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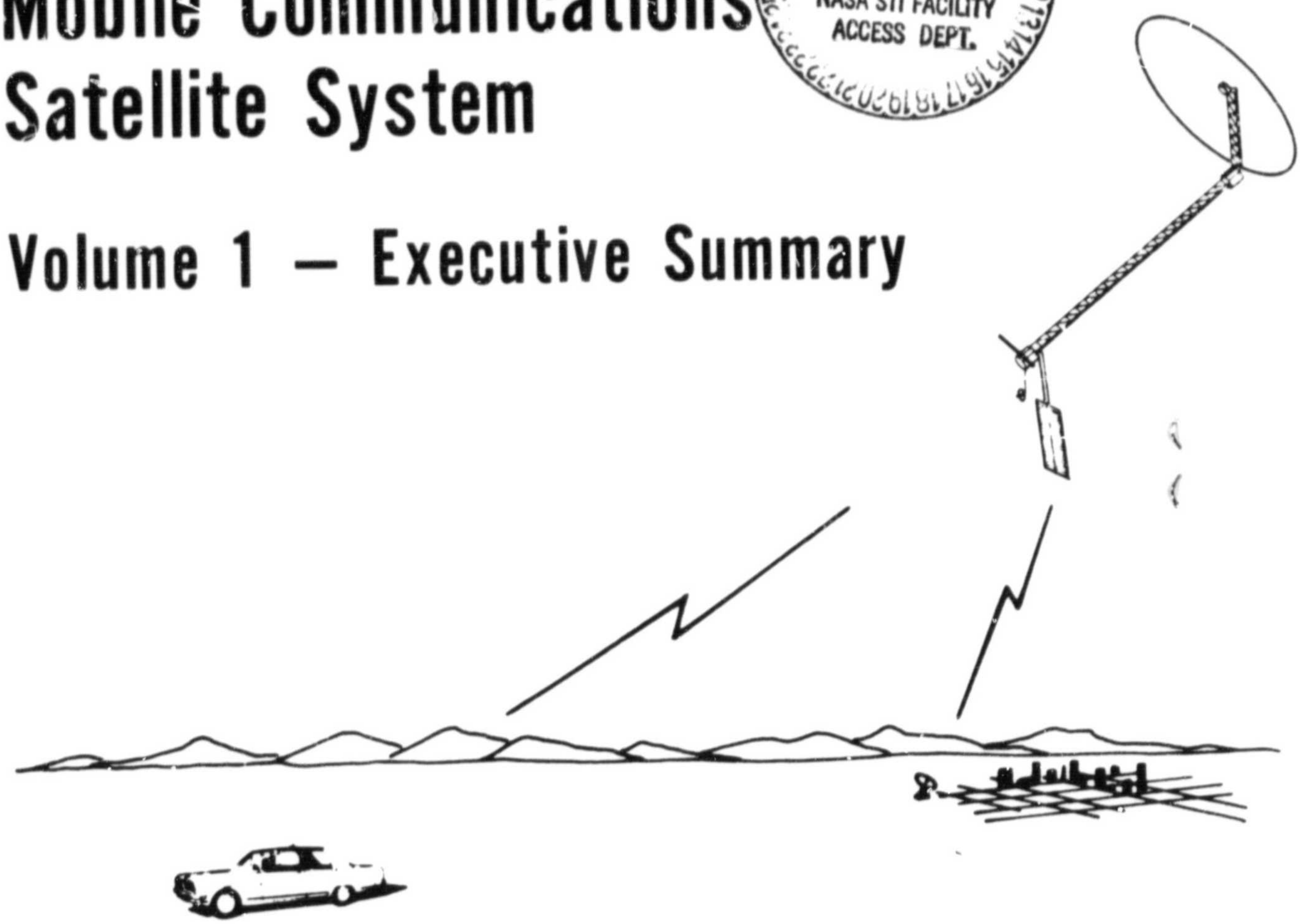
Requirements for a Mobile Communications Satellite System

Volume 1 — Executive Summary



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16. Abstract

Three types of satellite-aided mobile communications are considered for users in areas not served by (terrestrial) cellular radio systems. In System 1, mobile units are provided a direct satellite link to a gateway station, which serves as the interface to the terrestrial toll network. In System 2, a terrestrial radio link similar to those in cellular systems connects the mobile unit to a translator station; each translator relays the traffic from mobile units in its vicinity, via satellite, to the regional gateway. It is not feasible for System 2 to provide ubiquitous coverage. Therefore, System 3 is introduced, in which the small percentage of users not within range of a translator are provided a direct satellite link as in System 1.

While System 2 can operate with leased satellite capacity, Systems 1 and 3 require a dedicated satellite. A major portion of this study is concerned with the design of a satellite for System 1. A weight limit of 10,000 lbs, corresponding to the projected 1990 STS capability, is imposed on the design. Frequency re-use of the allocated spectrum, through multiple satellite beams, is employed to generate the specified system capacity. Both offset-fed and center-fed reflectors are considered. For an assumed 10-MHz allocation and a population of 350,000 subscribers, a two-satellite system is required. The reflector diameters corresponding to offset-fed and center-fed geometries are 46 m and 62 m, respectively. Thus, large-space-structure technology is inherent to the implementation of System 1.

In addition to establishing the technical requirements for the three types of satellite systems, the monthly service charge needed to provide a specified return on invested capital is computed. A net present value analysis is used for this purpose.

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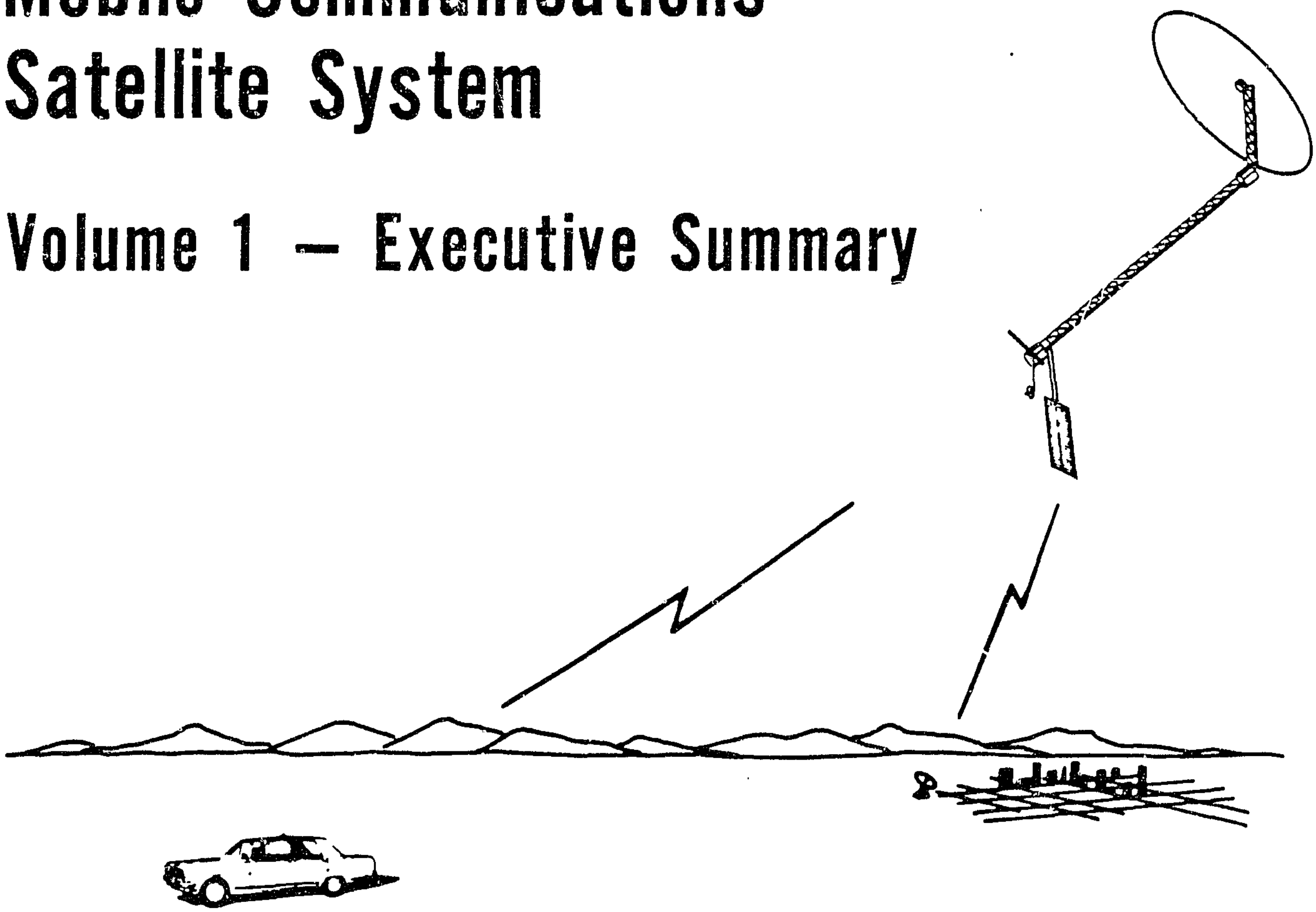

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1. INTRODUCTION

Current mobile radio-telephone service in the United States is extremely poor, primarily because of the limited amount of frequency spectrum allocated to this service. As a consequence, there are long waiting lists in metropolitan areas for service. Furthermore, mobile users typically experience long delays in placing calls. Finally, even where the grade of service is acceptable, the quality of reception may be unsatisfactory.

In an attempt to alleviate this situation, the Federal Communications Commission (FCC) has allocated a pair of 20-MHz UHF bands to a new type of mobile radio-telephone service, referred to as "cellular" radio (Reference 1). More specifically, 825-845 MHz is reserved for mobile transmit and 870-890 MHz for mobile receive. Frequency re-use of the indicated bands is made possible by (1) subdivision of each area served into cells, and (2) subdivision of the set of carrier frequencies available from the 20-MHz allocation into several subsets. By restricting communication within each cell to a single frequency subset and limiting transmit power levels, use of the same frequency subset in a number of different cells is made possible. In this way, a substantially higher system capacity than is suggested by the 20-MHz allocation can be achieved.

It is estimated that the Standard Metropolitan Statistical Areas (SMSAs) served by cellular radio will constitute 10 percent of the land area of the U.S.; the inhabitants thereof, 60 percent of the population (Reference 2). This would leave 90 percent of the land mass and 40 percent of the population unprovided for.

Three types of satellite systems are considered for the purpose of serving mobile users in rural areas and beyond, where a cellular system is not practical. In the first, referred to as System 1, direct mobile-to-satellite transmission links are established, as shown in Figure 1. A gateway station provides the necessary interface with the switched telephone network (STN). The remainder of the circuit between the mobile vehicle and a "land user" (i.e., a non-mobile user) is completed via an appropriate path through the STN. It is anticipated that a number of gateways will provide different points of entry to the STN.

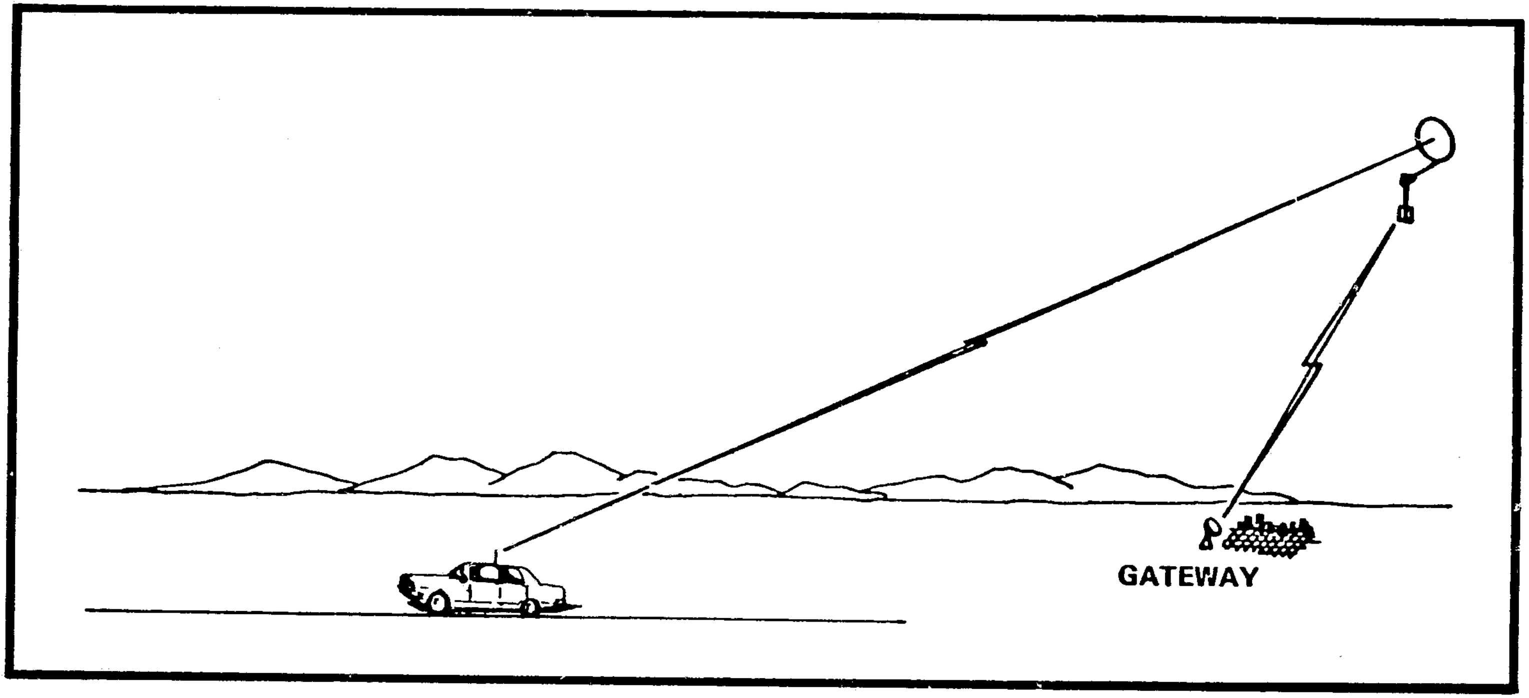

Figure 1. System 1 Configuration

A certain number of calls will be of the mobile-to-mobile variety. In the absence of satellite switching, each mobile user will be able to access the STN only through a single gateway. If the two mobiles involved in a call are provided connections to the same gateway, the circuit can be turned around in the gateway and need never enter the STN. If the mobiles are served by different gateways, the circuit must include a terrestrial portion between the two gateways. In either event, two satellite "hops" are required to complete the circuit.

