array power ratio | | 1.4 | 1.4 |

***** System Analysis output ******

| | | System 1 | System 2 |
|---|---|---|---|
| Orbit inclination | (Deg) | 0.0 | 37.0 |
| Beamwidth | (Deg) | 3.0 | 12.5 |
| RF power/channel-beam: Peak | (kW) | 2.8 | 10.4 |
| RF power/channel-beam: Average | (kW) | 2.0 | 7.4 |
| Wavelength | (Ft) | 38 | 38 |
| STS/Centaur orbit capability | (Lb) | 13846 | 19951 |
| STS ASE | (Lb) | 1000 | 1000 |
| Weight reserve | (Lb) | 2308 | 3325 |
| Antenna aperture | (M) | 267 | 34 |
| Antenna weight | (Lb) | 4453 | 636 |
| TT&C, DHS, Comm subsystems | (Lb) | 303 | 235 |
| Attitude control | (Lb) | 418 | 202 |
| Propulsion | (Lb) | 464 | 945 |
| Structures (Excl Antenna) | (Lb) | 609 | 1522 |
| Thermal control weight | (Lb) | 456 | 1286 |
| Total weight/channel-beam | (Lb) | 31 | 124 |
| EDI total weight | (Lb) | 899 | 660 |
| Total EDI weight/channel-beam | (Lb) | 58 | 51 |
| EPDS total weight | (Lb) | 1717 | 3917 |
| Total weight/channel beam | (Lb) | 94 | 386 |
| Power storage/channel beam | (Lb) | 0 | 0 |
| PAYLOAD weight/channel-beam | (Lb) | 169 | 612 |
| Maximum number of channel-beams: | | 13 | 10 |
| Residual weight | (Lb) | 12 | 1097 |
| Total weight/channel-beam | (Lb) | 353 | 1173 |
| Available payload weight | (Lb) | 4601 | 12827 |
| Non-beam-related weight | (Lb) | 6937 | 3799 |



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# APPENDIX F

# SUBSYNCHRONOUS ORBIT COVERAGE CONTOURS

Coverage regions for various subsynchronous orbits are presented in this appendix. Figures F-1a to F-1d show continuous, 1-hour coverage regions (in bold outline) for a particular 6-hour orbit of 28-degree inclination. Satellite visibility is defined by an elevation angle constraint of 20 degrees. Each 1-hour coverage region is found by taking the intersection of a pair of instantaneous visibility regions 1 hour apart. The time ticks on the ground track correspond to the visibility contours shown.

Figures F-2a to F-2c indicate 1-hour coverage regions for one of two 8-hour orbits used to construct the baseline 8-hour satellite system and its variations. A similar set of coverage contours for the other 8-hour orbit is provided in Section 3.3.

Regions of continuous, 2-hour coverage for a 12-hour orbit are shown in Figures F-3a and F-3b. Two-hour coverage regions have been chosen in this case for ease of visualization.

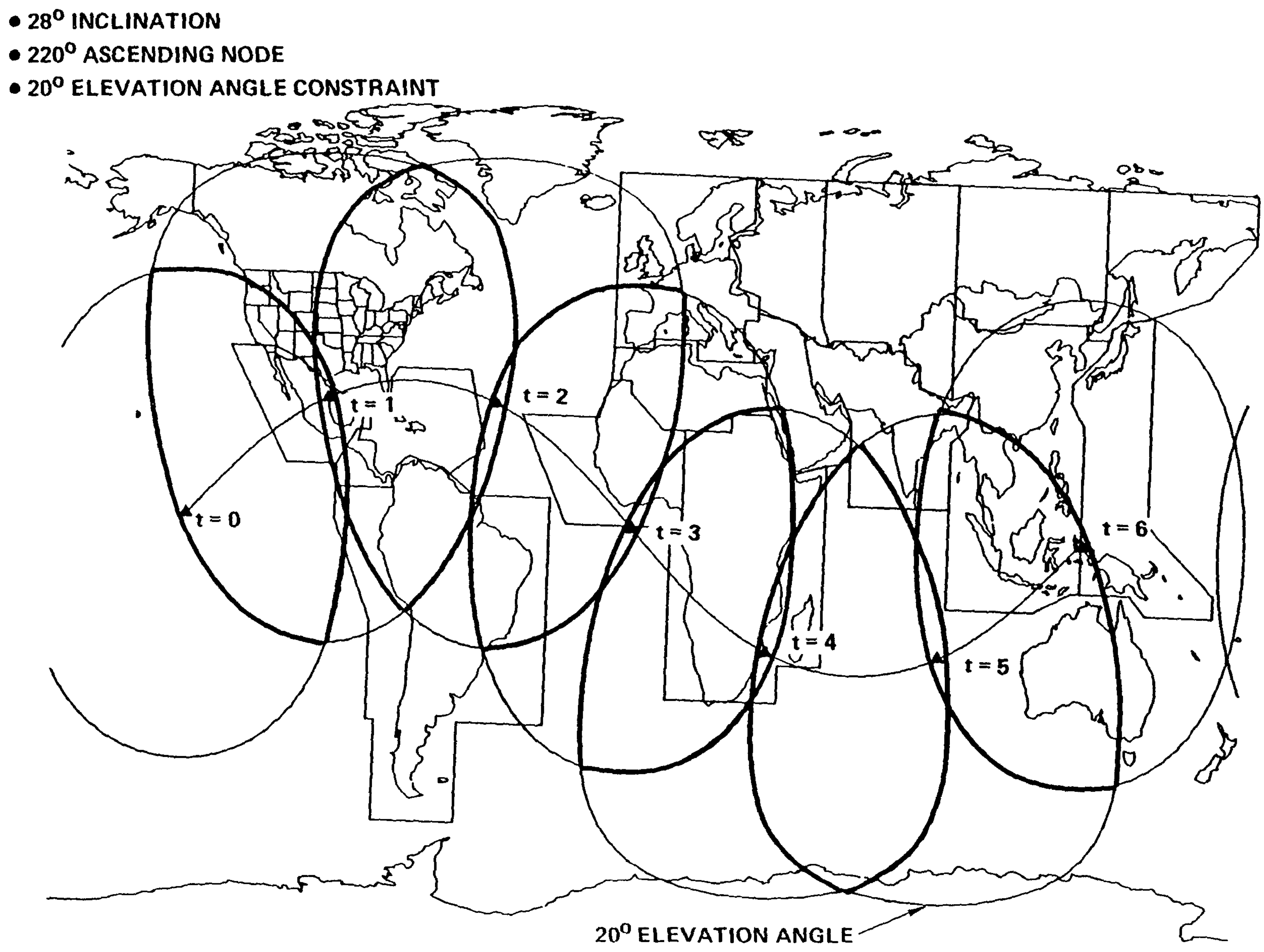


Figure F-1a. One-Hour Coverage Regions for 6-Hour Circular Orbit

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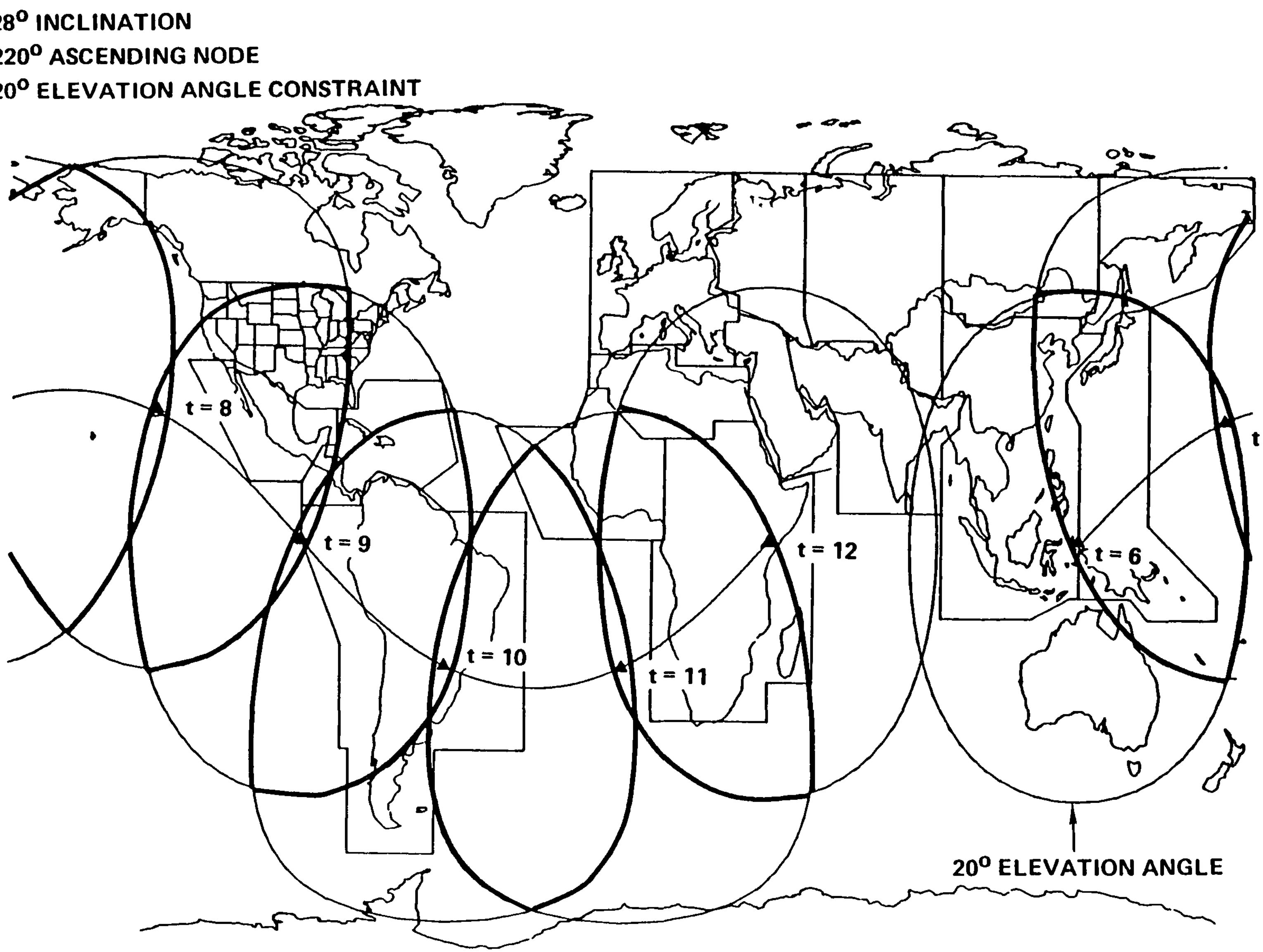


