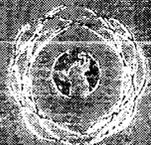


ECOSYSTEMS INTERNATIONAL, INC.



## FOREWORD

This document is part of the Final Report performed under contract NASW-3864, titled "NASA's Long-Range Technology Goals".

The objectives of the effort were:

- To identify technologies whose development falls within NASA's capability and purview, and which have high potential for leapfrog advances in the national industrial posture in the 2005-2010 era.
- To define which of these technologies can also enable quantum jumps in the national space program.
- To assess mechanisms of interaction between NASA and industry constituencies for realizing the leapfrog technologies.

This Volume details the findings pertaining to the advanced space-enabling technologies.

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- II. U.S. INDUSTRIAL SECTOR TECHNOLOGY GOALS  
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- III. SOCIAL, HEALTH, AND SECURITY TECHNOLOGY GOALS  
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## TECHNOLOGY REQUIREMENTS OF FUTURE SPACE MISSIONS

### D.0 OVERVIEW

While geopolitical considerations will continue to influence the national space program, we assume here that space missions of the future will increasingly be shaped by motivations of **utility**, i.e., the provision of products and services useful to industry and the public at affordable prices. The drive for utility will continue to include scientific space missions, but will require the mission planner to maximize the level of scientific knowledge produced **per dollar spent**.

This volume reviews the spectrum of future missions that NASA may be called upon to conduct in the early 21st century, with the aim of identifying core technologies that underlie and enable them. This analysis focuses on those "leapfrog" technology improvements that can reasonably be expected to result in **at least one-half order of magnitude improvements in mission effectiveness**.

In this study, we define leapfrog technologies in a special way. On the one hand, they transcend R&D efforts currently underway or planned by NASA for the medium term, and whose expected fruition lies before circa 1995. At the other extreme, they are not so "blue sky" as to clearly lie beyond 2010.

#### D.0.1 FUNCTIONAL CATEGORIZATION OF SPACE MISSIONS

In accordance with the principle of utility, we assume that space missions of the future will be planned and justified according to their perceived useful returns. In this context the word "functional" implies that proposed missions will not be justified as an end unto themselves, but because they will be expected to perform certain functions, directed of fulfilling specified objectives.

To illustrate, let us exemplify the mission "Mars exploration." Viewed from the functional perspective, the pertinent question is: For What Reason Do We Wish to Explore Mars? The corresponding motivations (other than geopolitical) could be one or combinations of the following:

- gathering data to enhance our understanding of how the solar system was formed, and/or how life originated in the universe. This objective would class the mission under the category of "scientific observations." Under the utility scenario, the mission planner would have to show that Mars provides more scientific "bang for the buck" towards achievement of this scientific objective than, say, investigating moon or the asteroids.
- assaying the availability, on Mars, of valuable materials, potentially mineable for subsequent return to Earth. This objective would class the proposed mission in the category of "exploitation of space resources." The mission planner would be called upon to show that the value of the materials retrieved compensates the cost of retrieval.
- evaluating Mars' potential as a habitat for man. This would also class the mission under the category "exploitation of space resources"--in this case, the exploitation would occur "in situ" rather than on Earth. In this specific case, however, so much remains to be learned before human settlement of Mars becomes technically feasible that we prefer to class this type mission under the category of "scientific observations." Note that the situation would be quite different in the case of a proposed Lunar settlement. Because much is already known about the moon this mission would clearly fall

within the "exploitation" category--key questions revolving around economic value rather than technical feasibility.

Figure 0-1 depicts a framework for the functional categorization of space missions. The rows of the matrix, designated "theater," categorize the mission's functions. The indicated intersections represent our projections of the theaters which are optimal for the stated functions. The theaters are ranked from top to bottom in terms of increasing  $\Delta v$  requirement. This also serves to rank the missions, from top to bottom, by cost, because a mission's cost is driven by its  $\Delta v$  requirements. Figure 4-2 shows how the functional categories defined here encompass and accommodate the more conventional designations of potential future space missions.

In this Volume, we analyze each of the functional space mission categories of Figure 0-1. In identifying the core technologies underlying each functional mission, we have found it useful to define several indicators of value and cost. These are:

- Dominant utility parameter(s)--these are the key technical characteristics of the products and services produced by the space mission: for example, ground resolution in the case of Earth Resources Survey
- Allowable cost threshold--this is the cost of the products or services which have the same technical characteristics as those provided by the space mission, and which are obtainable from competitive, nonspace means

Mission Functions Theater	Earth Resource Survey	Earth Atmosphere Observation	Commercial Communications	Terrestrial Navigation	Exploitation of Space Resources			Scientific Observations	Orbital Infrastructure	Supporting Space Transportation
					Materials	Energy	Human Habitat			
LEO	•	•	•	•	•	•	•	•	•	•
GEO	•	•	•	•	•	•	•	•	•	•
LUNAR					•		•	•	•	•
PLANETARY					•			•		•
TRANSPLETARY								•		•

The indicated intersections (•) reflect the optimum theater for maximum mission utility, based upon constraints imposed by the laws of nature and upon advances possible with projected engineering state-of-the-art of 2010. For example, Earth Resources Survey from the lunar theater is not shown as a valid functional mission because the projected cost/performance of sensors is not compatible with the resolution requirements nor with cost/performance achievable from LEO and GEO.

**Figure 0-1. Categorization of Space Missions Based Upon the Utility Criterion**

- Uniqueness--this is the "value" of a space-derived product that is unique, i.e., not achievable through competitive non-space means
- Opportunity cost--this is the maximum allowable cost of the space mission, i.e., the cost at which the products or services produced by the space mission become competitive with the cost of other, non-space alternatives. In the case of unique space products, the opportunity cost is the level at which the cost of the space mission equals the value of the unique products

It is important to reiterate that not all the products of space missions can be evaluated in economic terms: The data garnered from scientific observation missions are an example. However, even for products which have "intangible" value, such as scientific data, criteria of cost/effectiveness can be applied. For example, alternative mission implementations can be compared in terms of bits of scientific data produced per dollar spent.

**D.1 EARTH RESOURCES SURVEY**

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## D.1 EARTH RESOURCES SURVEY

### D.1.1 SIGNIFICANCE

The function of this category of missions to map surface features, aimed at discovering and inventorying natural resources.

We concentrate here upon observations which employ **imaging** techniques. These have been the most used from space systems. Other types of observations, important for seeking and inventory of natural resources, are not yet sufficiently developed to yield practical utility from space platforms, but are currently performed from airborne platforms via surface methods. These types of non-imaging observations include **geomagnetic, geogravitic, and soil moisture** measurements. These observations will eventually be performable from space. The methodology for assessing the dominant utility parameters, the allowable cost threshold and the opportunity costs of future advanced space missions designed to perform non-imaging observations is analogous to that followed here for the imaging observations. So are the methodology's results.

The **value** of the information obtained from a remote earth observation system varies with the **application** to which the information is put. Experience from aircraft and space-based systems, encompassing a gamut of applications, shows that value is a function of three dominant parameters:<sup>a</sup>

- Approximately 75%-80% of the value hinges on the ability to recognize **shapes**. The corresponding utility

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<sup>a</sup> "MLA Value Derived from an Analysis of National Land Mapping Activities"; ECOSystems International Inc., October 21, 1980 for NASA/GSFC.

parameter is the observing system's **geometric resolution.**

- Approximately 20%-25% of the value depends upon the discrimination of "color." The corresponding utility parameter is the system's **spectral resolution.**
- **Multiple** observations of the same area increase the value by approximately  $\sqrt{N}$ , where N is the number of revisits.

The allowable cost threshold is determined by what can be accomplished, at what cost, by the most competitive alternative means; i.e., by the resolution-revisit frequency combinations achievable by conventional aircraft survey systems.

The costs of an end-to-end remote sensing system fall into three categories:

1. Costs associated with **gathering** the data, up to and including the generation of the raw product, e.g., film, tape;
2. Costs associated with **interpreting** the raw products and elaborating them into finished products, e.g., maps;
3. Costs associated with deriving, from finished products, information needed by the final **user**, e.g., agricultural acreages, potential for findings of oil and gas.

Category 2 and 3 costs are common to all remote sensing systems. It is only in category 1 that a space-based system differs from its airborne counterpart. The category 1 costs thus characterize the space mission's utility and drive its technology.

## D.1.2 DATA GATHERING FUNCTION

Representative unit costs of data gathering for conventional aircraft remote sensing systems are shown in Table 1-1.

In principle, the product of the unit costs times the area of coverage of interest (e.g., square kilometers per year) provides the cost threshold, i.e., the maximum allowable dollars for the equivalent space system. A large body of literature has attempted to define the commercially practical area of coverage for an Earth resources observation satellite. The estimates range widely and a definitive assessment is not yet available.

A practical estimate of the economic value of space remote sensing can be obtained by gaging the current "mapping" business.

**Mapping** by federal and local civil governments and by private industry is the primary use of remote sensing in the U.S. today. Eighty-four percent of this mapping activity is funded by the federal government; of this, 64% is contracted to private industry. Approximately 5% of the total activity is funded by private enterprises, e.g., land developers, oil exploration companies. Table 1-2 lists the major map products currently produced by federal, state and local agencies. Table 1-3 summarizes, by category, the quantities of mapmasters currently being produced.

Total expenditures by federal, state, local and private users in FY 1983 approximated \$1,250 million (current dollars.) This is then the current market for mapping products. This market is forecasted to grow to \$1,700 million (in 1983 \$) by year 2000 and \$2,020 million by 2010<sup>b</sup>. Note that this "here and now"

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<sup>b</sup> Op. Cit.

TABLE 1-1

REPRESENTATIVE COSTS OF AIRBORNE REMOTE  
SENSING DATA GATHERING

<u>RESOLUTION METERS</u>	<u>UNIT COST \$/SQ. km FOR SINGLE DATA GATHERING VISITS<sup>a</sup></u>				<u>MULTIPLYING FACTOR FOR N REVISITS<sup>b</sup></u>
	<u>B&amp;W</u>	<u>MULTISPECTRAL</u>	<u>THERMAL IR</u>	<u>SAR</u>	
50	1	1.50	4	15	$N^{0.85}$
10	2	3	8	20	$N^{0.85}$
5	1	4	—	25	$N^{0.85}$
1	4	5	—	—	$N^{0.85}$

<sup>a</sup> FOR AREA COVERAGE OF 10,000 km<sup>2</sup>. PRICES REPRESENT THE AVERAGE OF THREE COMMERCIAL QUOTES, AND ARE IN 1982 DOLLARS. THEY INCLUDE DELIVERY OF IMAGE PRODUCTS AT 60% OVERLAP AND DO NOT INCLUDE ANY GROUND TRUTH EFFORT. PRICES ARE SOMEWHAT LOWER FOR LARGER COVERAGES.

<sup>b</sup> THE MULTIPLYING FACTOR ASSUMES THAT THE REVISITS ARE COORDINATED, I.E., CONTRACTED AS A SINGLE BATCH.

TABLE 1-2

PRINCIPAL CURRENT MAP PRODUCTS

<u>MAP PRODUCT</u>	<u>PRINCIPAL PRODUCING AGENCIES</u>
AERONAUTICAL CHARTS	NOS
BOUNDARY MAPS	IBC, DOS
CADASTRAL MAPS	COUNTIES, STATES
CENSUS MAPS	BC
CLIMATIC MAPS	NWS
EARTHQUAKE HAZARD	USGS
FEDERAL PROPERTY MAPS	BR, FWS, FS, NPS, USGS
FLOOD PLAIN MAPS	FIA, NOS, SCS, USCE, USGS
GEOLOGIC MAPS	USGS, STATES, NOAA/EDS, BU MINES
LAND USE	NOS, USGS
HYDROGRAPHIC CHARTS	NOS, USCE, USGS
SOILS MAPS	SCS
CLIMOMETRIC MAPS	USGS
SNOW COVER MAPS	NOAA/NESS
TOPO MAPS	USGS
WATER RESOURCES MAPS	USGS
AEROPHOTOS	ASCS, BLM, DMA, FHWA
ORTHO PHOTO MAPS	USGS, NOS, BIA



market is much larger than the sum-total of the markets which have been postulated for LANDSAT data in the past, e.g., agriculture, land use, pollution mapping.

The costs of data gathering (and of the other elements in the end-to-end mapping process) are shown in Table 1-4. The portion attributable to the **data gathering** function, i.e., sensing and providing the "raw" images, is approximately **5%** of the total costs.

TABLE 1-4

RELATIVE COSTS BY ACTIVITY IN THE  
END-TO-END PRODUCT CHAIN OF FEDERAL CIVIL MAPPING

<u>ACTIVITY</u>	<u>PERCENT OF TOTAL COST</u>
DATA COLLECTION	5
INTERPRETATION	21
CARTOGRAPHY	44
DISTRIBUTION	5
ARCHIVING AND SALES	11
RESEARCH & DEVELOPMENT	<u>3</u>
TOTAL COST	100
REVENUE FROM PUBLIC AND INTERAGENCY SALES	5

As shown, the **cost** of producing maps **exceeds** by a factor of twenty the revenue from their **sales**. In effect, map making is a public service, justified by its social value rather than solely by commercial considerations.

Approximately **87%** of the raw products used in mapping consist of Black & White (B&W) aerial photography. For example, the Agricultural Stabilization and Conservation Service, a major producer, generates annually B&W photography covering 1.3 million square kilometers. These are sold to map-making agencies and to the public at large.

The most significant utility parameter of B&W imagery is **geometric resolution**. Table 1-5 shows the minimum resolution required for the various standard map scales.

Analysis of the mapping "market" shows that most of the needs for B&W are met with a ground resolution of order 3 to 4 meters. At lower resolution, the addressable market drops sharply, as shown in Figure 1-1.

**Multispectral capability adds value to B&W imagery.** As a minimum, it strengthens the "capturability" of the addressable market if it can be provided at substantially the same price as B&W imagery. For certain customers, multispectral imagery would command a somewhat higher price. However, the market is quite price sensitive. While most users prefer color, its higher current price limits the demand. The curve labeled "MS" in Figure 1-1 reflects our estimate of the additional market addressable by multispectral imagery as a function of resolution.<sup>c</sup> The curve labeled "TIR" shows the additional addressable market if **thermal infrared** is added to the B&W and to the multispectral feature.

As regards the uniqueness parameter, space-derived imagery possesses several distinctive advantages, as demonstrated by LANDSAT experience:

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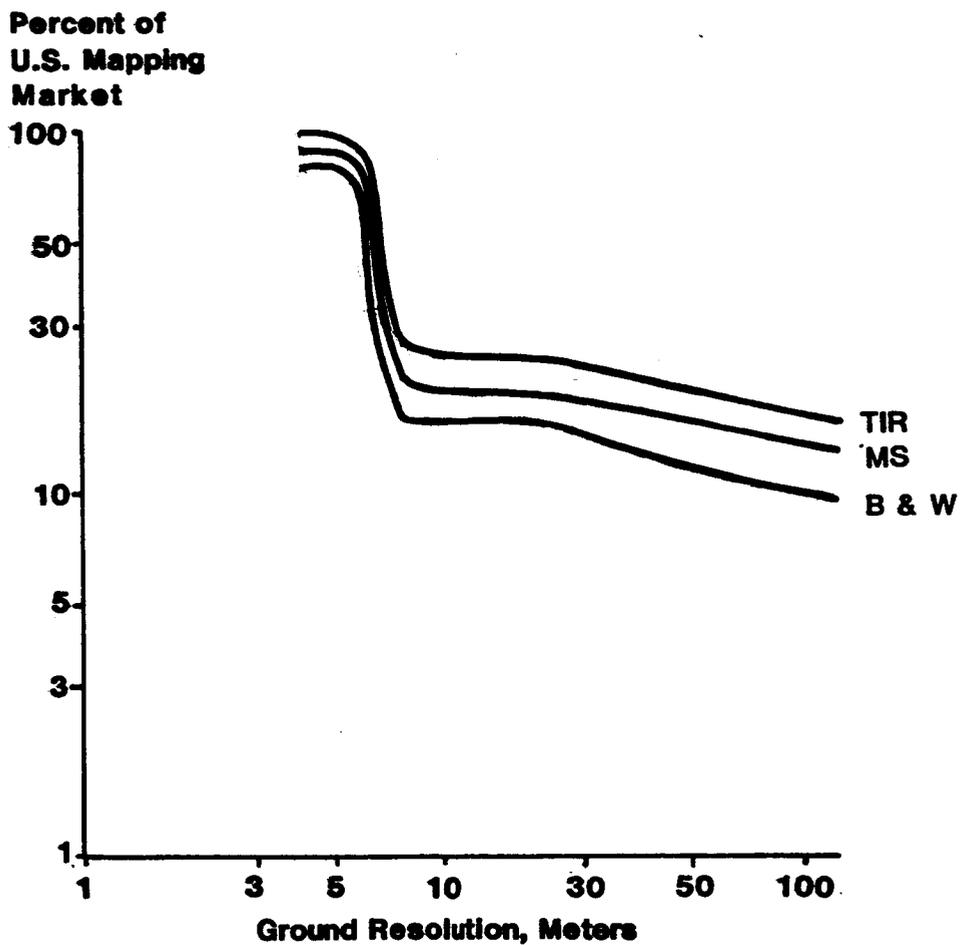
<sup>c</sup> Op. Cit.

TABLE 1-5

GROUND RESOLUTION REQUIRED AS A FUNCTION OF SCALE  
FOR STANDARD MAP PRODUCTS

<u>MAP SCALE</u>	<u>MINIMUM REQUIRED RESOLUTION, METERS</u>
1: 15,000,000	3,750
1: 11,000,000	2,750
1: 8,000,000	2,000
1: 7,500,000	1,875
1: 3,168,000	792
1: 2,500,000	625
1: 1,000,000	250
1: 500,000	125
1: 250,000	63
1: 150,000	38
1: 125,000	31
1: 100,000	25
1: 63,360	16
1: 62,500	15
1: 50,000	13
1: 31,680	8
1: 30,000	7
1: 25,000	6
1: 24,000	6
1: 20,000	5
1: 15,840	4

B & W - Black & White  
MS - Multispectral  
TIR - Thermal IR



**Figure 1-1. Addressable Market For Remote Earth Observations As A Function of Ground Resolution and Type of Imagery**

1. High geometric fidelity. RBV on LANDSAT 3 has shown geometric accuracy of order  $\pm 0.1\%$  in the "raw" image. This compares with geometric distortions of several percent in aircraft photography. For precision work, alleviation of these distortions require costly image rectification. At approximately \$50 per image (1983 \$), approximately 5% of the aerial imagery is currently rectified.

We estimate that the availability of RBV-type imagery with high geometric fidelity could expand total sales of remotely sensed products by approximately 4%.

2. High repetition rate--important to users who require observations spaced at frequent time intervals. Principal among these users are:

- Agricultural statistical services--desirable repetition is approximately 10 days during the growing season; for remote sensing systems operating in the visible/IR spectrum, this increases to 3 to 5 days to circumvent the masking effect of cloud cover. Estimated yearly U.S. market for these remote sensing products is approximately \$100,000-\$300,000.
- Geologic users--desirable repetition is four times per year, to allow observation of geological scenes under differing conditions of illumination, snowcover, humidity, etc.
- Disaster managers, e.g., floods--desired frequencies can be as high as every 3 days, to follow the progress of the phenomenon and associated damage-limiting activities.

The ability of spaceborne remote sensing to provide high repetition rates can expand the market by approximately 5%.<sup>d</sup> SAR imagery, which achieves high repetition rate by virtue of its insensitivity to cloud cover, can also expand the market by 5%.

Aggregating the features of high geometric fidelity and high repetition rate, unique to space remote sensing, we estimate that a B&W spaceborne remote sensing system producing imagery at approximately 3 to 4m resolution could address approximately 90% of the U.S. mapping market if the total price of the data collection did not exceed 5% of the total costs. Addition of multi-spectral and thermal imagery capabilities would meet the lion's share of the current mapping market. The U.S. addressable market for "raw" remotely sensed products is equivalent to \$62 million/year currently and \$85 million/year (in 1983 \$) in 2000.

We estimate that the multiplying factor for the world is approximately 3, thus establishing a **world-wide** addressable market of order \$270 million (in 1983 \$) by 2000.

The "**capturable market**," i.e., that share of the addressable market which a future earth observation satellite could actually expect to "sell" depends to a large extent upon the **competition** among satellite systems, both domestic and foreign. Because the capturable market would be affected by national policies of price support and by potential future improvements in price/performance of airborne remote sensing systems, an exact estimation is beyond the scope of this effort. However, a reasonable estimate for a "very good" (high resolution, low price) system is half of the world market--\$135 million. For an average (lesser resolution) system, between one-tenth and one-fifth of the world market.

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<sup>d</sup> Op. Cit.

This bounds the allowable cost of the spaceborne system and sets the technological challenge, i.e., achievement of the requisite capabilities as a function of the price of the product.

#### D.1.3 INTERPRETATION AND ELABORATION FUNCTION

Interpretation is the translation of features contained in the "raw" imagery into standard symbology and classifications, e.g., terrain topography, ground cover, urban habitats, water-bodies.

Elaboration, consisting of cartography and printing, converts interpreted data into finished map products. As shown in Table 1-4, it represents the largest share of current costs.

Whereas the **data gathering** function represents approximately **5%** of the costs of civil mapping (Table 1-4), **interpretation** accounts for over **20%**. Its addressable U.S. market is thus of order \$250 million/year currently, \$350 million/year (in 1983 \$) in 2000. Worldwide, the year 2000 market could be as high as \$750 to \$1,000 million/year.

Two technologies are currently employed for interpretation:

- **VS** (Visual System)-based, also known as photointerpretation (PI). This technique has been used since the inception of aerophotography, circa 1910.
- **Computer**-based, also known as automatic classification. This technique was pioneered by NASA beginning in the late 1960s, specifically to interpret multispectral data gathered from aircraft and/or satellites.

**VS**-based systems are currently used to interpret the **majority** of remotely sensed data. Its accuracy is of order 90% for "normal" civil products, 95% and better for high quality pro-

ducts. Much effort has been expended, and is ongoing (primarily on the part of DOD), to automate VS-based interpretation. Although progress has been encouraging, achievement of full **automation** is still a **goal**. DOD, for example, still employs approximately 4,500 photointerpreters.

Table 1-6 provides a calibration of the **accuracy** of automatic classification by computer-based systems using LANDSAT 1, 2, and 3 data. It shows that the automatic system has not yet reached the "utility" threshold. This may explain why LANDSAT market penetration has been limited. Somewhat improved results are anticipated from the higher-resolution LANDSAT Thematic Mapper Satellites.

Achieving improved interpretation through automatic assists remains a key technological driver affecting the commercialization of Earth Resources Survey.

#### D.1.4 USER INFORMATION FUNCTION

This function is the **end-result** of the mapping activity. It converts the interpreted data into the final information products sought by the ultimate users. This conversion occurs in two modes:

1. By the final user or intermediate specialist (value-added industry), from **map products** augmented by **auxiliary information**--e.g., combined use of land use and business activity censuses by country planners.
2. By the final user or intermediate specialist, from **raw** or partially interpreted products such as annotated aerial photography combined with **auxiliary information**--e.g., combined use of aerophotos, aeromagnetic/gravimetric surveys, geologic, seismic data by oil prospectors.

TABLE 1-6

ACCURACY OF CLASSIFICATION FROM LANDSAT

(AVERAGE OF 224 TESTS, 10 GEOGRAPHIC LOCATIONS, ONE SIGMA CONFIDENCE)

	<u>PROPORTION ESTIMATIONS<sup>a</sup></u>	<u>MAPPING</u>
<u>ACCURACY, ALL CATEGORIES</u>	74%	63%
<u>ACCURACY, BY CATEGORY</u>		
URBAN		30%
CROPLAND		55%
FORESTS		75%
WATER		86%
<hr/>		
<u>ACCURACY, THRESHOLD OF USER</u>		
ACCEPTANCE	96%	85% TO 90%
<hr/>		
<p><sup>a</sup> PROPORTION ESTIMATION IS THE MEASUREMENT OF THE TOTAL SURFACE COVERED BY A GIVEN SPECIES, E.G., WHEAT, WITHIN A CERTAIN REGION, E.G., HASKILL COUNTRY, REGARDLESS OF WHERE THE SPECIES IS LOCATED WITHIN THE REGION. PRIMARILY USED FOR CROP AND FOREST ACREAGE ESTIMATION. EASIER TO OBTAIN THAN MAPPING.</p>		

No comprehensive sizing of the dollars spent in performing the user information function has been developed. It is estimated <sup>e</sup> to be on the order of several billion dollars per year in the U.S., and that the largest share accrues to Mode 2.

Mode 2 has the largest potential for exploiting the unique characteristics (high geometric fidelity and repetitiveness) of raw space products. The Mode 2 market, if properly developed, could overshadow the data gathering and the interpretation markets defined above.

Key to addressing this market--indeed central to the long-term growth of earth observation systems--is the development of technologies for economically accomplishing the user information function. Of these technologies, embracing pattern recognition, radiometric classification, multi-sensor and multi-data correlation, the most challenging for long term development is that of **geometric pattern recognition**. Section E.4 presents the state-of-the-art and projections for progress in this core technology.

#### D.1.5 EARTH RESOURCE SURVEY FROM GEO

While the general mapping market is the same as for LEO-based observations, additional uniqueness and opportunity cost parameters pertain to Earth surface observations from GEO.

The dominant uniqueness feature of GEO-based observation systems, is the opportunity of observing phenomena in shorter times than possible from cost-effective LEO systems, i.e., minutes to hours instead of days to weeks. In part, this capability stems from the large field of view possible from GEO; in part, from the ability to exploit cloud dynamics, i.e., the fact

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<sup>e</sup> "Business case for remote sensing products" ECOsystems International, Inc., October 1979 for NASA Hq.

that cloud covers are often not continuous but patchy and moving, thus ground objects obscured at certain moments of time can become revealed shortly thereafter.

To date, the value of this added uniqueness feature has not been reliably and credibly quantified. In our estimation, its principal contribution would be to the warning of major meteorological disasters and consequent potential alleviation of their effects. This application belongs to the functional mission category of Earth atmosphere observations, treated in Section D.2.

Two factors dominate the opportunity cost parameter for earth observations for GEO.

First, the achievement of the required geometric resolution from GEO requires use of aperture diameters 40 to 50 times those needed from LEO. At optical wavelengths, a 10m diameter optical-precision aperture is needed to achieve the 4m resolution needed to meaningfully address the U.S. mapping market. Aside from their technical feasibility, the cost of fabrication and deployment of such large structures appears incommensurate with their utility within the time frame of this study.

Secondly, potential advantages of GEO observation systems are limited by their more restricted area of survey with respect to LEO systems. Whereas a single GEO system could serve the Western Hemisphere, three such would be required to address the world market.

The reasons above indicate that GEO Earth observation systems capable of cost/effectively addressing the remote sensing market lie beyond year 2010.

D.1.6      KEY TECHNOLOGIES

Table 1-7 summarizes the characteristics of a 2000-2010 era spaceborne remote sensing system that could address the civil remote data market, as described above.

Based on projections of sensor and spacecraft technologies<sup>f</sup>, achieving the necessary spaceborne technological capabilities does **not** appear to be particularly **difficult**. The principal engineering challenge is to achieve these performance characteristics within the allowable cost windows. Another constraint could be institutional, relating to public dissemination of high (3 to 4 meter) resolution imagery.

A more difficult problem is the development of improved **interpretation** and user information technology. Computer-based interpretation techniques, currently accurate to approximately 60-75%, could achieve requisite higher performance if they could be made to operate also on the geometric features of the data instead of only on their radiometric properties.

In summary:

- The **core spacecraft** and **sensor** technologies required to achieve a remote sensing spacecraft and associated ground processing and distribution system able to compete with conventional methods are essentially **available**. The principal challenge is **cost**. The annual yearly operating costs for a very good system, including interest, amortization, O&M, continuity R&D, should not exceed approximately \$130 million (in 1983 \$) in year 2000-2010

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<sup>f</sup> "NASA Space Systems Technology Model", NASA oast, January 1984

TABLE 1-7

CHARACTERISTICS OF FUTURE  
SPACEBORNE REMOTE SENSING SYSTEM

<b>GROUND RESOLUTION</b>	= 3 TO 5 METERS
<b>AREA COVERAGE, YEARLY</b>	
U.S.	= 2 TO 3 MILLION km <sup>2</sup>
WORLD, U.S. INCLUDED	= 10 TO 20 MILLION km <sup>2</sup>
<b>LOCATION OF COVERAGE</b>	= FOR MOST USERS, PREDESIGNATED AREAS
	= FOR A LIMITED NUMBER OF USERS, AD-HOC AREAS ON A QUICK REACTION CAPABILITY
<b>REPETITION FREQUENCY</b>	= FOR MOST USERS, APPROXIMATELY ONE TO THREE MONTH TIME BETWEEN TAKES
	= A LIMITED NUMBER OF USERS REQUIRE RE-IMAGING THE SAME SCENE AT 3 TO 5 DAY INTERVALS.
<b>SENSING WAVELENGTH REGIONS</b>	= PRIMARY: PANCHROMATIC (BLACK & WHITE) AND/OR SAR
	= SECONDARY: MULTISPECTRAL
	= TERTIARY: THERMAL IR
<b>TOTAL ALLOWABLE YEARLY COST "OF SPACE SYSTEM INCLUDING "RAW" PRODUCT GENERATION</b>	= "AVERAGE SYSTEM: \$30 MILLION
	= "VERY GOOD" SYSTEM: \$130 MILLION

- The truly **challenging** R&D problem is **automatic interpretation**, combining geometric pattern recognition with multispectral radiometric analysis.

## **D.2 EARTH ATMOSPHERE OBSERVATION**

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## D.2 EARTH ATMOSPHERE OBSERVATION

### D.2.1 SIGNIFICANCE

NASA's role is to provide enabling technologies to sister agencies for the benefit of the U.S. public. Thus NASA's basic reason for investigating the Earth's atmosphere is to acquire an understanding of its processes, through the pursuit of fundamental scientific knowledge of the dynamics, thermodynamics, and kinematics of the atmosphere's vital lower portion (troposphere and stratosphere); of its interaction with the significant boundaries, e.g., terrestrial/oceanic; and of the influence of solar forces.

The **utilitarian** reason for observing the Earth's atmosphere is the utilization of this knowledge to **predict** the atmosphere's future state. This is accomplished through the use of operational dynamic models for the larger space and time scales, and through a variety of other methods for the smaller space and time scales. Substantial improvements in the forecast could result in large economic benefits to the nation.

The combination of improved observation systems and dynamic models has contributed to remarkable progress in our understanding of the lower portion of the atmosphere during the last quarter century. The models describe and predict the atmosphere's behavior through the fundamental equations of motion and thermodynamics. The equations have been known for a long time, but their implementation in a practical and timely manner has primarily resulted from the major increase in computational speeds occurred since the mid and late 1950s.

### D.2.2 OBJECTIVES OF EARTH ATMOSPHERE OBSERVATION

The utilitarian reason for measuring routinely certain key parameters of the Earth's atmosphere is to predict its future

state, conventionally designated as the "weather forecast." Various analyses have shown that substantial improvements in the forecast would result in large benefits to the U.S. economy. Depending upon the accuracy and extent of the forecasts, these benefits could range upwards to billions of dollars per year. The key elements characterizing the quality of forecasts are:

- The **length** of the forecast
- The **accuracy** of the forecast
- The forecast's **resolution**, i.e., the geographic area over which the forecast extends reliably

The combination of improved observation systems with dynamic models of increasing sophistication has led to remarkable progress in our understanding of the atmosphere during the last quarter century. We now know that in order to improve the forecast, atmospheric observations must provide accurate, dense and frequently repeated data and that atmospheric models must be sufficiently sophisticated to describe and predict the state of the atmosphere. Since the 1960s, the density, frequency, and quality of atmospheric observations has been significantly enhanced through remote sensing, both by ground means (radar) and from satellites.

The key questions pertaining to atmospheric forecasts are: 1) What is the **state-of-the-art** of current forecasts? 2) What **forecast goals** can be set for 2000-2025? 3) What **key observation requirements** can be expected to allow major advances towards these goals? 4) What **technological goals** should be set for 2000-2025 to achieve the measurements associated with achieving the above major advances?

This section presents: 1) an assessment of the state-of-the-art of current prediction accuracies and suggestions for future forecasting goals; 2) key observation requirements that are expected to allow further major advances in prediction as

well as significant increases in our understanding of lower atmospheric processes; 3) a summary of the current status of atmospheric observations; and 4) recommendations as to future technological goals to achieve the measurement accuracies, timeliness and densities associated with improved prediction and to increase our scientific understanding.

#### D.2.3 STATE-OF-THE-ART OF FORECASTING

A weather forecast can be defined as "good" whenever the atmosphere behaves as predicted, with a precision and over a time span sufficient to satisfy user needs. Since user requirements differ significantly, there is no uniform, standard guideline for what represents a good forecast. Specific forecast requirements can be and have been established for various classes of users.

There are three basic forecasting space and time scales: the small or **mesoscale** area, covering areas of the order of  $10^6$  km<sup>2</sup> with a time span of minutes to a day; the intermediate or **synoptic** scale, whose areal domain extends from regional to global with the time scale from one to ten days; and the large or **climate** scale, whose areal domains are regional to global, and whose time domain extends for months, years, and decades into the future.

The most **mature** of the three forecasting scales is the intermediate or **synoptic**, which forms the basis for the regular forecast services provided by governments and private forecasters. The output from dynamic models is the primary information source that contributes to the forecast. The conventional measure of forecast accuracy, called the  $S_1$  score, measures the ability to predict the horizontal gradient of given atmospheric parameters, e.g., sea level pressure. The practical  $S_1$  range between near perfect and essentially worthless sea level pressure forecasts is 30 to 80, respectively. The  $S_1$  scores for a 30-hour National Meteorological Center (NMC) sea level pressure forecast

were about 65 in the mid-1950s, 55 by the early 1970s, and are in the 40-45 range currently. The latter corresponds to about a 3mb error in the prediction of sea surface pressure.

Similar improvements have occurred in the prediction of the geopotential heights associated with constant pressure surfaces (e.g., 500mb), which describe the state of the atmosphere above the Earth's surface and which are extensively used in the preparation of forecasts. While these results represent an impressive degree of improvement during the past 30 years, there are still large scale and rapidly developing atmospheric phenomena (e.g., cyclones) for which the forecast errors are much larger. These situations are often critical since they can produce significant adverse weather, e.g., major storms, snowstorms, floods.

The accuracy of prediction of precipitation has shown slower improvements during the last three decades, especially for heavy precipitation. The "threat score" measures the probability of predicting the area wherein precipitation exceeds a given threshold. Threat scores for 0.25mm of precipitation from NMC's fine mesh model for 24 hours in advance are 0.4; they have increased slightly since 1974. The scores are about 0.5 in winter, dropping to 0.3 in the summer, reflecting the larger scale organization and predictable nature of winter precipitation. The skill in predicting heavier precipitation is lower. Subjectively prepared NMC threat scores of 0.2 for daily precipitation of 250mm are typical. This score has not changed during the past two decades.

The next most advanced area of forecasting is the mesoscale, which includes severe storm prediction. Two National Weather Service Forecast Centers predict severe storms, i.e., tropical cyclones and severe thunderstorms, while other smaller scale forecasts are made by local forecasting offices, e.g., frost and freeze warnings, flash floods. Consistent statistics on forecast performance are available for tropical cyclones and severe thun-

derstorms (particularly those that produce tornados and/or intensive hail) but not for the other mesoscale phenomena. The most significant forecast for tropical cyclones is the prediction of the future motion of the cyclone's center. Over the past 20 years the 24-hour motion forecasts by the National Hurricane Center (NHC) have improved by approximately 10% to around 200km. This is roughly one-third of the average storm motion during the prediction interval. The forecast improvements for other time intervals are approximately equivalent. These improved motion forecasts have been achieved despite curtailments in the observing system: Improved forecasting methods have more than compensated for the reductions in the density and frequency of the data-gathering networks.

Severe thunderstorm threat areas (called watches) are identified several hours in advance by the National Severe Storm Forecast Center (NSSFC). Approximately 30% of all tornado-producing storms are successfully predicted to eventually occur within the watch areas; the percentage correct score for severe tornado-producing storms is somewhat higher. This compares with 20-25% in the 1960s. These improvements have been achieved despite reductions in the supporting observation system, particularly in the number of surface stations.

Long range or **climate** forecasting and modeling is the least developed branch of prediction. Most climate forecasting methods are based on statistical analyses of past occurrences; a 60-65% probability of success is currently considered high. The longest range forecast published by the National Weather Service is the 90 day outlook for temperature and precipitation deviations. There are no widely accepted methods of forecasting beyond 90 days.

D.2.4      FORECAST GOALS FOR THE FIRST QUARTER OF  
THE NEXT CENTURY

General Goals

A major question is where to place the emphasis on pursuing forecast improvement during the first quarter of the next century.

Intermediate range forecasting has experienced a steady improvement to the point where the dynamic models yield reasonably accurate forecasts of up to three days for surface pressure and for tropospheric circulation. The principal areas requiring improvement are the forecasting of extreme events, e.g., major snowstorms; the extension of accurate forecasting to longer intervals, e.g., five days and beyond; and the accuracy of precipitation predictions. While there is a strong need for these improvements, the other two major scales are further behind in relative forecasting skill. The benefits potentially accruing to improved forecasts in the other two scales are expected to be at least as great as those for the intermediate scale and, as the next century progresses, the benefits from improving climate scale forecasts are likely to become the most significant.

Sharp improvements in mesoscale prediction in the 0-24 hour range will have significant quantitative impact on many areas of the economy, e.g., agriculture, construction industry, transportation; and will induce indirect benefits accruing to more timely and precise information for the planning of our daily lives. This potential has been recognized by NOAA through the establishment of the Prototype Regional Operational Forecasting System (PROFS) intended to lead to the establishment of a large-scale regional forecast system.

Improved climate predictions will have a sweeping effect on how we manage our resources, plan agricultural strategies, and

decide how we coexist with our environment, including the assessment of man's influence on climate. Large improvements in climate forecasting skill will undoubtedly result in benefits that we cannot currently calculate, since new ways of using this information will be created.

Improving the mesoscale and climate forecasts depend heavily upon major improvements in the observed data. For the mesoscale, the critical need is to provide the measurements required to reliably forecast extreme conditions, e.g., tornados, severe freezes. These are the ones that strongly affect the economy and the public's well-being. Useful climate measurements require high accuracy and reliability to ensure that incipient trends are real and not merely within the uncertainty of the measuring system.

To be cost-effective, the high temporal and spatial resolutions needed for mesoscale observations require that the corresponding observing system be dominated by **remote sensing** methods. The trend in that direction is evidenced by the increasing emphasis on radar and satellite techniques coupled with the steady decrease in surface and radiosonde observations. **In situ** data sources are **expensive** and have relatively low resolutions compared with remote sensing methods.

A climate system requires consistent global measurement of numerous parameters, where small relative changes are measured with great accuracy. Whereas **in situ** data are plentiful over most continental areas, they are almost nonexistent over the oceans and sparse in polar regions.

The economic needs for large improvements in mesoscale and climate scale prediction, and the substantial contributions attainable from remote sensing, suggest that the **mesoscale** and the **climate** scales will become the **focus** of NASA's atmospheric sciences program over the next few decades. The observations

supporting these scales are also expected to lead to further substantive advances in intermediate range prediction.

### Specific Goals

In this section we present our assessment of realistic forecast improvement objectives for the three major scales for the first quarter of the next century. Significant drivers are identified for each scale. If the stated forecast objectives are met for the drivers, a wide range of other forecast goals should be achievable within each scale.

#### Mesoscale

**Severe storms** are extremely important and difficult-to-forecast mesoscale phenomena. Among severe storms, the tornado is the most violent and transient. Of principal importance would be to reduce the size and/or duration of the tornado threat watch areas. A reasonable goal is a factor of two reduction in the current time and space scales. The percentage of tornados occurring within the watch areas should be improved to approximately 60% from the current 30% for all tornadoes, and to approximately 80% for severe tornadoes. A large hail forecast accuracy of approximately 70% would represent a good forecast goal within the threat areas.

Approximately 30 minutes are normally required from the time a thunderstorm develops rotation until a funnel reaches the ground and becomes a tornado. Thus, a lead time of the order of 20 minutes is a reasonable goal for issuing tornado warnings.

The most significant forecast for **tropical cyclones** is motion prediction. The most important interval is 24 hours, for which a reasonable goal is the reduction of the forecast error from 200km to 125km. For 48-hour forecasts, the accuracy could be 250km. This improvement would result in major benefits in

coastal warning, evacuation activities, and storm preparations. Another useful forecast would be the 24-hour prediction of cyclone formation within six hours, and maximum wind speed within 5m/second.

**Flash floods** are usually the product of strong convective systems. Thus, they combine the requirements of severe storm prediction (thunderstorms and tropical cyclones) and those of smaller scale precipitation forecasting. There do not seem to be any statistics of forecasting performance for flash floods, but rather discussions of how good the forecasts have been for particular events (e.g., Big Thompson Flood in Colorado). Basing the forecast goals upon general precipitation forecasting objectives, a good target of forecast performance would be a 50% threat score for precipitation three hours before the event reaches flood proportions.

### Intermediate Scale

Improvements in forecasting accuracy on this scale are dominated by improvements in the dynamic models. In turn, these require higher grid resolutions, better description of the physics, improved initialization techniques, and more comprehensive and accurate data bases. By these means, better forecasts can be achieved of intermediate scale phenomena such as major **extratropical cyclones**, large **precipitation** systems (e.g., inter-tropical convergence zone, monsoon circulation), and large changes in the general **circulation** (e.g., **jet stream** migrations). A 30-40% reduction in the  $S_1$  skill scores would produce a near perfect representation of the tropospheric circulation 24 hours in advance. This would reduce the  $S_1$  scores for 24-hour predictions to about 30 for sea level pressure and to approximately 15 for the 500mb geopotential heights. These reductions in the  $S_1$  scores would lead to large improvements in the regular forecasts provided to the public daily by the NWS and by private forecasters.

The amount and thickness of the **cloud cover**, besides its obvious correlation with precipitation, has large effects on surface temperature forecasts. Cloud cover is also an aspect of forecasting which is very noticeable if it is incorrect. The combination of good cloud cover and circulation parameter forecasts should yield a surface temperature forecast accuracy of +2°C.

The accuracy of **precipitation** forecasting is not high, and the accuracy trend has not improved much over the past two decades. Better forecasts should result from higher resolution of measurements and sophistication of numerical models, plus a data base specifically aimed at precipitation forecasting. A good goal for 24-hour precipitation forecasting is a threat score of at least 0.7 for areas expecting up to 0.25mm of precipitation; and a threat score of at least 0.5 for areas expecting more than 250mm of precipitation.

### Climate

The most important climate forecasts concern **temperature** and **precipitation**. Forecasts should predict deviations of temperature and precipitation from normal and extend over monthly, seasonal, and annual periods. Numerous factors, e.g., solar radiation, presence of aerosols, clouds, trace gases, influence the forecast results. A good forecast goal for monthly and seasonal forecasts is an accuracy of >75% for 1 to 2 $\sigma$  deviations from the temperature and precipitation normals. A 65% accuracy for the same parameters would be acceptable for the annual forecast.

A second type of extremely valuable temperature and precipitation forecast would be the expected **trend** of the changes over very long intervals, e.g., decades. These could be estimated for some of the basic climate parameters (e.g., solar radiation). An example of a useful goal for temperature trend prediction would be that a 2°C global increase would be expected 40 years hence with +0.5°C accuracy.

A third category of climate forecasts are predictions of special parameters, e.g., ultraviolet radiation changes at the earth's surface based upon ozone trends. It is too early in the state of our knowledge to define acceptable forecast levels and forecast goals for these types of parameters.

#### D.2.5 OBSERVATION REQUIREMENTS

As indicated, atmospheric observations can be separated into three time and space scales: the small or mesoscale, the intermediate or synoptic scale, and the large or climate-related scale. Each scale requires unique sets of observations because of the special processes associated with it.

The **mesoscale** is dominated by events (e.g., thunderstorms) that are created and nurtured by processes produced by mass and wind field imbalance, creating strong gradients and rapid changes as the atmosphere struggles to return to a balanced state. The most demanding observation requirements are associated with severe thunderstorms, which can produce tornadoes, hail, and flash floods, and with tropical cyclones. Although most mesoscale phenomena are associated with strong, rapidly changing circulation features, some have quiescent characteristics (e.g., frost and freeze conditions, fog). If the requirements are satisfied for thunderstorms and tropical cyclones, just about all of the needs for other mesoscale phenomena are met.

The most demanding mesoscale observation requirements are for **temperature, moisture and wind profiles** every hour with 1km vertical resolution, from the surface to 20km altitude. The horizontal spatial resolutions should lie between 5 and 100km; the areal coverage ought to be of the order of  $10^6\text{km}^2$ . The vertical temperature profile accuracy requirement is  $+1^\circ\text{K}$ .

Other observation requirements are: 1) surface pressure, with the same coverage and temporal resolution as above, with lmb

accuracy; 2) precipitation, with a spatial resolution of 1-50km and temporal resolution of a few minutes (especially for convective precipitation); 3) cloud parameters, with spatial resolutions as high as 200m, and temporal resolutions as high as 30 seconds. More specific requirements can be found in the GOES-next Concept Study (1981).

The **synoptic** to hemispheric scale is associated with normal cyclonic (extratropical) storm development and the large scale circulation features in the middle and upper troposphere. It is the foundation for the conventional weather forecast extending for up to five days. The output from the dynamic models is the key component in the preparation of these forecasts: The quality of the corresponding observational data must be commensurate with the model's requirements of accuracy, resolution, and areal coverage. During the past two decades, dynamic models have become considerably more sophisticated. In addition to the basic global mass, moisture and kinematic fields, numerous other parameters can now be modeled, including diabatic heating, surface boundary conditions (including soil moisture), and radiation effects. By the end of the century it is expected that operational and research global models will have at least 100km spatial resolution at 20 vertical levels, requiring data in the vertical approximately every kilometer. Current forecast systems ingest data every 12 hours because the radiosondes supply the measurements at those intervals. Studies have shown that a higher data frequency will yield significantly improved results. Thus, the observation system of the future will need to ingest data at higher rates, typically every 1-6 hours.

The accuracy requirements for the synoptic to hemispheric scale are not expected to change substantially from what was specified for the Global Atmospheric Research Program (GARP) conducted in the 1970s. The specific requirements are given in the GARP planning documents.

The large, or **climate** scale requires the most comprehensive set of observation parameters, including long-term physical, chemical, and biological trends in the Earth's and atmospheric environment. This is because the ocean, the atmosphere and the biosphere function as an integrated system, and their interactions are crucial for long-term climatological phenomena. Another significant factor in climate studies, which has developed over the past several decades, is the recognition that man can alter the climate. Thus, it is important to separate natural variability from changes contributed by man.

Climate requirements span a large range of space and time scales, from regional areas and seasonal intervals to hemispheric and global ice age occurrences where the time intervals are measured in millennia. Sudden, short-time scale events (e.g., volcanic eruptions) can have a long-term effect on climate. The details as to what parameters ought to be measured and with what characteristics, e.g., resolutions, accuracies, are given in several documents related to the formation of a National Climate Program. See Reference 2 for an example.

Measurements of the **sun** are indispensable in climate studies because the transfer of energy from the sun to the earth is crucial to the climate process. The sun is the basic energy source driving the circulation of the atmosphere-ocean system. As the sun's energy enters and leaves the Earth-atmosphere system, it is affected by clouds, aerosols, trace gases, and surface reflective and absorption processes, all of which are candidates for measurement.

Research into the effects of **man-made** modification of natural atmospheric processes has been pursued to a limited extent during the past few decades. Most of the research has involved attempts to increase precipitation over local areas and to reduce the peak wind velocities in tropical cyclones. There are indications that a space-generated, Earth-directed artificial

energy source would induce worthwhile benefits in the case of atmospheric processes having relatively modest energy requirements. Modifying the temperature of the surface and/or of the lowest portion (e.g., 100m) of the atmosphere by a few degrees over limited areas would lead to favorable results in preventing and/or reducing the effects of frost and freeze, fog, pollution, and localized snow and ice melt. More specific requirements for these possibilities still need to be defined.

#### D.2.6 CURRENT STATUS OF KEY PARAMETER MEASUREMENTS

The rapid development of **remote sensing** from the ground (primarily radar) and from space has substantially contributed to the progress made by the atmospheric sciences during the last quarter century. Remote sensing can provide the coverage and resolution for many parameters that can not be practically done using **in situ** methods. Geosynchronous (GEO) satellites can perform high space-and-time resolution measurements over tropical and temperate latitudes; low altitude polar orbiting (LEO) satellites can acquire global, high spatial resolution data every 12-24 hours.

We will briefly describe the current status of the major techniques used to estimate the key atmospheric parameters, and will then use this information to identify where new technology is needed to satisfy future requirements.

**Surface temperature** is determined from LEO and GEO imaging systems using the visible, infrared and microwave portions of the spectrum. Data in the visible are the primary cloud detection method; infrared techniques assist in detecting clouds and are the primary means to measure the surface temperature. Microwave measurements are transparent to clouds; they are primarily useful over water. Infrared methods achieve accuracies of approximately  $+1^{\circ}\text{K}$  over water, with spatial resolutions as high as 1km. Microwave systems achieve similar accuracies at 100km resolution.