The 1979 World Administrative Radio Conference (WARC) allocated the 806-890 MHz band to land-mobile satellite service (LMSS). These frequencies are intended for the link between the satellite and the mobile vehicle. Should the FCC decide to allocate a portion of this band to LMSS within the U.S., substantial capacity could be generated through a system of frequency re-use analogous to that used in cellular systems. Multiple spot-beam coverage of the contiguous U.S. (CONUS) (Figure 2) can be provided through use of a large satellite antenna. If the full complement of carrier frequencies derived from the allocated band is divided into subsets, with each beam restricted to use of a single subset, a system of frequency re-use is established.

Any of the "fixed-satellite" frequency bands can be used for the links between the satellite and the gateway stations. Both C-band and Ku-band have the requisite characteristics for these links: ample bandwidth and rain attenuation that is not excessive. The more likely choice is Ku-band, because of lower utilization of the geostationary arc in this band.

As suggested in Figure 2, each gateway might typically provide the terrestrial interface for users in an area covered by 7 UHF beams. Accordingly, 12 gateways would be required for the beam pattern shown.

In System 2, mobile-unit transmissions follow a terrestrial path to a "translator" station (Figure 3). The translator concentrates the traffic from mobile units in its coverage area and relays this traffic through a satellite to a gateway station.

Transmission between mobile unit and translator is virtually identical to that between mobile unit and base station in a cellular system. In fact, the coverage areas of individual translators can be viewed as direct

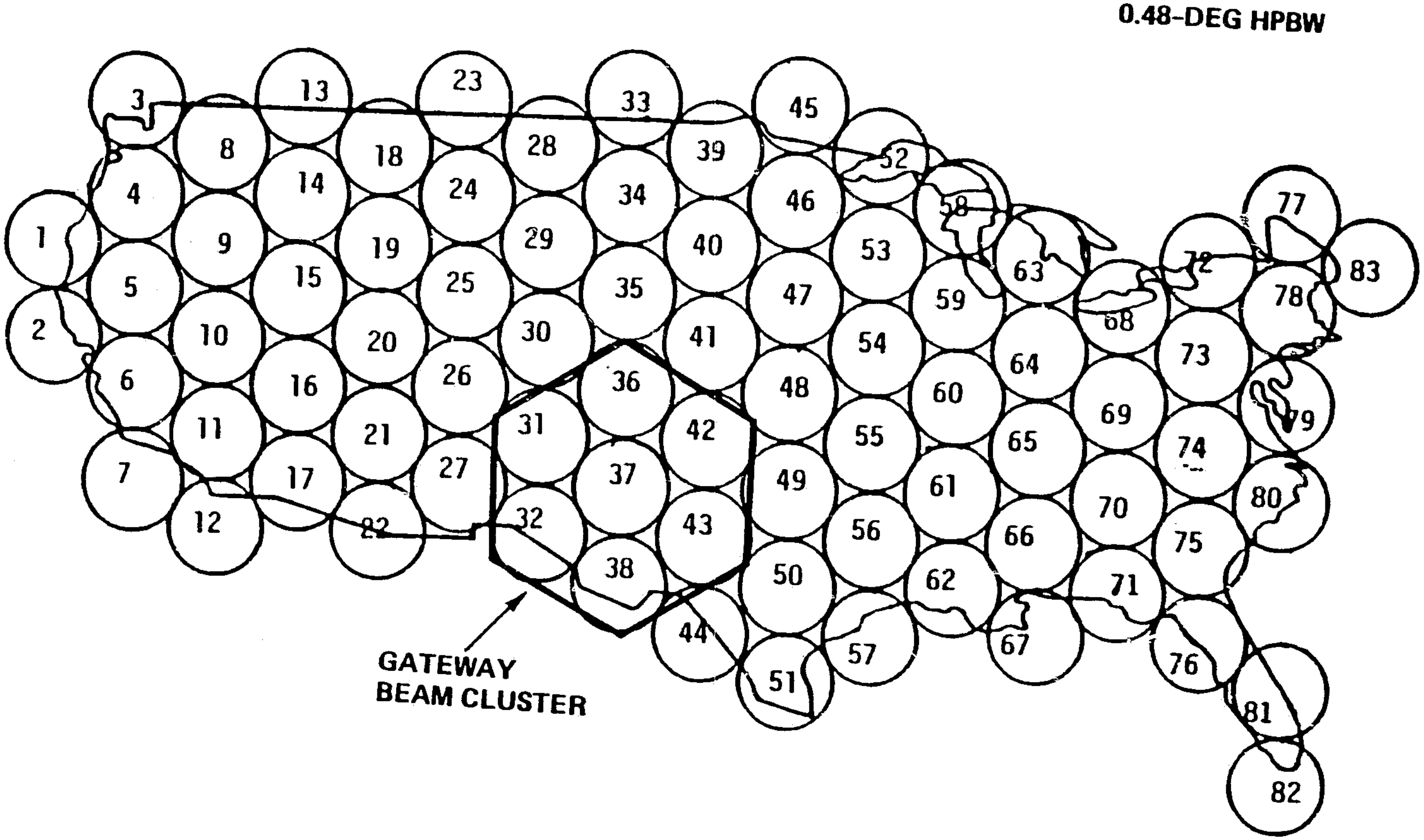

Figure 2. Typical CONUS-Coverage Beam Pattern

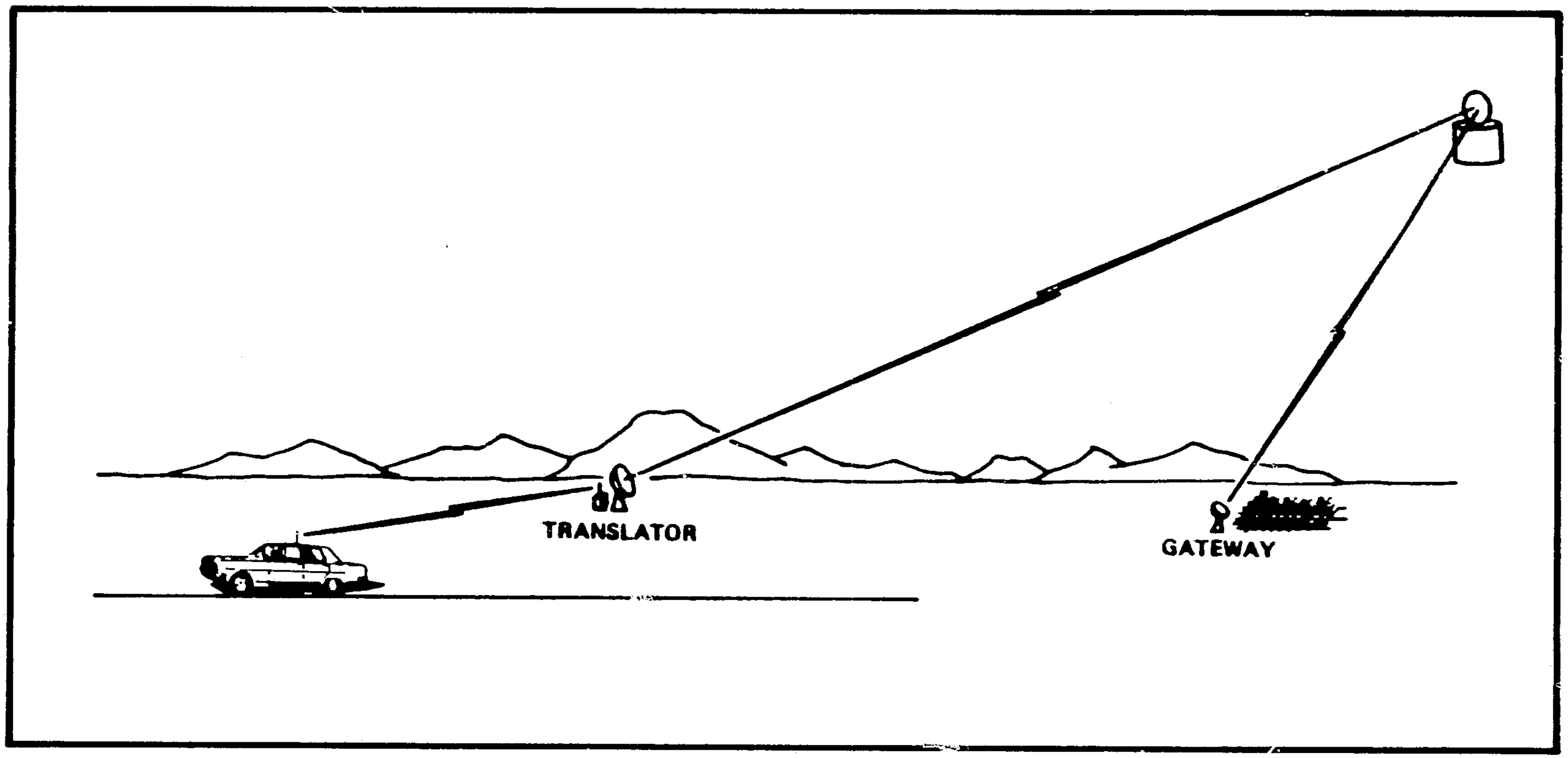

Figure 3. System 2 Configuration

extensions of the SMSA cell systems. Thus, the mobile units would use the same pair of 20-MHz allocations currently allocated to cellular use.

The distinction between System 2 and cellular systems lies in the translator/gateway link. The cellular systems use land lines to establish this connection. Land lines would be impractical for the distances encountered in a system covering much of CONUS. For example, with a dozen gateway stations, the typical translator/gateway distance is several hundred miles. Satellite links are therefore used for translator/gateway transmission.

Transmission in the gateway-to-translator direction is of the point-to-multipoint type. This transmission can be conducted at any of the fixed-satellite frequency allocations. Moreover, since standard domestic satellites can be used for this purpose, leased capacity can be used in place of a dedicated satellite. As a result, most of the System 2 cost is in the ground segment. This situation contrasts with System 1, in which the space segment cost is dominant.

The attractiveness of System 2 depends on the portion of CONUS that can profitably be served by translator stations. (System 1 coverage, by contrast, is universal.) Profitable coverage of a region by a set of translators depends on the range of an individual translator, because of the large fixed (i.e., channel-independent) component of translator cost. Much of this fixed cost lies in the tower, which is assumed to have a height of 500 feet, and in the satellite-related RF hardware.

Because System 2 cannot be expected to provide complete CONUS coverage, a variant of this configuration, called System 3, is introduced. This is a hybrid system, in which System 2 service is supplemented by direct satellite links to subscribers in the uncovered portions of CONUS (Figure 4). Because of the latter group of subscribers, a dedicated satellite is required.

To minimize the satellite requirements, these additional users, while mobile in nature, communicate only while at rest. (The associated equipment is referred to as a transportable unit, rather than a mobile unit.)

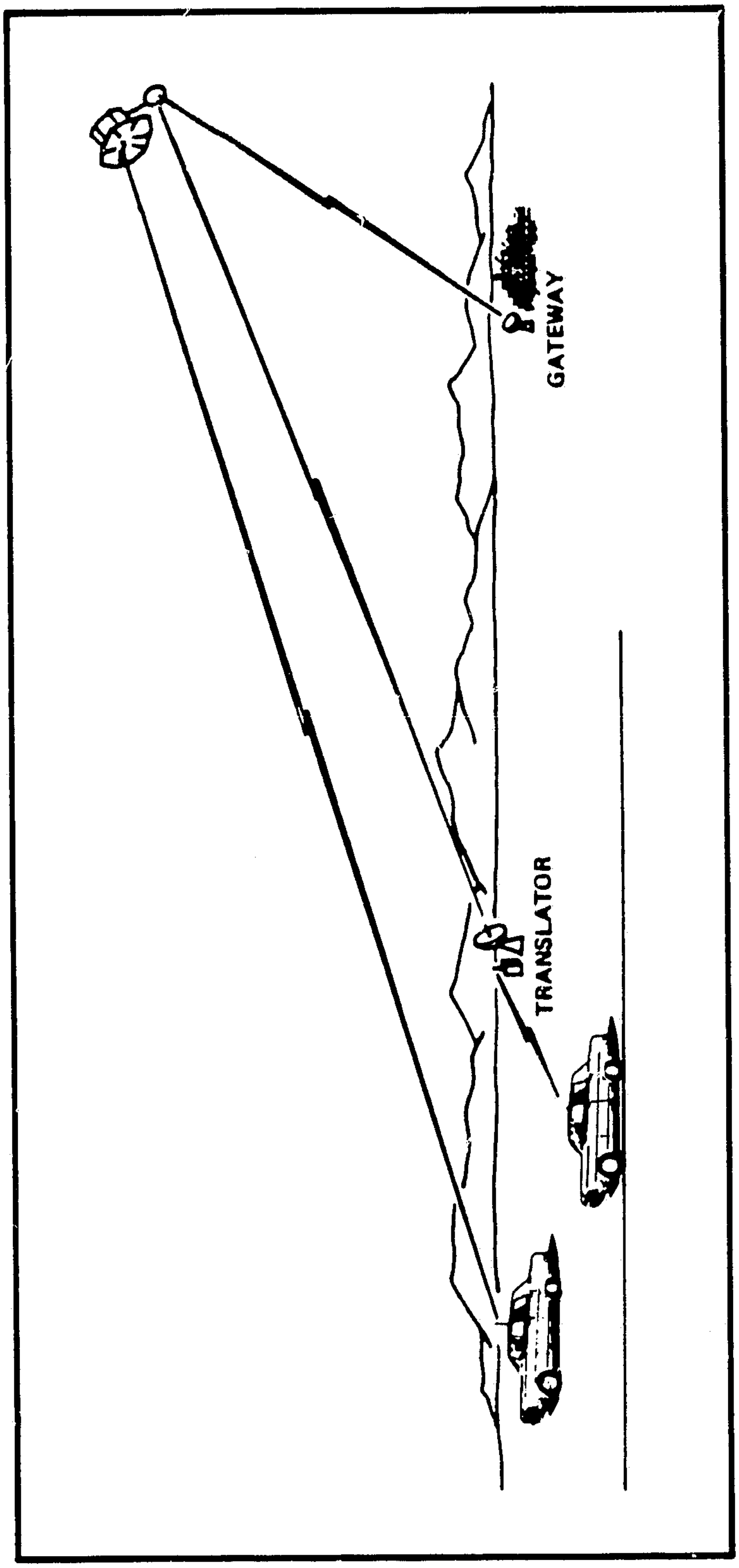

Figure 4. System 3 Configuration

This restriction allows the user to set up for transmission by deploying an antenna that would not be suitable for a moving vehicle. The added gain thereby achieved reduces the required satellite effective-isotropic-radiated-power (EIRP).

The dedicated satellite of System 3 greatly increases the space-segment cost over that associated with System 2. Moreover, the number of transportable users is expected to be a small fraction of the number of mobile users. Were the transportable users made to bear the full brunt of this added cost (by fixing the service charge for mobile users at the value found for System 2), the charge imposed on the transportable users would be prohibitive for most prospective subscribers.

