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Grady H. Stevens and Godfrey Anzic
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

NASA is conducting a series of millimeter wave satellite communication system and market studies to: (1) determine potential domestic 30/20 GHz satellite concepts and market potential and (2) establish the requirements for a suitable technology verification payload which, although intended to be modest in capacity, would sufficiently demonstrate key technologies and experimentally address key operational issues.

The first task is being addressed by four contractor studies which are nearing completion. Two satellite suppliers, Ford Aerospace and Hughes Aircraft, are independently addressing the system issues while two service suppliers, ITT and Western Union, are independently addressing the market issues. The second task is to be the subject of future contracted studies which will be initiated during the spring of 1979. This paper describes preliminary results and critical issues of the current contracted effort. Also included is a description of a NASA-developed multibeam satellite payload configuration which may be representative of concepts utilized in a technology flight verification program.

INTRODUCTION

NASA, as one element of a recently-developed five year program plan, is in the process of laying the foundation for a new 30/20 GHz satellite communications research technology and demonstration effort. Although the initial efforts are directed toward the millimeter wave area, it is expected that the technology developed can be extrapolated to the lower frequency bands in which commercial services are currently or soon will be offered. At present, four contractual studies are nearing completion which specifically address the 30/20 GHz bands. Ford Aerospace and Hughes Aircraft are performing independent system studies to evaluate the capability and cost of 30/20 GHz systems. ITT and Western Union are performing independent market studies to estimate the demand for 30/20 GHz systems in the 1990's.

These studies are part of a new long range comprehensive effort by NASA to (1) identify the critical issues involved in commercial utilization of satellite bands, (2) develop and carry out a research and technology program which will resolve these issues, and (3) if necessary, develop and fly a modest satellite communications payload to provide industry the opportunity for experimentation in new frequency bands and with new services.

30/20 GHZ PROGRAM APPROACH

The 30/20 GHz program plan is illustrated in Figure 1. Currently, Phase I is nearing completion with Ford Aerospace and Hughes Aircraft performing the system studies and ITT and Western Union performing the market studies. A preliminary review of the Phase I effort was presented to industry and government representatives in November. A similar detailed review of the final contract results is planned this spring. It is expected that this cooperative effort will result in a concensus of probable 30/20 GHz operational satellite system concepts together with their ultimate market potential. In addition, a list of critical issues involving technology, operations, and markets will be developed.

In the discussion to follow, it is assumed though not yet established that a flight payload is required and that critical issues can be resolved with a communications satellite payload with relatively small capacity. The requirements for such a demonstration program would be developed in Phase II, where the critical issues will be examined and experiments defined which will resolve these issues. It is anticipated that the experimental program will consist of both ground and space tests. The space experiments will be further separated into groups that can be performed in low earth orbit and groups that are more appropriately performed at geosynchronous altitude. The requirements of a satellite payload will then be defined which performs all the necessary geosynchronous experiments. The design and development of the flight payload and integration with a suitable bus will be conducted in Phase III. Following this will be a government/industry experiment period in Phase IV which will be focused on resolving the critical issues identified in Phase I. Commercial introduction of service in the 30/20 GHz bands would occur as the service demand develops.

CRITICAL 30/20 GHZ ISSUES IDENTIFIED TO DATE

Through the current studies, several issues or concerns have already been identified. One of the overriding concerns is signal attenuation due to rain. For commercial applications, the availability of the communication system to the user must be predictable with a confidence sufficient for supplier/consumer contractual purposes. This requires a thorough understanding of the rain attenuation derived from a significant statistical data base. For the 30/20 GHz bands, considerable data on fade statistics has been taken. However, only limited data has been generally made available and considerable disagreement exists among propagation specialists as to the impact of rain fade in these bands. Figures 2 and 3 show selected comparisons of estimates of fade statistics for various regions of the U.S.

Figure 2 compares several attenuation estimates with experimental data obtained from Comstar and ATS-6 beacons. At 0.01 per cent outage, the estimates differ by 25 dB or more. The fade at 0.01 per cent is significant no matter which estimate is used, and 10-35 dB of system margin would be required on the downlink if a reliability of 99.99% with respect to rain fade is to be maintained.

The same reliability can be obtained with less margin if ground-station diversity is employed at each site. Physical separation of the ground stations in this way provides a measure of statistical independence which improves with the separation distance. Figure 3 shows a comparison of rain attenuation statistics for dual stations and the single station statistics from which they were derived. The single station statistics for Atlanta were estimated using a proposed CCIR technique[1] and a fundamentally different technique developed at Virginia Tech[2]. Assuming the stations can be separated sufficiently to ensure statistical independence, joint statistics can be computed from the single station CCIR statistics as shown. An alternate method of Hodge[3] can also be used to develop joint statistics and this has been done using the single station CCIR statistics as shown.

A third method of developing joint statistics accounts for the variation of correlation between stations as a function of rainfall rate. Generally, one associates large fades with very intense rain cells which tend to be small. So it seems reasonable that one could select a separation between terminals which would significantly reduce the likelihood of both terminals being in the same intense rain cell. However, there is a recognized phenomenon that the cell size varies inversely with rain rate[4]. At low rain rates (under 5mm/hr), the cell size can be 10Km or larger. At higher rain rates (above 100 mm/hr) the cell size is generally under 2Km. Thus, the rain rate is likely to be correlated at low rain rates even though the separation may be as much as 10-20Km. In the lower frequency bands, this would be of no consequence since rain attenuation at 5mm/hr is insignificant. However, for the 30/20 GHz bands, 5mm/hr of rain can cause 5-10 dB fades depending on the model used to predict the fade. Consequently, for the lighter rain rates, the stations may not be statistically independent and may exhibit the same statistics as a single station. An attempt has been made by Hughes to account for this partial correlation and the results are shown in Figure 3. Note that for the low values of attenuation the joint statistics approach the single station statistics. This model indicates a very rapid trend toward independence with increasing rain rate (increasing attenuation). These implications will be further examined as the studies progress.

Comparing these three statistical attenuation approaches, one finds considerable disagreement for the joint statistics - nearly as much as there was in the case of single station statistics. This uncertainty in rain fade assessment will contribute a significant uncertainty to the probable commercial configurations. Perhaps the more recent COMSTAR data will resolve these questions and provide a generally accepted assessment. If not, there will likely be a need for propagation experiments as part of the communications satellite payload.

Whatever the assessment, it appears that dual station terminals will be required to achieve highly reliable communications. Interconnecting these diversity stations can lead to significant added cost if it is desired to provide these interconnects at the full allocated bandwidth. Figure 4 shows a comparison of cost estimates of various methods of providing the interconnect. Currently, terrestrial microwave links would be the favored method of interconnecting these stations. However, by 1985 the cost of optical fiberguide is ecpected to be significantly lower and could be a contender for this application. In any case, Figure 4 shows that terminal interconnect costs can be a significant contributor to total system costs if it is necessary to provide the full allocated bandwidth. It also shows that for a given capacity, it is least expensive to provide the interconnect at the T4 level instead of the T3 level.

Another issue arises in the use of multibeam technology. Past studies indicate an apparent advantage in the use of multibeam techniques in the 30/20 GHz bands due to increased satellite antenna gain as well as spectrum conservation[5].

Figure 5 shows the results of an early assessment of this effect. High gain antennas are used to direct small spot beams onto each ground site. This leads to lower power and potentially less expensive satellites. In addition, the spectrum can be reused allowing for improvement of capacity. Even in the two node case shown in Figure 5, the estimated cost per duplex link is lower than current costs. The situation is improved as the number of beams increases although the rate of improvement is slower as the number of beams approaches 10. Of course, the satellite would not be fully utilized over its life cycle as assumed in this figure. However, one can approximately account for this and other missing operational factors by inflating these costs by a factor of 2-4. Even so, the resulting costs appear attractive. These trends are being re-examined as part of the current studies and the network size is being extended to 40 spots.

Many network configurations are being evaluated and Figure 6 indicates a typical 10 node network based on current traffic trends. Note that some beams are isolated and interference between these beams is no problem. However, for this case, since cities in the northeast corridor and on the west coast are quite close, interference between beams can arise depending on the attainable antenna performance. This problem becomes more significant when direct service to a larger number of cities is desired. The evaluation of future traffic growth indicates that additional cities of interest would also be located in the northeast corridor, further aggravating the interference potential. This conclusion is a direct result of evaluation of current traffic growth trends which are expected to continue.

