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LANDSAT D

LOCAL USER TERMINAL STUDY

FINAL REPORT

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PREPARED FOR

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

UNDER

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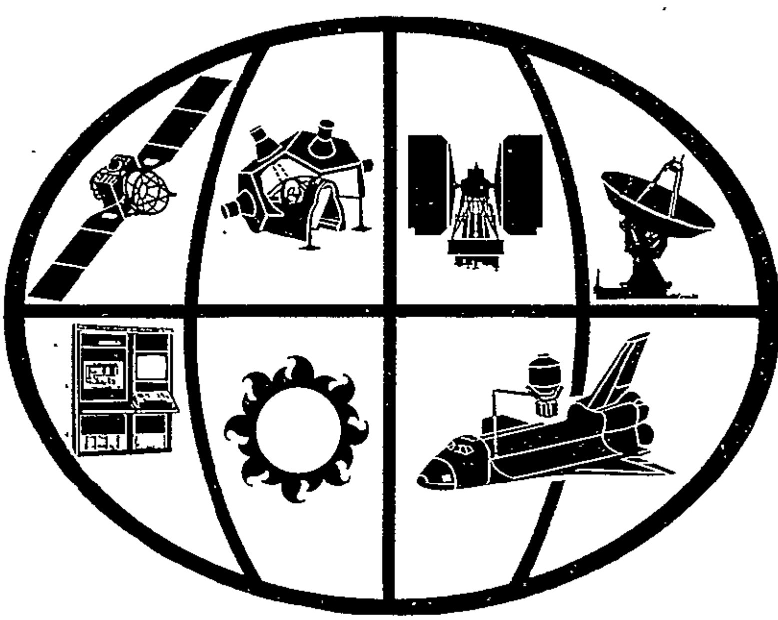

space division

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PREFACE

This study was undertaken in order to assess the impact of the LANDSAT D mission on existing, or planned, direct readout ground stations (Local User Terminals), and to determine potential LANDSAT D design alternates that might minimize this impact.

This study report summarizes the key findings of this study. These areas include the impact of the use of the Ku-band communications link, the effect of the higher Thematic Mapper data rate (120 Mbps), and the use of alternate methods of data acquisition by the Local User Terminal.

In addition, a questionnaire was developed (Appendix A), to be sent to all foreign organizations that expect to be receiving LANDSAT D data, in order to assess the magnitude of the impact of the LANDSAT D system in each case. Results of this questionnaire were not available at the time of this publication.

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1.0 INTRODUCTION AND SUMMARY

Beginning with LANDSAT "D" NASA will launch a series of earth observation satellites. The purpose is to provide US and foreign users of these data with higher resolution, more spectral bands, and more frequent observation. The baseline design for the LANDSAT D Spacecraft (see Figure 1) is that of the Modular Multi-mission Spacecraft (MMS) carrying a payload of the Thematic Mapper (TM) and the Multispectral Scanner (MSS). The system will provide two data links to the Earth, one a direct link to domestic and foreign ground stations and the other link via the Tracking and Data Relay Satellite System (TDRSS). The direct readout link will employ S-band for transmission of MSS data and Ku-band for transmission of both TM and MSS data. The S-band link will be identical to that carried on current Landsat 1 and 2 vehicles. In addition, there will be no on-board storage of data.

The spacecraft will be in either a 705 km or 915 km sun synchronous orbit with a nominal descending node time of 9:30 AM. With two similarly equipped spacecraft in-orbit, the LANDSAT D system will offer a 9 day repeatability cycle. Improved spacecraft pointing accuracy (0.01 degree) and stability ($< 10^{-6}$ degree/second) will improve the geometric fidelity of the acquired imagery.

The Thematic Mapper's spatial resolution has been increased to approximately 30 meters on the ground and its output data rate is assumed to be 120 megabits per second (Mbps). The Multispectral Scanner will maintain its 80 meter resolution and nominal output data rate of 15 Mbps. A "compacted" MSS data rate of 9 Mbps was also considered in the study. This reflects the fact that the MSS data stream may be made more efficient by suitable on-board buffering to remove unwanted data words (arising from the back scan of the MSS scan mirror). The sensor characteristics (resolution, word length, numbers of spectral bands) are not changed.