The alternative is to raise the mobile-user monthly service charge (MSC) and use the surcharge to subsidize the transportable service. In the extreme, if the same MSC should be imposed on both classes of user, the mobile user charge would exceed the MSC for System 2 by more than 50 percent. The benefits derived from the ubiquitous service provided by System 3 must be weighed against the additional charge that must be borne by the mobile users.

In addition to the MSC, a subscriber to any of the three systems must bear two additional costs. The first of these is the per-call charge to establish the circuit portion between the gateway and the toll office nearest the land user. With eight gateways (the number in one of the two System 1 baselines), the length of this terrestrial link is typically 400 miles. For a subscriber that incurs charges for an average of 10 minutes a day,* 20 days a month, at an assumed rate of 40 cents per minute, the monthly STN charge would be $80.

*A market survey performed by Arthur D. Little, Inc. indicates that, for cellular radio, the average number of calls expected per day is 5.7. The average call duration is expected to be 2.5-3.0 minutes, although the average for current mobile radio is only 1.6 minutes (Reference 3).

The final cost to the user is that associated with the mobile unit. This equipment may be either purchased or leased. In the latter event, the lease charge may be incorporated in the MSC. It should be emphasized that, in this study, the MSC is defined not to include the cost of the mobile unit.

While this study deals only with mobile radio-telephone, it is well recognized that other market segments exist for mobile radio service in non-urban areas. Three distinct market segments can be identified: mobile radio-telephone, commercial and public radio, and new services. In the latter category, two important sub-segments are the oil and gas industry and the intercity trucking industry. Public radio includes a number of "dispatch" applications.

A satellite designed for LMSS would be transparent to the specific service provided. To determine the economic viability of a land-mobile satellite system intended to service a variety of market segments, the non-telephone traffic and associated revenue must be taken into account.

It is reasonable to assume that a higher tariff per-minute-of-channel-occupancy would be imposed for non-telephone services than for telephony. Depending on the traffic ratio for these two categories, a significantly lower MSC for radio-telephone users could result from inclusion of non-telephone traffic. Thus, the MSC computed in this study should be regarded as an upper limit on the rate that would have to be charged in a mixed-traffic environment.

2. SYSTEM 1

Development of the System 1 baseline designs proceeded in stages. At first, an attempt was made to configure a system which satisfies the following constraints: (1) a pair of 10-MHz exclusive allocations to LMSS, (2) cellular-compatible modulation, and (3) a satellite design capable of accommodating an end-of-life (EOL) population of 180,000 voice subscribers. The latter population corresponds to the "baseline" subscriber scenario.

The basis for the frequency-allocation assumption is the original NASA petition to the FCC requesting the change in allocation depicted in Figure 5. The proposal called for a 6-MHz shift in the cellular allocations, coupled with new, contiguous 10-MHz bands for LMSS. A mobile unit that operates interchangeably with either system would be designed for composite 30-MHz transmit and receive bands.

For a mobile transceiver to be compatible with cellular-system operation as well as LMSS, the same modulation format would have to be used in both systems. Cellular systems employ narrowband FM, with 12-kHz peak deviation. The corresponding carrier spacing is 30 kHz.

For an assumed 0.026-erlang contribution per user during the busy hours, 180,000 subcribers produce a total traffic load of 4680 erlangs. The traffic capacity of a single satellite beam is determined by three factors: (1) frequency allocation, (2) carrier spacing, and (3) number of frequency sets that must be employed to limit interbeam co-channel interference. The value of the latter parameter was taken as 4; this was shown to be sufficient for an offset-fed satellite reflector. It was further assumed, during the initial study phase, that the subscriber population is uniformly distributed over CONUS. Accordingly, the required number of satellite beams is found by dividing the total system traffic load by the single-beam capacity.

The satellite weight bears a close relationship to the size of the reflector. The reflector diameter, in turn, increases as the square root of the required number of beams. It follows that a limitation on the single-beam capacity due to any of the three factors listed above places a floor under the satellite weight.

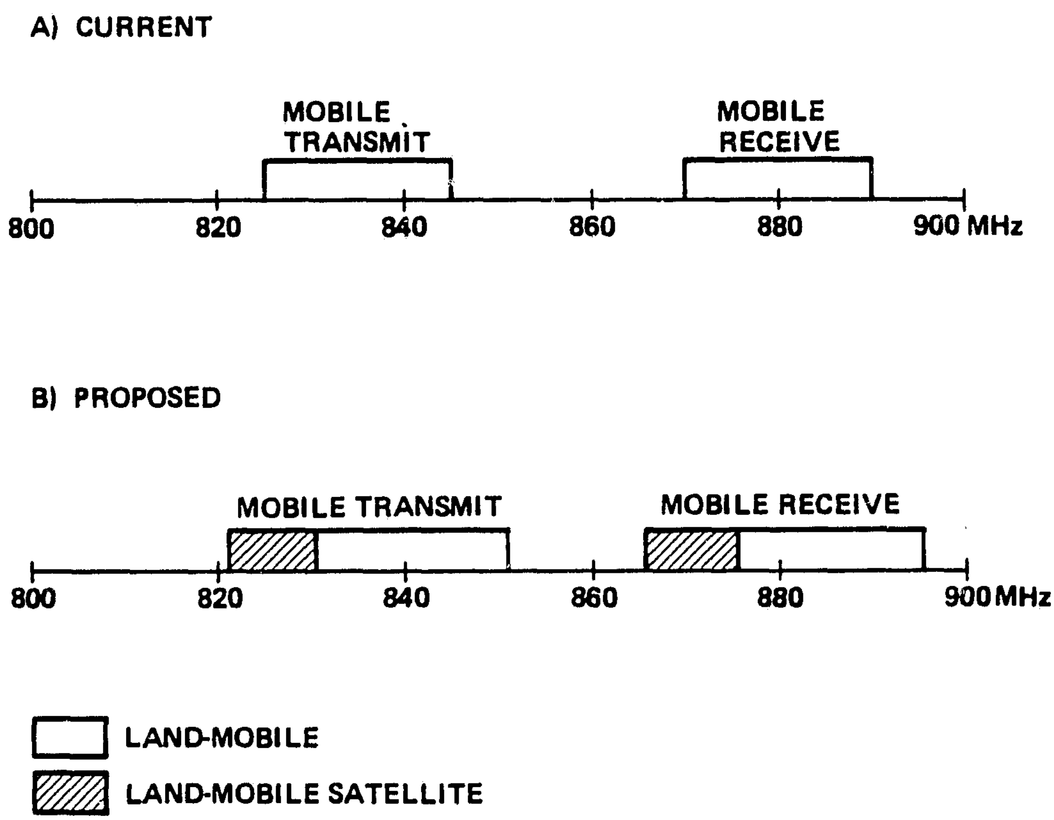

Figure 5. Frequency Allocations

On the other hand, the satellite weight is limited by the geosynchronous payload capability of the Space Transportation System (STS), in combination with orbiter transfer vehicles (OTVs) projected to be available in the 1995 time frame. Two OTVs were considered, a wide-body Centaur and an integral propulsion system (IPS) of the type under study at TRW. Both combinations have a projected payload capability of slightly more than 10,000 pounds.

With a pair of 10-MHz allocations and 30-kHz carrier spacing, it was determined that a single satellite designed to accommodate 180,000 subscribers exceeds the STS payload capability. Consequently, it became necessary to abandon cellular compatibility and/or consider a multiple-satellite system.

At this point a number of different system configurations were introduced to reflect the various dimensions of the problem. These options are enumerated in Table 1. In those cases where cellular compatibility was abandoned, 5-kHz peak-deviation FM (PDFM) was assumed in place of 12-kHz PDFM. The associated carrier spacing is only 12 kHz, as compared with 30 kHz for cellular systems. The narrower form of modulation is currently used in (non-cellular) terrestrial mobile radio. A carrier spacing of 25 kHz is employed in the latter systems to avoid adjacent-channel interference. However, narrower spacing is permissible with satellite transmission because of the more nearly uniform received signal levels.

The frequency re-use factor, introduced originally in the context of a single-satellite system, can be extended through use of multiple satellites. Both 2- and 3-satellite systems were considered. In either case, each satellite provides complete CONUS coverage. If there are N satellites, the satellite antenna diameter needed to generate a specified total system capacity is reduced by $\sqrt{N}$ relative to the single-satellite case.

The disadvantage of multiple satellites is that the user vehicle must be equipped with an antenna capable of discriminating between co-channel signals emitted by different satellites. To accomplish this function with an antenna of modest proportions, the satellites must be spaced in longitude by about 30 degrees. This limits the number of satellites to 3, if each is to be visible from all points in CONUS.

Table 1. System 1 Alternate Configurations

CASE	CELLULAR-COMPATIBLE MODULATION	FREQUENCY REUSE BY SATELLITE	FREQUENCY ALLOCATION (MHz)
1.	YES	NO	10 EXCLUSIVE
2.	YES	NO	4 EXCLUSIVE
3.	YES	YES	10 EXCLUSIVE
4.	YES	YES	4 EXCLUSIVE
5.	NO	NO	10 EXCLUSIVE
6.	NO	NO	4 EXCLUSIVE
7.	NO	YES	10 EXCLUSIVE
8.	NO	YES	4 EXCLUSIVE
9.	NO	NO	20 SHARED
10.	NO	YES	20 SHARED

A user antenna with the desired capability is pictured in Figure 6. It is essentially a linear array of 4 microstrip patches. Consequently, when the line-of-sight to the wanted satellite is normal to a line through the patch centers, the gain toward the satellite of the 4-patch combination if 6 dB higher than that of a single patch. The desired orientation is maintained, in the face of a change in user direction, through a monopulse tracking system.

The normal to the plane of the antenna is tilted away from vertical so that, when the antenna is rotated to the proper azimuth, the maximum elevation-angle difference between the satellite and the antenna boresight tends to be minimized. A typical design would provide two or more semi-permanent, user-selectable tilt-angle settings. The choice of setting would be made on the basis of user location.

It became apparent, as the study progressed, that with FCC consideration of cellular-radio license applications based on the current allocation depicted in Figure 5, there was diminishing probability of a change in this allocation. This left only the 4-MHz "reserve" bands immediately below the cellular bands as candidates for LMSS. Consequently, systems were configured to operate within this restricted allocation.

The possibility of designing a satellite system to share the 20-MHz cellular allocation was also considered. To minimize the effect of inter-system interference, the satellite system carriers are also spaced by 30 kHz, but are interleaved with those of the cellular system. Only the narrower form of FM was considered with a shared allocation.

Of the configurations examined, all but Cases 1, 2, and 6 lead to a satellite weight that is compatible with the STS geosynchronous payload capability, for the baseline subscriber scenario. However, it was recognized that larger populations, as well as a non-uniform geographic distribution, would have to be considered. This made it imperative to choose satellite designs with substantial growth potential. On this basis, Cases 7 and 10, which result in the lightest satellites, were selected for further study.

Although Cases 7 and 10 correspond to very different regulatory postures, the resulting satellite designs are quite similar. Therefore, only

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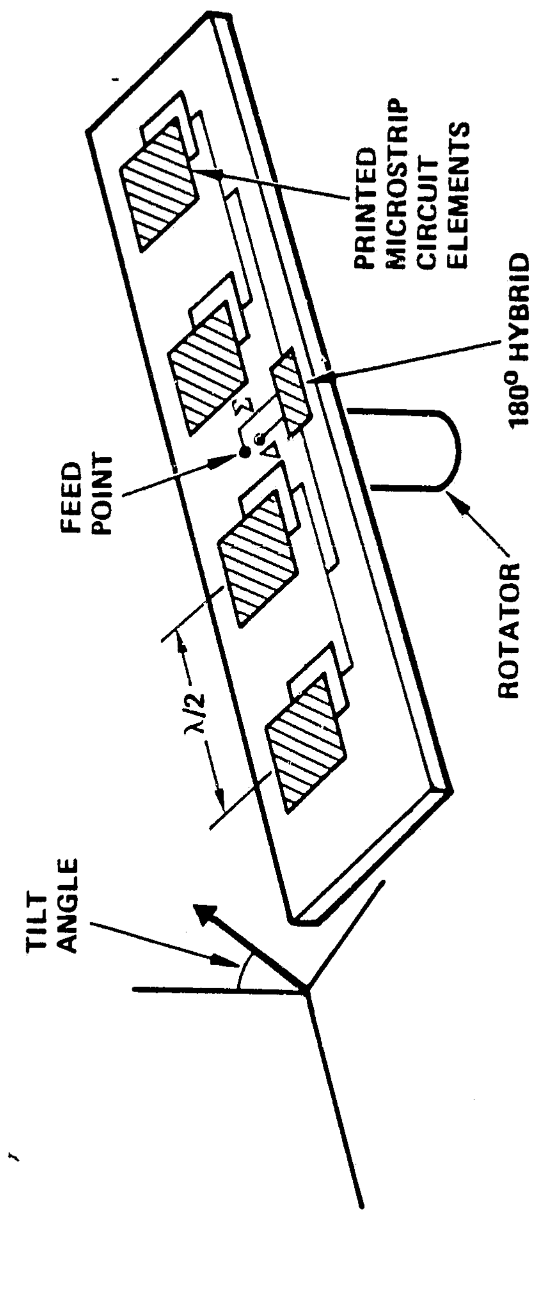

Figure 6. User Antenna Concept

Case 7 was explicitly pursued; conclusions regarding Case 10 can be inferred therefrom.

The alternate traffic scenarios considered are shown in Figure 7. Baseline system designs were ultimately developed for scenario B. The EOL traffic for this scenario is about twice that for the baseline scenario.

The geographic subscriber distribution adopted is shown in Figure 8. This distribution is essentially obtained by subtracting the SMSA population from the total population of each state and treating the remainder as if it were uniformly distributed over the area of the state.

Satellite sizing (i.e., selection of the reflector diameter) is based on the maximum number of subscribers that must be accommodated in a single beam. The non-uniformity depicted in Figure 8 is accentuated by the increased area illuminated by a beam of given angular diameter in the northern regions of CONUS. The beam area also increases with the longitudinal separation between the satellite and the region under consideration. In a multiple-satellite system, these factors cause the most densely populated beams (which correspond to the most westerly satellite) to appear in the northeast part of CONUS.

When both aspects of geographic non-uniformity are taken into account, it is found that, to accommodate subscribers in the densest beam, the satellite must be sized for a uniformly distributed population that is twice as large as the anticipated skewed population.

A pair of System 1 configurations were selected as baseline designs. Both utilize 2 satellites to handle the EOL subscriber population. The designs are distinguished by the satellite feed/reflector geometry. In the first case, in which 4 frequency sets are employed (Figure 9), the reflector is offset-fed (Figure 10). A total of 61 beams is required to generate the specified capacity (9,000 erlangs for the system, or 4,500 per satellite). The reflector diameter is 46 meters and the main-mast length is 69 meters. The latter dimension is required to limit the interbeam co-channel interference.