Whatever the optimum network size, the resulting interference can be minimized by designing the S/C antennas for low sidelobes and good scan performance. Figure 7 shows an estimate of performance for a particular antenna configuration. An east-west and a north-south cut of a typical beam is shown for the case where the beam is scanned 3 degrees off axis. In this case, a 4.3 meter offset cassegrain antenna having an f/D ratio of about 1.1 was assumed. From these curves, one can expect good sidelobe performance to be maintained over the U.S. with such an antenna. However, it still may be necessary to provide for further isolation of adjacent beams in the northeast corridor and on the west coast by using cross polarization discrimination or possibly frequency discrimination. Polarization discrimination is preferred because of the attendant frequency re-use capability. It is believed that polarization discrimination techniques can be effectively used in these bands for rain margins less than 10 dB on the downlink and perhaps less than 20 dB on the uplink.

Even if all of these techniques are used, measurable beam-beam interference will be present which will cause some degree of degradation. To arrive at an estimate of this degradation, NASA-Lewis has performed network simulations and Figure 8 shows the components used to simulate the 10 node network of Figure 6 which includes a link from New York to Los Angeles. In this simulation the worst interference case was considered. This was judged to be a link from New York to Los Angeles with Washington causing uplink cochannel interference and traffic to San Francisco causing downlink cochannel interference. The level of this interference would be reduced by the sidelobe performance of the antenna but would nevertheless produce a measurable degradation in BER performance. Adjacent channel interferers are also shown and these allow a determination of channel spacing effects. Intermodulation effects were not included.

With the selection of three channels per TWT, the intermodulation products can be placed sufficiently far away from the desired channels that they are easily filtered out. Therefore, for this case, this effect was disregarded and the satellite was treated as a linear channel. The results of this simulation are shown in Figure 9. The uplink interferer levels were varied from -15 to -30 dB while the downlink interference was set constant at -30 dB. The selection of -30 dB for the downlink is consistent with the much greater separation between beams on the west coast. The combination of beam separation and polarization isolation should easily meet this goal. In contrast, the Washington and New York City beams overlap and polarization discrimination must provide the bulk of the isolation. Therefore, for the uplink, it is appropriate to examine a variation on the isolation since here it is more uncertain as to what isolation is attainable. The simulation indicates that for a BER of 10^{-6}, sufficient spacecraft power must be provided to maintain an E_b/N_o of 14.6 dB if no less than 20 dB isolation is obtained on the uplink. Only about 0.7 dB of S/C power can be saved by improving the isolation on the uplink in excess of 30 dB. Even if both the uplink and downlink isolation were as much as -40 dB, only an additional 0.2 dB power advantage would be obtained. Apparently, for only two interferers, the adjacent channel interference and the intersymbol interference dominates the degradation from ideal performance (about 3 dB of degradation). Significant additional degradation only occurs when the uplink isolation is less than 20 dB.

With more cochannel interferers, which occurs for network sizes larger than 10 nodes, more isolation would be desired. For example, a 12 node network was also examined and in that case a 1.5 dB power advantage was obtained when improving isolation on the uplink from -20 to -30 dB.

This beam-beam interference will limit how closely one can place beams. As the number of nodes is increased, one must depend more on beam separation to achieve isolation since polarization isolation can only be used once. Other nearby beams must be isolated through sidelobe rejection and, hence, must be physically separated. At 10 nodes, traffic trends are such that two beams would touch (NY city and Washington). This cannot be improved significantly without using much larger apertures than are already assumed. The 10 node case of Figure 6 assumed the use of 4.3 meter aperture, nearly the maximum that can be fitted into the shuttle orbiter cargo bay. Thus, these spots are about as small as one could make them (assuming large unfurlable antennas are not practical at this frequency). Beams to other areas cannot arbitrarily be added. Instead, they must be placed according to traffic demand. Moreover, as more beams are added, the traffic in the additional beams would become so light as to make the economic justification of diversity stations questionable. Thus, these constraints, taken together, will limit the maximum number of beams per spacecraft. Consequently, there will be an upper limit to the frequency reuse obtained in this way. In spite of this limitation, the capacity of these multibeam satellites can be many times greater than current satellites. This raises the question of how best to match these large capacity systems with known trends in traffic growth. Even though the economy-of-scale effect might persist to 50 beams or more, this effect is of little value if the traffic pattern is not such that all links are not fully utilized.

A typical variation of traffic density between nodes as a function of the number of nodes in the network is shwon in Figure 10. The ratio of the required capacities of the maximum traffic link to the minimum traffice link in the New York City beam varies from about 5:1 in a 10 node network to about 12:1 in a 40 node network. The ratio of the required capacities of the maximum traffic link to the minimum traffic link in the spacecraft varies from about 25:1 in the 10 node network to about 188:1 in a 40 node network. With such variation in traffic among the various links, an equal division of bandwidth among nodes would result in an extremely under-utilized system.

This variation in required capacity raises the issue of the best access/modulation method to use. From the studies conducted to date, an FDMA configuration rapidly loses attractiveness for more than 10 nodes. TDMA offers more flexibility in that it can more efficiently allocate spectral resources among nodes having a wide variation in traffic demand, and in principle this technique would efficiently provide for interconnecting the larger number of nodes without the complexity of an equivalent FDMA configuration. Even so, for the larger number of nodes, some links may have insufficient traffic to justify the expense of a diversity station. Therefore, there is definitely an upper limit to the number of nodes one would try to interconnect if the users demanded high reliability.

The method of compensating for rain fades is another issue to be resolved. Diversity will be required but even with diversity, margins of as much as 10 dB may have to be used to ensure reliable links. One way of providing such a margin is to use a dual power mode TWT. It appears feasible to do this without a significant penalty in TWT efficiency provided one uses a properly designed depressed collector[6]. NASA-Lewis investigators estimate that in the high power mode such a device would have an overall efficiency of better than 37 per cent even with the TWT backed off 4 dB. In the lower power mode, the efficiency could be expected to exceed 22 per cent and this also includes a 4 dB backoff.

Alternatively, if the RF power required per channel is sufficiently low, solid state HPA's could be used. They may offer improvements in reliability as well as simplicity and compactness. However, they are not expected to be as efficient as the TWT even when the TWT is backed off. This could lead to a significant spacecraft power penalty whenever the communications power requirement dominates the spacecraft power requirement.

Another alternative is to resort to bandwidth reduction or coding techniques during a fade. However, since a 10-20 dB change would result in a significant reduction of throughput, the methods previously described are preferred at this time.

Figure 11 summarizes these preliminary issues. Other issues than these have arisen and by the end of Phase I it is anticipated that additional issues will be identified.

A POTENTIAL 30/20 GHZ DEMONSTRATION PAYLOAD CONFIGURATION

Issues such as those in Figure 11 will be the basis for a technology demonstration definition effort in Phase II. A hypothetical demonstration configuration is illustrated in Figures 12 and 13. Figure 12 indicates the selection of coverage for the experimental communications payload which can only cover a small portion of the U.S. The coverage for a propagation experiment, if required, is not shown but preferably it would allow CONUS coverage. The lesser coverage for the communication payload is believed to be sufficient for the communication tests and it would be significantly less complex and expensive than a full U.S. coverage configuration. A set of seven contiguous spots are included as well as one isolated spot. The seven contiguous spots would be representative of a typical cell in a contiguous beam system having extensive frequency re-use as in a direct-to-user type service. In such a system, each spot would have a separate portion of the frequency spectrum and filtering would be used to obtain isolation within the cell. Adjacent cells would depend on the sidelobe performance for isolation. The isolated spot would be typical of a trunking type system and can be used to determine isolation in both types of systems by assigning to it a portion of the spectrum common to one of the spots within the 7 spot cell. This isolation could be determined for various separations and the data used to calculate the isolation achievable in trunking systems or full coverage direct-to-user systems which might consist of 100 spots or more. Simultaneously, communication experiments could be performed with high density traffic being routed from the isolated spot to any spot in the cluster. This would simulate high density trunking. Alternatively, lower density traffic corresponding to direct-to-user service could be routed between the beams in the 7-spot cell. All this could be achieved with the use of a fixed array of 7 feeds and one movable feed or the selection of any eight of a large array of feeds. This latter method has the greater flexibility. The demonstration of multibeam techniques in this fashion should have general utility and the results could also be applied to enhancement of the capacity of the lower frequency bands. Such tests and demonstrations would provide engineering data describing typical levels of beam-beam interference and system degradation due to interference. Such results could be used to predict the results for almost any configuration. At the same time significant technology demonstrations could be achieved.