Figure F-1b. One-Hour Coverage Regions for 6-Hour Circular Orbit

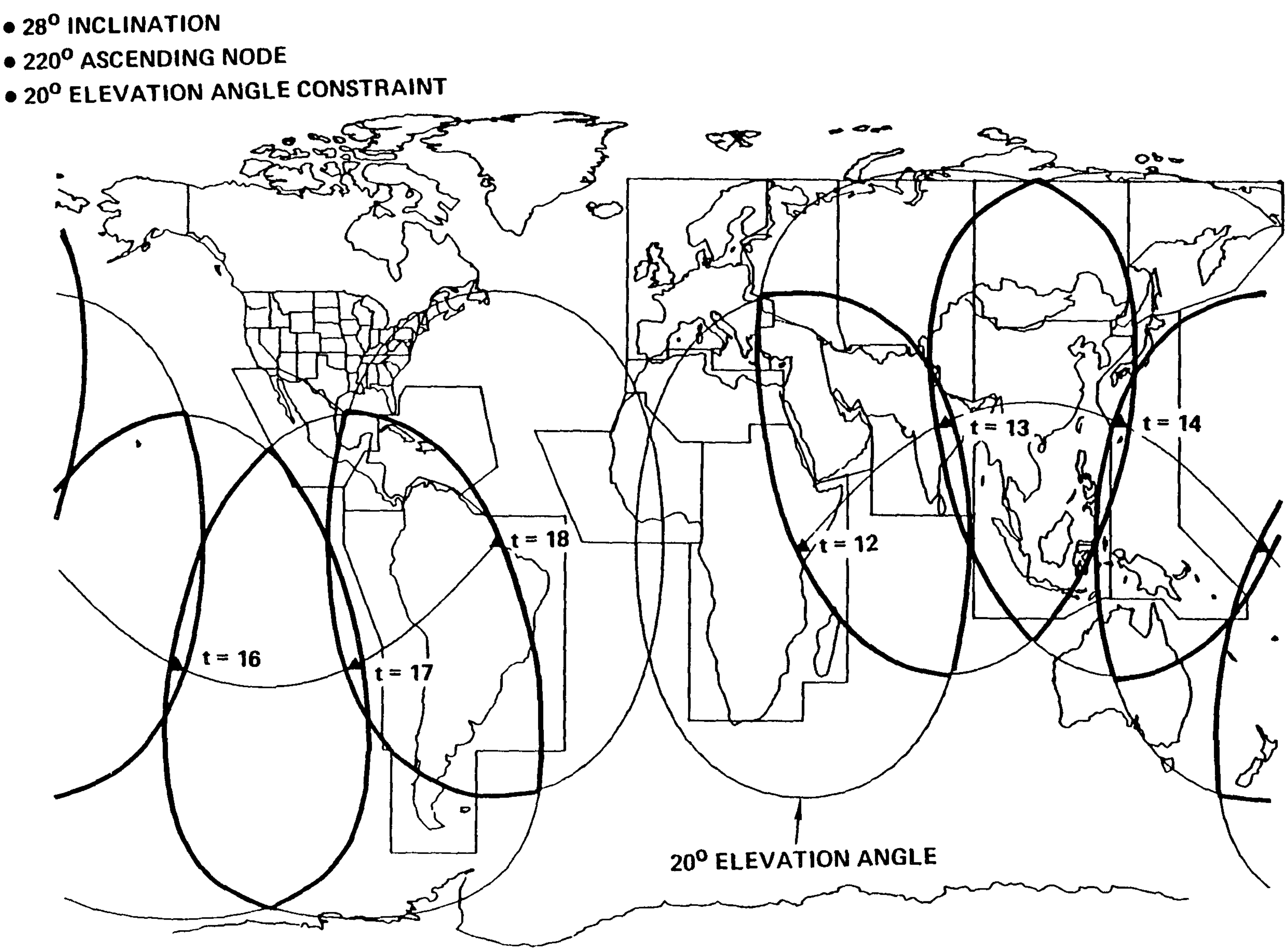


Figure F-1c. One-Hour Coverage Regions for 6-Hour Circular Orbit

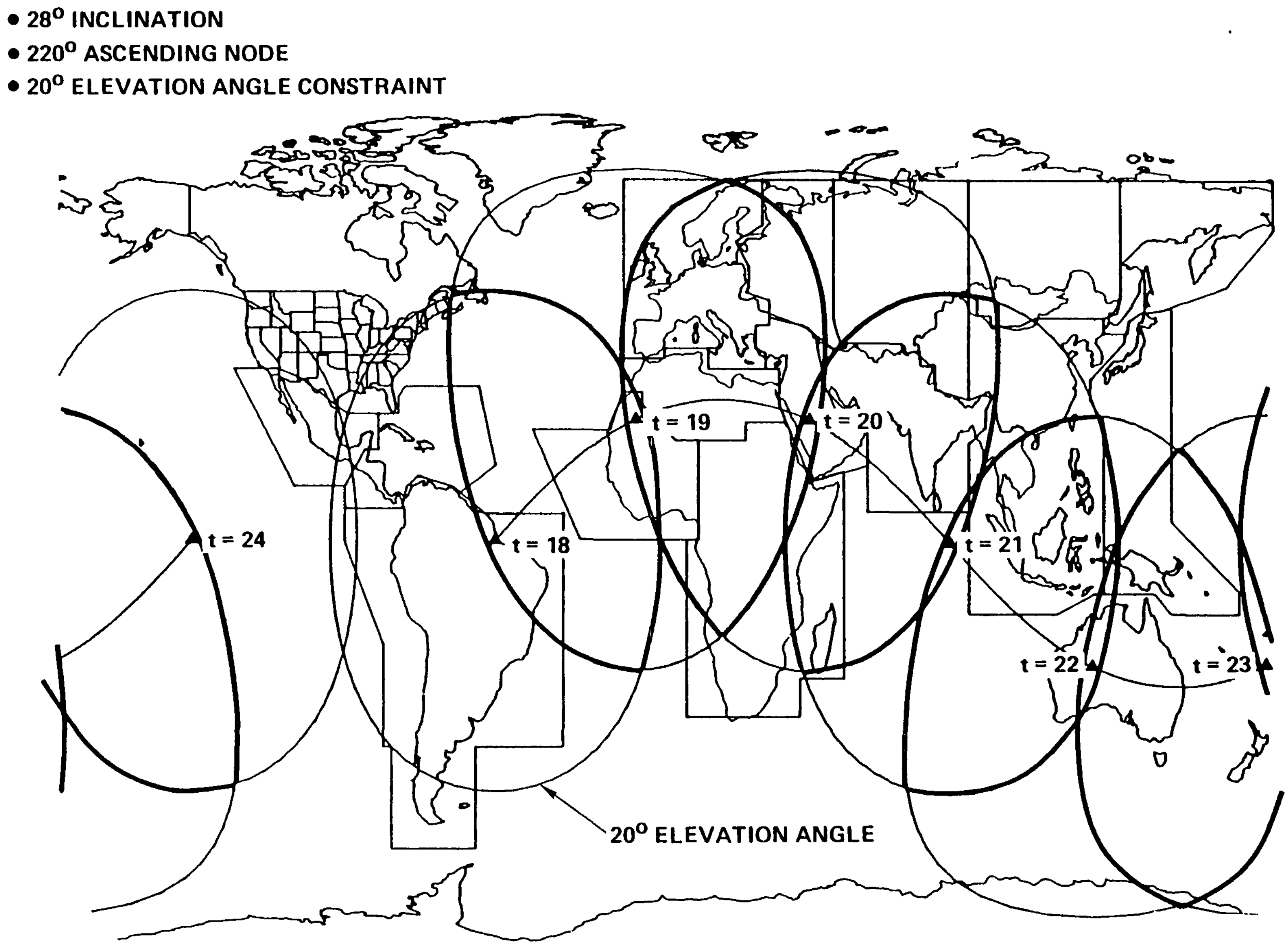


Figure F-1d. One-Hour Coverage Regions for 6-Hour Circular Orbit

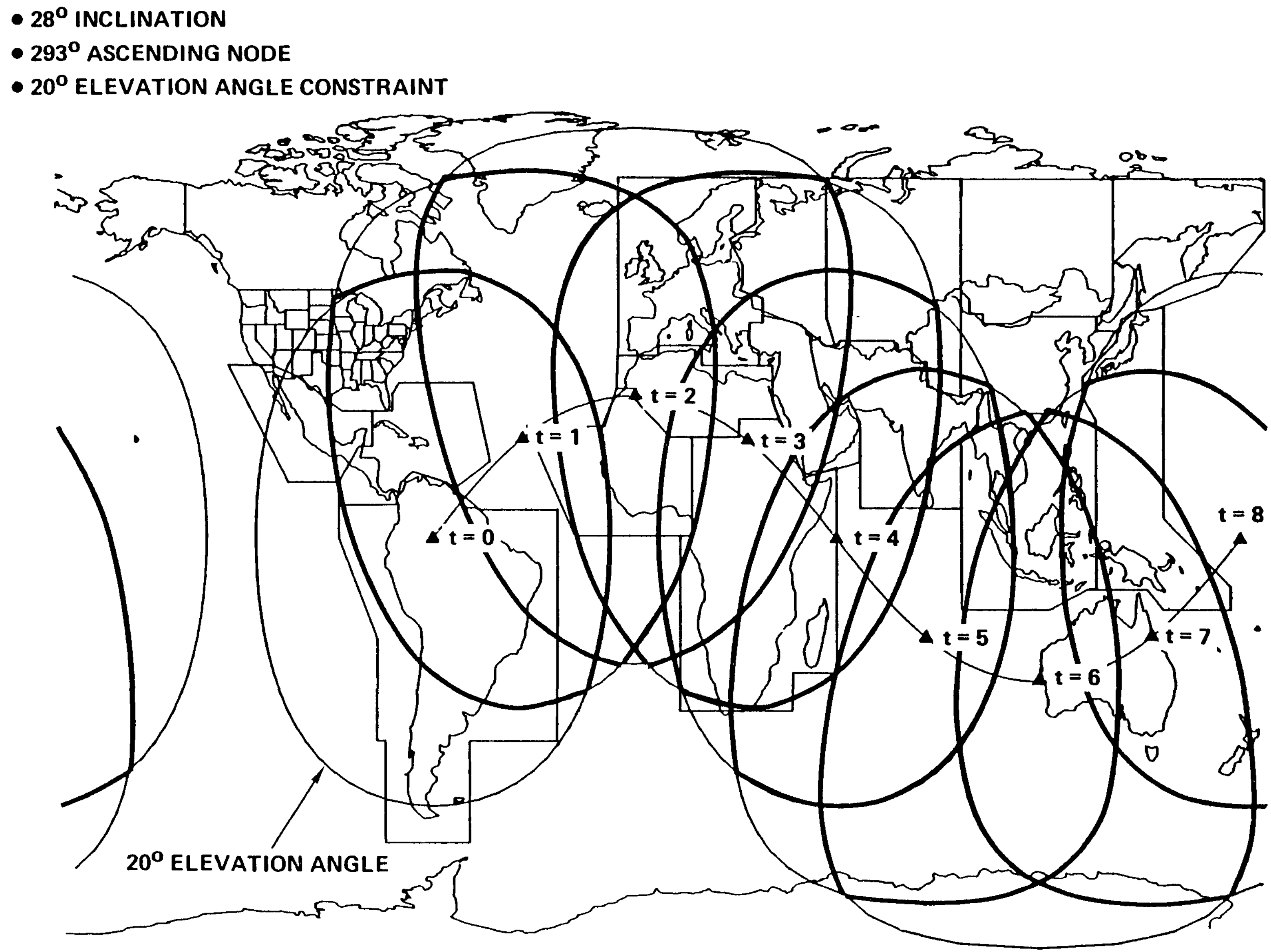


Figure F-2a. One-Hour Coverage Regions for 8-Hour Circular Orbit

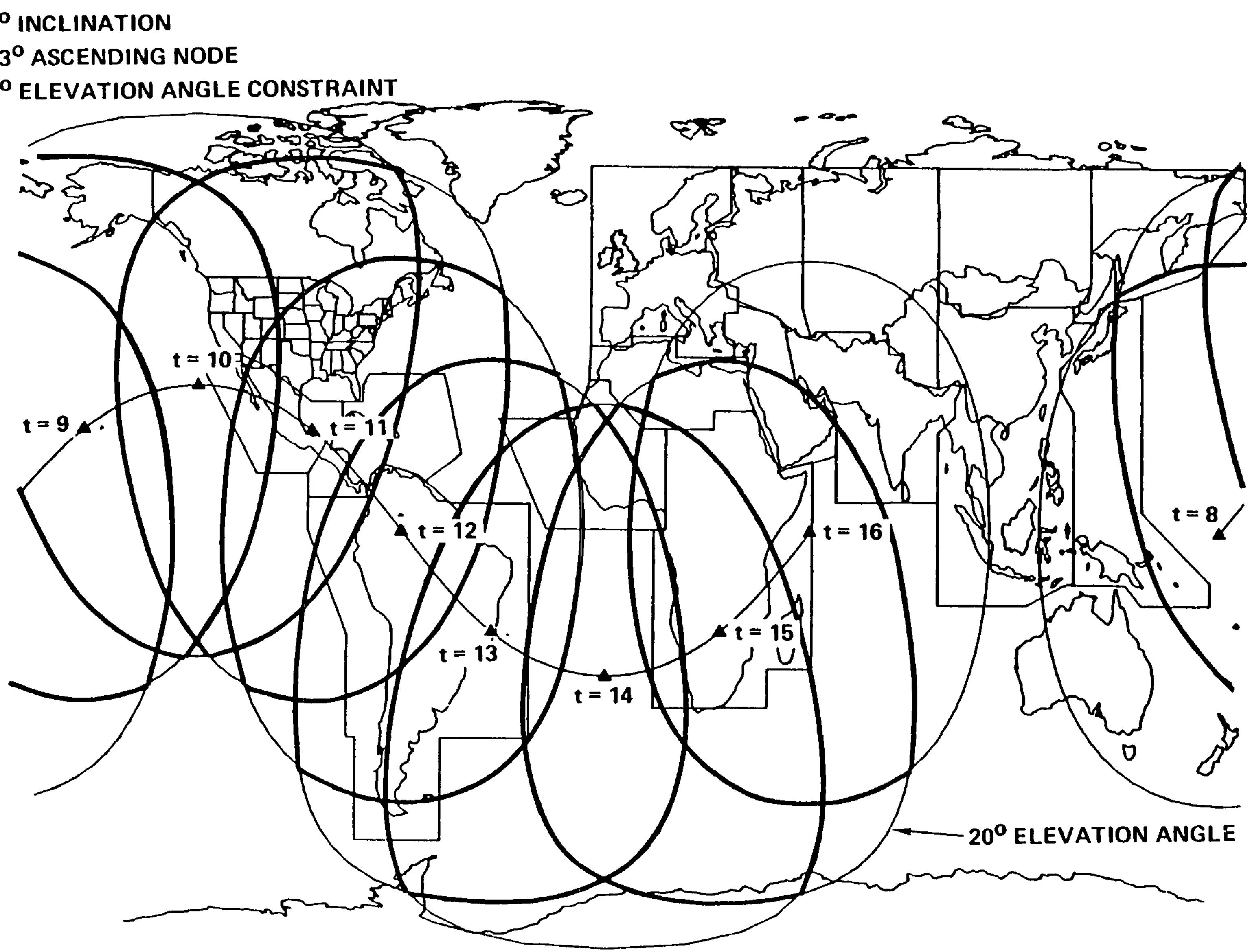


Figure F-2b. One-Hour Coverage Regions for 8-Hour Circular Orbit

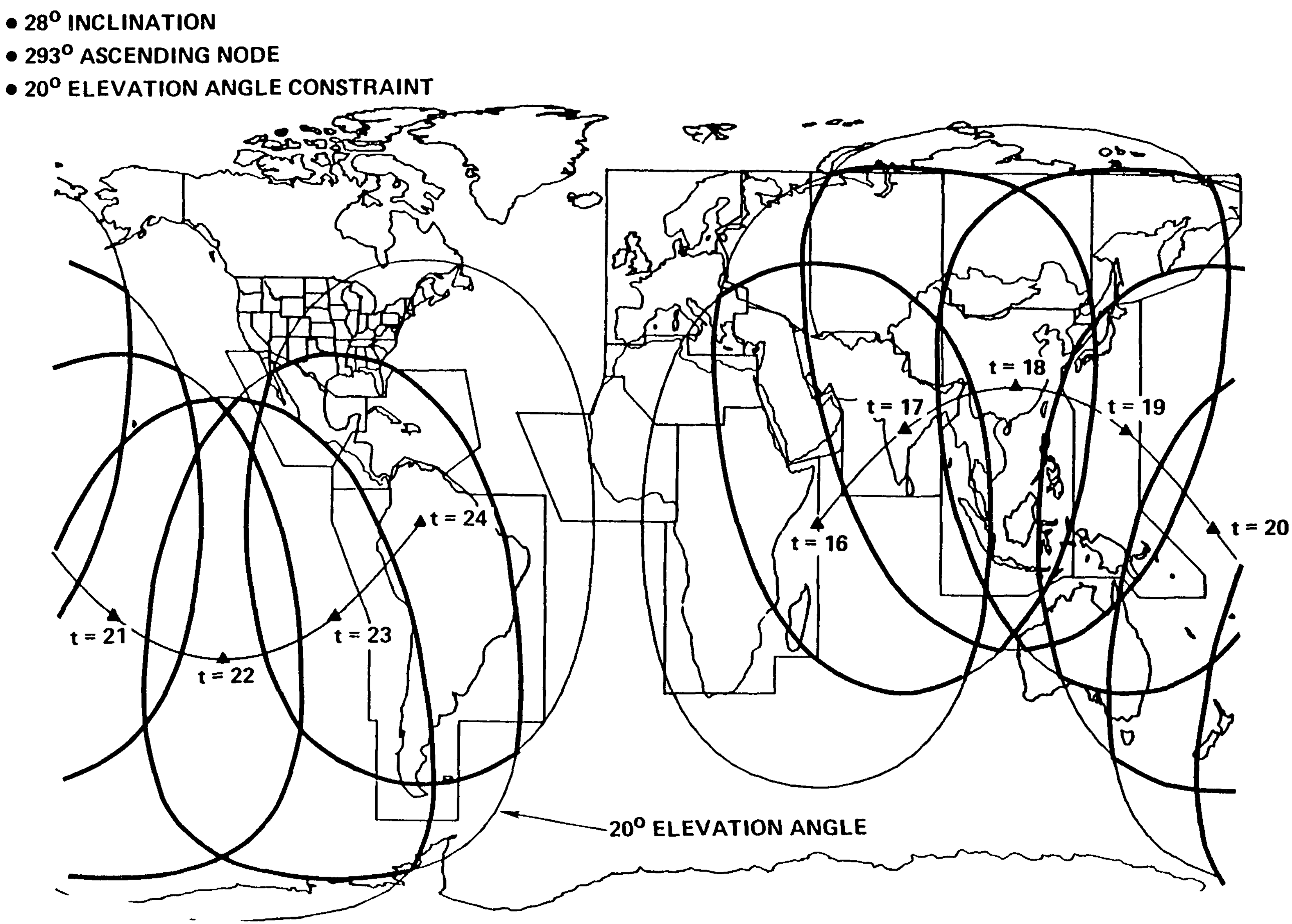


Figure F-2c. One-Hour Coverage Regions for 8-Hour Circular Orbit

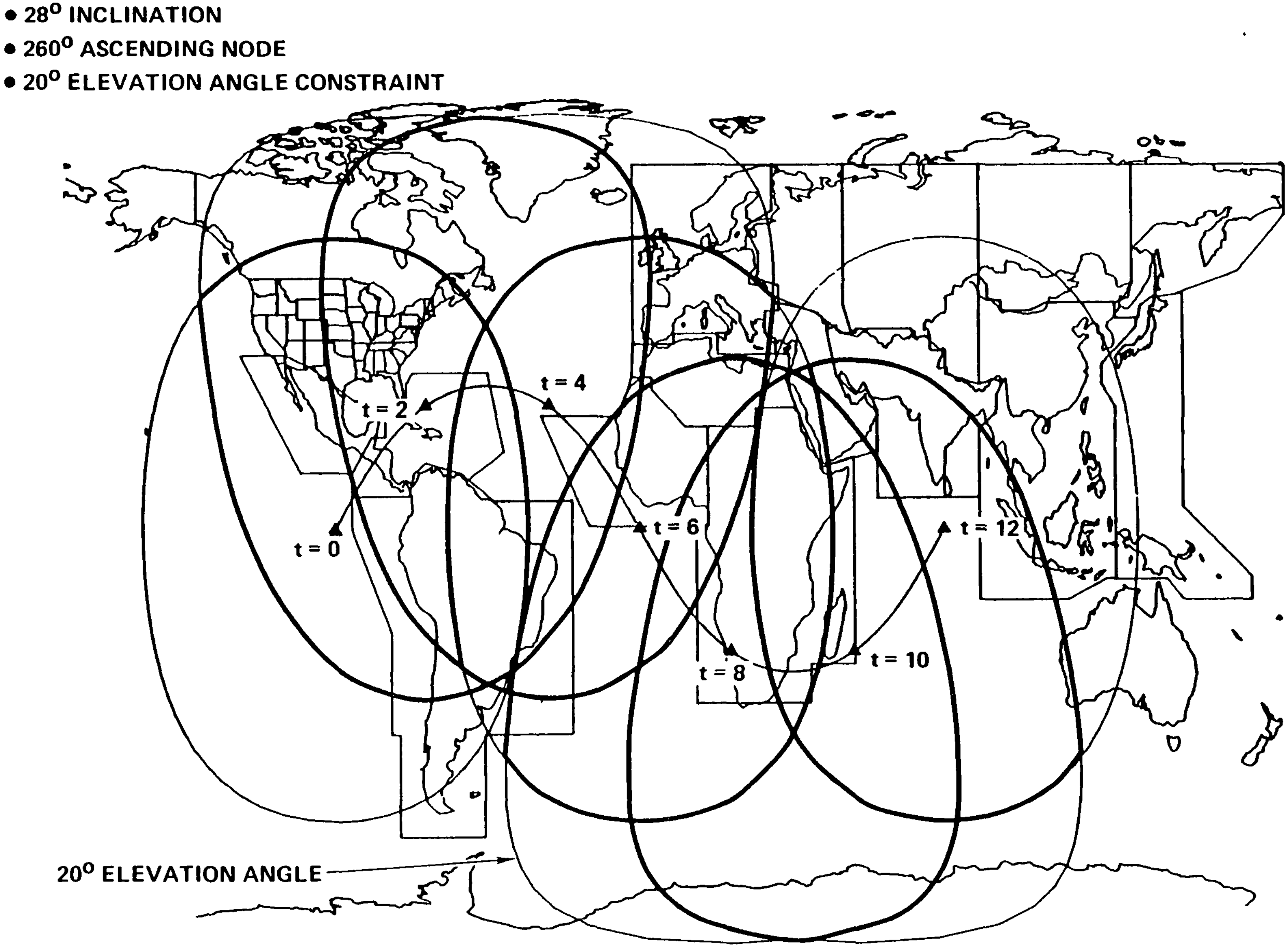


Figure F-3a. Two-Hour Coverage Regions for 12-Hour Circular Orbit

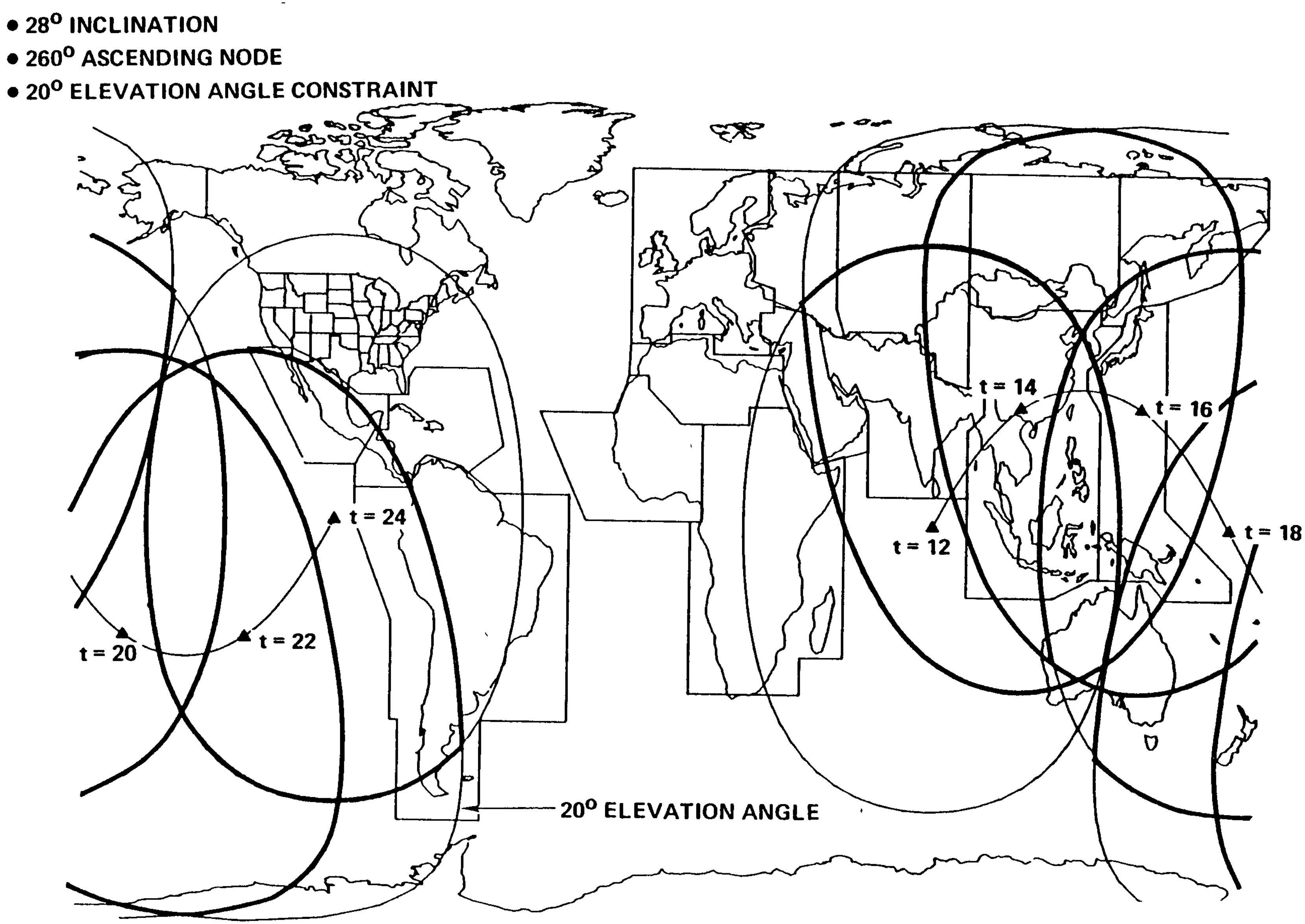


Figure F-3b. Two-Hour Coverage Regions for 12-Hour Circular Orbit

## APPENDIX G
## BROADCAST SERVICE ALGORITHM

The broadcast service algorithm is applied, in each 1/2 hour of the day, to determine the extent to which the channel-beam demand of the broadcast schedule can be satisfied by an appropriate set of satellite/zone assignments.

The problem which the algorithm is designed to solve can be stated as follows:

Let

$a_j$ = number of channel-beams demanded by Zone j

$$\alpha_{ij} = \begin{cases} 1 \text{ if Satellite i provides coverage of Zone j} \\ 0 \text{ otherwise} \end{cases}$$

$b_{ij}$ = number of channel-beams provided to Zone j by Satellite i

$C$ = satellite channel-beam capacity

Maximize

$$S = \sum_{i,j} \alpha_{ij} b_{ij}$$

subject to:

$$\sum_j b_{ij} \leq C \qquad \text{all } i \qquad (1)$$

$$\sum_i b_{ij} \leq a_j \qquad \text{all } j \qquad (2)$$

$b_{ij}$ = positive integer for all i,j

Condition (1) states that the number of channel-beams provided by a given satellite cannot exceed the (common) satellite capacity. Condition (2) ensures that the number of channel-beams provided to a zone does not exceed the zone demand. For the baseline system, there are 20 conditions of the first type and 15 of the second.

The above is an integer programming problem, which is essentially a linear programming problem with the variables constrained to be integers. A general solution to this problem (i.e., an algorithm which specifies $b_{i,j}$ for all i,j) is difficult to obtain. For present purposes, however, only the quantity S is of direct interest; individual satellite/zone assignments are not required. Therefore, the algorithm to be described makes individual satellite/zone assignments only when obviously optimum (i.e., when no other use of the satellite capacity can lead to a greater value of S). For the remaining satellites and zones, only the contribution to S is sought.