In the second design, the reflector is center-fed (Figure 11). Because of feed blockage of the reflector, the first inboard sidelobe of each beam (termed the comalobe) tends to be quite high. To avoid

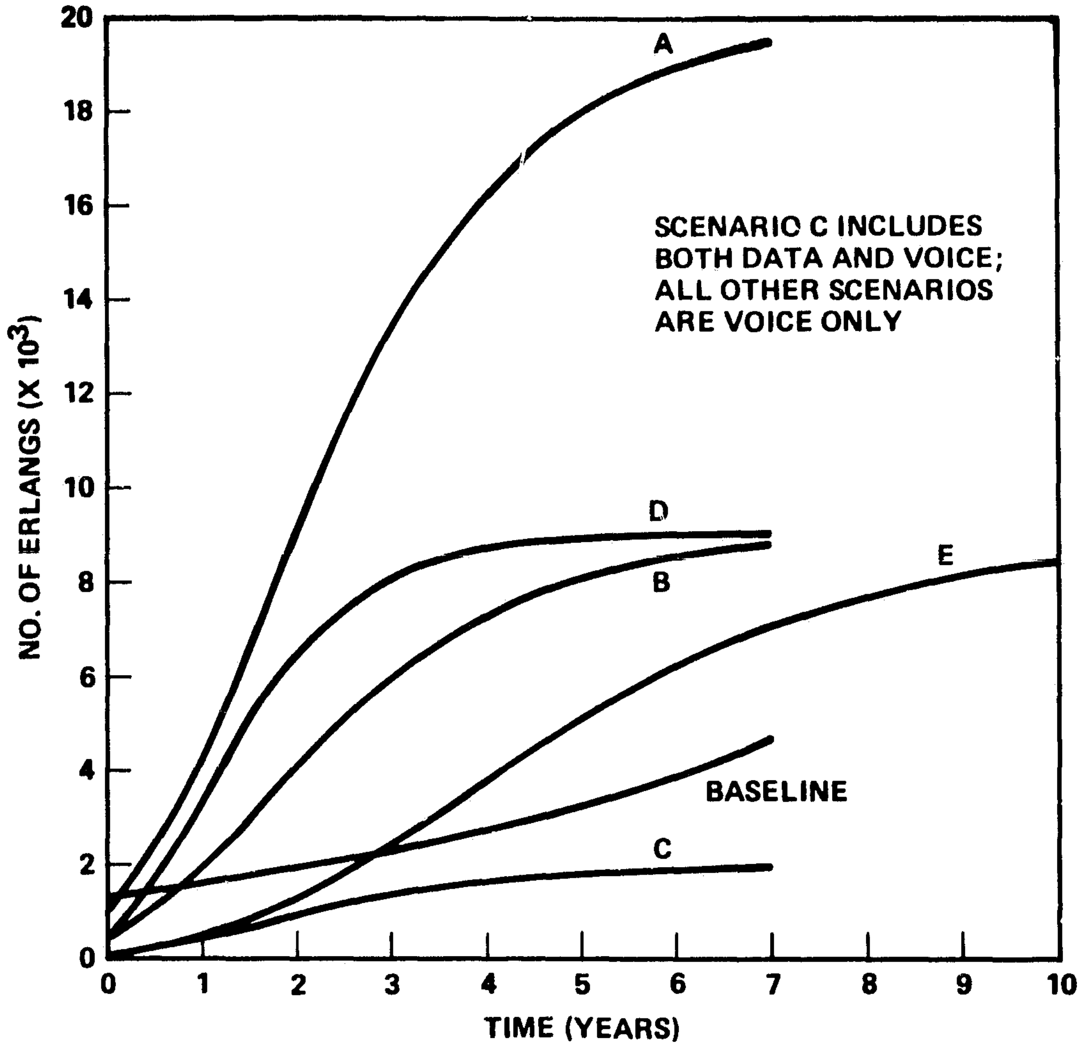

Figure 7. Traffic Scenarios

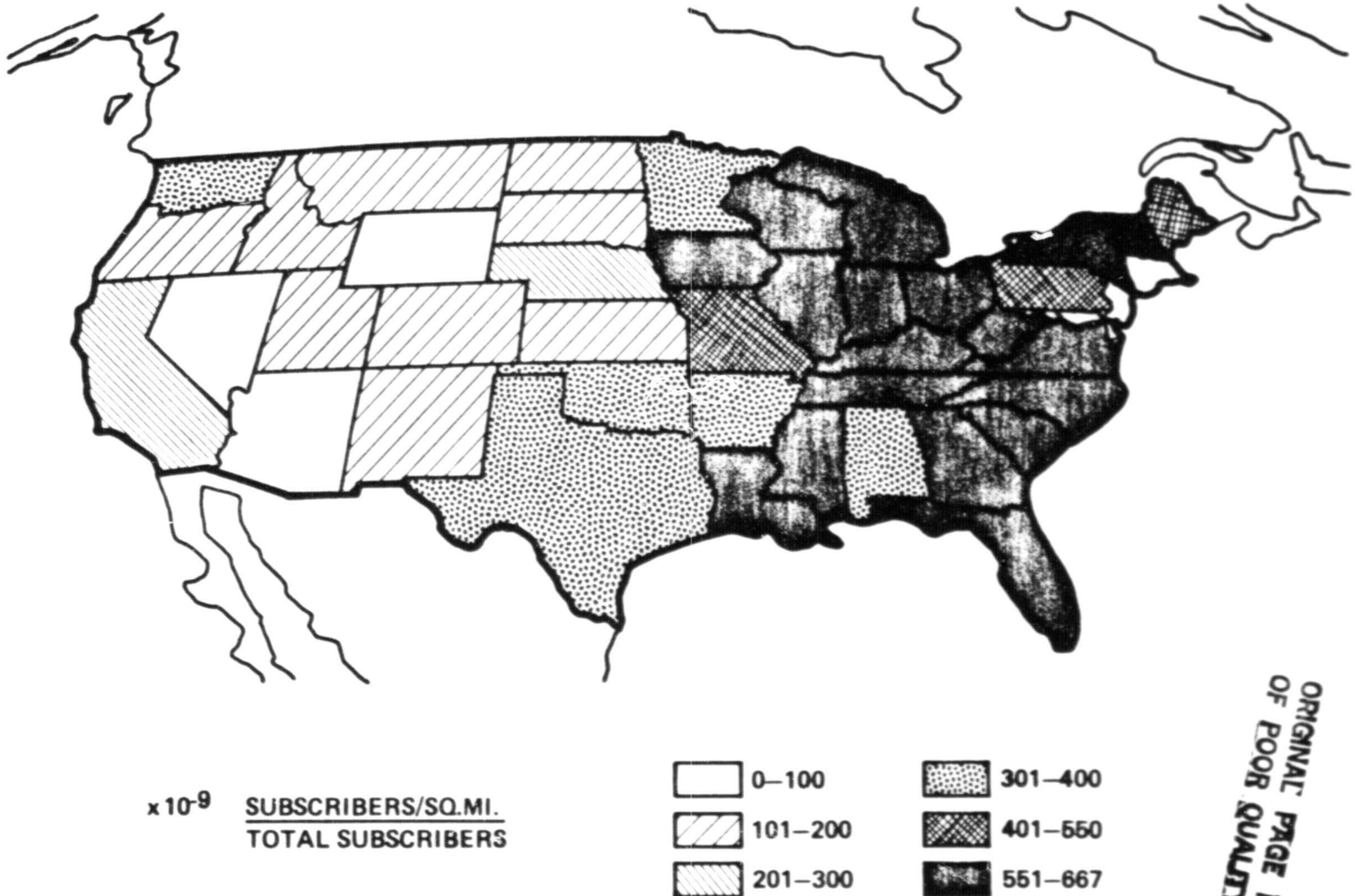

Figure 8. Geographic Subscriber Distribution

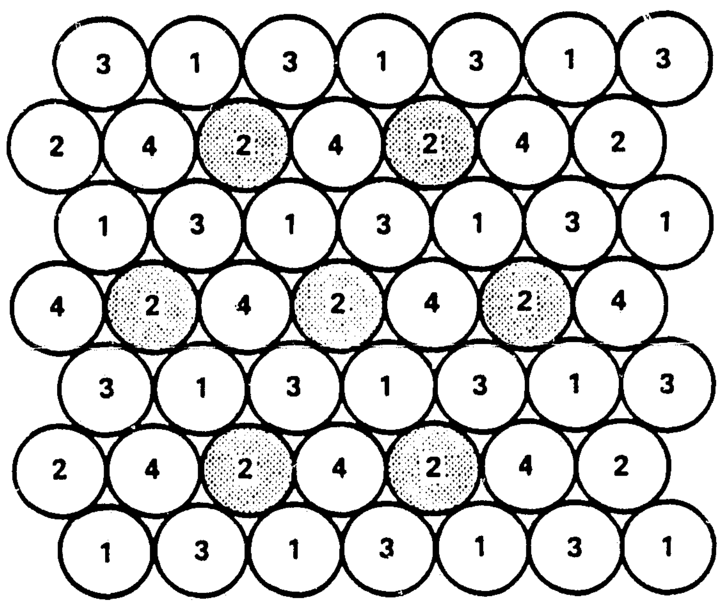

Figure 9. 4-Frequency-Set Beam Pattern

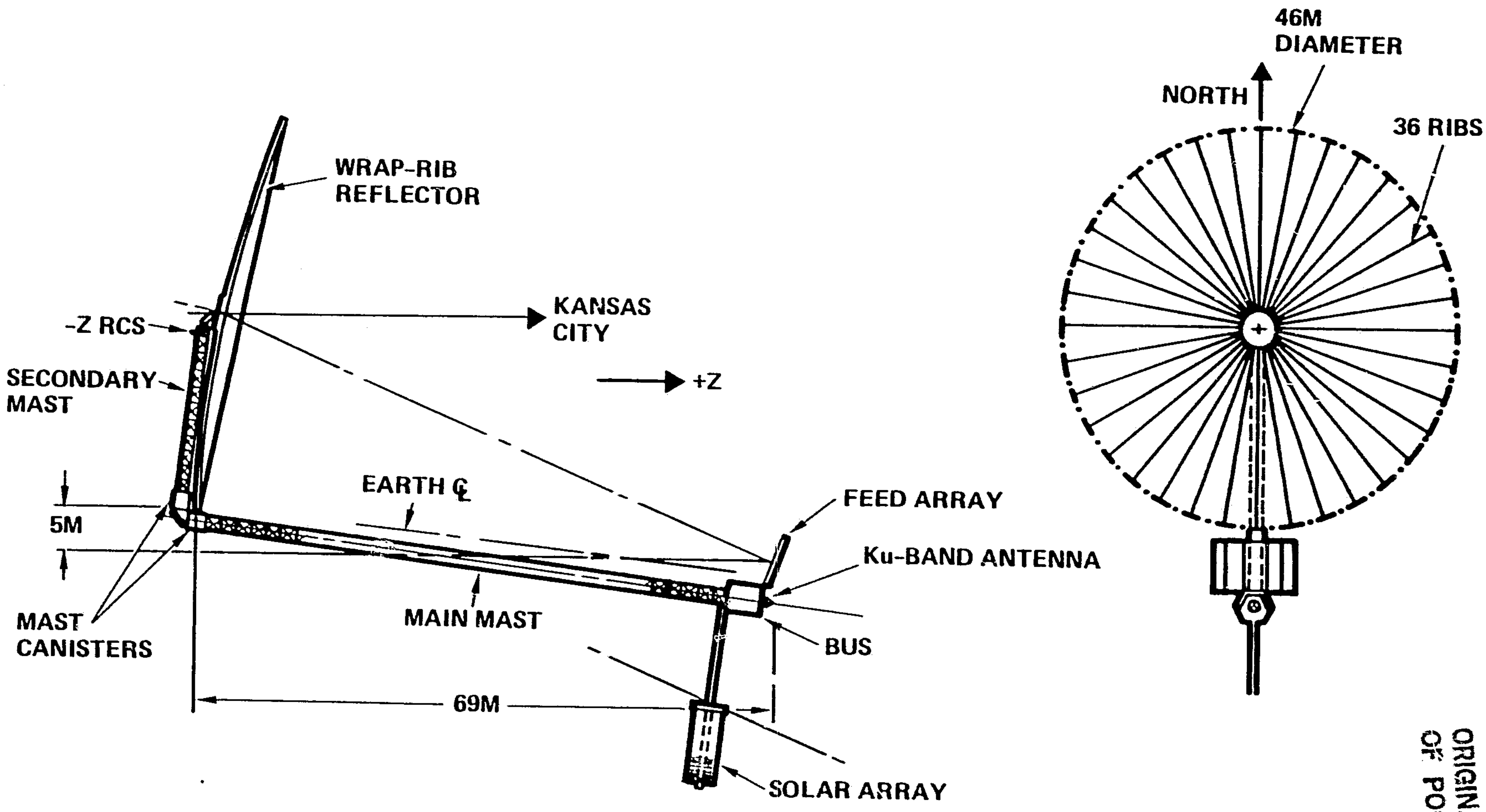

Figure 10. Offset-Fed Satellite Configuration

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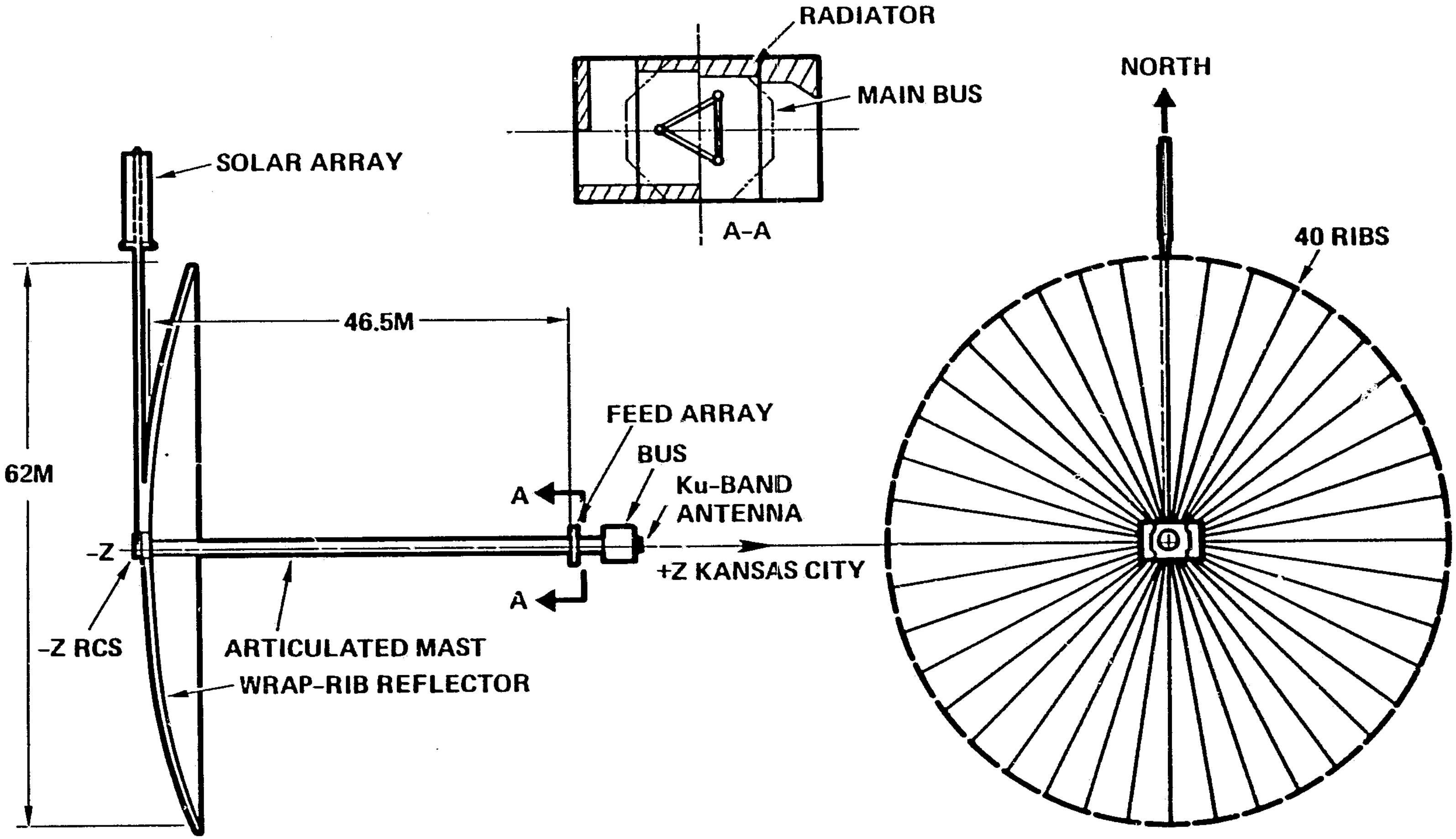

Figure 11. Center-Fed Satellite Configuration

interference from these sidelobes, co-channel beams must be spaced farther apart than with an offset-fed reflector. Accordingly, 7 frequency sets are used with the center-fed design (Figure 12). This leads to a requirement for 101 beams, which is satisfied through use of a 62-meter reflector. The mast length of 46.5 meters suffices for good sidelobe performance because of the center-fed geometry.

The reflector selected for both the offset-fed and the center-fed configurations is the Lockheed wrap-rib design. The mast is an articulated, expandable structure. A parametric analysis of the weight and stowed dimensions of both reflector and mast has been performed as an integral part of this study.

The great advantage of the center-fed design is its structural rigidity. As a result, fairly conventional attitude control procedures can be employed. On the other hand, substantiation of RF integrity for the center-fed design requires further development effort.

By contrast, the offset-fed geometry has heretofore been the accepted approach to attaining the desired RF performance. However, the traditional L-shaped mast results in a highly flexible and difficult-to-control structure. Substitution of a straight mast between reflector hub and feed assembly may provide acceptable RF performance, while considerably simplifying the attitude control problem.

Considerable effort has been expended in recent years in large-space-structure (LSS) development. This effort should be extended to include ground testing and, subsequently, an STS flight test of a scale reflector and mast section. Coordination of test results with analytical modeling is essential to successful development of a full-scale operational satellite.

The feed system for the two satellite designs is complicated by the need to "cluster" feed elements to form a pattern of contiguous beams with the desired sidelobe properties. A quite complex beamformer network is required to provide proper excitation to the different feed elements that contribute to formation of a common beam. Selection of a suitable feed-element type, specification of feed-element spacing and excitation, design of the beamformer network, packaging of the power amplifiers and the

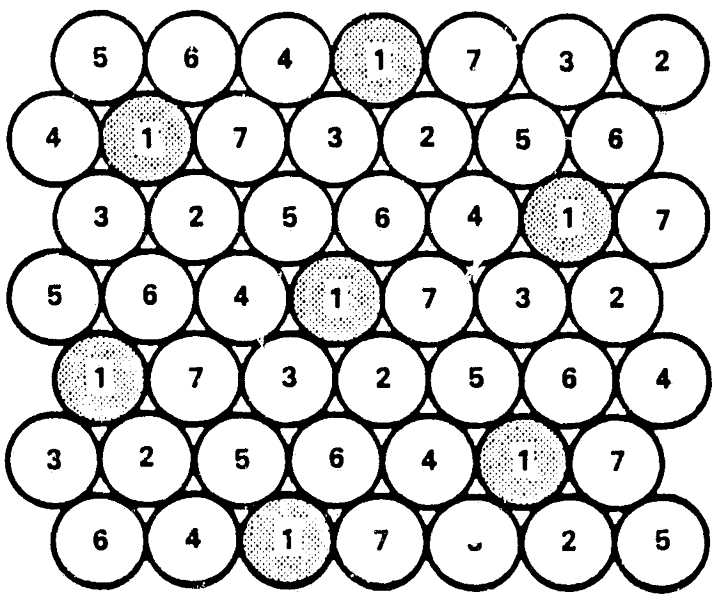

Figure 12. 7-Frequency-Set Beam Pattern