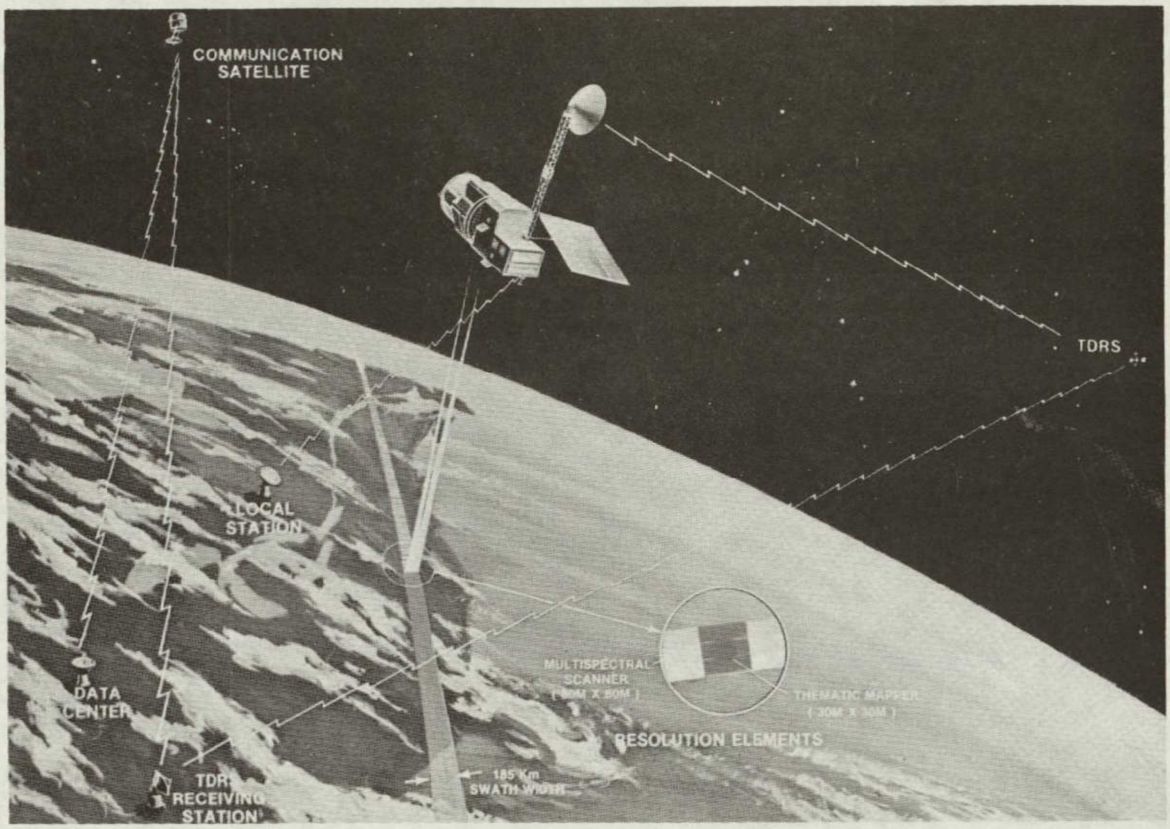

Figure 1-1. The LANDSAT-D System

As shown in Figure 1, the direct readout link, from the satellite to a Local User Terminal (LUT), is the most rapid and direct route for an LUT to acquire imagery of its reception area. The second link, from the LANDSAT D spacecraft to the TDRSS satellite, and on to the TDRSS receiving station in White Sands, New Mexico. allows for global acquisition of data, regardless of the presence of an LUT.

The purpose of this study was to determine the effect of the changes incorporated in the LANDSAT D system on the ability of a Local User Terminal to receive, record and process data in real time. In addition, alternate solutions to the problems raised by these changes were evaluated.

First, a loading analysis was performed in order to determine the quantities of data that a Local User Terminal would be interested in receiving and processing. The number of bits in an MSS and a TM scene were calculated along with the number of scenes per day that an LUT might require for processing. These then combined to a total number of processed bits/day for an LUT as a function of sensor and coverage circle radius (See Tables 2-1, 2-2 and 2-3). These figures will be used in later portions of the analysis in evaluating transmission, receiving and recording options.