Figure 13 is a block diagram of the total payload. It includes a multibeam communications payload as well as a 30/20 GHz beacon. The communications portion shows one method of interconnecting the eight spots. And in this package, three receivers are shown, one of which is provided for redundancy. One receiver would be used for the seven spot cell and one for the isolated beam. This would maximize the isolation between received signals for evaluation of beam-beam interference. For the same reason, independent transmitters are used on the downlink.

An 8x8 baseband processor is suggested in this concept. However, an IF processor could have been used and in fact for an 8x8 configuration, the IF processor would likely be an easier technology to pursue. The choice between baseband processing and IF processing is affected by the size of the network to be interconnected and the flexibility in switching required. If the current market studies show that a large number of beams are not warranted, the preferred configuration may be an IF processor.

In order to illustrate the impact of this payload on typical spacecraft, a hypothetical experimental configuration is shown in Figure 14. In-house studies indicate this payload could be carried aboard several existing busses such as those used in FLTSATCOM, INTELSAT-V, SYNCOM IV, as well as the NASA MMS. For illustration purposes, the payload is shown integral with an MMS bus. It includes two antennas, one each for the uplink and downlink. Both are of the offset cassegrain type but of relatively long focal length to diameter ratio. As mentioned previously, a ratio of 1.1:1 appears to be sufficient to ensure good scan performance over the U.S. The large main reflectors are positioned on opposite sides of the spacecraft while the subreflectors are nearer the center of the spacecraft nearly obscuring the up and downlink feed arrays. In this particular concept, feed arrays are used so that any eight feeds could be selected to perform a particular experiment. As shown the size of the antennas dwarf the MMS bus. However, these antennas cannot be made much smaller if one desires to demonstrate the generation and control of very narrow spot beams. On the other hand, the antenna weight is relatively low and the total payload weight is within the capacity of all the aforementioned busses. Alternative configurations including these busses will be examined in Phase II and III. The approximate envelope for a full scale 10 beam FDMA system is also shown to illustrate the potential growth. The weight budget illustrated only applies to the experimental configuration.

SUMMARY

NASA is proceeding with a comprehensive assessment of the commercial viability of the 30/20 GHz bands with the objective of demonstrating the required technologies and resolving the critical issues involved in operation of millimeter wave satellites in the U.S. As a result of this effort, NASA would provide the catalytic action to encourage the introduction of spectrum conservative commercial millimeter wave satellite services. This would offer an alternative to the expected congestion and, perhaps, saturation of C-band and Ku-band systems in the 1990's.

REFERENCES

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(2) Persinger, R.R.; Stutzman, W.L.: "Millimeter Wave Propagation Modeling of Inhomogeneous Rain Media for Satellite Communication Systems"; June 1978 NASA-CR-156817.

(3) Hodge, D.B.: "An Empirical Relationship For Path Diversity Gain". IEEE Transactions on Antennas and Propagation, Vol. AP-24, No. 2, March 1976.

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(5) Hilsen, N.B.; Et Al.: "Millimeter Wave Satellite Concepts", Volume 1, NASA CR-135227, September 1977.

(6) Kosmahl, H.G.: "A Novel, Axisymmetric, Electrostatic Collector for Linear Beam Mincrowave Tubes", NASA Technical Note D-6093, February 1971.