After the individual satellite/zone assignments have been made, groups of satellites are assigned to groups of zones. For each satellite/zone group pairing, it is assumed that the satellite coverage patterns permit the available satellite capacity to be used, as needed, to satisfy the channel-beam demand of the zones in the group. This assumption leads to an upper bound on S. Tightness of this upper bound is improved, in general, by keeping each group of zones as small as possible.

Initially, the following tests, which result in individual satellite/zone assignments, are performed.

1) If the capacity of a satellite exceeds the combined channel-beam demand of the zones that it "covers," the satellite is assigned to those zones.

2) If a satellite has visibility of only one zone, it is assigned to that zone.

3) If the channel-beam demand of a zone exceeds the combined capacity of the satellites that cover it, those satellites are assigned to that zone.

At the conclusion of these three tests, which are repeated until none of the conditions is satisfied, each remaining zone will be covered by satellites with a combined capacity that exceeds the channel-beam demand of the zone.

Next, a group of zones is formed by starting with an arbitrarily selected zone and adding one zone at a time. Each zone added to the group must be covered by at least one satellite that covers one or more zones already in the group. The process continues until either

a) The channel-beam demand of the zones in the group is at least as great as the total capacity of the satellites covering one or more zones in the group, or

b) The channel-beam demand of the zones in the group is less than the total capacity of the satellites covering one or more zones in the group, but no remaining zone is covered by a satellite that also covers a zone in the group.

In the first case, it is assumed that the associated satellite capacity can be fully utilized in satisfying the group channel-beam demand. In the second case, it is assumed that the group channel-beam demand can be fully satisfied by the associated satellite capacity.

The entire sequence of tests is repeated until no zones remain.

Operation of the algorithm is illustrated in Figure G-1. This example corresponds to the baseline 8-hour-orbit case, which involves a 20-satellite constellation. Seven of the 15 zones have nonzero channel-beam demands in the 1/2-hour period under consideration. Seven satellites have visibility of one or more zones during this period. The satellite coverage pattern is indicated by the Xs in the table. The capacity of each satellite is six channel-beams.

In applying the algorithm, the zones are considered both in the normal or forward sequence (i.e., 1, 2, 3, ... 15) and in the reverse sequence. This procedure leads, in this example, to different estimates of the broadcast service that can be provided. It is one of the few instances in which this phenomenon was observed.

For either zone sequence, Test 1 (described above) assigns Satellite 2 to Zone 14, after which Test 2 assigns Satellite 13 to Zone 7. In the latter case, only six of the 14 channel-beams demanded by Zone 7 can be provided by Satellite 13, leaving eight channel-beams to be provided by other satellites.