**Tropospheric and stratospheric temperature** profiles are determined by imaging in several infrared and microwave channels located in regions of the spectrum in which the transmission of a uniformly mixed gas (e.g., CO<sub>2</sub>) changes as a function of wavelength. The 4.3 and 15 micron CO<sub>2</sub> absorption regions are the principal infrared spectral regions that have been used. The 60 GHz O<sub>2</sub> absorption region has been employed in the microwave range. Profiling accuracies of order of 2°K over a 1km vertical average have been achieved in the 0-20km layer at spatial resolutions of 100-300km and vertical resolutions of 5-6km. Infrared techniques yield usable temperature profiles when the cloud cover is less than 60%. Microwave techniques can provide profiles everywhere except in the lowest 5-10km during heavy precipitation.

The determination of **moisture** profiles uses the same basic technique employed for measuring temperature profiles. The selected infrared regions are those where the absorption by water vapor changes significantly with wavelength. In the microwave region precipitable water has been determined using the 22 and 31 GHz channels. Infrared technique accuracies of +20-25% of relative humidity have been achieved in situations with up to 60% cloud cover, with spatial and vertical resolutions approximately the same as those for the temperature profiles in the lowest 10-15km of the atmosphere.

The **wind** field is inferred from satellite measurements by several methods. The most prevalent measures the motion of clouds from geosynchronous satellite images closely spaced in time. Wind altitude is estimated by determining the height of the cloud tops. Current accuracies are 3-8m/second. By this method, winds are mostly measured at two levels; near the boundary layer's top from cumulus clouds (which usually provide good coverage) and near the tropopause from cirrus clouds. Oceanic surface winds can be estimated from the surface wind stress on the water with approximately 2m/second accuracy. Clear

air winds above the surface have been estimated by tracking small moisture areas from a series of water vapor images from geosynchronous satellites.

Satellites provide perhaps the best method of measuring the amount, type, and elevation of **clouds**. Radiometric and stereographic methods can yield elevation accuracies of 1km or better (<500m for stereo). Multispectral radiometric techniques have been used globally from low orbiting satellites; the stereographic method uses two separated geosynchronous satellites simultaneously viewing a common area. Cloud cover can be determined with 10% accuracy when the spatial resolution of the data is of order of 1km.

**Precipitation** rates over water are estimated from passive microwave measurements. The microwave energy emitted at 19GHz from the precipitating particles exceeds that from the water background with its relatively low emissivity. The best results occur when the precipitation is stratiform and covers extensive areas and whenever the precipitation rate is relatively light compared with the rate in convective rain. Over land, convective rain cores can be identified and rain rates estimated from 37GHz space radiation reflected from the large ice particles associated with the heavier precipitation areas. A more indirect method estimates the precipitation rate (primarily for large areas of convective rain) from visible and/or infrared imagery; the rates and coverages are estimated from the aerial extent and altitude of the clouds. Over large areas the accuracy of these techniques is approximately +50%.

Measurements of total emitted and reflected **radiation** measurements have been periodically effected from satellites since 1959. Albedo and total emitted energy have been estimated from data covering the full spectral ranges of the reflected and emitted energy; or have been determined from higher spatial resolution and narrower spectral interval data. The albedo of the

Earth has been estimated at slightly less than 30% (it turned out to be lower than the presatellite estimates); and the effective radiative temperature of the Earth turned out to be higher than the estimates preceding the advent of satellite data.

The extent and boundaries of **snow** and **ice** are estimated by various, visible, infrared, and microwave imaging sensors. The accuracy is dominated by the spatial resolution of the instrument and is typically 1-5% of the actual areal extent of the cover. The elevation of ice over land is estimated to within 50cm from altimeters. Areas of melting ice and the water content of snow (to an accuracy of 3cm H<sub>2</sub>O) have been determined from microwave data. Land ice accumulation rates can also be measured from microwave data.

**Soil moisture** is determined from passive microwave measurements to an accuracy of approximately 30% by evaluating the changes in emissivity associated with a moist versus a dry surface. For areas with little or no vegetation, diurnal changes of temperature associated with wet and dry soil produce approximately 30% accuracy. Precipitation estimates are also used as a proxy indicator for determining soil moisture.

For **aerosols**, the tropospheric optical depth and stratospheric extinctions have been estimated from satellites using imagers in LEO and GEO. The aerosol information is also needed for atmospheric corrections to improve the estimates of terrestrial parameters. Stratospheric extinction coefficients between cloud top and 70km altitude have been estimated with 200km horizontal resolution with an accuracy of  $5 \times 10^{-6}$  /km.

Many **trace gases** in the troposphere and stratosphere (e.g., ozone, nitrous oxide, nitric oxide, methane) have been measured from satellites. **Ozone** profiles have been estimated using diverse sensors with 5-10% accuracy. The total **ozone** data have been useful for beginning to examine the possible effects of man's activities on the ozone layer.

Pressure measurements have not been made from satellites although there are concepts under study. Active techniques are required.

Major Deficiencies and What Current Planned  
Technology Is Expected to Satisfy

Although remote measurements from space in support of the atmospheric sciences have led to impressive results, there remain many unfulfilled requirements. Some of these can be satisfied with predictable future technology. For others, new technology is needed. We will consider initially what **advances** can be expected from the anticipated technology over the next **5-15 years**. Next we will discuss what is needed beyond the beginning of the next century.

The greatest deficiencies in remotely measuring the atmosphere are still associated with the most basic parameters: **pressure, temperature, moisture, wind, and precipitation**. Most of the deficiencies are caused by the **indirect** measurement methods currently used, by interference from clouds, and by the **coarseness** of currently achievable horizontal and vertical **resolutions**.

The present methods of temperature and moisture profiling exploit received passive energy within selected spectral channels. The spectral width of channels are broad: each spans several individual absorption lines. These relatively **low spectral** resolutions result in vertical resolutions of the order of **5-6km**, as compared to the resolutions achievable from radiosondes which are substantially better than **1km**. Vertical resolutions of **1km** or less are needed for accurate temperature profiling (order of  $\pm 1^\circ\text{K}$ ), to allow the determination of the atmosphere's fine structure so as to enable the delineation of significant features such as inversions, depth of the boundary layer and tropopause heights. Infrared profiling techniques provide the highest vertical resolution and accuracy (the latter

is related to resolution) in the lower and middle troposphere; whereas microwave methods provide the best vertical resolution in the upper troposphere and stratosphere. Infrared methods can not reliably yield profiles below the cloud tops when the cloud cover exceeds 60%; 60GHz microwave temperature profiles are usable under all cloud cover conditions, except where and when heavy precipitation is falling. The cloud interference problem is very important: It is especially serious for small scale and/or rapidly changing meteorological events since clouds usually cover a sizable percentage of the crucial areas.

The vertical resolution of passive **infrared** techniques for temperature and moisture profiling can be improved to approximately 3-4km (in clear and partly cloudy areas) by **increasing the spectral** resolution of the measuring channels by approximately one order of magnitude over what is now flown so as to approach the spacing of the individual atmospheric absorption lines. Instruments with improved spectral resolution have been designed for both LEO and GEO satellites. Spatial resolutions as high as 8km are planned to reduce cloud interference effects.

Passive **microwave** profiling requires significant **improvements** in vertical and horizontal **resolution**. The current horizontal resolution at the nadir of LEO microwave profiles is 110km. Improvement to 50km is planned. For the first time, the planned instrument will include water vapor profiling at 183 GHz. The spatial resolution of LEO sensors is signal-to-noise limited, because of the limited integration times possible from low orbits. No microwave measurements have been made from GEO, but instruments have been designed. Sensors in GEO are diffraction-limited because integration time is not a serious problem. A 4m GEO antenna could provide a 30km temperature profile resolution at 118GHz, and a 20km moisture profile resolution at 183GHz. At present, there is no known way to improve further the vertical resolution of passive microwave profiles.

**Active** profiling methods (e.g., **lidar**) offer a technique for improving vertical resolution. The backscatter of laser light from aerosols can provide 1-2km vertical resolution in atmospheric layers where the aerosol concentration is sufficiently high, probably in the lowest 10-15km. The expected horizontal resolution from sensors in LEO is approximately 200 km. This is a low figure: Whereas individual laser pulses have much higher resolution, numerous pulses are necessary to obtain a profile; further, clouds do interfere.

The accuracy of **surface temperature** measurements is limited over water by clouds and by the uncertainty in the knowledge of the intervening atmosphere. Over land, it is restricted by these factors, plus the uncertainty in the true values of surface emissivities. The cloud and intervening atmospheric effects (mostly water vapor) can be reduced with either very high resolution (1km or less) visible and infrared instruments and/or microwave sensors. As yet insufficiently known is the effect of instrument response time on infrared measurements associated with large and sudden changes of scene radiance (e.g., scene change from clouds to the surface). Over land, there is currently no known method to separate emissivity from skin heating effects in order to measure the true air temperature near the surface.

Measurements of **wind velocity** depend on the relationship between **cloud** and **wind** motion; or upon even more indirect approaches (e.g., sea state as a function of wind velocity). The cloud motion-wind relationship is reasonably good (1-3m/second) for most clouds, yet the technique is obviously restricted to areas where clouds are present. The performance of the cloud motion technique will be improved with the next generation GOES satellite, primarily by means of higher resolution infrared channels to assist night-time cloud tracking. The stereographic cloud top height measurement technique enhances substantially the accuracy of measurement of cloud moisture winds during the day-time. The new techniques can improve the accuracy to 1-3m/sec.

The problem of measuring **"clear air" winds** remain. The water vapor tracking technique has been tried; yet the wind-water vapor motion relationship is not as good as the cloud motion-wind comparison. The water vapor motions measured from satellites represent a layer a few kilometers deep which, if there is a reasonable amount of vertical wind shear, does not accurately represent the wind at any particular level in the layer. A potential technique under study for measuring clear air winds is the use of aerosol backscatter from doppler lidar on LEO satellites. This method is expected to produce 200km horizontal resolution and 1km vertical resolution of winds every 24 hours, with 1-2m/second accuracy in areas sufficiently clear of clouds to accommodate the required number of laser pulses to provide an adequate signal.

**Precipitation** totals and rates are **difficult** to measure with current techniques. Even ground-based rain gauges do not generally provide the horizontal resolution needed to accurately represent the areal distribution of rainfall totals or rates (especially in cases of convective precipitation). Remote rainfall estimation techniques (e.g., radar) are based upon assumed average drop size distributions; small errors in the assumption magnify the errors of estimate, because of the more-than-linear dependence between precipitation rate and the measured radar return. Use of radar has been proposed for LEO satellites: This should substantially improve the results of passive microwave systems, especially over land. Spaceborne radars must separate the ground return from the precipitation backscatter. From LEO, they can sense the same location at most once every 12 hours (usually considerably less due to viewing angle constraints). GEO passive microwave sensors would provide more timely data: Their combination with ground radar and with visible and infrared measurements of higher spatial resolution should yield good accuracies. However, GEO measurements will provide relatively low resolution (20km for a 4m antenna) and must use the higher frequencies (e.g., 90-180GHz), which are less desirable than the

low frequencies (e.g., 19GHz) usable on LEO. The low frequencies measure the energy emitted from the rain: At the higher frequencies, the rain rate is inferred from energy backscattered from the ice layer above the rain--a less direct approach.

Accurate **rain cloud** measurements are strongly affected by the sensor's spatial **resolution** and the utilization of multispectral techniques. Achievement of accuracy of  $\pm 5\%$  of cloud cover requires spatial resolutions no greater than 200m for most cloud situations--unless cloud type can be independently determined; in this case, multispectral methods are needed to estimate the cloud cover. The estimation of cloud type requires either sufficient resolution (20-200m) such that cloud texture characteristics can be discerned or the use of multispectral methods. Stereo from GEO can measure cloud top heights with approximately  $\pm R/2$  accuracy, where R is the sensor's spatial resolution, and when the separation between satellites is approximately  $60^\circ$  of longitude. Infrared methods are temperature dependent: Accuracies of 500m are possible when the radiometer's field of view is filled, the cloud is in the lower and middle troposphere and the cloud emissivity approaches unity. The analysis of deep convective cloud (one of the most important cloud measurements) is difficult, because IR systems often penetrate well into the upper troposphere or the lower stratosphere where temperature profiles are difficult to interpret. If all measurement parameters are equal, measurements from GEO are best for clouds, since the cloud's large diurnal changes can be captured. The higher spatial resolutions available in the infrared channels on the GOES-Next mission, along with the channel's high radiometric sensitivity, should lead to significant improvements in the calculation of cloud parameters.

The estimation of **soil moisture** with **infrared** techniques requires separating the changes in surface moisture from the effects of other variables, including vegetation, surface emis-

sivity and wind. Because the surface emissivity changes substantially as a function of soil moisture, microwave methods have the most promise although they are still affected by some of the factors listed above. The best wavelength tested thus far is in the 20cm range (1-2GHz). Use of this wavelength requires large antennas to achieve the desired resolutions of a few kilometers. No such large antennas have as yet been flown, although they have been proposed for the next decade.

There are **other** atmospheric and/or terrestrial parameters where substantial measurement deficiencies exist. Some of these would greatly benefit from higher spatial resolution (e.g., snow and ice), others would be advantaged by improved capability to measure at night (e.g., ozone profiles). For these, known or needed technological advances to overcome the current measurement deficiencies are discussed in the next section.

#### D.2.7 FUTURE TECHNOLOGY REQUIREMENTS

##### General

Several technological developments are needed to achieve the 2000-2025 forecast goals stated in Section D.2.4. The dominant technological requirements for GEO observation systems are centered upon achieving higher spatial resolutions. Secondary emphasis is on improved spectral resolution and on techniques for combining areal coverage with temporal resolution. For LEO systems, the requirement focus is the development of sensors to improve the vertical resolution of profiles, to measure parameters more directly (e.g., radar), and to improve spatial resolutions. Much of the LEO technology requirements are centered upon active sensors (e.g., lidar, radar).

The establishment of a space station during the 1990s offers opportunities to assemble, calibrate, repair, and service instruments and to involve manned participation in certain key experi-

ments. An area that should receive attention is the possibility of manufacturing less expensive sensors in a modular fashion to allow testing and easy interchange of components in space. This may reduce the overall costs of instruments, which have become the most expensive component of earth atmosphere observing space systems.

In addition to the new instrument technologies, there is a strong requirement for improved methods of transmitting, storing, analyzing, and disseminating in real-time the vast amounts of information that will be provided from the new sensors. Data rates of 1-10 gigabits/second are anticipated in the first quarter of the next century. Thus, archival systems capable of storing up to  $10^{17}$  bits per year will be needed, providing ready accessibility. Further developments of interactive systems are considered to be key to the effective analysis of this large volume of data. Interactive systems could be important in performing space station experiments using remote links between ground based experimenters and astronauts.

The data dissemination system of the early 21st century should allow any person with a terminal to access a distribution center to receive any level of information, ranging from real time data to geophysical parameters. This level of capability should allow NASA products to reach the high school level during the first quarter of the next century.

### Technology Requirements for Geosynchronous Orbit

We will discuss the requirements from two perspectives: what new and/or improved **sensors** are needed (some of which have been studied); and what **mission** characteristics (e.g., attitude control and pointing) are required to accommodate the sensors.

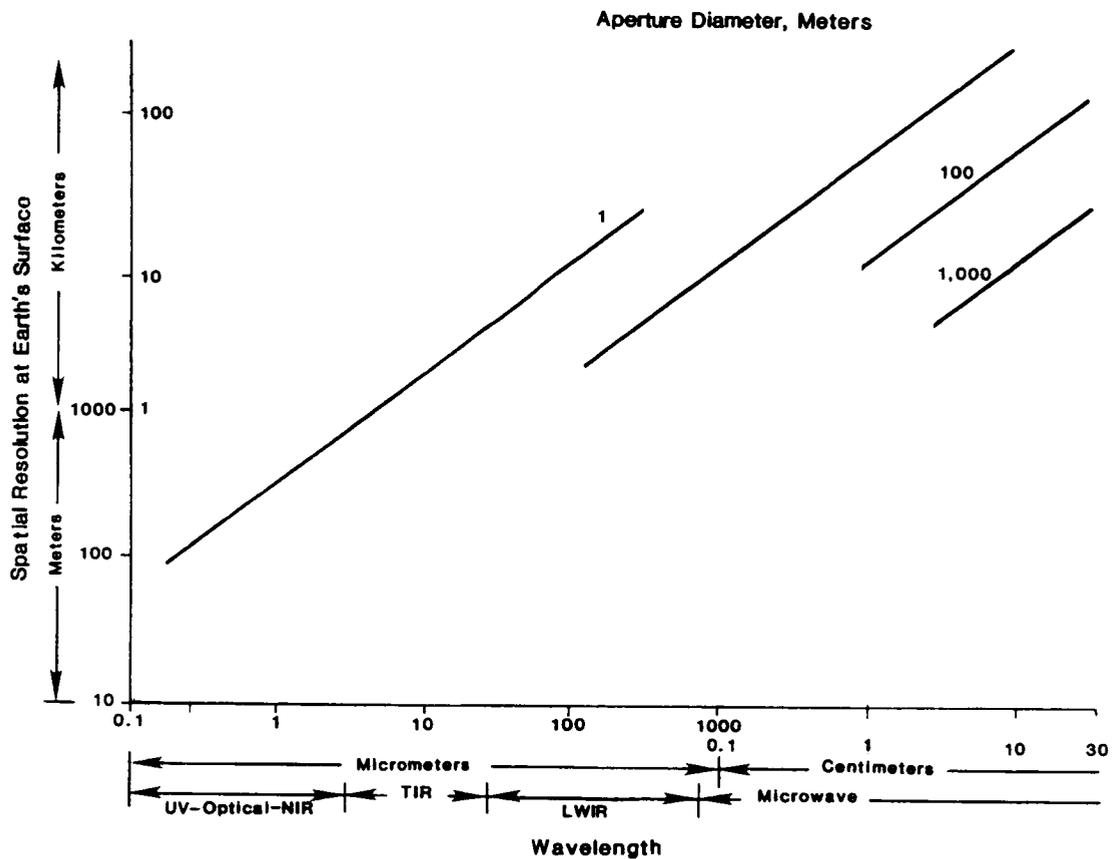
The achievement of high spatial **resolutions** from GEO--from the ultraviolet through the microwave spectrum--requires large

**telescopes** and **antennas** because of diffraction limits. Figure 2-1 shows the optical diameters required from GEO as a function of the spatial resolution achievable at or near the Earth's surface. The curves of Figure 2-1 were constructed using a practical formulation for the overall system resolution (twice Airy's limit).

Accurate surface temperature and cloud measurements at rapid intervals require a large imaging telescope. Figure 2-1 shows that to achieve the required resolution of 1km at 11 microns (thermal infrared), a diffraction-limited telescope with an approximate diameter of at least 1m is required, possibly somewhat larger (in the 1-2m range) so to achieve 1km resolution in the middle latitudes, well away from nadir. This telescope is larger than the current GEOS imager or what is planned for the GEOS-Next mission. Areal detector arrays could achieve the required coverage of the order of  $10^6\text{km}^2$  in a few seconds.

The 200m visible resolution requirement would be easily satisfied by the above suggested telescope. Moreover, 50-100m resolutions in the visible would be possible for earth resources applications. Telescopes of this size are currently technologically feasible (e.g., the 2.2m Hubble space telescope). If two such telescopes could survey the same area simultaneously, stereo would be possible, providing cloud top accuracies of 200-500m at night from the infrared channels, and 100m during the day from the visible channels. Another use for the large telescope would be to implement an independent, daytime temperature cloud height measurements using differential absorption in the region around 0.7 microns. This technique also requires very high spectral resolution.

The achievement of 1km spatial resolution in the microwave spectrum for accurate precipitation measurements and cloud tracking beneath cirrus clouds is a considerably more challenging task. At the low microwave wavelengths, e.g., 1.5mm, the antenna diameter needs to be 100m for a 1km nadir resolution. The antenna diameter would grow to 500-1000m at the 8 and 15mm



**Figure 2-1. GEO Aperture Diameter Versus Spatial Resolution and Wavelength**

Calculation of diffraction limited telescope/antenna size for sensors in geosynchronous orbit using  $\sigma = 2.44\lambda/D$ . The diagonal lines represent the required optical diameter to achieve the spatial resolutions along the ordinate at the wavelengths shown along the abscissa.

wavelengths, respectively, which have already been used for mapping precipitation areas over land and water. Use of even higher frequencies to reduce the antenna size would mean consideration of the 0.6mm spectral region for temperature profiling using an O<sub>2</sub> absorption band. At this wavelength, it will be necessary to carefully evaluate the effect of clouds on the determination of profiles. Since the highest surface spatial resolution requirement for vertical profiling is 5km, the antenna diameter at this wavelength could be around 10m. The substantial antenna diameters required to achieve high resolution microwave measurements, suggest that an exhaustive search be made to explore the as yet poorly known spectral range from 20-1000 microns to assess its potential value to atmospheric remote observations.

Deployment of **large antennas** in GEO is a challenging technological task for at least two reasons. First is the assembly of such large antennas. The space shuttle would probably have to ferry them in sections; they would almost certainly be assembled in LEO prior to boost into GEO. The second challenge is posed by the required antenna surface tolerance of order of 1/20th of a wavelength. This is not only difficult to accomplish in the initial construction phase: the tolerances are also affected by orbital environmental stresses (e.g., differential heating on the antenna surface). A potential substitute for single large antennas are incoherent techniques in which an array of smaller antennas might perform the same function as a coherent signal from a single large antenna. These techniques are currently under investigation.

A key adjunct to large apertures for obtaining better vertical resolution of infrared temperature and moisture profiling methods is to improve the **spectral** resolution to the point where the "wings" of the individual absorption lines become usable. This should enhance the vertical resolution to approximately 2km. It represents an order-of-magnitude improvement of

spectral resolution above and beyond the current designs. What is needed is to bring the resolution to  $0.2 \text{ cm}^{-1}$  in the 4.3 micron  $\text{CO}_2$  band. The integration time needed by sensors with this level of spectral resolution is high. Thus the technique is probably best suited for GEO satellites where long integration times are possible. Development of improved infrared detection arrays is important to reduce the dwell time.

Another major technological arena is associated with space-based energy sources for possible contribution to weather modification in cases where only relatively small amounts of energy are required. Techniques ranging from using reflected light to transmitting microwave energy need to be studied. Large reflectors, solar arrays and microwave antennas could be part of the system.

The second major performance consideration in GEO is the attitude control and determination system. The most demanding needs would be associated with the large imaging telescope. Accurate cloud motion calculations would require attitude determination of approximately 5 microradians over a 3 minute period. Absolute location accuracy of 1km is needed.

#### Technology Requirements from Low Earth Orbit

The requirements in LEO are for the development of **active** sensing methods and techniques to improve spatial resolution. The first would lead to better vertical resolution of profiles and more direct measurement of precipitation (e.g., radar). The second concerns methods for obtaining sufficient energy since diffraction is usually not the problem.

Attainment of sufficient on-board transmitter **power** is a major concern for the active methods. The double path techniques impose a power-law dependence of the loss between transmitted and received energy and the transmitter-to-target range (cube-law if

the target "fills the beam"). With current designs, hundreds of lidar shots are required to achieve a sufficient signal for a single temperature, pressure, and moisture profile. Spatial resolution suffers as a result--clouds cause a major impact since so many clear paths must be found. The high vertical resolution that can be achieved is compatible with desired higher spatial resolutions. Techniques to achieve higher transmitted power and/or greater receiver sensitivity are needed. Another technological area worth considering is how to exploit the backscatter principle in cloudy areas.

A particular area of concern for lidar is the number of pulses prior to failure. This number is now  $10^7$ - $10^9$ , meaning that typical apparatus lifetimes last only months. Lidar pulse requirements need to be increased to approximately  $10^{12}$  pulses to insure multi-year operation.

Typical LEO altitudes are approximately 50 times closer to the Earth's surface than GEO. Therefore, diffraction limits do not pose great problems except at very long wavelengths, e.g., 20cm. For example, if the diffraction limited telescope/antenna diameters in Figure 2-1 are divided by 50, only a 2m antenna would be needed to achieve a 1km resolution in the 1.5mm microwave range. Visible and most infrared measurements require small telescopes, less than 1m, for resolutions of 10m. However, since the spacecraft moves at 24,000-28,000km/hour relative to the Earth, sensor dwell times are short. The continued development of array technology is required to achieve higher spatial resolutions and to acquire sufficient signal energy. Multiple feed technology development in the microwave is needed for the same reason.

The precise **calibration** of sensors, necessary for all atmospheric observations, is particularly vital for measurements related to climate. Since inferences regarding climate processes are often made based upon parameter changes of a few tenths of a

percent (some of which may be caused by man), it is obvious that unknown measurement errors could lead to disastrous results. A space-based calibration facility needs to be available to constantly update the performance of sensors. Most climate-oriented sensors will be in LEO, with some in GEO. Thus such a space calibration facility should be available for both LEO and GEO sensors.

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**D.3 SPACE COMMUNICATIONS SERVING  
EARTH-BASED CUSTOMERS**

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## D.3 SPACE COMMUNICATIONS SERVING EARTH-BASED CUSTOMERS

### D.3.1 SIGNIFICANCE

The burgeoning demand for satellite communications for international and domestic voice, data and direct television broadcasting use is placing severe strains on two basic resources: available space in the geostationary arc and the radio frequency spectrum allocated for communications and broadcasting. Demand projections for satellite communication services indicate that, with current technology, spectrum saturation of current and planned satellite systems, in particular U.S. domestic C (6/4GHz) and  $K_u$  band (14/11GHz) systems, will occur in the early 1990s. Simple addition of the number of current and planned U.S. and Canadian DOMSATS in these bands points to a severe overcrowding of the North American geostationary arc in the same time frame. Answers to these twin problems of orbital arc overcrowding and spectrum saturation must be found to handle the traffic demands of the 1990s.

The purpose of this report is to identify and evaluate the system concepts and technologies that are most relevant to the development of next generation U.S. domestic satellite communication systems and that may become candidates for implementation. Because new development programs should reflect market demands and state-of-the-art technology, both aspects are surveyed and integrated in this report. The thrust is on technologies in the  $K_a$  band (30/20GHz) that appear to offer the best alternative to the present systems for meeting the demands in the 1990s.

The scope of this study is limited to the investigation of satellite systems for domestic applications. It is recognized that future improvements in the technology of terrestrial systems, such as fiber optics systems, will also compete for the lucrative communications market, in particular the domestic

market. Already single optical fibers have been shown to be capable of carrying data rates in excess of a gigabit with repeater spacings of about 25km. Thus a few fibers would be able to handle a large fraction of the domestic traffic. In 1988, the first transatlantic fiber optic cable is scheduled to go into service, with a capacity of more than 32,000 voice circuits. The inherent capacity of fiber optic cables is so high that this medium of communications cannot but influence greatly the satellite communications market of the future. The division of traffic between terrestrial and space links will depend upon the relative cost. Since satellite costs are independent of distance, there is, in general, some distance beyond which satellite links would be less expensive than the distance-dependent terrestrial-link costs.

#### D.3.2 THE COMMUNICATIONS EXPLOSION

A phenomenal growth in the use of communication satellites has occurred since the launch of the first commercial Early Bird in April 1966. In barely 15 years, the worldwide commercial INTELSAT system has progressed through six generations of increasingly higher capacity satellites (Table 3-1) to keep pace with the growing traffic demand. In 1983, INTELSAT's space segment consisted of 18 satellites providing communications to over 600 earth stations spread over many nations. Some 30,000 voice circuits are in full-time use in the INTELSAT system today. By 1987, a single INTELSAT VI satellite will have a capacity of 33,000 voice circuits--a far cry from the 140 voice circuits provided by Early Bird in 1966. The INTELSAT VI series purchase will raise the cumulative INTELSAT purchases--satellites plus launches--to almost \$3 billion in current dollars.

The demand for satellite communications is increasing worldwide, with the Western Hemisphere generating the bulk of the traffic. The early 1980s has been the era of an explosion in U.S. domestic satellite communications (DOMSATS) for commercial

TABLE 3-1

GENERATIONS OF COMMUNICATIONS SATELLITES

	INTELSAT I	INTELSAT II	INTELSAT III	INTELSAT IV	INTELSAT	INTELSAT V	INTELSAT VI
							
YEAR OF FIRST LAUNCH	1965	1967	1968	1971	1975	1979	1986
HEIGHT (cm)	60	67	104	528	500	1570	1180
WEIGHT IN ORBIT (kg)	38	66	152	700	790	967	1670
ELECTRICAL POWER(KW)	0.04	0.075	0.120	0.400	0.500	1.200	2.264
CAPACITY (TELEPHONE CIRCUITS)	240	240	1,200	4,000	6,000	12,000	33,000
DESIGN LIFETIME (YEARS)	1.5	3	5	7	7	7	7
INVESTMENT COST PER CIRCUIT YEAR	\$32,500	\$11,400	\$2,000	\$1,200	\$1,100	\$800	\$662
COST PER S/C ON ORBIT (MILLIONS OF \$)	11.7	8.2	12.2	33.6	46.2	67.2	153
COST PER TRANSPONDER YEAR (THOUSANDS OF '82 \$)	12,480	4,180	1,710	1,020	620	530	440

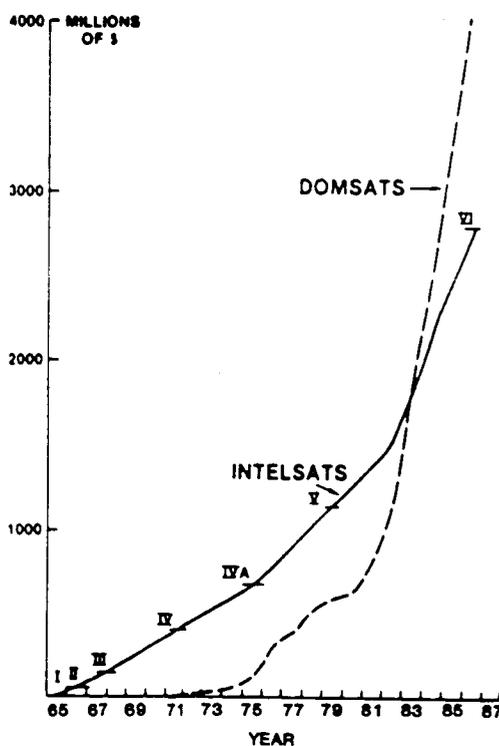


Figure 3-1. Cumulative Buys of Commercial Satellites

voice/data and television distribution from space. More than 40 U.S. DOMSATS will be in orbit by 1987, with the total cumulative investment approaching \$3 billion. Satellite purchases for domestic applications began seven years later than those of INTELSAT, but the cumulative sales (Figure 3-1) are expected to exceed those of INTELSAT by the mid 1980s. In future years, the DOMSAT market promises to grow much more rapidly than INTELSAT's. Figure 3-2 shows the launch schedules of INTELSATs and North American DOMSATS in orbit or under construction.

Direct broadcast satellites (DBS) are the most recent applications of the rapidly growing DOMSAT business in the U.S. and Canada. The Federal Communications Commission (FCC) has granted petitions of eight DBS applicants for television distribution to receive-only earth stations in the U.S. In a related action, the FCC in 1983 authorized the construction and launch of 19 additional DOMSATS to join the 20 satellites now serving the U.S. and Canada.

The U.S. industry has played an important role in creating a marketplace for satellite communications in numerous countries. Figure 3-3 illustrates the past, present and future procurements of communications and direct broadcast satellites on a global basis. This fast growing business which began in the mid 1960s with the INTELSAT satellites and progressed in the 1970s along with the growth of DOMSATS, is expected to drive an "explosion" in satellite technology and procurement in the 1980s. Current commercial satellites represent a very high state of technology, achieved through significant advances in antenna technology, improved reliability of satellite propulsion systems and on-board electronics. As the capability of the space segment is increasing, a very exciting and expanding marketplace in low-cost, small antenna Earth stations is rapidly emerging. Proponents of DBS are projecting a population of small receive-only earth terminals by the hundreds of thousands in the 1980s. The investment in the North American earth-segment market alone is expected to reach several billion dollars by the end of this decade.

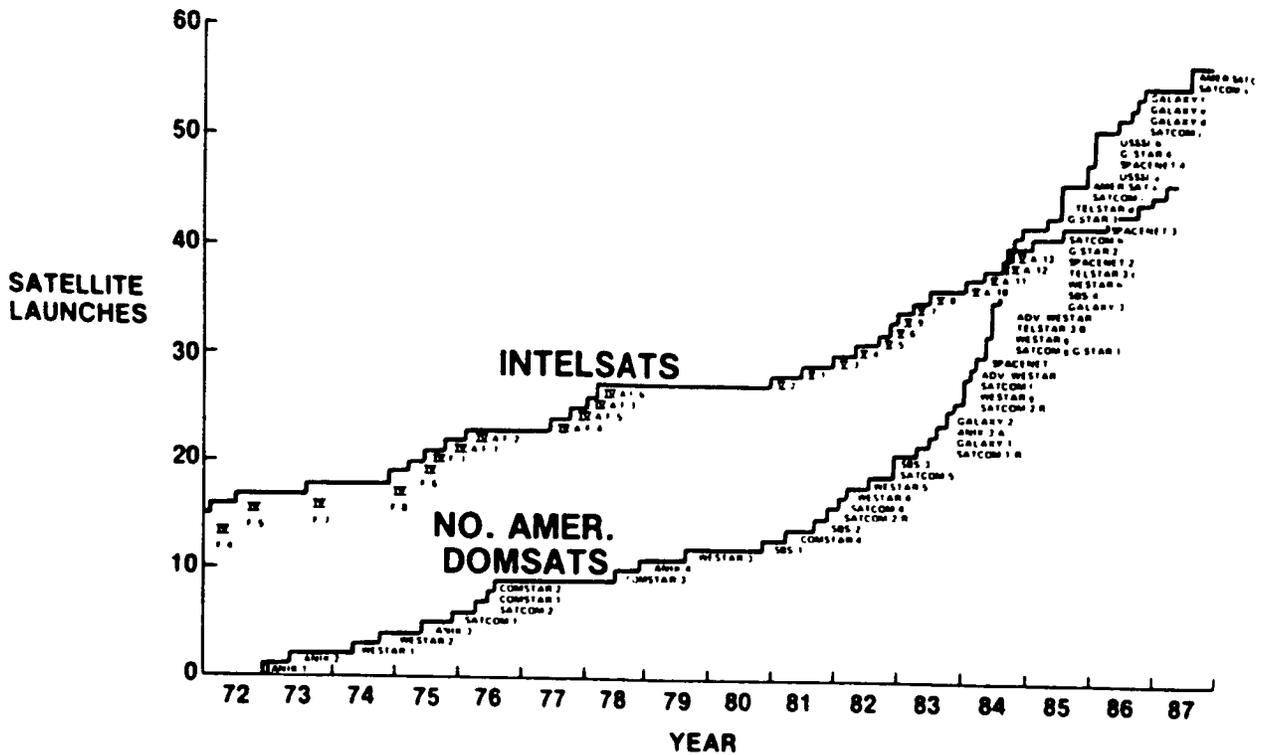


Figure 3-2. Launch Schedules of Intelsat and North American Domsats (Lovell & Fordyce)

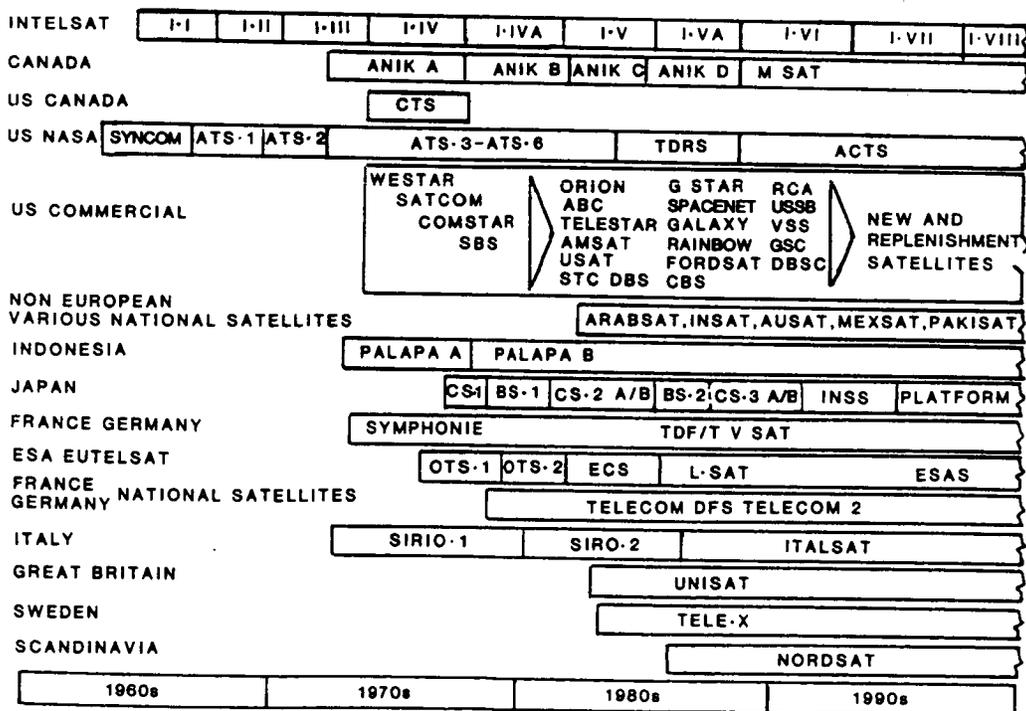


Figure 3-3. Global Procurement Of SATCOM/DBS (Lovell & Cuccia)

Architectures for next generation commercial satellite telecommunication systems must provide an increase in traffic capacity by more than an order of magnitude. Higher EHF bands appear to be a good alternative for meeting the demands of the 1990s.

### D.3.3 TRAFFIC PROJECTIONS AND ORBITAL ARC CAPABILITY

Market forecasts by the communication carriers and NASA (Ref. 1, 3, 4) indicate a rapid worldwide growth in demand for voice, data and television distribution from space. As shown in Table 3-2, the global satellite traffic is projected to approach 2400 "equivalent 36MHz transponders" by 1990, and over 10,000 by the year 2000. Projections of the U.S. domestic requirements by ITT (Ref. 2) are shown in Table 3-3. They indicate a growth in satellite traffic to 50Gbps by 1990 and 125Gbps by 2000. Assuming a 36MHz transponder can carry 42Mbps, the domestic requirement translates to approximately 1200 equivalent transponders in 1990 and 2900 transponders by the year 2000. The ITT demand assessments are conservative, because they are projections of existing services and do not include additional capacity necessary for providing new services, such as land-mobile communications, computer internetting, video conferencing, and emerging new needs for government communications. It is conjectured that the demand for DOMSAT services could grow to 5000 equivalent transponders by the year 2000.

The orbital arc suitable for deploying DOMSATs in relation to the North and South American continents is shown in Figure 3-4. The segment of the geostationary arc serving the continental United States (48 states) with elevation angles above five degrees lies between 60 and 140 West longitude. For simultaneous coverage of all the 50 states, the usable segment shrinks to 100° W to 140° W. A nominal intersatellite spacing of four degrees at C band and three degrees at  $K_u$  band leads to only ten and 13 orbital slots, respectively, for U.S. coverage. Since 500 MHz of bandwidth is allocated for domestic communications in both C and

TABLE 3-2

PRESENT AND PROJECT GLOBAL SATELLITE TRAFFIC  
REGIONAL AND DOMESTIC

EQUIVALENT 36MHz TRANSPONDERS			
	<u>1980</u>	<u>1990</u>	<u>2000</u>
VOICE	256	1316	4736
DATA	—	440	2728
VIDEO	55	503	2592
VIDEO CONFERENCING	—	<u>130</u>	<u>474</u>
TOTAL	311	2389	10530

SOURCE: LOVELL & CUCCIA

TABLE 3-3

TOTAL PRESENT AND PROJECT  
U.S. DOMESTIC TRAFFIC

	<u>1980</u>	<u>1990</u>	<u>2000</u>
VOICE (Mbps)	876	16215	51175
DATA (Mbps)	207	25435	47312
VIDEO (Mbps)	<u>1446</u>	<u>7952</u>	<u>22782</u>
TOTAL (Mbps)	2529	49602	121275
NO. OF 36MHz TRANSPONDERS <sup>a</sup>	60	1182	2887

<sup>a</sup> ONE 36MHz TRANSPONDER CAPACITY - 42Mbps

SOURCE: ITT - 1979

Available Orbital Arc For U.S. And Canada  
Domestic Communications Satellites

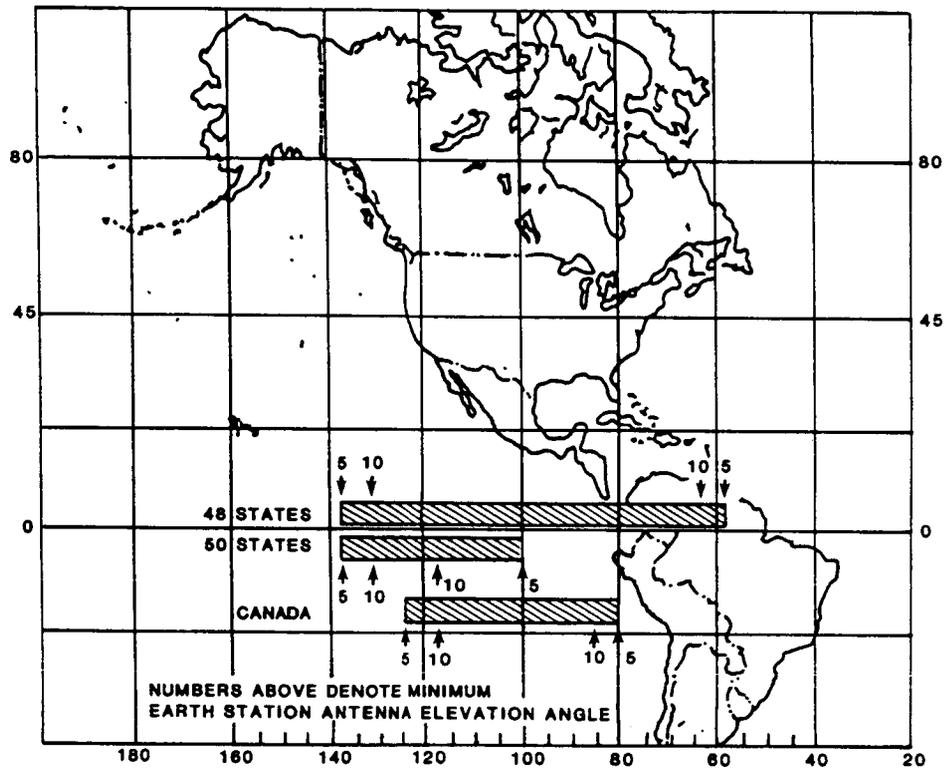


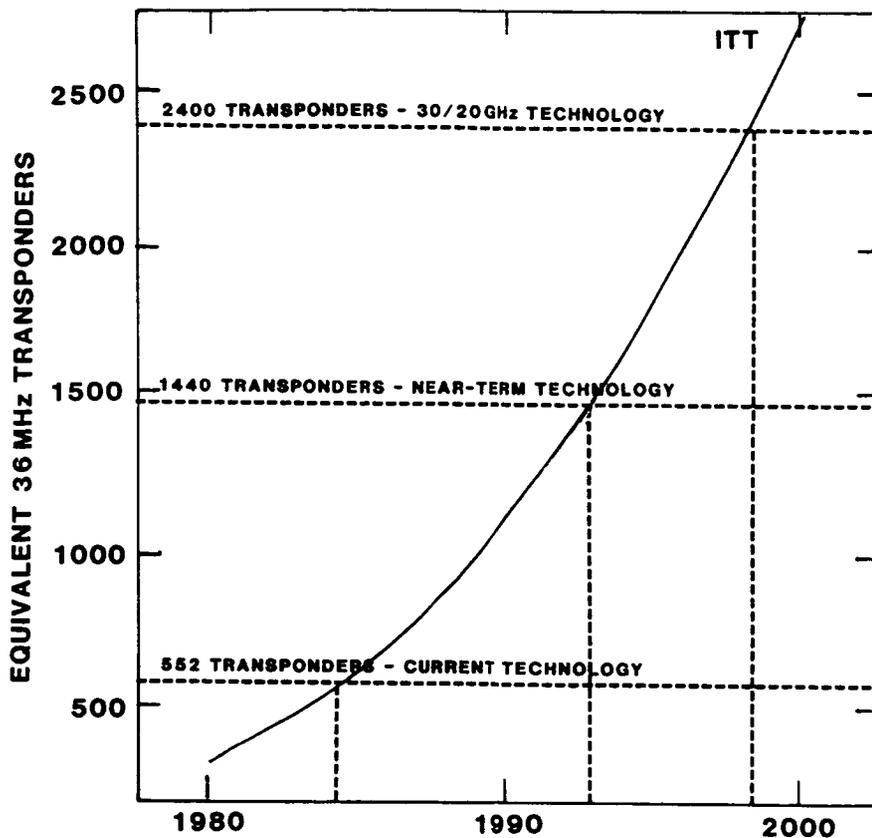
Figure 3-4. Geostationary Arc For U.S. And Canada

$K_u$  bands, with frequency reuse by dual polarization (in both bands), each orbital slot will have a spectrum capability of 1GHz or 24 equivalent transponders. The resultant capability of the orbital arc, with ten slots at C and 13 slots at  $K_u$  for U.S. coverage, is then 23GHz or 552 equivalent transponders. Figure 3-5 shows that, with current technology C and  $K_u$  band systems, saturation of the American arc would occur in the mid 1980s.

There is a strong trend to reduce the intersatellite spacing to two degrees at C band (the FCC has granted two degree spacing at  $K_u$  band in 1983) to provide relief from this impending saturation. Additionally, the use of spatial diversity is suggested at  $K_u$  band for spectrum reuse. The total orbital arc capability, with two degree satellite spacing, dual polarization, and dual spatial diversity (at  $K_u$  band only), leads to a total arc capability (Figure 3-6) of 1440 equivalent transponders. With these near-term improvements, the era of saturation of the orbital arc for U.S. coverage is extended to the early 1990s (Figure 3-5).

#### D.3.4 SYSTEM CONCEPTS AND ALLEVIATING TECHNOLOGIES

It is clear that current or near-term satellite technologies will not satisfy the forecasted demands of the 1990s and beyond. The solution to the potential spectrum and orbital arc saturation problem lies in the development of satellite technologies that would allow multiple-frequency reuse, so that the available spectrum can be used simultaneously in several different geographic areas for each orbital slot. This can be accomplished by DOMSATs using several independent spot beams, each beam providing full spectrum reuse through spatial discrimination. Narrow spot beams can be realized through the use of higher frequencies, in conventionally sized spacecraft antennas, or the employment of large aperture antennas on the satellite.



**Figure 3-5. Projected US Domestic Traffic Needs**

	Allocated Bandwidth		Polarization Diversity		Spatial Diversity		Orbit Slots		Geostationary Arc Capability
C Band	500MHz	X	2	X	1	X	20	=	20 GHz (480 Transponders)
K <sub>u</sub> Band	500MHz	X	2	X	2	X	20	=	40 GHz (960 Transponders)
Total Geostationary Arc Capability								=	60 GHz (1440 Transponders)

★ Assumption: Twelve 36 MHz Transponders Per 500 MHz Bandwidth

**Figure 3-6 Geostationary Arc Capability For U.S. Coverage With Near-Term C And K<sub>u</sub> Band Systems**

Space is a good environment for the deployment of large structures because aerodynamic drag is almost absent and gravity gradient forces are small. It is likely that an antenna, 150 to 200 feet in diameter and weighing less than 2000 pounds, can be erected in space. Up to the end of the century, use of higher frequencies, appears to be better alternative in the long run for commercial domestic applications. In addition to relieving the spectrum congestion and sharing problems between satellite and terrestrial radio-relay systems in the lower C and  $K_u$  bands, higher frequency DOMSATs can be more closely spaced, thereby providing more orbital slots. Intersatellite spacings on the order of one degree have been suggested for  $K_a$  band systems. Such a separation would provide 40 orbital slots within the prime North American arc for U.S. coverage (100°W to 140°W).

Assuming conservatively a five-fold reuse of the available 2500MHz bandwidth in the  $K_a$  band through spatial discrimination, each orbital slot will be able to support 12.5GHz of bandwidth or 300 equivalent transponders. Eight orbital slots will provide 100GHz of bandwidth (2400 transponders), which should be adequate (Figure 3-5) to meet the projected domestic telecommunication needs in the 1990s.