NASA WIDEBAND PROGRAM

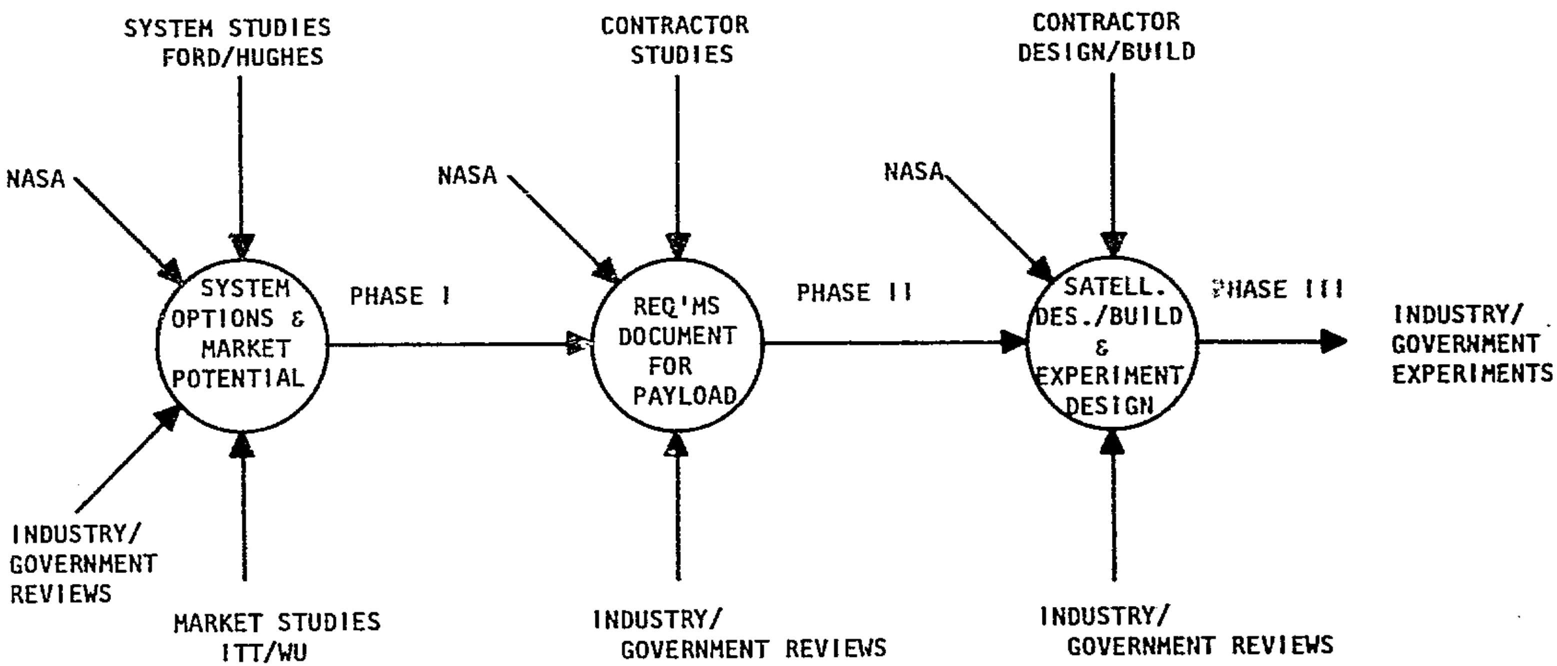


FIGURE 1

18 GHz RAIN ATTENUATION FOR CLIMATE ZONE 3

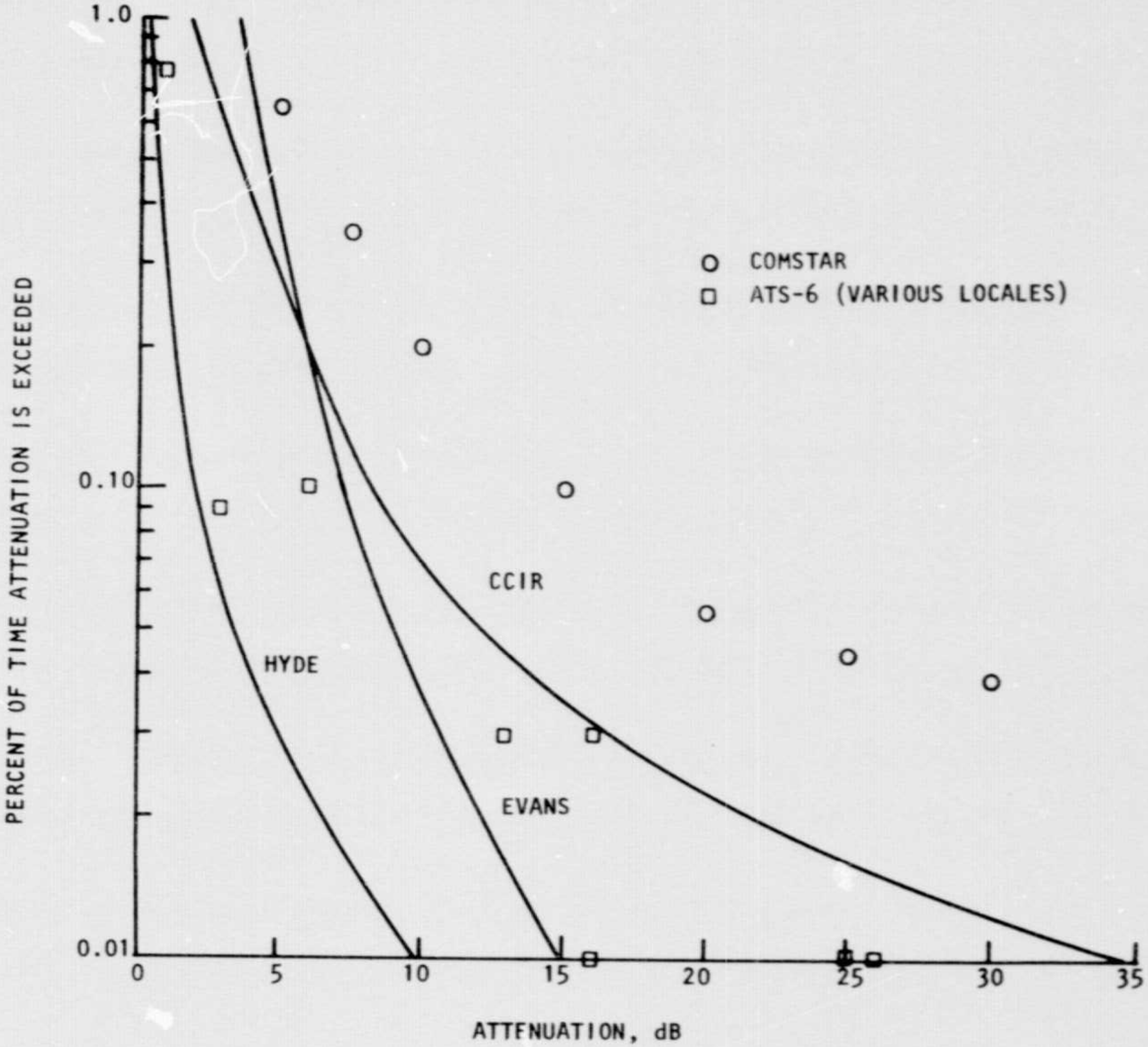


FIGURE 2

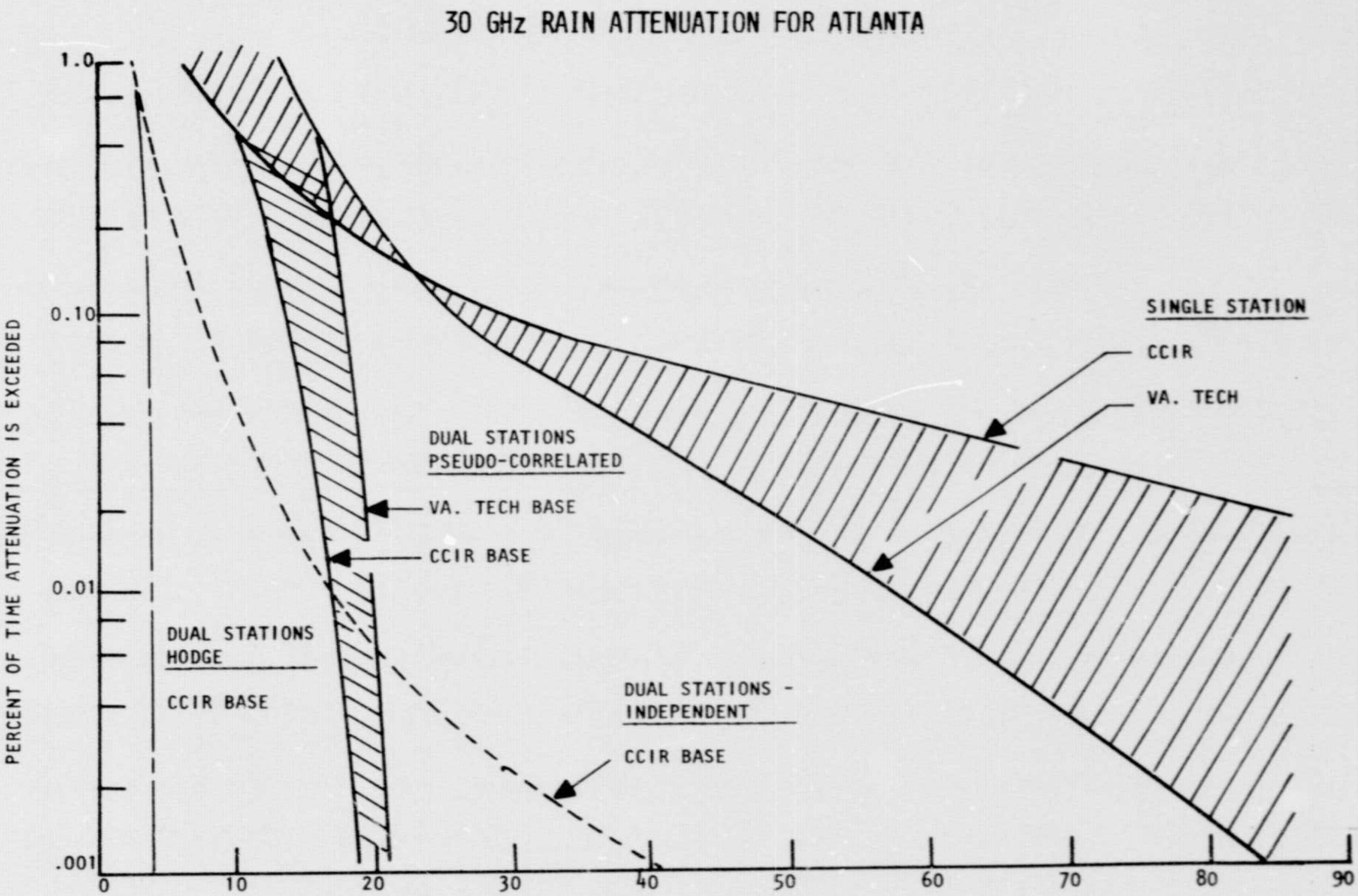

30 GHz RAIN ATTENUATION FOR ATLANTA
PERCENT OF TIME ATTENUATION IS EXCEEDED
1.0
0.10
0.01
.001
0
10
20
30
40
50
60
70
80
90
SINGLE STATION
CCIR
VA. TECH
DUAL STATIONS
PSEUDO-CORRELATED
VA. TECH BASE
CCIR BASE
DUAL STATIONS
HODGE
CCIR BASE
DUAL STATIONS -
INDEPENDENT
CCIR BASE

