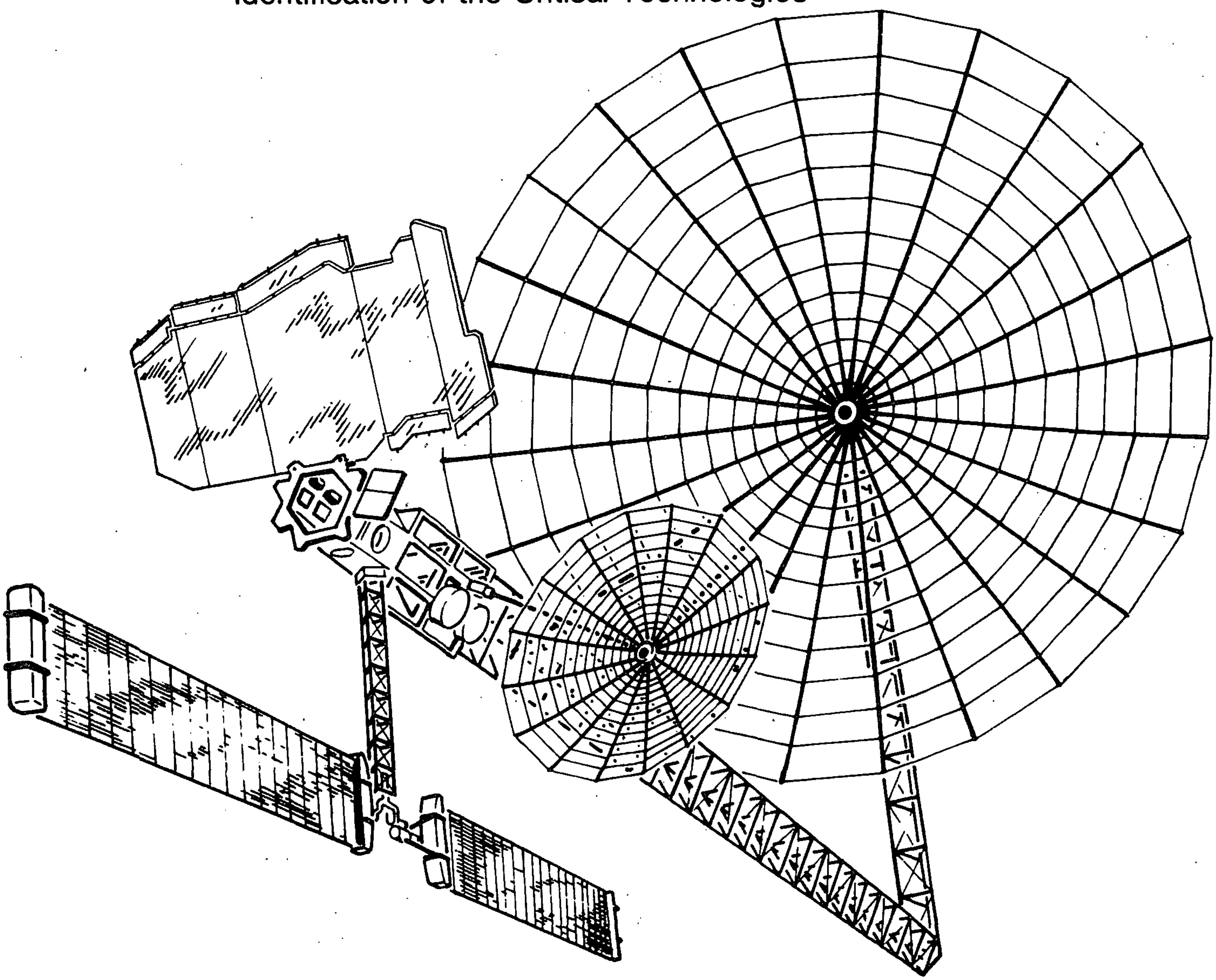
Land Mobile Satellite Service (LMSS):

A Conceptual System Design
and
Identification of the Critical Technologies



February 1982

NASA
National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

ADVANCE ANALYTIC

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JPL PUBLICATION 82-19

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A Conceptual System Design and Identification of the Critical Technologies

Part I: Executive Summary

Firouz Naderi
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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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This report is Part I of a two-part document, published under the same title with the following subtitles.

Part I: Executive Summary

Part II: Technical Report

Abstract

This two-part report describes a conceptual system design for a satellite-aided land mobile service. (Part I is the executive summary and Part II is the detailed technical report.) While mobile satellites of lesser capacity may be launched within the next 10 years using today's technology, these systems will serve as forerunners to the large, high capacity system of the 1990s described in this report. This advanced system is based on a geostationary satellite which employs a large (55-m) UHF reflector to communicate with small inexpensive user antennas on mobile vehicles. It is shown that such a satellite system through multiple beam antennas and frequency reuse can provide thousands of radiotelephone and dispatch channels serving hundreds of thousands of users throughout the U.S. Critical technology areas identified and discussed as requiring further development include that of a large ($\approx$60-m^2) UHF planar microstrip patch feed array capable of producing approximately 90 contiguous multiple spot beams, distributed sensing and actuation for the attitude control subsystem, large antenna structures, and small low-gain mobile vehicle antennas. The report concludes that such a system is technologically feasible for the 1990s and, indeed, by providing service to rural and remote regions, should complement the terrestrial networks serving the metropolitan areas, thus enabling ubiquitous mobile coverage of the U.S.

Foreword

Land Mobile Satellite Service (LMSS) implies the use of a satellite to provide telecommunication (such as telephone, paging, dispatch, data exchange, etc.) to mobile users. For the last decade, NASA and its contractors have studied LMSS from the standpoint of system design, technology assessment and development, applications, market size, financial viability, and institutional factors. The ATS series of NASA satellites has provided experimental verification of the feasibility and utility of mobile satellite communications. In the fall of 1979, the World Administrative Radio Conference allocated RF spectrum in the 806-890 MHz band for the LMSS, and thereby opened the door for future implementation of such a service. At the same time, JPL organized a team to study this new service. Since that time, JPL, in cooperation with other NASA centers, has conducted numerous major and minor studies related to LMSS, for both future commercial applications of the service and for proposed demonstration systems which could be launched by NASA.

In the past year, JPL's efforts have concentrated primarily on the conceptual development of future commercial LMSS systems. These efforts have involved both systems studies, under the sponsorship of the NASA Office of Space Science and Applications (OSSA), and technology development studies under the sponsorship of the NASA Office of Aeronautics and Space Technology (OAST). A broad spectra of systems have been studied from simple single-beam satellites with very limited capacity, but with readily available technology, to the large antenna, high capacity satellite requiring future technology. It is possible that within a few years one of the more simple systems could be launched to serve a limited user community. More complicated, higher capacity systems would follow leading to a relatively large satellite in the 1990s, such as that presented in this report. The study presented here is not meant to be a complete "Phase A" type of NASA system study of a large LMSS system, but rather: (a) provides a methodology for developing high capacity LMSS systems, and (b) identifies technology requirements and provides a system focus for the future development of these technologies.

The study evolves from hypothesizing the functional requirements for the LMSS system, to the design of the architecture of the LMSS telecommunications network, and finally to the conceptual design of the space and ground segments. The technology presented focuses on the development of the large spacecraft antenna which imposes the most technological challenge. This antenna is a total "system" in its own right in that elements of the RF antenna design, electronics, structures, and control are highly interrelated.

This report is part one of a two-part JPL document. Part I is the executive summary while Part II, which constitutes the main body of this document, is the technical report and provides a synthesis of the large LMSS system and the complementary technology development studies.

Many technical details are omitted in the executive summary and the interested reader is referred to Part II for such information. An outline of the content of Part II is provided within the executive summary.

Contents

Outline of the Main Report

Part II constitutes the main body of this document (roughly 400 pages) and contains technical details which were omitted in the executive summary. The outline of the content of Part II follows.

Chapter 1 introduces the concept of the land mobile service. It describes the conventional terrestrial mobile radio systems followed by the definition of the more advanced cellular concept. The similarities between a multiple beam satellite system and the terrestrial cellular system are pointed out and the operation of the satellite system is explained. The chapter concludes with a section on the potential frequency spectrum availability for the LMSS in the U.S.

Chapter 2 describes the architecture of the telecommunication network as the first step in the design of the LMSS system. The chapter starts with hypothesizing a set of functional requirements including the total number of users to be served by the LMSS. The design parameters are then defined at length and are systematically selected such that the resultant system is capable of serving the hypothesized number of users. The output of this design process is the determination of the required number of satellite beams, which in some sense, indicates the largeness of the LMSS system. The chapter then presents the design of the backhaul link and determines the number of multiple S-band beams required for the backhaul communication. Next, a conceptual procedure for call-routing and locating a mobile subscriber within the LMSS network is discussed. This section of the chapter explains the various steps in placing a call and develops the relationship between the UHF and the S-band multiple beams. A summary of the design parameters is presented at the conclusion of the chapter.

Chapter 3, which constitutes the core of Part II of this report, presents the design of MSAT, which is the spacecraft for the LMSS. The most important requirement affecting the design of MSAT is that of producing a prescribed number of multiple beams as set forth in Chapter 2. Starting with this requirement, Chapter 3 develops a conceptual design for MSAT describing most major subsystems individually. Naturally the bulk of the discussion is aimed at the design of the large UHF multiple beam antenna and its associated feed array, which are the most singularly prominent features of MSAT. The chapter begins with an overview of the overall design, and continues with a discussion of each subsystem. The material covered in this chapter includes the design of the feed array and the RF, control, power, propulsion, and thermal subsystems. The RF performance of the UHF antenna, including its beam isolation performance, is discussed at some length. The chapter concludes with the volume and mass properties of MSAT and its Shuttle launch considerations.

Chapter 4 considers the ground segment, notably the mobile vehicle antenna. This chapter presents three conceptual designs for the mobile antenna, including one which could potentially be used throughout the coverage area. Also presented is the design for a vehicle antenna to be used at low elevation angles, such as in Alaska. The other major topic discussed is that of the selection of a voice modulation scheme for LMSS which impacts the makeup of the mobile transceiver and affects the compatibility of the satellite with the terrestrial systems.

Chapter 5 amplifies the technology requirements for MSAT in connection with the RF, control, and structure of the UHF antenna. This chapter is meant to highlight various technology developments needed to support the conceptual design of Chapter 3.

The report also contains six appendices which for the most part consider alternatives to the baseline design presented in the main body of the report:

Appendix A considers an MSAT design using a standard cassegrain configuration for the UHF antenna and concludes that the design is not particularly attractive.

Appendix B also considers the folded optics but based on dual-shaped reflectors. The aim is to synthesize the surfaces of the main and the subreflectors for better RF performance or, equivalently, the same RF performance but a more compact spacecraft design. The appendix discusses the required software development and gives preliminary results.

Appendix C presents an LMSS system design based on a 4-sub-band frequency reuse plan in conjunction with the use of polarization diversity. This design is contrasted with the baseline which employs a 7-sub-band frequency reuse plan and only one sense of an orthogonal polarization. Noting the increase in LMSS capacity associated with the use of a 4- rather than a 7-frequency reuse plan, this appendix addresses the required characteristics of the UHF feed in order to enable the use of polarization diversity.

Appendix D presents the results of an intermodulation analysis study. The LMSS is inherently a Single Channel-Per-Carrier (SCPC) telecommunication system. As such, hundreds of carriers will be routed through common amplifiers causing intermodulation distortion. Further complicating the intermodulation distortion is the fact that not all signals within a power amplifier have equal powers. A summary of the analysis study is presented in this appendix.

Appendix E presents an outline for a systematic design of a multiple beam offset antenna. This appendix should further help the understanding of the antenna design presented in the main body of the text.

Appendix F considers the use of electric propulsion in order to reduce the weight of MSAT. The baseline design uses liquid propellant, which along with the associated hardware, constitutes nearly 25 percent of the weight of MSAT. Electric propulsion could potentially reduce this to only a few percent.

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p6-16

D1

Land Mobile Satellite Service

Background

To each of us the term "mobile radio" has different connotations. To some, it implies the type of dispatch used by police, firemen, taxicabs, and ambulances. To others, it means a personal two-way radio, such as the citizens band or amateur radio. Still others think of commercial mobile radiotelephones used by physicians and businessmen. The types and uses of mobile radios have increased at an enormous pace in the last 10 years as the cost and size of their electronics have diminished. The increased demand for these services has presented the system designers the challenge of accommodating an increasingly large market in precious little radio spectrum.

Within the next few years, mobile radios will take a quantum leap in technology and service with the introduction of a new concept referred to as the cellular mobile radiotelephone system. Its sophisticated control system and efficient use of the spectrum will provide a grade of service superior to that presently available. Furthermore, the system is expandable with growing markets and, indeed, should be less costly to the user as the system grows. Many believe that the elastic nature of the market will create a spiral effect of decreasing prices and increasing market demand. While recent mobile radio market forecasts differ in their assessments, even the most pessimistic foresees a remarkably strong growth curve in the next 20 years and beyond.

Most scenarios of the growth of mobile radios show the cellular mobile radiotelephone systems in the next decade capturing the lucrative markets in the metropolitan areas of the country with slower expansion into the medium-sized cities. Unfortunately, the majority of the geographical area of the country, and a significant portion of the population of the country represented by that area, will not be served by these advanced systems, primarily because these systems are not particularly cost effective in less densely populated areas. Market assessments conducted by the National Aeronautics and Space Administration (NASA) have consistently shown that in the less populated areas of the country, a strong market exists for dispatch, radiotelephone, and emergency services. A satellite system as described in this report is ideally suited to covering vast geographic areas on an economic basis. Many now believe that the solution to a truly national and ubiquitous mobile radiotelephone service will be composed of cellular systems serving the metropolitan areas, integrated with and complemented by a satellite system serving the rural and remote areas.

For the past several years NASA has been studying the need for a Land Mobile Satellite Service (LMSS) to extend current and planned mobile communication services into rural and less densely populated areas. The Federal Communications Commission (FCC), on the other hand, will soon be licensing terrestrial cellular mobile communications systems in many major metropolitan areas. An LMSS system would serve areas beyond those major metropolitan areas.

There are many segments to the potential mobile satellite market. This includes voice and data applications such as: commercial mobile radiotelephone; disaster assessment and relief; search and rescue operations; law enforcement; emergency medical services; terrorism control and national security; interstate trucking dispatch; monitoring of hazardous material transportation; forest fire containment; dispatch, monitoring, and control for widespread utility operations such as oil, gas, electric power, and water; and possible nationwide paging.

In 1979, the World Administrative Radio Conference (WARC) recognized the value of utilizing a geostationary satellite for mobile communication and allocated the 806-890 MHz band for mobile satellite service (excluding aeronautical) for domestic use within countries in two of its three global administrative regions and in part of the third, including all of North and South America. While this allocation does not imply a national allocation for mobile satellite service in this band (the FCC must approve), nor does it guarantee the economic viability of any such satellite service, it was a first step enabling system designers to develop potentially viable concepts. One satellite concept is presented in this report.

Many proposals and studies have been made in the last decade relative to the feasibility of LMSS systems. It now appears that present technology could support an LMSS system of modest capacity and could be launched within the next five years. As the technology develops, particularly in the satellite antenna area, even larger, higher capacity systems can be launched. These larger systems will attract hundreds of thousands of customers at a cost per user comparable to terrestrial mobile systems. This report describes the design of such a large LMSS system. The design does not include all the features or coverage area that might be included in the eventual system. Rather, the system described here includes most of the design features which drive the development of the technology. It is for this candidate system design that a technology assessment has been made which can serve as a focal point for future technology development.

The central component of the large LMSS system presented in this report is a spacecraft in geostationary orbit (22,000 miles above the equator) capable of relaying radio messages to hundreds of thousands of land mobile units throughout the U.S. The most prominent feature of this spacecraft, which sets it apart from other communication satellites, is its large antenna which enables communication with small, simple, and thus inexpensive, mobile equipment. Using this large antenna, the spacecraft forms multiple contiguous spot beams which provide a blanket coverage of the U.S. Judicious reuse of the available frequency band among these beams results in efficient utilization of the spectrum and allows service to thousands of users.

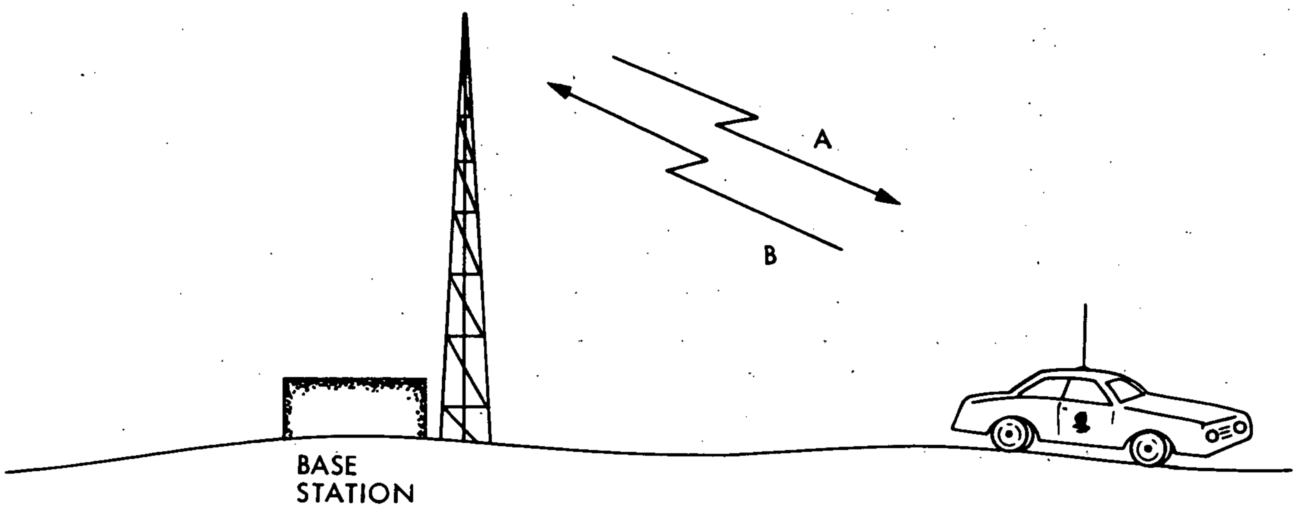
From the study presented here, it appears that this large capacity mobile satellite system can be both technically feasible and economically viable within the next 10 to 15 years. The smaller systems which may be launched prior to this will serve as stepping stones for the development of both the service and the technology.

Before describing the satellite system, we first review some of the fundamentals of the mobile radio which will be pertinent to the mobile satellite system design.