The next subject addressed was the feasibility of various methods of data relay from the US to a Local User Terminal. This assumes that the data has been relayed through the TDRSS satellite to White Sands, New Mexico. At this point the data may be transmitted directly to an LUT or subjected to further processing at a central processing facility first. The most widely discussed method of international data transmission makes use of the INTELSAT satellite system. This investigation establishes, however, that the INTELSAT system is extremely costly for transmission of high data rates to the point of pricing itself out of consideration. (See Section 3.0) This is due to established international agreements and tariff structures which are unlikely to change significantly over the next five years. Consequently, hard copy transmission such as air freight and air mail, with their inherent time delays, are concluded to be the most feasible methods of international data transmission.

The direct readout link was then evaluated (Section 4.0) from the point of view of the Local User Terminal. The facts that the direct readout link will be at Ku-band (15.0 GHz) and that the Thematic Mapper output data rate will be at 120 Mbps cause significant problems for the Local User Terminal. The analysis reveals that for the presently planned spacecraft configuration, due to power considerations, the maximum coverage circle radius for a Local User Terminal to receive 120 Mbps data from the spacecraft in a 705 km orbit, is 1000 km. (Note: Radius = 900 km for a 915 km orbit). This is less than half the coverage circle radius available from the S-band system with similar parameters. Further, in order to achieve even this 1000 km coverage circle, a 10-meter diameter antenna is required at the ground station. This size antenna is at the limit of current technology for tracking low earth orbiting spacecraft at Ku-band. One recommendation for a solution in the area is to incorporate a high gain steerable antenna on the spacecraft for the direct readout link.

The final section of analysis looks at the problems that a Local User Terminal will face in trying to record data at a 120 Mbps rate. The options are (1) to demodulate the data and record the desired portions of it at 20 Mbps or (2) to purchase the more expensive 120 Mbps recorders. A preliminary design and cost estimate for the necessary demodulator are presented.

The image processing requirements of Thematic Mapper data will certainly be more complex. Assuming that a Local User Terminal can process N MSS scenes per day, it will then only be able to process N/6.2 TM scenes per day with the same equipment, due to the higher data content per scene. If the Local User Terminal wishes to process N TM scenes per day (to maintain a fixed coverage circle radius, for example), he has three options: (1) he may purchase 7 copies of his present equipment, (2) he may purchase a completely new processing system designed to process image data at higher rates, or (3) he may follow a course somewhere in between option (1) and option

(2). A study which analyzed the requirement of, designed, and costed option (2) is currently being completed.[1] The tradeover point between option (1) and option (2) will be different for each foreign user and is a function of many factors including:

- hardware and software already owned
- desired TM throughput
- available capital
- modularity of presently owned systems

The final task of this study was the preparation of a questionnaire designed to help NASA assess the impact of the LANDSAT D system on each particular Local User Terminal. The questionnaire, presented as Appendix A, solicits complete descriptions of an LUT's ground station configuration, preprocessing functions, extractive processing facilities, applications plans and goals, data requirements, and attitudes toward LANDSAT D changes. As of this writing, results of the User Questionnaire are not available and hence are not included in this report.

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1. Contract NAS5-23412, "LANDSAT D Data Processing Facility Study".

2.0 LUT LOADING ANALYSIS

In order to realistically understand the problems that foreign users will have to solve in order to successfully make use of Thematic Mapper data, it is necessary to estimate the quantities of data involved. Once estimates of the number of bits per (Thematic Mapper and Multispectral Scanner) scene and the number of scenes an LUT may be interested in have been obtained, options for transmitting, recording and processing the data may then be evaluated.