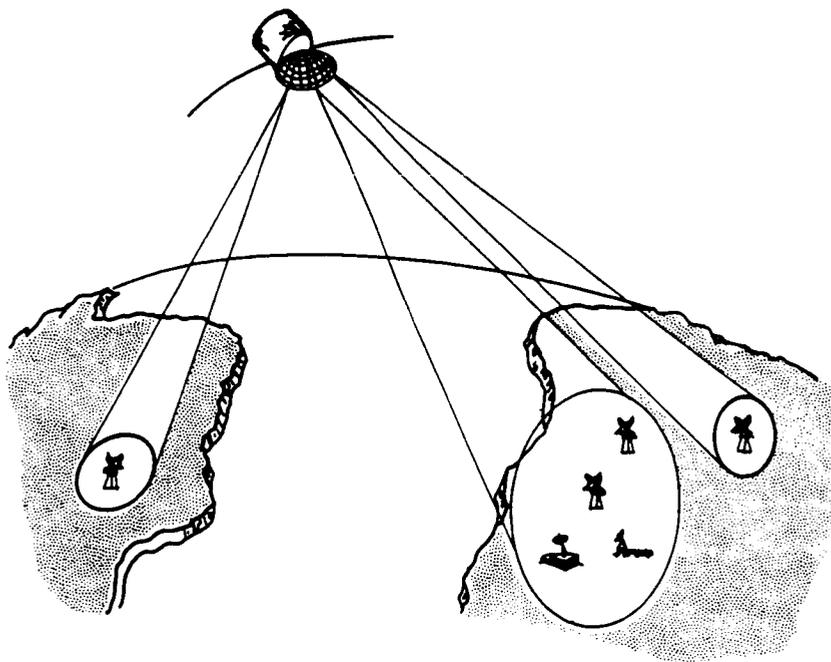
It is conceivable that future DOMSAT designs may include operation at all three (C,  $K_u$ ,  $K_a$ ) frequency bands. The intersatellite spacing will then be dictated by operation at C band. With a conservative four degree spacing, there will be ten orbital slots in the prime North American arc. Because of rain depolarization effects, frequency reuse by dual polarization will be feasible only in the C and  $K_u$  bands. Assuming four and ten times frequency reuse by spatial discrimination at  $K_u$  and  $K_a$  bands, respectively, each multifrequency satellite will be capable of supporting bandwidths on the order of 1GHz at C, 4GHz at  $K_u$  and 25GHz at  $K_a$ . Figure 3-7 shows that the total capacity of a multifrequency satellite would be 30GHz or 720 transponders. The North American arc capability would be 300GHz (7200 transponders),

	Allocated Bandwidth		Polarization Diversity		Spatial Diversity		Orbit Slots		Geostationary Arc Capability
C Band	500 MHz	X	2	X	1	X	10	= 10 GHz	(240 Transponders)
K <sub>u</sub> Band	500 MHz	X	2	X	4	X	10	= 40 GHz	(960 Transponders)
K <sub>a</sub> Band	2.5 GHz	X	1	X	10	X	10	= 250 GHz	(6000 Transponders)

Total Geostationary Arc Capability = 300 GHz  
(7200 Transponders)

★ Assumption: Twelve 36 MHz Transponders Per 500 MHz Bandwidth

**Figure 3-7. North American Geostationary Arc Capability For U.S. Coverage**



**Figure 3-8. Communications With Multiple-Spot Beams**

which should be more than adequate to handle the domestic demands (Figure 3-5) even in the late 1990s.

The use of multiple beams for frequency reuse raises the question of how to interconnect users located within different beams. This situation is depicted in Figure 3-8. For simplicity, only three beams are shown. In practice, of course, there will be many more beams to cover the total field-of-view. Users located within a common beam can communicate with each other in much the same fashion as they do currently. Users located within the coverage areas of different beams require some way of interconnecting their respective uplink and downlink beams.

One approach is to multiplex the outputs of each receive beam in the satellite and transmit the composite wide-band signal on the downlink to a large ground station. The required interconnection can be accomplished on the ground by conventional switching equipment. The signals can then be returned on a wide-band uplink to the satellite for demultiplexing and final retransmission on appropriate downlinks. This double-hop approach has the advantage that the complex switching function can be performed on the ground. The disadvantages are the requirement for wide-band uplinks and downlinks between the satellite and the ground station, and an additional time-delay of 1.4 seconds. The design of the wide-band links must be robust, because their disruption will cause the loss of all channels. A better solution to the interconnection problem might be to perform the switching in the satellite itself, either at a convenient RF frequency or at baseband.

Full exploitation of these advanced concepts will require significant technology enhancements and component developments with very tight tolerances. Moving from C to  $K_a$  band is not a matter of simple redesign or extrapolation of lower band technologies. It requires intensive research and development in key technology areas, such as multiple-beam antenna, satellite on-board processing and switching system.

## Atmospheric Effects

While the use of  $K_a$  band would offer relief from orbit and spectrum congestion it is highly susceptible to atmospheric propagation effects. In clear weather, water vapor and atmospheric oxygen are the principal causes of signal attenuation; however, these are negligible in comparison to the effects of rain, which is the dominant cause for signal attenuation.

Rain attenuation increases with frequency and with the size, density, and extent of the water droplets along the Earth-satellite path. During periods of high rainfall rate, the attenuation can be sufficiently high to make communication with an Earth station impossible, necessitating the use of diversity techniques if the outage cannot be tolerated. When the rain attenuation is not too high, its effects can be overcome with adequate link margin. The margin required depends upon the operating frequency, the elevation angle, the terminal location and the link availability desired.

Measured satellite link attenuation data are sparse and generally limited to a few locations in the continental U.S. Much of the predicted rain attenuation data are based on the applications of theoretical models to measured rainfall and climatological data. Several excellent models are available for predicting atmospheric attenuation in the millimeter bands (Ref. 4). Figures 3-9 and 3-10 show the attenuation as a function of link availability (Ref. 5). It is clear that high link availabilities, comparable to those presently provided at C band or by terrestrial systems will require fairly large link margins. Path diversity in such cases may be the better alternative to achieving high link availabilities. Two stations separated by perhaps 20km or more and interconnected by a terrestrial link can provide a significant improvement in system availability. Frequency diversity schemes are also feasible; one such scheme proposes switching back to the lower C or  $K_u$  band during periods of high rainfall.

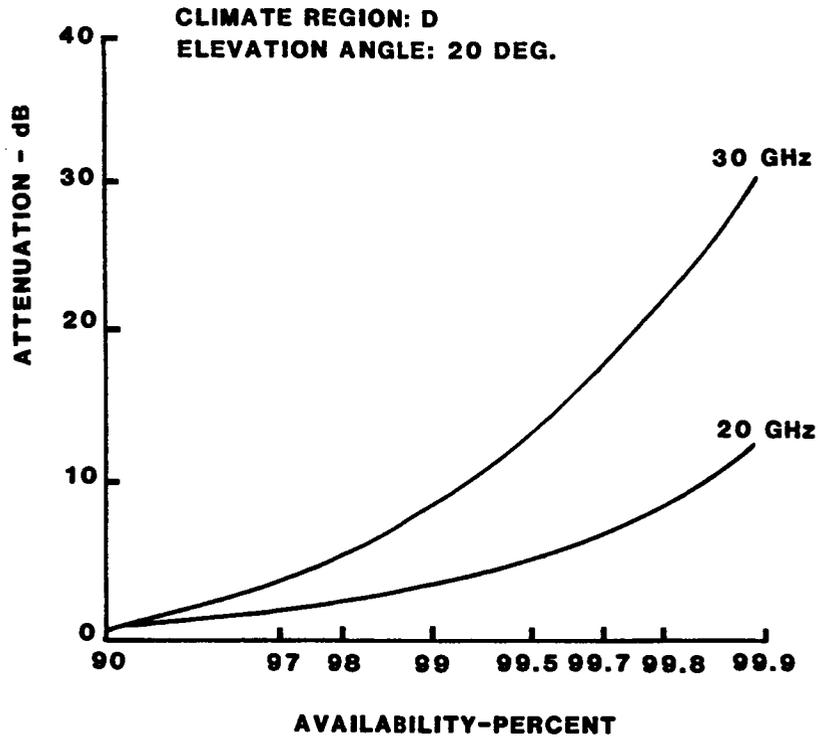


Figure 3-9. Atmospheric Attenuation - 20° Elevation

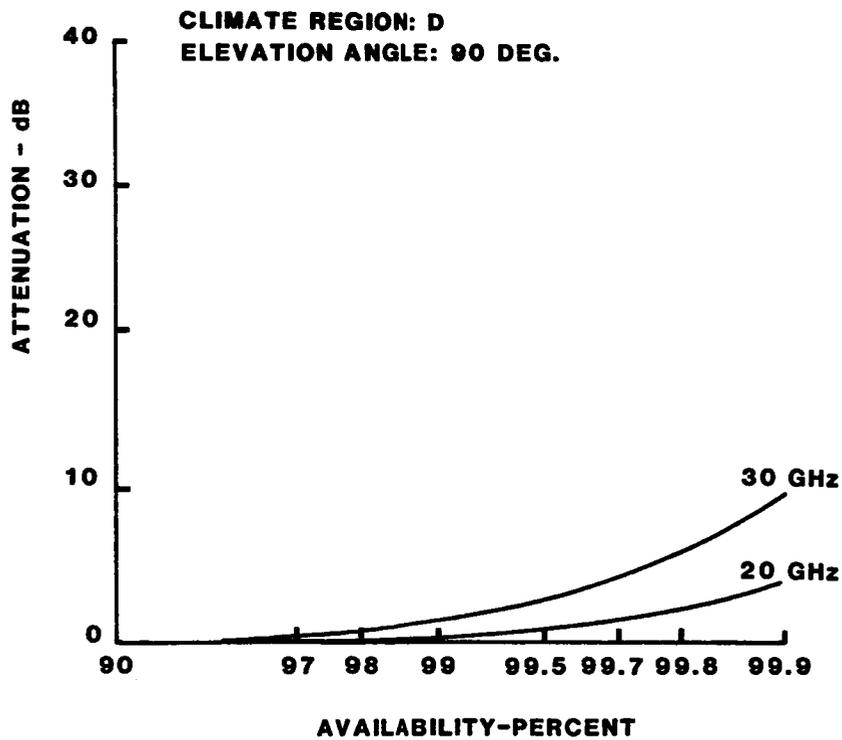


Figure 3-10 Atmospheric Attenuation - 90° Elevation

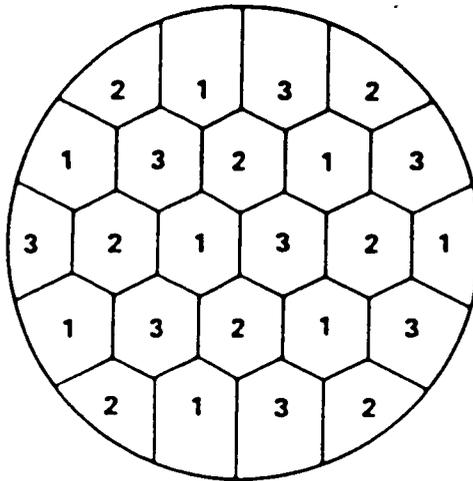
### D.3.5 TECHNOLOGIES IMPACTING SPACECRAFT DESIGN

Significant advances in spacecraft technology are needed to meet the capacity demands of the late 1990s and early 2000s.

Use of large satellite antennas, with many simultaneous spot beams and on-board processing/switching, emerge as the two most important technology development areas for meeting the twin challenges of conservation of spectrum and orbital arc. NASA has embarked on the development of the requisite spacecraft technologies in the  $K_a$  band. While the thrust of this NASA program is directed towards solving the problems of the domestic satellite market, the technologies will have much wider applications, e.g., to future INTELSATs and DOMSATs of other nations. Some advanced technologies may even find applications in operational systems in the lower bands for improved utilization of spectrum and orbital arc.

#### Multiple-Beam Antennas

One of the critical technologies for spectrum reuse is the multiple-beam antenna (MBA). Unlike today's DOMSATs, which cover the contiguous U.S. with a single stationary beam, the MBA will provide coverage with many spot beams. For example, roughly 75 half-degree spot beams are needed to cover the 48 states. This translates into an antenna aperture requirement of 1.4m at 30GHz. Larger apertures will produce narrower beams, and even more beams will be needed for the same coverage, e.g., 200 spot beams at  $0.3^\circ$  beamwidth. Good beam isolation (30dB or more) will be required for frequency reuse between closely spaced beams. Alternatively, adjacent beams may have to use different frequencies, which would lower the frequency reuse capability. Figure 3-11 shows an arrangement that uses three different frequencies to separate adjacent beams. It may be beneficial to use opposite sense polarization between adjacent beams for maximum isolation. Table 3-4 shows the number of beams required to cover the



**AREA DIVISION**  
**NUMBERS 1-3 INDICATE FREQUENCY ASSIGNMENT**  
**Figure 3-11 Coverage With Multiple-Spot Beams**

TABLE 3-4

MULTIBEAM COVERAGE OF CONUS

<u>3dB BEAM WIDTH (DEGREES)</u>	<u>NUMBER OF BEAMS</u>	<u>NUMBER OF FREQUENCY REUSES</u>
1.5	10	3
1.0	20	5
0.5	75	18
0.3	200	50

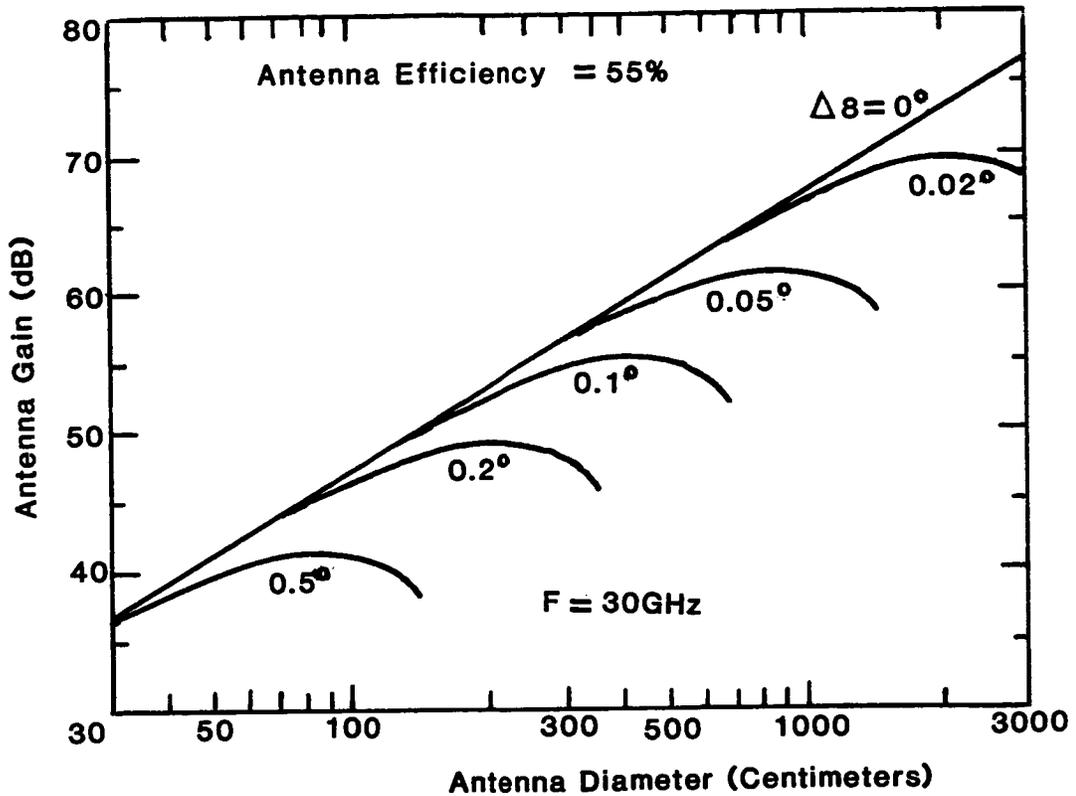
contiguous U.S. and the associated number of frequency reuse with different satellite antenna beam widths.

The use of narrow spot beams in DOMSATs has been restricted in the past by the frequency and the size of antenna aperture that could be accommodated by available launch vehicles. Of course, the space shuttle now makes it possible to launch spacecraft with larger apertures. This capability, together with shorter wavelengths in the  $K_a$  band, makes it possible to produce very narrow beams from geostationary satellites.

Antennas producing narrow beams will require very accurate pointing for aiming the beams at the user operating areas. Figure 3-12 shows the achievable antenna gain at 30GHz as a function of antenna diameter for different pointing accuracies. Beam widths on the order of 1/2 degree or less produce antenna gains exceeding 50dBi. Such high antenna gains, associated with narrow beam widths, will be limited by the achievable pointing accuracy. Larger diameters will not provide higher antenna gains without a concomitant improvement in pointing accuracy. Table 3-5 shows the antenna gain and diameter limitations at 30 and 20 GHz due to pointing errors.

Improved attitude sensing and control would be required to achieve high pointing accuracies from the spacecraft. One candidate technique is to use one or more monopulse feeds at 30GHz to provide the pointing error to the spacecraft attitude control system.

Antennas with gain greater than about 45dBi are almost always reflector surfaces illuminated by a feed. The surface accuracy of a reflector antenna limits the achievable gain. Figure 3-13 shows the loss in antenna gain due to antenna surface inaccuracy (Ref. 5). It is clear that the rms surface tolerance must be less than 0.04cm (0.015in.) at 30GHz for the loss in antenna gain to be less than 1dB. Several data points, illustrating the



**Figure 3-12. Antenna Gain Limitations Due To Pointing And Tracking Errors**

TABLE 3-5

ANTENNA GAIN AND DIAMETER LIMITATIONS DUE TO POINTING ERRORS

<u>POINTING ERROR</u> (DEGREE)	<u>GAIN LIMIT<sup>a</sup></u> (dB)	<u>ANTENNA DIAMETER LIMIT</u> (METERS)	
		<u>20GHz</u>	<u>30GHz</u>
0.5	39.7	0.73	0.48
0.2	47.7	2.86	1.25
0.1	53.7	3.72	2.47
0.05	59.7	7.40	4.94
0.02	67.7	18.53	12.37

<sup>a</sup> BASED ON 1.5dB LOSS; 55% ANTENNA EFFICIENCY

current status of spacecraft antenna surface accuracy, are shown in Table 3-6.

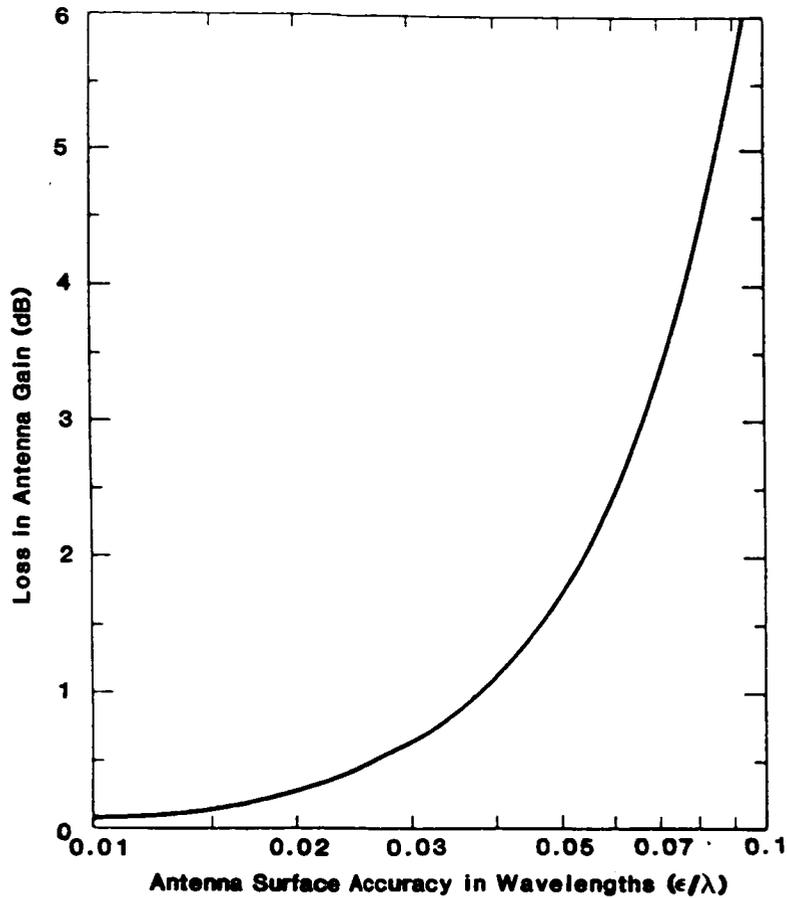
While each of the three generic types of antenna, e.g., reflectors, lenses and phased arrays, can be used as MBAs, the reflector with folded optics appears to be the best candidate for application in the early 1990s. A phased-array MBA would require a longer technology development effort and should be considered for the middle to late 1990s. The geometry of an offset Cassegrain antenna is shown in Figure 3-14. A cluster of feed horns illuminates a small subreflector, which in turn illuminates the main reflector. The offset eliminates beam blockage, providing lower sidelobes and higher beam-to-beam isolation than conventional Cassegrain antennas. The reflectors and feed horns can be rigidly mounted on the body of the spacecraft, to reduce misalignment errors and long lossy waveguide runs from the TWTAs and low-noise amplifiers. The antenna configuration can produce multiple-beams, with beam widths on the order of  $0.2^\circ$  and off-axis scan angles of  $\pm 3.5^\circ$ .

Another critical technology area associated with the MBA is the beam forming network (BFN) by which the multiple antenna feeds are connected to the satellite transmitter or the receiver. The BFN is a network made of continuously variable power dividers and phase shifters. With this network any desired amplitude and phase excitation can be achieved at the antenna feeds. Accurate amplitude and phase control of the feed horns is necessary for pattern shaping and beam scanning.

The design of the off-set feed reflector and the associated beam forming network requires significant technology development.

### On-board Switching

The use of multiple spot beams requires switching on-board the satellite to interconnect users located in different beams.

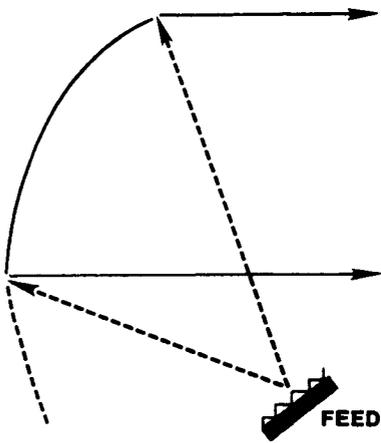


**Figure 3-13. Loss in Antenna Gain Versus Surface Accuracy in Wavelengths**

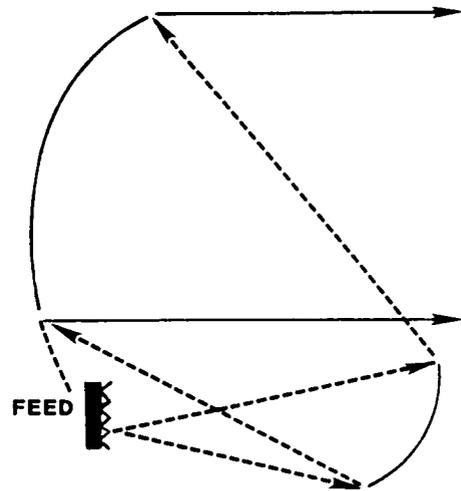
TABLE 3-6

SPACECRAFT REFLECTOR TECHNOLOGY

	<u>DIAMETER</u>		<u>RMS ERROR</u>	
	<u>FEET</u>	<u>METERS</u>	<u>INCHES</u>	<u>CM</u>
1. <b>ATS-6</b> ( <b>LOCKHEED</b> )	30	9.8	0.055	0.02
2. <b>VOYAGER</b> ( <b>FORD</b> )	12	3.9	0.010	0.004
3. <b>TDRSS</b> ( <b>HARRIS</b> )	16	5.3	0.018	0.007
4. <b>USAF</b> ( <b>GENERAL DYN.</b> )	8	2.6	0.005	0.002
5. <b>DEVELOPMENTAL</b> ( <b>HARRIS</b> )	50	16.4	0.050	0.02



**SIMPLE OFFSET FED REFLECTOR**



**DUAL OFFSET GREGORIAN REFLECTOR**

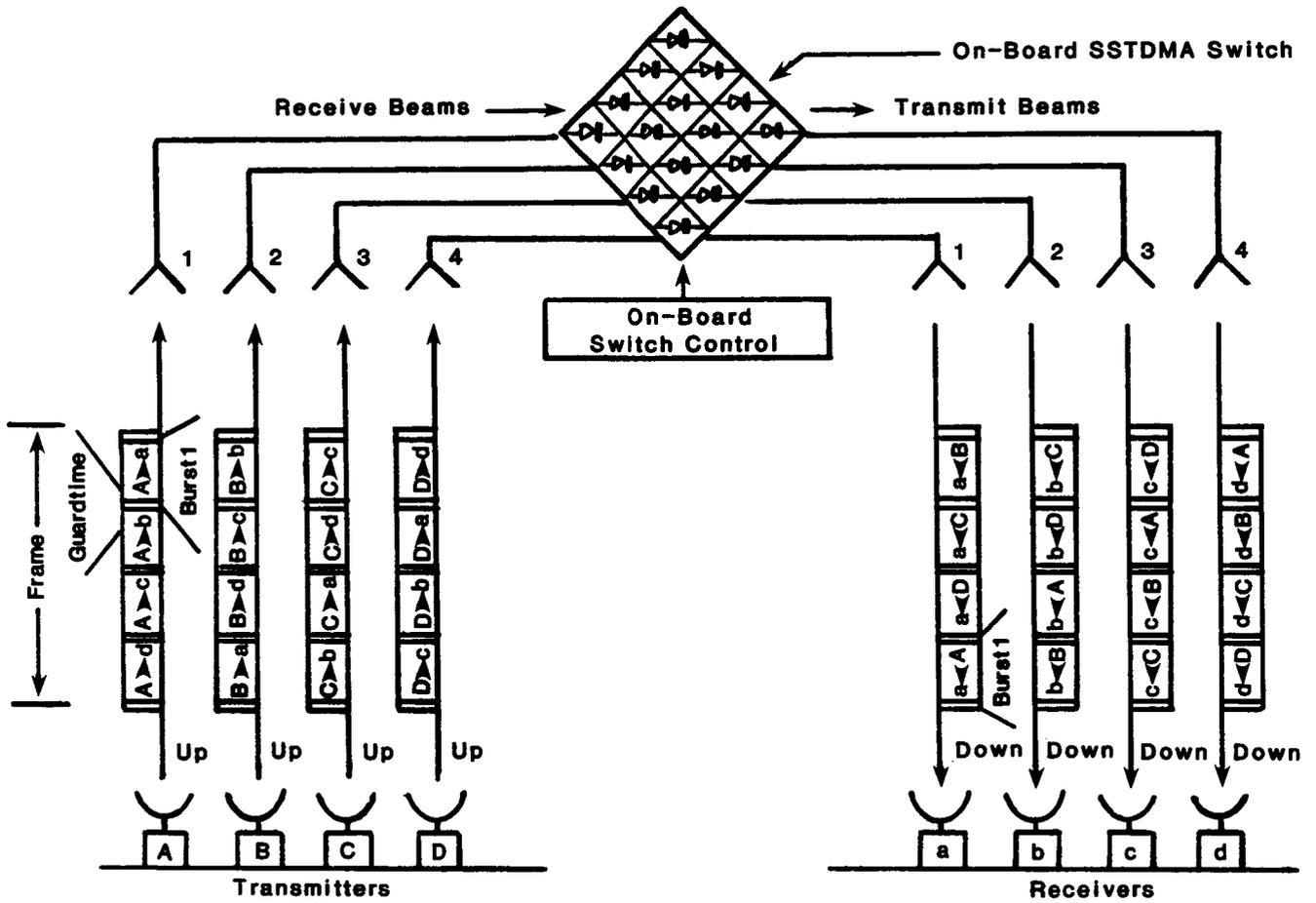
**Figure 3-14. Off-Set Cassegrain Antenna**

The switching function can be performed either at a convenient RF frequency or at baseband.

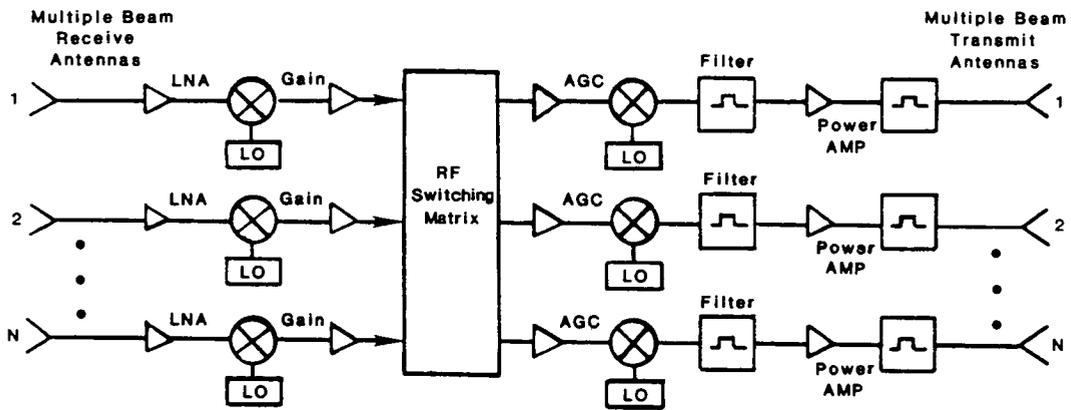
Satellite switched time division multiple access (SS-TDMA) combines the advantages of both TDMA (no TWT power-back off) and spot beams (high antenna gain and frequency reuse) with active switching in the satellite to interconnect the multiple uplinks to the appropriate downlinks. The basic concept of the SS-TDMA switching scheme is illustrated in Figure 3-15 for a four-channel system. Each Earth station is assumed to be in the coverage region of a separate spot beam. The high-speed on-board switching circuit interconnects a different combination of uplink and downlink beams in successive TDMA bursts. In four successive time bursts, each receive beam will be interconnected once with each transmit beam. This is an example of a fully connected 4 x 4 matrix switching scheme, as implemented at  $K_u$  band on NASA's TDRSS satellite. Other variations of this basic scheme are possible and have been proposed (Ref. 6,7). The central timing for TDMA synchronization can either originate from a ground master station or from the satellite itself and is received by all Earth stations. Figure 3-16 shows one possible transponder configuration in simplified form with multiple beams and RF matrix switching. On the transmit side, there is a separate RF power amplifier for each beam.

The switching in the spacecraft can be controlled by a ground master station via the control link. The switch elements themselves can be dual-gate gallium arsenide field effect transistors (GaAsFET). The GaAsFETs can also provide some amplification of the signals they switch to help make up for the insertion loss in the switch matrix.

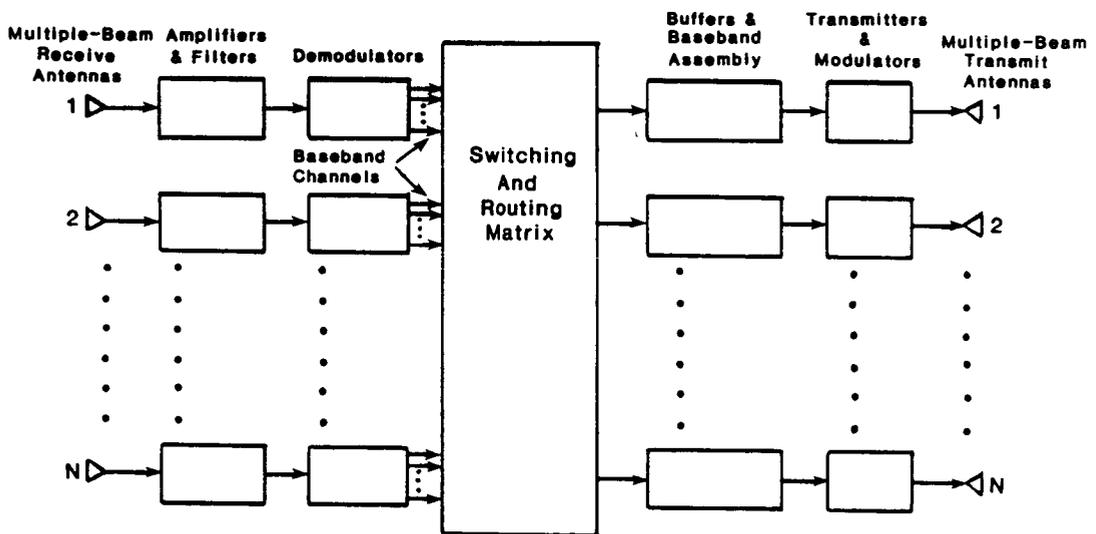
A number of key design parameters must be met to produce an operational RF switch matrix. A matrix size of about 20 x 20, comprising 400 switch elements, may be considered typical for early 1990s application. The switch should be capable of handling



**Figure 3-15. Basic Concept Of A 4-Channel Satellite-Switched TDMA System**



**Figure 3-16. SS-TDMA Repeater Using RF Switching**



**Figure 3-17. SS-TDMA Regenerative Repeater With Baseband Switching**

high data rates (1-5Gbps), with end-to-end losses of less than 15dB. The device switching time should not exceed 10 nanoseconds. Physically, the switch matrix must be designed to minimize weight, volume and power consumption, while being packaged in a manner suitable for spacecraft use. Critical technology elements include the GaAsFET switch/amplifier devices, the broadband couplers, the switching control circuit, and the packaging and integration of the matrix.

The design of the RF switch matrix in an SS-TDMA system becomes more difficult with a large number of antenna beams. A better solution, then, is to demodulate the user signals from the individual uplink beams in the satellite, and perform the switching function at baseband with high-speed logic and memory devices. The switched signals must then be remodulated and amplified for retransmission via the downlink beams. Figure 3-17 illustrates the general concept of an on-board regenerative repeater with  $N \times N$  switching and routing matrix. The satellite has independent transmit and receive antennas, each producing  $N$  spot beams over the coverage area. The outputs of the  $N$  receive beams are demodulated, switched, and remodulated for transmission via the  $N$  transmit beams. The design of the on-board baseband switching and routing matrix is a significant technical challenge; however, recent advances in high-speed digital processing technology indicate that even a large  $100 \times 100$  switching matrix can be implemented with today's solid-state technology. The versatility of GaAsFET as a low-noise receiver, as a power amplifier, and as a high-speed switching device makes an all solid-state on-board repeater design extremely attractive.

Several technologies are critical for the implementation of the baseband processor. One is the production of advanced large scale integration (LSI) circuits for such components as demodulators, digital switches, serial/parallel converters and decoders. Use of LSI technology is considered mandatory to reduce the weight and power consumption and provide the reliabi-

bility of the on-board processor so as to make it practical for satellite applications.

The level of technical risk associated with the development of the full on-board baseband processor is high; no such processor has ever been employed in a satellite communications system.

The development of the technology associated with such a processor, in conjunction with that of the multiple-beam antennas, can have a major impact on satellite communications with small Earth stations. Note that the use of multiple narrow beams will reduce the required transmitter power per beam, and, hence, the GaAsFET becomes a very attractive alternative to the TWT as a power amplifier.

### RF Subsystems

The RF subsystem technology emphasizes the design of the spacecraft receiver and the transmitter in the 30/20GHz band.

**Receiver**--The characteristics of the satellite receive system establish the carrier-to-noise ratio at the satellite input. This in turn determines the EIRP of the user transmitter. Thus, an improvement in receiver noise figure is directly reflected in a reduction in Earth station transmitter EIRP. A decrease in receiver noise of a few dB could result in a large system cost savings, because smaller diameter antennas could then be used at thousands of earth stations.

The spacecraft receiver operates by amplifying the 30GHz signal received through the antenna feed system. The amplified signal is then mixed with a local oscillator signal to produce an IF signal for on-board processing/switching. Thus, the important parameters for the receive system are the noise figure of the RF amplifier, the image response of the mixer, and the gain of the IF stage.

Current, near-term and far-term projections of receiver technology (Ref. 5) are summarized in Table 3-7. An overall noise figure of 5dB for the spacecraft receive system appears to be a reasonable goal for the early 1990s. The only operational 30/20GHz satellite, the Japanese CS satellite, has a noise figure of 11dB.

The development of GaAsFET as a low-noise device at 30GHz and as an IF amplifier, and the design of the mixer with enhanced image response characteristics are critical technology items for the spacecraft receive system.

**Transmitter**--The 20GHz downlink satellite transmitter must provide sufficient power to deliver adequate signal strength at the ground receivers without taxing the satellite's power system.

Two types of transmitters are candidates; each offers advantages and disadvantages.

1. Travelling Wave Tube (TWT)

The TWT is attractive because it could provide large amounts of power (70-100W) over the entire 3500MHz of bandwidth, with relatively high efficiency (35-40%). While the level of technical risk may be low, considerable developmental work is required to produce a TWT with these characteristics.

Table 3-8 presents the current 20GHz TWT technology and some near-term projections. The 20GHz TWTs presently used in the Japanese CS satellite operate at 4W power level.

2. Solid State Transmitters

Primary solid state candidates for satellite high-power amplifier devices are the Impatt diodes and the GaAsFETs. The

TABLE 3-7

LOW-NOISE SPACECRAFT RECEIVER AVAILABILITY AT 30GHz

<u>TYPE</u>	<u>NOISE FIGURE (dB)</u>		
	<u>PRESENT</u>	<u>NEAR-TERM</u>	<u>FAR-TERM</u>
MIXER/IF AMPLIFIER			
BROADBAND	7.5	—	—
IMAGE-ENHANCED	5.5	—	—
LOW-NOISE FET	—	5.0	2.5

SOURCE: FREDIANI

TABLE 3-8

CURRENT 20GHz TWTA TECHNOLOGY

<u>MANUFACTURER MODEL</u>	<u>POWER WATTS</u>	<u>EFF (%)</u>	<u>GAIN (dB)</u>	<u>BW (GHz)</u>	<u>COMMENTS</u>
HUGHES 1294H	4	17	50	1.0	FLOWN ON CS-1
THOMSON CSF	15	33	51	1.0	PROTOTYPE DEVELOPED
AEG TELEFUNKEN	22	38	50	3.0	PROTOTYPE DEVELOPED
----	7.5/75	30/50	30	3.5	PLANNED DEVELOPMENT
AEG	20	—	—	1.0	PLANNED DEVELOPMENT FY81 START
WATKINS- JOHNSON	20	40	50	1.0	PLANNED IR&D DEVELOPMENT

SOURCE: FREDIANI

reliability of solid-state devices is potentially high, but their power level and efficiency are lower than that of TWTs.

The critical technologies associated with the development of the Impatt diode transmitter include the development of the 4 to 6W Impatt devices themselves. Currently, individual device power levels are about 2W. Another critical technology is the development of efficient networks that will combine the output of the individual devices without introducing excessive signal loss.

GaAsFETs are capable of producing power levels of 0.5 to 1W at 20GHz. A number of such devices will have to be combined to produce output power levels up to 10W. Like the TWT, the GaAsFET offers large bandwidths.

As in the case of the Impatt diode transmitter, the development of the GaAsFET devices themselves represent a critical technology. Another important associated technology area is the design and construction of low-loss power combiners.

The development of solid-state transmitters carries a high level of technical risk.

The present, near and long-term availability of spacecraft RF power amplifiers is shown in Table 3-9.

#### D.3.6 TECHNOLOGIES IMPACTING EARTH STATION-DESIGN

The  $K_a$  band system will operate with a large number of earth stations with varying transmit and receive characteristics. The technology development effort, therefore, should emphasize advancements that would lead to a reduction in cost of the Earth segment.

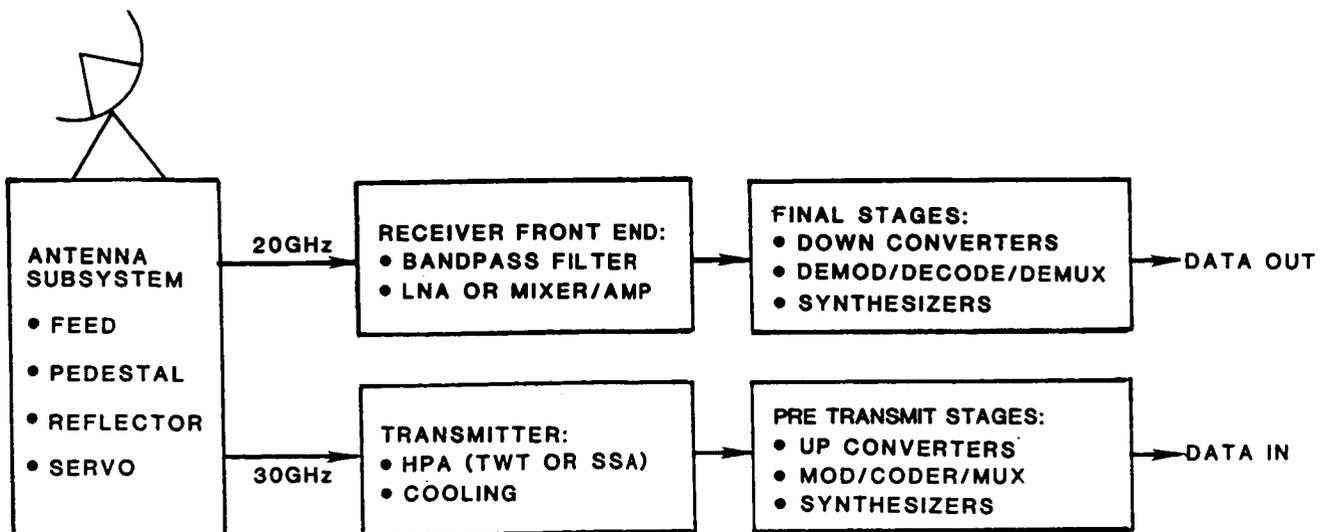
TABLE 3-9

RF POWER AMPLIFIER AVAILABILITY: SPACE SEGMENT

<u>AMPLIFIER TYPE</u>	<u>PRESENT</u>		<u>POWER OUTPUT (WATTS)</u>		<u>PAR TERM</u>	
	<u>20GHz</u>	<u>40GHz</u>	<u>NEAR TERM</u> <u>20GHz</u>	<u>40GHz</u>	<u>20GHz</u>	<u>40GHz</u>
<u>SOLID-STATE</u>						
● IMPATT						
ONE DEVICE	1	--	4	1	12	3
MULTIPLE DEVICES <sup>a</sup>	4	--	40	10	--	--
● FET						
ONE DEVICE	--	--	1	0.2	3	0.5
MULTIPLE DEVICES <sup>b</sup>	--	--	10	2	--	--
<u>TWTA</u>						
● HELIX	4	--	20/40	10/20	40/80	20/40
● COUPLED-CAVITY <sup>c</sup>	--	--	--	--	200	100

<sup>a</sup> 12 DIODE RESONANT-CAVITY COMBINER  
<sup>b</sup> 12 TRANSISTOR RADIAL OR PLANAR COMBINER  
<sup>c</sup> COUPLED-CAVITY TWTA<sup>s</sup> COULD BE DEVELOPED IN THE NEAR TERM IF NEEDED

SOURCE: FREDIANI



**Figure 3-18. A 30/20GHz Earth Station Components**

Figure 3-18 shows the basic components of a typical satellite communications Earth station. The critical frequency dependent components are: the antenna, the low-noise receiver, and the high-power transmitter. Other interfacing subsystem components--e.g., up/down converters, modems, multiplexers/demultiplexers, etc.--are generally not peculiar to any specific frequency band.

### Earth-Station Antenna

The center-fed and Cassegrain-fed parabolic reflector antennas appear to be the two most cost-effective approaches to commercial Earth stations. Shaped reflectors with off-set feed would be expensive and should be candidates primarily for large Earth station (>10m) designs. To achieve maximum gain at 30/20 GHz, the antenna surface tolerance and pointing/tracking errors should be kept to a minimum. Figure 3-13 shows the loss in antenna gain due to surface errors. At 30GHz, the surface tolerance error should be less than 0.04cm (0.015in.) for the loss in antenna gain to be less than 1dB. This surface accuracy is achievable currently with antenna diameters less than 3m.

Antennas having diameters greater than 3m are typically fabricated from panels and the factors contributing to the antenna surface errors include manufacturing and environmental factors (wind, gravity, temperature). For a given manufacturing process, the achievable antenna surface accuracy is related to the antenna diameter (Table 3-10). The cost of large diameter antennas with surface accuracies around 0.015in. is presently quite high because of the many measurements and adjustments required and the high cost of precision tooling. For antenna diameters greater than 10m it may be very difficult to achieve this accuracy with standard commercial technology. Table 3-11 illustrates the gain loss for a 12m antenna based on the available technology. At 30GHz adequate surface accuracy cannot be achieved even at the

TABLE 3-10

CURRENT ANTENNA SURFACE ACCURACIES ( $D > 2$ )<sup>a</sup>

<u>ANTENNA</u> <u>DIAMETER (METERS)</u>	<u>SURFACE</u> <u>ACCURACY (<math>\epsilon/D</math>)<sup>b</sup></u>	<u>COMMENTS</u>
2.5 - 6.0	$2 \times 10^{-4}$	STANDARD COMMERCIAL AVAILABILITY
	$10^{-4}$	LIMIT OF COMMERCIAL TECHNOLOGY
	$5 \times 10^{-5}$	MACHINED, CAST OR MOLDED PANELS
9.0 - 25.0	$10^{-4}$	STANDARD COMMERCIAL AVAILABILITY
	$5 \times 10^{-5}$	LIMIT OF COMMERCIAL TECHNOLOGY
	$2.5 \times 10^{-5}$	COMMERCIALY UNAVAILABLE
	$10^{-5}$	RADIO-TELESCOPE TECHNOLOGY

<sup>a</sup> D = ANTENNA DIAMETER  
<sup>b</sup>  $\epsilon$  = RMS VALUE OF SURFACE ACCURACY

TABLE 3-11

LOSS IN ANTENNA GAIN DUE TO ANTENNA SURFACE IN ACCURACY  
(ANTENNA DIAMETER = 12M)

<u>RMS SURFACE</u> <u>ACCURACY (cm)</u>	<u>LOSS (dB)</u>		<u>COMMENTS</u>
	<u>20GHz</u>	<u>30GHz</u>	
0.120	4.53	10.2	STANDARD COMMERCIAL TECHNOLOGY
0.060	1.15	2.6	LIMIT OF COMMERCIAL TECHNOLOGY
0.040	0.45	1.0	REQUIRED SURFACE ACCURACY
0.015	0.10	0.2	RADIO-TELESCOPE TECHNOLOGY

limit of current commercial technology. More than adequate surface accuracy is achieved for radio telescopes but this technology is not currently applicable to commercial satellite Earth stations because of its cost. The required surface accuracy falls within these bounds and new technology requires development. Further improvement in commercial technology will require new structural and thermal designs. As the wind and thermal loads are major contributors to the surface accuracy of exposed antennas, the use of radomes may be considered.

Antenna tracking and pointing losses are also important considerations in the design of  $K_a$  band Earth stations. The factors contributing to the overall antenna tracking accuracy include antenna beamwidth, servo-system accuracy and environmental factors (wind, temperature). Neglecting environmental effects, antenna tracking accuracy is limited to either a few hundredths of the antenna beamwidth by the angular sensitivity of the tracking feed or a few thousandths of a degree by the angular resolution of the servo system. The tracking technique employed generally depends on the beamwidth in the following manner: for beamwidths  $>0.5^\circ$ , a step-tracking system is generally used; while for beamwidths  $>0.5^\circ$ , some form of monopulse tracking is used with a concomitant increase in cost and complexity.

Figure 3-12 shows the achievable antenna gain as a function of antenna tracking accuracy at 30GHz. A step tracking system ( $0.2^\circ$ ) could not be used, without appreciable loss in gain, for antenna diameters exceeding 2m. For larger antenna diameters, some form of monopulse tracking would be required. The maximum achievable antenna gain and diameter limitations due to antenna tracking accuracy are shown in Table 3-5. For large antenna diameters ( $>12.5m$ ), the tracking accuracy requirement ( $0.02^\circ$ ) is at the limit of current technology.

## Receiver Front-End

Both a mixer front-end and a low-noise amplifier (LNA) front-end are viable design options at 20GHz. In the mixer front-end, the incoming 20GHz signal is first heterodyned to a convenient IF frequency and then amplified by a low-noise IF amplifier. In the LNA front-end, the incoming signal is amplified first by a low-noise preamplifier and then heterodyned by a mixer. In each case, paramps, FETs and tunnel diodes are candidate low-noise devices.

With cooled paramps the LNA front-end can provide very low noise temperatures (70-100°K) that are not possible with a mixer front-end. However, front ends with noise temperatures much lower than 250°K are not practical at 20GHz, because the noise contributed by atmospheric attenuation fluctuations would exceed the receiver noise. A 250-300°K receiver noise temperature is achievable with an LNA front-end using low-noise solid state devices.

The implementation of a low-noise 20GHz receiver front-end is not expected to stress the technology. The development of low-noise solid-state devices should be pursued. The current state-of-the-art in low-noise GaAsFET technology is shown in Figure 3-19.

## Power Amplifiers

The 30GHz transmitters must generate high EIRPs to provide adequate margins against atmospheric attenuation. At present, vacuum tube technology (TWT, Klystron) appears to be the only possible means of developing substantial power levels. Tube technology exists to cover the range from a few watts to several kilowatts. The major advantage of TWTs is their wider bandwidth response in contrast to the limited 50 to 100MHz bandwidth of Klystrons.