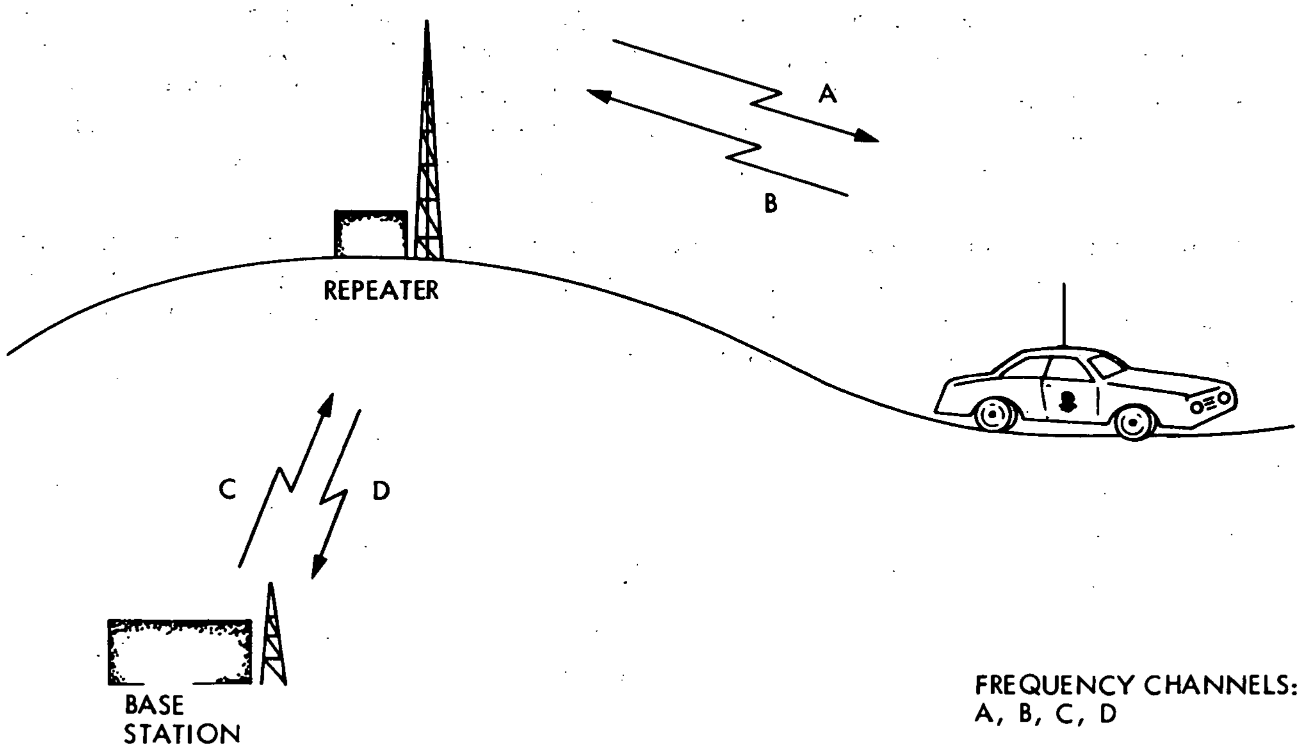
Conventional Mobile Radio System

Major components of a conventional (as opposed to a cellular) terrestrial mobile radio system are the base station and the transmitting tower (see Fig. 1(a)). Simply stated, telephone calls are routed to the mobile users by "broadcasting" the voice channels from the transmitter (or a repeater) over a given radius. The base station serves as the interface between the mobile telephone system and the regular telephone network thus permitting the mobile user to access any telephone in the country. Frequencies used by these systems are typically in the following bands: 30-44 MHz, 152-162 MHz, and 450-460 MHz.

Although conceptually simple from a frequency channel standpoint, such systems suffer from a number of technical difficulties. To begin with, the mobile user must stay in the coverage area (line-of-sight) of the base station or one of its repeaters. A more severe shortcoming, however, is its wasteful use of the precious little spectrum allocated to this service. Note that since the voice channels are broadcast over the entire coverage area, any one channel cannot simultaneously be used by more than one user, thus limiting the size of the market the system can address. To overcome these difficulties, a new concept called a cellular mobile radio system is proposed, as briefly explained on the following page.



a) Simple Base Station Configuration



b) Configuration With Repeater

Figure 1. Two Configurations for Terrestrial Mobile Radio Service

Cellular Mobile Radio System

The cellular mobile system now under development and field experimentation will correct most of the drawbacks associated with conventional systems. In a cellular system, the entire coverage area, for example, a major city and its suburbs, is divided into a number of cells, each with its own base station and frequency band. The frequency reuse concept is used to increase the utility of the available frequency spectrum as shown in Fig. 2. (The 3-frequency sub-band is used in Fig. 2 for illustrative purposes. In practice, the number of sub-bands is seven or more.) In this example, the total allocated band is divided into 3 sub-bands, designated A, B, and C, with each sub-band being assigned to a cell such that no cell is adjacent to a cell of the same sub-band. This insures that the transmissions in one cell do not interfere with the independent transmissions in the adjacent cells. However, through power control and geographical separation, the frequency sub-bands are reused in nonadjacent cells thereby providing efficient use of the available spectrum. In this way, any given frequency channel can be used in hundreds of separate geographic locations unlike the older broad coverage systems as depicted in Fig. 1.

When a vehicle roams from one geographical cell to another, the mobile unit's frequencies are automatically changed to a new set, compatible with the base station in that cell. The control and interconnection with the wireline network is handled by the mobile telephone switching office (MTSO) as shown in Fig. 2.

In addition to the frequency reuse aspect, the other major feature of the cellular system depicted in Fig. 2 is the different cell sizes accommodating varying user population densities. For example, the larger cells might represent less populated suburban areas while the smaller cells represent the more densely populated urban areas. Should the market in any given cell increase, the cell can be further subdivided into smaller cells to accommodate the increased traffic. These smaller cells represent a greater reuse of the available spectrum, thus providing more channels for the same coverage region.

Cellular systems operate in the 806-890 MHz band and are now undergoing field experiments in two areas. A system in the Washington-Baltimore area is operated by American Radio Telephone (ART), for which Motorola is manufacturing the mobile equipment, and the Bell System operates the Advanced Mobile Phone System (AMPS) in the Chicago area.

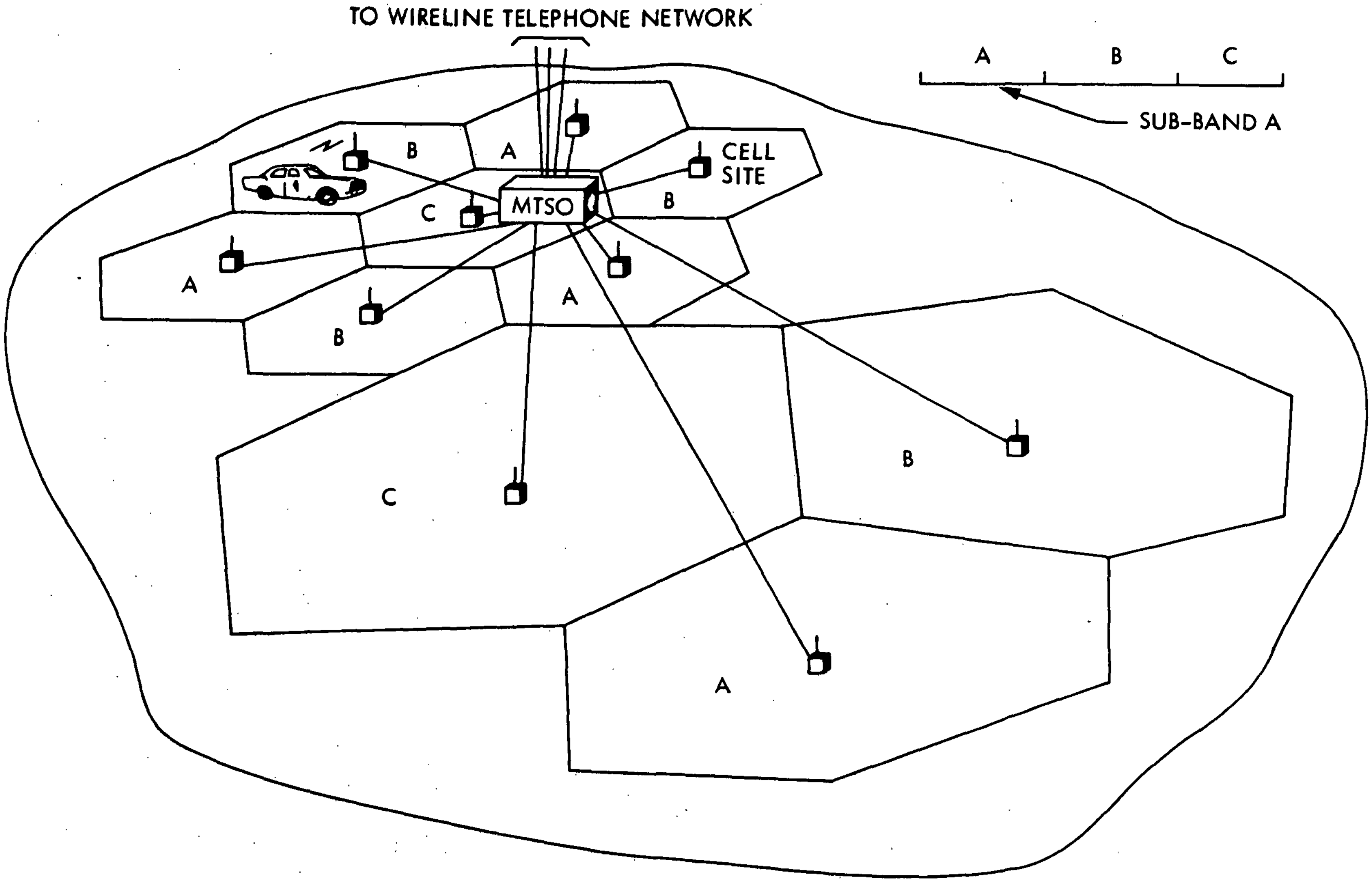


Figure 2. Cellular Layout Illustrating Cell Splitting and Frequency Reuse

The Satellite Concept

As sophisticated as the cellular mobile radiotelephone concept is, the fact remains that such a system may not provide coverage to the nonurban areas of the country. A geostationary satellite, on the other hand, is ideally suited for providing communication to virtually any geographic region, no matter how remote.

Conceptually, the satellite system is analogous to the cellular radiotelephone systems in design and similar in operation. For a geographic service area such as CONUS (the contiguous 48 states), the satellite antenna produces a number of contiguous beams whose footprints on the coverage area appear as in Fig. 3. These circular footprints nominally represent the -3 dB contours of the beam patterns. Frequency sub-bands are assigned to each beam as in the cellular case with no adjacent beams assigned to the same sub-band. In the design presented here there are 87 such beams. Following the discussion of the terrestrial systems, the satellite system is equivalent to the cellular system in that the beam footprints are equivalent to the cells, the satellite is equivalent to remote repeaters for each cell, and the ground base stations within the beam footprints serve the same function as base stations in the cellular systems, that is, control and wireline network interconnection.

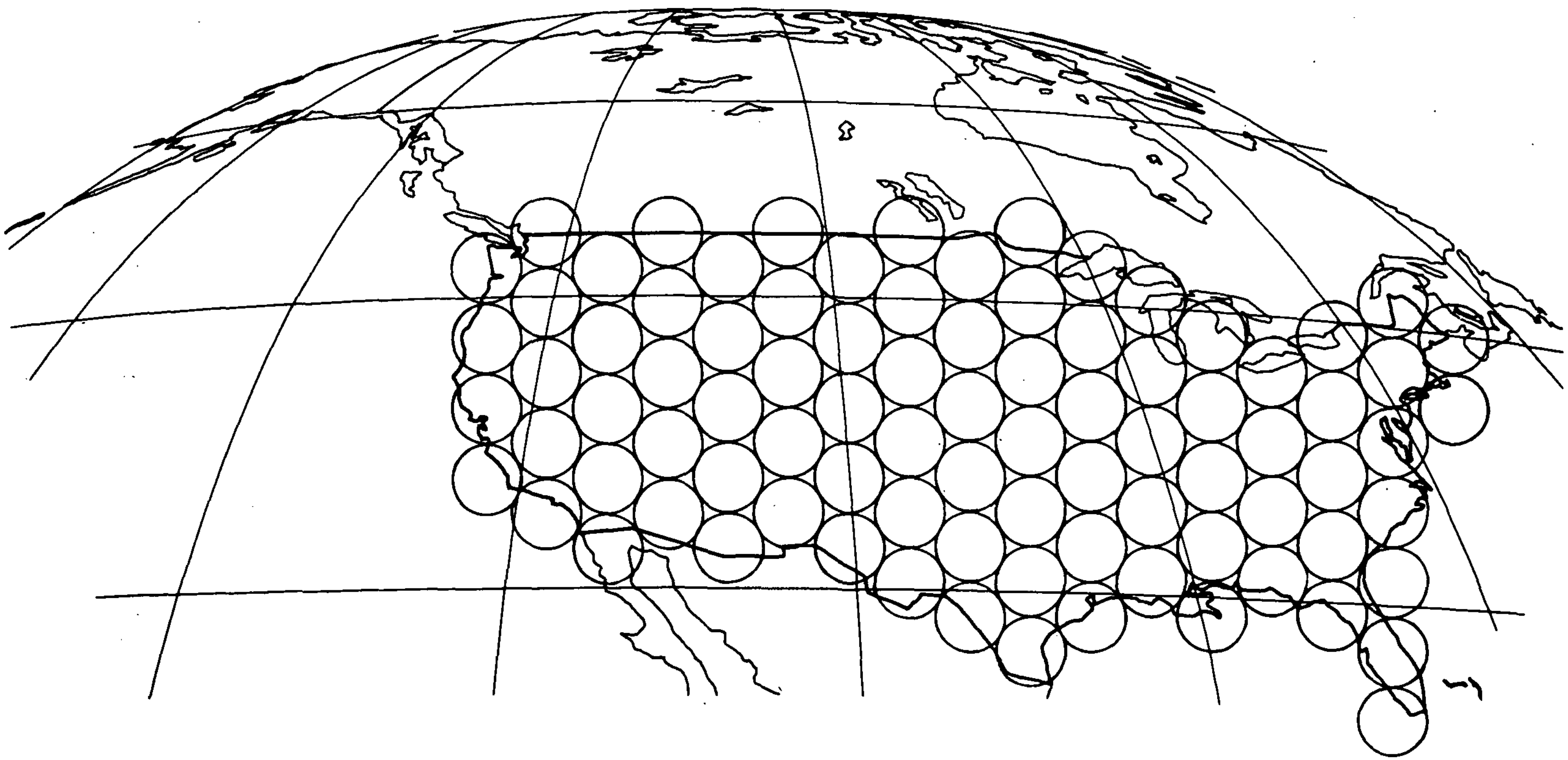


Figure 3. Satellite Beam Layout Illustrating Coverage of CONUS by 87 Beams

Satellite Operation

An LMSS network consists of the space segment (i.e., the spacecraft) and the ground segment which itself consists of two types of terminals, fixed and mobile. The fixed terminals, called the base stations, serve as the interface between the LMSS and the wireline network and, in general, control the operation of the LMSS by providing such functions as paging a mobile user, making channel assignments, call-routing, etc. In the design presented here there are 25 base stations serving the 87 beams of Fig. 4. On the other hand, mobile terminals, which number in the hundreds of thousands, are located on the subscribers' vehicles and provide users the means to access the satellite network.

A typical call may originate from a home telephone connected to the wireline network. This call is routed via the wireline network to a base station where it is transmitted to the satellite over the backhaul link. (The system presented here uses S-band for the backhaul link; however, other bands such as the C, K_u or K_a may also be used depending on their availability.) The satellite translates the backhaul frequency to UHF and relays the call over the UHF link to the mobile user. This completes a one-way connection. In the return link, the mobile transmits to the satellite over the UHF link, the satellite receives and relays the call back to the base station over the backhaul link, and the base station forwards the call through the wireline network to the originating phone. Additionally, calls may also originate from the mobile phone and be routed to a fixed phone or another mobile phone. (See Part II for details.)

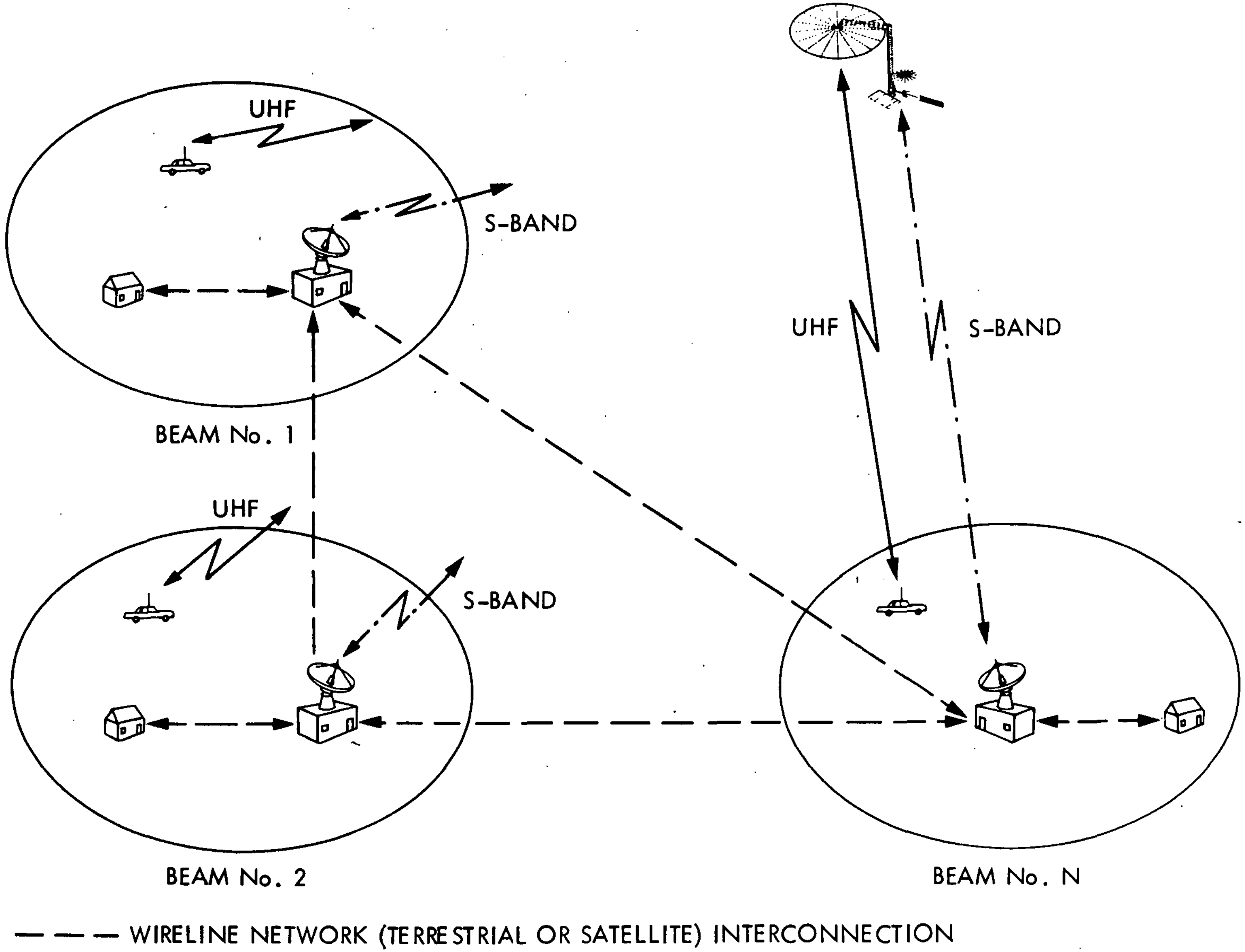


Figure 4. Signal Routing in a Land Mobile Satellite System

Frequency Allocation

A complete duplex channel in a land mobile satellite is made up of the forward channel, i.e., base station-to-mobile and the return channel, i.e., mobile-to-base station. Each one of these two channels is made up to two segments as shown below:*

a) Base station-to-mobile consists of:
   i) Base station-to-satellite (using S-band 2655-2690 MHz)
   ii) Satellite-to-mobile (using UHF 866-876 MHz)

b) Mobile-to-base station consists of:
   i) Mobile-to-satellite (using UHF 821-831 MHz)
   ii) Satellite-to-base station (using S-band 2550-2585 MHz)

At present no allocation exists in the U.S. for the LMSS. The design presented here assumes that 20 MHz of the reserve bands in the 806-890 MHz band will be allocated by the FCC for this service. (Part of the band has been allocated for the cellular mobile radiotelephone in the U.S., and internationally, the entire band has been allocated for LMSS.)

A compelling reason for selecting UHF for the LMSS is to produce a system which is compatible with the present cellular system to the greatest extent possible. This permits the user to have a single set of equipment in his vehicle for both the satellite and the cellular systems and enables the satellite system to take advantage of the economies of scale in the production of the mobile equipment. In the ultimate system, a user will place or receive a call from his vehicle and not know whether his call is routed via the satellite or the terrestrial link.

Another assumption made for this study is that the satellite/base station backhaul links will be in the 2.5-2.69 GHz band, which has an international allocation of 35 MHz for both the uplinks and downlinks for fixed satellite services. This band was chosen because it is rarely used for satellite service, whereas, C-band and K_u-band frequencies are in great demand.

*Consistent with NASA's proposal before the FCC.