In the forward zone sequence, Zone 4 becomes the first member of a group of zones. The combined capacity of Satellites 4, 9, and 18 (18 channel-beams) exceeds the channel beam demand of Zone 4. Therefore, Zone

- Satellite Capacity = 6 Channel-Beams

| ZONE | CHANNEL-BEAM DEMAND | 2 | 4 | 8 | 9 | 12 | 13 | 18 |
|---|---|---|---|---|---|---|---|---|
| | | | ZONAL COVERAGE | | | | SATELLITE NUMBER | |
| 4 | 3 | | X | | X | | | X |
| 5 | 2 | | | | | | | X |
| 6 | 6 | | | | X | | | X |
| 7 | ~~14~~ 8 | | X | | X | | (X) | X |
| 8 | 2 | | | X | | X | | X |
| 13 | 7 | | | X | | X | | |
| 14 | (4) | (X) | | | | | | |

| ADDITIONAL SATELLITE/ZONE ASSIGNMENTS | CHANNEL-BEAMS OF SERVICE |
|---|---|
| FORWARD ZONE SEQUENCE | |
| S 4, 9, 18 → Z 4, 5, 6, 7 | 18 |
| S 8, 12 → Z 8, 13 | 9 |
| REVERSE ZONE SEQUENCE | |
| S 4, 8, 9, 12, 18 → Z 4, 5, 6, 7, 8, 13 | 28 |

Figure G-1. Broadcast Service Algorithm Example

7 is drawn into the group because of its coverage by Satellite 4 (the lowest numbered, unassigned satellite that covers Zone 4). No additional satellites are considered, because Zone 7 has the same coverage as Zone 4. Nonetheless, the combined capacity of Satellites 4, 9, and 18 still exceeds the total demand of the zones in the group. Consequently, Zone 6 is included in the group (because of Satellite 9). However, the capacity of Satellites 4, 9, and 18 is still greater than channel-beam demand of the group.

Only when Zone 5 is added to the group (because of Satellite 18) does the total channel-beam demand (19) exceed the combined satellite capacity (18). The algorithm assumes that the satellite capacity of 18 channel-beams can be fully utilized (i.e., that all but one channel-beam of the zone demand can be satisfied). It is easily shown that this is, in fact, true.

The algorithm next forms a group comprising Zones 8 and 13, the two remaining zones. The combined channel-beam demand of nine can be met from the 12-channel-beam capacity of Satellites 8 and 12.

Thus, a total of 37 channel-beams of broadcast service can be provided during the 1/2-hour in question.

When the zones are considered in reverse order, all remaining zones after the assignment of Satellites 2 and 13 fall into a single group. The order in which the zones are included in the group, with the responsible satellites shown in parenthesis, is as follows: 13, 8(8), 7(18), 4(4), 6(9), and 5(18). At each step, the combined satellite capacity exceeds the total zone demand. Finally, when no zones remain, it is assumed that the total zone demand of 28 channel-beams can be satisfied from the combined satellite capacity of 30 channel-beams. This is not possible, of course, as application of the algorithm to the forward zone sequence has revealed a maximum broadcast service of 27 channel-beams.