FIGURE 3

SPACE DIVERSITY INTERCONNECT COST

30 KM LINK

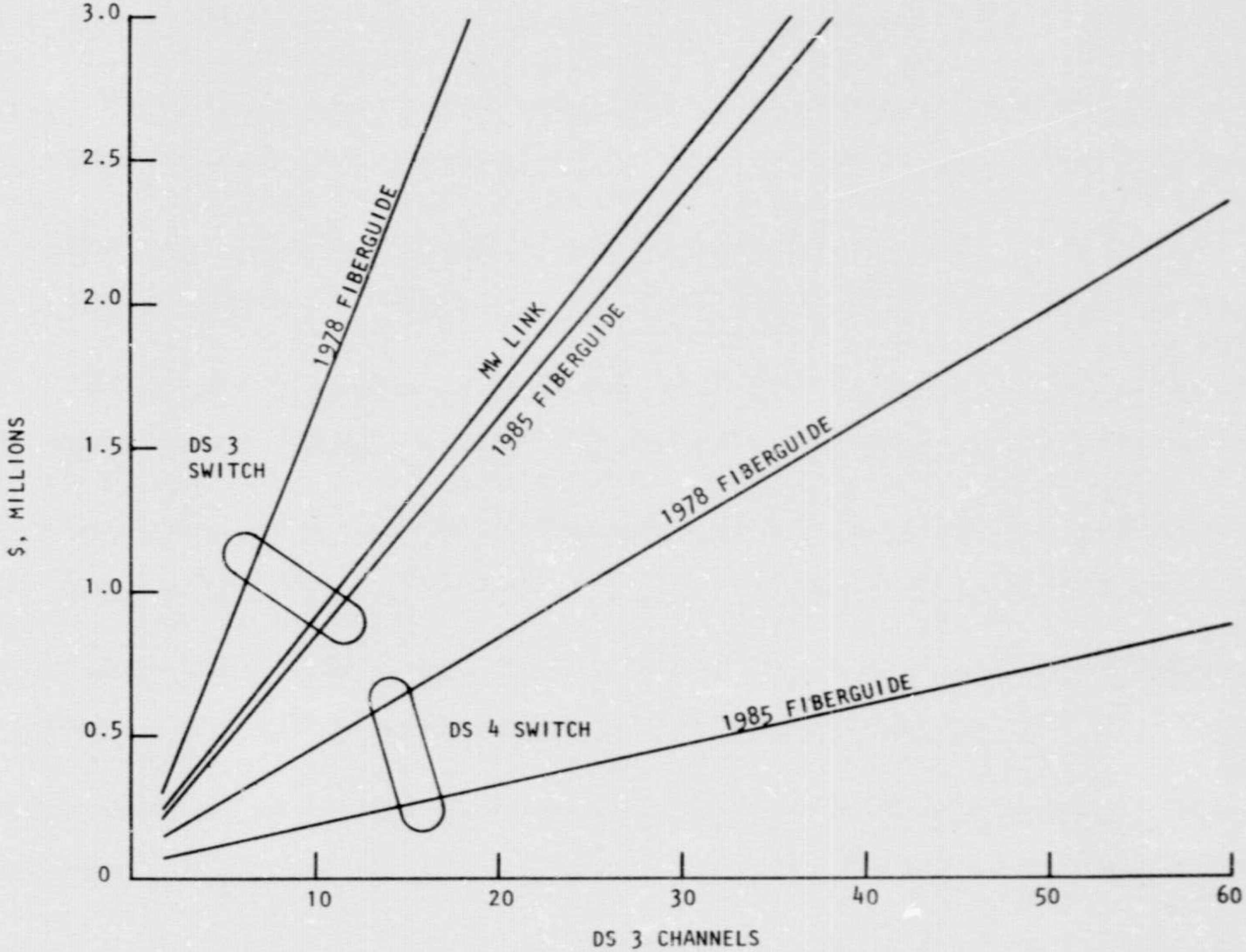


FIGURE 4

ESTIMATED COSTS FOR 30/20 GHz TRUNKING SYSTEM

(Cost variation with number of ground sites for a rain reliability of 99.9)

*NUMBER OF GROUND SITES	GROUND ANTENNA SIZE, M	GROUND COST $M	COST PER SATELLITE $M	SAT. WT. LBS.	LAUNCH COST (VEH)/COST	DUPLEX CAPACITY	MONTHLY COST/ DUPLEX VOICE LINK ** $
2	6.23	11.30	10.55	1877	(AC)/15.1	30,000	59.2
4	4.89	21.45	11.44	2104	(AC)/15.1	60,000	34.7
6	4.31	31.76	11.81	2090	(AC)/15.1	90,000	26.2
8	3.96	41.63	12.35	2200	(AC)/15.1	120,000	21.9
10	3.69	51.87	12.61	2334	(IUS)/25.9	150,000	21.2

* Two terminals per site (two-station diversity).

** Assumes 3 satellites, one on-orbit spare, one ground spare and full utilization of one satellite. Price would be approximately a factor of 2-4 higher to account for actual utilization and other operational factors.