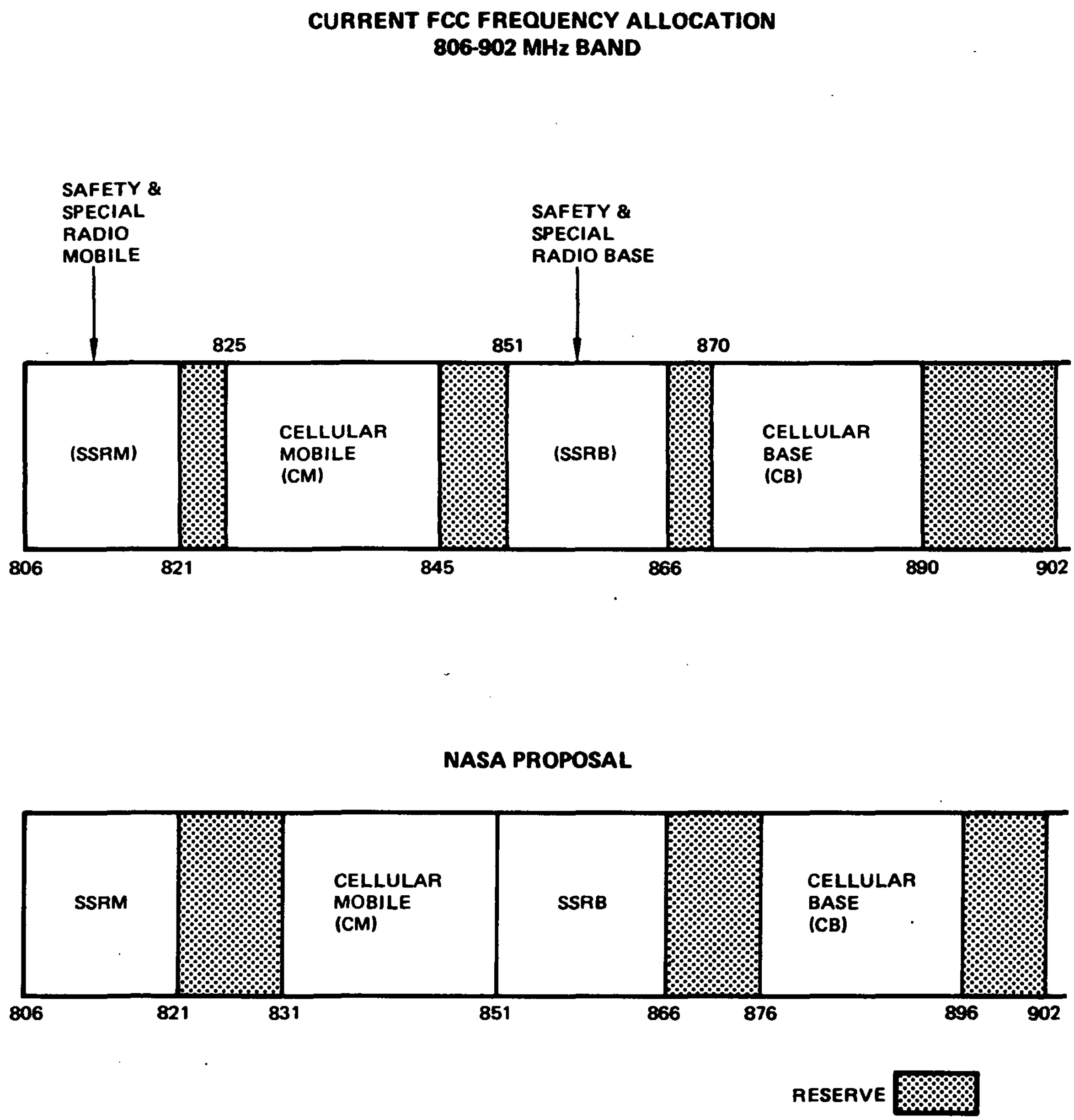


Figure 5. Frequency Allocation for the 806-902 MHz Band

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p 20-27

D2

LMSS Telecommunication Network Design

Hypothesizing the Functional Requirements

In order to develop a conceptual LMSS design, some general functional requirements must be hypothesized. These requirements should depict, as closely as possible, those likely to be imposed on the actual system. The design presented here has been influenced by the following set of self-imposed requirements. However, it should be noted that there are other viable LMSS concepts geared to a specialized market of users which may not necessarily be governed by the requirements put forth here.

- Area to be Served: The LMSS will serve the Continental United States (CONUS). In CONUS, LMSS will provide service to nonmetropolitan areas, i.e., suburban and rural, that are not now or are not likely to be served by terrestrial mobile radiotelephone service. It is expected that urban areas will be served by terrestrial cellular systems. Additionally, the following remark should be noted regarding the coverage requirement. Whereas the design presented in this document considers CONUS as the coverage area, more than likely, the ultimate satellite system will have to cover not only CONUS but Alaska and Hawaii as well. Other possibilities include an all Northern American coverage, which may make the most sense economically. However, it should be stated that the primary objective of this system design is not to design the ultimate operational system, but rather to provide a focus for the various LMSS related technology development activities within JPL and NASA, and to expose the critical technologies which require a long lead time. As such, it is felt that a system with only CONUS coverage is adequate to scope the challenges ahead. Critical technological barriers to provide coverage to other areas is not expected.

- Time Frame: The system will operate in the 1995-2005 time period. This requirement implies that the space segment, i.e., MSAT, will have a 10-year lifetime.

- Capacity: The system will be designed to have sufficient capacity to serve a population of users equal to the capturable market. For this study, the capturable market is defined as the number of users willing to subscribe to LMSS for charges comparable to that of the conventional mobile radio service.

- Type of Service: LMSS will provide duplex radiotelephone service. A subscriber to the LMSS service will be able to access any telephone connected to the wireline network. Conversely, the mobile LMSS user will be accessible from any telephone within the wireline network regardless of the current location of the mobile. Additionally, any pair of mobile users in the LMSS network will be able to communicate with each other. It must be further noted that while this LMSS design considers only radiotelephone service, the actual operational system will offer a mix of services including dispatch. The use of some of the channels in the dispatch mode will primarily increase the number of users which can be accommodated by LMSS and make the service more attractive from the investors point of view.

- Cost Considerations: The LMSS will have user charges, including the mobile equipment cost, comparable to similar costs and charges for the commercial terrestrial radiotelephone service.

- Compatibility: It is strongly desired that the LMSS system be as compatible as possible with the planned cellular mobile telephone systems as typified by Bell System's Advanced Mobile Phone Service (AMPS). Thus, a subscriber can use the same equipment (or with as little modification as possible) for both the terrestrial and the satellite system. This further ensures low-cost mobile equipment through the economies of scale inherent in cellular equipment.

- Quality: The quality of the voice channel in the LMSS should be comparable with the present day toll service. The call setup times and probability of a busy signal due to system capacity overload will be compatible with similar requirements for the cellular systems.

Some of the above constraints and ground rules have served to sharply reduce the number of options available for the design of the LMSS. As an example, an all digital system is ruled out at this time due to the cellular compatibility constraint. Such an all digital system could be very appealing from a satellite design standpoint.

Market Requirement

In order to determine the required system capacity for the LMSS, the demand must be forecast for such a service at the time frame the LMSS is to be offered. There were 91,000 mobile radiotelephone users in the rural area in the year 1980. The question at hand is what will the size of the market be at the turn of the century and what portion of this total market is potentially capturable by the LMSS.

In recent years, a number of market studies have attempted to answer this question. The results are somewhat varied. NASA, through Lewis Research Center, has initiated a contract in order to arrive at a more definitive answer to this question. For the purposes of the conceptual design presented in this report, however, the following two arbitrary assumptions were made.

a) The first generation LMSS will reach full capacity in the seventh year of its operation and operate at full capacity the last three years of its 10-year life.
b) The LMSS will be designed so that it has a capacity sufficiently large as to accommodate all the capturable market for such a service.

Assuming that the LMSS commences its commercial operation in 1995, it will be in its seventh year of operation in the year 2001. Further, assuming a 10 percent annual growth rate, the market for mobile radiotelephones in the rural area will increase from 91,000 in 1980 to approximately 673,000 by the year 2001. If it is rather arbitrarily assumed that by that year the LMSS will capture some 40 percent of this market, then based on all of the stated assumptions, the required capacity of the LMSS in terms of mobile radiotelephone users must be approximately 270,000. Accordingly, the design presented in this report is sized to be able to accommodate 270,000 radiotelephone users. It should be noted that these market assumptions were made to bound the conceptual design of the LMSS and do not reflect the result of the more detailed market study now underway by NASA.

Reiterating a point made earlier, the actual operational LMSS system will have users that require not only radiotelephone but dispatch and data channels as well. Due to the nature of dispatch, a channel used for this purpose can accommodate, on the average, two to three times the number of users a radiotelephone channel could serve. Thus, the same system which can serve 270,000 radiotelephone users can serve a much larger market if some of its channels are used in the dispatch mode. However, since the technical description of the system is relatively transparent to the mode of operation, this design is based on the requirement to serve 270,000 radiotelephone users with the additional explanation that almost twice the number could be served if half the channels are used in the dispatch mode.

Network Design Parameters

As is the case with any large, complex system, the design of the LMSS network involves a myriad of parameters with potential for many tradeoffs among them. The designer however does not have control over the selection of all of these parameters, as some may be dictated due to institutional, regulatory, economical or other considerations. The approach taken in this design has been to start with the total number of users to be served (i.e., 270,000) and arrive at the required number of satellite beams by systematically selecting various design parameters. The chart in Fig. 6 depicts the design process used. Note that the boxes to the left of the dashed line are assumed to be given and outside the control of the LMSS designer.

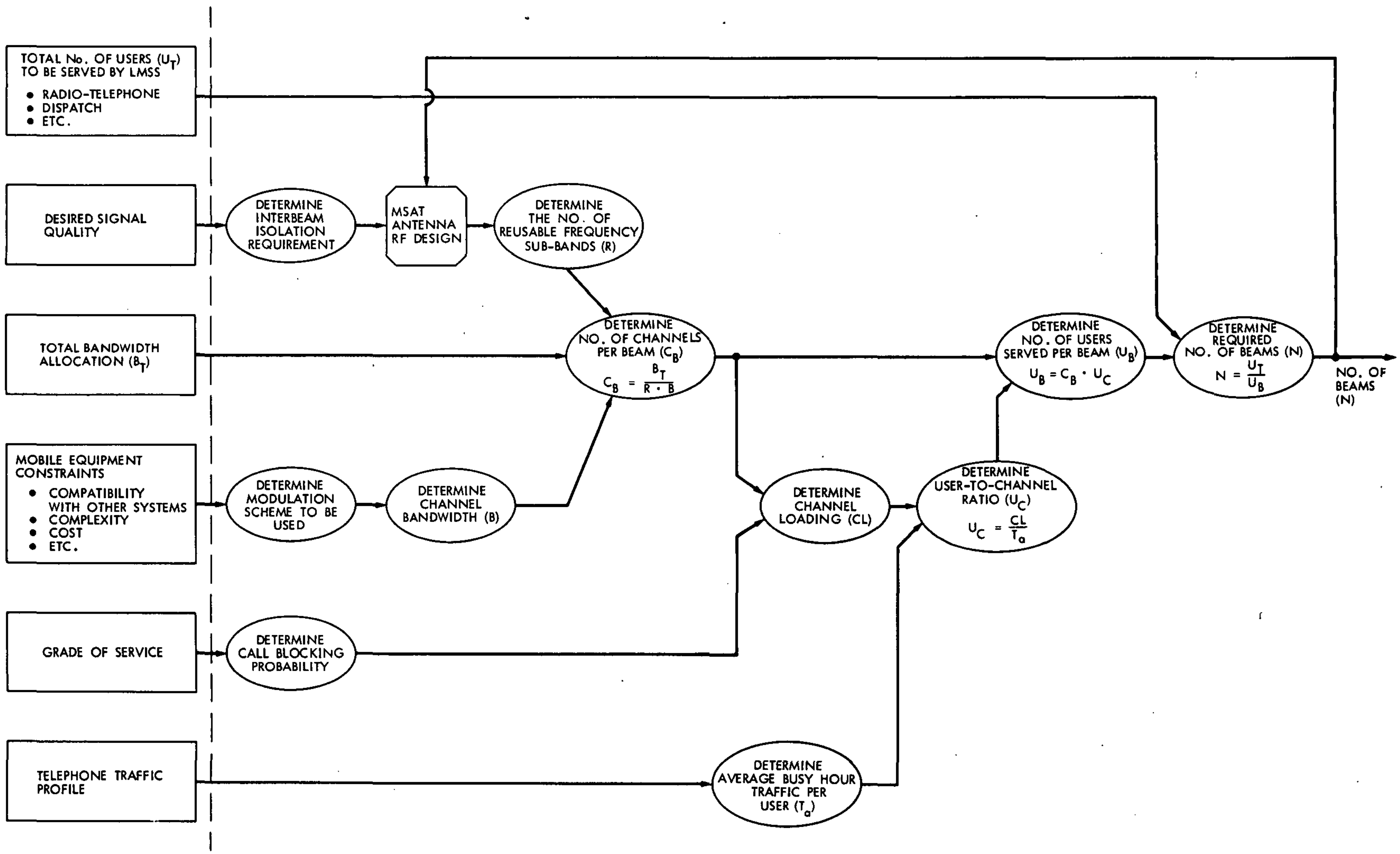

Figure 6. A Flowchart to be Used as a Procedural Guideline in the Design of LMSS Communication Network

Multiple Beam Layout

Following the procedure described on the previous pages, the number of required UHF beams were determined to be 87. Figure 7 shows a candidate multiple beam layout over the coverage area. As indicated by Fig. 4, the LMSS spacecraft requires two sets of multiple beams, one, produced by a UHF antenna, is used in communication between the spacecraft and the mobile users, and the second, produced by an S-band antenna, is used in communication between the spacecraft and the base stations. Figure 8 shows that by assigning a base station to a cluster of four UHF beams, 25 base stations would be required for the LMSS network. Twenty-five S-band beams are then required to provide coverage to these base stations as shown in Fig. 8.

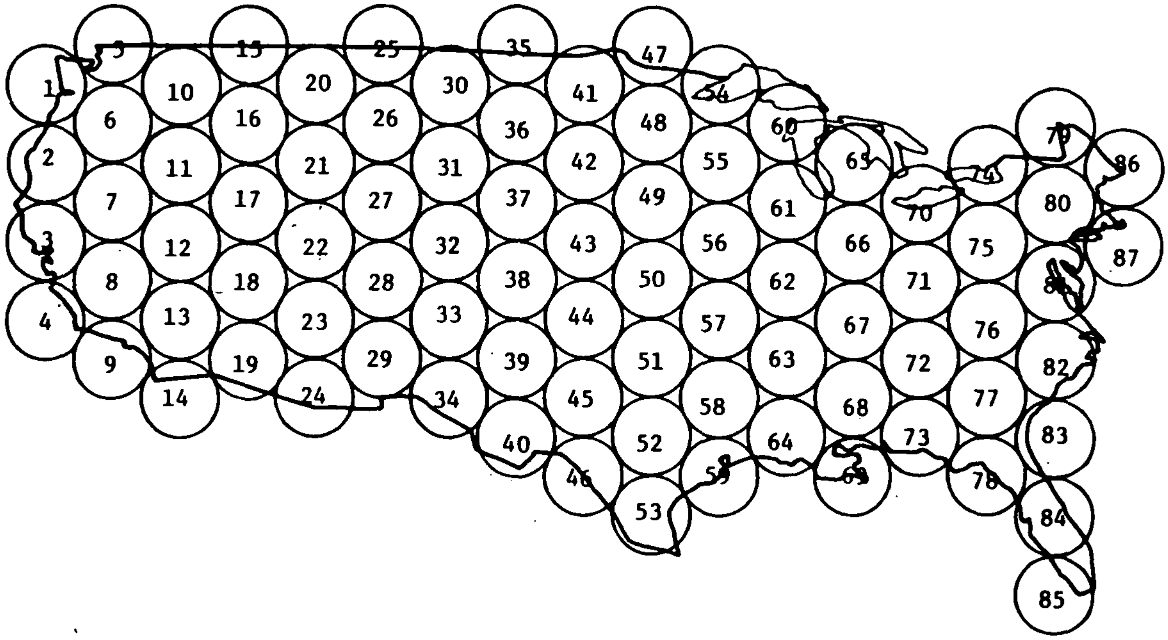

Figure 7. An 87-UHF Beam Layout

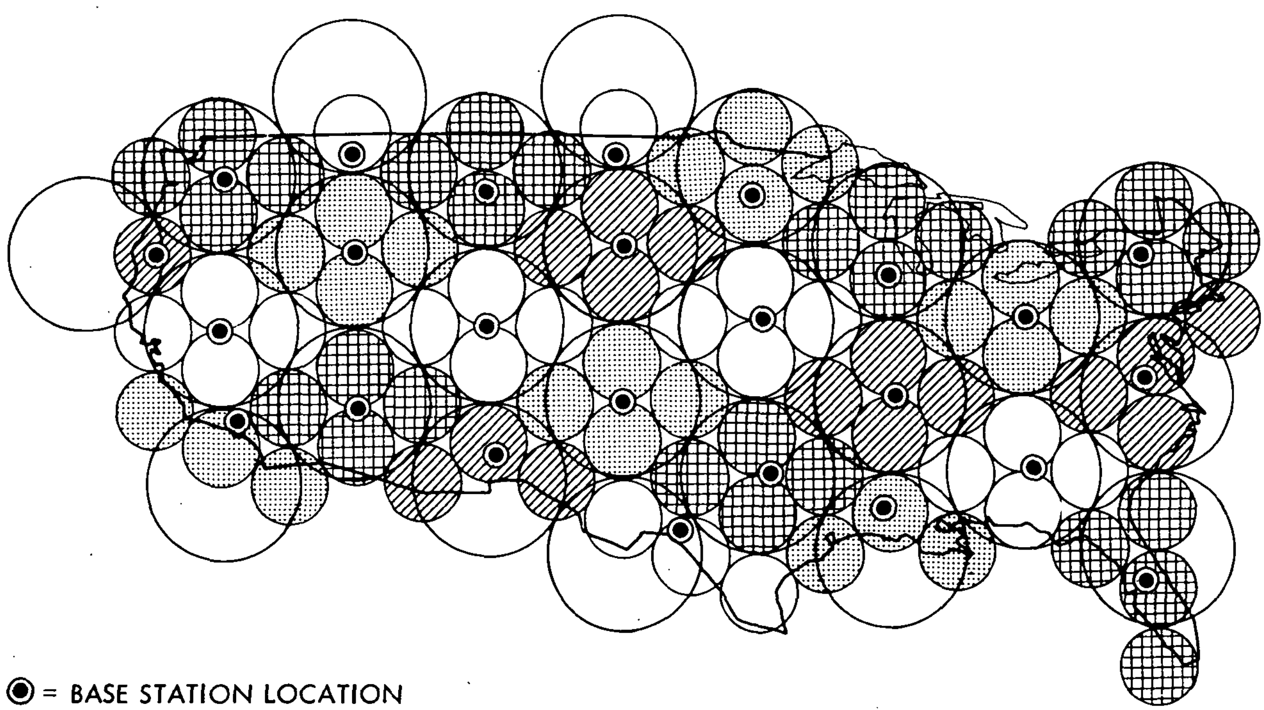

Figure 8. Superimposition of the S-band and UHF Beams

LMSS Network Design Summary

Table 1 summarizes the salient features of the LMSS network design. The network is based on 87 UHF beams each producing 95 channels for a total of 8,265 channels. It is assumed that the busy hour traffic is such that each beam can accommodate 3,135 users (i.e., user-to-channel ratio of 33) which results in a system capacity of 270,000 radiotelephone users. (If some of the channels are used for dispatch, the number of users accommodated by the LMSS rises dramatically. Assuming a partition of half radiotelephone channels and half dispatch channels, and a 100:1 user-to-dispatch channel ratio, the total number of users accommodated is roughly equal to 550,000.) The two 10-MHz UHF bands are reused approximately 13-fold by following a 7-frequency reuse plan amongst the 87 beams. (More on this later.)

The backhaul communication (i.e., satellite/base station link) is established via 25 S-band beams covering 25 base stations each serving up to four UHF beams. Two 35-MHz bands are reused approximately six-fold by following a 4-frequency reuse plan amongst the 25 S-band beams.