2.1 QUANTITY OF DATA PER SCENE

The first step in estimating the quantity of data per scene for a given sensor is to specify the following sensor characteristics:

- Scene size on the ground
- Instantaneous Field-of-View (IFOV)
- Number of Spectral Bands
- Number of Bits per Spectral Value
- Over-Sampling Factor in the Scan Direction

Once these characteristics are known, the quantity of image data per scene may be computed. However, since the raw data also contains a significant amount of calibration and synchronization information, the following characteristics are also necessary:

- Time to acquire a scene
- Sensor output data rate

The computation of the quantity of data per scene then proceeds in the following 7 steps:

1. Calculate the ground area per scene
2. The number of pixels/scene $= \dfrac{\text{ground area per scene}}{\text{ground area per IFOV}}$
3. The number of bytes/scene = (# of pixels)(# of spectral bands)

4. The number of image bits/scene = (# of bytes) (# of bits/byte)

5. The final image bits/scene = (# of image bits) (oversample factor)

6. The image data rate = $\frac{\text{final image bits/scene}}{\text{time/scene}}$

7. Total received bits/scene = $\frac{\text{(sensor output data rate)}}{\text{(change data rate)}}$ (final image bits/scene)

These calculations are performed for the Thematic Mapper and for the Multispectral Scanner in Tables 2-1 and 2-2.

2.2 NUMBER OF SCENES ACQUIRED PER GROUND STATION

In order to estimate the total data volume that an LUT might be required to record and process, it is necessary to estimate an average and a maximum number of scenes per day to be acquired by the ground station. These scene estimates will be a function of the desired radius of the LUT's coverage circle (See Figure 2-1).

The maximum and average scenes per day for various size coverage circles are presented in Table 2-3. The maximum number of scenes/day assumes two spacecraft (together) acquiring complete ground coverage every nine days. It is acknowledged that these figures represent a condition in which an LUT requires the capability to receive and process the complete data for every scene taken within its coverage circle of interest. It is highly probable that this will not be the case, and that data compressions of many kinds may be employed. For example, the 8 significant bits of every band may not be required, or all 6 spectral bands of the Thematic Mapper may not be necessary. Cloud cover or open ocean within a coverage circle may also reduce the number of scenes required. Finally, an LUT may wish to receive and/or process some scenes quickly and others as time is available. In any event, the maximum values are used in this study to size and bound the LUT's requirements.

THEMATIC MAPPER SENSOR PARAMETERS

Scene Size:	185 km x 185 km
IFOV:	30 meters x 30 meters
# of Spectral Bands:	5.06 *
Bits per spectral value:	8
Sampling in scan direction:	1.0 over sample
Time/Scene:	25 seconds
Sensor Output Data Rate:	120 Mbps

DATA/SCENE CALCULATION

1. 185 km x 185 km = 34,225 km^2/scene

2. $\frac{34{,}225\ km^2/scene}{900\ m^2/pixel}$ = 38,027,777 pixels/scene

3. 38M pixles/scene x 5.06 spectral bands = 192.4M bytes/scene

4. 192.4M bytes/scene x 8 bits/byte = 1538M bits/scene

5. 1539M bits/scene x 1.0/scan over sample = 1.54G bits/scene

6. $\frac{1.54G\ bits/scene}{25\ sec/scene}$ = 61M bits/sec - data rate

7. $\frac{120\ Mbps\ (data\ rate\ including\ cal.\ \&\ sync)}{61\ Mbps\ (data\ rate)}$ x 1.54G bits/scene = 3.0G bits/scene

Table 2-1. Thematic Mapper - Data/Scene

*Sixth Thematic Mapper spectral band has IFOV of 120 meters by 120 meters.

SENSOR PARAMETERS

Scene Size:	185 x 185 km
IFOV:	80 meters
# of Spectral Bands:	4.11*
Bits/Spectral Value:	6
Sampling in Scan Direction:	1.4 over sample
Time/Scene:	25 seconds
Sensor Output Data Rate:	15 Mbps

DATA/SCENE CALCULATION

1. 185 km x 185 km = 34,225 km^2/scene

2. $\frac{34{,}225\ km^2/scene}{6400\ M^2/pixel}$ = 5,347,656 pixels/scene

3. 5.347M pixels/scene x 1.4 oversample = 7.48M pixels/scene

4. 7.48M pixels/scene x 4.1 spectral bands = 30.7M bytes/scene

5. 30.7M bytes/scene x 6 bits/byte = 184.4 bits/scene

6. $\frac{184.4M\ bits/scene}{25\ sec/scene}$ = 7.37 M bits/sec - data rate

7. $\frac{15\ Mbps\ (data\ rate\ incl.\ cal.\ \&\ sync)}{7.37\ Mbps}$ x 184.4 M bits/scene = 375M bits/scene

Table 2-2. Multispectral Scanner - Data/Scene

*Fifth Multispectral Scanner Spectral band has IFOV of 290 meters by 290 meters.