low-noise receivers on the feed assembly, and mechanical design of the feed structure constitute a formidable development effort.

Development plans are presented for all relevant technology, based on a 1990 start for the flight program and a 1995 first launch.

The MSC that is appropriate for a given system configuration, in conjunction with a prescribed subscriber scenario, is determined by a net present value (NPV) analysis. By this method, the satellite project is treated as a series of cash flows, on an annualized basis, starting with the initial R&D expenditures and concluding at the end of the planned 7-year system life. The MSC, which determines the revenue flow for the assumed subscriber scenario, is chosen to provide a specified return on invested capital.

The MSC for the two baseline designs is shown in Figure 13 as a function of the required internal rate of return (IRR) for the project. The latter is interpreted as a real rate of return (i.e., a return in terms of constant dollars). The MSC is expressed in 1981 dollars.

The cumulative discounted cash flow (CDCL) corresponding to the offset-fed design is shown in Figure 14. All dollar amounts are referred, by the discounting process, to the start of the project. For an IRR of 15 percent, for example, the CDCL attains a maximum negative value of $500 million in the sixth year of the program. (Time 0 corresponds to the start of system operation — i.e., to initial revenue flow.)

It was indicated earlier that the satellite designs are similar for a 10-MHz exclusive allocation and a 20-MHz shared allocation. (There is at most a 10-percent weight penalty in the latter case.) Nominally, therefore, the preceding discussion regarding the baseline system designs and the associated MSC apply to a shared-allocation system as well. However, it can be shown that unacceptable levels of intersystem interference are introduced if the satellite system employs 5-kHz PDFM.

Potentially most damaging is interference injected into the satellite by cellular-system mobile units. Because a single satellite beam can encompass several complete cellular systems, there can be a number of cellular mobiles interfering with (i.e., transmitting on a frequency adjacent to) the same satellite mobile unit. The actual number of co-channel interferers depends on the size of the cellular-system subscriber population.

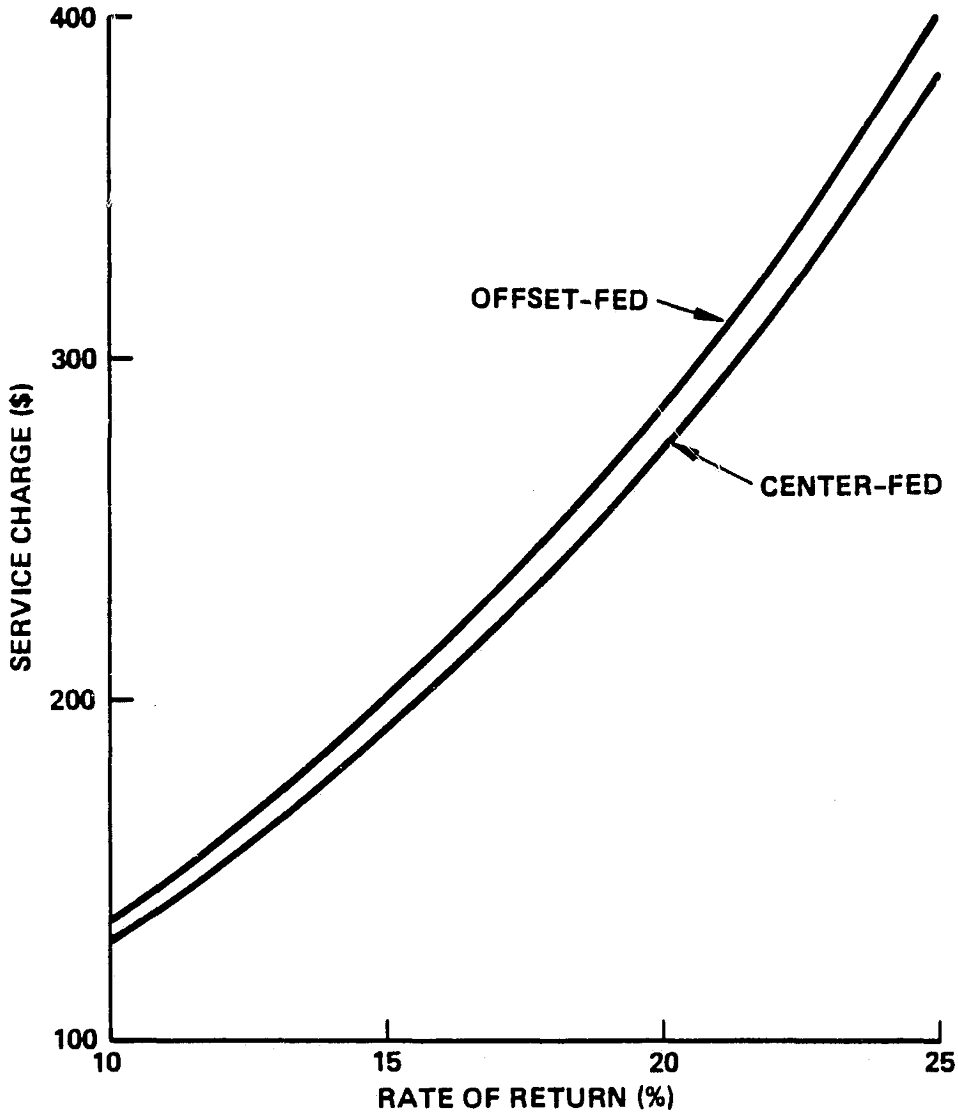

Figure 13. System 1 MSC - Baseline Configurations

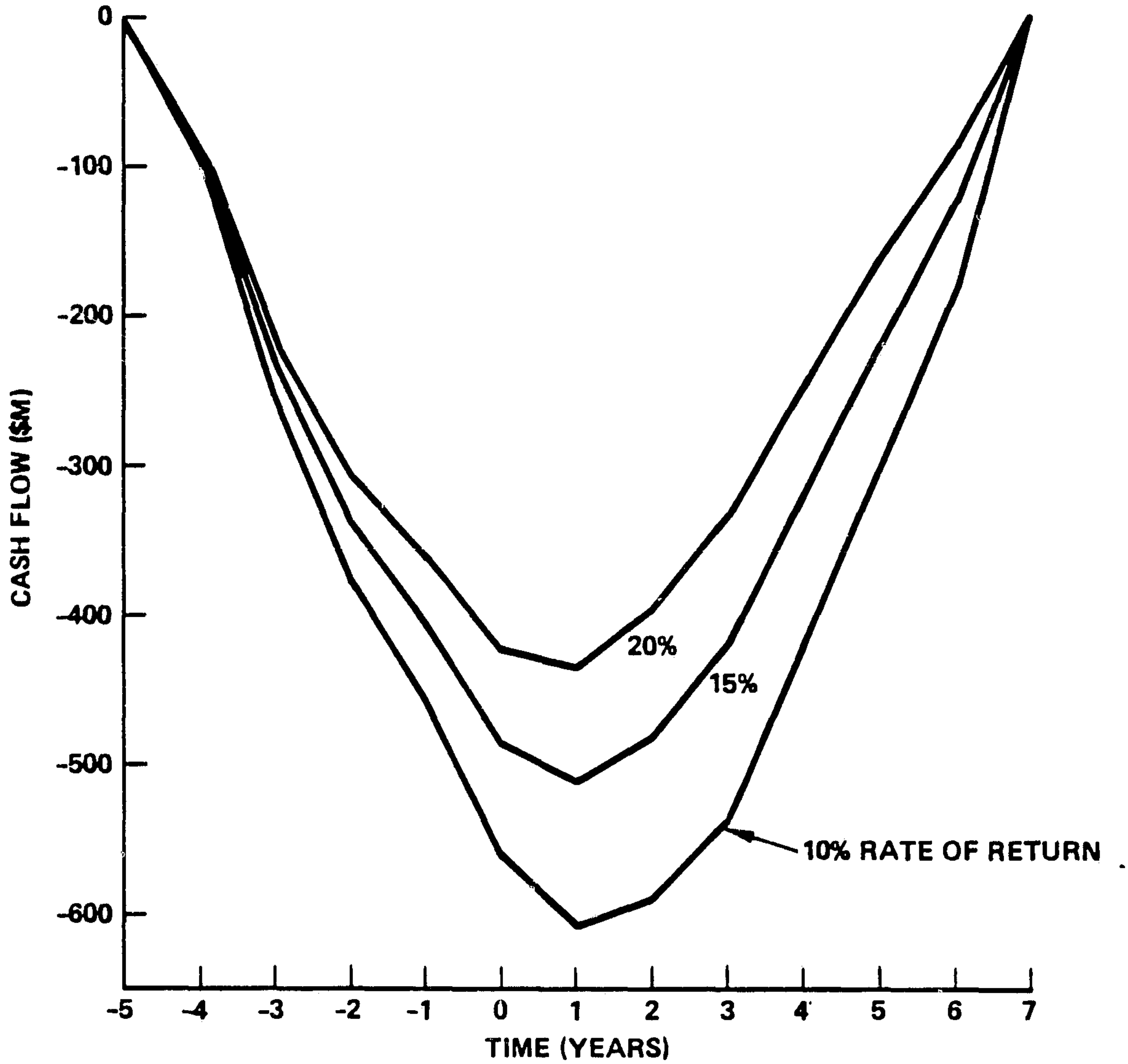

Figure 14. Cumulative Discounted Cash Flow for Offset-Fed Design

It is possible for satellite and cellular systems to share a common allocation, however, if the former employs a digital format such as linear predictive coding (LPC) in combination with frequency-shift-keyed (FSK) modulation. Based on a 2.4-kb/s voice encoding rate, carrier bandwidths no larger than 6 kHz are required with this format. Protection ratios established for such a system (Reference 4) offer promise that compatible operation is a real possibility.