Table 1. Salient Features of the LMSS Design

I - Given Parameters	
• Radiotelephone Users	270,000
• Coverage Area	CONUS
• Total Bandwidth	Two 10-MHz Bands in UHF (806-890) Two 35-MHz Bands in S-band (2500-2690)
• Grade of Service	2 percent Probability of System Overload
• Average Telephone Traffic-per-User During Busy Hour	0.026 Erlangs
• Other Constraints	Close Compatibility With the Terrestrial Cellular System
II - Derived Parameters	
• UHF Beams	
- Number of Beams	87
- Number of Reusable Sub-bands	7
- Number of Channels-per-Beam	95
- Polarization	Circular
- Polarization Diversity	Not Used
• S-band Beams (Backhaul)	
- Number of Beams	25
- Number of Reusable Sub-bands	4
- Number of Channels-per-Beam	95-380
- Polarization	Circular
- Polarization Diversity	Not Used
• Number of Base Stations	25
• Number of UHF Beams Served per Base Station	1-4
• On-board Switching	Not Provided
• Total Number of Duplex Channels	8,265
• User-to-Channel Ratio	33

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p30-67 D3

MSAT Design

MSAT Design Overview

The central component of an LMSS system is a communication satellite known as MSAT (for mobile satellite) and located at 110° W longitude in a geostationary orbit. The design of the LMSS telecommunication network calls for this satellite to produce two sets of multiple beams, one each in UHF and S-band.

A large, 55-m UHF antenna provides the communication between the mobile vehicle and the satellite, and a smaller 10-m S-band antenna relays the signals from MSAT to the base stations which serve as the interface between the LMSS and the regular wireline network.

The most prominent feature of MSAT is its 55-m offset-fed mesh deployable parabolic reflector. In addition to providing a large gain, which is needed to compensate for the low gain of the mobile antennas, this large reflector produces 87 narrow beams thus enabling efficient use of the available frequency spectrum through spatial diversity and frequency reuse.

The UHF reflector is fed by a large planar microstrip feed array. The array has an overall rectangular envelope of approximately 6.9 by 11.4 m and utilizes 134 feed elements to form the 87 UHF beams (see Fig. 9).

MSAT provides a total of 8,265 duplex voice channels each requiring an approximate RF power of 1/4 W. This results in a rather substantial requirement of 2 kW of RF power which must be provided by the MSAT power amplifiers. The prime power for the amplifiers, as well as other electronic equipment, is generated by two deployable solar arrays, each approximately 4 by 9 m, which are sized to produce 10 kW of DC power at the beginning of the mission.

MSAT, with its massive feed, large booms and reflectors, sheer size and low structural frequencies, constitutes a large flexible spacecraft whose attitude control presents a challenge of unprecedented proportions. First of all, MSAT dimensions are of the order of 100 m, making it considerably larger and more flexible than any spacecraft flown to date. Secondly, this very large satellite must be stabilized and pointed to very precise requirements (0.03 degrees). These challenges are met with an advanced control system design which combines state-of-the-art attitude control technology with emerging advanced control software and hardware technologies for in-orbit system identification, feed motion compensation, and distributed sensing and control, in order to achieve precise pointing and active vibration damping of this large satellite.

MSAT dissipates a substantial amount of power in terms of heat. The UHF power amplifiers, even with a 50 percent efficiency, dissipate 2 kW of waste heat, which must be disposed. The heat from the power amplifiers, which are physically distributed over the 58-m^2 area behind the UHF feed array, is transported via heat pipes to remote thermal radiators located at the top and bottom of the UHF feed panel as shown in Fig. 9.

The overall weight of the spacecraft at the beginning of the mission is approximately 4,000 kg (8,800 lb). Its launch requires a dedicated Shuttle cargo bay and an upper stage vehicle, with similar payload capabilities as the proposed wide-body Centaur. The spacecraft is designed for a 10-year lifetime and carries sufficient propellant to perform north-south and east-west stationkeeping during its life.

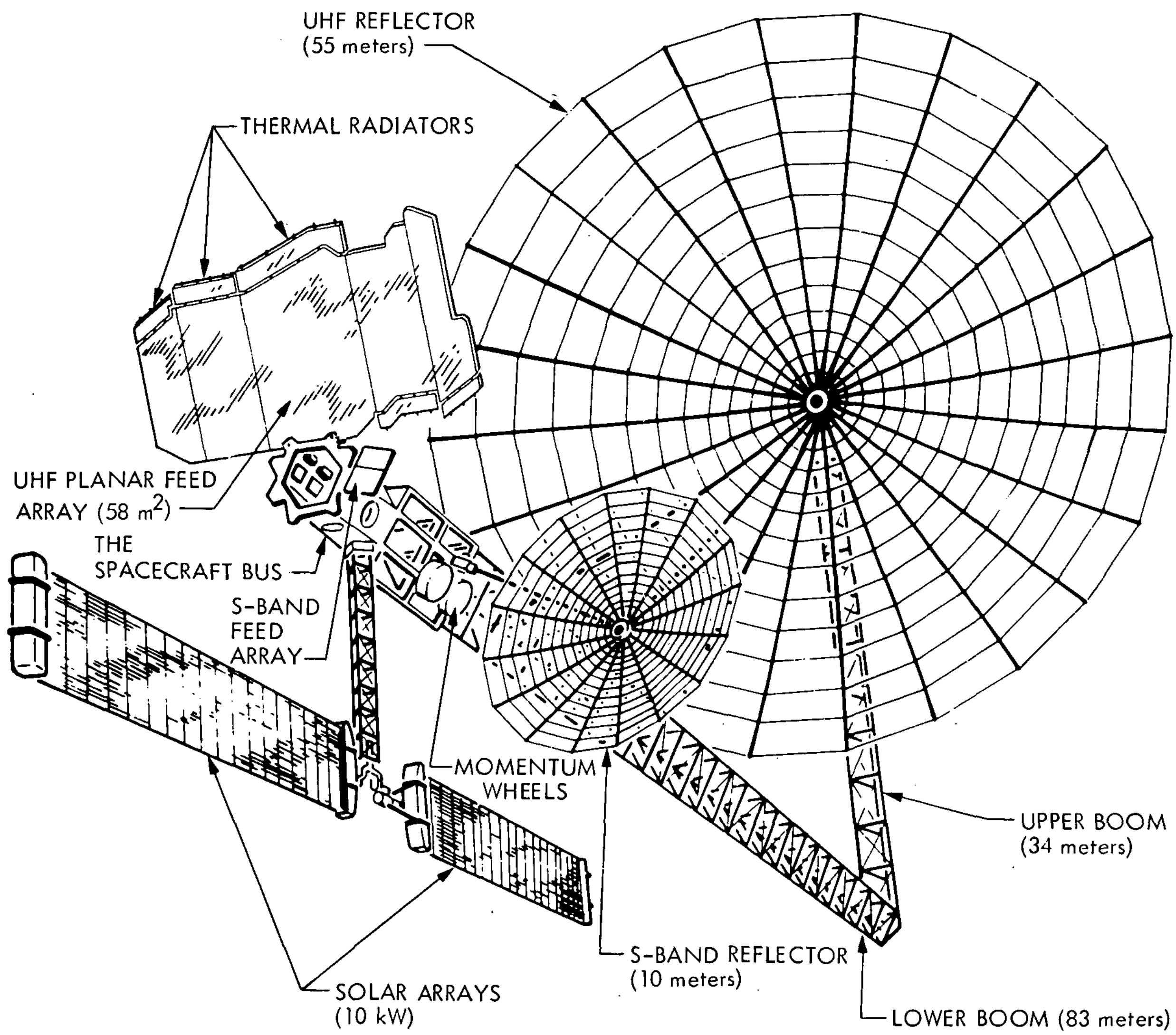


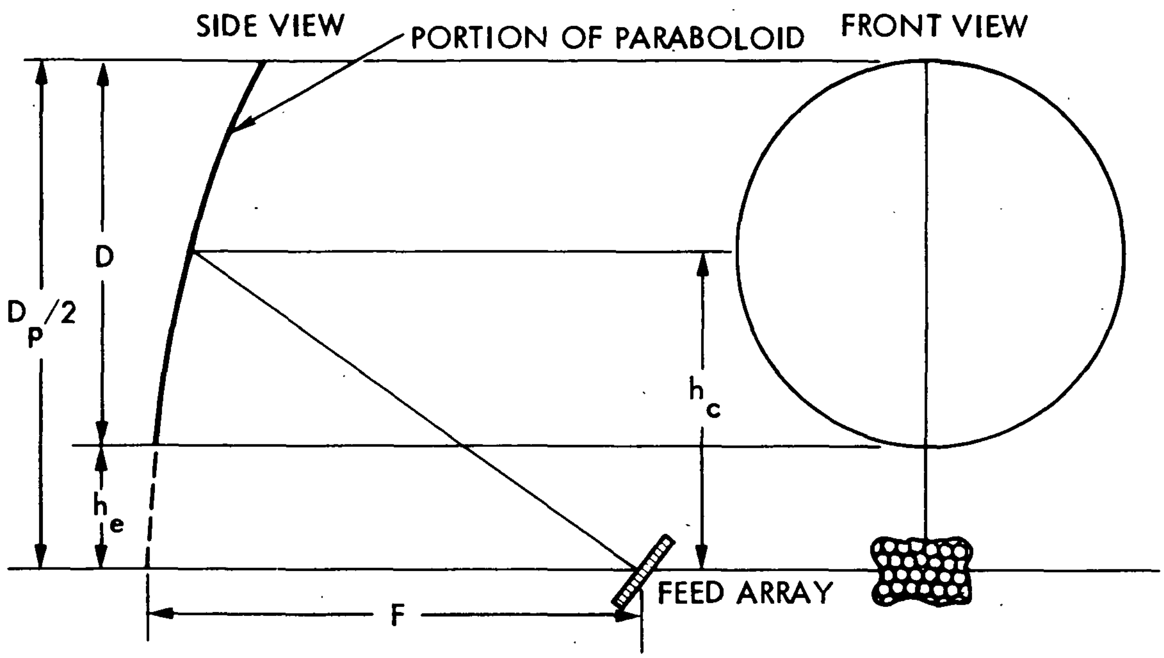
Figure 9. A Conceptual Drawing Depicting MSAT

UHF Antenna Geometry

The large 55-m UHF antenna is the most striking feature of MSAT. The selected antenna consists of an offset-fed wrap-rib mesh deployable reflector whose geometry is summarized in Table 2 and Fig. 10.

Table 2. UHF Direct-Fed Offset Reflector Antenna Parameters

Parameter		Value
N,	Number of Beams Covering CONUS	87
θ_B,	Cross-Over Beamwidth	0.45°
D,	Offset Reflector Diameter	55 m
D_p,	Parent Paraboloid Diameter	123 m
F,	Focal Length	82.5 m
h_e,	Reflector Edge Offset Height	6.5 m
h_c,	Reflector Center Offset Height	34 m
F/D_p		0.67
Latitude and Longitude of Central Beam on the Ground		37° N, 96° W
Maximum Scanning in East-West Direction		±8 BW
Maximum Scanning in North-South Direction		±4 BW



DEFINITION OF PARAMETERS:

F	FOCAL LENGTH OF THE REFLECTOR
D	REFLECTOR DIAMETER (DIAMETER OF THE CIRCULAR PROJECTED APERTURE)
D_p	DIAMETER OF THE GENERATING (PARENT) PARABOLOID
h_c	OFFSET DISPLACEMENT (HEIGHT) OF THE CENTER OF THE REFLECTOR APERTURE
h_e	OFFSET DISPLACEMENT (HEIGHT) OF THE LOWER EDGE OF THE REFLECTOR

Figure 10. Basic Geometrical Parameters of an Offset-Fed Single Reflector Antenna System

Overlapping Cluster Feed Concept

Successful design of a multiple beam antenna is predicated on the ability to provide adequate interbeam isolation for beams that operate on a common frequency band. For the LMSS, it is envisioned that a 17-dB net carrier-to-interference ratio is necessary (C/I is a frequently used index of isolation). The design presented here provides 27 dB C/I under idealized conditions in the satellite-to-mobile link. Thus, a 10-dB margin is provided for such degradation factors as the distortion of the reflector surface, dynamic misalignment of the feed and reflector, and the effect of uplink interference.

Achieving such stringent interbeam isolation requires RF patterns with very low sidelobes so as to minimize spillover from one beam to another. In turn, producing RF patterns with low sidelobes (-35 dB) requires physically large feed apertures which leads to the problem of feed packing as demonstrated in Fig. 11(a) and explained below.

If the footprints of adjacent beams on the coverage area are to crossover at approximately -3 dB power levels, then the associated feed elements producing these beams must be separated on the antenna focal plane at a distance not exceeding d_f as shown in Fig. 11(a). On the other hand feed elements needed to produce low sidelobe RF patterns have large physical aperture with diameter d much larger than available interfeed spacing of d_f.

The feed packing problem can be solved if each feed is composed of several smaller feed elements, some of which are shared by feeds of an adjacent beam. Figure 11(b) shows a 7-element cluster configuration where each beam is produced by a cluster of seven feed elements with four elements being shared by the cluster producing the adjacent beam.

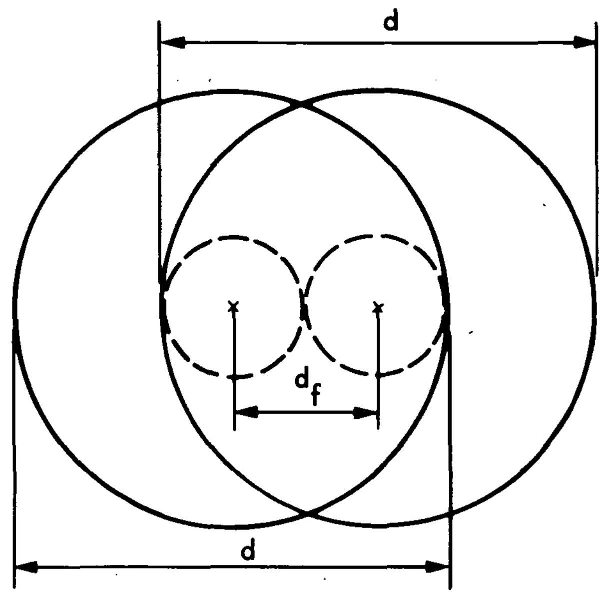


Figure 11(a). Two Overlapping Single Feeds (Physically Impossible). (The Dashed Circles Represent the Largest Physically Acceptable Single Aperture Sizes)

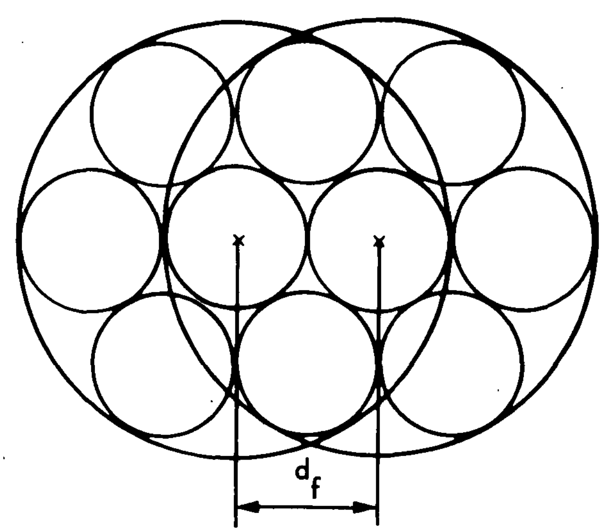


Figure 11(b). Two Overlapping 7-Element Cluster Feeds (Four Common Elements)

UHF Feed Array

Using the overlapping 7-element cluster feed concept discussed on the previous page, 134 feed elements are needed to produce the 87 UHF beams. Figure 12 shows this feed array where the small circles denote the aperture of each feed element. The boundary of CONUS is also superimposed on the same figure in order to show the correspondence between the feed elements and the area for which they provide coverage.

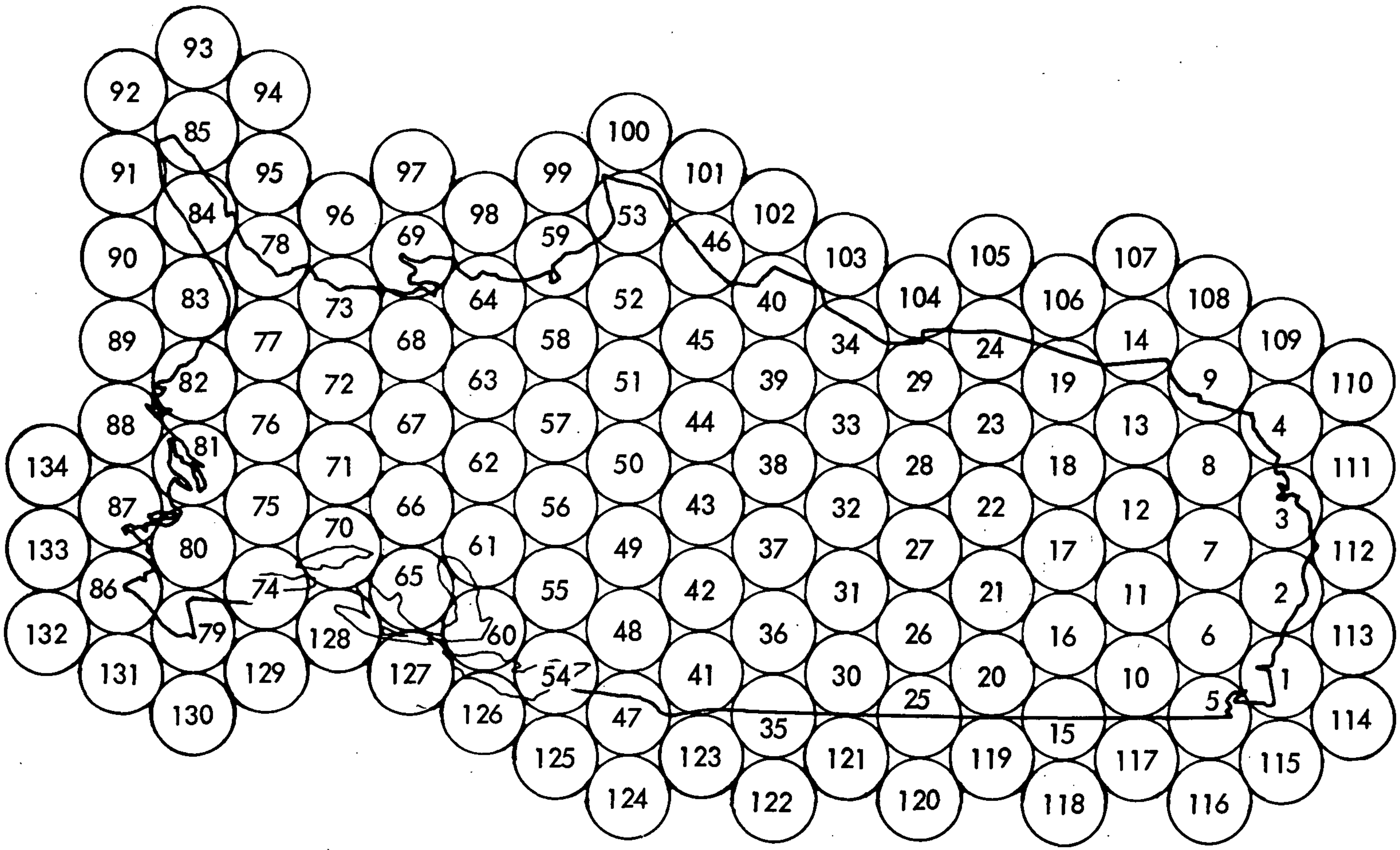
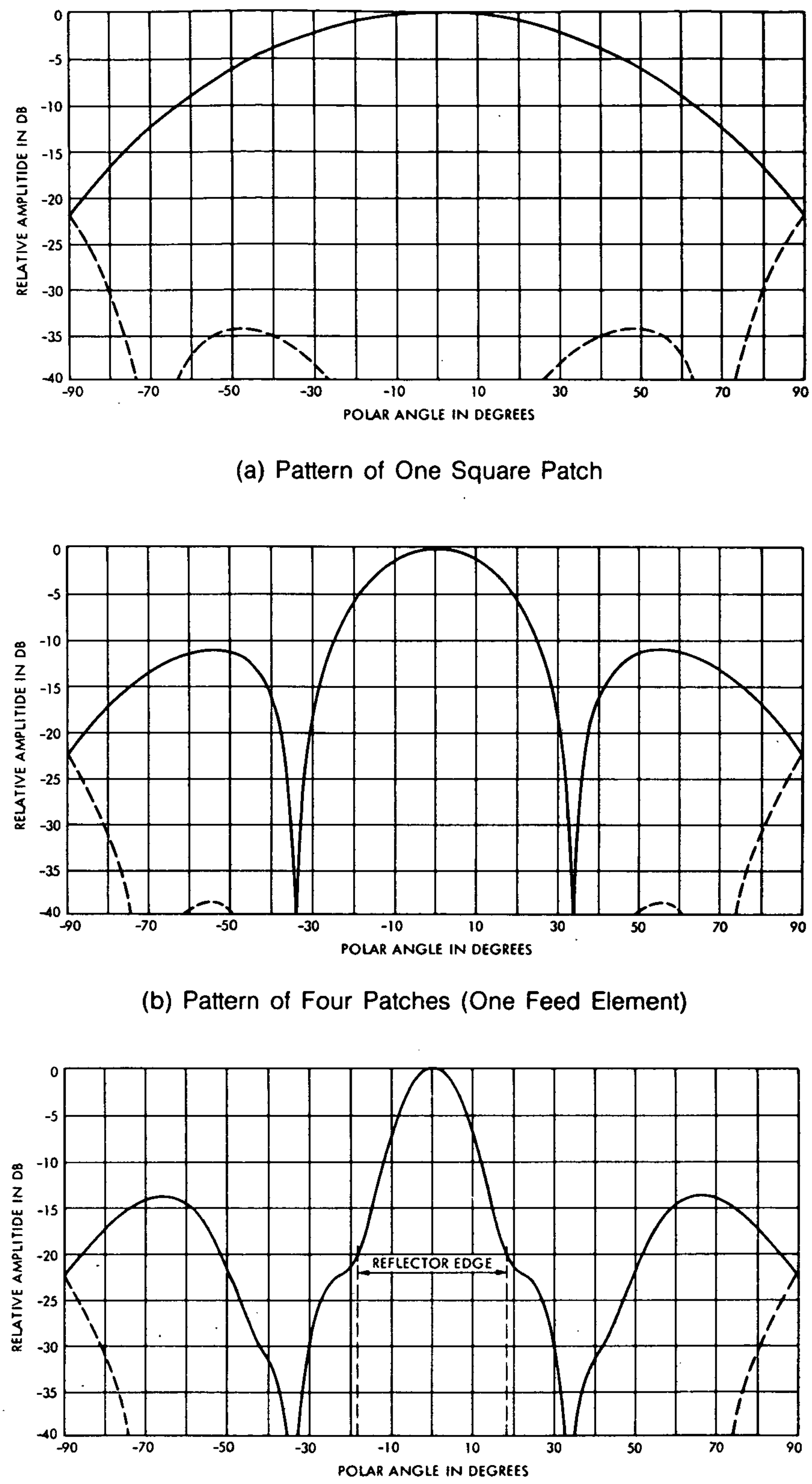


Figure 12. Feed Array Layout With a 7-Element Cluster Feed Arrangement. Each Circle Represents a Feed Element

Cluster Feed RF Pattern

The design presented here employs microstrip patch elements to realize the UHF feed array. Each of the 134 feed elements shown on the previous page is composed of four square microstrip patches. The choice of the microstrip patch has been based on the compactness which enables the stowage of this feed array within the allowable volume of the Shuttle cargo bay.