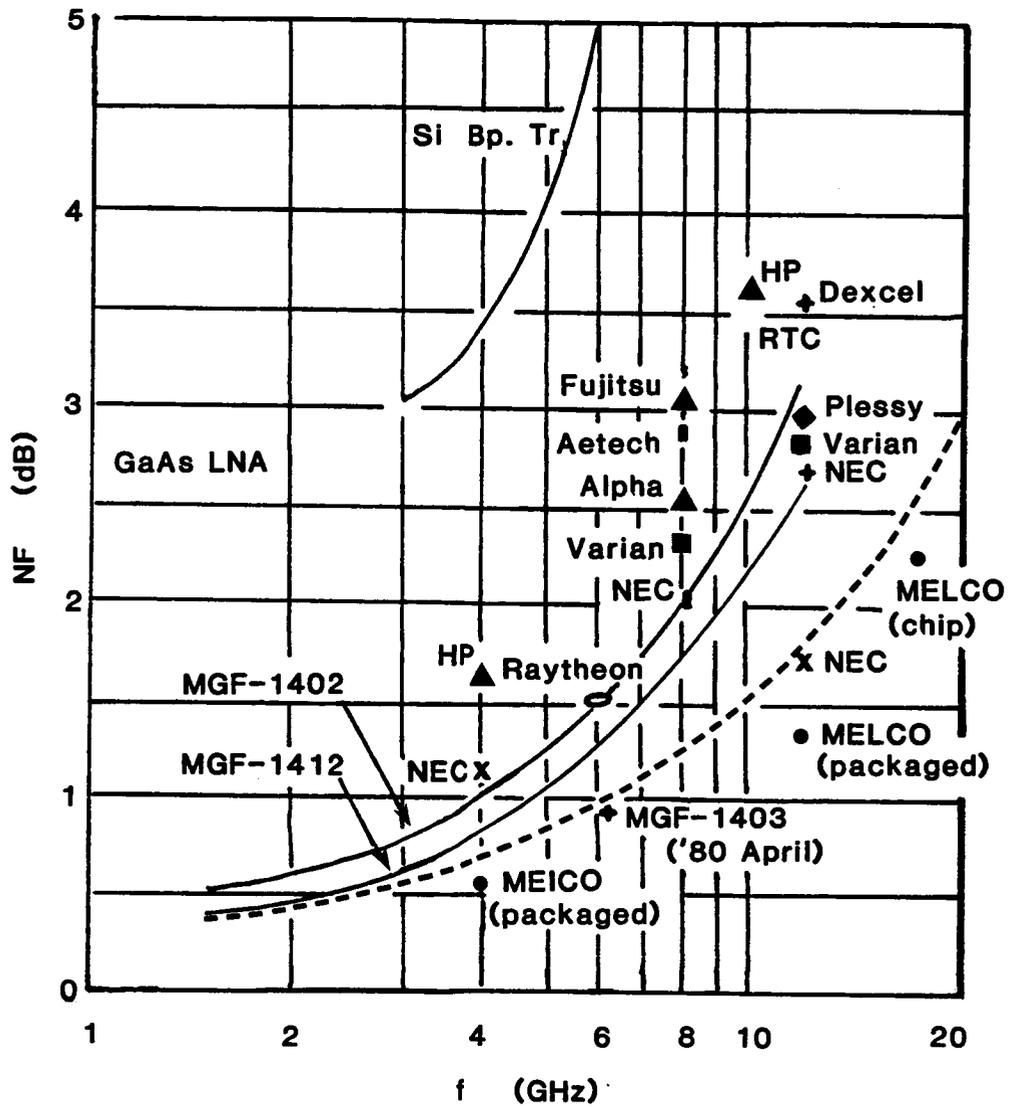


Figure 3-19. Low-Noise Device Development

For the Earth stations, coupled-cavity TWTAs are capable of providing the necessary power and bandwidth required at 30GHz. Their development for the  $K_a$  band application represents a reasonable extension of current technology. However, the need for improved efficiency, reduced cost and increased power requires a concentrated development program.

The high-voltage power supply and control subsystem accounts for a significant portion of the cost of a TWT amplifier. Large, precisely regulated direct-current power supplies are required for stable TWT operation. Tube protection logic circuits, overload tripods, and high-voltage crowbar devices contribute to the cost of TWT amplifiers.

The current and projected near-term and far-term availabilities of TWT amplifiers are presented in Table 3-12.

### Earth-Station Costs

Projection of Earth station costs is difficult, since some terminal components (antennas, LNAs, HPAs) still need further development and refinement. Further, the design of a cost-optimized terminal must take into account the satellite parameters such as EIRP, G/T and transponder characteristics. In the absence of this information, any estimate of Earth station costs can only indicate general trends.

The 30/20GHz terminal costs can be estimated by summing the cost of the antenna subsystem (with associated tracking system), and transmitter and receiver subsystem costs. The cost trends for each of these subsystems are provided in Figures 3-20, 3-21 and 3-22. The total Earth station cost for three representative terminal sizes is provided in Table 3-13.

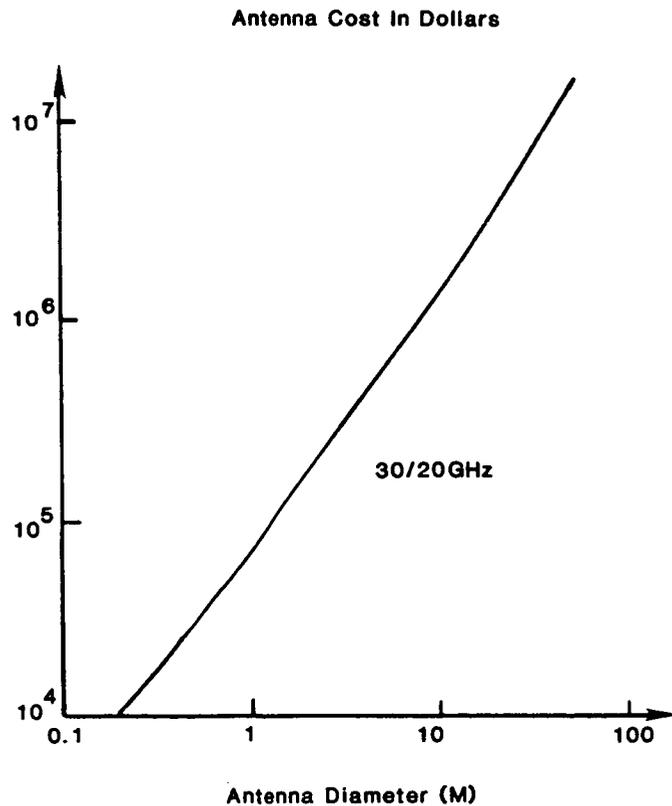
TABLE 3-12

30GHz TWTA AVAILABILITY: GROUND SEGMENT

<u>AMPLIFIER TYPE<sup>a</sup></u>	<u>PRESENT</u>	<u>NEAR TERM</u>	<u>FAR TERM</u>
AIR-COOLED TWTA <sup>b</sup>	200 W	500 W <sup>c</sup>	
LIQUID-COOLED <sup>b</sup> TWTA		1,000 W <sup>d</sup>	
SOLENOID-FOCUSED TWTA		2,000 W	10,000 W

<sup>a</sup> ALL TUBES ARE COUPLED-CAVITY DEVICES  
<sup>b</sup> PPM FOCUSED  
<sup>c</sup> LIMIT OF CURRENT AIR-COOLED TECHNOLOGY  
<sup>d</sup> LIMIT OF CURRENT PPM-FOCUSED TECHNOLOGY

SOURCE: FREDIANI



**Figure 3-20. Antenna Cost**

Transmitter Cost In Dollars

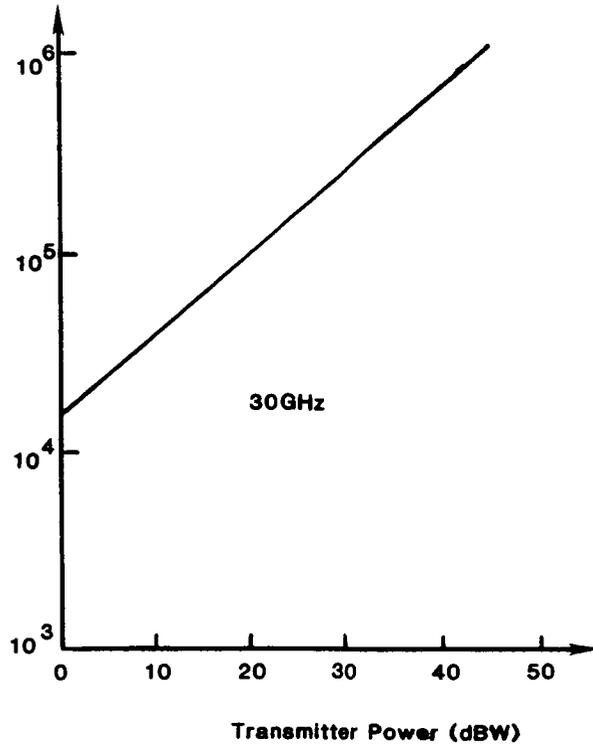


Figure 3-21. Transmitter Cost

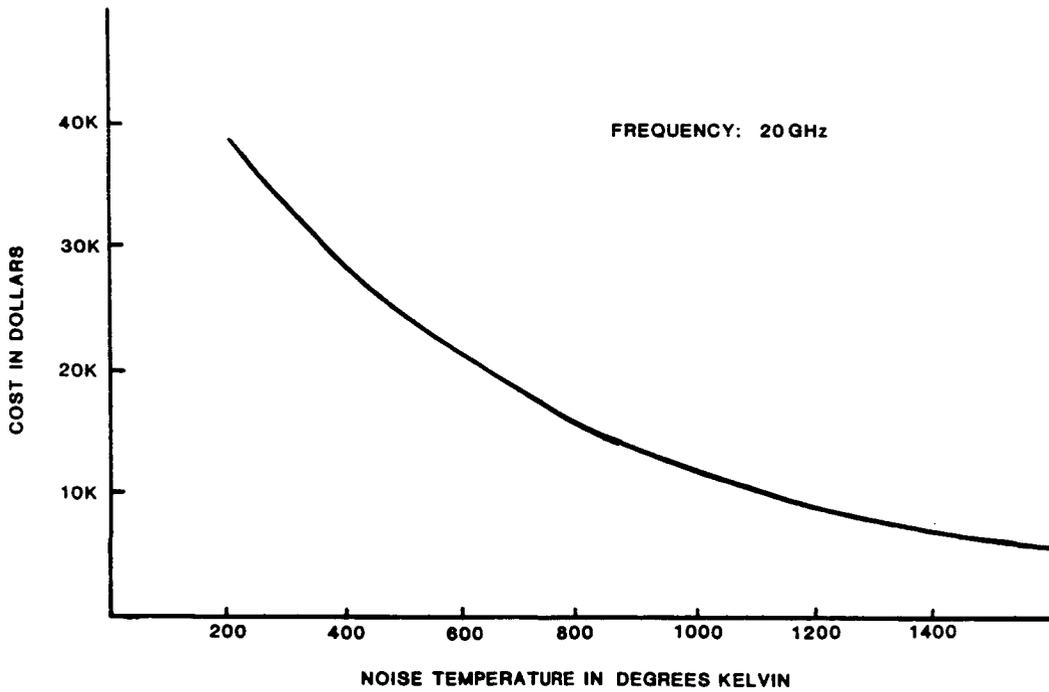


Figure 3-22. LNA Front End Cost Versus Noise Temperature

TABLE 3-13

30/20GHz EARTH-STATION COST ESTIMATE

<u>CHARACTERISTICS</u>		<u>SUBSYSTEM COST</u> (THOUSAND \$)			<u>TOTAL COST</u> (THOUSAND \$)	
<u>ANTENNA DIAMETER</u>	<u>TRANSMITTER POWER, W</u>	<u>RECEIVER NOISE, K</u>	<u>ANTENNA</u>	<u>TRANSMITTER</u>	<u>RECEIVER</u>	
3m	500	275°	340	280	35	655
3m	1,000	275°	340	375	35	750
5m	1,000	275°	665	375	35	1075

NOTE: ALL COSTS ARE IN CURRENT DOLLARS; DOES NOT INCLUDE INTEGRATION, INSTALLATION, SYSTEM TESTS OR PROGRAM MANAGEMENT

In the medium-term outlook, up to approximately 1995-2000, use of the  $K_a$  band (30/20MHz) offers the best hope of providing the needed satellite communications capacity to meet the traffic demands of the 1990s. The available wide bandwidth, coupled with frequency reuse through multiple spot beams will make it possible to accommodate the projected requirements of U.S. domestic communications through the end of this century. Moreover, much of the technology developed for  $K_a$  band will be applicable to new generations of satellites operating in conventional satellite bands; the capabilities of these satellites will be thereby enhanced and the radio frequency spectrum and orbital arc will be further conserved.

The orderly transition of U.S. DOMSAT systems to the  $K_a$  band will obviously require the timely availability of the necessary technology. Although a technology base exists from which the technology necessary to support future  $K_a$  band systems can evolve, currently an adequate commercial or production base in this frequency region is not available to provide the necessary support. Commercial interests, adequate to support technology developments in this band, are not likely to occur in the next decade. Consequently, the U.S. government must be the prime source of funding for  $K_a$  band technology development.

The evolution of U.S. DOMSATs to  $K_a$  band over the next decade affords opportunities for the development of improved system designs and efficient, reliable, cost-effective technology. The implementation of on-board processing, and multiple-beam antennas offers the potential for reducing Earth station size, complexity and cost.

Key points of the required technological developments are:

- A concerted, long-range critical technology development program is needed to support the development of key

spacecraft and Earth-station technologies. Technological innovations are needed for the development of multiple-beam satellite antennas that will form many simultaneous independent spot beams with good isolation between beams, for frequency reuse and higher antenna gains to smaller Earth stations. The design of the on-board processor, which will provide satellite switching, signal routing, demodulation/remodulation for greater network flexibility and communications performance, is a major technological challenge.

- Earth station antennas are limited in gain by pointing errors resulting from tracking errors and beam defocusing due to surface anomalies in the reflector. With reasonable sophistication, tracking errors can be held to an acceptable level with state-of-the-art technology. The technology to control surface anomalies is available but needs further development.
- Solid-state devices are currently improving in performance and should have application in both ground and space segments at EHF. With development in solid-state technology, it can be expected that low-noise FETs will be used in satellite front-ends and replace the parametric amplifiers in Earth station front-ends. High power FETs and Impatt diodes may provide higher reliability, lower-cost replacements for current thermionic devices.
- Improved TWTAs would remain the mainstay for RF power generation for the Earth stations. The TWT technology is relatively mature and has been successfully exploited at lower bands. However, the attendant problems of low producibility and high cost must be addressed by production technology efforts directed towards the development of the couple-cavity circuit.

- Another technology development area is the intersatellite crosslink that would operate at high microwave (60GHz) or optical (LASER) frequencies. Use of crosslinks will allow transmission of very high data rates between satellites and a wider choice of satellite locations in the crowded geostationary belt.

DOD's EHF program (MILSTAR) in support of military tactical and strategic requirements and NASA's pioneering efforts in the 30/20GHz band should provide the impetus to the industry for the development of the needed technologies for next generation military and commercial systems. Affordable terminals and service to a wide range of users are common goals for commercial and military programs. In addition to advancing the state of EHF technology, the development efforts must minimize the associated cost and risk in a manner that is time-phased with both space and ground-segment deployment.

In the further future (2205-2010), use of 30/20MHz technology will probably become saturated by the expected growth of the domestic telecommunications traffic. A major technological trend competitive with DOMSATS is the oncoming massive use of fiber optics. This protends the advent of significant bandwidths at low user costs, including the eventual capability of piping "TV by wire" into homes; possibly eroding into the direct broadcast satellite (DBS), as well as on the terrestrial TV broadcast markets and potentially freeing a portion of the UHF-TV spectrum for other uses.

Among innovative uses, mobile radio is rapidly growing. By 2000, if current trends continue, the U.S. may contain above 50 million mobile transceivers for uses of radiotelephone, dispatch, paging, conveyance of data. Several NASA studies indicate that a land mobile satellite system (LMSS) would significantly contribute to alleviating the mobile band congestion (beginning to be experienced now in urban centers), at a considerably improved

price/performance with respect to conventional terrestrial systems, and particularly applicable to accommodating mobile traffic in the rural areas. Key to implementation to LMSS for CONUS is a large geosynchronous antenna (50-plus meters in diameter).

This type solution is also applicable to relieve the DOMSAT traffic among "fixed" terminals. Key to its eventual implementation is the ability to deploy geosynchronous systems featuring large-diameter antennas as well as the necessary highly reliable, long life spaceborne switching systems.

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**D.4 SPACE-BORNE NAVIGATION ASSISTS  
TO EARTH-BASED USERS**

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#### D.4. SPACE-BORNE NAVIGATION ASSISTS TO EARTH-BASED USERS

##### D.4.1 BACKGROUND

The term "Earth-based" embraces objects located and/or traveling on the Earth's surface, under water, and within the Earth's atmosphere, and whose points of departure and destination are located on the Earth's surface. It does not include orbiting objects.

The term "navigation assist" refers to systems that provide a traveling or temporarily stationary object with externally generated positional information.

A primary advantage of navigation assist systems is that the bulk of systems costs is concentrated in a few centralized installations while individual mobile objects can be equipped with low-cost equipment.

Satellite-based navigation has been operational since 1967 with the advent of the global all-weather TRANSIT program, deployed by the U.S. Navy primarily to support precision navigation requirements for the Polaris and Poseidon SLBMs. TRANSIT has a single fix accuracy of order of 0.25 nautical miles, requires about 10-20 minutes for a fix, and has an interval between fixes of approximately 2 hours. TRANSIT receivers currently (1984) cost between \$40,000 and \$100,000.

Before TRANSIT became operational, the USAF and Navy began studying an alternate, advanced space-based navigation system. The Navy preferred to upgrade the TRANSIT concept with its TIMATION system; whereas the Air Force preferred a totally different approach, then called 621B.

In 1972, DOD married the two concepts into what is now called the Global Positioning System (GPS) or NAVSTAR. This system improves the TRANSIT system's performance in four ways:

- GPS provides +20m accuracy anywhere, against TRANSIT's 400m.
- GPS provides a three-dimensional (3D) position fix, TRANSIT only 2D.
- GPS provides a position fix in a few seconds, TRANSIT requires 10-25 minutes.
- GPS provides continuous coverage versus TRANSIT'S 2 hour interval between fixes.

Besides TRANSIT and GPS, several government agencies, primarily NASA, sponsored other space-based navigation systems. Table 4-1 recapitulates the characteristics of the more popular navigation systems, including the two land-based systems currently in operation, LORAN C and Omega.

#### D.4.2 FREQUENCY ALLOCATIONS

Land-based navigation-assist systems employ low frequencies, because the navigation signal must follow the curvature of the Earth. Satellite-based systems operate line-of-sight, thus can and do use higher frequencies. All space-based navigation systems except TRANSIT and PLACE employ frequencies between 1200 and 1600MHz. This is not the result of engineering trade studies indicating that this frequency range is best; rather, it is an assigned frequency band for radio navigation.

Table 4-2 lists the frequency bands available for radio navigation. Most of the possible choices under 10GHz are in use or in high demand. Above 10GHz, the choice is still reasonably open, because the technology necessary to support millimeter waves only emerged in the mid-1970s. Assuming technology will shortly reduce their cost to a competitive level, the pros and cons of millimeter bands can be summarized as follows:

TABLE 4-1  
 MAJOR CHARACTERISTICS OF THE MOST POPULAR NAVIGATION  
 AND SURVEILLANCE SYSTEMS, 1960 to 1984

SYSTEM	FREQUENCY 1	TYPE OF POSITION FIX	COVERAGE	FIX ACCURACY (km)	AVAILABILITY	NUMBER OF SATS REQUIRED FOR FIX	NUMBER OF SATS REQUIRED FOR GLOBAL COVERAGE	NUMBER OF GOOD STATIONS REQUIRED	NUMBER OF POSSIBLE SUBSCRIBERS	APPLICATIONS	USER EQUIPMENT	USER COST WITHOUT INSTALLATION	GOOD STATIONS COST (PRO-CUREMENT ONLY)	CONTROL SEGMENT (PRO-CUREMENT ONLY)	AMBIGUITY RESOLUTION
<b>LAND-BASED</b>															
LORAN C	100 H	HYPERBOLIC	2800-5500	0.1 TO 1	CONTINUOUS	----	----	3/FIX	UNLIMITED	N(2D)	R/C/D	3-5K <sup>b</sup>	UNKNOWN	UNKNOWN	WAVEFORM
OMEGA	10-14 H	HYPERBOLIC	GLOBAL	4 TO 9	CONTINUOUS	----	----	8 <sup>a</sup>	UNLIMITED	N(2D)	R/C/D	3-5K <sup>b</sup>	UNKNOWN	UNKNOWN	MULTIPLE TONES
<b>SATELLITE-BASED</b>															
<b>OPERATIONAL</b>															
TRANSIT	150 400 H	DOPPLER	GLOBAL	0.4	EVERY 2 HOURS	1	6	1 <sup>a</sup>	UNLIMITED	N(2D)	R/C/D	10-100K <sup>b</sup>	UNKNOWN	UNKNOWN	GEOMETRY
GPS	1200 1600 H	HYPERBOLIC PLUS	GLOBAL	0.02	CONTINUOUS	4	18	5 <sup>a</sup>	UNLIMITED	N(3D)	R/C/D V(3D)	150K <sup>b</sup>	\$5M <sup>c</sup>	\$150M <sup>c</sup>	WAVEFORM
<b>EXPERIMENTAL</b>															
FLARE	1600 H 4000 H 6000 H	TRILATERATION	REGIONAL	2 TO 4	CONTINUOUS POLLED	2	8 TO 10	2	200	N(2D) S(2D)	X	15-30K	\$2M <sup>c</sup>	\$50M <sup>c</sup>	WAVEFORM
MARSAT	1660 H	TRILATERATION	REGIONAL	2 TO 4	CONTINUOUS	2	8 TO 10	2	1000	N(2D)	X	15-30K	\$2M <sup>c</sup>	\$50M <sup>c</sup>	WAVEFORM
<b>PROPOSED</b>															
ABROSAT	1500 1600 H	TRILATERATION	REGIONAL	4 TO 8	CONTINUOUS	2	8 TO 10	2	1000	N(2D)	X	15-30K	\$2M <sup>c</sup>	\$50M <sup>c</sup>	WAVEFORM
RIPLEX	1600 H	ANGLES	REGIONAL	1 TO 2	CONTINUOUS	1	4	4	5000 (RANDOM ACCESS)	S(2D)	T	1K	\$(0.5M) <sup>c</sup>	\$20M <sup>c</sup>	MULTIPLE RECEIVER ON SATELLITE

a - FOR GLOBAL COVERAGE, OTHERS ARE FOR REGIONAL COVERAGE

b - ACTUAL PRICE 1984, OTHERS ARE PROPOSED COSTS AS OF MID 1970S

c - ESTIMATED

N - NAVIGATION; S - SURVEILLANCE; V - VELOCITY

2D - TWO DIMENSIONAL; 3D - THREE DIMENSIONAL

R - RECEIVER; C - MINICOMPUTER; D - DISPLAY; X - TRANSPONDER; T - TRANSMITTER

TABLE 4-2

FREQUENCY BANDS AVAILABLE FOR RADIO NAVIGATION

<u>RADIO NAVIGATION</u>		<u>SATELLITES</u>	
● <u>GENERAL</u>		● <u>AERONAUTICAL MOBILE</u>	
10.00	- 14.00 kHz	1542.5	- 1558.5 MHz
90.00	- 110.00 "	1644.0	- 1660.0 "
5.46	- 5.47 GHz	43.0	- 48.0 GHz
9.30	- 9.50 "	66.0	- 71.0 "
14.00	- 14.30 "	95.0	- 101.0 "
24.25	- 25.25 "	142.0	- 150.0 "
31.80	- 33.40 "	190.0	- 200.0 "
		250.0	- 265.0 "
● <u>MARITIME RADIO NAVIGATION</u>		● <u>AERONAUTICAL RADIO NAVIGATION</u>	
285.0	- 325.0 kHz	43.0	- 48.0 GHz
2900.0	- 3100.0 MHz	66.0	- 71.0 "
5.470	- 5.65 GHz	95.0	- 101.0 "
		142.0	- 150.0 "
		190.0	- 200.0 "
		250.0	- 265.0 "
● <u>MARITIME DIRECTION FINDING</u>		● <u>BROADCASTING</u>	
405.0	- 415.0 kHz (410 kHz IS THE DIRECTION- FINDING FREQUENCY)	2500.0	- 2690.0 MHz
		41.0	- 43.0 GHz
		84.0	- 86.0 "
● <u>LORAN</u>		● <u>EARTH EXPLORATION</u>	
90.0	- 110.0 kHz (410 kHz IS LORAN C FREQUENCY)	21.2	- 22.0 GHz
		51.0	- 52.0 "
		65.0	- 66.0 "
1800.0	- 2000.0 (LORAN A)		
● <u>LAND RADIO NAVIGATION</u>		● <u>FIXED</u>	
1638	kHz	2500	- 2535 MHz
1708	"	2655	- 2690 "
		3700	- 4200 "
		5925	- 6425 "
		6625	- 6875 "
		10.95	- 11.20 GHz
		11.45	- 12.2 "
		12.5	- 12.75 "
		14.0	- 14.5 "
		17.7	- 20.2 GHz
		27.5	- 30.0 "
		40.0	- 41.0 "
		50.0	- 51.0 "
		93.0	- 95.0 "
		103.0	- 105.0 "
		141.0	- 142.0 "
		151.0	- 152.0 "
		220.0	- 230.0 "
		265.0	- 275.0 "

PRO

CON

- More frequency bands available
- Relatively unaffected by the ionosphere
- Smaller satellite components, especially antenna size
- Higher transmitter power required because of space loss
- Much higher tropospheric attenuation

The crucial role of the availability of frequency bands speaks for itself--no band, no system. Both GPS and TRANSIT use a dual frequency, see Table 4-1, for the sole purpose of providing data to correct for ionospheric-induced transmission delays. Above 10GHz, the ionospheric effects are for practical purposes negligible.

One of the more promising concepts listed in Table 4-1 is RIPLE (Radio Interferometry Position Location Experiment). However, to achieve the position accuracy shown requires a  $400\lambda$  baseline ( $\lambda$  being the wavelength of the transmission). At the frequency proposed (1500MHz) this translates into four 40m booms extending from the satellite's body. At 40GHz, the required antenna length is only 1.5m, eliminating the need for the booms by mounting the antenna on the satellite's periphery. Furthermore, the antenna width at 1500MHz of about 0.3m (to provide Earth coverage plus some tolerance for the spacecraft attitude control system) reduces at 40GHz to the order of a few centimeters.

Conversely, with omnidirectional reception of the navigation signal at the mobile object, higher frequencies require more power. For example, to service the same geographic area, a 40 GHz system would require 28dBi, i.e., 625 times more power. This limitation is very likely the pacing item for any space-based navigation system using 40GHz. To compound the problem, while tropospheric refraction at 1500MHz causes nominally less than

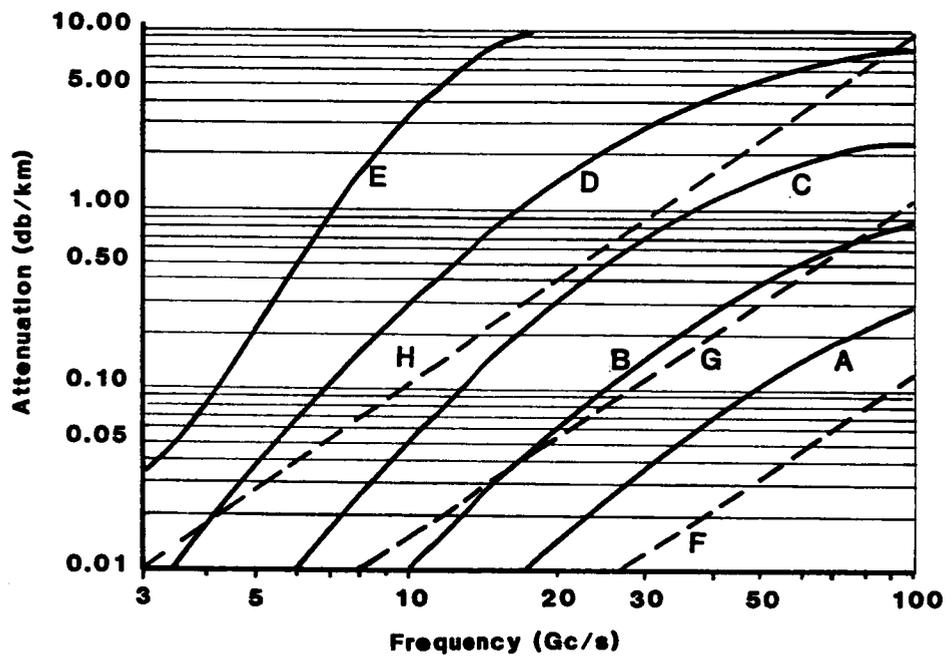
1dB1 of attenuation and is essentially impervious to local weather conditions such as severe rainstorms, at 40GHz the attenuation is much higher, as illustrated in Figure 4-1. Typically the signal must traverse approximately 10km of troposphere; by multiplying the vertical scale of Figure 4-1 by ten, the amount of attenuation at various frequencies can be appreciated. Of course, in dry climates or for aircraft flying below 10km, the magnitude of the attenuation decreases substantially.

#### D.4.3 TYPE OF POSITION FIX

Table 4-1 lists the types of position fixes employed by each system. Although other several systems have been proposed and tested, the ones listed have proven to be the most adaptable to several navigation on or near the Earth's surface (land, sea, air).

LORAN C and Omega obtain position fixes by the intersection of two hyperbolas. The basic measurement technique is range differencing from pulse arrival differences, wherein the navigator measures the difference in range between two transmitters of known coordinates. The range difference provides a line of position (LOP), which in theory is a hyperbola. A third station provides another LOP, whose intersection with the first LOP provides the fix. In actuality the hyperbolas are distorted by propagation anomalies, thus stored or computed corrections are necessary to obtain the accuracy shown.

GPS positioning is accomplished by the intersection of three hyperboloids (hyperbolas of revolution) with their foci at satellites. A 3D fix results by virtue of the three surfaces intersecting at a point. Another feature of GPS is that it also provides a time transfer relative to universal time coordinates (UTC) to an accuracy of better than 100 nanoseconds. The GPS receiver measures the apparent time delay between each satellite and the navigator. This time delay, called a pseudorange, is the



- Attenuation in rainfall of intensity: A. 0.25 mm/hr (drizzle)  
 B. 1 mm/hr (light rain)  
 C. 4 mm/hr (moderate rain)  
 D. 16 mm/hr (heavy rain)  
 E. 100 mm/hr (very heavy rain)
- - - - Attenuation in fog or cloud: F. 0.32 gm/m<sup>3</sup> (visibility < 600 m)  
 G. 0.32 gm/m<sup>3</sup> (visibility about 120 m)  
 H. 2.3 gm/m<sup>3</sup> (visibility about 30 m)

**Figure 4-1. Attenuation Due to Precipitation**

sum of the actual time delay (proportional to range) and the offset between the satellite clock and the navigator's clock. When measuring four pseudoranges, one to each of four satellites, the navigator can compute both position and UTC time.

PLACE, MARSAT, and AEROSAT use only two satellites, yielding a LOP from the intersection of two spheres, each with a radius equal to the measured range between satellite and navigator. They thus provide a 2D fix. Knowledge of the navigator's altitude, added to the local radius of the Earth, can provide a third sphere and can thus supply trilateration, i.e., the intersection of three spheres.

RIPLE, an interferometer system, measures the angle to the navigator relative to the satellite's body axes. These must be determined relative to an Earth-fixed coordinate frame. Concepts have been developed and tested using the ATS-F satellite to provide a continuous determination of spacecraft attitude using the same signals used to navigate.

TRANSIT is a doppler system. The navigator essentially measures the time when the received doppler passes through zero and the rate of change of doppler as it passes through zero. Given the satellite ground track, computed from information stored in the satellite and transmitted to the navigator, the time of zero doppler places the navigator on a LOP which intersects the ground track at right angles. The doppler slope provides information to compute the navigator's distance on the LOP from the ground track. Doppler systems are very sensitive to errors in the navigator's velocity. Typically, this sensitivity is 700m position error per meter/second doppler velocity error. Errors in the navigator's altitude also affect accuracy. A ship-board TRANSIT system typically corrects for the height of the antenna above the water line and for local tides.

## Range/Coverage

Geographic coverage depends on the number of satellites. With the exception of GPS and TRANSIT, all space systems listed in Table 4-1 employ geostationary satellites. All exhibit strong interaction between coverage and accuracy, see Figure 4-2.

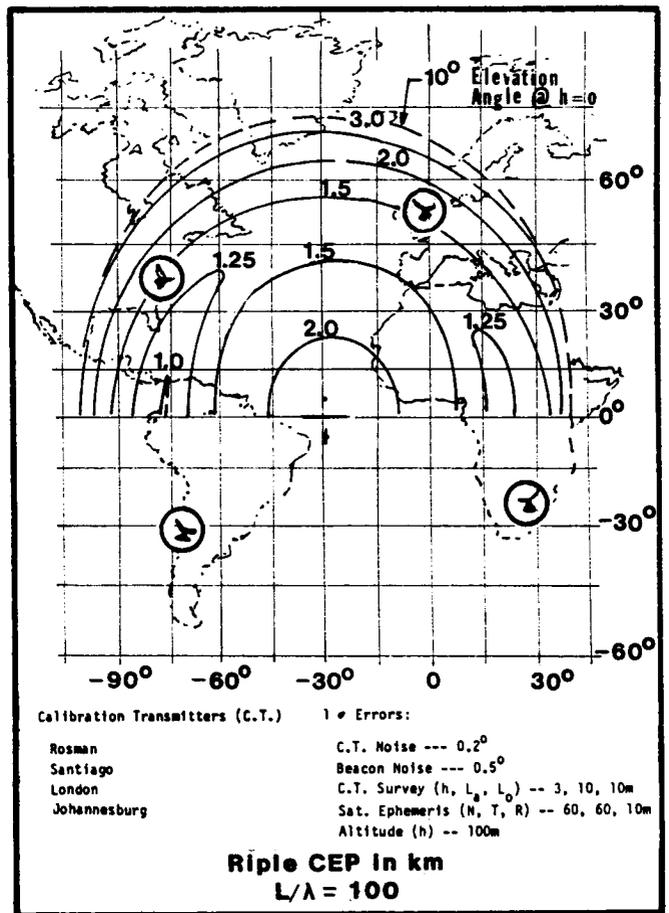
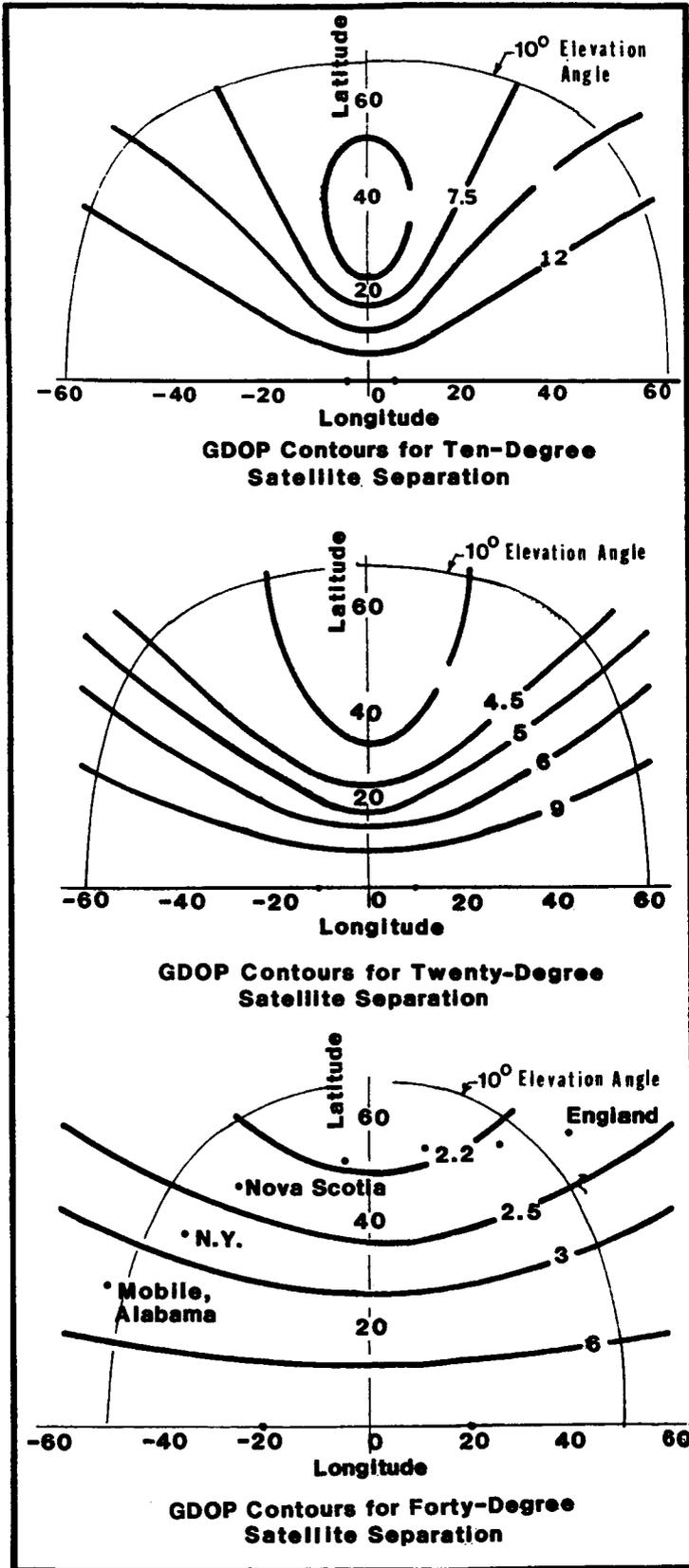
In the PLACE, MARSAT and AEROSTAT satellite systems, the separation between geostationary satellites is conducive to good accuracy; however, as the separation increases, the overlap between satellite coverages needed to provide a fix decreases.

Geometrical dilution of precision (GDOP) is a mathematical term which provides a measure of the worsening of navigation accuracy per unit of measurement error. For example, if the ranging accuracy were 1m, then a GDOP equal to three would mean the navigator would experience a 3m position error. Figure 4-2 shows that the accuracies of the above three systems vary from very poor to very good (essentially zero) near the equator and the polar regions. RIPLE has poorest accuracy at the fringes of its coverage. For a variety of reasons, almost all space-based navigation systems have a usable minimum elevation angle above the horizon of five to ten degrees. GPS is one system where navigation is enhanced by utilizing satellites at low elevation angles. GPS specifies the minimum to be five degrees.

## Position Accuracy

Table 4-1 shows representative accuracies (relative to a common grid of Earth fixed latitude and longitude) achievable by satellite-based navigation. GPS is the most accurate. In the 1990s, with design improvements already under way, it should approach the 1m level. On occasion, position location is based on the so-called relative navigation. For example, there may be a requirement to determine the distance between two or more navigators separated by 100km to 1m accuracy; yet their location

**GDOP Accuracy Contours**



**Figure 4-2. Coverage Versus Accuracy**  
(See Text for Explanation)

relative to a latitude-longitude grid may be uncertain or in excess of 1000m. Under these conditions, some systems provide substantially better accuracies than indicated in Table 4-1.

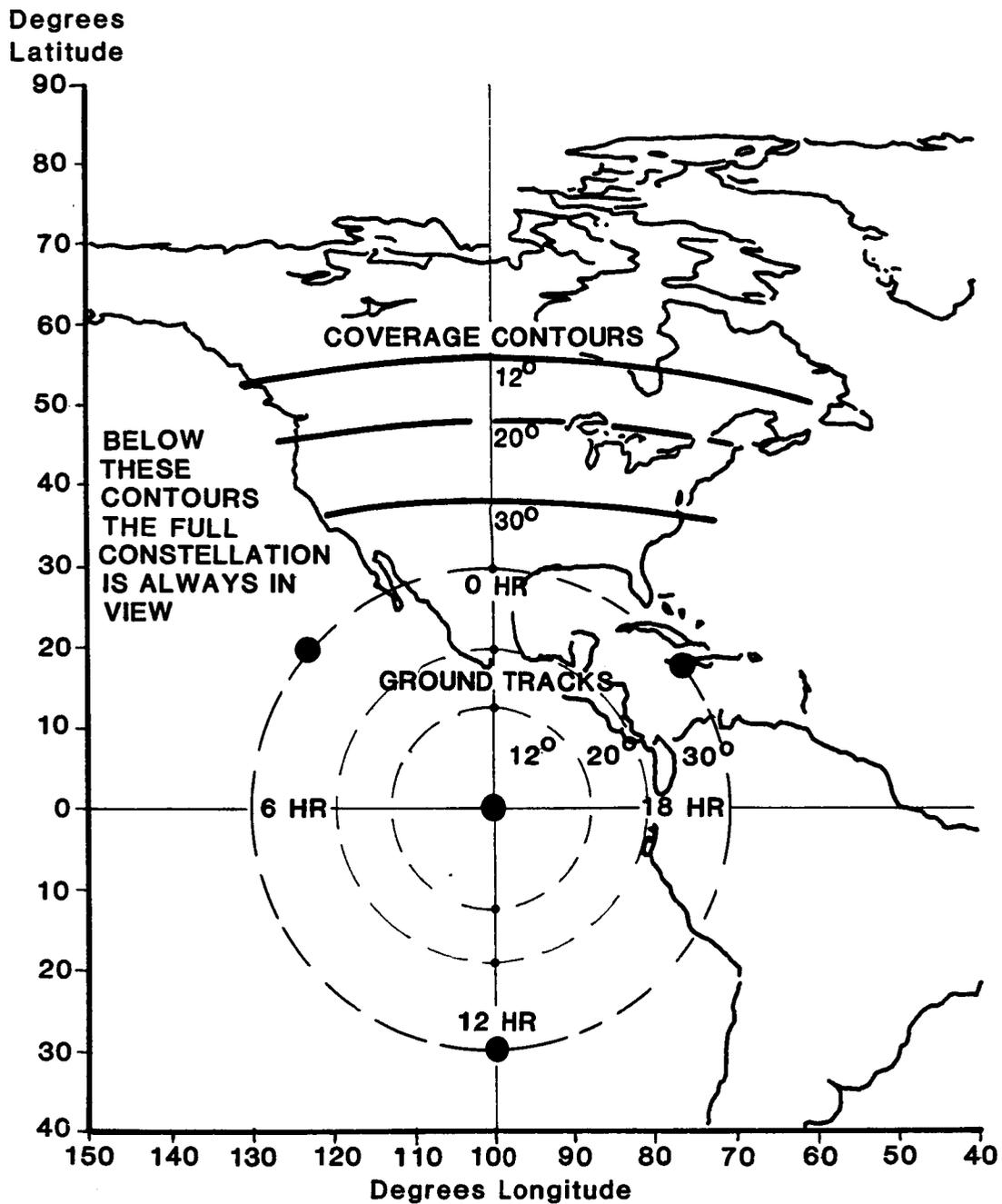
Experiments conducted during the developmental phases of GPS when the full potential of  $\pm 20\text{m}$  had not yet been realized, showed relative accuracies in the submeter range between navigators separated by several kilometers. The potential accuracy of relative navigation is heavily dependent on the relative magnitude of errors involved in the position fix. In general, if the position fix error is dominated by the user's measuring equipment, there will be little improvement between relative and absolute accuracies.

#### Position Fix Update Availability

With the exception of TRANSIT, all systems shown in Table 4-1 are continuously available. The signal is always there for the navigator to use. The update interval refers to the time required for a fix in normal operation. For example, GPS can compute a position fix every 6 seconds (1.5 seconds with some receiver designs); RIPLE in intervals of 10 to 20 seconds. In some systems, e.g., PLACE, the update interval is conditioned by the user's access to the satellite, which is dictated by the number of users, communication channels, and modulation techniques, e.g., TDMA, CDMA, FDMA.

#### D.4.4 NUMBER OF SATELLITES REQUIRED FOR GLOBAL COVERAGE AND POSITIONING

All space-based navigation systems require signals from one to four satellites. This poses severe restrictions on possible satellite orbits. For example, Figure 4-3 shows how satellite separation affects trilateration.



Inner circle provides greatest regional coverage but lowest accuracy. Dots are satellite positions at a given time. Inner satellite is geostationary, outer satellites rotate following ground tracks as shown.

**Figure 4-3. Orbit Ground Tracks and Coverage Contours**

Only orbits with a period of 24 hours remain relatively stationary with respect to the Earth. If one of these orbits also has zero inclination, it remains truly stationary with respect to the Earth. If the 24-hour orbit is inclined, the satellite motion appears, as in Figure 4-3, resulting in 12 out of 24 hours being spent over either the northern or southern hemisphere. If regional navigation in the northern hemisphere is the requirement, additional satellites would be required to compensate for the time spent over the southern hemisphere.

If, in addition to non-zero inclination, a non-zero eccentricity is used and the argument of perigee is adjusted to occur in the proper place, the satellite's ground tracks appear to move in circles centered at the equator, see Figure 4-3, and the time spent in one hemisphere is reduced from 12 hours typically to 8 hours. This type of satellite orbit was the keystone of the AF 621B system and for several "look-alike" systems proposed for an advanced CONUS Air Traffic Control System, circa 1968.

When a regional system is expanded to global coverage, the number of satellites required increases, sometimes dramatically, Table 4-3. For example, doppler techniques require only one satellite at a time in a low altitude orbit to provide the doppler effect. Conversely, synchronous satellites produce little or no doppler effect. Table 4-3 indicates that to achieve 100% availability using doppler techniques would require 48 satellites. GPS, which requires four satellites visible simultaneously and which has an orbital altitude of order of 10,000 nautical miles requires only 18. Notice that the number of satellites is not reduced when orbital altitude is increased from 10,000 (12 hour period) to 20,000 nautical miles (24 hour or synchronous period). Significant to satellite design is that satellites operating in 12 hour orbits require one fourth as much transmitter power as those operating from 24 hour orbits to achieve the same received signal level.

TABLE 4-3

NUMBER OF SATELLITES REQUIRED FOR GLOBAL  
COVERAGE VERSUS NUMBER NEEDED PER POSITION FIX

<u>ALTITUDE (NAUTICAL MILES)</u>	<u>NO. OF RINGS</u>	<u>SATELLITES PER RING</u>	<u>TOTAL SATELLITES FOR 100% AVAILABILITY</u>
<u>4 PER FIX</u>			
475	9	17	153
1000	6	13	78
5000	4	7	28
10000	3	6	18
SYNCHRONOUS (20000)	3	6	18
<u>2 PER FIX</u>			
74	5	17	85
1000	4	11	44
5000	2	7	14
10000	2	6	12
SYNCHRONOUS (20000)	2	5	10
<u>1 PER FIX</u>			
475	6	8	48
1000	4	6	24
5000	2	4	8
10000	2	3	6
SYNCHRONOUS (20000)	2	3	6

D.4.5 NUMBER OF GROUND STATIONS REQUIRED FOR  
THE CONTROL SEGMENT

All space systems listed in Table 4-1 require some means of locating satellites in real time and of providing calibration data to correct for satellite equipment delays--oscillator drifts and so forth. These calibrations are provided by the ground-based control segment. Table 4-1 lists the number of ground stations needed for the control segment function. These stations are typically separated by thousands of kilometers, posing a problem as to their location. GPS, for example, uses five ground stations, called monitor stations. Their sole function is to provide the data needed to determine the location of the satellites and to calibrate satellite-borne equipment, particularly the cesium atomic clocks. These five stations are located at Colorado Springs, Hawaii, Kwajalein Islands in the Pacific, Diego Garcia Island in the Indian Ocean, and Ascension Island in the South Atlantic. In addition, a computing complex is located at Colorado Springs (called MCS, Master Control Station). Three ground antennas (GAs) are located at Kwajalein, Diego Garcia, and Ascension. These GAs are used to upload every satellite with new satellite ephemerides and atomic clock calibrations every 8 hours.

For regional coverage, the RIPLE system, see Figure 4-3, requires four ground stations, widely separated. The trilateration systems require only two stations, also widely separated. The expansion of the trilateration or interferometer systems to provide global coverage could produce an inordinate number of and practical difficulties associated with obtaining suitable ground stations.

All of the data obtained at every ground station must be relayed to a common point for processing. The data rates are very low, well under 100 bits/second.

GPS could function with as few as three MSs (any three) with almost no performance degradation; TRANSIT can function with only one ground station. Satellites in non-24 hour orbits provide substantial relative motions between satellite and ground. This motion is highly beneficial in estimating satellite ephemeris. The payoff of variable ephemeris is fewer ground stations.

#### D.4.6 APPLICATIONS

Three categories in Table 4-1 relate to the application of ground stations, namely,

- 2D or 3D
- navigation or surveillance
- with or without velocity fixes

The distinction between 2D and 3D has been made. Only GPS has the inherent capability to provide velocity information, because GPS's waveform measures doppler in very short intervals (1.5 seconds). Since it is physically impossible to measure doppler instantly, what is measured and called doppler is a change in phase divided by time. If the time interval is short, the change in phase divided by time approximates a derivative, hence approaches doppler, which is a time derivative of phase. GPS was designed to service users moving at supersonic, even hypersonic speeds; hence the motivation for providing a good doppler approximation.