FIGURE 5

ANTENNA COVERAGE FOR 10 SITE TRUNKING SYSTEM

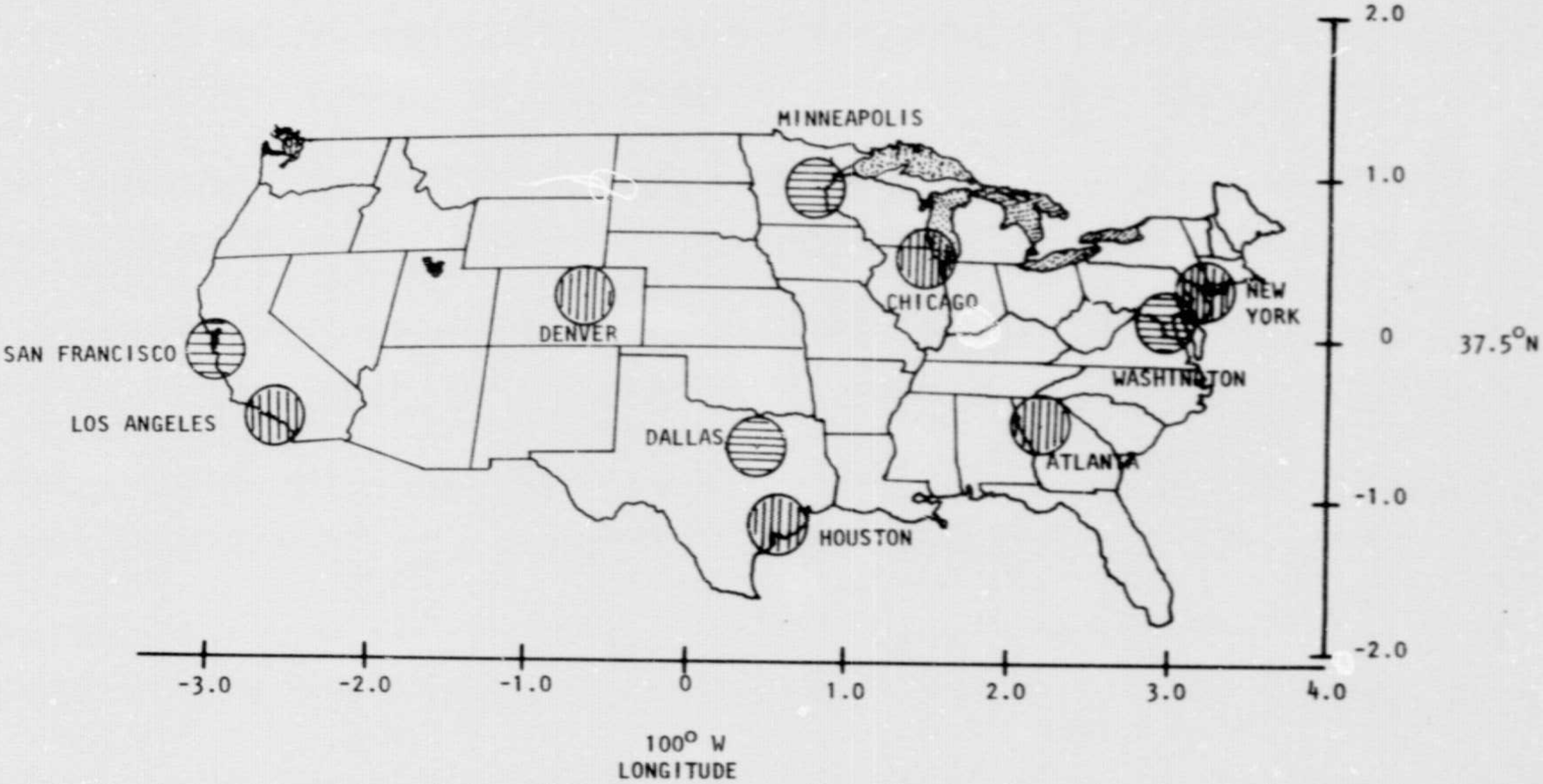
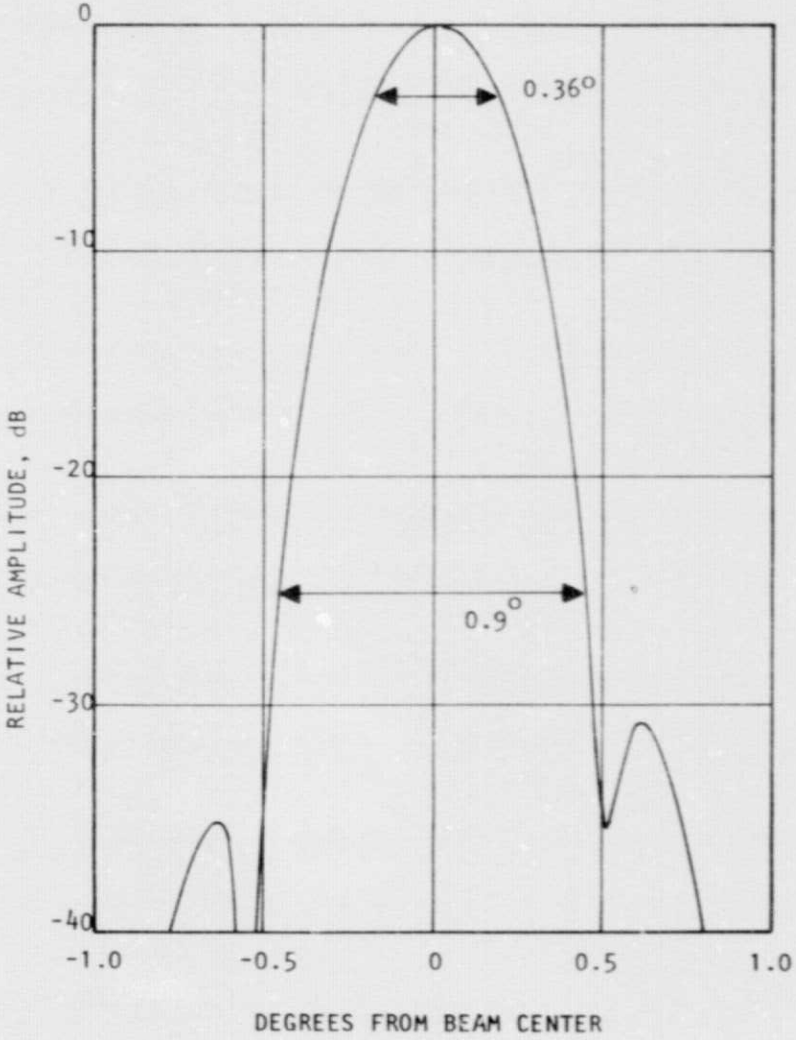
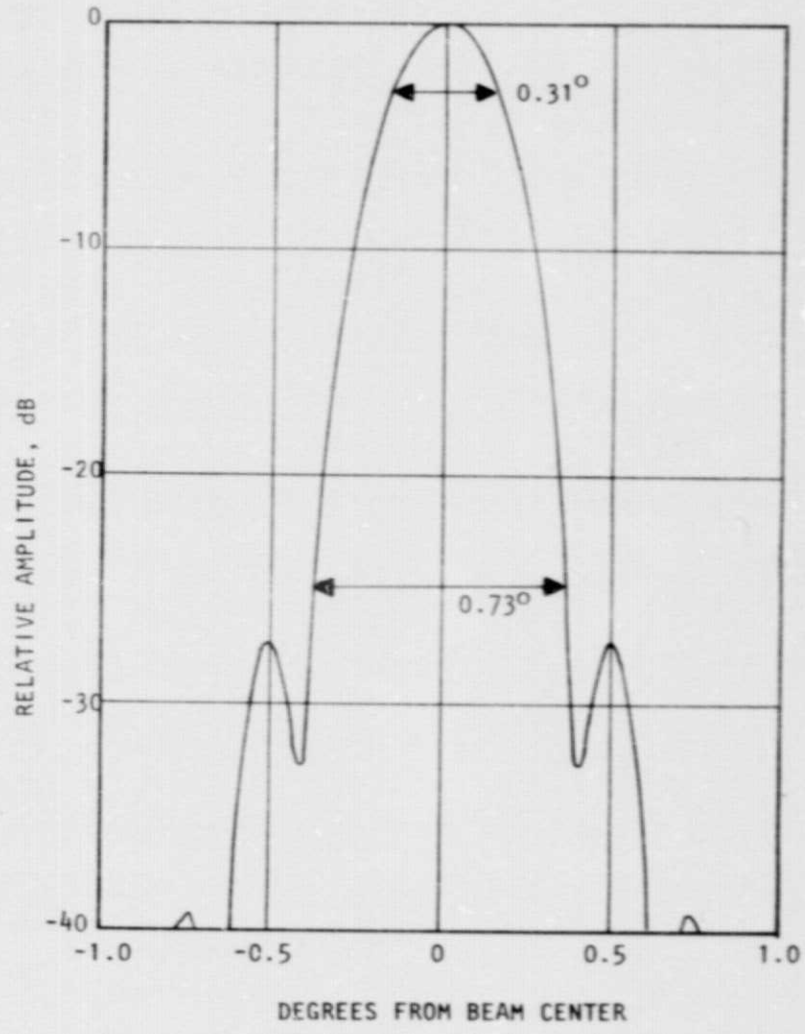