Of course, LPC can also be used in a system designed to operate with an exclusive frequency allocation. Because the carrier spacing is only half that of the FM format used in the baseline designs, the required frequency re-use factor is also halved. Whereas 2 satellites are required to handle the scenario B traffic with FM transmission, a single satellite would suffice with LPC. This greatly simplifies the mobile-unit antenna design.

A similar conclusion does not apply to a shared-allocation system that employs LPC. In this case, the carriers must be interleaved with those of the cellular system and therefore remain on 30-kHz centers. For this reason, the system design is similar to that for the baseline, exclusive-allocation system, regardless of the type of modulation employed.

In addition to the all-voice traffic scenarios, a scenario comprising a mix of voice and data has been examined. This is designated as scenario C in Figure 7. In erlang terms, the EOL traffic appears rather small. However, half of the 2,000 erlangs represent data channels at 56 kb/s. The data-channel bandwidth is considerably greater than the voice-channel bandwidth, regardless of the modulation/coding format adopted. Moreover, the required power per-unit-bandwidth is significantly larger for the data channels. Thus, considerable satellite resources of bandwidth and power are required despite the light erlang loading. The satellite requirements are reduced somewhat by the assumption of a uniform geographic distribution of subscribers.

The salient features of a satellite system designed to accommodate scenario C with either a 10-MHz or a 4-MHz exclusive allocation are shown in Table 2. The modulation/coding options are restricted to QPSK with rate 3/4 coding and uncoded BPSK. Uncoded QPSK is not feasible because the

Table 2. System Designs for Scenario C

	FREQUENCY ALLOCATION		
	10 MHz	4 MHz	
MODULATION	BPSK	QPSK	BPSK
CODING	UNCODED	RATE 3/4	UNCODED
NO. OF SATELLITES	1	1	2
USER REQUIREMENTS			
CODEC	NO	YES	NO
ANTENNA	PHASED ARRAY	PHASED ARRAY	DEPLOYABLE

combination of co-channel interference and intermodulation noise sets an unacceptable upper limit on the achievable carrier-to-noise ratio.

The MSC for a voice subscriber with scenario C is shown as a function of IRR in Figure 15 for the three systems considered. It was assumed, in deriving the MSC, that the charge per-unit-bandwidth is the same for voice and data. Note that this leads to a data-channel service charge that depends on the modulation/coding format adopted.

In light of the recent NASA petition to the FCC requesting a pair of 4-MHz exclusive allocations for LMSS, it is appropriate to assess the implications of such a bandwidth constraint. The factor-of-2.5 bandwidth reduction (relative to a 10-MHz exclusive allocation) necessitates a similar increase in the frequency re-use factor for the system, for the same EOL population. Whereas 2 satellites are needed to accommodate scenario B with a 10-MHz allocation using 5-kHz PDFM, 4 satellites would nominally suffice with a 4-MHz allocation, because of the weight margin in the baseline designs. However, because of the high subscriber density in Eastern CONUS and the need to maintain a large longitudinal separation between satellites for user discrimination, the desired capacity would not in fact be achieved.

The scenario B population can be accommodated in a 4-MHz allocation by adopting the narrower-bandwidth, LPC format. Two satellites would be required in this case, necessitating the more complex form of user antenna.

As shown above, scenario C can also be accommodated in 4 MHz. Two options are available: a single-satellite system that employs QPSK with rate 3/4 coding, or a 2-satellite system that used uncoded BPSK. The former option requires that a codec (coder/decoder) be incorporated in mobile units designed for data transmission. It also requires a mobile antenna with a moderate amount of directivity. On the other hand, the latter option may have to be restricted to transportable operation because of the mobile-unit antenna requirements.

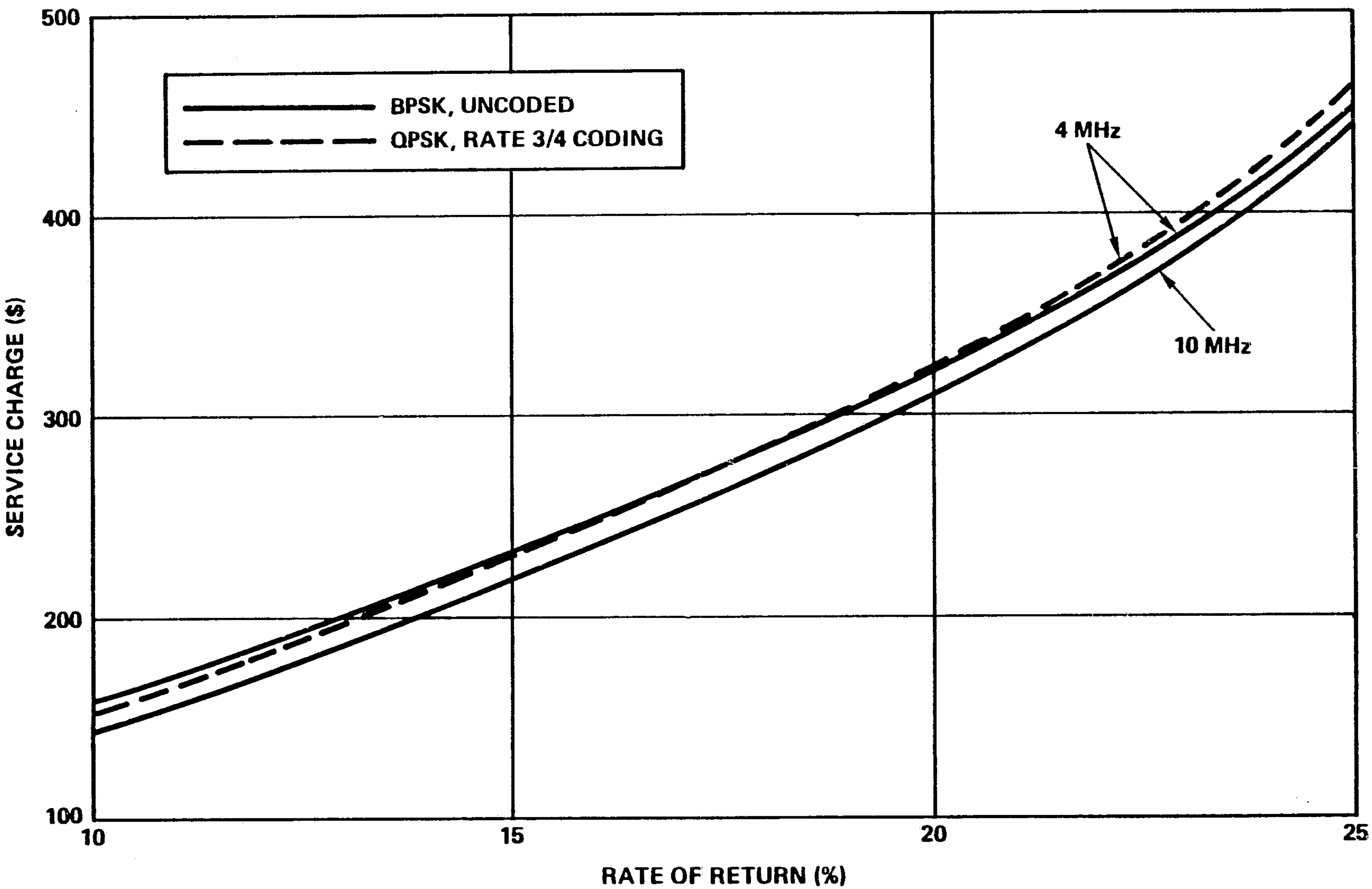

Figure 15. MSC for Scenario C

3. SYSTEM 2

The economic viability of System 2 is strongly dependent on the coverage area of an individual translator station. Coverage areas will differ considerably, depending on the elevation of the station and local propagation conditions. To simplify the analysis, a uniform coverage area, corresponding to open terrain, has been assumed. This assumption tends to maximize the coverage area and is therefore optimistic for undulating terrain in which translator/mobile communications is not possible from many locations.

An antenna tower height of 500 feet has been selected as the maximum value that can be justified economically. It is assumed that, in all cases, the site selected permits a guyed tower to be erected, as the cost of such a tower is much lower than that of a free-standing tower.

With a 500-foot tower, the translator range in open terrain is approximately 40 miles. To achieve this range, a low-noise pre-amplifier, resulting in a 4.5-dB noise-figure receiver, is included in both the mobile unit and the translator station. (A mixer front-end is typically used in cellular systems, with a resulting noise figure of about 9 dB.) Mobile units are equipped with 3-watt transmitters. For balanced transmission between mobile and translator, the latter must radiate about 1.5 dB more power than is commonly used in cellular systems.

With a 40-mile transmission range, about 800 translators are needed for complete CONUS coverage. It was initially assumed that System 2 service is economically viable over 50 percent of CONUS. A total of 400 translators is required to provide this service. If the cellular systems in place by the mid-1990s are presumed to cover 10 percent of CONUS, 60 percent of CONUS will be covered by one type of system or the other.

The instantaneous traffic requirements at the translator stations are relatively small and quite dynamic, reflecting the random nature of call arrival times. A time-division-multiple-access (TDMA) transmission format has been selected for the translator/gateway links. This permits aggregation of the traffic from a large number of translator stations on a single carrier, thereby minimizing the satellite capacity requirements. In fact, depending on the maximum permissible carrier bit rate in relation to the traffic offered, it may be possible for all translators controlled by a given gateway to share a common carrier.

The specific transmission parameters adopted are those identified with Digital Communication Corporation's DYNAC terminal. Voice-channel digitization is accomplished by 32-kb/s delta modulation; this is coupled with QPSK transmission. The maximum carrier bit rate is 8.8 Mb/s. Five such carriers, with a composite bit rate of 44 Mb/s, can be supported in a typical 40-MHz satellite transponder.

Design of the translator/gateway links is based on leased satellite capacity rather than a dedicated satellite. One reason for this choice is that standard earth terminals, insofar as the RF components are concerned, can be employed at both the translator and the gateway sites in conjunction with satellites similar to those in commerical service today. Additionally, the capacity requirements, especially in the early years of operation, are far less than that available from typical commercial satellites. Therefore, cash flow requirements can be considerably reduced through leasing.

For example, scenario B requires 15 40-MHz transponders at EOL, but only 3 in the first year of operations. At a lease rate of $2 million/year per transponder, first-year lease charges would be $6 million, growing to $30 million in the seventh year.

Of the fixed-satellite frequency allocations, either C-band (6/4 GHz) or Ku-band (14/11 GHz) would be suitable for the translator/gateway links. C-band has been selected for the purpose of developing satellite lease charges and earth-station equipment costs because of the relatively mature state of satellite service at these frequencies.

In computing an MSC for System 2, it was assumed that the rate of translator installation is 100/year. Four years are required, therefore, for complete installation of the system. The point at which installation is complete is assumed to coincide with the start of system operations (i.e., time 0) in the definition of the various traffic scenarios (see Figure 7). For the baseline scenario only, service is assumed to be provided to those areas covered by translators once the first 100 translators are installed. This requires that all gateways be in place at that time.

For all other scenarios, gateway installation can be delayed until all 400 translators are deployed.

The cost associated with the translators can be divided into fixed and variable components. The total fixed cost depends only on the number of translators. While the variable cost for a particular translator depends on the number of subscribers served, a modified subscriber distribution merely shifts the variable costs among the translators without changing the total amount. Therefore, as long as all 400 translators belong to a system for which a single MSC is computed, the subcriber distribution is immaterial. For simplicity, a uniform geographic distribution has been assumed.

The MSC required with the baseline subscriber scenario is given by the lower curve in Figure 16. Sensitivity of the MSC to variations either in total coverage or in single-translator coverage is illustrated by the upper curve. By the first interpretation of this curve, 70 percent of CONUS is covered, with each translator again capable of communicating with mobiles 40 miles distant. A total of 560 translators is required to provide the added coverage.

If, instead, the translator radius of coverage is reduced to 34 miles, 560 translators are needed to provide the original 50-percent CONUS coverage. The number of subscribers captured is assumed to be the same as in the previous case, since the subscriber density can be expected to diminish rapidly once the most profitable 50 percent of CONUS has been covered. With an identical subscriber scenario, as well as identical equipment costs, the MSC is the same for the two cases.

The complement of 560 translators represents an increase of 40 percent over the original 400 translators. Yet the MSC increase is only 20 percent for a 10-percent IRR, increasing to 23 percent for a 25-percent IRR. The smaller percentage increase in MSC is attributable to the sizable variable cost component of an individual translator station. This component depends on the number of subscribers supported by the translator. Since the total subscriber population is assumed invariant to the number of translators, the system-wide total of the variable cost components is invariant as well.