For very slowly moving users, less than 100ft/second a less demanding doppler approximation is tolerable. Almost any of the systems listed in Table 4-1 could provide some level of doppler capability. However, the determination of velocity vector from doppler is like the determination of position, which makes use of multiple satellites.

As a side issue, if a navigator measures a non-zero doppler from six stations simultaneously, 3D position can be uniquely determined. Doppler is a function of the relative distance and velocity between transmitter and receiver; a single doppler measurement is a non-linear algebraic function of the three components of position and velocity. Six doppler measurements provide non-linear algebraic equations within six unknowns, which can then be solved with a minicomputer. This concept has received very little attention, probably due to high measurement accuracy requirements, the need for six stations all mutually visible, and the non-zero doppler requirement which is restrictive in terms of usable coverage.

Navigation is the position location capability of an autonomous user. Surveillance is the capability of a central authority to determine user location. Navigation requires receivers and a minicomputer. Surveillance requires only transmitters; an exception is the air traffic control application, in which a central authority initiates a surveillance function by a polling procedure requiring both a receiver and transmitter but not a minicomputer. Navigation is essentially an unsaturable system, whereas surveillance is saturable and therefore can only have a finite number of subscribers. In Table 4-1, this distinction between navigation and surveillance appears under the column labeled "Number of Possible Subscribers." The sole exception to this distinction is RIPLE which is a random access system. The number of RIPLE users is definitely limited by the probability of mutual interference, but a very large number of users can subscribe to the system if a high level of probable interference is acceptable. Probability can be calculated on the failure to get through after n trials. In effect, since regular position updates are not important to the user of RIPLE, it has been proposed for such applications as search and rescue, and tracking meteorological balloons, icebergs and migratory animals. RIPLE is one of the lowest cost systems; many of its applications are based on throw-away user equipment.

D.4.7      USER EQUIPMENT

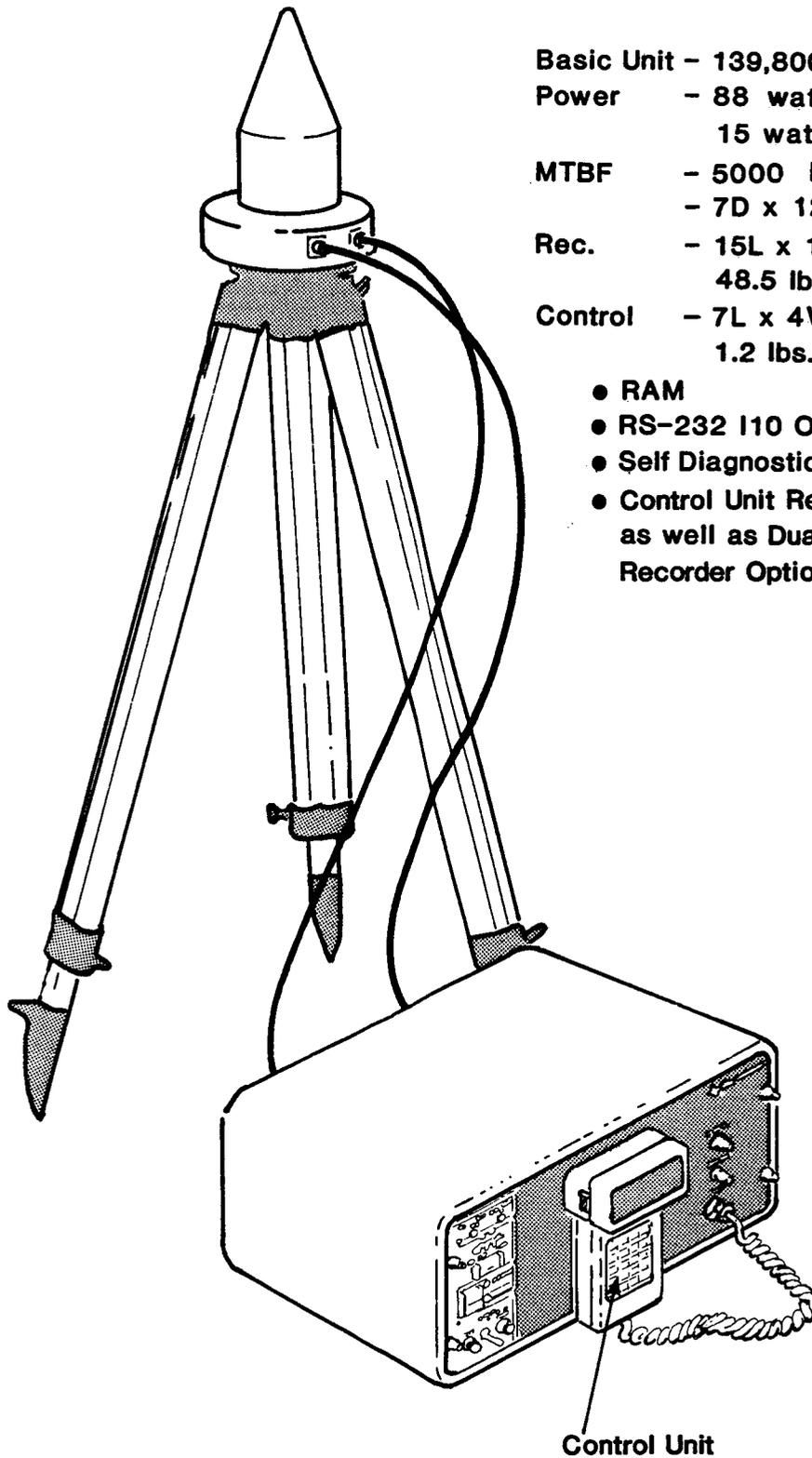
Table 4-1 lists three major classes of user equipment:

- receiver/computer/display--autonomous navigation capability,
- transponder--polled surveillance capability,
- transmitter--random access surveillance capability.

TRANSIT and GPS costs for this equipment are current. Since TRANSIT equipment has evolved over 20 years, significant cost reductions in the future are unlikely. Since GPS is not yet fully operational, its cost can be expected to drop significantly over the next five to ten years.

The Air Force is currently developing military versions of GPS navigation units. Cost data for these units are unlikely to differ significantly from the TI 4100 receiver. However, the Air Force units differ in terms of the number of satellites a receiver can track simultaneously, i.e., from one to five. Four satellites are tracked sequentially for slowly moving users, e.g., manpack; the number increases up to five as user dynamics increase and/or higher accuracies are required, e.g., for high-performance aircraft such as the F-15.

GPS transmits two codes, called C and P. The C code has a 1MHz chip rate using Gold code modulation, whereas the P code has a 10MHz chip rate and uses a pseudonoise modulation with a repeat cycle of one week. The C code requires a considerably simpler receiver design, although some loss in accuracy can be expected. The TI 4100 receiver, shown in Figure 4-4, can operate on either the C or P codes, which may partially explain its cost of \$150,000. But it also multiplexes up to four satellite signals at a very high rate, thereby reducing its channels to one.



**Basic Unit - 139,800 Plus Options**  
**Power - 88 watts operating**  
           15 watts standby  
**MTBF - 5000 Hrs**  
           - 7D x 12H, 3.5 lbs.  
**Rec. - 15L x 18W x 8H, inches**  
           48.5 lbs.  
**Control - 7L x 4W x 2H, inches**  
           1.2 lbs.

- RAM
- RS-232 I10 Option
- Self Diagnostic Aids
- Control Unit Recording  
as well as Dual Cassette  
Recorder Option

**Figure 4- 4. TI 4100 NAVSTAR Navigator**

With a C code as the only requirement, the cost of a TI 4100 may be less than \$50,000. The TI 4100 shows a relatively high level of LSI (Large Scale Integration), including RF, IF and computer elements.

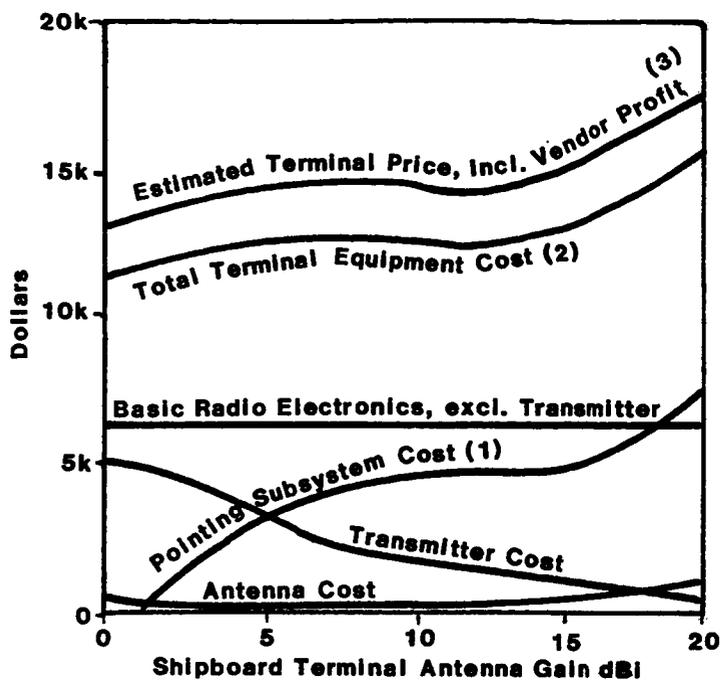
Plans for the next generation GPS involve VLSI (Very Large Scale Integration). The advanced design will likely reduce the size by at least 4:1 and power by 10:1. The largest single element may well be the antenna element whose size is essentially fixed by the 1600MHz frequency.

In contrast to GPS, consider the preliminary cost sheet for MARSAT generated in the mid-1970s, Figure 4-5. The major trade identified is the antenna-gain, which translates into lower satellite transmitter power, but also means more accurate pointing of the antenna because gain is inversely related to beamwidth. The direct user costs, which are approximately \$15,000 per unit, are not significantly dependent on the antenna gain. As this gain approaches 20dBi, the installation costs for ships begin to grow rapidly, and become much higher for aircraft.

Thus, although unit costs may decrease over the years, it is prudent to consider the cost of installation as part of total user cost.

#### D.4.8 ACCESS AND USER FEES

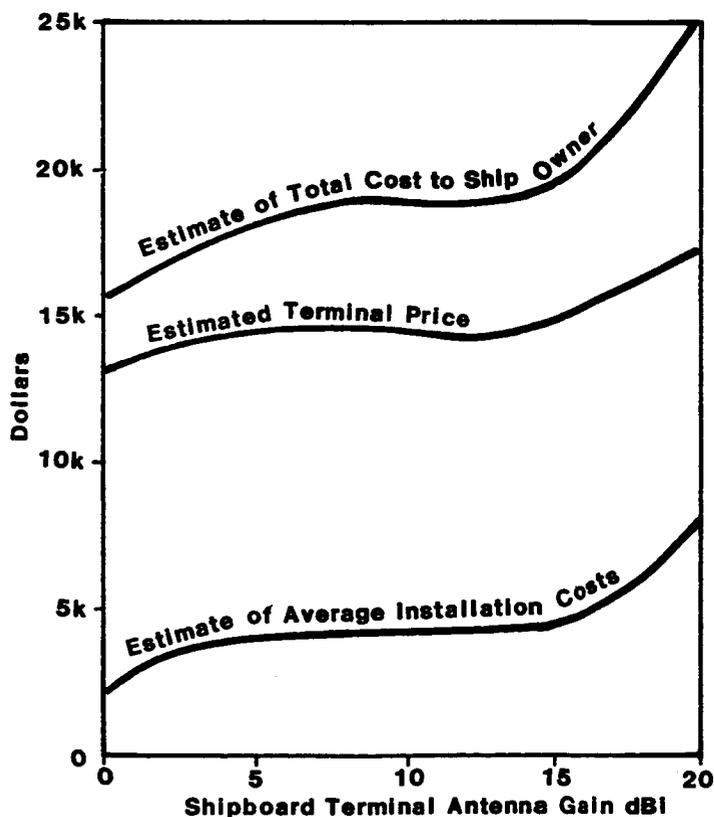
TRANSIT is currently the only fully operational, space-based navigation system. It is operated by the U.S. Navy and its services are available to anyone with a TRANSIT receiving system. TRANSIT requires no user fees. GPS has a built-in capability called "selective availability" that can selectively limit accuracy in part or in total for any given class of user. The motivation for this selective availability is not primarily economic but military. It would be unthinkable to supply a potential enemy with a highly advanced navigation service in times of



ESTIMATE OF SHIPBOARD TERMINAL SYSTEM COSTS  
(Excluding Installation)

Meters:

1. Pointing subsystem costs include all appropriate mechanical and electronic components necessary to function.
2. All equipment costs assume manufacture of at least 200 units.
3. Estimated vendor price includes 15% mark-up.



ESTIMATE OF TOTAL SATELLITE TERMINAL COST  
TO SHIP ORDER INCLUDING INSTALLATION

**Figure 4-5. Estimated User Costs for MARSAT System**

national crises. "Selective availability" is based on the fact that it is necessary to know the positions of navigation satellites versus time (ephemerides) and certain calibration data (atomic clock time offsets and drift) relative to all the other satellites. These data can be altered, but not sufficiently to arouse suspicion or to be completely denied by means of encryption.

These same GPS features can be used for commercial application where the necessary navigation data would be encrypted. Only subscribers who have the proper key could use the system. For example, the data encryption standard (DES) provides a commercially available, low-cost means of data encryption, with access a matter of control of the keys.

The amount of data that must be encrypted in any space-based navigation system is very small. For example, GPS needs only 15 32-bit words every 4 hours per satellite. GPS actually broadcasts data at 50 bits/second, but this includes the data from all the other satellites plus special notices to users, etc.

Developing an alternative to a direct means of decryption is not a simple procedure. For example, the USSR is developing a system similar to GPS, which offers ostensibly the only viable alternative to a circuitous means of decrypting the data. The mere concern that access will be denied at any time that keys are changed may be sufficient to discourage unauthorized users of these systems.

This problem of selective availability does not exist for surveillance. Satellite data are not transmitted to the user as part of the navigation function. Rather, these data are retained at a central repository where they are used to determine the location of the user. The user location can then be encrypted and transmitted to the user via some communication link.

Jamming (intentional or unintentional) is the major problem associated with surveillance. However, a simple waveform, with very poor rejection of interfering signals, is needed to keep user costs low. Frequency bands that are, and will probably continue to be, relatively unused for a long time--e.g., the 40 GHz band--might be considered for commercial surveillance.

#### Space-Based Costs

The anticipated launch cost reduction from use of Shuttle flights have not materialized. Therefore, the numbers shown in Table 4-4, derived from a MARSAT study, are probably on the low side. The significant trade-off is in satellite transmission power. The 400, 1000 and 2500W numbers refer to the power generated by the satellite solar panels. Less than 10% of this power is available for signal transmission. While these numbers should not be taken literally, the factors entering into the subtotals and totals are real, as well as the relative amounts among these factors.

The MARSAT study showed that the capital expenditure exceeded revenue for nine to 12 years, depending on subscription revenue; the imbalance reached a maximum of about \$100 million total in the sixth year. The cost analysis showed a revenue to cost slope of about +\$40 million per year in the eleventh year. These numbers, of course, are dependent on the number of subscribers, which in this case was assumed to be in the thousands.

#### D.4.9 AMBIGUITY RESOLUTION

In most cases, the simplest waveforms of requisite accuracy also lead to ambiguous determination of position, i.e., multiple solutions based on the measured data. Waveforms are sometimes made more complex to eliminate multiple solutions. Omega, for example, eliminates ambiguities by using multiple frequencies.

TABLE 4-4

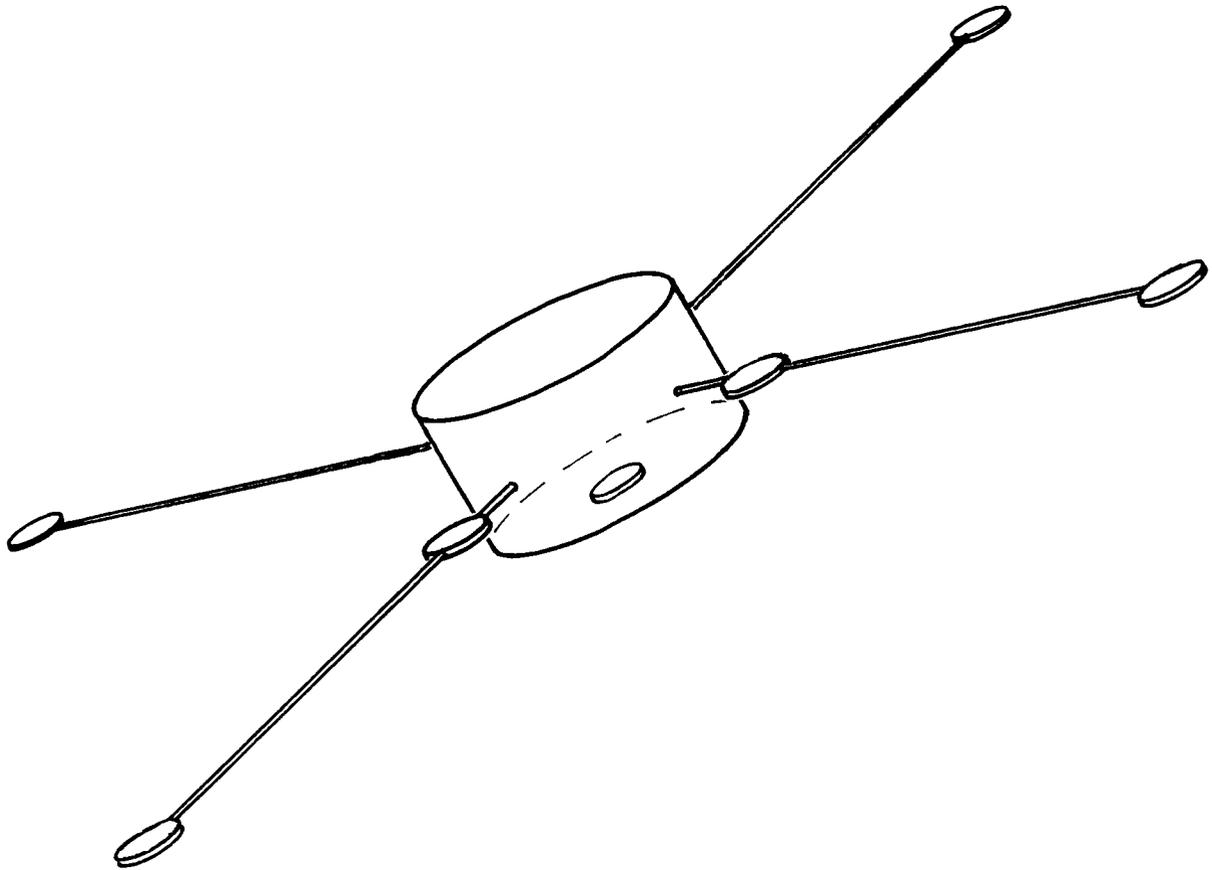
MARSAT SPACE AND EARTH SEGMENT COSTS(7 YEAR (1974-1980), 3 OCEAN SERVICE)  
(210 AVAILABLE CHANNEL YEARS)

<u>COST ITEM</u>	(A) DELTA CLASS SPIN-BODY MOUNTED CELLS (400 W DC)	(B) DELTA CLASS 3-EXPANDABLE PANELS ( ~ 1000 W dc)	(C) CENTAUR CLASS 3-EXPANDABLE PANELS ( ~ 2500 W dc)
SATELLITE DESIGN & DEVELOPMENT	12	25	35
SATELLITE UNIT RECURRING @ \$3.5M, \$7M, & \$11M + SPARES	12	24	36
LAUNCH VEHICLES @ \$5.8M \$6.5M & \$17M	17.4	19.5	51
PRO RATA SHARE OF FIRST GENERATION AEROSATS & LAUNCH VEHICLES	9.3	13.5	28
SATELLITE/BOOSTER FAILURE CONTINGENCY FUND (20%)	<u>7.7</u>	<u>11.4</u>	<u>23.4</u>
SUBTOTAL	58.4	93.4	175.4
RETURN ON NET INVESTMENT @ 25% PER YEAR	<u>43.8</u>	<u>69.8</u>	<u>131.5</u>
<b>SUB-TOTAL SPACE</b>	<b>102.2</b>	<b>163.2</b>	<b>306.9</b>
NON-RECURRING EARTH TERMINALS	16	16	16
RECURRING GROUND OPERATIONS	28	28	28
RECURRING TERRESTRIAL LEASE LINES FOR INTERCONNECTION	<u>12.6</u>	<u>12.6</u>	<u>12.6</u>
<b>SUBTOTAL GROUND</b>	<b>56.6</b>	<b>56.6</b>	<b>56.6</b>
<b>TOTAL</b>	<b>\$158.8M</b>	<b>\$219.8M</b>	<b>\$363.51</b>

ADDED COST WITHOUT PARTICIPATION IN AEROSAT PROGRAM	19.6	28.4	58.9
AVERAGE ANNUAL COST	\$22.7M	\$31.4M	\$51.9M
REQUIRED STRIP ANTENNA GAIN	10dB	6dB	2dB

GPS, on the other hand, eliminates ambiguities by a more complex waveform. Simple waveforms have the desirable characteristic of lowest cost, certainly with regard to user equipment and to some extent to the satellite equipment. However, they are susceptible to man-made multipath and/or unintentional interference. In a crowded spectrum, such waveforms are not feasible. L band, for example, is notoriously overcrowded. There are many L band radars operating at very high power levels ( $>10\text{kW}$ ) using magnetrons for their output devices, which unavoidably spill some of their power into other frequency slots. A typical low-cost user set would have from 1 to 10W of transmission power and, very probably, the received power at the satellite of the user's transmission would be buried in the noise produced by the L band radars. Therefore, simple waveforms should be used for underused frequency bands and not overcrowded ones.

The problem of ambiguity resolution can be solved by using these multiple simple waveforms, e.g., similar to side tone ranging, or by using multiple receiving elements at the satellite, whence multiple measurements can be used to resolve the ambiguity. RIPLE is a prime example of this technique, wherein a system of seven antennas was arranged as shown in Figure 4-6. The effective baselines achieved with this seven antenna configuration were  $3\lambda$ ,  $20\lambda$ ,  $190\lambda$ , and  $400\lambda$ . Each baseline contributes to the resolving of ambiguities. Four baselines are used because the number of resolving steps depends on the magnitude of the measured phase error, which is a function of many variables. As the measured phase error decreases, the number of resolving steps also decreases. Multipath may also be a problem with simple waveforms. The extent of the multipath depends on several key factors, namely, the height of a user antenna above reflecting surfaces, user speed (speed helps to diffuse the multipath effects), directive antenna, reflective index of surface (land is much better than water).



**Figure 6. Ripple Ambiguity Resolving Antennae**

D.4.10 THE FUTURE

It appears that GPS will be the primary navigation service for at least the next 20 years. There are no known plans to require subscriber fees for GPS, despite the discussions between the FAA and the Department of Defense to consider subscription fees. Historically, the U.S. government has not charged directly for navigational aids of any kind. The lowest cost user sets will be \$10,000, probably closer to \$50,000; any more accurate market prediction would be dependent upon the postulated demand. The cost of TRANSIT receivers is still in the \$40,000 to \$100,000 range after 20 years; only a much higher level of production would lower GPS costs in the future.

GPS will be operated by the Space Command of the USAF and designated as a military weapon system. Hence, its non-military use will depend upon the implicit permission of the Department of Defense. However, this defense-controlled status of the GPS will likely be challenged by many groups outside of the Department of Defense.

While the FAA is currently spending billions to upgrade its ground-based ATC system, numerous users state a need for a low-cost, accurate, large coverage navigation and/or surveillance system. Some of these users are:

<u>USERS</u>	<u>USES</u>
USCG, AF, Navy/Marines	Search and rescue, global
NOAA	Meteorology, global
DOE	Trucking (radioactive shipments tracking in CONUS)

USERS (continued)

USES (continued)

NS, Canadian Railroad

Search for misplaced box-cars in CONUS, Canada

Shipping, private

Global/regional surveillance, particularly coastal areas

USCG, NOAA, private shipping in polar regions

Iceberg location

FAA

Traffic control commercial and general aviation in CONUS

However, among these users or in the industrial world, there is as yet no entrepreneur willing to fund the R&D and capital investment ( $\approx$ \$100 million) required, although each and every one would avail himself of the services. In any case, one of the potential users, the FAA, would insist upon a positive (or at least firm) control over the system control operation.

To date, the satellite designs for navigation and surveillance have been based on global or very large regional coverage, e.g., CONUS. Potential millimeter wave designs, accompanied by multiple spot beams achieved through electrically steerable beams, can substantially reduce the satellite power requirements, thereby offsetting to some extent the large space and tropospheric losses attendant with millimeter waves.

Conversely, the use of large spacebeam antennas could achieve similar results at already assigned frequencies.

A potential market for these systems probably lies in a surveillance system, using one or two geostationary satellites at

or near 40GHz or featuring large space antennas and integrated with a communications satellite. Key to these is the achievement of low user costs, and reduction of some problems presented by the receiving antenna, especially if the user is highly mobile.

An upgraded RIPLE concept looks attractive in every respect save one: the need for four widely dispersed ground stations. The waveform can be very simple, i.e., a sine wave, or as complex as GPS, depending on user costs, interference rejection needs and multipath effects. At 40GHz, a  $400\lambda$  or even a  $1000\lambda$  baseline system is very mechanically feasible (3m, 7.5m booms). At the current frequency assignment of 1,600MHz, these become 75m, 190m respectively. Ambiguity resolution should not be problematical if several baselines are incorporated as in RIPLE. A polled or random access system, or conceivably some combination of these systems, could be devised. Computational requirements for a control system similar to RIPLE are well below the one MIP engine and 1 million bytes of storage consistent with many middle level commercially available computing systems. Operator skill requirements would normally not exceed those of a radio or TV station. A one or two operator shift is also envisioned.

#### Key Technologies and Technology Development Areas

Overall, the current global positioning system is adequate to fulfill the needs of Earth-surface navigation system for at least the next 20 to 25 years. Further R&D activity in the design of the space segment appears necessary. The commercialization problem is posed by the high cost of user terminals.

The need for a surveillance system is evident. The problem of its commercialization requires coordinating numerous user requirements; thus, it presents a significant business challenge.

## **D.5 SCIENTIFIC OBSERVATIONS**

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## D.5 SCIENTIFIC OBSERVATIONS

### D.5.1 SIGNIFICANCE

We consider here the purely **scientific** missions, as distinct from missions oriented to beneficial uses--e.g., Earth Resources Survey, Meteorology--or missions aimed at improving the techniques of spaceflight--e.g., biomedical research, test of spacecraft subsystems.

Since space exploration began in 1957, NASA has launched more than 300 scientific space missions. Authoritative descriptions and synopses of NASA's space sciences program are periodically published by the National Science Foundation (NSF) and by NASA itself.

Because there is no uniformly accepted categorization of the objectives of NASA's space sciences programs, we follow here Professor Gamow's 1965 definition, according to which the objectives of NASA's space observation program can be categorized within the following four classes:

- Understanding of the mechanisms underlying the **origin** and **evolution** of the **universe**
- Understanding the causes and processes of the **origin** and **evolution** of **life** in the universe
- Exploring the possible presence of **intelligence** in the universe
- Assessing the potential of the solar system--including the Earth--as a **habitat** for **man**. This includes lunar and planetary missions, as well as scientific investigations of the Earth's environment, e.g., magnetosphere, upper atmosphere--whose ultimate purpose

is to assess the continuing suitability of planet Earth as mankind's habitat.

We note that Gamow's third objective--search for the presence of extraterrestrial intelligence--while potentially of the highest interest, is, for valid practical reasons, currently funded at a very low level. We, nevertheless, will retain this element of Gamow's classification, for reasons of philosophical completeness.

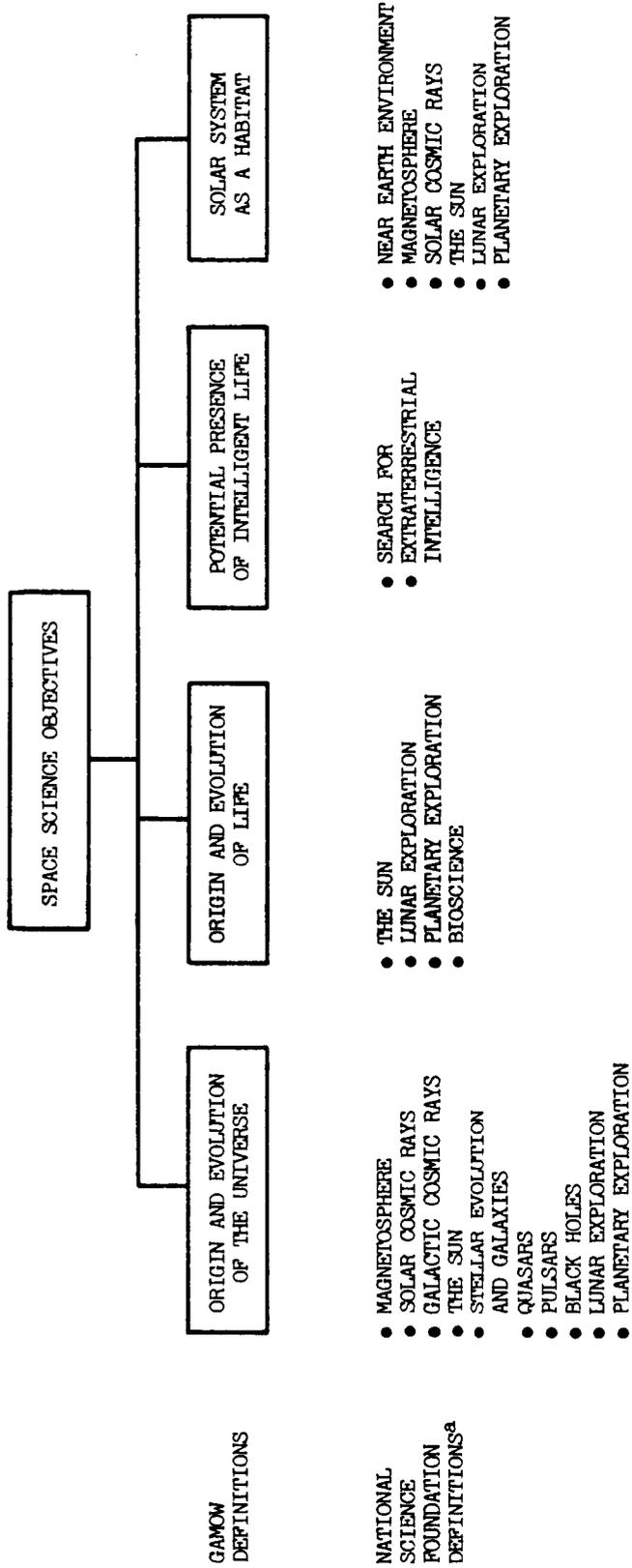
Figure 5-1 shows the match between Gamow's classification and the categorizations of space science developed by the NSF.

Figure 5-2 presents the principal areas of current interest to space science.

Frequently, NASA's scientific missions embrace **multiple** objectives. Typical is the Viking mission remote and in situ sensing of Mars, whose aims were:

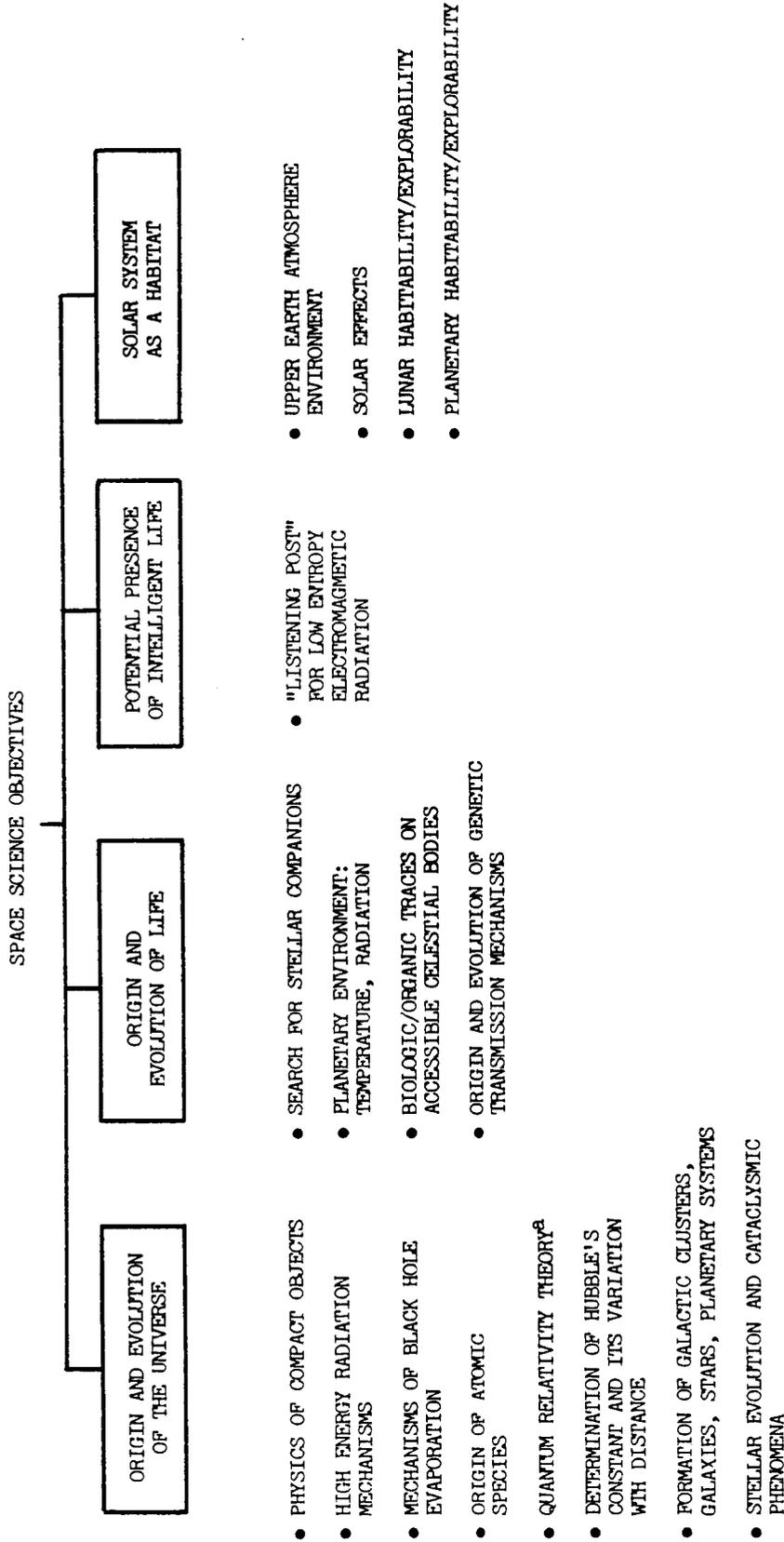
- Search for biological and organic constituents--Gamow's definition would place this aim within the objective of "origin and evolution of life"
- Improved understanding of planetary physics, morphology, chemistry--this would fit within the objectives "origin and evolution of the solar system" (as a proxy for understanding the evolution of the universe) and "assessment of Mars" potential as a human habitat."

Figure 5-3 depicts the distribution, by stated **primary** objective, of NASA's scientific space missions launched since 1964. By primary is meant the officially approved objective--albeit several of these missions were in effect multi-purpose.



<sup>a</sup> NOTE: SOME NSF DEFINITIONS FIT WITHIN MORE THAN ONE GAMOW DEFINITION

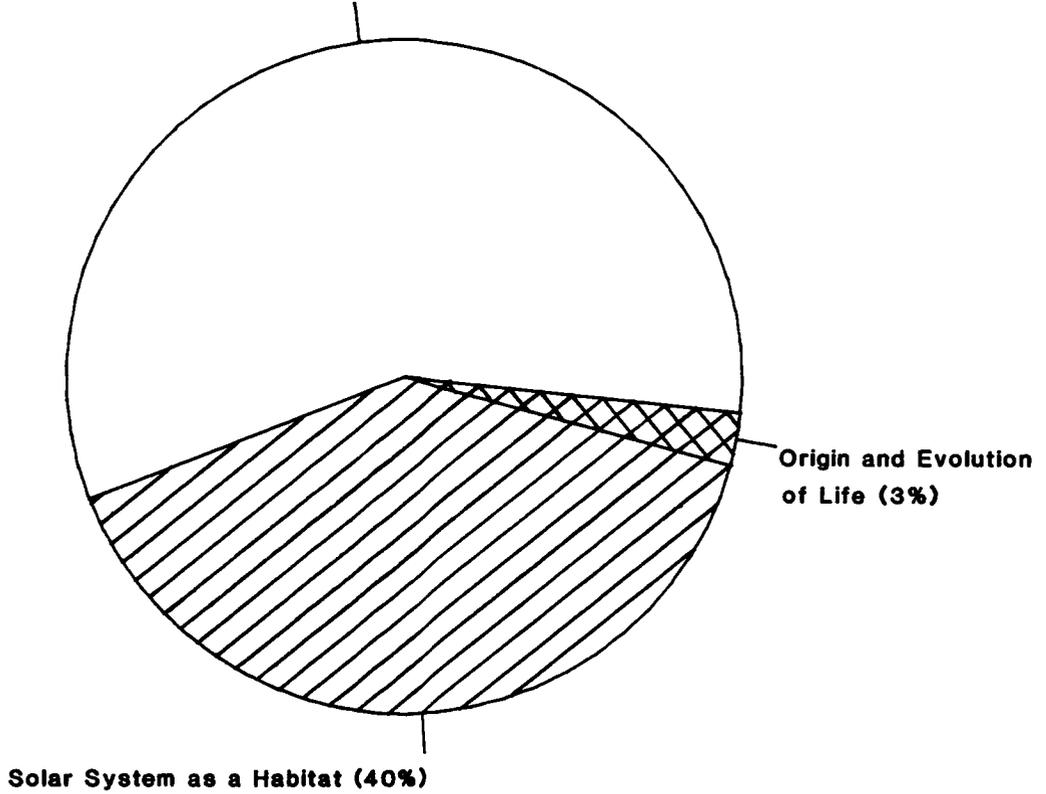
**Figure 5-1. Match Between Gamow's and the NSF's Definitions of Space Science**



<sup>a</sup> BEING DEVELOPED AS A LOGICAL NEED TO JUSTIFY SPACE SCIENCE FINDINGS OF THE LAST 2 DECADES

**Figure 5-2. Principal Space Science Research Areas**

**Origin and Evolution of the Universe (57%)**



**238 Missions, 1964-1981**

**Figure 5-3. Distribution of Scientific Space Missions by Primary Stated Objectives**

Almost 60% of these missions had as their primary purpose research into the origin and evolution of the universe. The knowledge garnered from these missions--also designated as "space astronomy" missions--has since the early 1960s revolutionized our knowledge of the universe. Their findings have also stimulated significant advances in our understanding of the basic physics of matter. Figure 5-4 exemplifies some of the milestones of space astronomy.

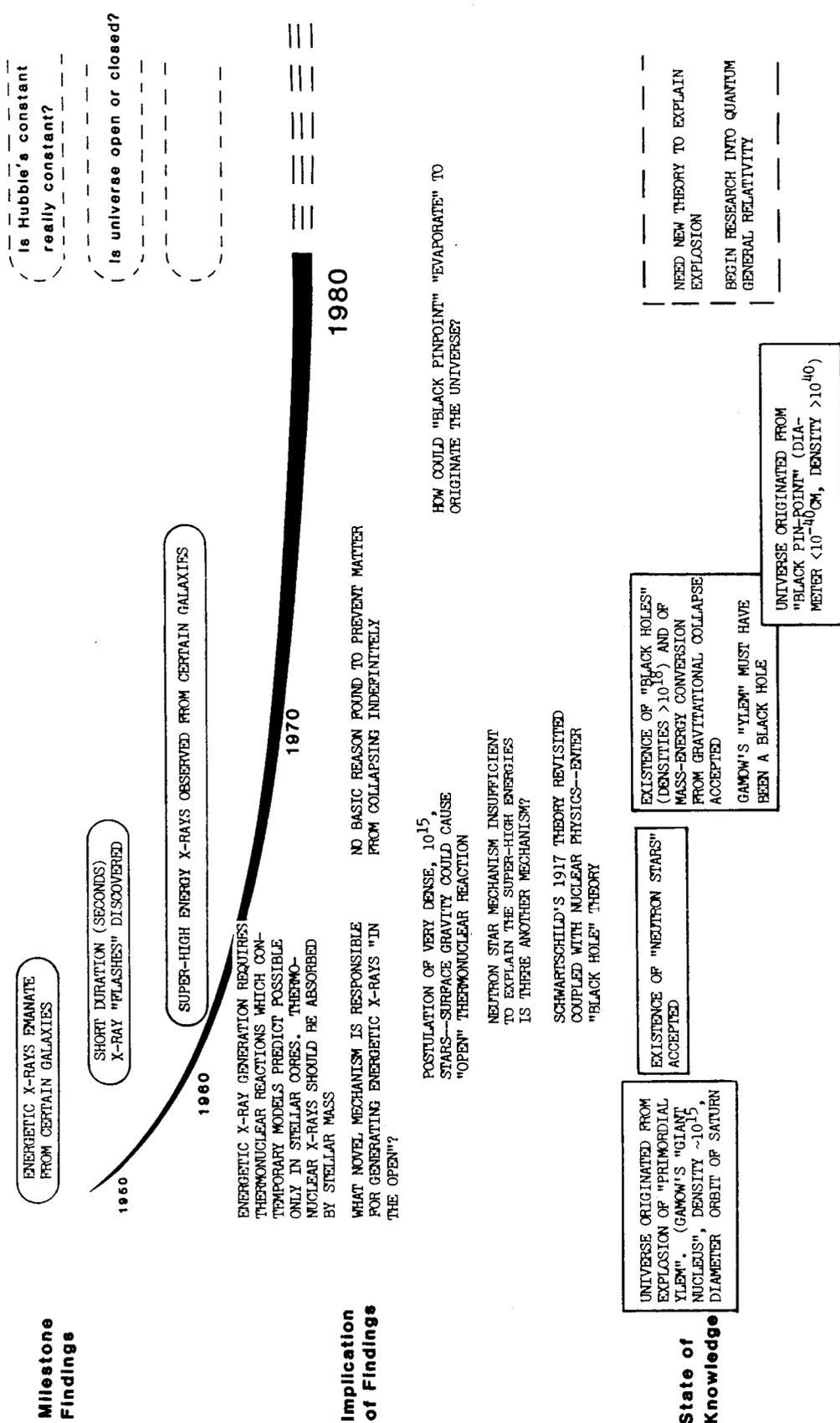
Approximately 40% of NASA's scientific missions fit within the objective of "assessing the suitability of the solar system as a habitat for man." Less than 10% of the space science missions have been launched for the primary purpose of investigating the origin and evolution of life. No space mission has as yet been flown for the specific purpose of investigating the presence of intelligent life in the cosmos.

#### D.5.2 SCIENTIFIC CONSIDERATIONS

Space science researchers seek continuous improvements of the quality of the scientific information derived from space science missions. This means:

- How to obtain data from **ever-larger cosmic distances**
- at ever-increasing **spatial** and **spectral** resolutions
- over ever-larger regions of the universe
- over the **entire** wavelength region of the electromagnetic **spectrum**.

The advantages of the space environment in pursuit of these objectives have been analyzed since the early 1960s and are by now well-known: elimination of the absorbing and distorting effects of the Earth's atmosphere; order-of-magnitude reduction



**Milestone Findings**

Is Hubble's constant really constant?

Is universe open or closed?

1960  
ENERGETIC X-RAYS EMANATE FROM CERTAIN GALAXIES

1960  
SHORT DURATION (SECONDS) X-RAY "FLASHES" DISCOVERED

1960  
SUPER-HIGH ENERGY X-RAYS OBSERVED FROM CERTAIN GALAXIES

1960  
ENERGETIC X-RAY GENERATION REQUIRES THERMONUCLEAR REACTIONS WHICH CON-TEMPORARY MODELS PREDICT POSSIBLE ONLY IN STELLAR CORES. THERMO-NUCLEAR X-RAYS SHOULD BE ABSORBED BY STELLAR MASS

1960  
WHAT MODEL MECHANISM IS RESPONSIBLE FOR GENERATING ENERGETIC X-RAYS "IN THE OPEN"?

**Implication of Findings**

1970  
NO BASIC REASON FOUND TO PREVENT MATTER FROM COLLAPSING INDEFINITELY

1970  
POSTULATION OF VERY DENSE,  $10^{15}$  STARS--SURFACE GRAVITY COULD CAUSE "OPEN" THERMONUCLEAR REACTION

1970  
NEUTRON STAR MECHANISM INSUFFICIENT TO EXPLAIN THE SUPER-HIGH ENERGIES IS THERE ANOTHER MECHANISM?

1970  
SCHWARTSCHILD'S 1917 THEORY REVISITED COUPLED WITH NUCLEAR PHYSICS--ENTER "BLACK HOLE" THEORY

1980  
HOW COULD "BLACK PINPOINT" "EVAPORATE" TO ORIGINATE THE UNIVERSE?

1960  
UNIVERSE ORIGINATED FROM EXPLOSION OF "PRIMORDIAL YLEM". (GAMOW'S "GIANT NUCLEUS", DENSITY  $\sim 10^{15}$ , DIAMETER ORBIT OF SATURN)

1960  
EXISTENCE OF "NEUTRON STARS" ACCEPTED

1970  
EXISTENCE OF "BLACK HOLES" (DENSITIES  $> 10^{16}$ ) AND OF MASS-ENERGY CONVERSION FROM GRAVITATIONAL COLLAPSE ACCEPTED

1970  
GAMOW'S "YLEM" MUST HAVE BEEN A BLACK HOLE

1970  
UNIVERSE ORIGINATED FROM "BLACK PIN-POINT" (DIAMETER  $< 10^{-40}$  CM, DENSITY  $> 10^{40}$ )

1980  
NEED NEW THEORY TO EXPLAIN EXPLOSION

1980  
BEGIN RESEARCH INTO QUANTUM GENERAL RELATIVITY

**State of Knowledge**

**Figure 5-4. "Return" From Space Astronomy in Understanding Origin and Evolution of Universe**

of backgrounds interference, e.g., residual sky radiation, man-made electromagnetic interference.

The single major technological driver to fully exploit these space environmental advantages is the ability to deploy ever-larger collectors of radiation, at all wavelengths. The principal impediment is cost.

Let us illustrate this requirement by selected examples.

Of significance to the objective "origin and evolution of life," see Figure 5-2, is the ascertainment of the presence of stellar companions, i.e., **planets circling stars**. Evidence of the presence of planetary systems, including assessment of their orbital distances from the central star, would demonstrate similarity with environmental conditions which have prevailed in the solar system--and would constitute a strong statistical inference in favor of the origination and evolution of life forms in other planetary systems. To attempt this measurement, we have available approximately 50 stellar neighbors within a radius of 10 light-years from the Earth. The resolution needed to identify planetary companions of these stars is of order 0.01 arc second; its achievement would require an orbiting optical telescope with a diameter of order 10m.

Of importance to the objective "origin and evolution of the universe" is to ascertain whether Hubble's constant (ratio between the speed of recession of galaxies and their distance) is truly a constant, or whether galactic recession velocities **slow down** at very large distances.