FIGURE 6

18 GHz ANTENNA PATTERN AT 3° SCAN ANGLE



(a) EAST-WEST DIRECTION

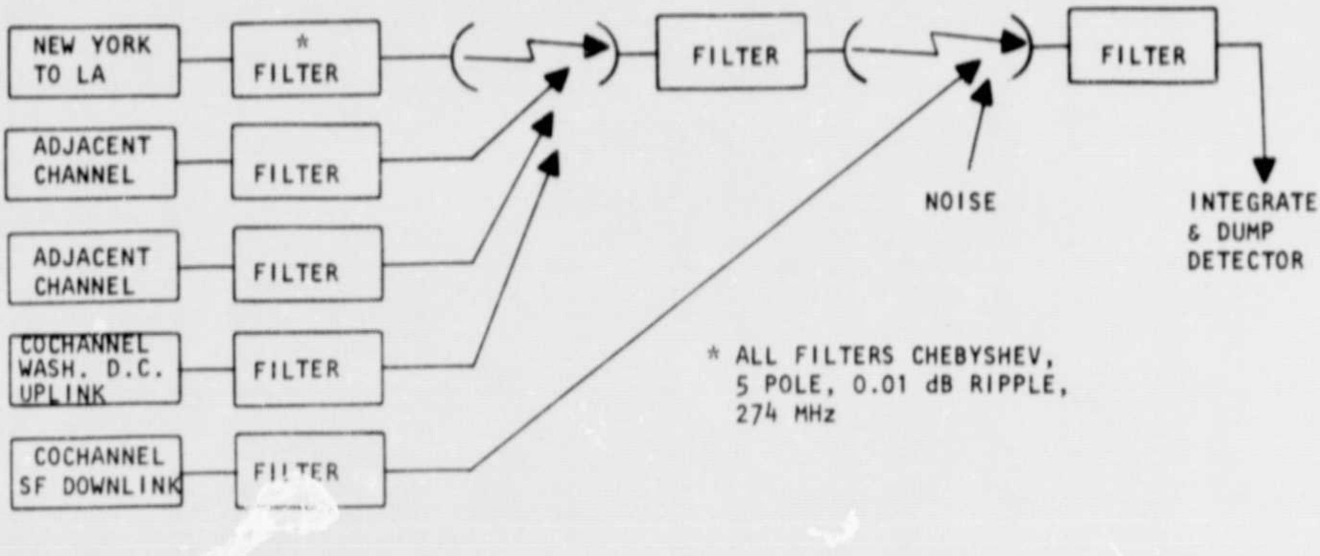


(b) NORTH-SOUTH DIRECTION

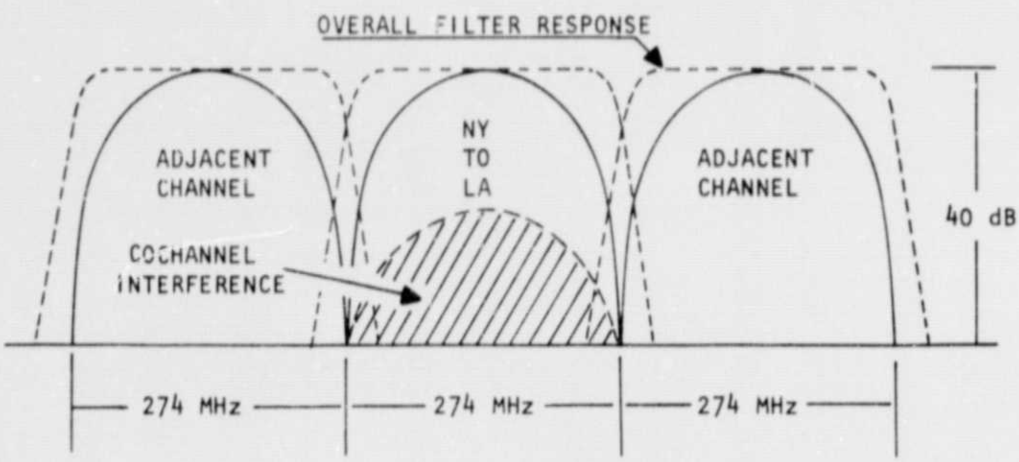
FIGURE 7

SIMULATION OF NY-LA 274 Mbs QPSK

COMM. CHANNEL



(A) ELEMENTS OF NETWORK SIMULATION



(B) POWER SPECTRUM OF RECEIVED SIGNAL

FIGURE 8

BER PERFORMANCE OF NY-LA
274 MBS QPSK LINK

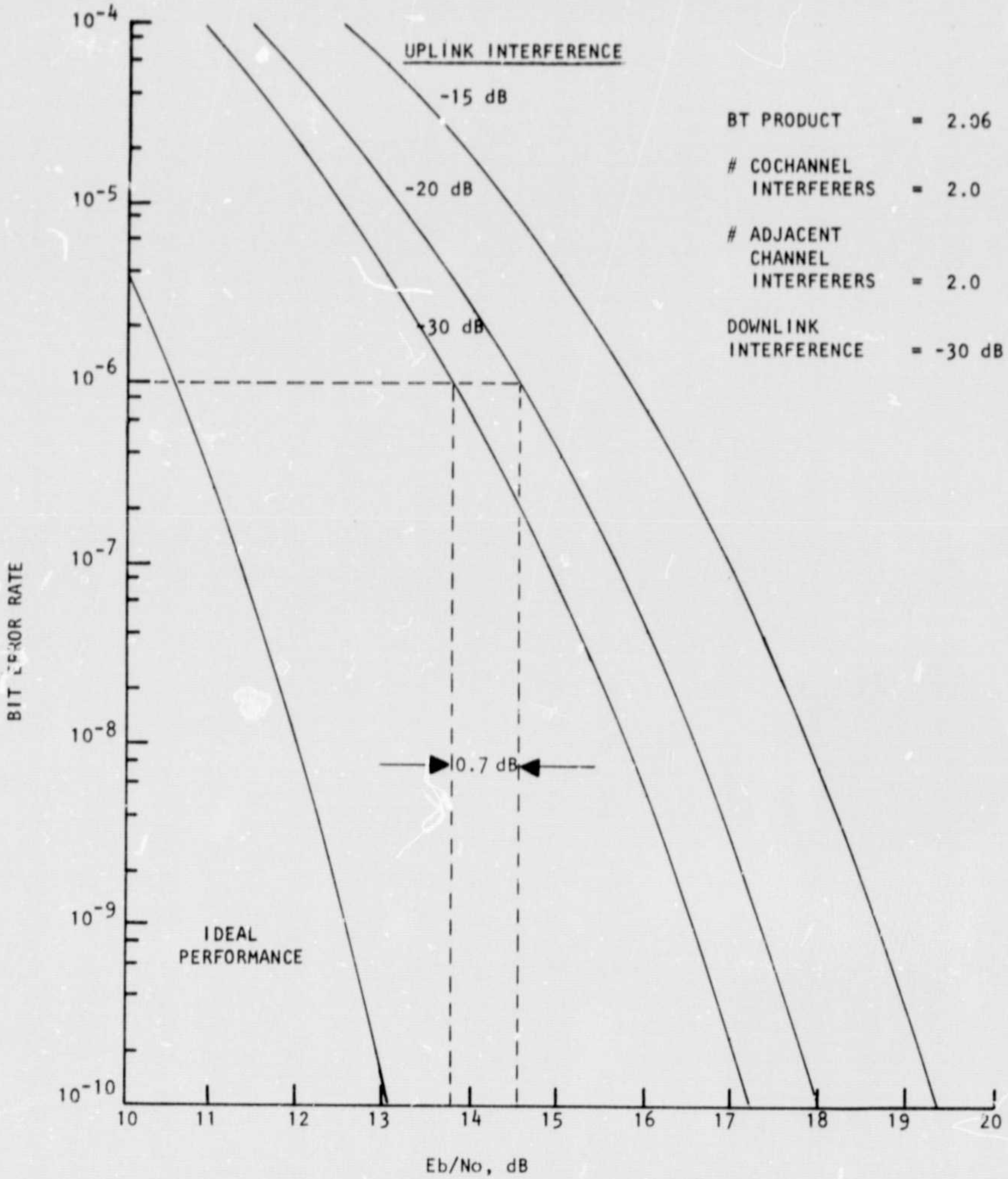


FIGURE 9

VARIATION OF TRAFFIC AMONG NETWORK LINKS AS A FUNCTION OF NETWORK SIZE

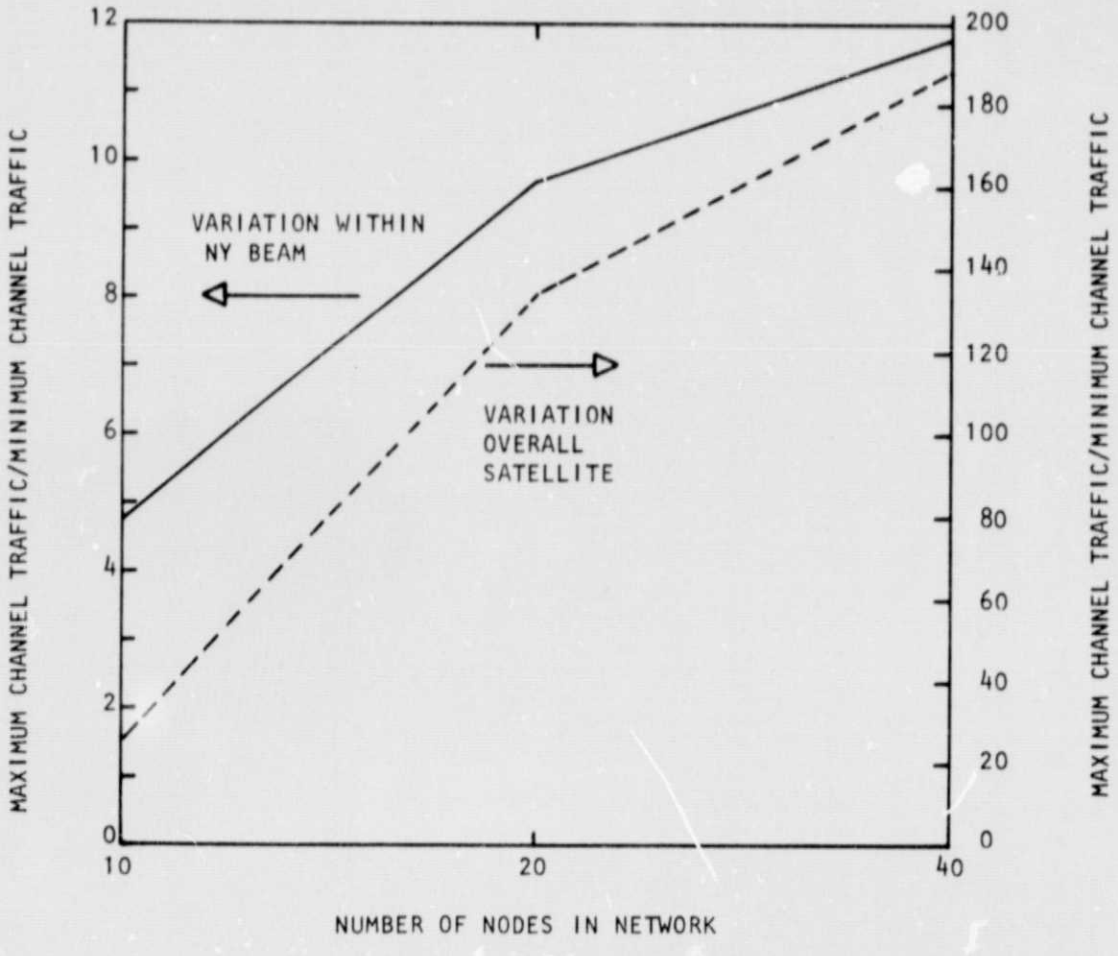


FIGURE 10

PRELIMINARY 30/20 GHz ISSUES

- PROPAGATION ASSESSMENT
  - WHAT ARE THE MARGINS REQUIRED TO ACHIEVE RELIABILITY WITH RESPECT TO RAIN OF UP TO 99.99%?
  - WHAT ARE THE OPTIONS AND MOST EFFECTIVE METHOD FOR RAIN FADE COMPENSATION?
- BEAM-BEAM ISOLATION
  - WHAT IS NEEDED?
  - MINIMUM USABLE C/I?
- NETWORKING METHOD
  - FDMA, TDMA, HYBRID?
- MARKET ASSESSMENT
  - IS THERE A MARKET FOR REDUCED RELIABILITY SERVICES?
  - IS THERE A MARKET FOR WIDEBAND SERVICES?