Figure 3-13(a) shows a typical far-field pattern cut of a single circularly-polarized patch. Figure 3-13(b) shows the pattern of four such patches, uniformly fed, that form an element of the 7-element cluster. Seven such 4-patch elements are used to produce a cluster pattern which is shown in Fig. 3-13(c). The progressively increasing taper in Fig. 13(a,b,c) is quite evident. These patterns were produced with the power levels of the six outer elements of a cluster equal and 13.5 dB below the center element. The far-field RF pattern for the antenna were also calculated and it was shown that patterns with -35 dB sidelobe were achievable.



(a) Pattern of One Square Patch

(b) Pattern of Four Patches (One Feed Element)

(c) Pattern of a Cluster of Seven Elements (28 Patches)

Figure 13. Far-Field Patterns (in Offset Plane) of Circularly-Polarized Feed Elements. (Dashed Curves Represent Cross-Polarized Component)

Frequency Reuse Plan

In a multiple beam frequency reuse antenna system, the total allocated frequency band is subdivided into a number of smaller sub-bands each of which is assigned to a particular beam. As shown in Fig. 14, beams which are sufficiently apart are assigned the same frequency sub-band and in this way the total allocated bandwidth is reused several-fold.

Figure 14 shows a 7-frequency reuse plan where a total of seven sub-bands are reused amongst the 87 UHF beams. In this figure, if beam 71, as an example, is taken to be a reference beam, then all beams shown as hatched represent cochannel beams (i.e., beams operating on the same frequency band as beam 71). The sidelobes of these beams in the direction of beam 71 must be kept low to limit the interference.

It must also be pointed out that polarization isolation (i.e., some cochannel beams being right circularly-polarized and some left circularly-polarized) can be used to either improve the beam isolation or conversely increase spectrum efficiency. However, the latter is possible if the orthogonally polarized beams have low levels of cross polarization. Since at this time the ability of microstrip elements to produce these low cross-polarization levels cannot be ascertained, the baseline design presented here is based on the use of single polarization. An alternative system based on polarization diversity is presented in an appendix of Part II of this report.

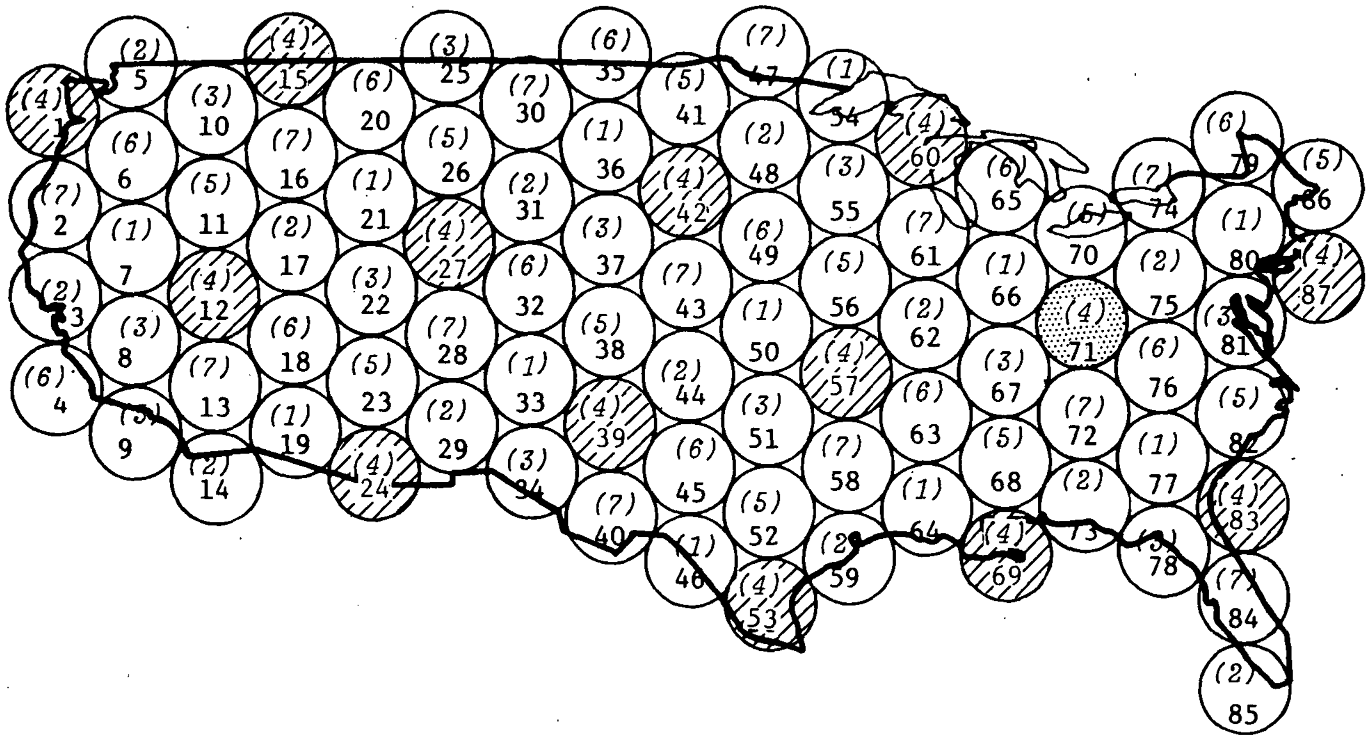


Figure 14. Layout of 87 Beams Covering CONUS With 7-Frequency Reuse Arrangement. Numbers in Parentheses Designate Frequency Assignments

Beam Isolation Performance

Following the frequency reuse plan outlined on the previous page, a contour plot of I/C (interference-to-carrier ratio) levels at beam 71 is obtained and shown in Fig. 15. It can be observed that anywhere within the footprint of beam 71 (the inner circle) the C/I is better than 27.5 dB. This calculation is for the satellite-to-mobile link and assumes a perfect antenna (i.e., no surface distortion, proper feed dish alignment, etc.) and idealized conditions. Beam 71 was chosen to illustrate beam isolation performance because it is one of the worst affected by interference.

Allowing a 10-dB margin for various degradation factors (further study is required to quantify the effect of these factors) the net achievable C/I should still exceed the required 17 dB, as illustrated in Fig. 15.

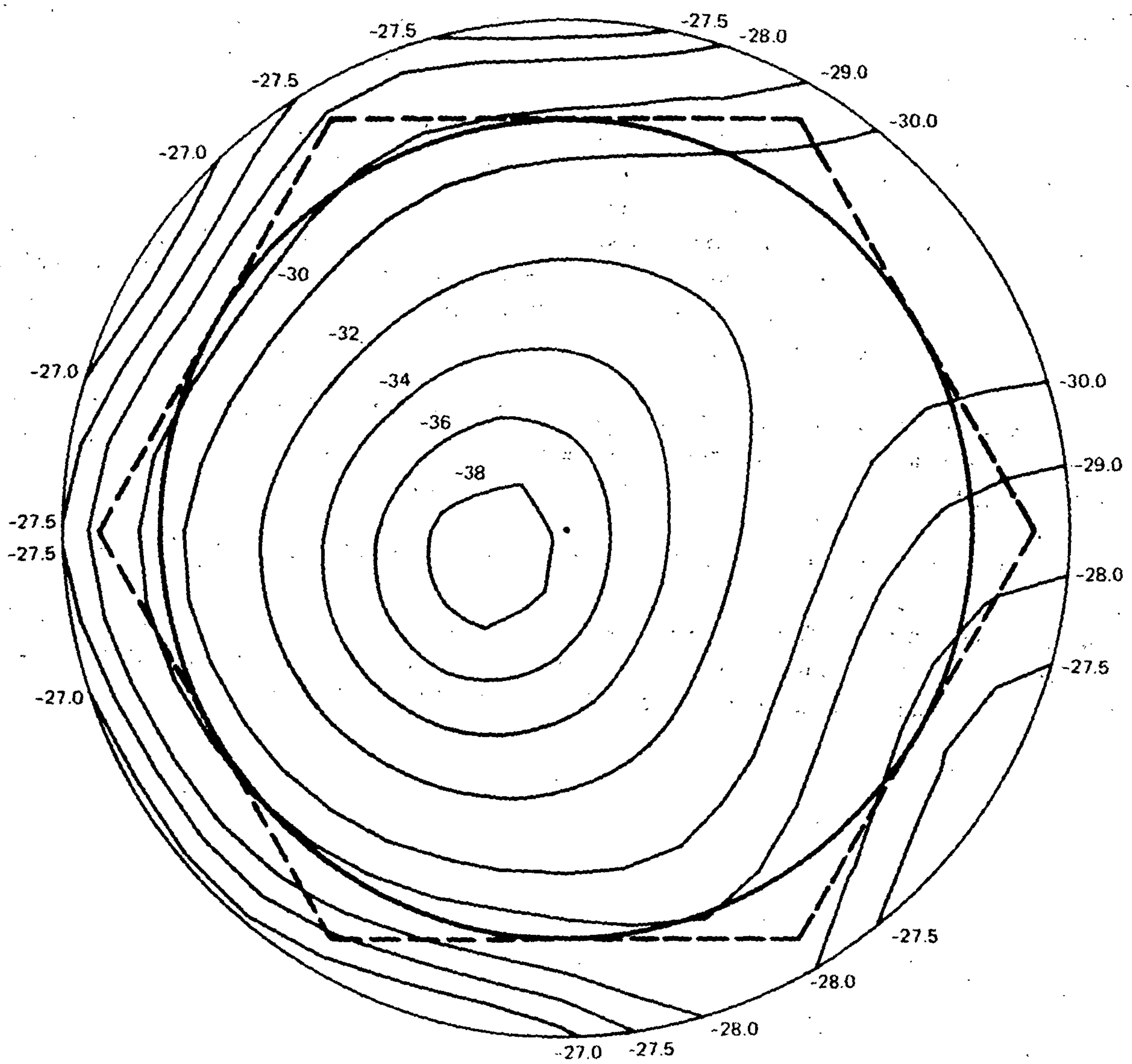


Figure 15. Contour Plot of I/C (Interference/Carrier) Levels at Beam 71 (the Inner Circle)

Beam Forming Network

It has been mentioned that with the overlapping cluster feed concept, the number of feed elements required exceeds the number of beams formed. For example, 134 feed elements are needed to form 87 UHF beams. Proper excitation of these elements requires a network of power dividers and power combiners which is normally referred to as the Beam Forming Network (BFN). A block diagram of the MSAT RF subsystem is shown in Fig. 16 indicating that four beam forming networks (one each for transmitting and receiving at UHF and S-band) are required. Using the beam forming network number 2 as an example, the general function of BFN is an 87 to 134 mapping where the signals intended for the 87 beams are routed to the 134 feed elements. More specifically, the role of this BFN is two-fold:

a) The signals intended for a given beam must be divided seven ways, not necessarily all equal, and each portion is to be routed to one of the seven elements in the cluster which produces that beam.

b) Since most of the feed elements contribute to the formation of more than one beam, the signals from each of the beams associated with a given element must be combined before being routed to that element. It should be mentioned that some feed elements contribute to the formation of as many as seven beams.

The problem, then, is how to connect a beam port of the BFN to the 7-element cluster associated with that beam and conversely how to connect each feed element to, and up to, the seven different beam ports with which that element is associated. It is the purpose of the BFN to fulfill this requirement.

The challenge in designing and implementing the BFN is to make it light and compact. The design used for MSAT uses stripline technology in an innovative manner to combine the functions of beam forming network 2 and 3 in one multilayer network colocated with the UHF planar array. Similarly, beam forming network 1 and 4 are combined to form another network colocated with the S-band planar feed array. A cutaway drawing showing the detail of this multilayer assembly appears later in this report.

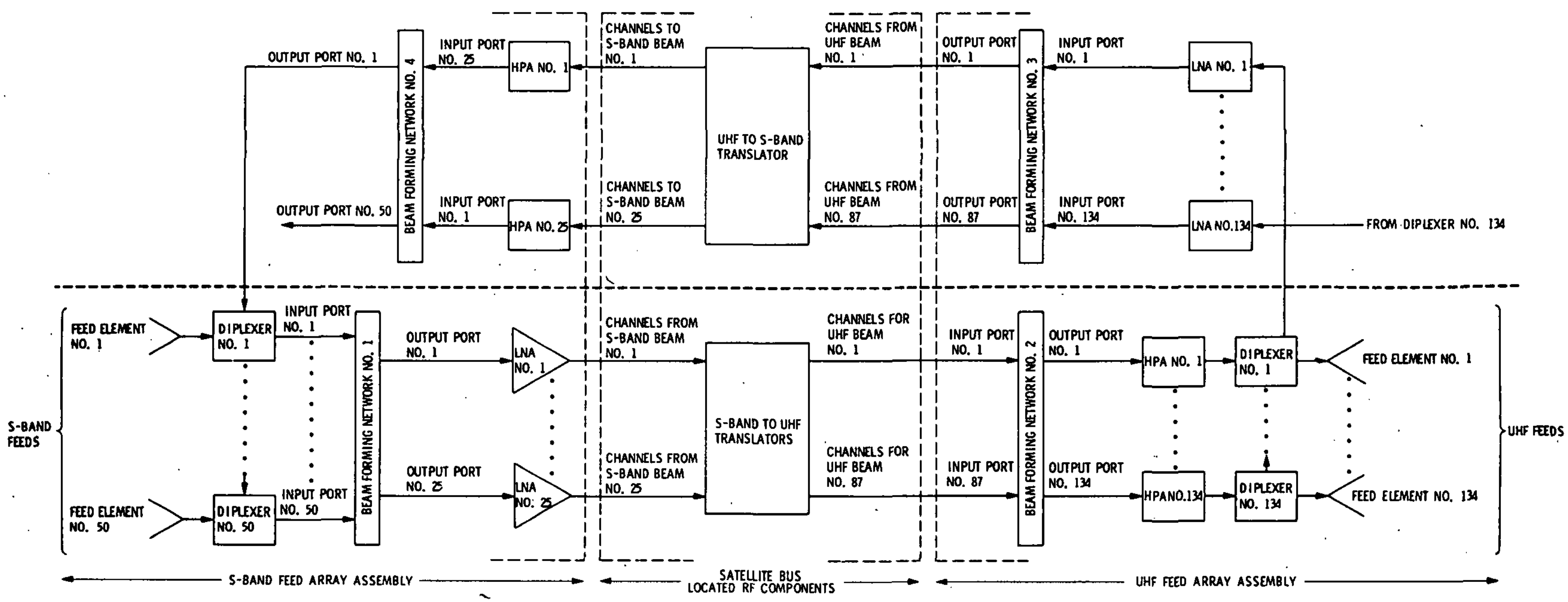


Figure 16. Simplified Block Diagram of the RF Subsystem

LMSS Link Budget

There are four distinct links in the LMSS: mobile user-to-satellite, satellite-to-mobile user, base station-to-satellite, and finally, satellite-to-base station. The satellite-to-mobile user link is the most critical of the four links since it establishes power, thermal, and RF subsystem requirements for MSAT. Over this link, MSAT provides direct-to-the-user service and as such must communicate with small mobile antennas and fairly simple transceivers. This then establishes the first constraint in designing the telecommunication links for MSAT. The mobile antenna is small and because the vehicle constantly moves about, the antenna must be omnidirectional in azimuth and may have only a marginal gain in the elevation (maximum of 5 dB in the present design).

The above characteristics of the mobile antenna give rise to another problem, namely fading. Typically, a mobile receiver encounters two types of propagation anomalies: (1) direct path wave attenuation due to obstructions such as structures, hills, etc., which is known by the term "shadowing," and (2) reflected and delayed waves simultaneously arriving at the receiver from different directions, known as "multipath fading," because the multiplicity of waves tend to add or subtract in a time-varying fashion.

To maintain acceptable performance, the satellite-to-mobile link must have sufficient margin to allow for fading. This margin would be substantially higher if in addition to fading, shadowing is also to be considered. However, due to the severe penalty that such a margin would impose on the MSAT power requirement, and since MSAT's primary coverage is in the rural area which presumably is void of too many man-made structures, the shadowing margin has not been included in the MSAT link design tables. The fading margin is set at 5 dB.

Figure 17 summarizes the main features of the LMSS telecommunication links. It should be noted that each UHF channel requires an average of 240 mW assuming that the system employs Voice Operated Switching (VOX). Using VOX, voice carriers are turned off when speech is not present (about 60 percent of the time) and this results in a 4-dB power saving on the satellite.

While the RF power-per-UHF channel is a rather small 240 mW, since the system has over 8,000 channels, the total MSAT RF requirement is in excess of 2 kW. Optimistically assuming 50 percent efficient linear UHF amplifiers, the total beginning-of-life prime power for MSAT must be approximately 10 kW which can be obtained from two solar array panels of 4 by 9 m.