Table 2-3. Maximum and Average Numbers of Scenes Per Day as a Function of Coverage Circle Radius

Radius of coverage circle (km):	500	1000	1500	2000
Ground Coverage of scenes: Assumes Square with side = (2xradius)	30	115	260	450
Avg. Scene/day 2 Sats - 18 day coverage	3.3	12.7	28.9	50.0
Avg. TM - Raw Data (G bits/day) 3.0 G bits/scene	9.9	38.1	86.7	150.0
Avg. TM - Proc. Data (G bits/day) 1.54 bits/scene	5.08	19.56	44.5	77.0
Avg. MSS - Raw Data (G bits/day) 375M bits/scene	1.2	4.76	10.8	18.75
Avg. MSS - Proc. Data (G bits/day) 184.4 M bits/scene	.61	2.34	5.33	9.22
Max. whole scenes in one day (Assumes traces 1500 km apart)	8	18	34	60
Max. Raw Data (G bits/day) - TM	24.0	54.0	102.0	180.0
- MSS	3.0	6.75	12.75	22.5
Max. Proc. Data (G bits/day) - TM	12.32	27.72	52.36	97.4
- MSS	1.475	3.319	6.269	11.06

3.0 DATA RELAY FROM THE U.S. TO LOCAL USER TERMINALS

Once the Thematic Mapper and/or multispectral scanner data has been relayed to White Sands via the TDRSS, there are two possible scenarios for data transfer to foreign users: (1) the raw data will be immediately transferred to foreign users; or (2) the data will be transmitted to NASA/GSFC for some amount of processing and then relayed to foreign users. The data (of either type) may be relayed to foreign users either as hardcopy (magnetic tape or film), or via electronic data relay links such as communications satellites.

Hardcopy transmission provides significant cost advantages over satellite data relay methods, however the time delays incurred in transmitting magnetic tapes from the TDRSS terminal at White Sands, New Mexico to the LUT may be as long as 3 - 4 days, which may be an unacceptable delay.

Representative costs for air freight are:

Washington to London	$1.77/lb.
Washington to Tokyo	2.40/lb.
Washington to Sydney	3.13/lb.

Assuming an approximate weight of 25 lbs. for the HDDT (High Density Digital Tape) tapes for one scene, one gets an approximate cost of $50/scene for tape transmission of the data. (Note: These costs assume airport pickup and delivery.) Airmail costs would be approximately $80/scene, while surface mail cost would be approximately $15/scene.

3.1 SATELLITE DATA RELAY

Technologically, the most efficient method of relaying data to foreign users is via a communications satellite. The INTELSAT system is presently the sole provider of commercial international satellite communications traffic. A list of the most likely foreign users, the location of the INTELSAT ground station, the nearest city for the INTELSAT link, and the location of the LANDSAT ground station for each country is as follows:

Country	INTELSAT Terminal	Nearest City	Landsat G/S
Canada	Mill Village		Ottawa
Brazil	Tangua	Rio de Janeiro	Cuiaba
Italy	Fucino	Rome	
Zaire	Nsele	Kinshasa	Kinshasa
Iran	Asadabad	Tehran	Tehran
Chile	Longovilo	Santiago	
Japan	Ibaraki		

INTELSAT, the owner and director of the INTELSAT system, is an organization composed of member countries which finance and use the system. (Service is also available to non-member users.) In each member country, a Signatory is designated as the sole organization responsible for the rights and obligations, including financial contributions, of membership. In the United States, the Signatory is the Communications Satellite Corporation (COMSAT). In Great Britian, the Signatory is the British Post Office (BPO). In most other foreign countries, the Signatory is a Government ministry. Since Comsat is the only U.S. body that can access an INTELSAT satellite, and since this constitutes a monopoly, the Federal Communications Commission has issued the following regulations concerning COMSAT'S operations: (1) COMSAT must sublease the rights to access the satellite to other companies; (2) COMSAT may not lease service directly to the public. COMSAT thus operates as a "carrier's carrier". To date, COMSAT has made arrangements with several U.S. companies (including RCA, Western Union, ITT and ATT) to provide commercial traffic to the public.