This requires independent determinations of galactic speed and distances. While the former is achievable with reasonable accuracy by doppler frequency measurements, the latter is currently accomplished via "ladder measurements." This begins with measurement of the geometric parallax of the nearer stars,

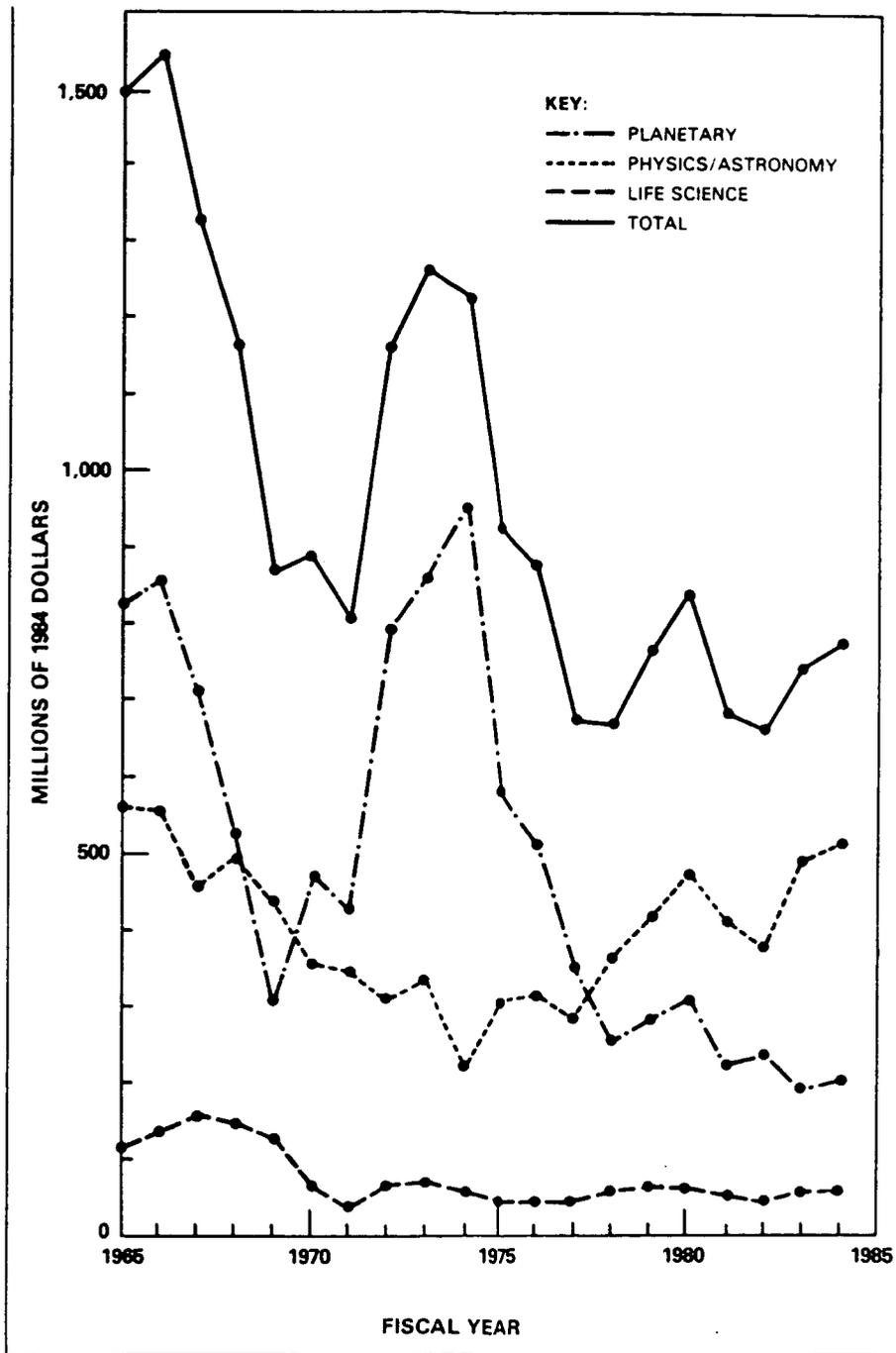
progresses through luminosity-period measurements of variable stars (cepheids), finally extrapolates these to galaxies of increasing remoteness. With best terrestrial telescopes, errors of measurement of Hubble's constant for distant galaxies are currently of order  $\pm 50\%$ . This much error does not allow us to determine whether Hubble's constant is truly a constant. Achievement of significant improvements of accuracy would require an orbiting optical telescope diameter on the order of 10m.

Analogous requirements for larger, energy-collecting apertures apply to the scientific remote sensing of the surface features of our sun's planets. Observation of the outer planets in particular would benefit by use of large radio communications antennas to increase the resolution, as well as the speed of the observations.

The key **return** from space science missions is **information**. The effectiveness parameter is the value-versus-cost per unit of information produced by the mission.

The "value" of scientific data, while intuitively very high, cannot be quantified objectively to the satisfaction of all segments of the scientific community, let alone all strata of our society. Part of the difficulty is that much of this research is apt to bear unforeseeable fruits, years and even decades after the research has been accomplished. However, the effect of **reducing mission costs** would be to permit more missions, producing more **data** per available **dollar**.

Figure 5-5 shows that total constant dollar funding for space science research has declined by approximately 50% during the last twenty years. This decrease in funding has caused the cancellation or postponement of some proposed missions. The ameliorative approach to this situation is to reduce the mission's costs.



**Figure 5-5. Space Sciences Funding**

Ref: Planetary Exploration Through Year 2000,  
 A Core Program, NASA Advisory Council, Washington, D.C. 1983

In what follows, we assess and analyze the costs of scientific missions, with a view to identifying what major technological improvements could lead to their reduction.

#### D.5.3 COST ASSESSMENT OF SCIENTIFIC SPACE MISSIONS

Generally, the cost of scientific space missions comprises two major elements: the cost of the **scientific payload** and that of the **launch**.

The cost of each payload is in general peculiar to the mission's objective: thus comparisons of absolute costs among diverse payloads are apt to be misleading. Nevertheless, certain trends become evident by comparing the **percentage distribution** of costs among the major elements of the various missions.

To perform this comparison, eleven missions were selected, having sufficiently diverse characteristics of cost and sophistication--as well as availability and reliability of pertinent cost data--as to constitute a representative mix of space science missions in general. The selected missions cover the time frame 1964-1984; mission costs in constant dollars range from \$20 million to \$70 million; the missions employed four different launch vehicles; the payload weights ranged from 300 to 4,000kg; the scientific sophistication varied from relatively simple to complex. To ensure adequate representation of average mission costs, very expensive missions such as the Hubble Telescope were deliberately excluded.

The launch costs corresponding to one of these missions--the Cosmic Background Explorer--whose launch was effected by shuttle, were assumed at the shuttle's "tariff" rate rather than at the actual launch costs. This is because the actual launch costs would have been abnormally high, since at that time the shuttle's flight frequency happened to be abnormally low.

Table 5-1 summarizes the costs of the selected missions by the two major elements of **launch** costs and **payload** costs.

Table 5-2 further subdivides the mission costs into their principal subelements. Payload costs are subdivided into the costs of the **spacecraft** (the carrier **bus**), of the experimental flight **equipment**, and of other materials and services, principally to support **research** data processing and scientific **analysis**.

Launch costs are subdivided into launch **vehicle** costs and launch **services** costs, the latter including propellants, engineering services and launch support services.

Both Tables 5-1 and 5-2 show significant variations among mission costs in terms of absolute dollar expenditures.

Table 5-3 depicts the percentage distribution of the total mission costs among the major cost elements. Note that despite the variations in absolute mission costs, the relative distribution of costs among major elements is significantly uniform.

For the average space science mission, Table 5-3 shows that **launch costs** account for approximately **40%** of the total (about half of this cost being for launch services); the costs of the **instrumentation** represent **20%**; the costs of the **spacecraft** supporting the instruments (including structures, controls, on-board utilities, and data transmission) averages almost **40%**. Approximately **3%** of the total mission cost is devoted to the processing and analysis of the **scientific data**, including support of the scientific investigators.

#### D.5.4 ASSESSMENT OF THE COSTS OF SCIENTIFIC INSTRUMENTATION

The highest costs are seen to be concentrated in three mission elements--**launch**, support **spacecraft**, and experimental

TABLE 5-1

WEIGHTS AND COSTS OF SELECTED SPACE SCIENCE MISSIONS  
(1972 CONSTANT \$)

MISSION	YEAR	LAUNCH VEHICLE	WEIGHT (LBS)		COSTS (\$ MILLION)		
			VEHICLE	PAYLOAD	LAUNCH	PAYLOAD	TOTAL
OGO-A	1964	ATLAS AGENA	326,526	1071	23.36	37.80	61.16
OGO-B	1965	-DO-	-DO-	1118	22.86	37.80	60.66
OGO-C	1966	-DO-	-DO-	1135	22.15	36.45	58.60
OGO-D	1967	-DO-	-DO-	1216	21.50	36.45	57.95
OGO-E	1968	-DO-	-DO-	1347	20.59	45.13	65.72
OGO-F	1969	-DO-	-DO-	1393	19.59	43.94	63.53
INTERPLANETARY MONITORING PLATFORM-I	1971	DELTA	417,865	635	11.21	9.46	20.67
OAD-C COPERNICIUS	1972	ATLAS CENTAUR	326,526	4859	19.74	50.66	70.40
SOLAR MAXIMUM	1980	DELTA	417,865	5105	12.33	34.38	46.72
COSMIC BACKGROUND EXPLORER	1983	SHUTTLE	619,980	9093	14.48 <sup>b</sup>	22.90	37.38
ACTIVE MAGNETOSPHERE PARTICLE TRACER EXPERIMENT	1984	DELTA	417,865	1676	14.02	13.80	27.82

<sup>a</sup> APPORTIONMENT OF SHUTTLE LAUNCH WEIGHT (4,500,000LBS.) TO PAYLOAD WEIGHT  
<sup>b</sup> AT SHUTTLE TARIFF COSTS. ACTUAL LAUNCH COST WAS \$123.37 MILLION.

TABLE 5-2  
COST BREAKDOWN FOR ELEVEN SELECTED  
SPACE SCIENCE MISSIONS (1972 CONSTANT \$)

MISSION	PAYLOAD COSTS (\$ MILLION)			LAUNCH COSTS (\$ MILLION)		
	SPACECRAFT	EXPERIMENT	R&A <sup>a</sup>	VEHICLE	SERVICES AND SUPPORT	TOTAL
OGO-A	24.38	12.64	0.78	14.02	9.34	23.36
OGO-B	24.38	12.64	0.78	13.72	9.14	22.86
OGO-C	24.38	11.29	0.78	13.29	8.86	22.15
OGO-D	24.38	11.29	0.78	12.90	8.60	21.50
OGO-E	24.38	19.98	0.77	12.36	8.23	20.59
OGO-F	24.38	18.78	0.78	11.75	7.84	19.59
INTERPLANETARY MONITORING PLATFORM	4.36	5.09	0.01	4.99	6.22	11.21
OAO-C	37.56	10.12	2.98	12.28	7.46	19.74
SOLAR MAXIMUS	18.18	12.31	3.89	5.51	6.82	12.33
COSMIC BACKGROUND EXPLORER	16.78	5.16	0.96	6.77	7.71	14.48
ACTIVE MAGNETOSPHERE PARTICLE TRACER EXPERIMENT	7.63	3.20	2.97	6.29	7.73	14.02

<sup>a</sup> RESEARCH AND ANALYSIS

TABLE 5-3

PERCENTAGE DISTRIBUTION OF MISSION COSTS  
FOR SELECTED NASA SPACE SCIENCE MISSIONS

MISSION	PAYLOAD			LAUNCH	
	SPACECRAFT	EXPERIMENTS	OTHER	VEHICLE	SERVICES
OGO-A	39.86	20.66	1.27	22.94	15.27
OGO-B	40.20	20.84	1.28	22.62	15.06
OGO-C	41.60	19.26	1.34	22.68	15.12
OGO-D	42.07	19.48	1.34	22.26	14.85
OGO-E	37.10	30.40	1.17	18.80	12.53
OGO-F	38.37	29.55	1.22	18.53	12.33
INTERPLANETARY MONITORING PLATFORM	21.09	24.63	0.05	24.14	30.09
OAO-C	53.35	14.37	4.24	17.44	10.60
SOLAR MAXIMUS	38.92	26.35	8.34	11.79	14.60
COSMIC BACKGROUND EXPLORER	44.89	13.8	2.56	18.12	20.62
ACTIVE MAGNETOSPHERE PARTICLE TRACER EXPERIMENT	27.42	11.5	10.60	22.7	27.78
<b>AVERAGE</b>	<b>38.62%</b>	<b>20.98%</b>	<b>3.03%</b>	<b>20.18%</b>	<b>17.16%</b>
COEFFICIENT OF VARIATION %	21.91	29.93	111	18.06	37

**instruments.** The high costs of the instrumentation are commonly attributed to the need for space hardening and high reliability. In this regard, it is interesting to compare on an "apples to apples" basis the costs of high quality terrestrial scientific equipment with those of space-hardened equipment designed to perform identical functions.

The costs of selected high quality ground and space application instruments are compared in Table 5-4.

TABLE 5-4

COSTS OF TERRESTRIAL AND SPACEBORNE  
SCIENTIFIC INSTRUMENTATION OF EQUIVALENT TECHNICAL PERFORMANCE

<u>Instrument</u>	<u>Approximate Cost, 1983 Dollars</u>	
	<u>Ground/Airborne Version</u>	<u>Space Version</u>
<b>UV spectrometer</b>	300,000	5,277,000
<b>Radar Altimeter</b>	200,000	5,270,000
<b>Multispectral Scanner</b>	300,000	40,000,000
<b>Return Beam Vidicon System</b>	35,000	19,000,000

Note that the spaceborne equipment costs between **one** and **three orders of magnitude** more than its terrestrial counterpart.

D.5.5 SIGNIFICANCE OF THE FINDINGS AND TECHNOLOGY GOALS FOR  
THE NEAR-TERM

By its very nature, the scientific portion of the space sciences program cannot be prioritized in terms of value. As regards breadth and balance among objectives, the observational

experimental portions of the space sciences program appear to be ably structured and pursued by NASA.

The program is, however, subject to funding ceiling constraints. Thus, of crucial importance is the capability to achieve **more observations per dollar** spent. Thus technologies aimed at cost reduction can be expected to lead to major improvements in the "return" of space science missions.

The analysis of space science mission costs of Section D.5.3 indicates that the mission's "business end," i.e., experimental equipment plus scientific analysis, accounts for only one-quarter of total costs. The remaining three-quarters are almost evenly divided into launch and support spacecraft costs.

Technologies to **reduce launch costs** are treated in Section D.8, "Supporting Space Transportation." The near and medium term technologies essentially boil down into:

- Manufacturing techniques to reduce launch vehicle costs
- Automation and management techniques to lower cost of launch services

Technologies to **reduce support spacecraft** costs could be handled by "standardization" of spacecraft design. An example is the Soviet "Cosmos" series. With due regard for the peculiarities of the Soviets' method of accounting, these spacecraft are reported by the Soviets to cost 0.8 million 1973 rubles in the "standard" version, 3.5 million 1973 rubles in "special" versions requiring significant adaptation to accommodate novel experimental gear.

Another area of potential cost reduction is the **experimental equipment** itself. Data reported in Section D.5.4 indicate that, on an equivalent performance basis, high quality ground-based scientific observation equipments costs at least one order of magnitude and up to three orders of magnitude less than the corresponding space versions. We note that scientific space equipment does not in general provide technical performance better than equivalent ground or airborne equipment. The reasons for the high costs are instead traceable to:

- Need for long life in the absence of maintenance
- Need for performing periodic calibration in an automatic manner

The Soviets have overcome the scientific instrument cost problem--to a significant extent, forced by their more limited technology--through the use of man. Among the 1,000 or so experiments conducted in the Salyut Space Station series, while many were of a trivial nature--e.g., the test of the "Strelka" spaceborne teletypewriter--several were of high scientific value, e.g., the "Filin" energetic x-ray observatory, the 300mm medium-infrared telescope. Soviet sources indicated that the costs of the related instrumentation were significantly alleviated by the availability of maintenance, repair and calibration skills provided by the cosmonauts.

In the space shuttle the cost of an experimenter (assumed of 150kg gross weight), at the June 1984 tariff, is approximately \$300,000. By comparing this with the instrument costs of Table 5-4, man appears indeed to be a very economical surveyor of maintenance.

The reasons for the higher costs of scientific space instrumentation relate directly to the instrument's reliability. The tradeoff of reliability with cost can be one

means of lowering mission cost for automatic missions.

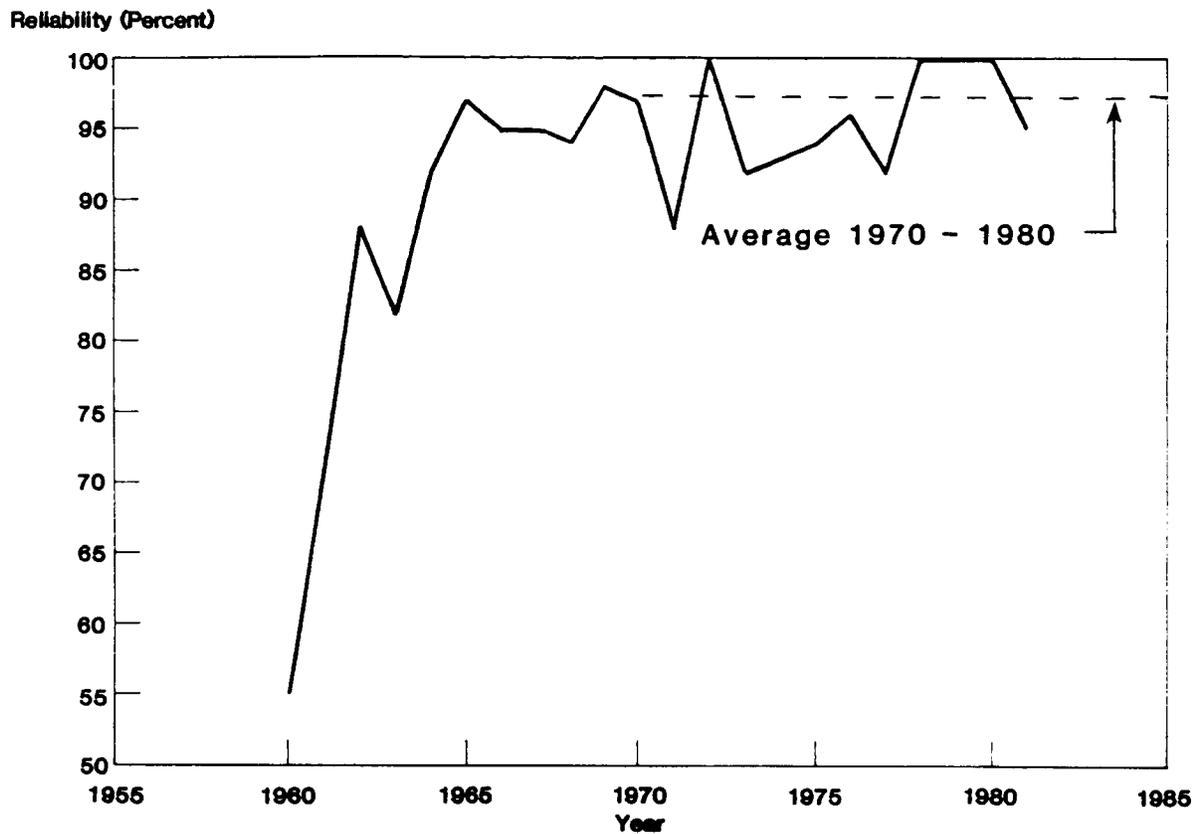
Figure 5-6 shows that the unmanned missions launched by NASA since 1970 had an average "launch" reliability of 95%. One could argue that, in order to achieve a balanced system, there is little point in pushing the instrument's reliability well beyond the 95% level. Let us specify, for the sake of illustration, an instrument reliability ten times this level, i.e., 99.5%. Figure 5-7 shows a parametric cost-reliability curve used by commercial spacecraft purchasers. With reference to this curve, let us designate as unity the cost associated with reliability 99.5%.

Suppose an unmanned mission has been designed to collect data over a span of one year with a reliability of 99.5%. If the reliability of such a mission were reduced to 50%, i.e., data collection lasts only six months, the relative cost would reduce to approximately 30%. In order to collect the same amount of data as expected from a 99.5% reliable system, it will be necessary to launch two missions of 50% reliability each.

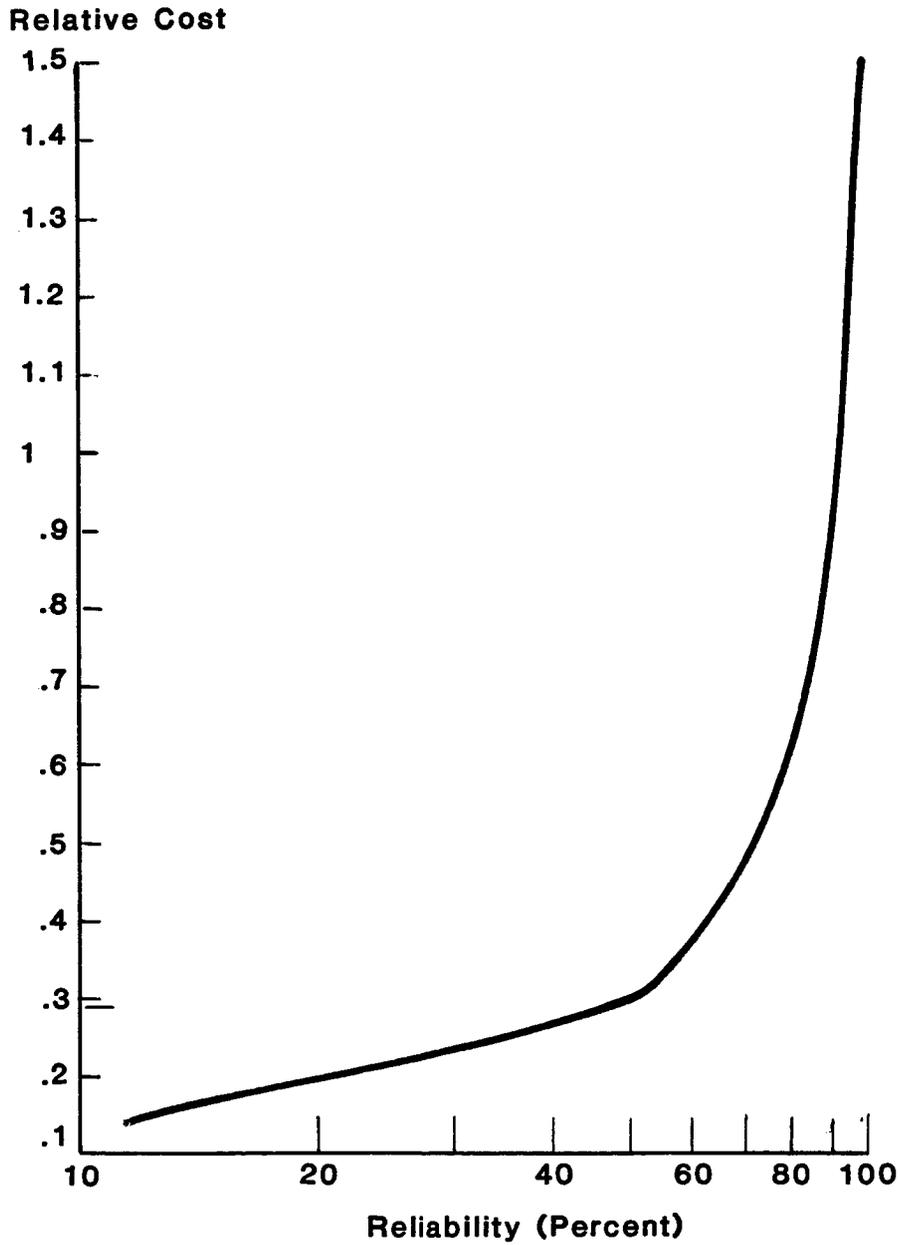
This shows that two systems each having 50% reliability will cost only 60% compared to a system with reliability of 99.5% (current NASA mission reliabilities). The net cost reduction achieved will be 40%.

This simplified analysis of cost versus reliability, indicates that significant cost reductions might be achieved for an unmanned mission by lowering the reliability of the payload.

Compare the cost differentials between terrestrial and space equipment shown in Table 5-4. The space shuttle's orbital stay period of 7 to 8 days is small vis-a-vis the time spans required by space science observations. However, if the tariff for a space station were of the same order as the the shuttle's, the performance of scientific observations from the space station could greatly reduce the costs of the related instrumentation.



**Figure 5-6. Reliability of NASA Launch Vehicles (1960 - 1981)**



Source: Adapted from COMSAT data.

**Figure 5-7. Reliability Versus Cost for Space Missions**

D.5.6      LONG-TERM TECHNOLOGY GOALS

Technologies to reduce space transportation costs are treated in Section D.8, "Supporting Space Transportation." The key long-term technology is the development of advanced propellants with high specific impulse.

As regards advances in scientific instrumentation, the single major technology, which pervades the requirements for all observations, is the ability to deploy in space large energy-collecting apertures, ranging across the electromagnetic spectrum.

**D.6 EXTRACTION OF COMMERCIALY USEFUL  
MATERIALS FROM THE MOON**

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## D.6 EXTRACTION OF COMMERCIALY USEFUL MATERIALS FROM THE MOON

### D.6.0 SUMMARY/ABSTRACT

The potential value of lunar material--at least for the next 25-75 years--lies in the fact that the moon lies in a shallow gravity well, more readily accessible to cislunar and translunar space than are competing materials from the Earth. However, to the best of our current knowledge, there are no known materials on the moon that do not exist on Earth; there are no known materials for which transportation to Earth is justified under present economic conditions or those foreseeable within the time frame of this study (2005-2010); finally, there are no known or postulated concentrations of ore bodies that would make extraction for use on Earth economically attractive.

At some time in the future--possibly in 50 years or more--there may be societal benefits (e.g., air pollution abatement) coupled with new technology (e.g., highly economical propulsion) that will make it attractive to "move the mine and smelter out of our back yard"--that is, redirect material extraction efforts from the Earth to the Moon.

However, while lunar material processing could conceivably result in by-products (there are no obvious candidates from known compositions) that might be of interest for return to Earth, these would be only secondary to the production of materials destined for use in space structures.

There is a significant group of material/process/use combinations in space that could potentially become attractive for commercial, scientific and military endeavors. The practicality and timing of these endeavors depend on the schedule and economic development of advanced space transportation systems and of spaced-based process technology.

#### D.6.1 SIGNIFICANCE

While the use of lunar materials has been the subject of extensive studies for many years, the reality of lunar material applications will depend upon the constraints of economic, political, physical, and technological readiness (the ability to utilize advantageous physics at any point in time), and on the extent of societal commitment to subsidize these endeavors. Such societal subsidies would not be unique, as witnessed by many historical examples, including support of art and science by nobility in the Middle Ages and the construction of the transcontinental railroads in the 19th century United States.

The lunar soil composition at a few locations on the lunar surface is known in great detail. From remote sensing and geologic history, the composition of the lunar surface over the near-equatorial regions can be inferred. However, when the uncertainties increase, available factual information is applied to the development of composition models at greater depths and extending as far as the polar regions. There are indications, in some cases backed up by sound physical reasoning, that hitherto unsuspected materials and conditions may exist (e.g., water at the lunar poles).

Requirements and limits on extraction, beneficiation, and manufacturing processes can be estimated, based on physical laws and on terrestrial analogs. The mechanics of transporting processing facilities to the moon and of moving products from the moon to the Earth or to Earth orbit are well established. The trends and probable progress in this transportation technology can be estimated for the next 25 years.

Thus it is possible to examine various scenarios for the use of lunar materials--including starting materials (materials needed to initiate exploitation activities), processes, product uses and use locations--and to establish probable limits for the

application and enabling technologies associated with those scenarios, with a reasonable degree of confidence.

Because of the difficulty and cost involved in moving mass from the Earth's surface to space and to the moon, a major consideration (in fact the dominant factor, as will be shown later) in this analysis is mass, i.e., the mass of equipment and propellant needed to move products to the point of use and extract and process local materials.

#### D.6.2 AVAILABLE LUNAR MATERIALS

Samples returned from near-equatorial lunar surface locations by the Soviet Luna and the U.S. Apollo missions have been analyzed in great detail (in fact, in more detail than most terrestrial samples). In addition, information is available from on-site experiments (Surveyor, Apollo), from near-lunar space instruments (e.g., Ranger, Apollo Command Module), and from other space and Earth-based observations.

##### Known Materials

These physical measurements, combined with other astrophysical observations and with established physical principles, have contributed to reasonably consistent models of lunar history and structure (for example, Ref. 1, 2, and 3). These models allow extrapolation of known sample compositions to most of the near-equatorial surface with reasonable confidence.

There are two main geological provinces on the moon, the maria and the highlands.

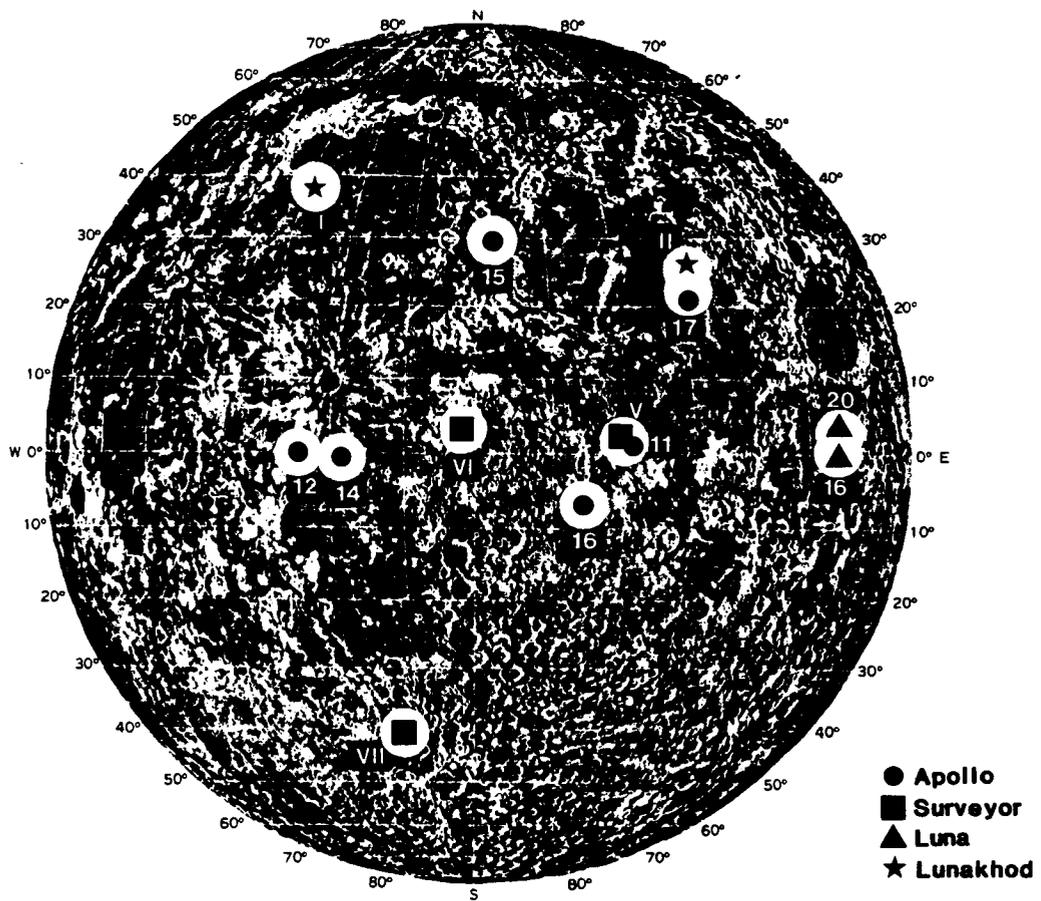
The maria are characterized by basalts high in Fe and Mg silicates and in other respects similar to terrestrial basalts. They differ from terrestrial basalts in their higher Ti, somewhat higher Fe, the presence of Fe in lower oxidation states, and lower content of Na and K.

The highlands are igneous, formed by cooling and solidification of molten rock. Made up primarily of minerals similar to those on Earth, they include materials scattered by the impact of extralunar bodies, are richer in Ca and Al and have less Ti, Mg, and Fe than the lunar basalts.

The entire lunar surface appears to be covered by a layer of regolith, ranging in size from large boulders to fine dust. The only apparent bedrock visited during the Apollo missions was along the walls of Hadley Rille, see Figure 6-1. The "soil" layer appears to extend many meters. Seismic and other measurements indicate that fragmentation extends several kilometers. These conditions, which appear reasonably uniform over the surface, would be significant factors in any mining operations, enhancing the feasibility of surface collection or open-pit type operations, but presenting serious barriers to conventional deep mining.

No evidence from exploration, from remote measurements or from analysis of samples indicates any concentration of minerals analogous to what is found in terrestrial ore bodies. Furthermore, there is no evidence from any source, including historical models, of the past existence of any tectonic, hydrothermal, hydromechanical, or biological processes analogous to those which produced mineral concentrations on earth.

Clearly, general conclusions from limited data can be misleading. Samples have been returned from only a limited area of the moon surface (six Apollo sites, two Luna). Lunar exploitation proponents state that one should consider how many ore bodies might be found on Earth by examination of samples from only eight sites. In reality, this position neglects certain obvious facts. When considering the extensive stirring and random redistribution produced by meteorite impacts, the limited number of samples actually collected represents a much more extensive survey.



Mission	Landing site	Latitude	Longitude	EVA duration (hours)	Traverse distance (km)	Date
11	Mare Tranquillitatis	0°67'N	23°49'E	2.24	—	July 20, 1969
12	Oceanus Procellarum	3°12'S	23°23'W	7.59	1.35	Nov. 19, 1969
14	Fra Mauro	3°40'S	17°28'E	9.23	3.45	Jan. 31, 1971
15	Hadley-Apennines	26°06'N	3°39'E	18.33	27.9	July 30, 1971
16	Descartes	8°60'S	15°31'E	20.12	27	April 21, 1972
17	Taurus-Littrow	20°10'N	30°46'E	22	30	Dec. 11, 1972

**Figure 6-1. Apollo, Luna, And Surveyor Landing Sites**

It is convenient to categorize lunar surface materials in terms of oxide content and mineralogical composition as shown in Tables 6-1 and 6-2, respectively (from Ref. 4, based on data from Ref. 5). From these tables it can be seen that the surface is a silicate-rich mixture of oxides not unlike the composition of many terrestrial regions, but with several important differences. There are no significant quantities of hydrated minerals or minerals containing carbon, sulfur, or halides. The surface composition is approximately 45% oxygen, an important factor which will be discussed later.

There are small amounts (<1%) of metallic iron, mostly physically attached to, or enclosed in, silicate mineral fragments. These metallic particles have been derived from reducing conditions during the formation of the moon or may be related to asteroids, containing iron, that have impacted the moon.

There are small amounts (approximately 10ppm) of hydrogen and trace amounts of other solar wind derived elements in the surface of lunar soil particles. Since this accumulation, which results from the stopping distance of the ions, lies near the surface of the particles, the highest concentration is in the first fraction of the soil. Hydrogen will be a valuable commodity to facilitate almost any lunar operation and thus will be one of the secondary products extracted if the soil is processed; because of its small quantity, it is not expected to be practical to extract hydrogen as a primary product.

The extensive analysis of the Apollo samples (for example, see the proceedings of the Lunar Science Conferences held annually since 1970) has not indicated any economically attractive concentrations but has indicated factors which might become important for lunar processing. For example, the concentration of titanium is higher than in typical terrestrial soils (but not higher than in terrestrial titanium ores). In addition,

TABLE 6-1

COMPOSITION OF LUNAR MATERIALS

	<u>WEIGHT PERCENT</u>	
	<u>LUNAR ANORTHITE (Highlands)</u>	<u>LUNAR BASALT (Maria)</u>
SiO <sub>2</sub>	44 - 45	37 - 41
MgO	6 - 7.6	6.8 - 10
FeO/Fe <sub>2</sub> O <sub>3</sub>	5.1 - 6.2	18.2 - 19.6
Al <sub>2</sub> O <sub>3</sub>	26 - 27	6.8 - 10
TiO <sub>2</sub>	0.2 - 0.4	10 - 13
CaO	15.1 - 15.4	10 - 12
Na <sub>2</sub> O	0.3 - 0.35	0.32 - 0.44
K <sub>2</sub> O	0.06 - 0.08	0.04 - 0.09
MnO	0.06 - 0.1	0.28 - 0.29
Cr <sub>2</sub> O <sub>3</sub>	0.11 - 0.14	0.27 - 0.61
P <sub>2</sub> O <sub>5</sub> /P	0.03 - 0.05	0.05 - 0.09
S	0.03 - 0.15	0.15 - 0.19
C	0	0
H <sub>2</sub> O	0	0

TABLE 6-2

AVERAGE MINERALOGY OF  
PREDOMINANT LUNAR MATERIALS  
AVERAGE WEIGHT PERCENT

	<u>AVERAGE</u> <u>WEIGHT PERCENT</u>
<b><u>LUNAR ANORTHOSITE</u></b>	
PLAGIOCLASE (Ca RICH)	83
OLIVINE	16
PYROXENE (PRIMARYLY PIGEONITE)	1
ILMENITE	1
<b><u>LUNAR MARE BASALT</u></b>	
PYROXENE (PRIMARYLY AUGITE)	50
PLAGIOCLASE (Ca RICH)	27
ILMENITE	20
OLIVINE	3

the fines appear to have a higher concentration of alkali-metal oxides than the average, a factor that could be important for processes requiring molten material without importation of fluxes from Earth.

Thus, all available reliable information indicates that lunar extraction processes will be dealing with "dilute" sources, and without the benefit of processing aids like water, carbon, fluxes, gases, solvents, and fluids of various kinds that are so commonly used for Earth processes.

### Possible Materials

An adequate interpretation of the apparently homogeneous lunar surface could be instrumental in determining the economics associated with lunar materials extraction.

A plausible model was developed by Watson et al. in 1961 (Ref. 6) for predicting the presence of water in the form of permafrost in the permanently shadowed craters at the lunar poles. Subsequent analyses (including Ref. 7) have failed to prove or disprove of this model. The verification or disproval of this vital resource will require a lunar polar mission.

If present in large amounts (e.g., order of 1000 metric tons), water could easily be electrolyzed into hydrogen and oxygen propellants and as such would have a profound effect on all space operations. In addition to these effects on space transportation, water would have an effect on the economics of lunar materials transported to Earth orbit or surface. As shown in section D.6.5, there are profound differences in the limits of practical transportation from the moon on the basis of the relative amount of lunar oxygen; the effects of lunar water would have an even more dramatic effect on the economics of transporting lunar materials.

Earth observers have identified "transient phenomena" on the lunar surface, attributed to a release of subsurface gases. A Russian astronomer, Kozyev, in 1959 observed and obtained spectra of gases released from the crater Alphonsus; at Lowell, a number of observers reported a glowing red spot near Aristarchus on two occasions. While these phenomena appear to have been too numerous to dismiss, they have not been sufficiently consistent to indicate a high probability of a significant (large quantity) resource. An adequate confirmation would require consistent observations to establish localities and gas composition, and on-site verification of the practical, economic benefits of a deposit. The infrequency of past observations and the time required for verification make this an unlikely resource prior to the year 2010.

Irregularities in the trajectories of lunar orbiters have been interpreted as the effects of lunar "mascons." While these were initially thought to be the results of the impact of extralunar bodies, this theory is now considered unlikely. The mascons appear to be higher density rock zones resulting from the basalt flooding of basins, unlikely to contain enriched deposits and probably too deep for reasonable access.

#### D.6.3 PROCESSING

In considering lunar materials processing, it is useful to use the three processing categories defined by Steurer (Ref. 4):

- 1) Mining and material conditioning--Changes in situ minerals into feedstock. Includes acquisition (the general equivalent of terrestrial mining); comminution (grinding, crushing); sizing and beneficiation.
- 2) Primary processing--Changes feedstock into primary products (e.g., the lunar analog of ingots or bar stock). Includes extraction (e.g., metal from ore), shaping and post-treatment (e.g., firing bricks).

- 3) Secondary processing--Changes primary products into end products (e.g., metal rod stock into a structure or lunar bricks into a shelter). Includes fabrication, assembly and installation.

The present analysis of "extraction of useful products," will consider primarily mining and conditioning and to some extent primary processing. Secondary processing as defined by Steurer will apply chiefly to items for end use in space.

The issue is not the specifics of individual candidate processes. Rather, the examination of processing to determine the practical limits for the extraction of useful lunar products. A broad spectrum of lunar material processes has been the subject of paper studies and a few have been examined in the laboratory. The extraction of metals and oxygen from the mixed oxides of the lunar surface is theoretically possible and has been demonstrated experimentally by several investigators.

Most terrestrial mining, beneficiation, extraction and manufacturing processes are postulated on the presence of abundant and easily available solvents and reactants such as carbon, water, air and other fluids. Since these solvent and reactant materials are not present on the Moon and are costly to supply, processes specifically adapted to the Moon will be required, the specifics of which remain to be developed.

The key to developing these processes is the estimation of equipment required and the assessment of practical limitations. The present analysis defines types of processes and estimates equipment and power needs, production capacity, etc., based on physical principles, logic and carefully considered terrestrial analogs. As will be shown this approach strongly indicates the limits of practical and of cost sensitive extraction processes.

## Equipment

Consider initially the mass of equipment required for the simpler operations associated with "mining and material conditioning," for example, excavating and moving material on the lunar surface. It is possible to reduce this mass from terrestrial levels by the application of "aerospace" materials and fabrication processes--e.g., the use of costly, high-performance alloys; elaborate machining to remove unnecessary material, engineering design especially tailored to the lower lunar gravity. The latter's effect would be relatively small. This is because problems of repair, replacement, and refurbishment on the Moon will drive the design to increased safety margins and reliability. To a first approximation, it is reasonable to use the mass of commercial terrestrial equipment for comparable functions. Significant mass differences can result from differences in locomotion power requirements. Internal combustion engines are obviously impractical; both the power for and thermal regulation of electric motors pose problems. Effective designs with precise estimates are possible when conditions are exactly specified (for example, the Lunar Rover, was designed, built and successfully operated).

Terrestrial earth movers, conveyors, and hoppers can collect and move a mass of material equivalent to their own mass over reasonable distances in a matter of minutes. The mass of such equipment will be of order of  $10^{-5}$  to  $10^{-6}$  the mass of raw material moved over the lifetime of a lunar facility. This factor is insignificant when compared to power plant and transportation requirements for processes and products that utilize most of the material collected. However, if processing is primarily for materials present only in small concentrations, such as strategic metals or trapped solar wind hydrogen, the mass of mining equipment no longer remains relatively insignificant; in fact, it can become prohibitive.

The type of equipment used for primary lunar processing can typically handle throughputs equal to the equipment mass, in a time span ranging from an hour to perhaps a day. On this basis, the mass of the equipment would be  $10^{-3}$  to  $10^{-5}$  the mass of the feedstock (or, for candidate processes utilizing most of the feedstock, the mass of the product). Analogous to the material handling equipment, the relationship to product mass changes dramatically if we consider extracting resources present in small concentrations.

In terms of secondary processes, particularly assembly and installation, factors like the necessary control capability, adaptability to process specifics--e.g., size, hole location--and to manipulation will make equipment mass requirements significantly more important. However, such processing is unlikely in the next half century except perhaps for specialized products needed on the moon itself. Thus, for the present, we will not carry out detailed analyses in this area.

### Energy Requirements

Another major consideration in evaluating the utility of processing extraterrestrial materials is the anticipated energy requirement, which affects the cost, complexity, and above all, the mass of the power plant to be used.

The status of space power technology applicable to lunar processing has been examined by Jones (Ref. 8a). Solar photovoltaics are a well established technology in which future progress can be projected with reasonable confidence. Since they represent a minimum specific mass (mass per power) for technologies foreseeable by 2010, they can be used as a reasonable baseline for this analysis. Other power systems would yield corresponding results, adjusting for differences.

A nuclear system would operate continuously and would have equal annual power production and product output at double the mass/capacity level; the continuous operation, possible with a nuclear source, would avoid serious problems associated with shutdown during the lunar night.

Jones (Ref. 8a) estimated future photovoltaics at 15-8 kg/kWe for what he defined as "in-development," and 5-3kg/kWe for what he defined as "on frontier." Using the upper and lower extremes of 15 and 3kg/kWe, the power plant facility mass requirement for processing 1000 metric tons/year can be computed for typical operations.

The general range of energy requirements for various types of processes is shown in Table 6-3. In the last three columns the power plant capacity required for processing 1000 metric tons/year and the power plant mass at the 15kg/kWe and 3kg/kWe levels have been calculated.

If a product requiring excavation and three typical beneficiation steps is used as an example, the power plant would have a mass of 20-100kg (0.02-0.1 tons) for a product output of 1000 metric tons/year. Thus, for a ten year operation the power plant's mass would be approximately of order of  $10^{-5}$  to  $10^{-6}$  the mass of the product.

At the other extreme, for vapor phase processing, a 60 to 300 ton power plant could produce the process energy at  $10^{-2}$  the mass of the throughput.

The resources associated with processing and power equipment are defined in Section D.6.5.

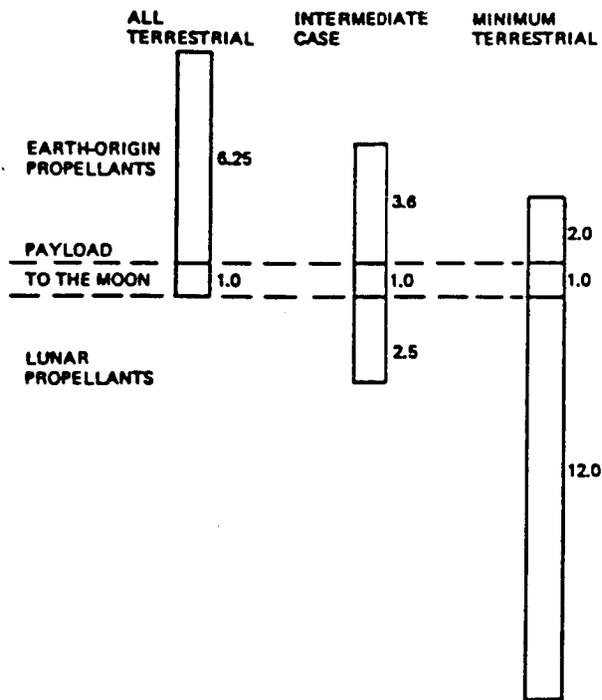
#### D.6.4 TRANSPORTATION

This section discusses the major issues associated with transporting non-terrestrial materials. We hypothesize as base-

TABLE 6-3

TYPICAL ENERGY AND POWER PLANT REQUIREMENTS

OPERATION	ENERGY REQUIREMENT	POWER PLANT FOR 1000 TON/YEAR THROUGHPUT		
		CAPACITY FOR 1000 TONS/YR (kWe)	MASS FOR 1000 TONS/TON ENERGY DENSITY (kg/kWe)	
			15	3
EXCAVATION	0.1	$2 \times 10^{-2}$	0.3	0.06
BENEFICIATION	10	2	30	6
MELTING	500	125	$2 \times 10^{-3}$	375
ELECTROLYSIS	$10^4$	$2 \times 10^{-3}$	$3 \times 10^4$	$6 \times 10^3$
VAPOR PHASE	$10^5$	$2 \times 10^4$	$3 \times 10^5$	$6 \times 10^4$



**Figure 6-2. Propellant Source Options For Transportation Of Equipment And Supplies To The Moon**

line a conventional chemical lunar hydrogen/lunar oxygen ((LH<sub>2</sub>/LO<sub>2</sub>) derivative of current technology, and assume that a space-based Orbit Transfer Vehicle (OTV) will have been developed and will be operational in sufficient quantities and capacity to meet the needs for transport of lunar materials and the development of aerobraking for return to Earth orbit.

The impact of advanced technologies such as "mass drivers," nuclear electric propulsion, etc. on the use of lunar materials in space has been discussed elsewhere (Ref. 8b and 9). These technologies are not considered here since their development by 2010 appears unlikely. Conditions may arise in the future, beyond the time scale of this study, that may warrant the development of these major new technologies to enhance the exploitation of lunar materials.

Transportation costs from Earth and/or lunar surface to LEO will dominate all large-scale use of space, including the use of lunar materials. Key initial parameters in these estimates are the transport of equipment and power supplies to extract lunar materials, and the vehicles and propellants to transport these to the moon. Transport vehicles and propellants are the dominant parameters: The need to transport propellants from the earth to LEO can be relieved by the production and the use of oxygen from the moon.

Major transport options from Earth surface to LEO are possible in the next 25 years. A launch cargo vehicle based on Shuttle technology could reduce launch costs significantly; a whole new vehicle system, albeit costly to develop, could further reduce launch costs even more (Ref. 10). Since projected costs are uncertain, our analyses will be based on comparing mass options in LEO rather than costs. Options will be compared on the basis of cost in Section D.6.5, using selected possible scenarios of Earth surface-to-LEO costs. These analyses are based strongly on the work by Frisbee (Ref. 8b and 9).

Each scenario assumes some kind of operating space station in LEO, some kind of transfer facility in low lunar orbit (LLO), an operational OTV for LEO to LLO transport, and an operational lunar transport vehicle (LTV) for transport between the lunar surface (LS) and LLO.

The movement of raw materials, products and equipment on the lunar surface is considerably less energy intensive and, therefore, less costly than transport in space. Therefore, in this initial analysis, surface transportation is neglected. Likewise, the advanced state of Earth-atmospheric entry technology, and the small energy increment required to initiate entry from LEO, make it unnecessary to consider LEO to Earth return in this analysis.

#### LEO to Moon Transportation

Initial transportation of equipment will depend totally on propellants originating on Earth. After the establishment of a lunar operating facility to produce oxygen, operating supplies and additional equipment can be transported as needed to expand or modify the lunar production facilities.

Three scenarios for the chemical transport of equipment from LEO to LS were examined by Carroll et al. (Ref. 11). One of these considers only terrestrial propellants; another assumes the use of terrestrial hydrogen and lunar oxygen representing a minimum terrestrial propellant; the final case assumes use of terrestrial oxygen for the outbound LEO to LLO leg and lunar oxygen for all other transport.

The result of these scenarios are summarized in Figure 6-2, reproduced from Ref. 11. It shows that the optimum approach for transporting equipment and supplies to the moon hinges on the cost of launch from Earth to LEO and the cost of producing lunar oxygen. The latter depends in part on the Earth-to-LEO equipment cost.

Alternate transport modes, such as solar electric propulsion, could be used for the LEO-LLO leg of the system. Such alternatives probably will be practical only if the transportation system can be used subsequently for moving the products as well. Otherwise, the launch mass required for a typically mass intensive system will exceed any potential savings. In any case, the difference from a chemical propulsion system would typically be small.