It is clear from this example that the achievable broadcast service, as predicted by the algorithm, can vary with the order in which the zones are considered. For each system examined in this study, the algorithm was exercised 48n times, where n varied between 3 and 6. In all but a small percentage of these cases, the algorithm produced the same result in the forward and reverse directions. It is highly unlikely that the same overestimate would result from considering the zones in the two directions. It may be concluded that, for the broadcast schedule and satellite constellations considered in this study, the algorithm in most cases accurately predicts the broadcast service that can be provided.

# APPENDIX H
# COSTING METHODOLOGY

Life cycle costs are based on a 20-year program span. This span includes nonrecurring or development, production, launch, and operations and maintenance costs. The nonrecurring category includes the cost of building the feeder-link station facilities.

Production facility costs are not included among the nonrecurring costs, however. These costs will vary, depending on antenna size and life-cycle quantity. Because of the large number of satellites required for most systems, production facility costs are a small fraction of the life cycle cost.

The life-cycle quantity is based on a 7-year satellite life and an arbitrary 10-percent allowance for spares. When development time is accounted for, the time remaining in the 20-year program span requires that the number of satellites manufactured be double the fleet size plus the spare allowance.

All production costs have been calculated using a 90-percent learning curve. No penalty has been imposed for interrupted production. Normally, when production is interrupted for an appreciable period of time, learning resumes at the first unit.

Most of the space segment costs are either known or assumed (e.g., launch costs), or can be found from well established cost estimating relationships (CERs). The principal exception is in the area of antenna recurring costs. There is no known precedent for costing a cable-catenary or phased-array antenna of the size needed for this application. A "bottoms-up" approach has therefore been adopted to compute antenna recurring costs.

The approach taken to estimate the nonrecurring and recurring cost of each subsystem is indicated in Table H-1. Nonrecurring antenna costs are obtained from cost estimating relationships (CERs) based on TRW's cost history of manufacturing smaller antennas, together with an appropriate complexity factor for each type of antenna. Included in the nonrecurring cost of the cable-catenary antenna is the cost of building a 30-meter

Table H-1. Subsystem Costing Methodology

| Subsystem | Nonrecurring Costs | Recurring Costs |
| --- | --- | --- |
| Antenna | TRW weight-based CERs with appropriate complexity factor | Detailed estimate |
| Electrical power<br>Thermal<br>Attitude control<br>Propulsion<br>TT&C<br>Structure | TRW weight-based CERs relating to TRW cost history | TRW weight-based CERs relating to TRW cost history |
| Transmitters | RCA/PRICE Model* | RCA/PRICE Model* |

*Extrapolation from current data base

prototype to validate the design and for use by Manufacturing to devise a means of assembling a full-scale version of the antenna.

Nonrecurring and recurring costs of the remaining subsystems, except for the transmitters, are based on CERs related to TRW cost history. The transmitters are larger and weigh far more than any transmitter built for space application. Consequently, the RCA/PRICE model was exercised over a range of weights and quantities. TRW globals were used with RCA/PRICE complexities.

Antenna Recurring Cost Methodology

The methodology used to determine antenna recurring costs is depicted in Figure H-1. For each of the two antenna designs, a work breakdown structure (WBS) was created. The RCA/PRICE model was used to develop costs for each defined part in the antenna. Quantity, weight, and complexity parameters were used to develop unit costs and dollars/pound costs.

Each assembly was defined in relation to the number of interfaces and the quantity required. By working with Manufacturing, estimates were made for the number of hours per assembly, based on the tooling and manufacturing support required. Hours/assembly was then converted to dollars/assembly.

The methodology outlined is appropriate for both the cable-catenary and the phased-array antenna, since each uses a similar type of truss construction.

The cable-catenary beam structure is illustrated in Figure H-2. The parts are made from graphite epoxy. The legs (battens and longerons) are thin-wall tubing, which are made in large quantities. The connector hinge and the end pieces are molded plastic pieces, also made in large quantities. The connector hinge is self-locking in the extended position.

The triangular assemblies are constructed first, after which the longeron legs are added. After a full-length boom has been assembled, the diagonal wires and tensioning devices are attached. The full unit is then tested and packed into a canister to await top assembly.

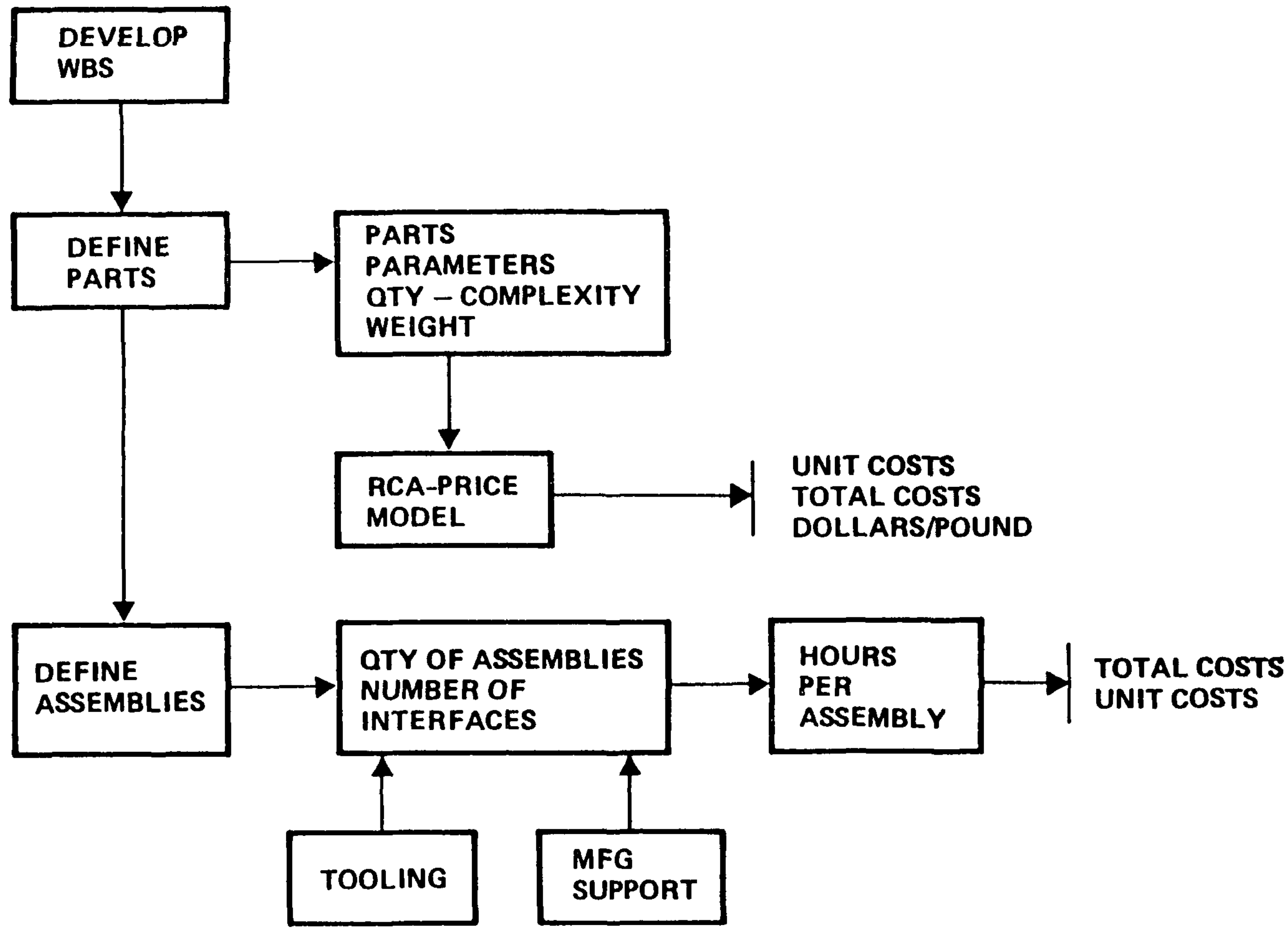


Figure H-1. Antenna Recurring-Cost Methodology

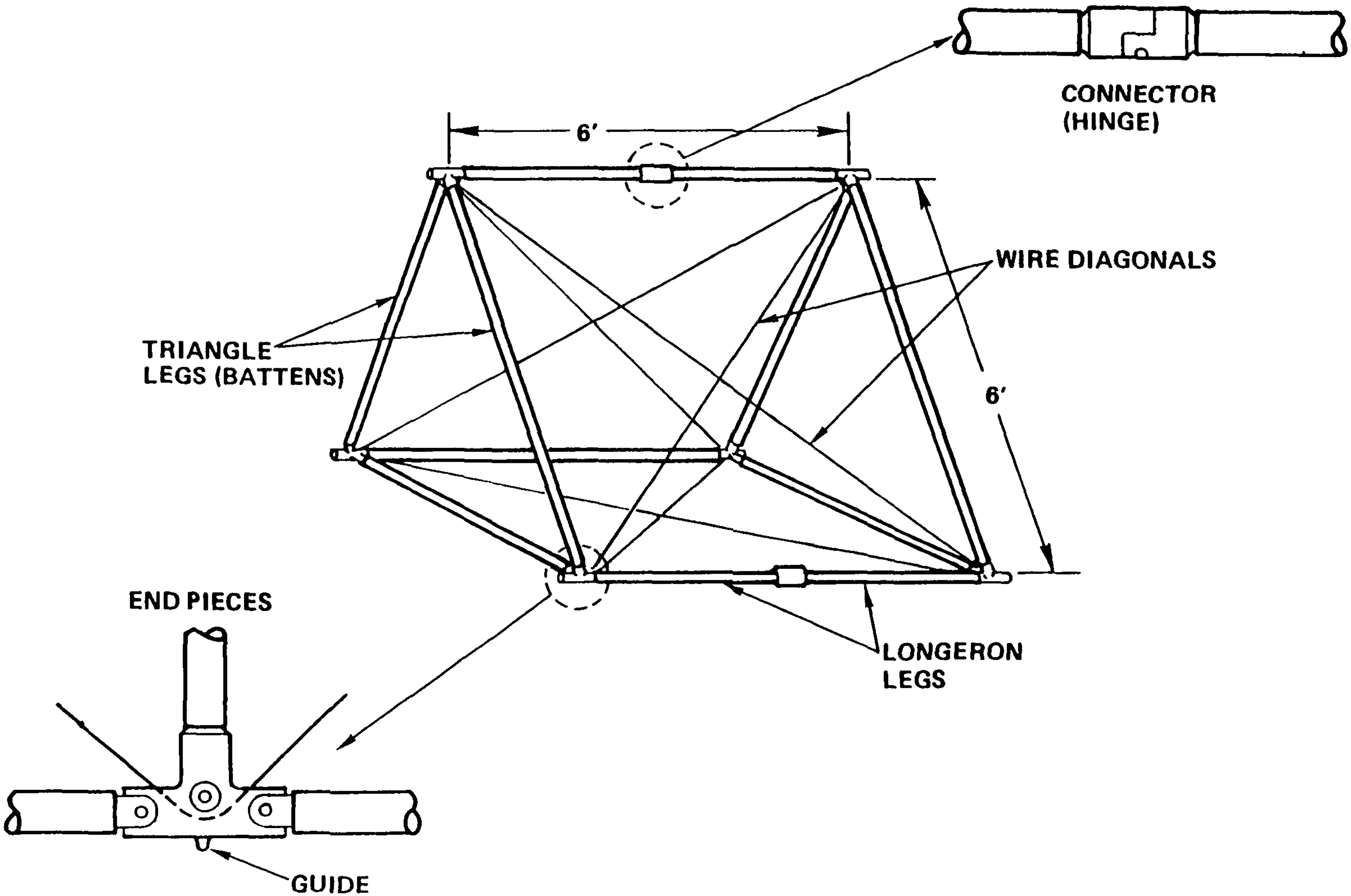


Figure H-2. Cable-Catenary Boom Structure

This general type of construction is also used on the phased-array antenna. The triangular assembly is not required, however, since only one side of the structure shown is needed for the phased-array truss assembly.