FIGURE 11

HYPOTHETICAL 30/20 GHz EXPERIMENTAL
SATELLITE SPOT BEAM CONFIGURATION

FIGURE 12

HYPOTHETICAL 30/20 GHz EXPERIMENTAL PAYLOAD

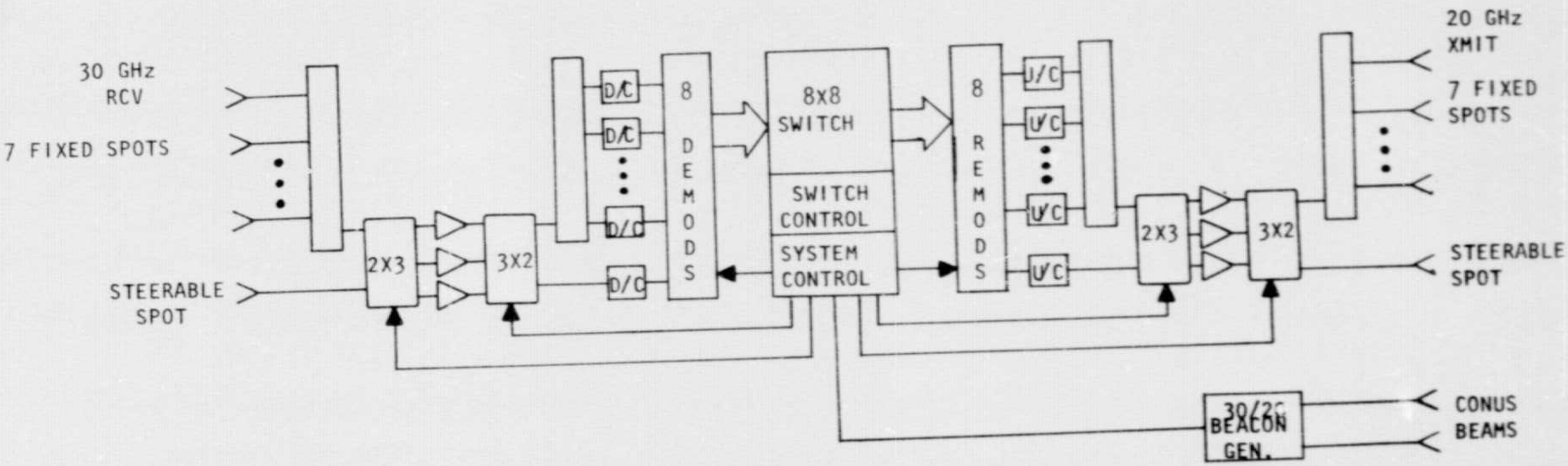
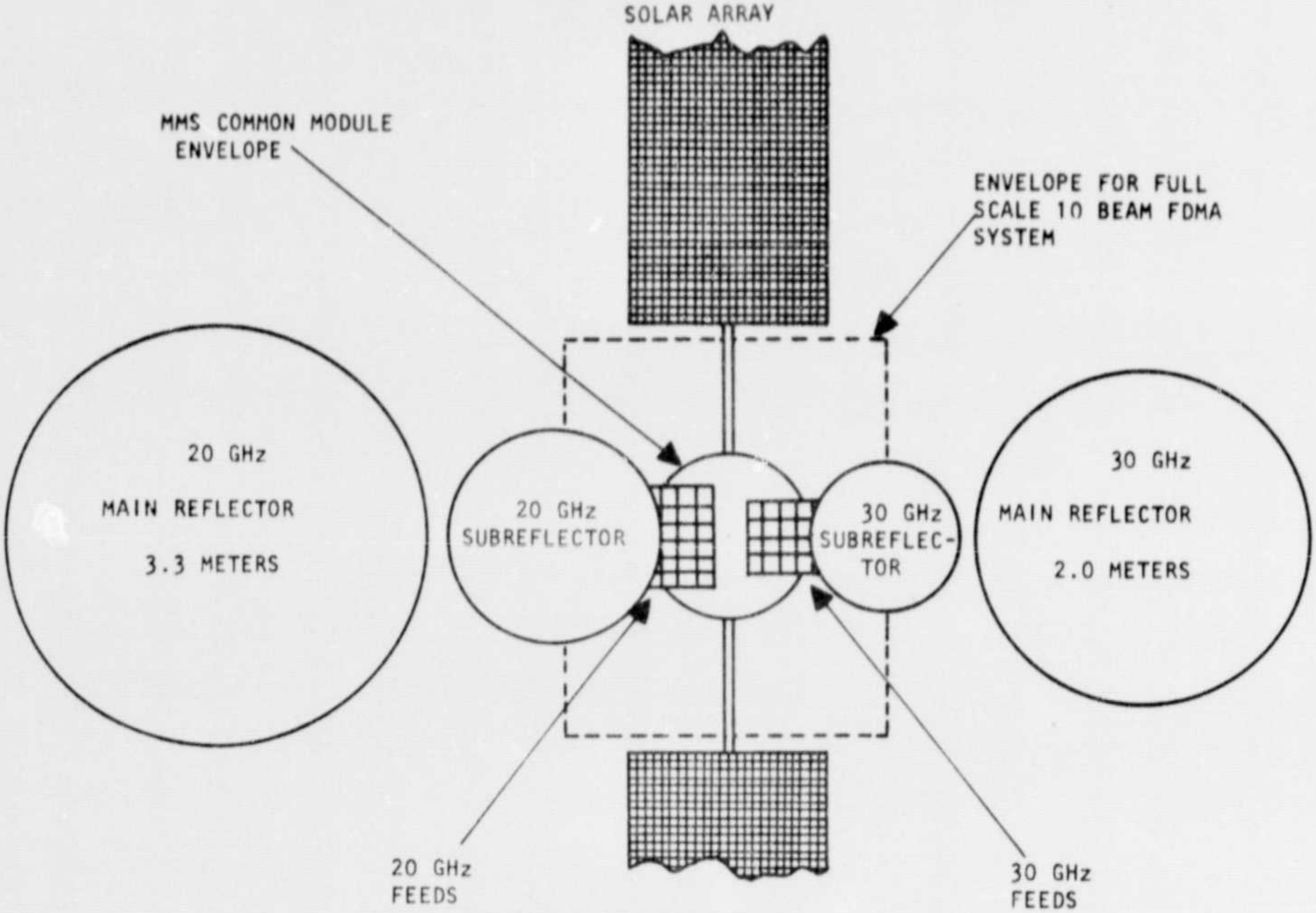


FIGURE 13

HYPOTHETICAL 30/20 GHz EXPERIMENTAL SATELLITE



EXPERIMENTAL CONFIGURATION
WEIGHT BUDGET, Kg (POUNDS)

ANTENNAS	113.4	(250)
COMMUNICATIONS & BEACON	136.1	(300)
POWER SYSTEM	27.2	(60)
COMMON MODULE	22.7	(50)
	299.4	(660)
MMS	589.7	(1300)
	889.1	(1960)
AKM & FUEL	467.2	(1030)
TOTAL	1356.3	(2990)

FIGURE 14