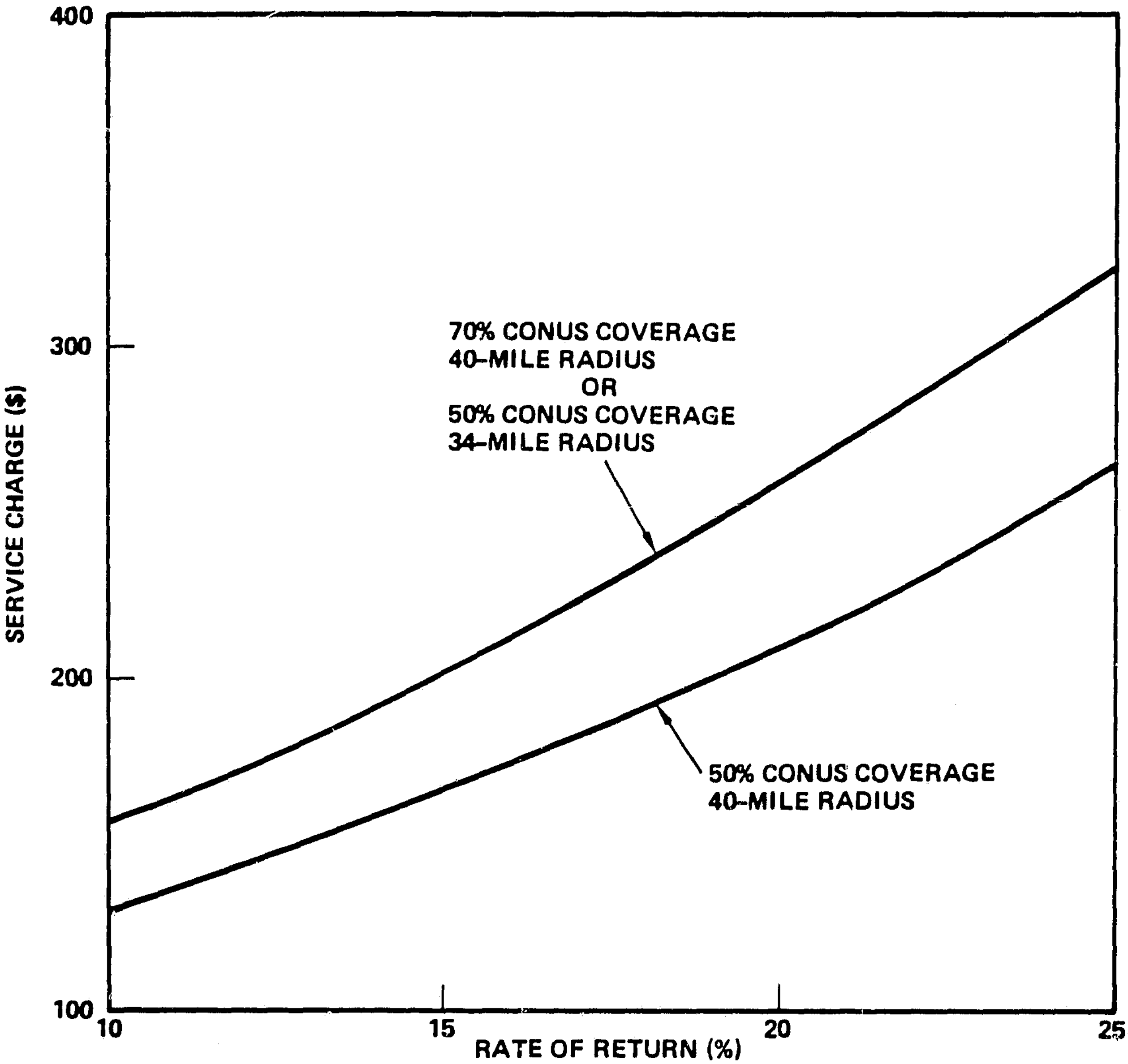

Figure 16. System 2 MSC - Baseline Scenario

MSC profiles for the alternate traffic scenarios are shown in Figure 17. Because the revenue stream for scenario E stretches over 10 years, the MSC in this case increases more rapidly with increasing IRR than in the other cases.

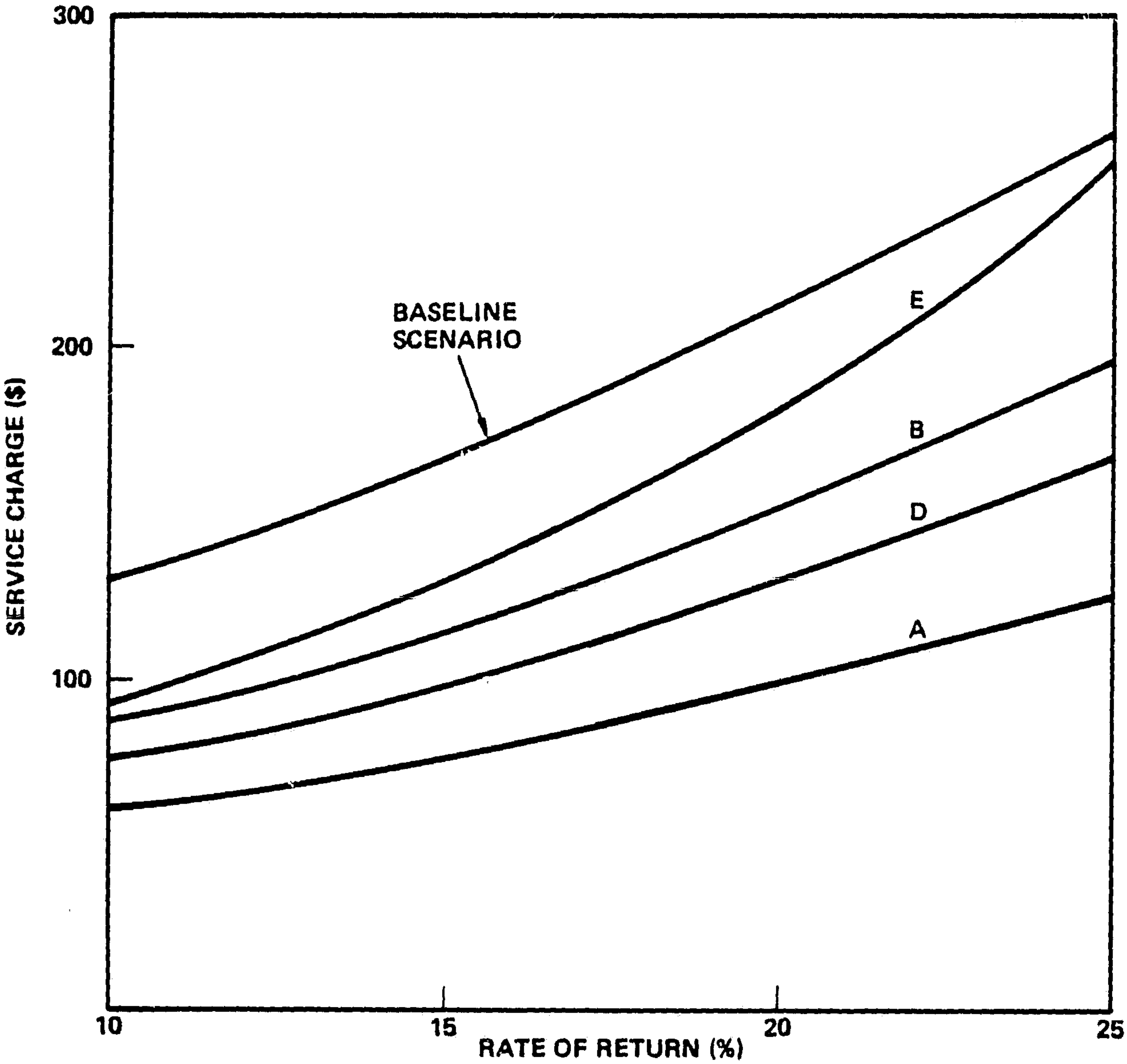

Figure 17. System 2 MSC - Different Traffic Scenarios

4. SYSTEM 3

From a user point of view, System 3 operates in the same manner as System 2 in those areas serviced by translator stations. Outside these areas, transportable units communicate directly through the satellite in much the same manner as with System 1.

A dedicated satellite is required to service the transportable units. Because the number of transportable units is expected to be small, the satellite should be made as simple as possible. One way to accomplish this is to provide complete CONUS coverage with a single satellite beam. Although a single beam may provide adequate bandwidth for the transportable population, the reduced satellite antenna gain implies large per-carrier transmit power for both the satellite and the transportable unit. These power levels can be kept manageable only by increasing the transportable-unit antenna gain.

The achievable antenna gain, for a practical installation that has to operate while the user vehicle is in motion, is limited. (For example, a gain of about 8 dB can be realized over an elevation-angle range of 20 to 60 degrees with a 3 x 3 phased array which is 18 inches on a side.) For this reason, communication with the transportable units is restricted to periods when the user vehicle is at rest.

The antenna selected for the transportable units is a collapsible helix. When extended, it has a length of 3.5 feet. A means must be provided to point this antenna in the direction of the satellite while the vehicle is at rest. A boresight gain of about 15 dB is achievable with an antenna of this type.

The satellite requirements for System 3 are obtained by associating a traffic scenario for the transportable users with each of the System 2 traffic scenarios for the mobile users. The EOL transportable traffic associated with the baseline mobile scenario is assumed to be all voice; in magnitude, it is the maximum amount compatible with single-beam CONUS coverage. This number depends on the carrier spacing assumed for transportable transmission. At the point in the study when this question was first addressed, alternate modulation formats to the cellular format had not yet been considered. Consequently, the carrier spacing was taken as 30 kHz.

The frequency band specified for transportable transmission is 821-825 MHz. The complementary band for satellite transmission is 866-870 MHz. This spectrum allocation permits 133 carriers at a spacing of 30 kHz. After allowances for signaling channels and call blockage, the satellite capacity is approximately 120 erlangs of voice traffic. This is only 2.6 percent of the EOL baseline traffic postulated for the mobile population.

A common transportable traffic scenario is associated with mobile scenarios B, D, and E. This is a voice/data mix comprising 120 erlangs of voice and 120 erlangs of data. The data are constituted as follows: 40 percent at 56 kb/s and 60 percent at 9.6 kb/s.

The voice carriers are assumed spaced by 12 kHz, corresponding to use of 5-kHz PDFM. The data-carrier spacing for the two data rates is 40 kHz or 8 kHz, respectively, corresponding to QSPK transmission. It is readily verified that these values lead to a total bandwidth occupancy of 4 MHz, so that frequency re-use is not required. (For simplicity, erlangs and channels have been treated as synonomous for the alternate traffic scenarios.)

A non-cellular-compatible modulation format for transportable voice transmissions is not nearly so objectionable as a non-compatible format for mobile users. In the remote areas where transportable units are expected to operate, cellular compatibility may have little significance.

The transportable traffic corresponding to scenario A is a voice/data mix comprising 300 erlangs of voice and 300 erlangs of data. The data are divided between 56-kb/s and 9.6-kb/s carriers as in the previous case. Since a single-beam is just adequate for the transportable traffic associated with mobile scenarios B, D, and E, the transportable traffic associated with mobile scenario A requires a 2.5-fold re-use of the 4-MHz allocation. This can be accomplished through use of 4 frequency sets and a CONUS-coverage beam pattern generated by a 20-meter satellite antenna. Thus, insofar as the transportable traffic is concerned, the satellite for scenario A could be made similar to the offset-fed baseline for System 1, except that the antenna would be much smaller.

In addition to providing for the transportable traffic, the dedicated System 3 satellite payload must accommodate the mobile population. It is assumed that a transponder structure similar to that in current domestic satellites is included for this purpose. The number of 40-MHz transponders required at EOL with each of the scenarios is shown in the table below.

Traffic Scenario	Number of Transponders
Baseline	8
A	30
B	15
D	15
E	14

Despite the much larger volume of mobile traffic, the satellite power requirements for all but scenario A are dominated by the transportable traffic. This can be attributed to the large antenna gain of the translator stations compared with that of the transportable units (50 dB versus 15 dB). For scenario A, the high gain of the multibeam satellite antenna adopted for the transportable traffic results in a larger power requirement for the mobile traffic.

For scenarios B, D, and E, the transportable data-traffic power requirements are much larger than the power needed to support the voice traffic. This is attributable to: (1) the larger data-channel bandwidth, (2) the larger power per-unit-bandwidth required for data transmission, and (3) the 4-dB average power reduction that accompanies the use of voice activation.

For these three scenarios, the EOL power capability of the TDRS bus is well matched to the combined transportable/mobile power requirements. Although TDRS has a pair of 5-meter reflectors, frequency re-use would not be employed. Instead, each reflector would be assigned half the carrier frequencies and would be used to provide 50-percent CONUS coverage. The advantage of a pair of reflectors is that higher antenna gain is available than would result from a single beam covering all of CONUS. The satellite power requirements are correspondingly reduced.

For the baseline scenario, on the other hand, a single CONUS-coverage beam suffices from a power standpoint because of the absence of data traffic. In fact, even with the reduced antenna gain, the total satellite power requirement is only 60 percent of that associated with scenarios B, D, and E. The 7-year capability of the FLEETSAT bus exceeds by about 20 percent the baseline-scenario power requirements. Moreover, FLEETSAT has a 12-foot antenna that provides complete CONUS coverage at the frequencies of interest. Thus, this bus is ideally suited to the baseline-scenario requirements.

The MSC required for the baseline scenario is shown in Figure 18. As suggested earlier, identical charges are imposed on transportable and mobile subscribers. The solid curve corresponds to a transportable carrier spacing of 30 kHz. Although substantially more transportable subscribers could be supported with either the narrower form of FM or (especially) LPC, the resulting transportable population would still be too small in comparison with the number of mobile subscribers to significantly reduce the MSC.

The MSC difference for mobile subscribers between System 3 and System 2 can be obtained by comparing the solid curve in Figure 18 with the lower curve in Figure 16. For a 10-percent IRR, the System 3 MSC is higher by 57 percent.

Sensitivity of the baseline-scenario MSC to variations in the cost of different system elements is shown in Figure 19. Unlike Systems 1 and 2, no single element is dominant. While translator costs are the largest contributor to the MSC, space-segment costs are a close second.

For scenarios other than the baseline scenario (which is all voice), the same charge per-unit-bandwidth has been imposed on both data and voice. The MSC for these scenarios, exhibited in Figure 20, pertains to a voice subscriber. The relationship between the MSC profiles is similar to that for System 2. The MSC levels are generally higher than those for System 2, however, because of the higher space-segment cost.