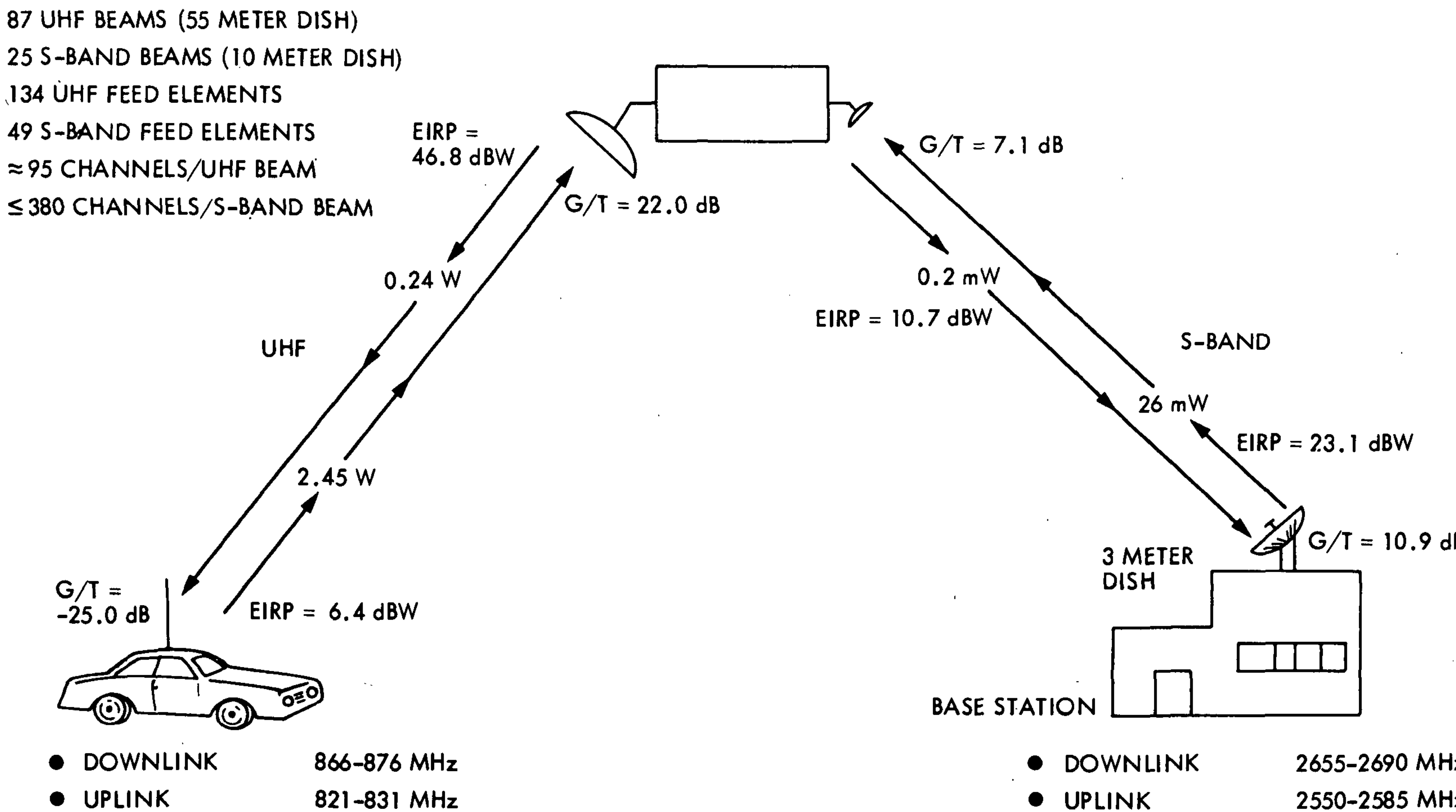


Figure 17. Summary of the Telecommunication Link Parameters

UHF Feed Thermal Hardware

The MSAT UHF feed array proposed in this report has an overall RF power output of approximately 2 kW. This power is produced by 134 amplifiers, one each per feed element. Assuming 50 percent efficiency, the solid state power amplifiers dissipate approximately 2 kW of waste heat with the heat source physically distributed over the approximately 58-m^2 area of the feed array.

Each feed element is supported by an electronic module, which in addition to the power amplifier contains a diplexer and a low-noise amplifier. The thermal requirement of the UHF feed array is to maintain the electronic module's temperature at 25° C ±15°, and additionally, the dimensional thermal stability of the feed array panel surface must be held within 7 mm rms (corresponding to a 5-degree phase error in the RF radiation).

The thermal hardware should be selected so as to minimize the overall weight. The MSAT feed array thermal design considered two basic heat rejection approaches (Fig. 18), local and remote radiators. In the local radiator approach, separate radiating surfaces are installed on the back of the feed panel at each of the power amplifier locations. In the remote approach, the waste heat is transported to radiators mounted on the edge of the feed panel capable of rejecting to space from both sides. The selection between these two approaches must consider the total weight of the radiator and heat transport network. It can be shown that under the worst-case orbital environment, the single-sided local radiator requires six times the area of the remote radiator.

Thus, it was determined that even though in the remote radiator concept a mechanism is required to transport the wasted heat from the source to the remote radiator, the total hardware weight is still considerably less than the local radiator concept. The heat transport mechanism selected for MSAT uses heat pipes which carry the waste heat from the 134 power amplifiers to the thermal radiators located at the edge of the UHF feed array assembly.

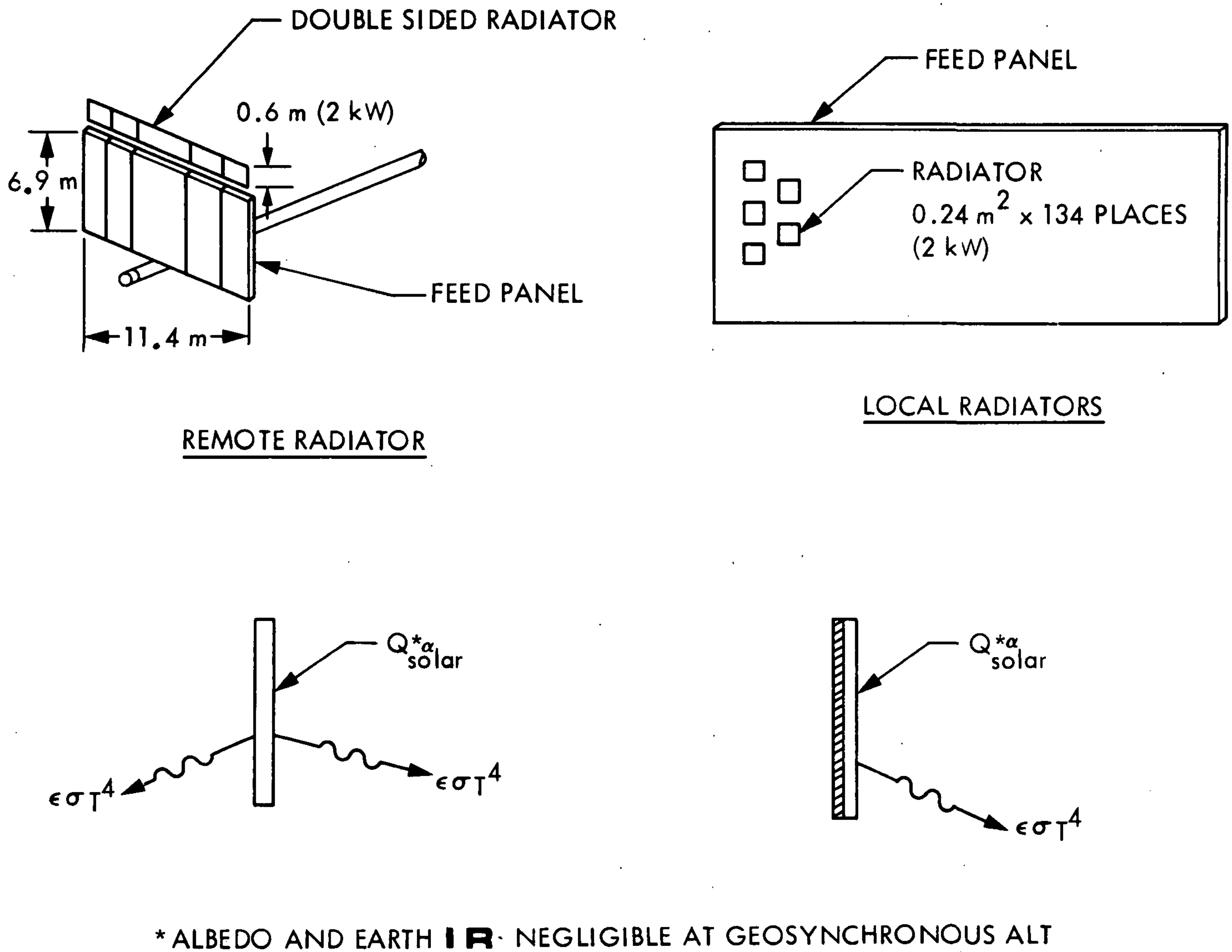


Figure 18. The Remote and Local Thermal Radiator Concepts for the MSAT UHF Feed Array

UHF Feed Array Assembly

The UHF feed array assembly is located at the focal point of the MSAT UHF reflector. It is supported by a short boom hinged to the MSAT bus structure near the electronics bus. Figure 19 shows a view of the face of the feed array assembly. As shown, the assembly is 6.9 by 11.4 m. A structure of this size will not fit within the Shuttle orbiter's cargo bay envelope and therefore must be folded. After allowance is made for other satellite components that must also be stowed, the feed assembly must be folded into five parts. The stowage requirement necessitates that the feed assembly not exceed 25 cm in thickness. Figure 19 shows the manner in which the feed assembly is broken down into the five panels and folded in the stowed condition. The circles in this figure schematically show the location of the 134 feed elements. Thermal radiators are shown at the ends of the panels and are used to dissipate the excess heat from power amplifiers located in the feed assembly structure.

The feed array assembly includes the following major subassemblies: the feed elements; the beam forming network; the RF electronics which include the power amplifiers, low-noise amplifiers, and diplexers; and the thermal control system.

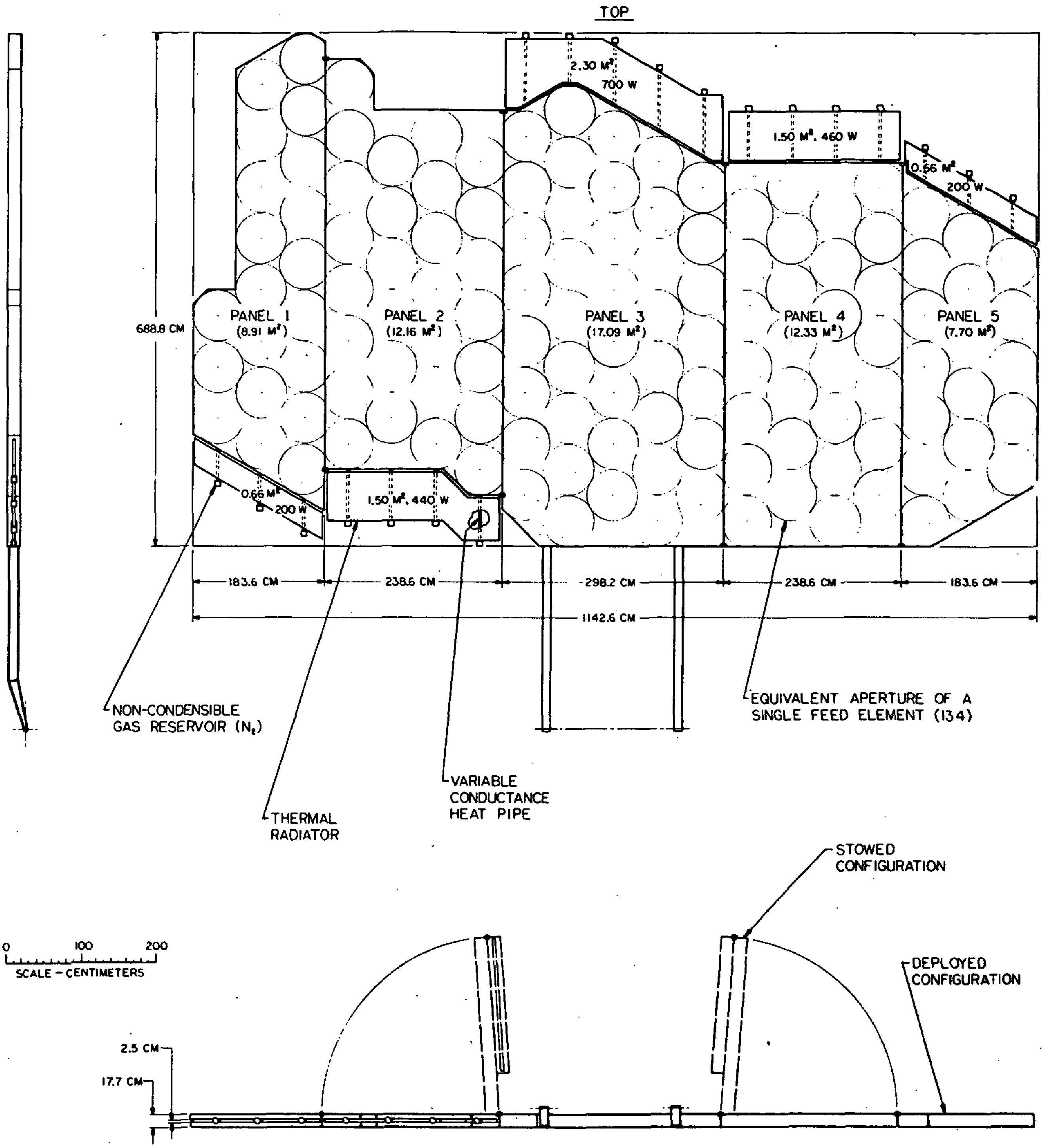


Figure 19. LMSS Feed Panels and Thermal Radiators

UHF Feed Array Assembly (Cont.)

Figure 20 shows a 3-dimensional cutaway drawing of the feed array assembly showing the interrelationship of each major subassembly. A brief description of the overall structure follows.

The top layer contains the feed elements. Each feed element consists of four microstrip square patch subelements which can easily be seen. The feed layer consists of foil patches supported by a fiberglass skin which in turn is separated from a ground plane by a 1.8-cm-thick honeycomb.

Next, there is a 2.5-cm-thick honeycomb isolating layer separating the feed layer from the beam forming network. The beam forming network consists of two back-to-back microstrip boards each constructed of 0.32-cm-thick honeycomb dielectric and covered with 0.013-cm-thick fiberglass printed circuit board skins. Another 2.5-cm-thick honeycomb isolating layer separates the beam forming network and the transmission line layer. The transmission line layer, also made of printed circuit board skins and honeycomb, connects the individual beam ports on the beam forming network to cables at the lower edge of the feed array assembly, which in turn connect to the bus located electronics.

Due to the honeycomb and face skin technology utilized for the above panels and the way the above panel layers are bonded to each other, a strong and rigid structure is formed. However, an additional structure is needed to tie the panels to the satellite structure and to support the RF electronics. This additional structure is shown just below the panels and consists of a series of channels which run parallel to the panel hinges or along the height of the overall feed assembly. Mounted between the channels are the power amplifiers, low-noise amplifiers, and diplexers. The amplifiers are connected via a heat sink to heat transfer pipes, which run alongside some of the channels and transport the waste heat to remote radiators located at either end of each feed assembly panel.

The last layer consists of a thermal blanket that covers the backside of the feed array assembly. A hinge joint is also shown in the figure. Not shown, but an important consideration, are the cables or flexible microstrip boards that are required to provide continuity in the beam forming network across the panel hinge lines.

The final feed array assembly thickness is 18 cm so the assembly can easily be accommodated within the 25-cm allocation as dictated by space limitations of the Shuttle.

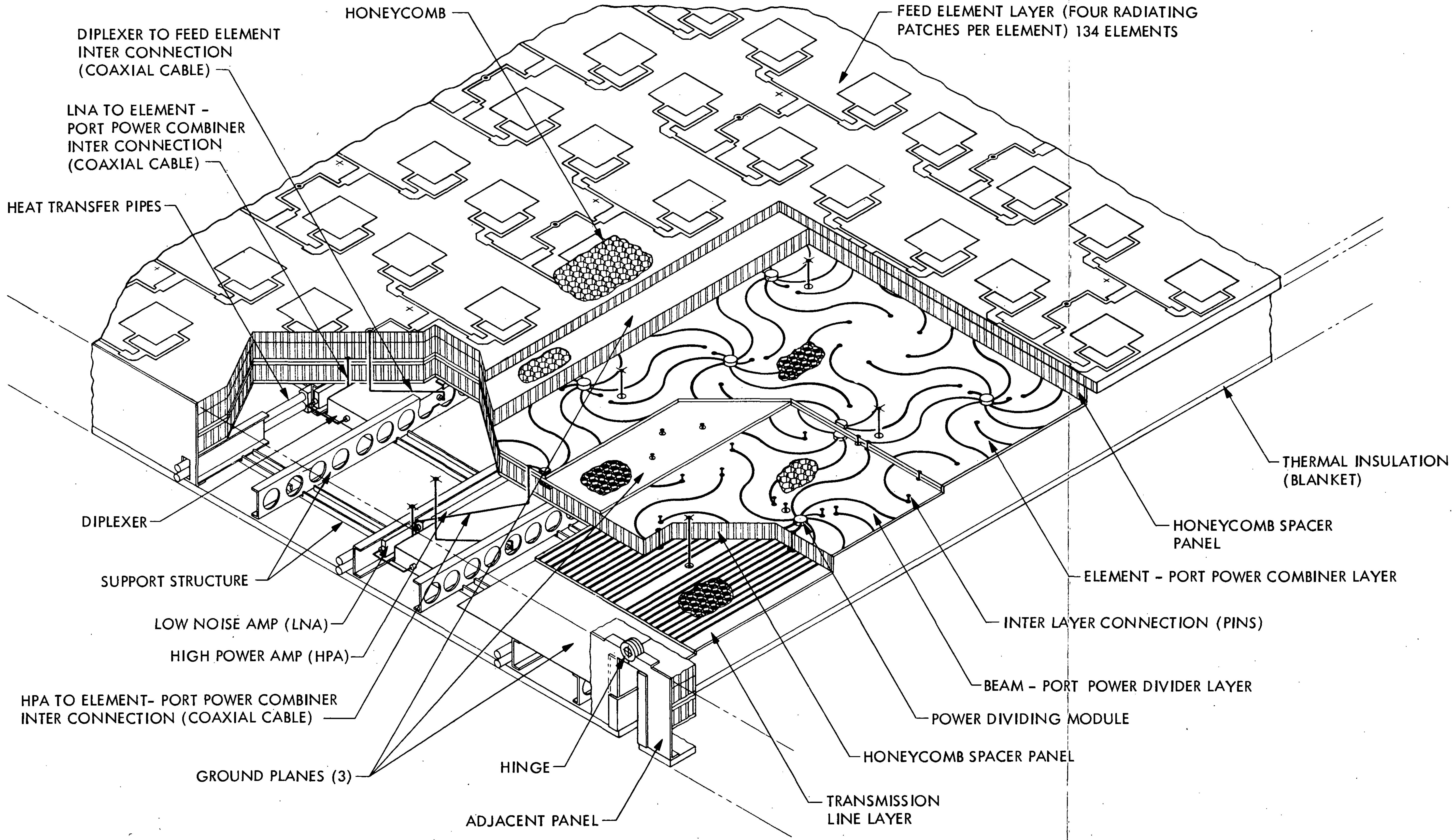


Figure 20. LMSS UHF Feed Array Assembly (Cutaway Showing Subassemblies)

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UHF Feed Array Assembly Mass Summary

As discussed in the last few pages, the UHF feed array assembly houses much more than just the radiating elements. Many electrical components normally housed in the satellite bus are colocated with the feed array assembly. Accordingly, this structure constitutes a considerable percentage of the total MSAT mass. The mass breakdown for the feed assembly is given in Table 3 below.

Table 3. UHF Feed Array Assembly Mass Summary

Item	Mass, kg	
Radiating Elements		113
RF Electronics		305
Power Amplifiers	122	
Low-Noise Amplifiers	31	
Diplexers	152	
Beam Forming Network		244
Cables		120
RF	61	
DC	59	
Thermal Control Hardware		232
Heat Radiators	72	
Heat Transfer Pipes	69	
Heat Sink Flanges	91	
Structure		156
Total		1170

UHF Antenna Structure

The most imposing feature of MSAT is its large UHF antenna which consists of the planar feed array (6.4 by 11.9 m), the reflector (55 m) and an L-shaped boom (83 by 34 m) connecting the reflector to the satellite bus (see Fig. 9). The structure of the feed array has already been discussed on the previous pages. The structure of the reflector and the supporting mast (sometimes referred to as the feed support structure) is now discussed.