The format used to develop the cable-catenary antenna recurring costs is shown in Table H-2. Costing is done on the basis of the life-cycle number of antennas, which is shown at the top of the chart. Thus, the TOTAL QTY of any part shown is equal to the product of UNIT QTY (which is the number needed for a single top assembly) and the life-cycle number of units.

The total production cost (PROD COST) associated with any part is the product of the entries in three columns: $/#, WT/PART, and TOTAL QTY. It is generally found that the weight per part is proportional to the antenna diameter. The $/# column is developed with the aid of RCA/PRICE.

Assembly costs are based on the number of labor hours involved. Entries in the HOURS column, which are computed on a per-assembly basis, are multiplied by TOTAL QTY to yield PROD COST.

The antenna design lends itself to a high degree of repetition. Thousands of identical parts are produced, so that automated manufacturing procedures can be implemented. "Learning" is taken into account, but is only significant for the first 1000 units because of flattening of the learning curve.

The key problem in producing this antenna is final assembly. There is no facility large enough to accommodate these large assemblies. Therefore, the plans for assembly are to construct pie-shaped sections which are specially folded so that they can be joined to one another while in the folded state.

The format for the phased-array antenna recurring cost development (Table H-3) is similar to that for the cable-catenary antenna. The phased-array truss assembly resembles the cable-catenary boom assembly, in that the truss constitutes one side of the triangular boom construction. Both the number of trusses and the individual part weights are proportional to the aperture size.

Table H-2. Cable-Catenary Antenna Recurring-Cost Development

REFLECTOR DIA M = 267
NO OF ANTENNAS = 20

| | LENGTH | UNIT QTY | TOTAL QTY | WT/ PART | PROD COST | HOURS | $/# | TOTAL WEIGHT |
|---|---|---|---|---|---|---|---|---|
| BOOM ASSY | 438 | 8 | 160 | | | XXXX | | |
| TRIANGLE ASSY | | 576 | 11520 | | | XXXX | | |
| LEGS(BATTENS) | | 1728 | 34560 | 0.3625 | | | XXXX | 12527 |
| END PIECE | | 1728 | 34560 | 0.0767 | | | XXXX | 2650 |
| WIRE(FT)(DIAGONALS) | | 29376 | 587520 | 0.0081 | | | XXXX | 4769 |
| LONGERONS ASSY | | 1728 | 34560 | | | XXXX | | |
| LEGS | | 3456 | 69120 | 0.1227 | | | XXXX | 8480 |
| CONNECTOR-HINGE | | 3456 | 69120 | 0.1227 | | | XXXX | 8480 |
| END PIECE | | 3456 | 69120 | 0.1227 | | | XXXX | 8480 |
| WIRE(FT)(CATENARY WIRE) | | 41905 | 838100 | 0.0011 | | | XXXX | 897 |
| MESH(SQ.FT) | | 602060 | 12041200 | 0.0002 | | | XXXX | 2967 |
| MECHANISMS | | 8 | 160 | 22.0000 | | | XXXX | 3520 |
| CANNISTER | | 8 | 160 | 79.1502 | | | XXXX | 12664 |
| TIP MASTS | | 16 | 320 | 35.4527 | | | XXXX | 11344 |
| TOTAL BOOM | | | | | | | | 76778 |
| FEED MAST ASSY | 411 | 1 | 20 | | | XXXX | | |
| TRIANGLE ASSY | | 68 | 1360 | | | XXXX | | |
| LEGS(BATTENS) | | 204 | 4080 | 0.7714 | | | XXXX | 3147 |
| END PIECE | | 204 | 4080 | 0.0849 | | | XXXX | 346 |
| WIRE(FT)(DIAGONALS) | | 3468 | 69360 | 0.0081 | | | XXXX | 562 |
| LONGERONS ASSY | | 204 | 4080 | | | XXXX | | |
| LEGS | | 408 | 8160 | 0.2961 | | | XXXX | 2416 |
| CONNECTOR-HINGE | | 408 | 8160 | 0.2961 | | | XXXX | 2416 |
| END PIECE | | 408 | 8160 | 0.2961 | | | XXXX | 2416 |
| MECHANISM | | 1 | 20 | 14.4414 | | | XXXX | 288 |
| CANNISTER | | 1 | 20 | 71.4435 | | | XXXX | 1428 |
| MECHANISMS(CATENARY) | | 8 | 160 | 8.7500 | | | XXXX | 1400 |
| TOTAL MAST | | 1 | 20 | | | | | 14419 |
| FEED ASSEMBLY | | 1 | 20 | | | XXXX | | |
| FEED POST | | 16 | 320 | 9.8100 | | | XXXX | |
| CROSSED DIPOLE FEED | | 16 | 320 | 1.9600 | | | XXXX | |
| CROSSED DIPOLE FEED | | 16 | 320 | 1.5300 | | | XXXX | |
| SPLASH PLATE | | 1 | 20 | | | XXXX | | |
| MESH | | 1 | 20 | 0.0011 | | | XXXX | |
| MESH SUPPORT | | 16 | 320 | 3.0000 | | | XXXX | |
| SUPPORT POST | | 16 | 320 | 1.0000 | | | XXXX | |
| MISC. HARDWARE | | 50 | 1000 | 0.5000 | | | XXXX | |
| TOTAL FEED ASSY | | | | | | | | |
| TOP ASSY | | 1 | 20 | | | XXXX | | |
| TOTAL HARDWARE COST | | 1 | 20 | | | | | |
| PRODUCTION EFF @ 85% | | | | | | | | |
| SUSTAINING ENG @ 15% | | | | | | | | |
| GRAND TOTAL | | | | | | | | |
| FIRST UNIT COST | | | | | | | | |



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## Table H-3. Phased-Array Antenna Recurring-Cost Development

APERTURE M = 115
NO. OF ANTENNAS = 20
NUMBER OF FEEDS = 121

| | UNIT QTY | TOTAL QTY | WT/ PART | PROD COST | HOURS | $/# | TOTAL WEIGHT |
|---|---|---|---|---|---|---|---|
| FEED ASSY | 121 | 2420 | | | XXXX | | |
| FEED POST | 121 | 2420 | 9.8100 | | | XXXX | 23740 |
| DIPOLE-LONG | 121 | 2420 | 1.9600 | | | XXXX | 4743 |
| DIPOLE-SHORT | 121 | 2420 | 1.5300 | | | XXXX | 3703 |
| SPASH PLATE ASSY | 121 | 2420 | | | XXXX | | |
| MESH | 121 | 2420 | 0.0020 | | | XXXX | 5 |
| MESH SUPPORT | 484 | 9680 | 0.4000 | | | XXXX | 3872 |
| SUPPORT POST | 121 | 2420 | 0.4000 | | | XXXX | 968 |
| MISC HARDWARE | 1210 | 24200 | 0.1000 | | | XXXX | 2420 |
| TOTAL FEED ASSY | | | | | | | |
| TRUSS ASSY | 220 | 4400 | | | XXXX | | |
| STRUT ASSY | 1320 | 26400 | | | XXXX | | |
| STRUT | 1540 | 30800 | 0.1766 | | | XXXX | 5440 |
| STRUT END PIECE | 3080 | 61600 | 0.3532 | | | XXXX | 21758 |
| LONGERON ASSY | 2640 | 52800 | | | XXXX | | |
| LEGS(LONGERON) | 5280 | 105600 | 0.1699 | | | XXXX | 17937 |
| HINGE | 2640 | 52800 | 0.1699 | | | XXXX | 8969 |
| END PIECE | 5280 | 105600 | 0.1699 | | | XXXX | 17937 |
| DIAGONAL(WIRE) | 1 | 20 | 0.0095 | | | XXXX | 21 |
| TOTAL TRUSS ASSY | | | | | | | |
| MESH WIRES(DIAGONALS | 1 | 20 | 0.0050 | | | XXXX | 2190 |
| MESH SUPPORT(POLES) | 85 | 1700 | 0.7200 | | | XXXX | 1224 |
| MESH | 1 | 20 | 0.0011 | | | XXXX | 3786 |
| TOP ASSY | 1 | 20 | | | XXXX | | 7199 |
| TOTAL HARDWARE COST | | | | | | | |
| PRODUCTION EFF. 85% | | | | | | | |
| SUSTAINING ENGRINEERING 15% | | | | | | | |
| GRAND TOTAL | | | | | | | |
| FIRST UNIT COST | | | | | | | |

The largest phased array considered (applicable to the 15-megahertz subband of Band 1) has an aperture of 136 meters, as compared with the 267-meter cable-catenary for the Band 1 geostationary system. For the 26-megahertz subband of Band 1, the phased array in the 8-hour satellites is a relatively small 80 meters on a side. The phased-array top assembly, therefore, does not create the same problems as the cable-catenary top assembly in terms of providing a sufficiently large facility.

Moreover, the phased array can be assembled in one plane, on the flat. Each square can be assembled, in turn, and then be partially collapsed while the next square is assembled.

Space Segment Costs

Space segment costs are divided into two groups (Table H-4): satellite costs, which are shown above the double dashed line, and launch costs, which appear below. The leftmost three columns of figures relate to the weight of the satellite subsystems. The first column gives the weight for a single subsystem unit. By this definition, a satellite may contain more than one subsystem unit of a given type. (For example, the phased-array antenna of the baseline 8-hour-orbit system contains 64 feed elements, each of which is powered by a separate transmitter.) The total weight of a given subsystem is found by multiplying the unit weight by the number of units per satellite as given in the second column.

The TOTAL COST column is the sum of the COST NR (nonrecurring cost) and COST RECURR columns. The latter is the total recurring cost over the life-cycle number of satellites (shown at the upper left) and is obtained from COST FU (first-unit cost) with the aid of a 90-percent learning curve. The first-unit cost in this context is the cost associated with the first complete satellite (e.g., 64 transmitters).

The satellite cost is the sum of five elements: (1) hardware costs, (2) assembly, integration, and test, (3) program management, (4) system engineering, and (5) mission assurance. TRW historical CERs, based on a percentage of hardware costs, are used to obtain the last four items. The price to the customer is obtained by adding an assumed 12-percent profit to the cost.