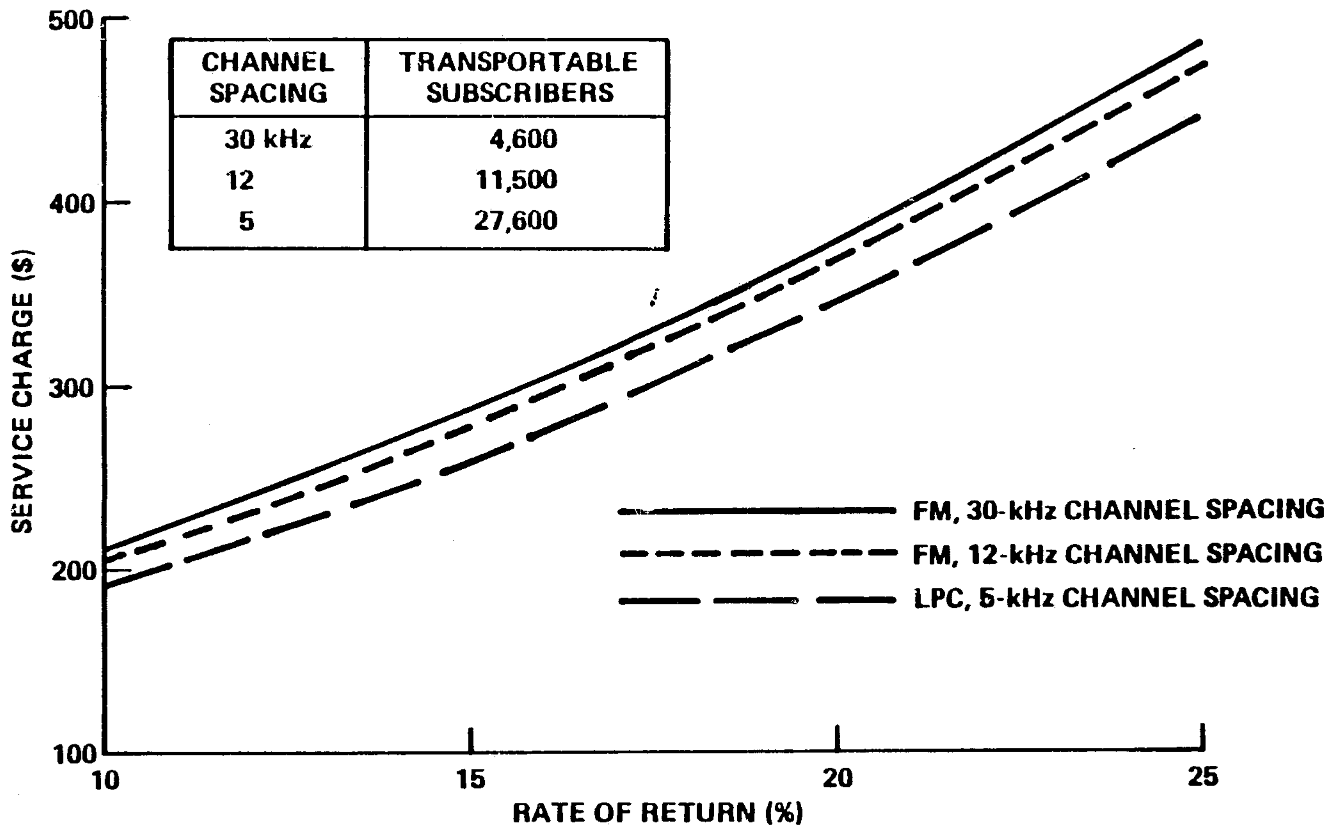

Figure 18. System 3 MSC - Baseline Mobile Scenario

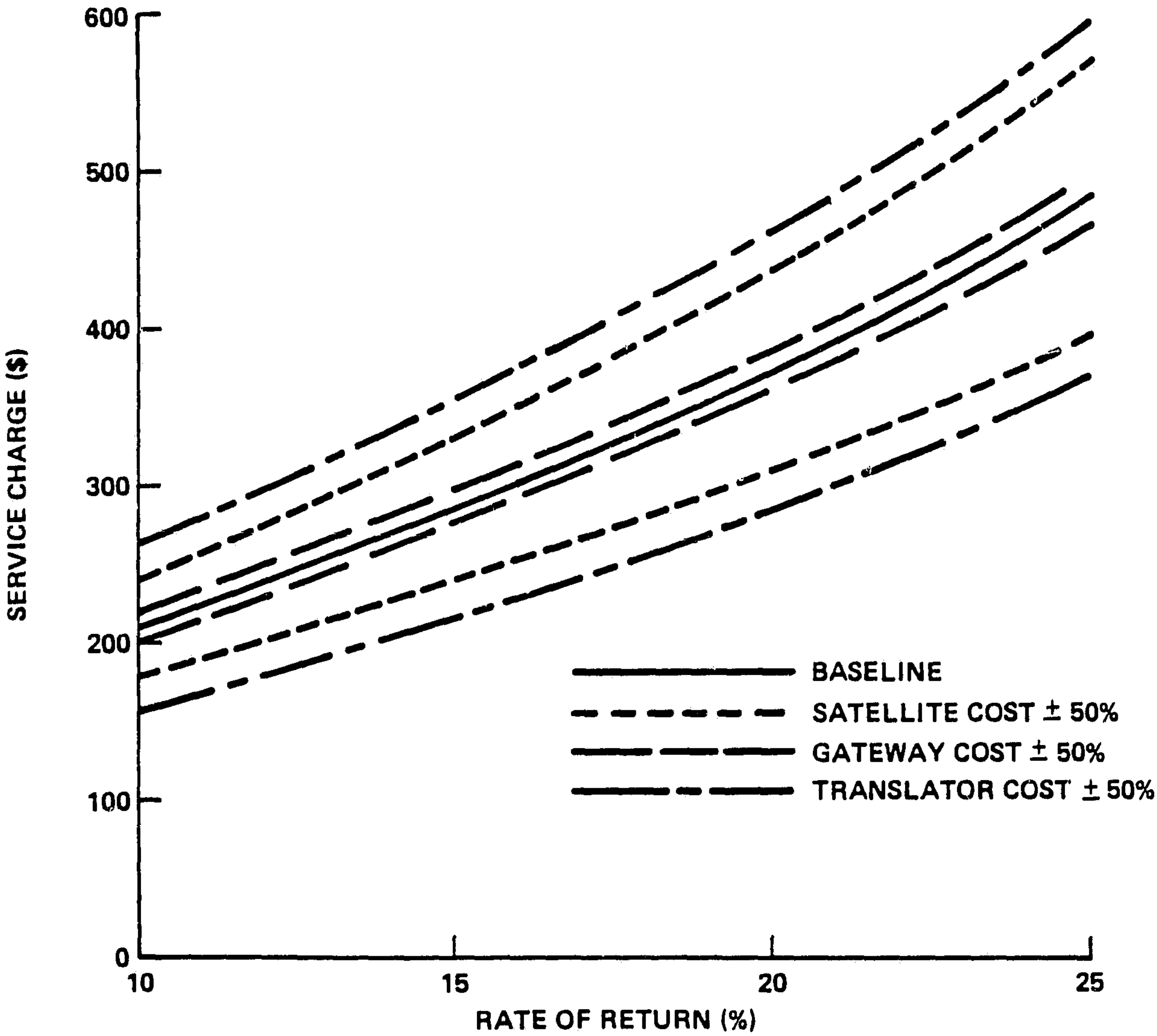

Figure 19. System 3 MSC - Cost Variations

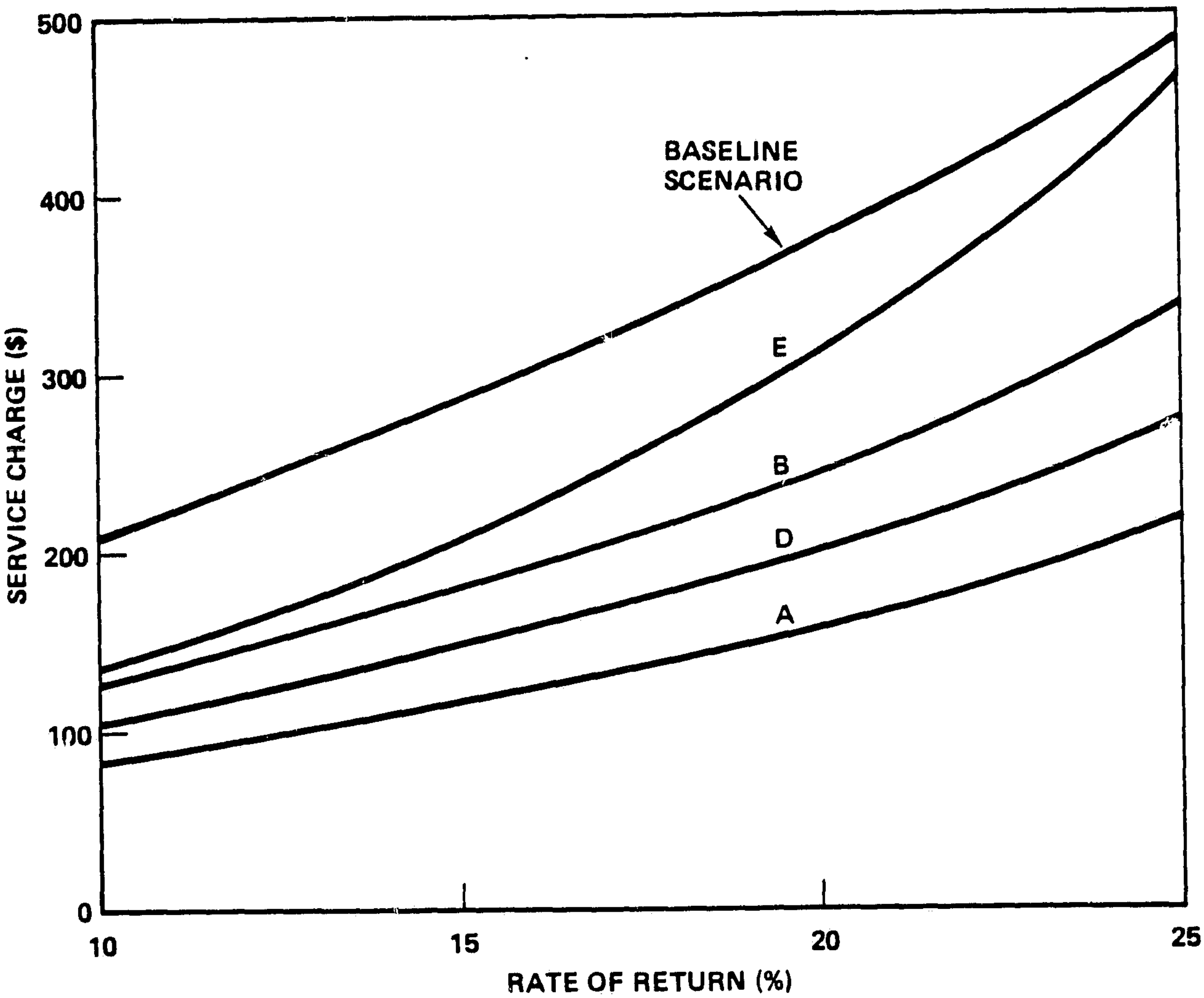

Figure 20. System 3 MSC - Different Traffic Scenarios

5. CONCLUSIONS

A variety of land-mobile satellite system configurations has been examined. These systems are differentiated by frequency allocation, modulation format, traffic scenario, and number of operational satellites. For comparison with Systems 2 and 3, attention will be focused on a System 1 design intended to accommodate traffic scenario B, and which is based on a pair of 10-MHz exclusive allocations.

A single operational satellite could accommodate the EOL traffic with a digital modulation format such as LPC. The major attraction of this alternative is that it permits a relatively simple user antenna design. It also results in a somewhat lower MSC because a total of 3, rather than 4, satellites need to be produced.

The design of such a system was not fully developed during this study. Instead, the System 1 baseline designs, which require two operational satellites, are based on the use of 5-kHz PDFM. The MSC profile for the center-fed feed/reflector geometry is repeated in Figure 21. Also shown are the MSC profiles for Systems 2 and 3. The latter curves correspond to a 40-mile translator-station range.

Care should be exercised in using Figure 21 to compare the economics of the three systems. The MSC selected for each system should correspond to an IRR that accurately reflects the risk inherent in the project. It may reasonably be argued that the large space structure in System 1 represents a larger technological risk than is found in System 2, and that System 3 falls somewhere in between from a risk standpoint. It follows that the actual MSC disparity between systems is larger than that obtained by consideration of a fixed IRR.

In addition, the MSC depends on the subscriber scenario. If the annual percentage growth of the subscriber population is assumed to be the same for the three systems, the subscriber scenario may be characterized by the EOL population. Identical EOL populations have been assumed for all three systems (namely, that corresponding to scenario B). Clearly, however, the number of subscribers that decide to use a particular service will vary inversely with the MSC imposed. Therefore, the MSC difference between systems can only be accentuated by taking into account the demand elasticity for land-mobile satellite communications.

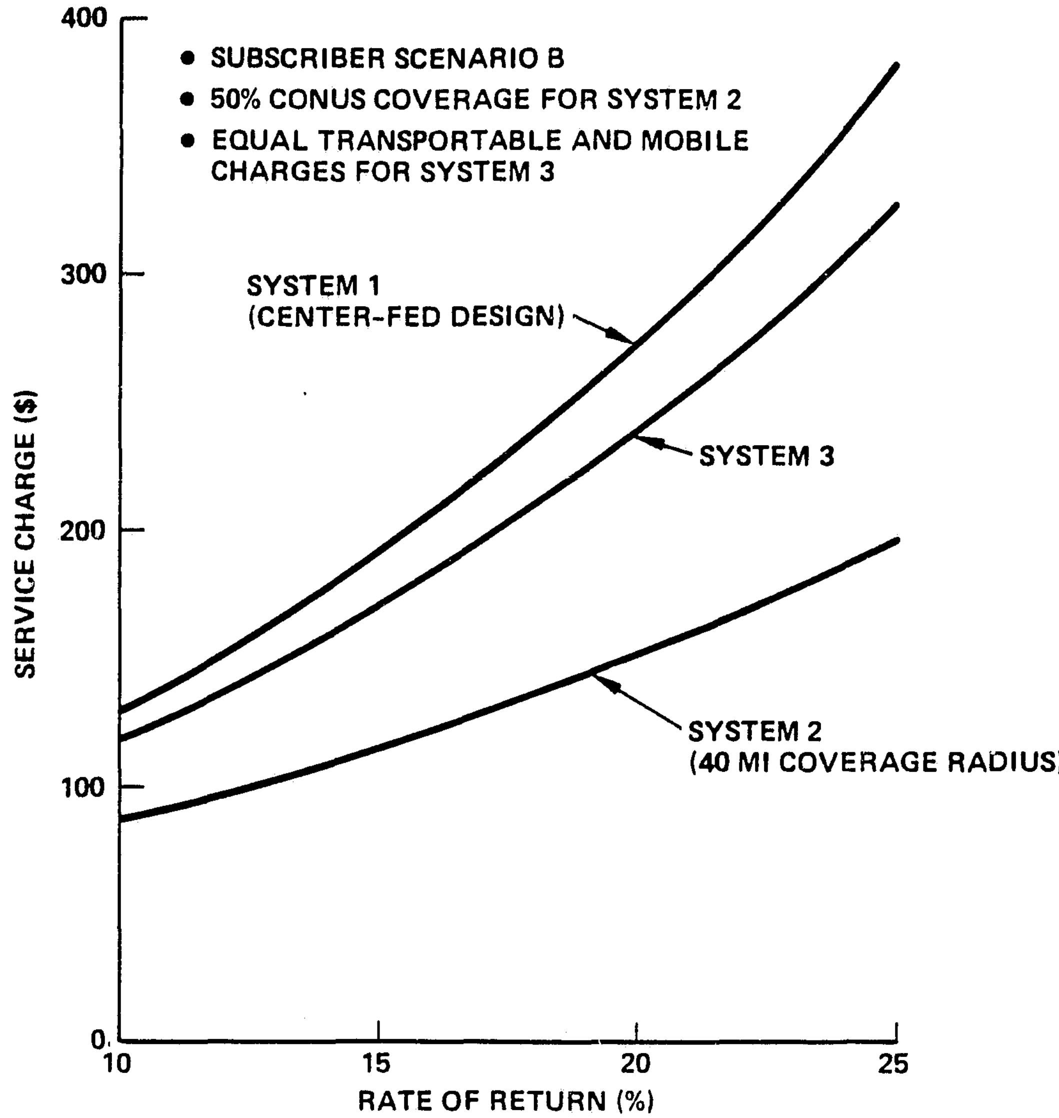

Figure 21. MSC System Comparison

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