The MSAT design presented in this document uses the wrap-rib antenna concept. The best known application of this antenna is probably the ATS-6 spacecraft, which used a 9.1-m parabolic axisymmetric reflector operating up to 8 GHz. However, the ATS-6 antenna used aluminum ribs, conventional thermal blankets, and copper-plated dacron mesh, which represents about a 15-year-old technology.

The reflector structure for both axisymmetric and offset-fed wrap-rib antennas consists of the ribs, hub assembly, and mesh (see Fig. 21). The ribs for the offset reflector are based on graphite epoxy technology because of (1) improved thermal and stiffness properties as compared to aluminum (which was used on the ATS-6), and (2) the level of maturity of this technology. The cross section of the ribs will be full lenticular, the shape required for the larger size antennas.

The mesh will be 2-bar, tricot knit, gold-plated molybdenum wire. This wire was selected because of its relatively low stiffness. This characteristic will accommodate the 2-directional tension field, while the antenna experiences large thermal changes, without imparting a large load to the rib structure or developing wrinkles in the RF reflective surface.

The deployable L-shaped mast structure (see Fig. 9) represents a new technology development and is being pursued under the NASA LSST (Large Space Structure Technology) program. Preliminary studies have indicated that the cross section of this boom (an equilateral triangle) should be limited to 2.41 m (95 in.) on each side for Shuttle stowage of MSAT.

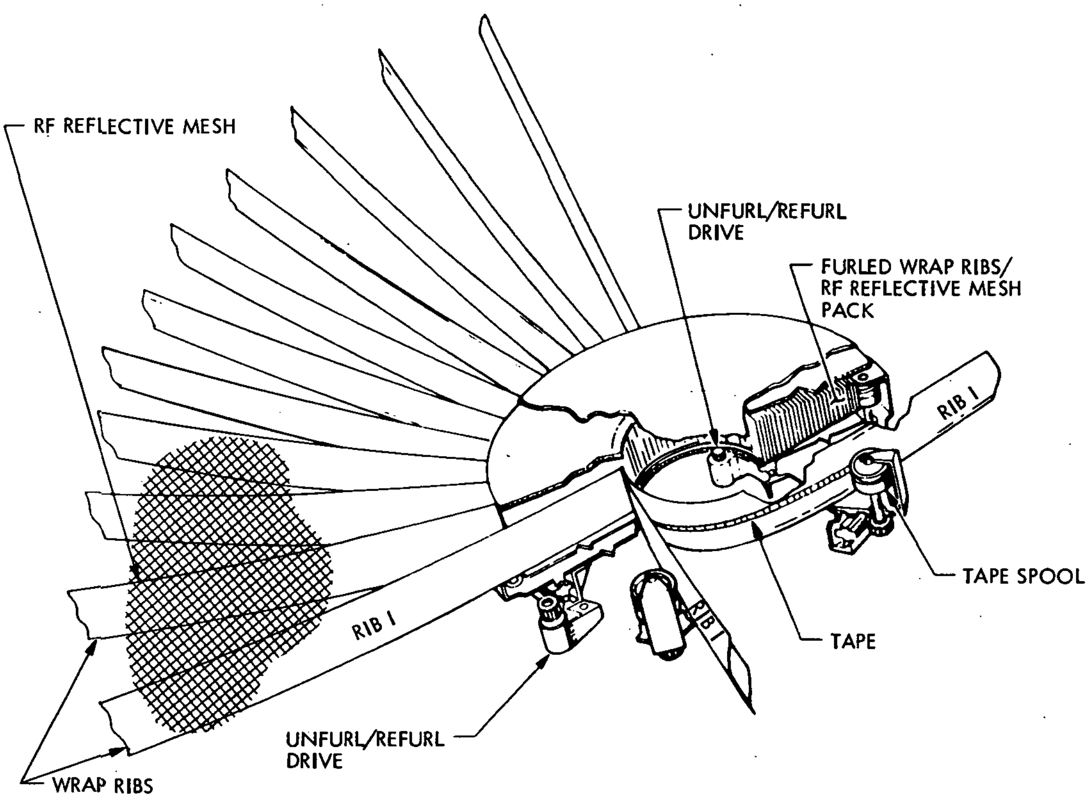


Figure 21. Wrap-Rib Reflector Concept

MSAT Deployed Configuration*

Figure 22(a,b) provides two views of MSAT in the deployed configuration. In Fig. 22(a), V_p is the vertex of the parent UHF paraboloid reflector and F is the focal point. The longer boom is aligned with the local vertical which is 6 degrees from the antenna boresight. (In the nomenclature used here, the antenna boresight is defined to be the same as the boresight of the central UHF beam which is aimed at the center of the coverage area.) The UHF reflector offset height (6.5 m) is selected so as to provide an unobstructed path not only for the central beam but also for the southern-most scanned beam whose boresight is roughly 2.5 degrees from the antenna boresight. This offset height insures that all the beams clear the top of the UHF feed array.

Figure 22(b) shows MSAT as viewed from Earth. Shown in this figure are the deployable solar arrays as well as the S-band feed and S-band reflector.

*Figures 22 and 25 on MSAT configuration and stowage are extracted from the results of a configuration study performed by the Boeing Aerospace Company under contract to JPL.

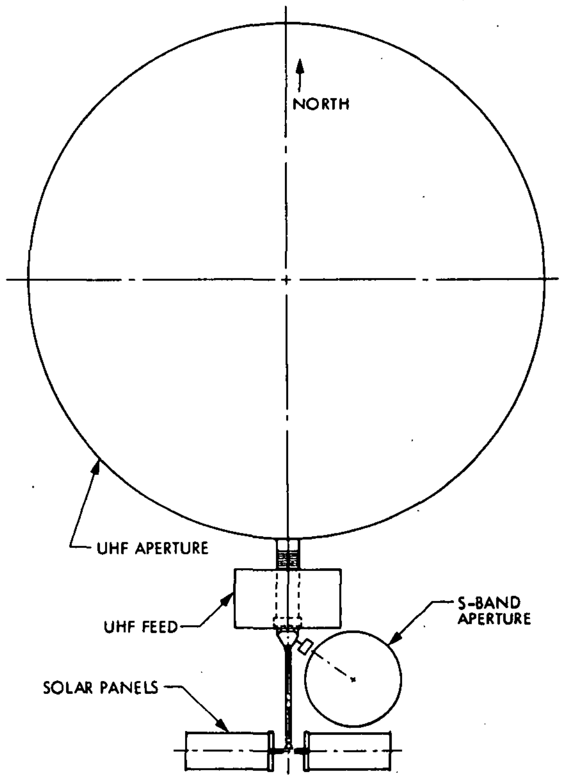


Figure 22(b). MSAT as Seen From Earth

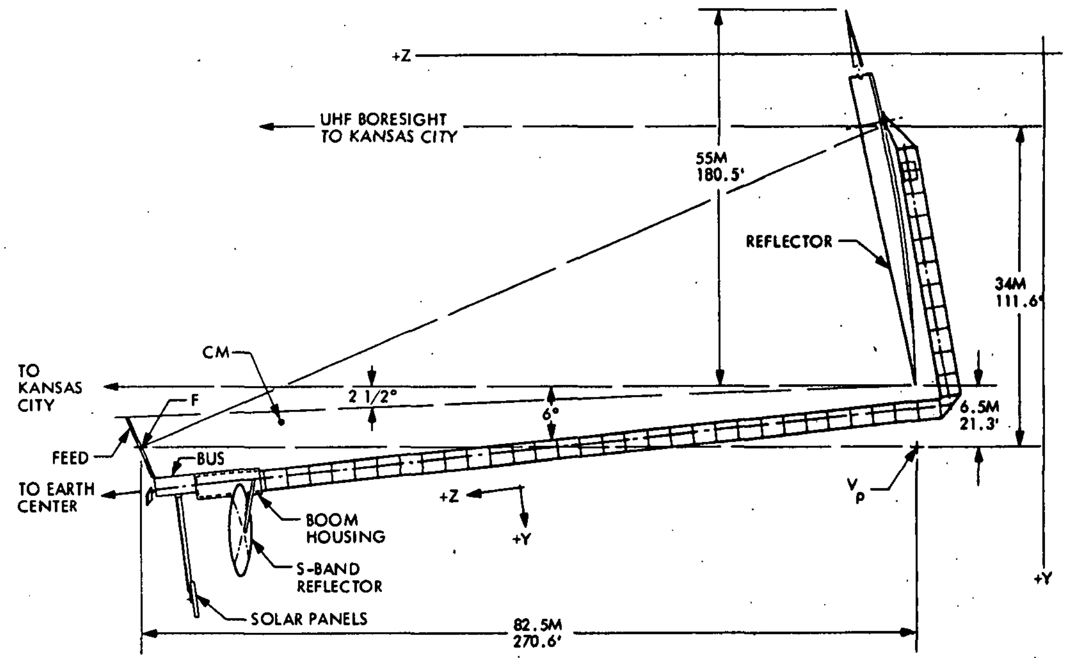


Figure 22(a). Side View of MSAT

MSAT Attitude Control

MSAT, with its massive feed, large booms and reflectors, and low structural frequencies, constitutes a large flexible spacecraft whose attitude control presents a challenge of unprecedented proportions. These challenges are met with an advanced control system design which combines state-of-the-art attitude control technology with emerging advanced control software and hardware technologies for in-orbit system identification, feed motion compensation, and distributed sensing and control, in order to achieve precise pointing and active vibration damping of this satellite.

The ACS design is shown schematically in Fig. 23. Fundamentally, the system makes use of distributed sensing and actuation to point and stabilize the antenna. Primary attitude control of MSAT is placed at the feed bus, and controlled to 0.02 degrees, using a high bandwidth gyro-based control loop which is nested within an attitude determination and gyro drift correction loop using star trackers. The reflector and the remainder of the structure are then stabilized and controlled with respect to the feed bus to an equivalent 0.01 degrees by means of (i) an optical dish sensor located at the feed, which monitors the motion of the reflector with respect to the feed, and (ii) 6 degrees-of-freedom (DOF) control actuators to provide forces and torques at the feed and at the hub. These six DOF actuators include three small fine-pointing reaction wheels (20 N-m-s) and three attitude control and stationkeeping jets (0.2-0.9 N thrust) at each location.

The optical sensor is also used to carry out the necessary alignment checkout and to perform the dynamic measurement required for in-orbit systems identification.

In addition to the small fine pointing wheels, three larger wheels are provided for disturbance management. These wheels are sized to allow 100 percent management of cyclic solar pressure torques, and partial management of gravity gradient and balancing torques with four momentum dumpings per day.

Total mass of the control hardware needed to implement the ACS design is 458 kg (1009 lb) of which 279 kg (615 lb) corresponds to ACS electronics, sensors and actuators, and 178 kg (394 lb) corresponds to propellant needed to combat gravity gradient and dynamic balancing disturbance torques. The average power requirement for the ACS subsystem is 260 W.

Technology developments are required in both control software and hardware for meeting challenges presented by MSAT. New design and analysis techniques are being developed to deal with high-dimensional dynamics, inevitable model errors, and in-orbit system identification. Development and demonstration of feed/reflector motion sensing and control are progressing under the LSST program. The optical shape/vibration sensor, which is required for the demonstration and implementation of feed/reflector motion sensing and control, must be developed. Other advanced control devices needed in the ACS design can be obtained via direct applications or moderate extensions of current hardware technologies.

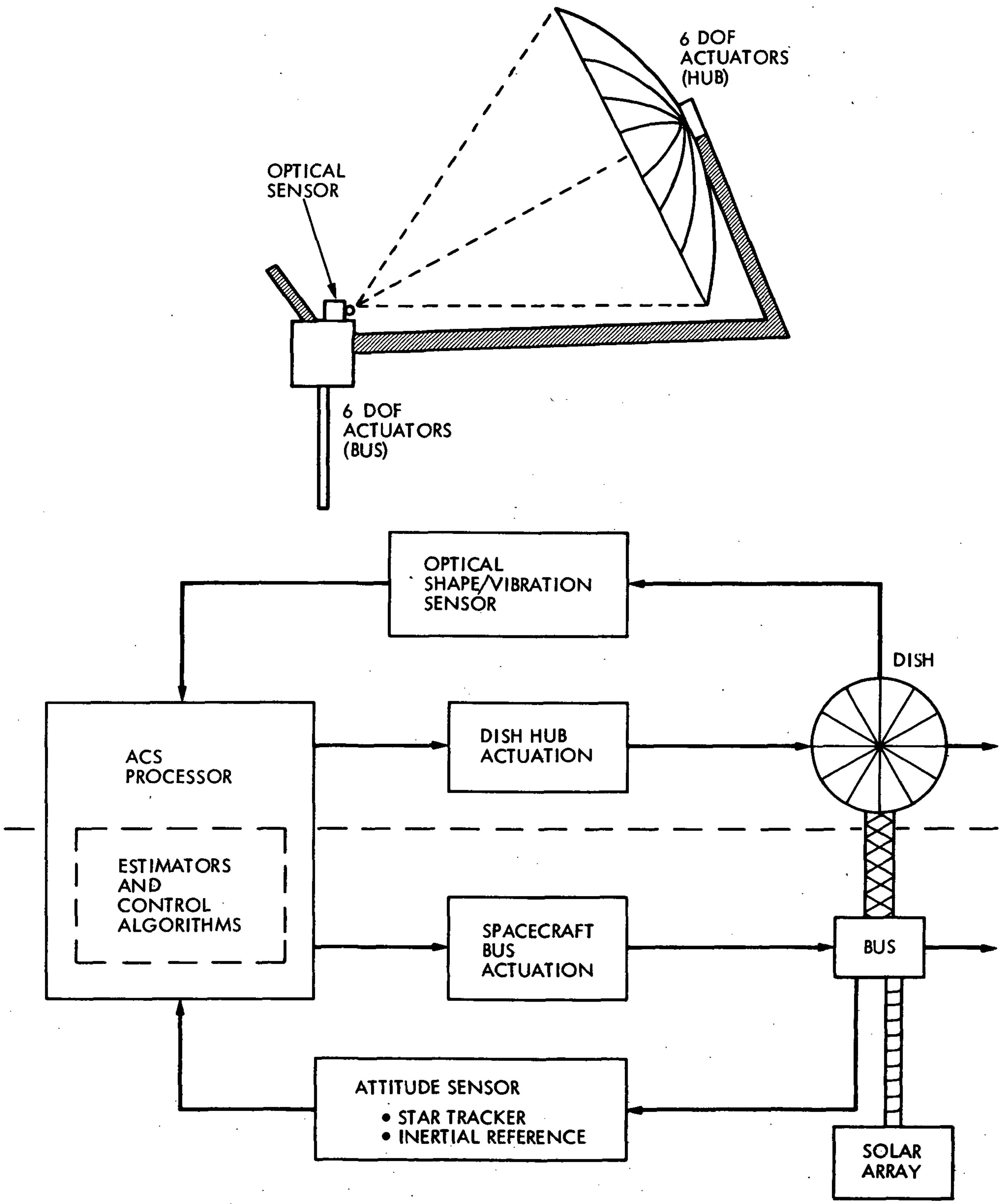


Figure 23. MSAT ACS Schematic Diagram

ATS-6 vs MSAT

Stowage of MSAT inside the Shuttle is a considerable challenge because of the volume limitation of the Shuttle's cargo bay and the large dimensions of MSAT. To put this in proper perspective, Fig. 24 shows a conceptual drawing of MSAT. Drawn to the same scale are the Shuttle and ATS-6 with its 9-m antenna which to date is the largest deployable satellite antenna flown in a nonclassified mission.

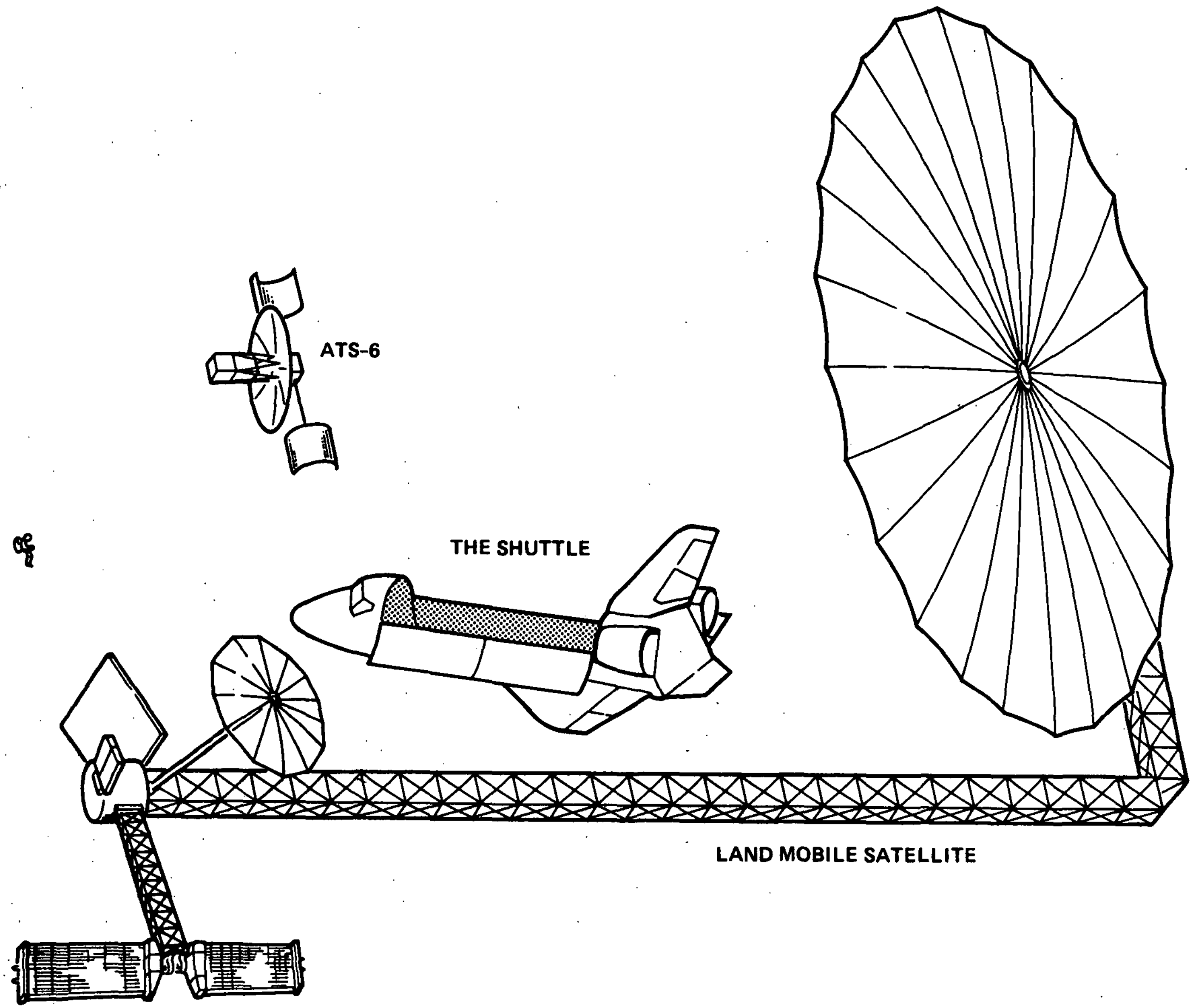
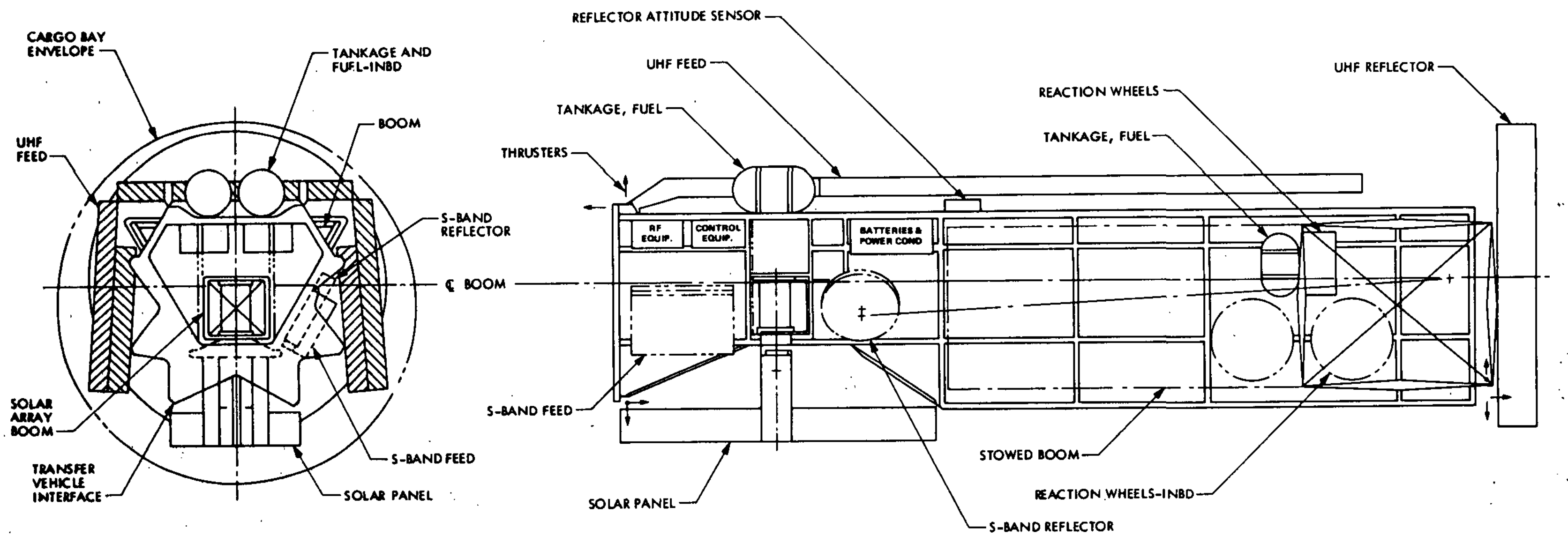


Figure 24. Scaled Drawing of MSAT, ATS-6, and the STS Shuttle

MSAT Stowage

The stowed configuration of MSAT not only must have a radial envelope which fits within the 4.57 m (15 ft) diameter of the Shuttle's cargo bay, but it must also be compact in the axial direction so as to allow sufficient room for the upper stage vehicle.