## Table H-4. Space Segment Cost Analysis

QUANTITY = 20 — MILLIONS 1984 DOLLARS

| SUBSYSTEM | UNIT WEIGHT | # PER SATELLITE | TOTAL WEIGHT | COSTS NR | COSTS FU | COSTS RECURR | TOTAL COSTS |
|---|---|---|---|---|---|---|---|
| ANTENNA(PHA-ARRAY) | 2816 | 1 | 2816 | | | | |
| T T & C | 261 | 1 | 261 | | | | |
| ATTITUDE CONTROL | 256 | 1 | 256 | | | | |
| PROPULSION | 995 | 1 | 995 | | | | |
| STRUCTURE(EXC ANTENNA) | 1440 | 1 | 1440 | | | | |
| THERMAL | 1238 | 1 | 1238 | | | | |
| E D I | 632 | 1 | 632 | | | | |
| E P A D | 3027 | 1 | 3027 | | | | |
| PAYLOAD | | | | | | | |
| SYSTEM ENGR. | | | | | | | |
| TRANSMITTER | 84 | 64 | 5400 | | | | |
| FEED CABLING | 10 | 64 | 640 | | | | |
| TOTAL HARDWARE | | | 16705 | | | | |
| A I & T | | | | | | | |
| PROGRAM MGMT | | | | | | | |
| SYSTEM ENGR | | | | | | | |
| MISSION ASSUR | | | | | | | |
| TOTAL S/C | | | | | | | |
| TOTAL S/C WITH 12% PROFIT | | | | | | | |
| CENTAUR | | | | | | | |
| STS/SVBS ASE | | | | | | | |
| LAUNCH INTEGRATION | | | | | | | |
| STS LAUNCH | | | | | | | |
| TOTAL SPACE COSTS | | | | | | | |

Launch costs involve the four elements shown. STS and Centaur costs, in 1984 dollars, are assumed to be $100 million and $58 million, respectively.

# APPENDIX I
# SATELLITE WEIGHT ESTIMATES
# FOR SINGLE-CHANNEL SYSTEMS

Table I-1 contains a weight breakdown by subsystem for the 15 single-voice-channel satellites for which advanced technology has been assumed. Each sheet of Table I-1 is devoted to a single satellite orbit. Subsystem weights for the remaining three satellites, for which current technology is assumed (see Table 8-2), are given in Table I-2.

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# Table I-1. Satellite Weight Estimates with Advanced Technology

| System Analysis Parameters: | System 1 | System 2 | System 3 |
|---|---|---|---|
| OTV choice | CustCryo | CustCryo | CustBiPp |
| Orbit choice | Geosync | Geosync | Geosync |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cable-catn | Cable-catn | Cable-catn |
| Operate during eclipse | No | No | No |
| STS KSC nominal lift capacity -(Lb): | 65000.0 | 65000.0 | 40000.0 |
| Max # of beams (shown=Unlimited) --: | 1000.0 | 1000.0 | 1000.0 |
| Field strength (micro-V/M): | 300.0 | 150.0 | 50.0 |
| Ref GEO beamwidth (Deg): | 5.5 | 12.2 | 20.0 |
| Elevation angle (Deg): | 20.0 | 20.0 | 20.0 |
| Operating frequency (MHz): | 26.1 | 26.1 | 26.1 |
| Peak/Avg solar array power ratio : | 1.7 | 1.7 | 1.7 |

***** System Analysis output ******

| | System 1 | System 2 | System 3 |
|---|---|---|---|
| Orbit inclination (Deg): | 0.0 | 0.0 | 0.0 |
| Beamwidth (Deg): | 5.5 | 12.3 | 20.1 |
| RF power/channel-beam: Peak --(kW): | 68.6 | 84.3 | 25.2 |
| RF power/channel-beam: Average (kW): | 40.3 | 49.6 | 14.8 |
| Wavelength (Ft): | 38 | 38 | 38 |
| STS lift to parking orbit -----(Lb): | 65000 | 65000 | 40000 |
| STS/OTV delivery capability -- (Lb): | 13287 | 13287 | 5016 |
| Weight Pld+OTV+ASE (Lb): | 64770 | 64770 | 40194 |
| STS ASE (Lb): | 1000 | 1000 | 1000 |
| Weight reserve (Lb): | 2214 | 2214 | 836 |
| Antenna aperture (M): | 146 | 66 | 40 |
| Antenna weight (Lb): | 2205 | 1111 | 752 |
| Number of feeds (Cross-Beam only): | 0 | 0 | 0 |
| TT&C, DHS, Comm subsystems - (Lb): | 281 | 254 | 239 |
| Attitude control (Lb): | 330 | 252 | 217 |
| Propulsion (Lb): | 379 | 357 | 134 |
| Structures (Excl Antenna) ---- (Lb): | 787 | 896 | 243 |
| Thermal control weight (Lb): | 50 | 830 | 50 |
| Total weight/channel-beam --- (Lb): | 634 | 780 | 233 |
| EDI total weight (Lb): | 145 | 612 | 145 |
| Total EDI weight/channel-beam (Lb): | 644 | 467 | 124 |
| EPDS total weight (Lb): | 277 | 2994 | 86 |
| Total weight/channel beam --- (Lb): | 2326 | 2861 | 854 |
| Power storage/channel beam - (Lb): | 0 | 0 | 0 |
| PAYLOAD weight/channel-beam -- (Lb): | 3045 | 3741 | 1131 |
| Maximum number of channel-beams: | 0 | 1 | 0 |
| Residual weight (Lb): | 6613 | 22 | 2313 |
| Total weight/channel-beam ---- (Lb): | 6649 | 7848 | 2342 |
| Available payload weight ----- (Lb): | 6613 | 7870 | 2313 |
| Non-beam-related weight ------ (Lb): | 4459 | 3203 | 1867 |

Table I-1. Satellite Weight Estimates with Advanced Technology (Continued)

| System Analysis Parameters: | System 1 | System 2 | System 3 |
|---|---|---|---|
| OTV choice | CustCryo | CustCryo | CustBiPp |
| Orbit choice | Molniya | Molniya | Molniya |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cable-catn | Cable-catn | Cable-catn |
| Operate during eclipse | No | No | No |
| STS KSC nominal lift capacity -(Lb): | 65000.0 | 65000.0 | 40000.0 |
| Max # of beams (shown=Unlimited): | 1000.0 | 1000.0 | 1000.0 |
| Field strength (micro-V/M): | 300.0 | 150.0 | 50.0 |
| Ref GEO beamwidth (Deg): | 6.8 | 14.4 | 28.0 |
| Elevation angle (Deg): | 20.0 | 20.0 | 20.0 |
| Operating frequency (MHz): | 26.1 | 26.1 | 26.1 |
| Peak/Avg solar array power ratio : | 1.7 | 1.7 | 1.7 |

***** System Analysis output ******

| | System 1 | System 2 | System 3 |
|---|---|---|---|
| Orbit inclination (Deg): | 63.4 | 63.4 | 63.4 |
| Beamwidth (Deg): | 6.2 | 13.1 | 25.4 |
| RF power/channel-beam: Peak --(kW): | 100.4 | 112.6 | 47.3 |
| RF power/channel-beam: Average (kW): | 59.1 | 66.2 | 27.8 |
| Wavelength (Ft): | 38 | 38 | 38 |
| STS lift to parking orbit (Lb): | 65000 | 65000 | 40000 |
| STS/OTV delivery capability -- (Lb): | 19452 | 19452 | 8776 |
| Weight Pld+OTV+ASE (Lb): | 64738 | 64738 | 40161 |
| STS ASE (Lb): | 1000 | 1000 | 1000 |
| Weight reserve (Lb): | 3242 | 3242 | 1463 |
| Antenna aperture (M): | 130 | 62 | 32 |
| Antenna weight (Lb): | 1882 | 1059 | 619 |
| Number of feeds (Cross-Beam only): | 0 | 0 | 0 |
| TT&C, DHS, Comm subsystems - (Lb): | 277 | 252 | 232 |
| Attitude control (Lb): | 318 | 247 | 202 |
| Propulsion (Lb): | 1212 | 1172 | 525 |
| Structures (Excl Antenna) ---- (Lb): | 1333 | 1415 | 569 |
| Thermal control weight (Lb): | 978 | 1091 | 487 |
| Total weight/channel-beam --- (Lb): | 928 | 1041 | 437 |
| EDI total weight (Lb): | 993 | 755 | 371 |
| Total EDI weight/channel-beam (Lb): | 848 | 610 | 226 |
| EPDS total weight (Lb): | 4550 | 4945 | 2095 |
| Total weight/channel beam --- (Lb): | 4294 | 4814 | 2023 |
| Power storage/channel beam - (Lb): | 0 | 0 | 0 |
| PAYLOAD weight/channel-beam -- (Lb): | 4644 | 5204 | 2198 |
| Maximum number of channel-beams: | 1 | 1 | 1 |
| Residual weight (Lb): | 18 | 67 | 11 |
| Total weight/channel-beam ---- (Lb): | 10715 | 11670 | 4884 |
| Available payload weight ----- (Lb): | 10733 | 11737 | 4895 |
| Non-beam-related weight ------ (Lb): | 5477 | 4473 | 2418 |

Table I-1. Satellite Weight Estimates with Advanced Technology (Continued)

| System Analysis Parameters: | System 1 | System 2 | System 3 |
|---|---|---|---|
| OTV choice | CustBiPp | CustBiPp | Pam-A |
| Orbit choice | 3*Sync | 3*Sync | 3*Sync |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cable-catn | Cable-catn | Cable-catn |
| Operate during eclipse | No | No | No |
| STS KSC nominal lift capacity (Lb) | 65000.0 | 65000.0 | 65000.0 |
| Max # of beams (shown=Unlimited) | 1000.0 | 1000.0 | 1000.0 |
| Field strength (micro-V/M) | 300.0 | 150.0 | 50.0 |
| Ref GEO beamwidth (Deg) | 3.4 | 7.2 | 16.6 |
| Elevation angle (Deg) | 20.0 | 20.0 | 20.0 |
| Operating frequency (MHz) | 26.1 | 26.1 | 26.1 |
| Peak/Avg solar array power ratio | 1.7 | 1.7 | 1.7 |

***** System Analysis output ******

| System Analysis output | System 1 | System 2 | System 3 |
|---|---|---|---|
| Orbit inclination (Deg) | 116.6 | 116.6 | 116.6 |
| Beamwidth (Deg) | 11.4 | 24.1 | 55.6 |
| RF power/channel-beam: Peak (kW) | 25.1 | 28.2 | 16.6 |
| RF power/channel-beam: Average (kW) | 14.8 | 16.6 | 9.8 |
| Wavelength (Ft) | 38 | 38 | 38 |
| STS lift to parking orbit (Lb) | 29871 | 29871 | 29871 |
| STS/OTV delivery capability (Lb) | 11589 | 11589 | 7012 |
| Weight Pld+OTV+ASE (Lb) | 29762 | 29762 | 20679 |
| STS ASE (Lb) | 1000 | 1000 | 1000 |
| Weight reserve (Lb) | 1931 | 1931 | 1169 |
| Antenna aperture (M) | 71 | 33 | 14 |
| Antenna weight (Lb) | 1178 | 646 | 381 |
| Number of feeds (Cross-Beam only) | 0 | 0 | 0 |
| TT&C, DHS, Comm subsystems (Lb) | 257 | 234 | 211 |
| Attitude control (Lb) | 258 | 206 | 162 |
| Propulsion (Lb) | 706 | 698 | 421 |
| Structures (Excl Antenna) (Lb) | 748 | 801 | 446 |
| Thermal control weight (Lb) | 282 | 310 | 50 |
| Total weight/channel-beam (Lb) | 232 | 260 | 154 |
| EDI total weight (Lb) | 288 | 280 | 145 |
| Total EDI weight/channel-beam (Lb) | 143 | 135 | 76 |
| EPDS total weight (Lb) | 4668 | 5136 | 46 |
| Total weight/channel beam (Lb) | 4502 | 5047 | 2981 |
| Power storage/channel beam (Lb) | 0 | 0 | 0 |
| PAYLOAD weight/channel-beam (Lb) | 1176 | 1316 | 786 |
| Maximum number of channel-beams: | 1 | 1 | 0 |
| Residual weight (Lb): | 93 | 28 | 3979 |
| Total weight/channel-beam (Lb) | 6054 | 6759 | 3997 |
| Available payload weight (Lb) | 6147 | 6787 | 3979 |
| Non-beam-related weight (Lb) | 3510 | 2870 | 1864 |