### Moon to LEO

A wide range of scenarios for transporting materials from the moon to LEO and GEO have been studied by Frisbee (Ref. 8b). The assumed baseline was a lunar transport vehicle (LTV) between LS and LLO, using a cluster of RL10-II engines, with a vehicle dry mass of approximately 11.5 tons and a payload capacity of approximately 50 tons. The assumed OTV was based on a Boeing study (Ref. 12); RL10-II technology with aerobraking was used for return to LEO. Selected results from Ref. 8b are summarized in Table 6-4. The most significant result is the payload ratio, that is, the ratio of returned lunar payload to the mass of starting propellant on LEO.

Scenario No. 1 illustrates the use of terrestrial propellants to move materials in space. The payload ratio is 0.18; that is, it is possible to return less than 0.20kg of payload from the moon to LEO for every kilogram of propellant expended to orbit the payload. In other words, if the objective is to move lunar oxygen to LEO for use as a propellant, it is necessary to use more than 5kg of propellant for every kilogram of propellant delivered. This is generally not productive: A payload of very high value would be required to warrant such an operation.

In Scenario No. 2, where lunar oxygen and terrestrial hydrogen are used, a payload of 2.25kg can be returned for every kilogram of starting propellant in LEO--in this case hydrogen.

TABLE 6-4

SELECTED LUNAR-TO-LEO TRANSPORTATION OPTIONS

CASE	CONDITIONS	PROPELLANTS				LUNAR PAYLOAD TO LEO	PAYLOAD RATIO
		TERRESTRIAL		LUNAR			
		O <sub>2</sub>	H <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub>		
1	BASELINE OTV = ALL TERRESTRIAL PROPELLANTS	321	53.1	0	0	66.9	0.18
2	BASELINE OTV, LTV = MINIMUM TERRES- TRIAL PROPELLANT	0	17.9	107.2	0	40.2	2.25
3	LIMIT CASE OTV AND LTV OF ZERO DRY MASS	0	13.8	82.7	0	62.7	4.54
4	LUNAR H H <sub>2</sub> AVAILABILITY ASSUMED	0	0	89.8	14.9	54.1	0

TABLE 6-5

APPROXIMATE ACQUISITION COST  
OF TYPICAL EQUIPMENT

FULL SIZE AUTOMOBILE	\$5-10/kg
CONSUMER ELECTRONICS	\$10-100/kg
COMMERCIAL AIRCRAFT	\$100-200/kg
COMMUNICATION SATELLITES	\$50,000/kg
ONE-OF-A-KIND SPACECRAFT	\$1.0 MILLION/kg

Of course, more than 2kg of lunar oxygen are used for every kilogram of payload. The advantage of such an operation would depend on the difficulty of producing the oxygen and on the value of the payload.

To examine the effects of and motivation for improving the capacity-to-dry mass of the OTV and LTV transporters, a limit case study was performed. While it is impossible to reduce the vehicle mass to zero, it is useful to examine the effects of such a limit case. The results, shown in Scenario No. 3, using a payload ratio of 4.5, constitute a significant improvement, albeit not as dramatic as might be intuitively expected.

The studies by Frisbee (Ref. 8b) examine a variety of parameters, including improvements in specific impulse and changes in fuel/oxidizer ratio (to take advantage of the space availability of the oxygen). The advantageous effects of these were relatively small compared to the zero mass case.

Scenario No. 4 assumes the availability of water or other sources of fuel on the moon. No terrestrial fuel is required and the payload ratio, as defined, becomes infinite.

Several important conclusions applicable to lunar materials for use in LEO can be reached, from the four scenarios summarized in Table 6-4. Since an additional flight is required to return such products to Earth, these conclusions, along with assumptions about Earth-to-LEO transportation costs, can bound the limiting economics of lunar-to-Earth transport using conventional chemical propulsion, as shown in Section D.6.5. The conclusions of Carroll et al. (Ref. 11) regarding the practical limits of transporting lunar products to LEO, with conventional chemical propulsion are given below:

- Lunar oxygen or some other "unconventional" low-cost propulsion is needed to make transport of lunar products practical.

- Products whose performance is directly proportional to their mass could have an advantage over competitive terrestrial products.
- The transport of structural metal alloy parts will likely not be practical.
- Components made from unrefined or partially refined lunar material will not be practical for structural applications, but may be competitive for uses like radiation shielding.

#### D.6.5 COST ASSESSMENT

The major costs involved in the extraction of industrial lunar material are a fraction of processing equipment, of the transportation of this equipment to the processing site, and of the transportation of products to their point of use on earth or in space. This last factor will dominate all other costs. All assessed costs are in 1984 dollars.

The cost of the processing equipment is uncertain because the processes required to extract lunar material are imperfectly known. Reasonable estimates are possible, however, on the basis of analogous space and terrestrial equipment (see Table 6-5).

The cost of transporting processing equipment and products will hinge on and be proportional to the Earth-to-LEO launch costs and the cost of lunar oxygen production.

Like many other costs, the cost of Earth-to-LEO launch depends on bookkeeping factors. A useful figure can be obtained by using the projected operation costs of Shuttle at \$100 million per mission and a projected payload of 30 metric tons or \$3,300/kg (\$3.3 million per metric ton). A much lower number of \$150/lb (\$330/kg; \$330,000/metric ton) has been estimated by

Talay (Ref. 9) for future large scale operations with a new launch vehicle system. For this estimate, the authors assumed a Shuttle-derived vehicle, annual payload level of several thousand tons per year, 100% payload for each launch, and operating lifetime of 15 years. These estimates do not include the initial procurement cost of the transportation system. Whereas costs somewhere near these levels may be achievable some day, the value of \$330/kg must be considered a low limit value for the time frame of this study (up to 2010).

Although equipment costs for extracting products from the moon will be high, they will be less expensive than the cost of communication satellites or "one of a kind spacecraft, see Table 6-5. Using the satellite value (\$50,000/kg) and the relationship between the mass of mining and material conditioning equipment to product from Section D.6.3, namely  $10^{-5}$  to  $10^{-6}$ , the contribution of equipment cost to product cost is less than \$1/kg. Even at the high value of  $10^{-3}$  for secondary processing equipment (Section D.6.3), the contribution is approximately \$50/kg, a small number compared to transportation costs.

The cost of mature space photovoltaics in large quantities has been estimated by Carroll (Ref. 8c) at \$10/W or \$10,000/kW(e) capacity. In Section D.6.3, photovoltaic power plant requirements were tabulated for various processes. Beneficiation requires 2kW(e) capacity for 1000tons/year or a cost of \$20,000 to produce  $10^4$  tons over 10 years, or \$2/ton. Even for energy-intensive vapor phase separation, at  $2 \times 10^4$  for 1000 tons/year or \$200 million/ $10^4$  tons, the cost contribution is approximately \$20/kg.

Useful limits and relationships for transportation costs, dominated by launch propellant costs as illustrated, can now be determined. For comparison, the approximate price of several typical commodities are listed in Table 6-6. At a projected cost of \$3,300/kg for Earth-to-LEO launch, the Earth-to-GEO cost will

TABLE 6-6

APPROXIMATE PRICE OF  
SELECTED COMMODITIES

<u>MATERIAL</u>	<u>PRICE</u>	<u>DOLLARS/ KILOGRAM</u>
IRIDIUM	\$600/TROY OZ	19,000
PLATINUM	\$475/TROY OZ	14,000
GOLD	\$372/TROY OZ	12,000
PALLADIUM	\$140/TROY OZ	4,500
SILVER	\$8.61/TROY OZ	280
ZIRCONIUM	\$15/LB	33
NICKEL	\$3.25/LB	7.15
ALUMINUM	\$0.81/LB	1.78
FINISHED STEEL	\$0.27/LB	0.59
PIG IRON	\$213/TON	0.23
COAL, LOW SULFUR	\$45/TON	0.05

SOURCES: IRON AGE, APRIL 16, 1984; WALL STREET JOURNAL, MAY 8, 1984

exceed \$10,000/kg, since for every kilogram of payload, 2 to 3 kg of propellant is required for LEO to GEO orbit transfer. Similarly, using all terrestrial propellants (>6kg of propellant kg of payload), 1kg of payload delivered to the moon would cost \$24,000/kg, or a little less than twice the current price of gold.

By considering the return of lunar payload to LEO as equivalent to return to Earth (because of the low energy and mass ratio allowed by atmospheric braking), and by using all terrestrial propellant as per scenario No. 1, Section D.6.3 (Ref. 8a), the cost of return from moon to LEO is approximately \$18,000/kg, well in excess of the price of gold. Thus, if there were solid gold bars on the surface of the moon and there was no cost involved in collecting them, the cost of the terrestrial propellant required for Earth return would exceed their landed value.

If lunar oxygen were to become available and its cost were negligible, then the conditions of scenarios Nos. 2 and 3 in Section D.1.4 could be applied. Neglecting the cost of producing the payload and the oxygen for transport the cost of returning lunar payloads might lie in the range of approximately \$1000/kg or \$30/troy oz, i.e., three times the price of silver and one fifth the price of palladium.

If the optimistic future lower limit of a launch cost of \$330/kg launch cost is used, transport to the moon with all-terrestrial propellant would cost \$2,400/kg. Similarly, returned lunar payload using all-terrestrial propellant would cost \$1,800/kg (\$55/troy oz), substantially more than the current price of silver but significantly lower the price of gold.

If the optimistic values of Earth-to-LEO transportation are used and the cost of lunar oxygen is assumed to be insignificant, the return of lunar payload to earth in the cost range of \$100/kg might eventually become possible. However, it is difficult to

identify a product that would warrant such a cost, especially when added to the cost of extraction. Recall that the lunar surface is a dilute source, without indications of ore bodies. Materials that might warrant such high costs (e.g., rare earth elements) are present only in ppm quantities and would require processing of large quantities of material to yield a small amount of product. At 100 ppm, 10 tons of material would need to be processed to yield one kg of product. Earlier, it was estimated that a single "mining and material conditioning" operation for materials in abundant supply would cost \$1/kg of throughput. At 100ppm, this would increase to \$10,000/kg of product.

Note that for both the high and low extremes of Earth-to-lunar launch and assuming use of lunar oxygen, the transportation cost of lunar materials to LEO is approximately one third that of terrestrial materials delivered to LEO. Thus, the return to LEO at a fraction of the cost of Earth-to-LEO transportation is a potentially attractive option.

#### D.6.6 CONCLUSION: LUNAR MATERIALS

Our analysis shows that, by large margins, typically of orders of magnitude, the extraction and transportation of lunar materials to Earth is unlikely to be practical in the next 20 to 30 years. We have found no indications that further study, new ingenuity, or developments of foreseeable technology will modify this conclusion for the period of interest. There is evidence (Ref. 11, 13) that extraction of lunar materials for use in space might become economically attractive before 20 years. The corresponding technology would eventually permit the economical return of lunar materials to Earth, beyond the 25-year time frame. These required techniques include, but are not limited to: a) a significantly improved understanding of the composition and structure of the moon; b) the accelerated development of space transportation and lunar processing technology; and c) the

development of by-products that could be economically practical for return to Earth.

If a period of 50 years or more is considered, technical as well as social, economic, political and other factors can change significantly. Under such changed conditions, the conclusions reached here would no longer be appropriate. The scientific and space-operational use of the moon, motivations of prestige, plus the development of lunar resources for use in space, may become catalysts to accelerate the eventual process of extraction and transporting lunar materials to Earth.

From the standpoint of utility, the principal impediment to lunar materials extraction is the cost of transportation. Thus, the technological driver is low-cost space transportation.

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**D.7 EXTRACTION OF COMMERCIALY USEFUL PRODUCTS  
FROM THE ASTEROIDS**

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## D.7 EXTRACTION OF COMMERCIALY USEFUL PRODUCTS FROM THE ASTEROIDS

### D.7.0 SUMMARY

Asteroids represent a source of diverse materials, distributed across the solar system. Analysis of meteorites shows concentrations of metallic Fe/Ni as well as other materials. Some asteroids are more accessible to the Earth than the moon--that is, it requires less energy to travel to and from these asteroids during part of their solar orbit. However, these low-energy opportunities occur only at extended intervals, such as once every two to five years.

A priori knowledge of the structure and composition of any given asteroid is not available. Such knowledge will be necessary for economically successful exploitation operations. An exploration and assay or sample return mission is an essential precursor to commercial asteroid operations. At the present state-of-the-art, such a mission is costly and time consuming. Low-energy mission opportunities occur at intervals of approximately five years. Trip durations to nearby asteroids last approximately one year. Several of these missions, or visits to several asteroids on a single mission, may be necessary to obtain sufficient information as to material composition and value. Thus, 10 to 15 years might elapse before it would be commercially practicable to even begin designing a space factory for extracting materials from asteroids; another five years to design and build such a factory and await a good launch opportunity; and several more years to reach selected asteroids and bring materials back. For example, should preparations for these exploratory missions begin in 1984, the first extracted material could not be expected until about the middle of the first decade of the 21st century. NASA has recently announced plans for a comet mission for the mid-1990s; since the asteroid missions are to follow this comet program, the extraction of asteroid material before 2015 or 2020 is very unlikely.

The cost/benefits of returning asteroid material to Earth do not appear attractive with current technologies. The nature of the asteroid orbits require major variations in the energy (propellant) required to travel to and from them. At least some (but not all) of them probably contain water that can be electrolyzed into propellants resulting in potentially significant savings. These uncertainties make it impossible to set limits to the probable value and cost of the return of materials to Earth, comparable to the estimations which are possible for returning lunar materials. Despite these uncertainties it is possible to define limiting quantitative estimates of mission costs based upon equipment costs and the cost of the equipment's transportation to the asteroids. These quantitative estimates strongly suggest the impracticality of such an operation within the time frame of this study, 2010.

#### D.7.1 SIGNIFICANCE

The extraction of useful materials from the asteroids, primarily for use in space, has been examined by a number of investigators. A few studies have analyzed scenarios for the return of entire asteroids or major fragments thereof to the moon, to LEO, and even to the Earth's surface, for purposes of extraction of materials. Additionally, the use of asteroids as giant and very destructive projectiles aimed at specific targets on the Earth has been studied. In a very imaginative and creditable science fiction account, Herrick (Ref. 1) describes plans for the controlled impact of an asteroid fragment to "dig" a new Atlantic/Pacific canal in central America and simultaneously deposit a treasure of hundreds of billions of dollars worth of nickel and scarce heavier elements at the Earth's surface.

Examination of the Apollo samples and extensive remote sensing shows that the moon is a well-mixed, well characterized and dilute source of materials. Located near the Earth, it is reachable in a few days. In contrast, there are thousands of

asteroids scattered throughout the solar system. In terms of energy expenditures, a few of these are easier to reach than the moon; yet transit times would be considerably longer, typically of the order of one year.

Extraction of materials from the asteroids will require processes that operate efficiently under microgravity conditions. Whereas microgravity is advantageous for certain processes, it significantly complicates numerous others, e.g., extraction of materials, because no terrestrial experiences or corollaries as yet exist on which to base microgravity processes. Therefore, development and verification of asteroid materials is expected to be more time consuming, difficult and costly than will development of processing in the 1/6g lunar gravity.

In the next 20 to 30 years, the time needed to travel to even the nearest asteroid will constitute a significant barrier to the exploitation of asteroid materials. Moreover, overall projected costs, based on equipment acquisition and Earth-to-LEO launch costs, weigh heavily against the practical extraction of asteroidal material for return to Earth under current and reasonably predictable technological conditions.

#### D.7.2 ASTERIODS AND METEORITES

Meteorites--bodies that originated in outer space and have survived transit through the atmosphere--constitute a sample, although not necessarily representative, of the near-Earth asteroids. From these meteorites inferences can be made about what materials would be available in asteroids with the same composition as a meteorite.

To understand the asteroids' potential as a source of materials, it is necessary to understand their locations, the compositions and structures of meteorites, and the relationships between

asteroids and meteorites. To this effect, a brief tutorial on asteroid astronomy is included in this study.

The following definitions are useful in understanding the discussions that follow:

- **Meteoroid**--a small, solid extraterrestrial body in space; typically 1km in diameter or smaller (thus smaller than an asteroid)
  
- **Meteor**--a heated, glowing non-terrestrial body passing through the atmosphere, including the trail of heated debris
  
- **Meteorite**--an extraterrestrial body or fragment thereof that collides with the Earth's surface after having passed through the atmosphere
  
- **Fall**--a meteorite whose descent through the atmosphere has been witnessed
  
- **Find**--a meteorite found upon, or buried within, the ground

Meteorites have been hypothesized to be remnants of an unconsolidated planet, or products of the catastrophic destruction of a planet, and/or the remains of comets. Small fragments rain on the earth in large quantities, occasionally in spectacular clusters. On rare occasions, large chunks fall with catastrophic results. These large pieces have been cited as the cause of major craters in Canada, South Africa and elsewhere in the world. Some authors have blamed them for the extinction of the dinosaurs. They have also been assigned as the cause of the cratered surfaces on the moon, Mars and the moons of other planets.

Asteroids are scattered throughout the solar system. They range in composition from mostly stony objects to bodies composed largely of metallic elements, primarily Fe/Ni, to bodies containing varying amounts of carbon.

Determination of the composition and structure of a meteorite sample is simple. Determination of the composition of a specific asteroid or, more importantly, the identification of a particular asteroid with a specific composition and structure is more difficult. To this end, extensive exploration and/or assay missions will likely be required.

Asteroids are typically classified by their orbits in space; meteorites are classified by their composition and structure. Remote observation of the asteroids has been used to examine their characteristics and thus assign probable composition-structure characteristics corresponding to the meteorite classification.

#### Types of Asteroids by Location

Asteroids are commonly grouped into seven classes, defined by their orbits. Of these, only the three classes of near-Earth asteroids (Amor, Apollo, and Aten), plus the postulated Earth Trojans, are of interest as material sources in the near future and for possible return to Earth. The others may be sources of propellant, equipment, staging, etc. for space exploration 50 to 100 years hence.

The best known and most numerous asteroids lie within the main belt located in a band between Mars and Jupiter. Their location was predicted by Titus von Wittenburg in the Titus-Bode Law of Planetary Distances in 1766. The Titus-Bode Law also predicted the location of Uranus, discovered at the appropriate orbit in 1781. The first observation of the largest among asteroids, Ceres, occurred in 1801, near the predicted orbit. With

additional discoveries through the 19th century, there was frequent speculation that the asteroids were the remains of an exploded planet. The orbits of the Main Belt asteroids range from 2.1 to 3.3AU (1AU equals the mean distance between the sun and the Earth) and for the most part are more elliptical than the orbits of the planets. Remote observation shows varied characteristics. Approximately one-third appears to match carbonaceous chondrite meteorites; these appear to be concentrated primarily at the outer edge of the belt. Only approximately 5% of the meteorites found on Earth are of the carbonaceous chondrite type.

A second group of asteroids is located in the outer solar system beyond the orbit of Jupiter. Some of the satellites of Saturn and Jupiter appear to be asteroidal and may have been captured from these outer groups.

A third group of remote asteroids, called Trojans, are located in Lagrangian points (gravitationally stable regions) in the orbit of Jupiter. Because of their distance, the Jupiter Trojans are not particularly significant in themselves as material sources but are important as physical evidence to support the hypothesis that similar Earth Trojans may exist in corresponding Lagrangian locations in Earth orbit. Trojans would have great interest for exploitation; they would have distinct access and operational advantages over other near-Earth asteroids, as will be described later.

The three remaining classes, all in the general category of "near-Earth," are the most interesting for early exploitation. The outermost of these, called Amor, crosses the orbit of Mars while remaining outside Earth's orbit. The second, called Apollo, crosses the orbit of Earth and has orbits mostly outside that of Earth and inside that of Mars. The third group, Aten, are Earth crossers with orbits mostly inside the orbit of Earth. The discovery of this group is recent and only a few have been found.

The largest of the Amor group is 30km in diameter. It has been estimated that there are 1500  $\pm$ 500 with diameters  $>1$ km and as many as 10,000  $\pm$ 5,000 total. Of the Apollos, 30 were known as of 1978, the largest being 8km in diameter; the total population with diameters  $>1$ km is estimated to be 700  $\pm$ 300. Several new near-Earth bodies have been found recently.

The Amor and particularly the Apollo groups are of primary interest for exploitation because they have orbits which bring them close to Earth and allow relatively low-energy trajectories for fly-by, rendezvous and material return. Unfortunately for early exploitation they come close to Earth at intervals varying from two to five years, thus, limiting opportunities for low-energy missions. In the meantime their elliptical orbits carry them out to  $>2$ AU, frequently opposite the sun from the Earth or  $>3$ AU from Earth. Since one-way radio communication time is 8.3 minutes per AU, round-trip communication to a processing facility on an asteroid would be nearly an hour. Any effective teleoperation would become impractical.

#### Types of Meteorites--Composition and Structure

Meteorites as a sample of the material of asteroids are generally classified into three categories by composition and structure:

- **Stones**--mixed oxide minerals analogous to terrestrial stones
- **Stony irons**--mixtures of stone and metal
- **Irons**--an Fe/Ni mixture

The stones are subdivided into chondrites and achondrites. The chondrites are so called because they contain chondrules, small BB size spherules, and are further subdivided into carbonaceous chondrites (CCs) and ordinary chondrites.

The achondrites are stones without chondrules, either because their origin was different or because they have been modified by partial melting and resolidification. In fact there is an enigma in the nomenclature, in that the type I CCs, a small but important subclass, do not contain chondrules.

Of primary interest among the stones are the three recognized classes of CCs, which contain various amounts of chemically combined "volatiles" including water, organic compounds and carbon. There are three recognized classes of CCs. Type I CCs, which, appear to have undergone minimum modification by heat or pressure since their formation, contain the most water (8-22%), volatiles and carbon. They are the least plentiful among the falls, representing less than 1% of the total. Evidence from lunar samples and spectrographic measurements of asteroids in space indicates a higher population than would be indicated from fall statistics. The low population in type I CCs falls may result from their typically weak structure and resulting tendency to break up more readily during atmospheric entry.

The type II and III CCs generally show evidence of increasing thermal and/or pressure modifications and lower content of water, volatiles and carbon.

The "stone" portions of the CCs, the ordinary chondrites, the achondrites and the stony portions of the stony irons are made up of minerals like those of the Earth and contain mixtures of various oxides with typically a high content of  $\text{SiO}_2$ . Like terrestrial and lunar materials, these can be processed and used as silicates or decomposed, with some difficulty, into elemental oxygen and metals.

The irons represent an end point of a range from small amounts of metal inclusions through the stony irons to the irons. The irons contain an Fe/Ni mixture, typically 8-12% Ni but occasionally as high as 20% Ni. Other metallic elements vary

from sample to sample ranging from fractions of a part per million to hundreds of part per million.

Additional classifications and definitions of this group of materials will be introduced later, as needed to identify those bodies of specific interest for potential exploitation.

### Composition and Structure of Asteroids

Remote sensing measurements--spectroscopic, optical polarization, and radar--allow the classification of individual and of groups of asteroids. While such classifications appear reasonable and consistent for astronomical purposes, their reliability may not be sufficient to launch a \$100 million resource mission to a specific asteroid. Most likely, an exploration and assay or a sample return mission(s) will be required to select one or more asteroids for exploitation.

From assays of the meteorites found on Earth, a possible chemistry and structure for the near-Earth asteroids can be inferred. However, beyond the knowledge of meteorite composition and structure, speculation begins.

However, these meteorites gathered from the Earth's surface and taken to the laboratory for examination have been altered from their state in space by entry through the atmosphere and by exposure to the terrestrial environment. Although atmospheric heating affects the characteristics and the chemistry/structure of the surface layer, the entry thermal pulse is short enough in duration that only the first few millimeters and not the bulk of the meteorite is significantly affected. The effects of terrestrial water and atmosphere are not so easily dismissed, particularly for old finds. Some of these effects can be analyzed. For example, isotope studies have demonstrated that at least some of the water in CCs is of extraterrestrial origin.

Meteorites in laboratories and in collections probably represent a poor quantitative sample of total near-Earth population of asteroids. The more fragile meteorites, particularly the Type I CCs, tend to break up during atmospheric entry and to decompose more rapidly when exposed to weathering and thus are under-represented in collection populations. At the other extreme, iron-containing meteorites are over-represented because they resist atmospheric entry well and are easily identified and retrieved and because they do not resemble terrestrial rocks.

Statistics on meteorite falls indicate the following approximate population of near-Earth asteroids: 95% stones, including 5% CCs, 81% ordinary chondrites and 9% achondrites; 1% stony irons; and 4% irons. Of the 5% CCs, approximately 1% are type I, which contain the most water, volatiles, carbon and organics. In contrast, observation of the main belt indicates that approximately one-third of the asteroid population matches the characteristics of CCs and that the population of chondrites is much less than indicated by the fall population.

The <1% type I CCs and the 4% irons would appear to be of greatest interest for exploitation. However, exploitation strategy might make other types desirable. For example, exploitation of a stony iron might have as its primary objective recovery of iron/nickel metal and as its secondary objective extraction of asteroidal oxygen from oxides for use as propellant.

Within the population of the asteroids are materials that are definitely of interest for use in space ventures and potentially for extraction and return to Earth as well.

The diversity and probable percentage contribution of available materials are illustrated in Table 7-1. Note that in addition to Fe and Ni present in the metallic state, other metals, such as Al and Mg, can be extracted by decomposition of their oxides. Furthermore, some asteroids contain water, carbon and

TABLE 7-1

PERCENTAGE COMPOSITION OF METEORITE MATERIALS

	<u>ORDINARY CHONDRITES</u>	<u>CARBONACEOUS CHONDRITES</u>	<u>STONY IRONS</u>	<u>IRONS</u>
<b><u>METAL OXIDES</u></b>				
SiO <sub>2</sub>	36.00 - 40.00	23.00 - 33.00	17.00 - 35.00	--
MgO	23.00 - 25.00	15.00 - 23.00	6.40 - 23.00	--
FeO/Fe <sub>2</sub> O <sub>3</sub>	9.00 - 14.30	10.00 - 24.00	4.40 - 7.70	--
Al <sub>2</sub> O <sub>3</sub>	2.60 - 2.80	1.70 - 2.70	0.00 - 4.10	--
TiO <sub>2</sub>	0.11	0.08 - 0.12	--	--
CaO	1.87 - 1.92	1.50 - 2.30	0.00 - 3.00	--
Na <sub>2</sub> O	0.93 - 0.94	0.54 - 0.76	0.00 - 0.17	--
K <sub>2</sub> O	0.10 - 0.11	0.05 - 0.07	0.00 - 0.03	--
MnO	0.26	0.17 - 0.20	0.00 - 0.22	--
Cr <sub>2</sub> O <sub>3</sub>	0.33 - 0.41	0.28 - 0.51	0.00 - 0.68	--
NiO	--	0.30 - 1.56	0.00 - 0.4	--
<b>TOTAL (AVERAGE CONTENT)</b>	85.10	75.10	43.40	-0-
<b><u>FREE METALS</u></b>				
Fe	07.10 - 17.40	0.00 - 2.30	28.00 - 49.00	80.00 - 93.00
Ni	1.00 - 1.70	0.00 - 1.00	4.00 - 4.70	5.50 - 19.00
Co	0.07 - 0.10	0.00 - 0.06	0.00 - 0.30	0.50 - 1.00
Pt/Au	--	--	?	ppm
<b>TOTAL (AVERAGE CONTENT)</b>	8.30	0.16	52.70	97.60
<b><u>OTHER COMPOUNDS</u></b>				
FeS	5.60 - 6.00	6.00 - 17.00	0.00 - 7.40	0.60 - 4.60
C	--	0.50 - 3.60	0.00 - 0.08	0.01 - 0.60
P <sub>2</sub> O <sub>5</sub> /P	0.23 - 0.26	0.27 - 0.32	0.00 - 0.11	0.15 - 0.20
H <sub>2</sub> O	0.24 - 0.30	1.00 - 20.50	0.00 - 0.70	--

organics which can be extracted for use as life support, processing reagents, and/or propellants for transportation of equipment, materials or products. In addition to the materials listed in Table 7-1, other elements are present, generally "concentrated" in the stone or metal phase, in amounts ranging from fractions of parts per million to as high as parts per thousand (i.e., cobalt). The concentration of these varies significantly (by orders of magnitude) from one meteorite to another. As an illustration, list of a few of the "minor" elements and their range of concentrations are shown in Table 7-2. (Extensive additional information is available from Ref. 3).

The range of compositions of selected meteorites shown in Figure 7-1 (Ref. 2) indicates the probable range of composition of various asteroids. In this figure the compositions are arranged from left to right with increasing metal content.

#### D.7.3 PROCESSING

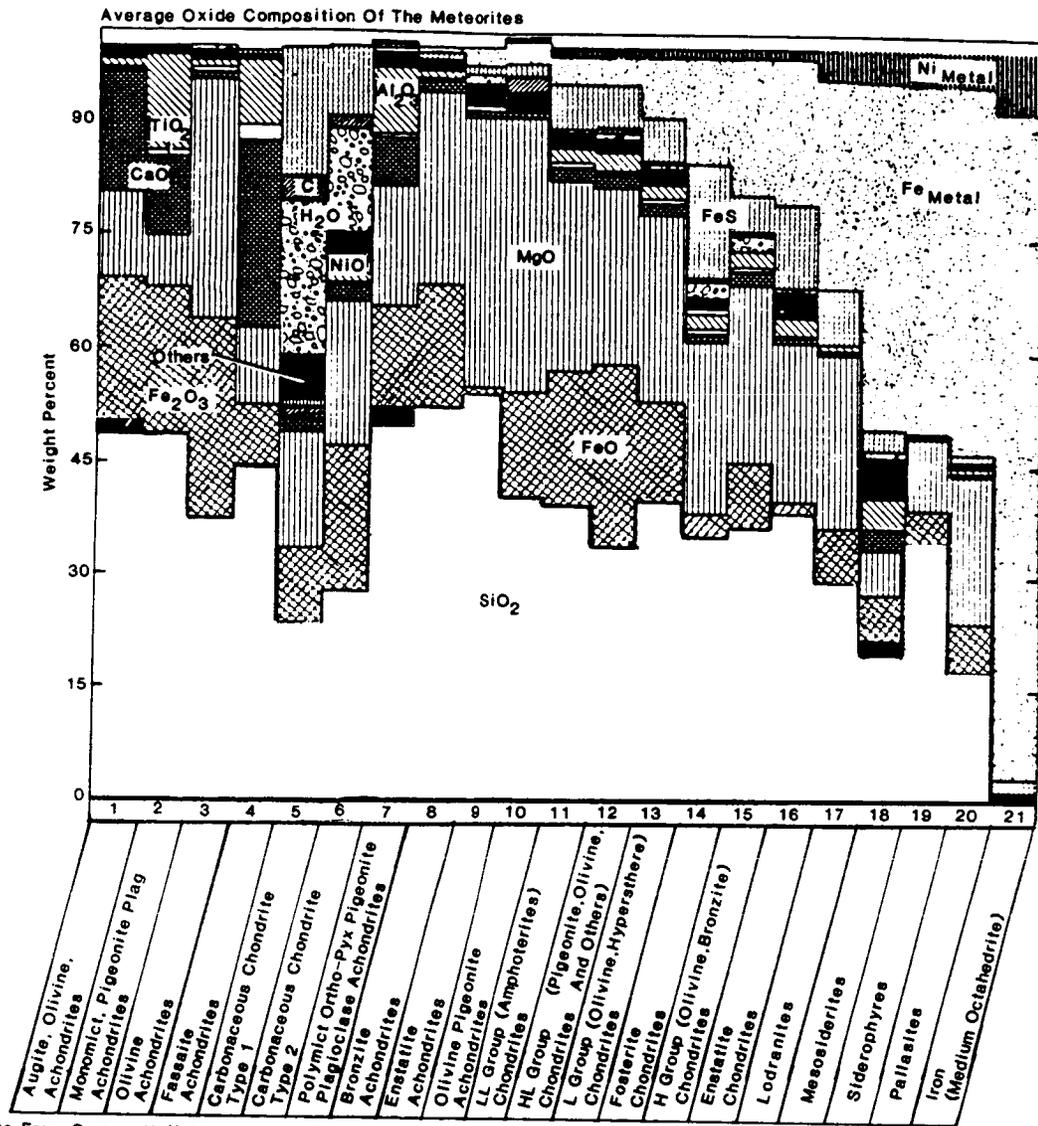
In general, in considering nonterrestrial materials processing, the three processing categories defined by Steurer (Ref. 2) are useful:

- 1) Mining and material conditioning--Changes in situ minerals into feedstock. Includes acquisition (the general equivalent of terrestrial mining); comminution (grinding, crushing); sizing and beneficiation (concentration)
- 2) Primary processing--Changes **feedstock** into **primary products** (e.g., the space analog of ingots or bar stock). Includes extraction (e.g., metal from ore); shaping; and post treatment (e.g., firing bricks)

TABLE 7-2

CONCENTRATION OF SELECTED MINOR ELEMENTS  
IN METEORITES

<u>ELEMENTS</u>	<u>CONCENTRATION</u> (ppm)
Co	5000
Cu	8.00 - 450
Zn	1.00 - 37.0
Rh	0.10 - 2.5
Ir	0.01 - 15.0
Pt	0.50 - 30.0



Data From Gomes, Keil 1981 Except For Enstatite Chondrites, Story Irons, And Irons Which Are From Mason 1971

**Figure 7-1. Range Of Compositions Of Selected Meteorites**

- 3) Secondary processing--Changes **primary products** into **end products** (e.g., metal rod stock into a structure or space bricks into a shelter). Includes fabrication, assembly, and installation

Because the present analysis is addressed to "extraction of useful products for use on Earth," our major consideration will be mining and conditioning, with some attention to primary processing. Secondary processing as defined by Steurer applies primarily to items for end use in space.

The issue here is not the specifics of individual candidate processes, but the practical limits for extraction of useful products from asteroids. Processes for nonterrestrial materials have been discussed in studies and a few have been examined in the laboratory. The extraction of metals and oxygen from mixed oxides is theoretically possible and has been demonstrated experimentally by several investigators (Ref. 4d,5,6), but never in the microgravity environment of the asteroids.

Possible strategic approaches for exploiting asteroidal materials include:

- Rendezvousing a complete in-space processing facility with an asteroid, mining the body and processing the material into finished or semifinished products on site for transport back to Earth or elsewhere in space
- Rendezvousing a relatively simple mining and cargo vehicle with an asteroid and collecting unrefined or slightly refined bulk material for transport to a processing site on the moon, in LEO, on Earth or elsewhere
- Moving an entire asteroid or fragment (after simple fragmentation) to LEO, to a libration point, or to impact the moon or the Earth for subsequent processing

there. Such an approach could use a simple propulsion system, even as simple as explosive charges to simultaneously fragment and propel.

### Processing in Microgravity

All the above strategies that do not use return to the moon or Earth require that processing be carried out in microgravity. Should it prove desirable or necessary to provide artificially induced gravity effects for some parts of the system, these can be obtained by spinning the processing vehicle.

Microgravity presents major advantages. (It is being exploited in shuttle flights for special processing like crystal growth and pharmaceutical separation.) However, the lack of gravity, in addition to the lack of readily available processing fluids like water and air that are the basis of standard phase separation processes, will require development of processes that can use concentration gradients, electric fields, etc., to provide phase separation in the place of terrestrial gravity. This is not an insurmountable barrier, but process development will require significant forethought and ingenuity.

For example, cutting a large iron asteroid into smaller chunks for subsequent handling or processing, either in its original orbit or in LEO, will pose considerable problems in a microgravity environment. Sawing is a possibility, even though FeNi is fairly tough. Momentum will tend to carry saw fragments away from the cut only along the axis of the blade, because there will be no gravity to reduce rebound or accumulation at the blade attach points. An alternative is laser cutting, a very effective terrestrial method for tough materials such as FeNi. However, in the microgravity environment of an asteroid, there is no gravity to help remove the molten zone and, in fact, surface tension would tend to keep it in place until it could resolidify. Furthermore, at an asteroid, even if the molten material could be

coaxed out, there is no atmosphere to oxidize the fresh surfaces and thus discourage rewetting and return.

Crushing material from a stony asteroid also illustrates difficulties presented by a nonterrestrial environment. Terrestrial processes use working fluid (air, water) or gravity to remove newly generated fines so that effective work on the remaining coarse fraction can continue. Furthermore, beneficiation via standard processes such as segregation by size, density, etc., depends on gravity and fluids.

Thermal decomposition of hydrated minerals to extract water, electrolysis of compounds to produce gaseous products, and other processes which result in a vapor phase product depend on gravity for phase separation. Without gravity the gaseous phase generated at the reaction zone will tend to become a serious inhibitor to further reaction and process yield.

These barriers to effective exploitation of asteroidal materials are obviously not insurmountable, but they are likely to add significantly to the complexity, the cost and the development lead time for the development of processes.

### Processing Equipment

Although the processes for exploiting asteroidal materials have yet to be identified and/or developed, there are reasonable methods for estimating their mass and cost.

Let us first consider the mass of equipment associated with the simple operation of mining and material conditioning, e.g., excavating, handling and moving material. The mass can be reduced from that of terrestrial by using aerospace materials and fabrication processes (e.g., high-performance alloys; elaborate machining to remove unnecessary material). In addition, the designing specifically to operate in the microgravity environment

should also be able to reduce the mass, but that effect would be relatively small. However, the difficulty of repair, replacement, and refurbishment at an asteroid will require an increased design margin (higher mass) for reliability. Therefore, it is reasonable to use the mass of commercial terrestrial equipment as comparable. Significant mass differences might result from the differences in power for locomotion. Internal combustion engines are obviously impractical, and both the power for and thermal regulation of electric motors can be major problems. Effective designs with precise estimates are possible when greater accuracy is required (for example, a simple device, the Lunar Rover, was designed, built and operated).

Terrestrial earth-movers, conveyors, hoppers can collect and move a mass of material equivalent to their own mass a reasonable distance in a matter of minutes. Thus, the mass of such equipment would be  $10^{-5}$  To  $10^{-6}$  the mass of raw material moved over an operating lifetime of ten years. If the difficulty of loading and unloading in microgravity is considered, an equipment mass of  $10^{-4}$  to  $10^{-5}$  of the product mass would be more reasonable for asteroid processing. If we consider processing primarily for materials present only in small concentrations, like the noble metals, the fraction of the final product becomes much more significant.

Terrestrial primary processing equipment can typically handle throughput equal to the equipment mass in anywhere from an hour to perhaps a day. This basis plus a consideration of microgravity factors suggests that the mass of equipment would be  $10^{-3}$  to  $10^{-4}$  the mass of the feedstock (or for candidate processes using most of the feedstock, the mass of the product). Like material handling equipment estimates, the relationship of equipment mass to product mass changes dramatically if the resources to be extracted are present in small concentrations.

## Process Energy Requirements

The status of space power technology applicable to processing of nonterrestrial materials has been examined by Jones (Ref. 4a). Because the technology of solar photovoltaics is well established its future progress can be projected with reasonable confidence. In the period of interest, it represents minimum mass per power capacity. Therefore, solar photovoltaics represents a reasonable baseline for lunar or near-Earth processing and for one candidate system for asteroid processing. Since the near-Earth asteroids have highly elliptical orbits which vary from about 1AU to 2-4AU, efficient photovoltaic systems are not necessarily practical and nuclear systems must be considered. The Earth Trojans, if they exist, maintain orbits at about 1AU. Therefore, if they are found and if they contain materials of interest, photovoltaics would become a prime candidate power source for processing.

Jones (Ref. 4a) estimated future photovoltaics at 15-8 kg/kW(e) for what he defined as "in-development" and 5-3kg/kW(e) for what he defined as "on frontier." Likewise, Jones has estimated current and future nuclear energy systems. If selected values of 150kg/kW(e) for "in development" radioisotope thermoelectric and "frontier nuclear fission MHD" at 5kg/kW(e) are used, the power plant facility mass requirements for processing 1000 metric tons/year for typical operations can be calculated.

The range of energy requirements for various types of processes is shown in Table 7-3, adapted and simplified from Jones (Ref. 4a). The second column of Table 7-3 shows the calculated power plant capacity required for processing 1000 tons/year, assuming full-time operation and maintenance of 1AU power input to the photovoltaics. The last three columns of Table 7-3 show the power plant mass required for 1000 tons/year at the levels of 150kg/kW(e) for the highest mass nuclear case, 15kg/kW(e) for the voltaic. The 3kg/kW(e) photovoltaic is essentially equivalent to the 5kg/kW(e) nuclear system.

TABLE 7-3

ENERGY AND POWER PLANT REQUIREMENTS

<u>OPERATION</u>	<u>ENERGY REQUIRED</u> kWh/TON	<u>CAPACITY FOR 1000 TON/YEAR</u> kW(e)	<u>POWER PLANT MASS FOR 1000 TON/YR THROUGHPUT</u>		
			<u>MASS FOR ENERGY DENSITY (kg/kW(e))</u>		
			<u>150</u>	<u>15</u>	<u>3</u>
EXCAVATION	0.1	$10^{-2}$	1.5	0.15	0.03
BENEFICIATION	10	1	150	15	3
MELTING	500	60	104	103	200
ELECTROLYSIS	$10^4$	$10^3$	$1.5 \times 10^5$	$1.5 \times 10^4$	$3 \times 10^3$
VAPOR PHASE PROCESSING	$10^5$	$10^4$	$1.5 \times 10^6$	$1.5 \times 10^5$	$3 \times 10^4$

TABLE 7-4

COMPARISON OF TRANSPORTATION  
FROM VARIOUS BODIES TO LEO

<u>BODY</u>	<u><math>\Delta v</math> TO LEO W/AEROCAPTURE</u> km/second	<u>FREQUENCY OF OPPORTUNITY</u>	<u>TIME OF FLIGHT</u>
ANTEROS	0.5-2	2-3 YEARS	10 MONTHS
NEAR-EARTH ASTEROIDS	0.2-2	2-5 YEARS	6-14 MONTHS
EARTH TROJANS <sup>a</sup>	1.4-2	CONTINUOUS	8-10 MONTHS
PHOBOS/DEIMOS	1.5-2	1-2 YEARS	6-14 MONTHS
MOON	3.2	CONTINUOUS	DAYS
MARS	5.6	1-2 YEARS	6-14 MONTHS
EARTH SURFACE	8.2	CONTINUOUS	MINUTES

<sup>a</sup> EXISTENCE NOT PROVEN

As an example, if a product requires three beneficiation steps, the power plant would have a mass of 9-450kg (0.02-0.5 tons) for an output of 1000 tons/year. Thus, for a ten-year operation the power plant would be approximately  $10^{-5}$  to  $10^{-6}$  the mass of the output product. At the other extreme, for vapor phase processing, a 30-1500 ton power plant could produce the process energy at  $10^{-1}$  to  $10^{-2}$  the mass of the throughput.

The economic significance of processing and power equipment on asteroid resources and their practicality will be defined in Section D.7.5.

#### D.7.4 TRANSPORTATION

Some asteroids are more accessible from the Earth than the moon, depending on time of flight and departure time. Table 7-4 shows the change in velocity ( $\Delta v$ ) required to move from various places in space to LEO, how often such a low-energy opportunity occurs, and how long the trip takes.

Energy change, which is a measure of propellant requirements, is proportional to  $\Delta v^2$ . Thus, it takes only a fraction (1/2 to 1/100) of the energy and 0.7 to 0.10 of the propellant to return material to LEO from an asteroid as it does from the moon. However, while transit to and from the moon can be performed at any time in a few days, the orbits of the asteroids are such that the low-energy mission opportunities occur infrequently, e.g., every two to five years for any single asteroid. In fact, the lowest-energy opportunities occur even less frequently, approximately at ten-year intervals. Furthermore, the lowest energy opportunities require one way transit times of order of one to several years.

The Earth Trojan asteroids maintain a nearly constant location relative to the Earth and would thus have a major advantage if opportunities for missions were continuous. They still would

require transit times of approximately one year, but could have  $\Delta v$  requirements even lower than those shown in Table 7-4 if transit times of over two years were allowable. (The advantages of Earth Trojan orbits which allow practical use of photovoltaics have been discussed earlier.)

The variation in the orbits of accessible asteroids, uncertainties as to which asteroids contain materials of interest, and the ability to trade thrust for time in mission opportunities makes it very difficult, and meaningless for purposes of this discussion, to select a simple, meaningful set of sample transportation cases.

Furthermore, the presence (in some asteroids) of water, should be easily extractable and convertible into propellants even if chemically combined, makes it impossible to establish simple limits on practical materials based only on launch costs of propellants for transport.

### Transportation for Exploration

To carry out a particular general survey or examine a specific site on the moon required only a few days to get there; the mission can be launched at any time or even delayed for a fraction of a month to await the appropriate time of lunar day.

To examine a particular asteroid may require a wait of two to five years for a launch opportunity and most of another year getting there. For samples to be returned to earth for examination will require another year or more. Strategies have been developed for visiting several asteroids in a single mission, but such missions are far in the future of NASA's plans.

A time line for an optimistic scenario for exploiting asteroidal material illustrates the schedule problem. The time line is essentially independent of whether material is returned to LEO, the moon or the Earth's surface.

Planning, design, fabrication and launch of a multi-asteroid assay mission	5 years
Multi-asteroid rendezvous, (simple) composition and structure measurements	7 years
Planning, design, fabrication and launch of an asteroid exploitation facility	5 years
Transit to selected asteroid	1 year
Extract quantities of material	1 year
Return of initial material to near-Earth	1 year

The five-year cycle for plan-to-launch of exploration and exploitation vehicles may seem excessive except when one considers that the Galileo spacecraft scheduled for launch to Jupiter in 1986 was begun in 1978. The five-year estimate includes allowance for waiting for an optimum launch. Thus, even if the decision is made in 1984 to proceed with the exploitation of asteroid material, it would be the early part of the next century before resources would become available. Staehle (Ref. 7) made somewhat more optimistic estimates but they were for simple operations of extracting water for use as propellants in space.

#### Transportation for Processing Equipment

The long interval between opportunities and the long trip time to an asteroid will dictate delivery of an entire processing facility in a single mission. The mass and therefore the cost of the transport vehicle will become important factors.

In contrast, multiple deliveries can be made to the moon at intervals of a few days, making it possible to amortize cost

factors over numerous trips and reduce their significance. For purposes of this study, it is reasonable to assume that the equipment transport vehicle will be of the order of 30% the total of the equipment mass.

Since it is impossible at this time to predict which asteroids will be of interest, delivery propellant requirements remain very uncertain. For purposes of this analysis, a reasonable value is 3kg of terrestrial propellant in LEO per kilogram delivered at the asteroid. The delivered mass includes the process equipment power plant and the essentially one-way delivery vehicle.

Based on these assumptions, the total mass (T) that must be initially delivered to LEO, includes the mass of the process equipment (M), the transport vehicle (0.3M), and 3kg of propellant per kilogram to be delivered;

$$T = M + 0.3M + 3(M + 0.3M) \quad (1)$$

or

$$T = 5.2M \quad (2)$$

This quantity does not include transport equipment or propellants for material return.

### Transportation for Products

If at least some of the asteroids contain extractable water that can be converted into propellants, an optimistic scenario assumes that no terrestrial propellants will be required for return of extracted materials. However, the equipment to produce the propellants must be accounted for. Carroll (Ref. 4b) has shown that equipment amounting to less than 5% of the product mass will be sufficient to extract propellants from lunar material. A total of approximately 2kg of propellant is required for every kilogram of payload returned from the moon; an equivalent

value is a reasonable estimate for asteroid return. Thus, the equipment to extract the "free" propellant will amount to 10% of the returned payload mass.

Although the task of extracting propellants from water is easier, the greater ease is counterbalanced by the difficulty of operating in microgravity; thus the lunar value can be initially assumed for the asteroids.

Since transport vehicles for lunar materials can make a round trip in a few days and hundreds of trips over their lifetime, their mass and cost per unit cargo mass can be considered relatively small. In the case of asteroid return, round trip times are measured in years and the mass and cost cannot be neglected. Frisbee (Ref. 4c) estimates lunar cargo vehicles at approximately 20% of the cargo mass. Each vehicle can be used for four or five round trips during its lifetime so that the earth to LEO launch mass will amount to 4 to 5% of the returned product mass. However, the terrestrial propellant required for the outbound leg would be 3kg of propellant per kilogram of vehicle or approximately 60% of the returned product mass.

#### D.7.5 COST ASSESSMENT

While it is not possible to establish cost limits for asteroidal materials as readily as for lunar materials, some useful values can be estimated.

The cost factors to be considered are those of the processing equipment, the power plant to supply process energy, the transport vehicles to move the equipment to the processing site, the transport vehicles to move the products to the point of use, the launching of all equipment and terrestrial propellants for the equipment transport. In previous sections, these quantities have been estimated in relationship to the material throughput or the returned payload. As shall be seen, the results tend to be

dominated by one or another of these factors. However, it is useful to comment on each for possible future reference as new information or technology becomes available.

Earth-to-LEO launch costs in the near future are based on mature Shuttle flights at \$100 million per mission and payload of 30 tons. This yields an upper limit of \$3300/kg. A lower limit of \$330/kg is based on the work by Talay et al. (Ref. 8). Likewise, an acquisition cost for processing equipment and transport vehicles of \$50,000/kg, based on the cost of mature communications satellites (see Table 7-5), will be used. Because the necessity of operating in microgravity and the improved reliability necessary for completely autonomous operation at one-hour round trip communication distance from Earth must be considered, these values are probably too low for asteroid exploitation.