The UHF feed array dominates development of the launch configuration. The array consists of five hinged, rigid panels that cannot be collapsed into a small volume as can the booms and reflectors. It is therefore necessary to lay out the feed stowed cross section, shown cross-hatched in Fig. 25(a), sufficiently inside the 4.57-m (180-in.) Shuttle cargo bay dynamic envelope to compensate for upper stage vehicle load alleviation motions. The remainder of the stowed elements must then be fitted inside or forward of the feed panels. This results in limiting the thickness of the UHF feed panel to 25 cm which in turn impacts the selection and the design of the feed elements. Also limited by the stowage constraint is the cross-sectional size of the L-shaped boom supporting the UHF reflector. For a triangular cross section, the sides of the triangle must be confined to 2.41 m (95 in.) which may result in a low-frequency boom and influence the selection of a control subsystem. Figure 25(b) shows the stowed configuration in the axial direction. The elbow in the large L-shaped boom is straightened out and the entire boom collapses into a canister. The large UHF wrap-rib reflector is wrapped in a compact disk as shown at the right-hand side of Fig. 25(b).



(a) (b)

Figure 25. MSAT in Stowed Configuration

MSAT Mass Summary

MSAT is estimated to weigh approximately 4,000 kg (8,800 lb) at the beginning-of-life. The weight breakdown in terms of major subsystems is given in Table 4. Also shown in this table is the percent of the total weight allocated to each subsystem. It is interesting to note that MSAT weighs only twice that of TDRSS, even though it is a physically much larger satellite.

This can be attributed to the fact that MSAT, by virtue of being a 1990s satellite, uses lightweight components particularly in the electrical subsystem. It should be noted that while the primary power of TDRSS is 1.7 kW, MSAT has roughly six times as much primary power, yet weighs only twice as much.

The propulsion subsystem weighs approximately 1/4 of the total MSAT weight. Most of this weight can be attributed to the propellant needed to perform north-south stationkeeping. Future studies should consider concepts that eliminate the need for north-south stationkeeping (for example, by constantly steering the satellite antenna) or consider electric propulsion.

Table 4. MSAT Mass Breakdown

Item		Mass,-kg(lb)	Percent of Total
1. UHF Reflector; Mast and Cables		472.7 (1,040)	%11.8
- UHF Reflector and Mast Attachment		336.4 (740)	
- Upper Mast and Cables		40.9 (90)	
- Lower Mast and Cables		95.4 (210)	
2. S-band Reflector		68.6 (151)	%1.7
3. S-band Feed Array Assembly		77.7 (171)	%1.9
4. UHF Feed Array Assembly		1,168.4 (2,571)	%29.2
- Radiating Elements	113.6 (250)		
- Electronics	304.5 (670)		
- Beam Forming Network	243.6 (536)		
- Cables	119.5 (263)		
- Thermal Hardware	231.8 (510)		
- Structure	155.4 (342)		
5. RF Electronics in the Bus		(227.3) (500)	%5.7
6. ACS		279.5 (615)	%11.4
- Hardware at the Hub	40 (88)		
- Hardware at the Bus	239.5 (527)		
7. Electrical Subsystem		347.7 (765)	%8.7
8. Bus Structure, TTC and Cage		386.4 (850)	%9.6
9. Propulsion Subsystem		969.1 (2,132)	%24.2
- Propellant at the Bus	686.2 (1,510)		
- Tankage at the Bus	692 (152)		
- Propellant at the Hub	194.8 (428)		
- Tankage at the Hub	19 (42)		
10. Total		3,997 (8,793)	

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p 70-71

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Mobile Vehicle Antenna

Mobile Antenna Concepts

Based on the current LMSS design, the ground mobile vehicle antennas must meet these requirements: (1) low cost; (2) reasonably conformal to or easily stowable in the vehicles; (3) circularly-polarized; (4) transmitting at 821-831 MHz band, and receiving at 866-876 MHz band; (5) omnidirectional pattern in azimuthal plane; and (6) a minimum of 3-dB gain in the angular region from 19 to 60 degrees from the horizon in elevation plane. This angular region of coverage is determined by assuming that MSAT will be at 110° W longitude, and the vehicle will roam anywhere in CONUS with a possible vehicle tilt of ±3° from the zenith due to road conditions. The following describes three classes of antennas that are currently under various stages of development to satisfy the above requirements.

Figure 26 shows the crossed-drooping dipole design, including the inverted "U" type and the inverted "V" type. The dipoles are drooping downward to increase radiation at low elevation angles. Computer programs have been developed to facilitate the design of the antenna. One design of the inverted "U" type shows that the antenna can meet all LMSS RF requirements by adjusting the radiation pattern in the elevation plane to two different positions. This pattern adjustment can easily be done by varying the separation (height) of the radiating elements from the ground plane (top of the vehicle). Breadboarding of this design is planned to verify the calculations.

Figure 27 shows the quadrifilar helix design. Four identical helices are wound equally spaced on a cylindrical surface and fed with signals equal in amplitude, and 0, 90, 180 and 270 degrees in relative phase. Measured results of the breadboard at 845 MHz show that the antenna provides high directivity (6.2 dBi) elevation pattern close to horizon (28 degrees from horizon) with excellent ellipticity (⩽1.5 dB) in the regions of interest. The antenna also has good azimuthal pattern and is expected to meet the LMSS bandwidth requirement. Further work on this design involves developing techniques to adjust the position of the elevation pattern without using separate antennas.

Figure 28 shows the element design of a possible microstrip array antenna. This element is small in size and relatively low in cost. It consists of two layers of microstrip patches of different configurations wrapped around a cylindrical ground cylinder. The outer layer shown provides horizontally-polarized radiation, while the inner layer provides vertically-polarized radiation. Measurements of the breadboard at 956 MHz show that the element produces circularly-polarized radiation, omnidirectional in azimuthal plane, and a peak (0 dBi gain) towards the broadside in the elevation plane. Further work on this design involves broadbanding of the element, and breadboarding a complete array to demonstrate gain and scan capabilities for LMSS application.

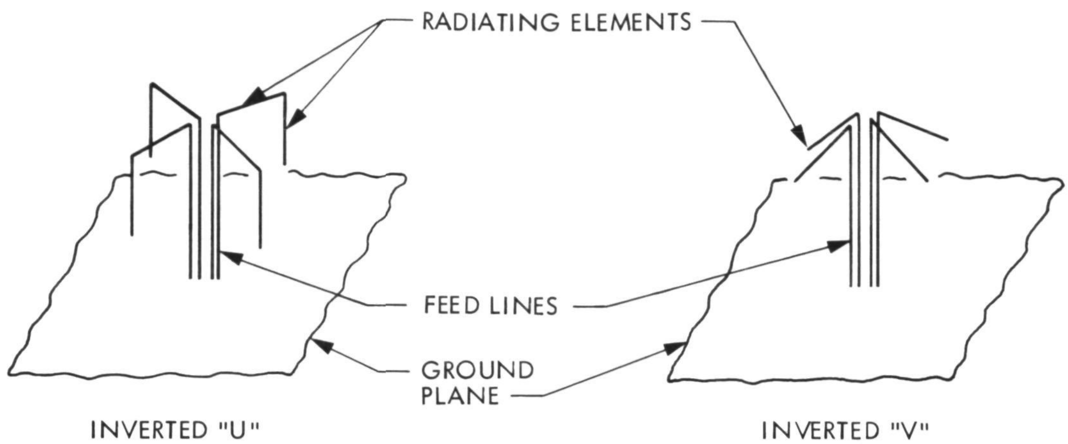


Figure 26. Crossed-Drooping Dipole Design

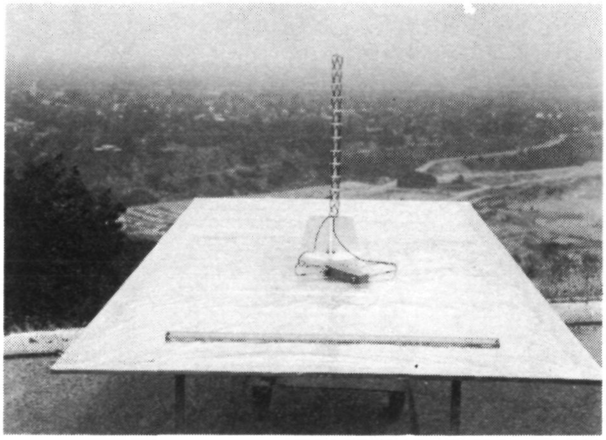


Figure 27. Quadrifilar Helix Design

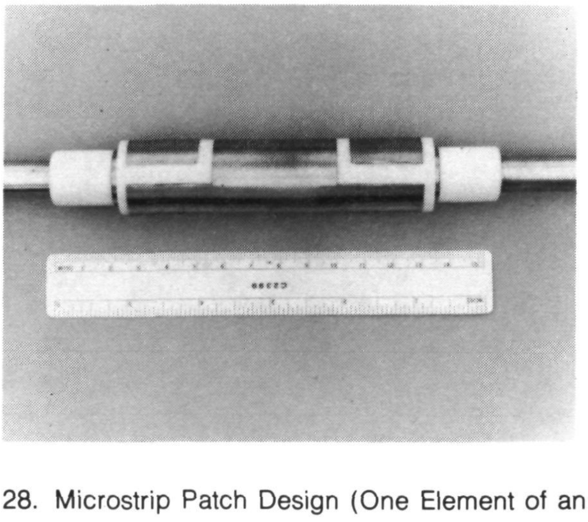
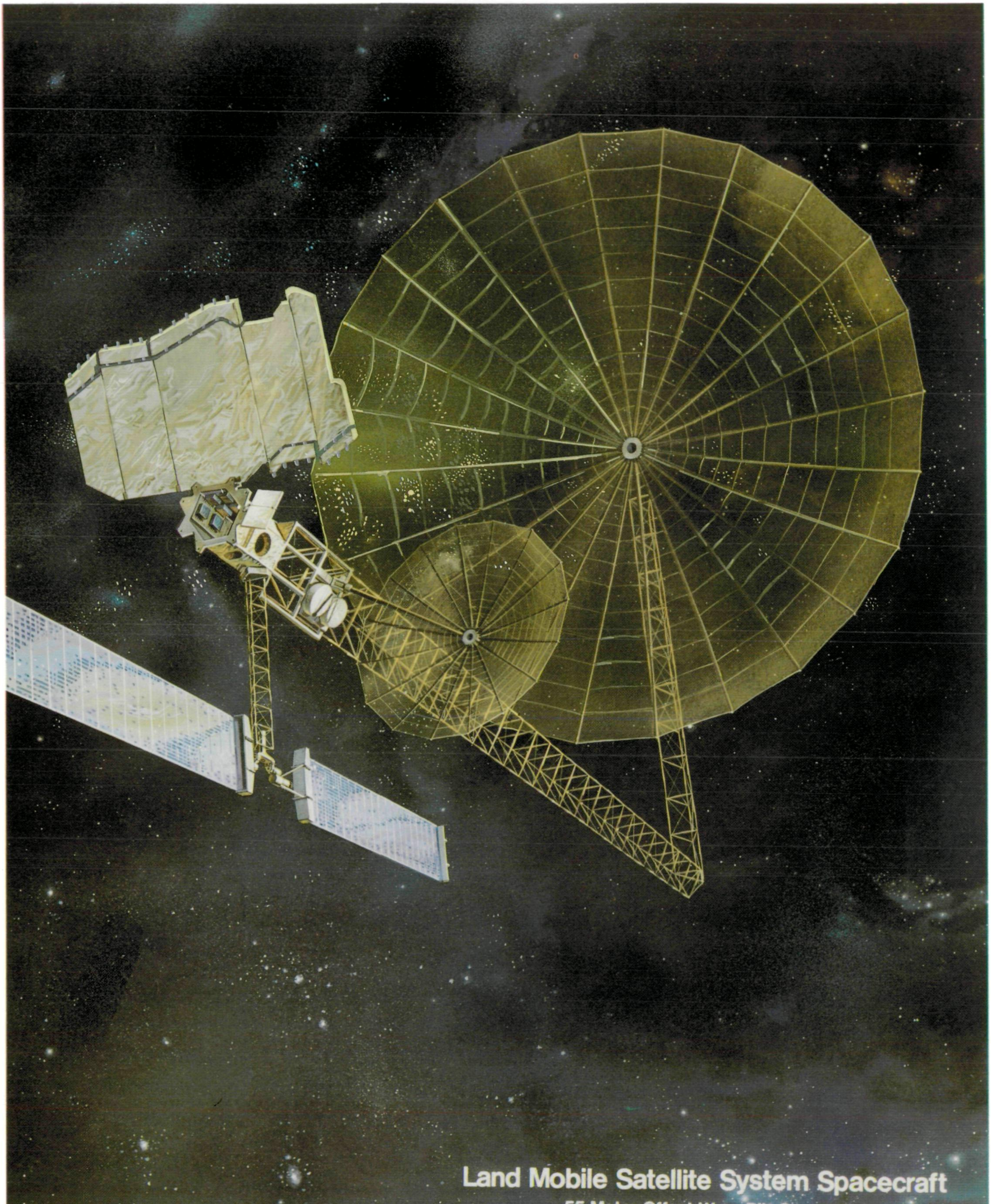


Figure 28. Microstrip Patch Design (One Element of an Array)

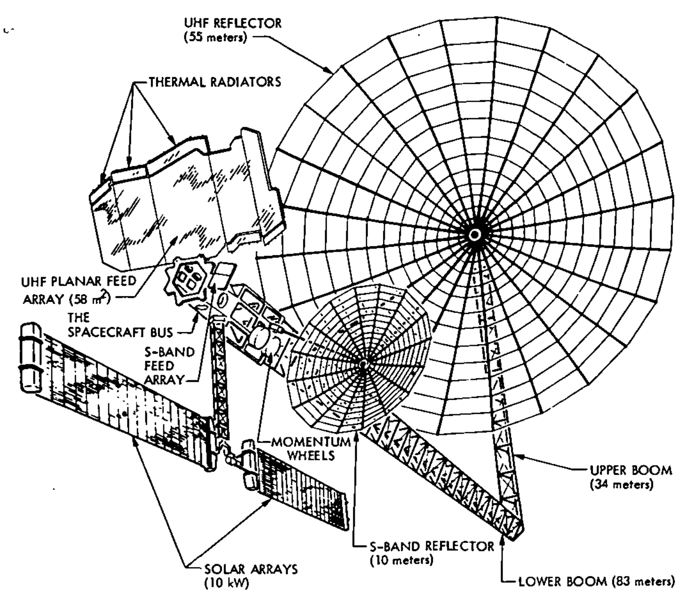

Land Mobile Satellite System Spacecraft
55-Meter Offset Wrap Rib Concept

LAND MOBILE SATELLITE SYSTEM (LMSS) SPACECRAFT

This is a preliminary configuration of a spacecraft in the geostationary orbit, capable of relaying radio messages to hundreds of thousands of land mobile units throughout the continental United States (CONUS). Its intended application ranges from emergency medical to disaster relief, from law enforcement to truck dispatch. In addition, it will provide two-way mobile telephone channels for commercial use in the rural areas not adequately served by the terrestrial systems.

The configuration, as shown, includes a 55-meter offset-fed UHF parabolic antenna supported by an L-shaped boom. The shorter boom at the right points to the north and is approximately 34 meters, and the longer boom, pointing to the Earth's center, is about 83 meters. The large panel in the upper left is the UHF planar feed array capable of producing approximately 90 spot beams covering CONUS. The feed array area is on the order of 58 square meters. The use of multiple spot beams allows a 10-fold reuse of the available spectrum in the 806-890 MHz band.

The mobile units communicate through the satellite to base stations which serve as the interface to the telephone network. Communication between the satellite and the base stations is through the 10-meter S-band antenna shown in the center of the picture. The power requirement for this spacecraft is in the range of 10 kW of DC power at the beginning of life and its estimated weight is 4000 kg. The spacecraft is sized for a single Shuttle launch and a 10-year life beginning in the mid-1990's.



This conceptual drawing represents one phase of a configuration study performed by the Boeing Co. for the Jet Propulsion Laboratory. The study was based on a preliminary LMSS system designed by JPL under joint sponsorship by the NASA Office of Space Science and Applications and Office of Aeronautics and Space Technology through its Large Space Systems Technology Program.

NASA

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL 400-142 February 1982

To the reader:

With the potential rapid growth of the mobile radio market over the next decade, the concept of providing mobile communications via satellite has emerged as a viable solution for mobile services to rural and remote areas. For the past decade, the National Aeronautics and Space Administration, within its charter to promote new space applications, has studied and demonstrated the technical feasibility of a mobile satellite system. Today through its field centers and contractors, NASA continues the study of the land mobile satellite service (LMSS) in terms of technical feasibility, economic viability, and regulatory constraints. In addition, it has initiated programs to develop those technologies critical to the eventual implementation of such a system.

For the past two years, the Jet Propulsion Laboratory (JPL), under the sponsorship of the NASA Office of Space Science and Applications and the Office of Aeronautics and Space Technology, has conducted numerous LMSS related studies and technology development. To provide a focal point for technology development and a means of assessing the available technology, JPL developed the hypothetical mobile satellite system of the mid-1990s. This strawman system design, which is detailed in the enclosed report, features a large satellite capable of serving hundreds of thousands of users at affordable prices. While it is not meant to be the ultimate LMSS system design, the strawman system has served to guide the development of LMSS technologies such as large multiple beam satellite antennas, control of large flexible space structures, satellite electronics and power amplifiers, mobile vehicle antennas, and efficient modulation techniques. The large satellite antenna technology is in actuality a system design in its own right in that it dominates the spacecraft in terms of size and weight and involves a great deal of interaction between the flexible structure, the control of the structure and the satellite itself, and the resultant RF beams. The development of these three interrelated technologies, i.e., structures, controls, and RF, has been an integral part of the technology program at JPL and has been treated in an interdisciplinary system manner. As such, the strawman LMSS system design has been of great benefit to the development of large space antenna systems in general.

While the system presented in the enclosed report features large antennas and technologies of the future, smaller capacity systems, perhaps forerunners of these larger systems, can be built with today's satellite technology. These smaller satellites could provide invaluable service to remote areas for emergency services and for a variety of rural communications needs. At the same time, they could serve as the technology base for the eventual larger capacity systems. Given the projected dramatic growth in mobile communications services and the satellite technology to support it, an LMSS system will soon be an idea whose time has come.

William J. Weber
Manager,
Satellite Communications
Supporting Research and Technology

May 1, 1982

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
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Pasadena, California