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Table I-1. Satellite Weight Estimates with Advanced Technology (Continued)

| System Analysis Parameters: | System 1 | System 2 | System 3 |
|---|---|---|---|
| OTV choice | CustBiPp | CustBiPp | Pam-A |
| Orbit choice | 6Hrs | 6Hrs | 6Hrs |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cross-beam | Cross-beam | Cross-beam |
| Operate during eclipse | No | No | No |
| STS KSC nominal lift capacity (Lb) | 40000.0 | 38000.0 | 13000.0 |
| Max # of beams (shown=Unlimited) | 1000.0 | 1000.0 | 1000.0 |
| Field strength (micro-V/M) | 300.0 | 150.0 | 50.0 |
| Ref GEO beamwidth (Deg) | 5.0 | 10.0 | 10.0 |
| Elevation angle (Deg) | 20.0 | 20.0 | 20.0 |
| Operating frequency (MHz) | 26.1 | 26.1 | 26.1 |
| Peak/Avg solar array power ratio | 1.7 | 1.7 | 1.7 |

***** System Analysis output ******

| | System 1 | System 2 |
|---|---|---|
| Orbit inclination (Deg) | 28.0 | 28.0 |
| Beamwidth (Deg) | 13.3 | 26.6 |
| RF power/channel-beam: Peak (kW) | 54.3 | 54.3 |
| RF power/channel-beam: Average (kW) | 31.9 | 31.9 |
| Wavelength (Ft) | 38 | 38 |
| STS lift to parking orbit (Lb) | 40000 | 38000 |
| STS/OTV delivery capability (Lb) | 11008 | 10301 |
| Weight Pld+OTV+ASE (Lb) | 39838 | 37854 |
| STS ASE (Lb) | 1000 | 1000 |
| Weight reserve (Lb) | 1835 | 1717 |
| Antenna aperture (M) | 34 | 11 |
| Antenna weight (Lb) | 636 | 125 |
| Number of feeds (Cross-Beam only) | 16 | 4 |
| TT&C, DHS, Comm subsystems (Lb) | 235 | 205 |
| Attitude control (Lb) | 202 | 151 |
| Propulsion (Lb) | 559 | 522 |
| Structures (Excl Antenna) (Lb) | 777 | 752 |
| Thermal control weight (Lb) | 50 | 583 |
| Total weight/channel-beam (Lb) | 533 | 533 |
| EDI total weight (Lb) | 145 | 401 |
| Total EDI weight/channel-beam (Lb) | 270 | 256 |
| EPDS total weight (Lb) | 67 | 3286 |
| Total weight/channel beam (Lb) | 3249 | 3249 |
| Power storage/channel beam (Lb) | 0 | 0 |
| PAYLOAD weight/channel-beam (Lb) | 2589 | 2520 |
| Maximum number of channel-beams: | 0 | 1 |
| Residual weight (Lb): | 6501 | 39 |
| Total weight/channel-beam (Lb) | 6641 | 6558 |
| Available payload weight (Lb) | 6501 | 6597 |
| Non-beam-related weight (Lb) | 2672 | 1988 |

Table I-1. Satellite Weight Estimates with Advanced Technology (Continued)

| System Analysis Parameters: | System 1 | System 2 | System 3 |
|---|---|---|---|
| OTV choice | CustBiPp | CustBiPp | Pam-A |
| Orbit choice | 8Hrs | 8Hrs | 8Hrs |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cross-beam | Cross-beam | Cross-beam |
| Operate during eclipse | No | No | No |
| STS KSC nominal lift capacity -(Lb): | 42000.0 | 38000.0 | 14500.0 |
| Max # of beams (shown=Unlimited) --: | 1000.0 | 1000.0 | 1000.0 |
| Field strength -------- (micro-V/M): | 300.0 | 150.0 | 50.0 |
| Ref GEO beamwidth ---------- (Deg): | 5.0 | 10.0 | 12.0 |
| Elevation angle ------------ (Deg): | 20.0 | 20.0 | 20.0 |
| Operating frequency -------- (MHz): | 26.1 | 26.1 | 26.1 |
| Peak/Avg solar array power ratio : | 1.7 | 1.7 | 1.7 |

***** System Analysis output ******

| | System 1 | System 2 |
|---|---|---|
| > Orbit inclination ---------- (Deg): | 28.0 | 28.0 |
| > Beamwidth ----------------- (Deg): | 10.4 | 20.8 |
| > RF power/channel-beam: Peak --(kW): | 52.9 | 52.9 |
| > RF power/channel-beam: Average (kW): | 31.1 | 31.1 |
| > Wavelength ---------------- (Ft): | 38 | 38 |
| > STS lift to parking orbit -----(Lb): | 42000 | 38000 |
| > STS/OTV delivery capability -- (Lb): | 10000 | 8793 |
| > Weight Pld+OTV+ASE ---------- (Lb): | 42016 | 38153 |
| > STS ASE -------------------- (Lb): | 1000 | 1000 |
| > Weight reserve ----------------(Lb): | 1667 | 1465 |
| > Antenna aperture ------------ (M): | 46 | 17 |
| > Antenna weight -------------- (Lb): | 1036 | 206 |
| > Number of feeds (Cross-Beam only): | 25 | 6 |
| > TT&C, DHS, Comm subsystems - (Lb): | 243 | 214 |
| > Attitude control ------------ (Lb): | 218 | 166 |
| > Propulsion ------------------ (Lb): | 475 | 416 |
| > Structures (Excl Antenna) ---- (Lb): | 666 | 621 |
| > Thermal control weight ------- (Lb): | 569 | 569 |
| > Total weight/channel-beam --- (Lb): | 519 | 519 |
| > EDI total weight ------------ (Lb): | 419 | 396 |
| > Total EDI weight/channel-beam (Lb): | 274 | 251 |
| > EPDS total weight ----------- (Lb): | 2040 | 2005 |
| > Total weight/channel beam --- (Lb): | 1966 | 1966 |
| > Power storage/channel beam - (Lb): | 0 | 0 |
| > PAYLOAD weight/channel-beam -- (Lb): | 2633 | 2513 |
| > Maximum number of channel-beams: | 1 | 1 |
| > Residual weight (Lb): | 31 | 219 |
| > Total weight/channel-beam ---- (Lb): | 5392 | 5249 |
| > Available payload weight ----- (Lb): | 5423 | 5468 |
| > Non-beam-related weight ------ (Lb): | 2910 | 1860 |

Table I-1. Satellite Weight Estimates with Advanced Technology (Continued)

| System Analysis Parameters: | System 1 | System 2 | System 3 |
|---|---|---|---|
| OTV choice | CustBiPp | CustBiPp | CustBiPp |
| Orbit choice | 12Hr/Inc | 12Hr/Inc | 12Hr/Inc |
| Power storage choice | NiH2 | NiH2 | NiH2 |
| Antenna choice | Cross-beam | Cross-beam | Cross-beam |
| Operate during eclipse | No | No | No |
| STS KSC nominal lift capacity -(Lb): | 56000.0 | 48000.0 | 21000.0 |
| Max # of beams (shown=Unlimited) --: | 1000.0 | 1000.0 | 1000.0 |
| Field strength -------- (micro-V/M): | 300.0 | 150.0 | 50.0 |
| Ref GEO beamwidth ----------- (Deg): | 5.0 | 10.0 | 13.0 |
| Elevation angle ------------- (Deg): | 20.0 | 20.0 | 20.0 |
| Operating frequency --------- (MHz): | 26.1 | 26.1 | 26.1 |
| Peak/Avg solar array power ratio : | 1.7 | 1.7 | 1.7 |

***** System Analysis output ******

| | System 1 | System 2 |
|---|---|---|
| > Orbit inclination ---------- (Deg): | 37.0 | 37.0 |
| > Beamwidth ------------------ (Deg): | 7.5 | 15.1 |
| > RF power/channel-beam: Peak --(kW): | 51.9 | 51.9 |
| > RF power/channel-beam: Average (kW): | 30.6 | 30.6 |
| > Wavelength ------------------ (Ft): | 38 | 38 |
| > STS lift to parking orbit -----(Lb): | 56000 | 48000 |
| > STS/OTV delivery capability -- (Lb): | 12009 | 9965 |
| > Weight Pld+OTV+ASE ----------- (Lb): | 55768 | 48210 |
| > STS ASE ---------------------- (Lb): | 1000 | 1000 |
| > Weight reserve ----------------(Lb): | 2002 | 1661 |
| > Antenna aperture -------------- (M): | 65 | 28 |
| > Antenna weight --------------- (Lb): | 1897 | 461 |
| > Number of feeds (Cross-Beam only): | 44 | 12 |
| > TT&C, DHS, Comm subsystems - (Lb): | 254 | 229 |
| > Attitude control ------------- (Lb): | 240 | 191 |
| > Propulsion ------------------- (Lb): | 501 | 412 |
| > Structures (Excl Antenna) ---- (Lb): | 774 | 701 |
| > Thermal control weight ------- (Lb): | 50 | 560 |
| > Total weight/channel-beam --- (Lb): | 510 | 510 |
| > EDI total weight ------------- (Lb): | 145 | 398 |
| > Total EDI weight/channel-beam (Lb): | 295 | 253 |
| > EPDS total weight ------------ (Lb): | 98 | 2709 |
| > Total weight/channel beam --- (Lb): | 2654 | 2654 |
| > *Power storage/channel beam - (Lb): | 0 | 0 |
| > PAYLOAD weight/channel-beam -- (Lb): | 2661 | 2557 |
| > Maximum number of channel-beams: | 0 | 1 |
| > Residual weight (Lb): | 6044 | 82 |
| > Total weight/channel-beam ---- (Lb): | 6119 | 5974 |
| > Available payload weight ----- (Lb): | 6044 | 6056 |
| > Non-beam-related weight ------ (Lb): | 3963 | 2248 |

Table I-2. Satellite Weight Estimates with Current Technology

• 50 $\mu$V/m Field Strength

| Subsystem | Weight (lb) | | |
|---|---|---|---|
| | 6 HR | 8 HR | 12 HR |
| Antenna | 200 | 200 | 400 |
| Transponder | 1120 | 1600 | 1900 |
| Electrical power | 1150 | 1100 | 1200 |
| Thermal control | 400 | 600 | 700 |
| Structure | 500 | 600 | 700 |
| Attitude control | 300 | 350 | 400 |
| Propulsion | 200 | 300 | 340 |
| DHS, TT&C, COMM | 200 | 200 | 220 |
| Satellite | 4070 | 4950 | 5860 |
| Reserve (20%) | 815 | 990 | 1170 |
| Total | 4885 | 5940 | 7030 |

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