The cost of photovoltaics at \$10,000/kW(e) is based on the estimate of Carroll (Ref. 4b). This holds for Earth-operable photovoltaics, i.e., those not insured to resist the LEO or GEO solar radiation environment. To the extent that the asteroid environment is milder than LEO or GEO, the price level of \$10,000/kW(e) can be assumed as a very low limit. For nuclear propulsion, a value of at least an order of magnitude higher would be in order based on the current cost of space power, but for the calculations here, the same value as photovoltaics is optimistically used. That value will warrant review in the future if it becomes an important factor.

For convenient reference, a selected list of typical current commodity prices have been listed in Table 7-6. These will help the reader put the following cost estimates into perspective.

If the lower limit of processing equipment mass is set at  $10^{-5}$ kg/kg throughput, with a procurement cost of \$50,000/kg, the equipment cost would be \$0.50/kg. This throughput would correspond to a simple mining and material conditioning process, where

TABLE 7-5

APPROXIMATE ACQUISITION COST  
OF TYPICAL EQUIPMENT

FULL SIZE AUTOMOBILE	\$5-10/kg
CONSUMER ELECTRONICS	\$10-100/kg
COMMERCIAL AIRCRAFT	\$100-200/kg
COMMUNICATION SATELLITES	\$50,000/kg
ONE-OF-A-KIND SPACECRAFT	\$100,000/kg

TABLE 7-6

APPROXIMATE PRICE OF SELECTED COMMODITIES

<u>MATERIAL</u>	<u>PRICE</u>	<u>\$/kg</u>
IRIDIUM	\$600/TROY OZ	19,000
PLATINUM	\$475/TROY OZ	14,000
GOLD	\$372/TROY OZ	12,000
PALLADIUM	\$140/TROY OZ	4,500
SILVER	\$8.61/TROY OZ	280
ZIRCONIUM	\$15/LB	33
NICKEL	\$3.25/LB	7.15
ALUMINUM	\$0.81/LB	1.78
FINISHED STEEL	\$0.27/LB	0.59
PIG IRON	\$213/TON	0.23
COAL, LOW SULFUR	\$45/TON	0.05

SOURCES: IRON AGE, 1984; WALL STREET JOURNAL

the entire throughput is a product similar to a collection of loose rubble from the surface of an asteroid for return to LEO for subsequent processing. At the high end of  $10^{-3}$ kg/kg throughput, which might correspond to extraction of the metal phase from a stony iron body, the contribution of equipment to product cost becomes \$50/kg. For materials present in smaller quantities, for example Ni at 10% of the metal phase, the processing equipment will cost \$500/kg Ni. For Pt at 0.5 to 35ppm (see Table 7-2) the equipment costs would exceed \$1 million/kg.

In the case of the cost of process energy equipment, the calculations will be limited to an intermediate process, melting, and an intermediate power system mass of 15kg/kW(e) (see Table 7-3). Calculations for other cases are straightforward. In the selected case, a 60kW(e) plant is sufficient to produce 1000 tons/year for ten years or 10,000 tons. At a procurement cost of \$10,000, the plant procurement contribution is \$60/ton or \$0.06/kg of product. At the selected level, the total mass is 900 kg/10,000 tons of product, which will require launch from Earth of equipment, transport vehicles and propellant of approximately 4.5 tons. At the low cost of \$330,000/ton for Earth-to-LEO launch, the cost will be \$1.5 million for an eventual output of 10,000 tons of product or \$1.50/kg. At the upper cost of \$3300/kg, the cost will be \$15/kg.

Earlier it was estimated that if asteroid propellant is used for the return of products, the equipment that must be put into LEO for propellant extraction will be 10% of the payload, the transport vehicle 5%, and the terrestrial propellant for the outbound leg 60% of the payload for a total of 75%. At the nominal Earth-to-LEO launch cost of \$3300/kg, the payload return contribution (excluding acquisition of the equipment) would be in excess of \$2000/kg or about one-fifth the value of gold. At the lower limit of launch cost, the contribution would be approximately \$250/kg, approximately the value of silver.

The return of asteroid materials to Earth does not look attractive under current economic and technological conditions. However, both of these are subject to change with time.

The exploitation of asteroid materials for use in space may very well become economically attractive considering the high cost of the delivery of materials from Earth to space. Should such an endeavor be undertaken, some by-products might become attractive for return to Earth.

#### D.7.6 CONCLUSIONS

It is important to keep in mind that time--time required for exploration, time needed for assay and/or sample-return missions, and time to put a processing facility in place--is the major current barrier to asteroid exploitation. Additionally, even with optimistic estimates, the economics of asteroidal materials for use on Earth do not look attractive for the era 2000-2010.

The economics are expected to evolve significantly during the 20 to 30-year minimum interval required to exploit asteroids as a source of materials. Thus, at a future point in time, when more definitive information is available about the exploitation of asteroids in specific orbits, a re-examination of this analysis will be essential.

The current outlook regarding the practicality of asteroid exploitation is essentially negative. An analytical methodology has been established. In the future new and/or improved values can be substituted to obtain new quantitative answers with perhaps more positive conclusions.

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## **D.8 SUPPORTING SPACE TRANSPORTATION**

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## D.8 SUPPORTING SPACE TRANSPORTATION

### D.8.1 SIGNIFICANCE

The **price/performance** of space transportation (ST) is key to the deployment of useful payloads within all space theaters. In the light of the utility and cost indicators identified in Volume I, Section 4.2, the utility parameter of ST can be defined as the weight (kilograms) of payload placed within the target theater.

Varying with the utility of the mission, the allowable cost threshold must be commensurate with the value of the useful product provided by the payload. A general desideratum is that the cost be as **low** as possible.

We focus here upon the most demanding element of ST, the Earth surface-to-LEO leg. The corresponding propulsion systems must be capable of simultaneously providing high **thrust** and high **energy**. High thrust combined with high energy is also needed for ST systems aimed at **landing** on atmosphereless celestial bodies (where atmospheric braking cannot be employed), or at **departing** from celestial bodies having significant levels of surface gravity, e.g., Moon, Mars.

The conclusions drawn in what follows are also valid for ST systems operating between space theaters in which gravity is in equilibrium, and where the thrust can be low, e.g., transfer from LEO to GEO. The difference is that whereas STs operating from gravity "wells" are dominated by the need for **thrust**, STs connecting gravityless theaters are driven by the **time** requirements for **transiting** between theaters.

As an illustration, it is obvious that the thrust required to lift from the Earth's surface must be higher than the vehicle's weight. This is because, if the thrust-to-weight ratio were less than unity, the vehicle would not lift, regardless of how much energy were to be contained in the propellant.

On the other hand, take-off from LEO, bound say for GEO, can occur at any thrust level. Low thrust levels merely imply lower accelerations, hence more time to reach the required  $\Delta v$ , thus longer time to effect the transfer. If the thrust is T Newtons and the vehicle's mass is M kilograms, the vehicle's acceleration a will be  $a = \frac{T}{M}$  meters/second. The velocity attained after t seconds will be  $\Delta v = at = \frac{T}{M} t$ . Attainment of the velocity increment of 3,000m/seconds needed to transfer from LEO to GEO will require a time of approximately  $3,000 \times \frac{M}{T}$  seconds. Say the thrust-to-weight ratio  $\frac{T}{M}$  were of order 1 (high thrust), the transit time would approximate 3,000 seconds or 50 minutes. If on the other hand the thrust-to-weight ratio were 0.01 (low thrust), the required transit time would be 300,000 seconds or 3.5 days. If this rather lengthy transit time were acceptable from the standpoint of the mission's objectives, significant advantages would accrue to the mission's performance. This is because, with current state-of-the-art, very high specific energy systems (e.g., electric propulsion) can be made, provided the thrust requirements be kept low. The corresponding mass ratios are considerably lower than for current propellants capable of high thrust-to-mass ratios, but which possess relatively limited specific energy levels.

#### D.8.2 DRIVERS OF SPACE TRANSPORTATION

In general, ST cost is dominated by:

- The **exchange ratio**, i.e., the lift-off weight required to place a given weight of payload in a given space theater, starting from the Earth's surface (or from an intermediate station, e.g., a LEO platform)
- The cost of the **support structure** required to contain the fuel, accommodate the payload, provide the thrust, supply the required guidance and control functions

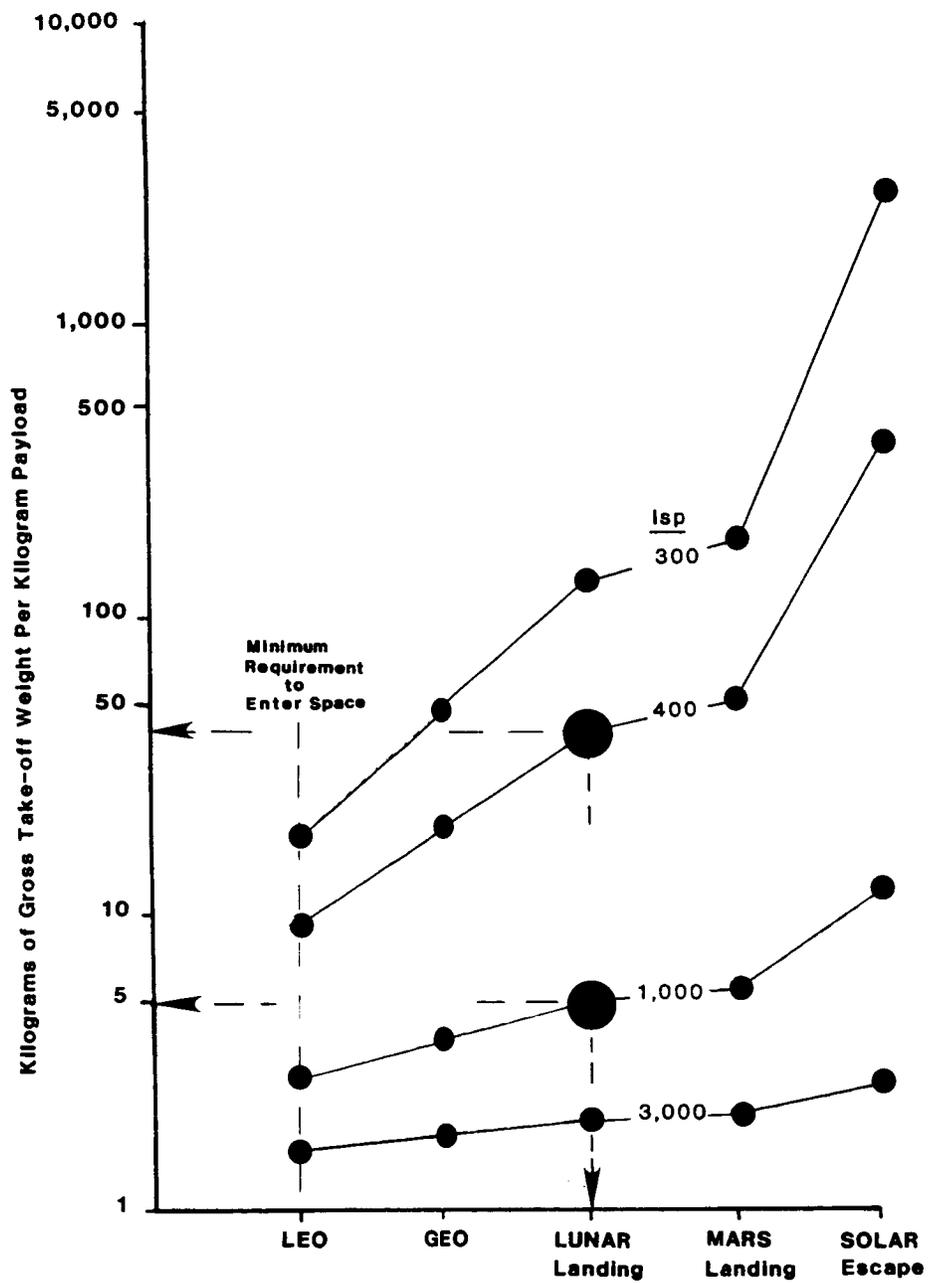
Figure 8-1 depicts representative **exchange ratios** for ST systems operating from the Earth's surface, as a function of the specific impulse of the propellant. The data reported in the Figure are based upon:

- State-of-the-art structural efficiencies (ratio of weight of fuel to weight of fueled lift-off structure exclusive of payload), of order 90%
- State-of-the-art thruster technology (available thrust engine efficiency) of order 95%

Tables 8-1 and 8-2 synopsise key **cost** parameters of current ST, in terms of dollars per kilogram of liftoff structure and dollars per kilogram of payload. These costs are exclusive of the costs of the payloads themselves and of the RDT&E effort involved in researching and developing the launch vehicle. They reflect the launch vehicle's manufacturing cost, including fuel and the cost of the launch services.

The data presented in Tables 8-1 and 8-2 indicate that:

- The costs of ST for expendable launch Vehicles (ELVs) split approximately equally between acquisition of the launch vehicle's **hardware** and the provision of launch **services**. Fuel costs are essentially negligible, approximately 1.5% of total ST costs, see Table 8-2.
- The current costs of ST launch vehicle structures range from **\$500** to **\$4000** per kilogram. By contrast, costs of large commercial aircraft are of order **\$140/kg**, including avionics and all other on-board equipment. Note that aircraft need be reusable numerous times, ELVs only once: moreover, aircraft reliabilities need be much higher than ELVs.



**Figure 8-1. Exchange Ratios as a Function of Space Theater, Technology and Propulsion**

TABLE 8-1

CHARACTERISTICS OF SPACE TRANSPORTATION SYSTEMS

VEHICLE	WEIGHTS, kg		STRUCTURAL EFFICIENCY, %	COSTS, (1983 \$) THOUSANDS <sup>a</sup>			SPECIFIC COSTS, \$/kg (1983)	
	STRUCTURE	FUEL		LAUNCH VEHICLE	FUEL	LAUNCH SERVICES	LAUNCH VEHICLE STRUCTURE	TRANSPORTING PAYLOAD TO LEO <sup>b</sup>
SCOUT G-1	3,300	18,133	84.6	\$3,400	\$90	\$3,250	\$1,030	\$38,500
ATLAS F	8,504	112,330	93	\$7,760	\$214	\$5,059	\$4,828	\$16,405
ATLAS CENTAUR	13,306	134,611	91	\$27,850	\$884	\$26,776	\$2,093	\$24,600
DELTA	20,464	168,829	93	\$10,313	\$379	\$14,308	\$504	\$9,900
SHUTTLE COLUMBIA	284,982	1,739,857	86	SEE TABLES 8-5, 8-6, AND FIGURE 8-2.				

<sup>a</sup> CY 1983--ESCALATION EXPECTED IN CY 1984

<sup>b</sup> LOW INCLINATION (>28°), LOW ALTITUDE (>500km)--INCLUDES COSTS OF VEHICLE, FUEL, LAUNCH SERVICES

TABLE 8-2

PERCENTAGE DISTRIBUTION OF SPACE TRANSPORTATION COST  
FOR EXPENDABLE LAUNCH VEHICLES

<u>VEHICLE</u>	<u>TOTAL COST THOUSANDS 1983 \$</u>	<u>PERCENTAGE ALLOCATION</u>		
		<u>VEHICLE</u>	<u>FUEL</u>	<u>LAUNCH SERVICES</u>
SCOUT G-1	6,740	50.4	1.4	48.2
ATLAS F	13,042	59.6	1.6	38.8
ATLAS CENTAUR	55,510	50.2	1.6	48.2
DELTA	25,000	41.3	1.5	57.2
SHUTTLE	SEE TABLES 8-5, 8-6 AND FIGURE 8-2			

- The **structural efficiencies** of ELVs--defined as the ratio of the weight of the fuel to the total weight of the lift-off structure, exclusive of payload--are currently, for the larger ELVs, of order 93%.

The latter point indicates that current ELV technology has approached a "saturation" or "**diminishing return**" situation, where further increases of structural efficiency portend only modest increases in the exchange ratio.

To quantify this point, Table 8-3 shows the **sensitivity** of the exchange ratio to improvements of structural efficiency. Comparison between Tables 8-1 and 8-3 leads to the conclusion that further improvement of current structural efficiencies would have only marginal benefits; at the most, they can lead to further increases of payload weight of an additional 10% over and above what can be accomplished currently with a given liftoff weight and fuel.

An important question is how advances of technology have affected the launch costs.

Table 8-4 exemplifies the historical **evolution** of (constant dollar) costs for the Scout Vehicle. This is a vehicle of ancient vintage, procured in periodic batches whose manufacturing can thus be expected to take advantage of improving manufacturing techniques and technology.

We notice that whereas the hardware costs have been reduced by 18% in 11 years--a compound yearly drop of 1.5%--the total ST cost has remained substantially the **same**. The decreased costs of the hardware have been made up by the augmented cost of the launch **services**, primarily the cost of the contracted engineering support and, to a lesser extent, of the government service personnel overhead. Similar conclusions apply to the other expandable launch vehicles.

TABLE 8-3

EFFECT UPON PAYLOAD WEIGHT OF INCREASING  
THE LAUNCH VEHICLE'S STRUCTURAL EFFICIENCY

<u>ISP</u>	<u>WHEN STRUCTURAL EFFICIENCY INCREASES FROM 93% TO</u>	<u>PAYLOAD INCREASES BY<sup>a</sup></u>
300	95% 100%	6% 16%
400	95% 100%	4% 14%
500	95% 100%	4% 12%
1,000	95% 100%	2.5% 6%

<sup>a</sup> FOR 28°, 500KM LEO

TABLE 8-4

HISTORICAL EVOLUTION OF LAUNCH COST FOR SCOUT  
(CONSTANT 1972 \$)

<u>ITEM</u>	<u>1969</u>		<u>1980</u>	
	<u>\$</u>	<u>%</u>	<u>\$</u>	<u>%</u>
HARDWARE ACQUISITION	1,357,655	47.11	1,115,555	34.81
LAUNCH SERVICE	23,040	0.80	13,167	0.47
RANGE SERVICE	400,402	13.89	258,571	9.22
ENGINEERING SUPPORT	830,476	28.82	932,676	33.27
ADMINISTRATION				
● DOD	18,385	0.64	22,427	0.80
● NASA	94,008	3.26	198,730	7.08
GOVERNMENT PERSONNEL OVERHEAD	43,997	1.59	171,917	6.13
<b>TOTAL</b>	<b>2,881,851</b>	<b>100.00</b>	<b>2,803,427</b>	<b>100.00</b>

The space shuttle presents a somewhat different situation than ELVs because of its significantly different operating characteristics--namely the fact that the shuttle is manned and reusable. Table 8-5 and Figure 8-2 show the space shuttle's costs by major elements as a function of the number of yearly flights; and present a detailed cost distribution for the expected 1985 scenario of 13 projected flights.

Note that the space shuttle costs are reduced significantly as a function of the number of yearly flights, up to approximately 18 to 20 flights per year. At higher traffic rates, the trend of cost reduction begins to slow.

The distribution of costs among the major cost elements as a function of flight frequency is shown in Table 8-6.

The assumptions underlying the NASA cost model shown in Tables 8-5 and 8-6 and Figure 8-2 are that the space shuttle's R&D and the four orbiter's manufacturing costs are sunk and not amortized, because of their continuing reusability. The hardware referred to includes only the recurring costs such as the costs associated with the external tank. The reduction in hardware costs as a function of flight frequency and time (compare Tables 8-5 and 8-6) are assumed due to "learning effect."

Note that the shuttle's split between launch vehicle and services costs is substantially similar to that for ELVs (approximately fifty-fifty). The difference is that the larger portion of the services is for mission operation support, which includes flight support, research, and project management costs.

#### D.8.3 NEAR AND MEDIUM-TERM TECHNIQUES AND TECHNOLOGIES

Reduction of the cost of ST is the major key to expanded space activities. Our analysis leads to the following findings:

TABLE 8-5

COST PER SHUTTLE FLIGHT (MILLION 1975 \$)<sup>a</sup>

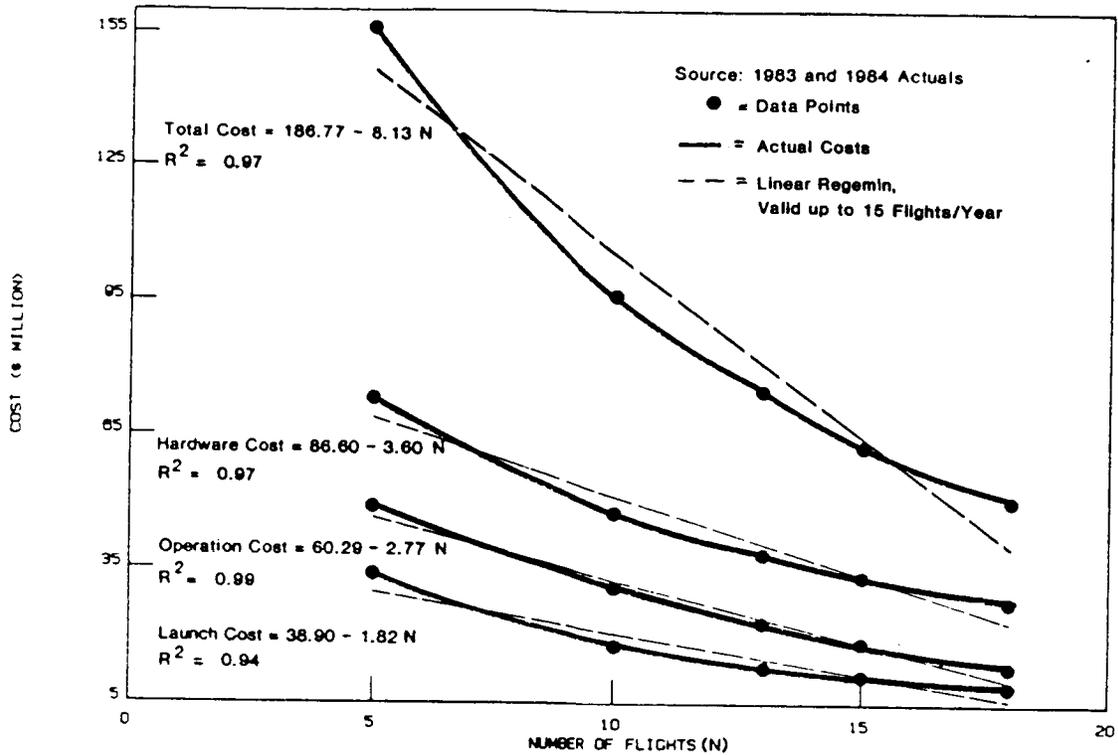
<u>ITEM YEAR</u>	<u>1983</u>	<u>1984</u>	<u>1985</u>	<u>1986</u>	<u>1987</u>	<u>1988</u>	<u>1989</u>	<u>1990</u>	<u>1991</u>	<u>1992</u>	<u>1993</u>	<u>1994</u>
<u>HARDWARE</u>												
● SOLID ROCKET BOOSTER	25.7	17.6	14.4	13.2	12.3	11.9	11.5	11.1	10.8	10.6	10.5	10.03
● EXTERNAL TANK	23.2	16.2	12.2	10.5	9.6	9.0	8.8	8.7	8.6	8.5	8.4	9.2
● GASE SPARES	2.0	1.0	0.8	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6
● ORBITER HARDWARE	16.0	8.6	7.4	6.0	5.0	4.2	4.3	4.1	4.0	4.8	3.7	2.7
● CREW EQUIPMENT	2.1	1.1	1.1	0.6	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
● MAIN ENGINE	3.6	2.9	2.2	2.0	1.9	1.4	1.4	1.4	1.4	0.6	0.4	0.4
<b>SUBTOTAL</b>	<b>72.6</b>	<b>47.4</b>	<b>38.1</b>	<b>33.0</b>	<b>30.0</b>	<b>27.5</b>	<b>27.0</b>	<b>26.3</b>	<b>25.8</b>	<b>25.5</b>	<b>24.0</b>	<b>23.6</b>
<u>LAUNCH</u>												
● LAUNCH OPERATION	31.0	15.5	11.9	10.1	10.8	8.5	8.5	8.5	8.5	8.5	8.5	8.5
● PROPELLANTS	2.0	1.5	1.1	1.0	1.0	0.8	0.7	0.7	0.7	0.7	0.7	0.7
<b>SUBTOTAL</b>	<b>33.0</b>	<b>17.0</b>	<b>13.0</b>	<b>11.1</b>	<b>11.1</b>	<b>9.3</b>	<b>9.2</b>	<b>9.2</b>	<b>9.2</b>	<b>9.2</b>	<b>9.2</b>	<b>9.2</b>
<u>OPERATION SUPPORT</u>												
● FLIGHT OPERATION	25.5	14.6	11.7	9.5	7.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
● NETWORK SUPPORT	0.9	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
● RESEARCH & PROJECT MANAGEMENT	22.1	15.4	10.5	8.0	6.5	5.7	5.7	5.7	5.7	5.7	5.7	5.7
<b>SUBTOTAL</b>	<b>48.5</b>	<b>30.5</b>	<b>22.6</b>	<b>17.8</b>	<b>14.7</b>	<b>12.8</b>						
<u>ADMINISTRATION</u>	1.1	0.8	0.6	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
<b>TOTAL</b>	<b>155.2</b>	<b>95.7</b>	<b>74.3</b>	<b>62.4</b>	<b>56.2</b>	<b>50.0</b>	<b>49.4</b>	<b>48.7</b>	<b>48.2</b>	<b>47.9</b>	<b>46.4</b>	<b>46.0</b>

<sup>a</sup> THE COST FIGURES EXCLUDE DEVELOPMENT AND MANUFACTURING COST OF ORBITER (BECAUSE REUSABLE) AND OF PAYLOAD

## ECONOMY OF SCALE

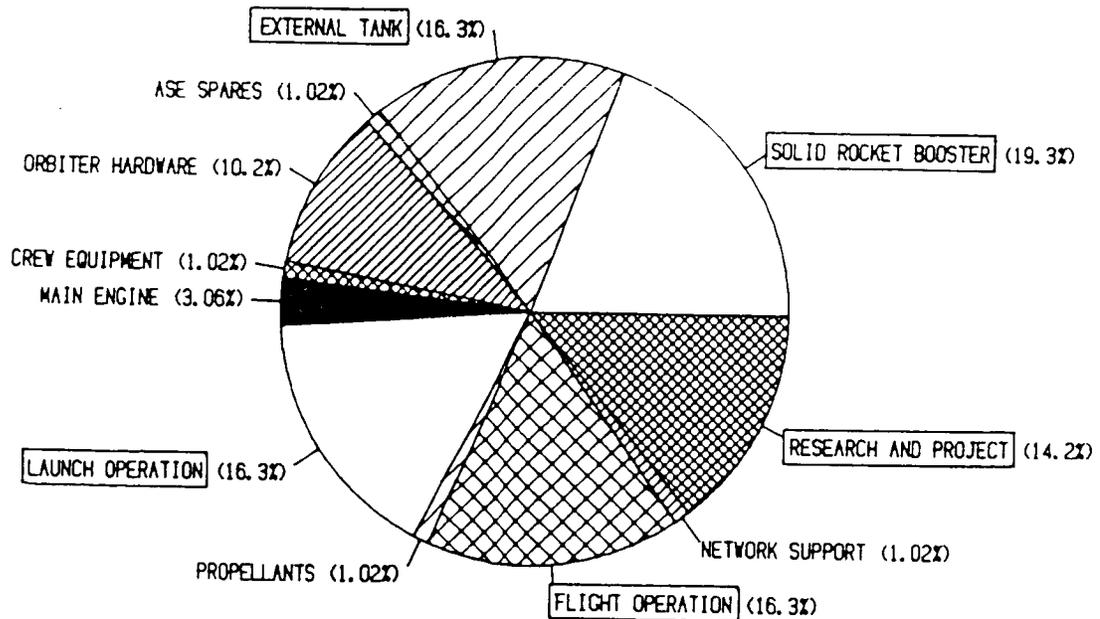
### Cost Per Shuttle Flight Versus Yearly Number of Flights

(1975 CONSTANT DOLLARS)



## COST DRIVERS

### Distribution of Total Shuttle Flight Cost (1985, 12 Flights/year)



**Figure 8-2. Orbiter Transportation Economics**

TABLE 8-6

PERCENTAGE DISTRIBUTION OF TOTAL COST FOR SHUTTLE FLIGHT<sup>a</sup>

<u>ITEM YEAR</u>	<u>1983</u>	<u>1984</u>	<u>1985</u>	<u>1986</u>	<u>1987</u>	<u>1988</u>	<u>1989</u>	<u>1990</u>	<u>1991</u>	<u>1992</u>	<u>1993</u>	<u>1994</u>
HARDWARE	46.77	49.53	51.28	52.88	53.38	55.0	54.65	54.00	53.53	53.24	51.72	51.30
LAUNCH	21.26	17.76	17.50	17.79	19.75	18.6	18.62	18.89	19.09	19.21	19.83	20.00
OPERATION SUPPORT	31.25	31.87	30.42	28.52	26.16	25.6	25.92	26.29	26.56	26.72	27.59	27.83
ADMINISTRATION	0.71	0.84	0.80	0.81	0.71	0.80	0.81	0.82	0.82	0.83	0.86	0.87
NO. OF FLIGHT	5	10	13	15	18	18	18	18	18	18	18	18

<sup>a</sup> EXCLUSIVE OF ORBITER DEVELOPMENT AND MANUFACTURING COSTS--ORBITER ASSUMED TO BE FULLY REUSABLE

1. The current costs of ST launch vehicle structures range from \$500 to \$4000 per kilogram. By contrast, costs of large commercial aircraft are of order \$140/kg, including avionics and all other on-board equipment. Note that aircraft need be reusable numerous times, ELVs only once.
2. The cost of the launch services is approximately as high as the cost of the launch vehicle's structures, including fuels.

These findings suggest areas of technique and technology concentration for achieving significant near-term advances in the utility of ST, without the need for "leapfrog" advances in the state-of-the-art:

1. Reduction of launch vehicle **structural** costs through improved fabrication technology and novel materials,

Note that the emphasis is **not** on **lighter** structures per se--because the structural efficiency is already so high as to be at the point of diminishing returns--but on **less expensive** structures.

2. Reduction of the cost of launch services through **automation** of service functions and use of innovative **management** techniques,
3. Reduction of launch vehicle **structural** and **launch services** costs through tradeoffs against mission reliability.

While the latter is not acceptable for those aspects of the space shuttle mission which affect astronaut safety, it should be considered for those aspects involved with only inanimate equipment, and with launches of free flyers from shuttle.

It is definitely worth considering for ELVs.

#### D.8.4 KEY ADVANCED TECHNOLOGIES

In seeking core ST technologies, our analysis of the utility requirements of ST leads to the following key finding:

- Further increases in **structural efficiency**, albeit important for other reasons, portend relatively modest increases in the **exchange ratio**. A major impact upon the exchange ratio is only possible by upgrading the propellant's **specific impulse**.

In the late 1950s and early 1960s, considerable research was expended in investigating high-energy propellants capable of also providing high-thrust. The "taming" of the LOH-LOX reaction and the advent of the "hydrogen technology" in the mid to late 1960s has led to a decline in this research on NASA's part.

Table 8-7 lists the theoretical characteristics of potential advanced propellants. These were drawn from a recent USAF survey of the field. Of the 26 technologies reviewed by the USAF, Table 8-7 lists the six which appear most practical for the 2005-2010 era.

TABLE 8-7

ADVANCED PROPELLANTS  
FOR HIGH-THRUST APPLICATIONS<sup>a</sup>

<u>NOMENCLATURE/COMPOSITION</u>	<u>STATUS</u>	<u>THEORETICAL ISP, SECONDS</u>	<u>PRINCIPAL CHALLENGES/REQUIREMENTS</u>	<u>PRINCIPAL RESEARCHER(S)</u>
FREE-RADICAL HYDROGEN	KNOWN	2,130	<ul style="list-style-type: none"> <li>o VERY LOW TEMPERATURES &lt;0.1K</li> <li>o ACHIEVEMENT OF HIGH DENSITIES</li> </ul>	PRINCETON, MIT, JPL
METALLIC HYDROGEN	EXISTENCE POSTULATED, NEEDS DEMONSTRATION	1,700	<ul style="list-style-type: none"> <li>o LOW TEMPERATURES, &lt;4K</li> <li>o HIGH PRESSURES, 1-10M BAR</li> <li>o STABLE STORAGE</li> </ul>	AMSTERDAM UNIVERSITY
METASTABLE HELIUM	KNOWN	3,150	<ul style="list-style-type: none"> <li>o SHORT LIFETIME, 2.5 HOUR THEORETICAL</li> <li>o SUPPRESSION OF SPIN-ORBIT DECAY COULD INCREASE LIFETIME TO 8 YEARS</li> </ul>	JPL
PULSE IMPLSION FUSION	EFFECT KNOWN, NEEDS TECHNOLOGY, ENGINEERING	6,330	<ul style="list-style-type: none"> <li>o RADIATOR TO REJECT HEAT</li> <li>o PRACTICAL IMPLSION METHOD</li> <li>o THRUST EXHAUST SYSTEM</li> </ul>	DOE, JPL
PULSE EXPANSION FUSION	EFFECT KNOWN, NEEDS TECHNOLOGY, ENGINEERING	> 10,000	<ul style="list-style-type: none"> <li>o RADIATOR TO REJECT HEAT</li> <li>o PRACTICAL MICROFUSION METHOD</li> </ul>	DOE, JPL
OZONE-ATOMIC HYDROGEN	KNOWN	3,000	<ul style="list-style-type: none"> <li>o STABLE STORAGE</li> <li>o INCREASED LIFETIME</li> </ul>	---

<sup>a</sup> SOURCE: U.S. AIR FORCE ROCKET PROPULSION LABORATORY, AFSTC

**D.9 ENERGY GENERATION FROM SPACE**

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## D.9 ENERGY GENERATION FROM SPACE

### D.9.1 SIGNIFICANCE

A commodity plentiful in Earth-orbital space is energy from the sun. With suitable choice of orbit, this energy could be made available to a spacecraft essentially 100% of the time. If it could be conveyed to Earth without losses, a capture area the size of the District of Columbia could supply all the world's electrical power needs.

Solar-powered satellites (SPS) have been proposed as sources of space-generated energy for use on Earth. Numerous implementations of SPS have been considered--in LEO, in GEO, SPS-to-central power stations, SPS directly to use. Analysis of terrestrial use requirements shows that the most practical deployment of SPS is in GEO and that energy transmission should occur from SPS to a central power station on Earth.

### D.9.2 SPS COST MODEL

The SPS utility/cost parameter is the price (dollars/kWh) of the energy conveyed to the terrestrial power central. The cost of an SPS system, like that of most industrial systems, can be subdivided into three categories:

- **Actuarial costs**, i.e., the amortization of the investment for constructing and deploying the space and ground portions of the system over the system's expected lifetime; and the cost of money, i.e., the interest on the investment.
- **Process costs**, i.e., the cost of the primary and auxiliary physical inputs. For SPS, the primary energy input is free.

- **Operating costs**, i.e., the costs of operating and maintaining the system.

Table 9-1 lists the principal economic studies related to the cost of energy from SPS.

The results reported in these studies depend critically upon three assumptions underlying the studies:

- Postulated decrease of the costs of future space transportation,
- Assumed progress in reducing the cost of solar collectors and solar-electrical converters,
- Hypothesized infrastructure for SPS transportation, deployment and maintenance. Assumptions made in the literature range from direct Earth-to-GEO launch, to transfer to GEO from logistic manned space station(s) sited in LEO, to lunar extraction of materials and moon-to-GEO launch.

In analyzing the SPS economics to arrive at its core enabling technologies, we have made use of a simplified, computerized model, which uses evolutionary state-of-the-art projections derived from OAST data. The model provides a calibration of the approximate costs of SPS-derived energy, shows how the costs can be expected to reduce with time, and projects when SPS might become economically practical.

The model takes into account the costs of constructing SPS and the costs of Earth-to-GEO transportation. It omits R&D costs, O&M costs, and costs involved in the construction and deployment of a supporting space infrastructure; accordingly, the model's results are optimistic.

TABLE 9-1

PRINCIPAL ECONOMIC STUDIES  
ON SOLAR POWER SATELLITES

<u>ORGANIZATION</u>	<u>YEAR</u>	<u>SCOPE</u>	<u>CONTENT</u>
MARSHALL SPACE FLIGHT CENTER	1979	CONCEPT DEFINITION	REFINES AND UPDATES REFERENCE SYSTEM CONCEPT, EVOLVES VIABLE SUBSYSTEMS.
MARSHALL SPACE FLIGHT CENTER	1979	COST MODEL DEVELOPMENT	PROVIDES ACCURATE AND RELIABLE ESTIMATES OF THE COSTS OF CERTAIN SPS ELEMENTS.
MARSHALL SPACE	1979	ECONOMIC FACTORS RELATING TO THE DEVELOPMENT AND IMPLEMENTATION OF THE SATELLITE POWER SYSTEM	EVALUATES IMPACT OF ECONOMIC FLIGHT CENTER EVALUATION METHODOLOGIES ON SPS CONCEPT SELECTION.
JOHNSON SPACE CENTER	1979	CRITIQUE, MODIFY, MAINTAIN REFERENCE SYSTEM	CRITIQUES ALL PARTS OF THE BASELINE SYSTEM, MODIFIES AND INTEGRATES LATEST SUPPORT STUDIES INTO THE SYSTEM.
JOHNSON SPACE CENTER	1979	REFINE SPACE CONSTRUCTION AND MAINTENANCE APPROACH AND CONSTRUCTION FACILITIES	ANALYZES AND REFINES CONSTRUCTION, FABRICATION, ASSEMBLY AND RELATED ACTIVITIES WHICH OCCUR IN LEO AND GEO ORBIT LOCATIONS AND AT THE RECTENNA SITE.
JOHNSON SPACE CENTER	1979	DEFINE INDUSTRIAL AND EARTH TRANSPORTATION COMPLEX	DEFINES INDUSTRIAL AND EARTH-BASED TRANSPORTATION REQUIREMENTS IMPOSED ON THE U.S.; IDENTIFIES EXPANSION IN PRODUCTION CAPABILITY AND CREATION OF NEW INDUSTRY TO SUPPORT SPS.
JOHNSON SPACE CENTER	1979	COST ANALYSIS AND SCHEDULE ANALYSIS	PERFORMS A TOTAL COST ANALYSIS INCLUDING UPDATING AND INTEGRATING IDENTIFIABLE AND ACCESSIBLE ELEMENTS, COST FLOW REQUIREMENTS WITH TIME, AND DECISION MILESTONES.
MARSHALL SPACE FLIGHT CENTER	1979	SPS CRITICAL MATERIALS ASSESSMENT	DEVELOPS INFORMATION BASE FOR SELECTING MATERIALS FOR THE SPS.
SCIENCE APPLICATIONS INCORPORATED AND HERBERT E. KIERULFF, JR.	1978	FINANCIAL/MANAGEMENT SCENARIOS	ASSESSES ALTERNATIVE FINANCIAL MANAGEMENT SCENARIOS TO DEVELOP AND OPERATE THE SPS.
INTERNATIONAL TECHNICAL SERVICES	1978	INTERNATIONAL ORGANIZATIONS	EVALUATES THE ADVANTAGES OF DEVELOPING AN INTERNATIONAL ORGANIZATION TO MANAGE AND FINANCE THE SPS.
ARGONNE NATIONAL LABORATORY AND HARZA ENGINEERING	1978	SPS UTILITY INTEGRATION	PROVIDES A REVIEW OF UTILITY SYSTEMS THAT COULD EMPLOY SPS POWER AND DETERMINES THE PROBLEMS OF SPS INTEGRATION INTO THE UTILITY SYSTEMS.
ARGONNE NATIONAL LABORATORY	1979	ALTERNATIVES CHARACTERIZATION-COST	PLACES VARIOUS COSTS ON A SOMEWHAT UNIFORM BASIS AND PROVIDES A CONSISTENT TRACEABLE COST DATA SET FOR COMPARISON.
ARGONNE NATIONAL LABORATORY	1979	COMPARATIVE EVALUATIONS-COSTS AND PERFORMANCE	ENABLES COMPARISONS OF COSTS OF ENERGY OF THE SPS WITH ALTERNATIVE ENERGY SOURCES AND THEIR EFFECTIVENESS IN AN ELECTRIC UTILITY SYSTEM.

Tables 9-2 and 9-3 show the model's structure and its assumptions. The assumed development scenario is: 1) deployment of a 1MW prototype (approximately 10,000m<sup>2</sup> collector area) in ten years (1994); 2) deployment of an industrial-scale facility ranging between 1MW and 1GW ten years later (2004).

Use of the model yields the following principal conclusions:

1. Current costs of coal-fired electric generation, including costs of fuel and amortization of the central generating plant, run on the order of \$0.01 to \$0.02/kWh. Fuel costs account for \$0.0075 to \$0.01; the remainder are attributable to amortization of facilities. (The current industrial sales price of electric energy, of order \$0.06 to \$0.08/kWh, includes the amortization of the distribution network. This would also apply to SPS-generated energy.)
2. In constant dollars (not accounting for inflation), these costs are not expected to rise significantly in the future, because of the ample availability of coal in the U.S.
3. For the postulated family of SPS, the computed costs of electric energy (\$1 per kWh) at the power central on Earth are these:

	<u>1994</u>	<u>2004</u>
PROTOTYPE (1MW)	13.33	--
INDUSTRIAL SCALE		
10MW	--	4.24
100MW	--	2.38
1GW	--	1.34

TABLE 9-2

ASSUMPTIONS USED FOR SPS COST MODEL  
IN 1984 DOLLARS

ITEM	SYMBOL	EXPERIENCE		OAST FORECAST	VALUE USED IN MODEL
		1970	1984		
COST OF SOLAR COLLECTORS, SPACE-RUGGEDIZED, \$/m <sup>2</sup>	C <sub>c</sub>	100,000	50,000	35,000	\$50,000 IN 1984
HISTORICAL COST DECREMENT FACTOR, 1/year	b	0.95	0.95	0.95	0.95
WEIGHT OF SOLAR COLLECTORS, SPACE USABLE, kg/m <sup>2</sup>	W	17	1.7	0.8	1.7 IN 1984
HISTORICAL WEIGHT DECREMENT FACTOR, 1/yr	d	0.85	0.9	0.9	0.9
WEIGHT RATIO STRUCTURE/COLLECTOR	k				0.35
COST OF STRUCTURE, \$/kg	C <sub>1</sub>	700	500		\$500 IN 1984
WEIGHT RATIO (CONVERTER + PLUS STRUCTURE) (COLLECTOR)	a				0.2
COST OF CONVERTERS & ASSOCIATED STRUCTURE, \$/kg	C <sub>2</sub>	6,000	3,000		\$3,000 IN 1984
COST OF EARTH-GEO TRANSPORTATION, \$/kg	C <sub>3</sub>	20,000	8,000		\$8,000 IN 1984
HISTORICAL TRANSPORTATION COST DECREMENT FACTOR	f	0.94		0.94	
LIFE OF SPS, YEARS	T	7	10	15	20 (OPTIMISTIC)
INTEREST RATE, PERCENT	I				10
SYSTEM EFFICIENCY, END-TO-END, PERCENT	n	5	8	10	10
ENERGY UTILIZATION FACTOR (AVERAGE-TO-PEAK)	u		0.45		0.50 (OPTIMISTIC)
ENERGY LEVELIZATION FACTOR	h			0.625	0.625
ECONOMY OF SCALE FACTOR	S		0.66 to 0.85		0.75 (TYPICAL INDUSTRY)

TABLE 9-3

LOGIC OF SPS ENERGY COST MODEL

● <u>WE INITIALLY COST OUT A PROTOTYPE SPS (SOLAR COLLECTOR AREA 10,000 m<sup>2</sup>, USEFUL OUTPUT APPROXIMATELY 1 MW)</u>	
COST OF COLLECTOR, 1984	10,000 C <sub>c</sub>
WHERE C <sub>c</sub> = UNIT COST OF SOLAR CELLS IN 1984, \$/m <sup>2</sup>	
COST OF COLLECTOR STIFFENING STRUCTURE, 1984	10,000 WkC <sub>1</sub>
WHERE C <sub>1</sub> = UNIT COST OF STRUCTURE, \$/kg	
W = UNIT WEIGHT OF COLLECTOR, kg/m <sup>2</sup>	
k = WEIGHT RATIO STRUCTURE/COLLECTOR	
COST OF DC/MICROWAVE (OR LASER) CONVERTER PLUS SUPPORTING STRUCTURE, 1984	10,000 WaC <sub>2</sub>
WHERE C <sub>2</sub> = UNIT COST OF CONVERTERS & STRUCTURE, \$/kg	
a = WEIGHT RATIO (CONVERTERS PLUS STRUCTURE)/(COLLECTOR)	
TOTAL COST OF SPS HARDWARE, 1984, C <sub>H</sub>	C <sub>H</sub> = 10,000 x (C <sub>c</sub> + WkC <sub>1</sub> + WaC <sub>2</sub> )
WEIGHT OF SPS HARDWARE, 1984, W <sub>H</sub>	W <sub>H</sub> = 10,000 x W x (1 + k + a)
COST OF EARTH-GEO TRANSPORTATION, 1984, C <sub>T</sub>	C <sub>T</sub> = W <sub>H</sub> C <sub>3</sub>
WHERE C <sub>3</sub> = UNIT COST OF SPACE TRANSPORTATION, \$/kg	
TOTAL CAPITAL INVESTMENT, 1984, C <sub>TOT</sub>	C <sub>TOT</sub> = C <sub>H</sub> + C <sub>T</sub>
● <u>WE PROJECT THE REDUCTION OF COSTS AND WEIGHTS WITH TIME</u>	
FUTURE COST OF SPS HARDWARE, C' <sub>H</sub>	C' <sub>H</sub> = C <sub>H</sub> b <sup>t</sup>
WHERE b = HISTORICAL YEARLY COST DECREMENT FACTOR	
t = TIME IN YEARS FROM 1984	
FUTURE WEIGHT OF SPS HARDWARE, W' <sub>H</sub>	W' <sub>H</sub> = W <sub>H</sub> d <sup>t</sup>
WHERE d = HISTORICAL YEARLY WEIGHT DECREASE FACTOR	
FUTURE COST OF EARTH-GEO TRANSPORTATION, C' <sub>3</sub>	C' <sub>3</sub> = C <sub>3</sub> f <sup>t</sup>
WHERE f = HISTORICAL COST DECREASE FACTOR	
FUTURE TOTAL CAPITAL INVESTMENT	C' <sub>TOT</sub> = C' <sub>H</sub> + W' <sub>H</sub> C' <sub>3</sub>
FUTURE YEARLY ACTUARIAL COST, C' <sub>A</sub>	C' <sub>A</sub> = C' <sub>TOT</sub> x ( $\frac{1}{T} + i$ )
WHERE T = SPS LIFE, YEARS	
i = INTEREST RATE, FRACTION	
● <u>WE CALCULATE THE AVERAGE ENERGY (kWh/YEAR) DELIVERED BY SPS PROTOTYPE</u>	
WHERE 1.36 = SOLAR CONSTANT, kWh/m <sup>2</sup>	E <sub>A</sub> = 10,000 x 1.36 x n u x 8760 x h
n = OVERALL SYSTEMS EFFICIENCY	
u = UTILIZATION FACTOR OF ENERGY ON EARTH	
8760 = NO. HOURS IN ONE YEAR	
h = SOLAR CELL LEVELIZATION FACTOR <sup>a</sup>	
● <u>WE COMPUTE THE FUTURE ACTUARIAL COST OF ENERGY FROM THE PROTOTYPE SPS, \$/kWh</u>	
	C' <sub>E</sub> = $\frac{C'_A}{E_A}$
● <u>WE ASSESS THE COST REDUCTIONS FROM ECONOMY OF SCALE OF LARGER SPS</u>	
ACTUARIAL FUTURE COST OF ENERGY FROM LARGE SYSTEMS, \$/kWh	C' <sub>E</sub> <sup>n</sup> = $\frac{C'_A}{10,000} (S-1)$
WHERE A = COLLECTION AREA OF LARGE SYSTEMS	
S = SCALE FACTOR FOR ECONOMY OF SCALE	
<sup>a</sup> TAKES INTO ACCOUNT PROGRESSIVE DEGRADATION OF SOLAR CELL OUTPUT DURING LIFETIME	

4. The capital investments required to implement industrial SPS systems, circa 2004, break down as follows:

<u>SPS SYSTEM</u>	<u>CAPITAL INVESTMENT IN 2004</u>	
	<u>\$ MILLION (1983)</u>	
	<u>HARDWARE</u>	<u>SPACE TRANSPORTATION</u>
10MW	1,040	42
100MW	5,818	237
1GW	32,720	1,333

5. The key enabling technologies of SPS are **cost reductions** of space-hardened **solar converter** production and of space **transportation**. Should the costs of space transportation decrease as assumed in the model, the key to practicality of a photovoltaic SPS is reduction of solar collector costs and weights. In order to compete with the coal-fired electric energy cost of order \$0.02/kWh by 2004, the cost of space-hardened solar cells would need to drop to approximately 1/100 of its current level, i.e., by a yearly compound decrement of 0.8 compared to the 0.95 currently experienced. Should the current rate of technological progress be maintained, the era of practical **realization** of a photovoltaic SPS would begin circa **2040-2050**.
6. In net, assuming that space-hardened solar cell technology will continue to evolve at the current pace, practical **realization** of a photovoltaic SPS lies beyond the time frame of this study, i.e., **beyond 2010**.
7. Analogous conclusions apply to SPS systems employing thermodynamic conversion.