Three methods of using the INTELSAT system--voice-grade rental, wideband rental, and transponder rental--were investigated, and are discussed in order below. The reliability figures for the INTELSAT System for the year 1975 (average) are as follows:

Space Segment	99.992
Earth Segment	99.952
Overall	99.892

It is planned that starting in about 1980, the first of the INTELSAT V satellites will be available in the Atlantic Region. INTELSAT is considering the introduction of Time Division Multiple Access coding, (with hopefully more bits for less money) in the Atlantic Region on a gradual basis beginning in the early 1980s.

INTELSAT has indicated that voice-grade PSK SCPC (Phase Shift Keyed-Single Channel Per Carrier) channels with capacities of up to 56 Kbits/sec are available in quantity over any ocean (see Figure 3-1). INTELSAT's rate for one-year lease of a voice-grade channel to a signatory is currently about $8,000. INTELSAT has established a charge for a 1.544 Mbps PSK channel which is equivalent to 24 times the per channel rate. INTELSAT can also provide a group facility in its FM system consisting of the equivalent of 12 voice-grade channels, to transmit data at 48 Kbps.

It is important to point out, however, that the charge for a voice-grade link to a customer must also include terrestrial charges and the carrier's costs for the ground stations. These are much higher since the ground stations are operated on a profit basis.

COMSAT and a carrier were contacted for representative rates for half-circuit costs. These carriers operate the transmission link from a gateway city, to a ground station, and on to a satellite. Each foreign country has its own charge for the half link from the satellite to its gateway. A trans-Atlantic relay through a European country, or a trans-Pacific relay, would be necessary for U.S. traffic to countries served only by the Indian Ocean Satellite.

The gateway cities for White Sands and Goddard would be San Francisco and Washington, respectively. Data would have to be transmitted to the gateway cities via a terrestrial data link (see Section 3.2) or via a domestic communications satellite. Costs from San Francisco and Washington to their respective INTELSAT satellites are $12,000 and $6,925/voice-grade channel/month. Estimated half link costs from the satellite to each of the foreign countries per voice-grade channel per month are as follows:

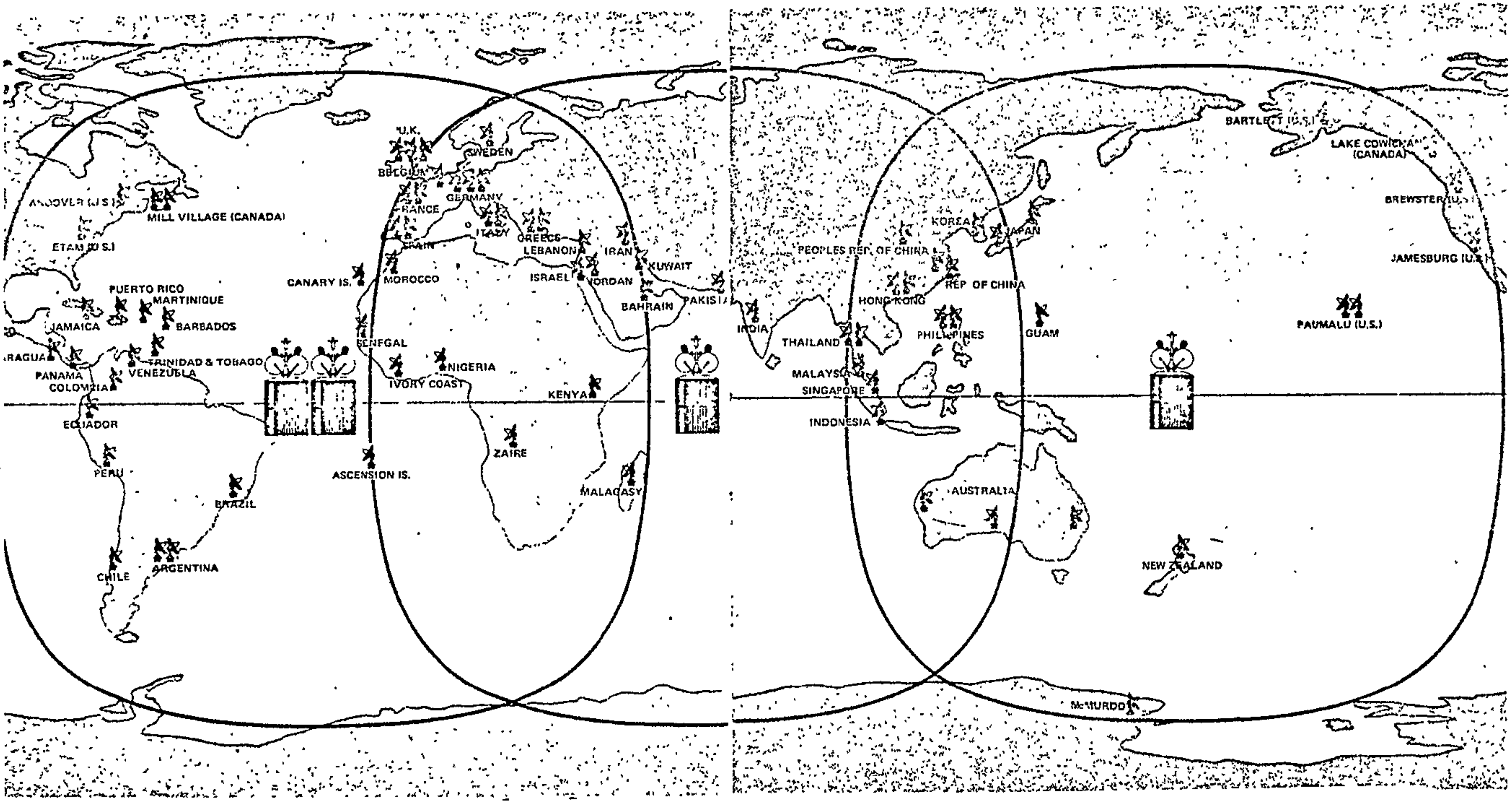


Figure 3-1. The Global System of INTELSAT IV Satellites and Operational Earth Stations (As of December 1972)

Country	Est. Half Link Cost
Brazil	$22,800 - 30,400
Italy	21,900 - 29,200
Zaire	24,000 - 32,000
Iran	33,000 - 44,400
Chile	30,400 - 40,600
Japan	37,200 - 49,600

At 64 K bits/sec. one voice-grade channel can handle about 5.5 Gigabits/day with continuous transmission. This figure may be compared with the expected LUT data volumes/coverage (see section 2.2).

The possibility of obtaining wideband service from the INTELSAT system was briefly investigated. It is possible to lease any number of voice-grade channels on the satellite; leased; however, the charge is essentially n x c where n is the number of channels leased, and c is the single channel cost. There are discounts, on the order of 10 - 20%, available for lease of a large number of channels; however, they do not seriously affect the order of magnitude of the cost. Present tariff restrictions, international agreements, etc., prohibit channels wider than voice grade from being leased, and it was the collective opinion of all parties contacted that this would remain so for the foreseeable future.

The final possibility investigated was that of renting an entire transponder on the satellite. It was at this stage that several legal complications were encountered. One protected (with back-up) transponder, with 36 MHZ bandwidth can be used to relay 40 Mbps now, or 60 Mbps (using QPSK) in the future, may be leased by a Signatory for $3M/year. It is also possible to rent one-half or one-quarter of a transponder with proportional associative costs and bit rates. Several countries, such as Norway, Brazil, Algeria, and Nigeria, have done this. However, these transponders may be used for <u>domestic</u> transmission only; they <u>may not</u> be used for international traffic. The reason for this is that if transponders could be rented for international traffic, those users would receive a preferential rate below that of normal users. For example, if the U.S. and the U.K. rented a transponder for $3M, they could derive 700-1000 voice-grade channels or half circuits (referred to as units of utilization). This would amount to $250/half circuit/month. The standard INTELSAT rate for rental of a voice-grade channel to a Signatory is $690/month. Therefore, if international traffic on a leased transponder were allowed, a preferential rate would be in existence. Present INTELSAT regulations do not allow preferential rates.

In one instance in the past, however, this restriction was relaxed. Spain and Mexico jointly rented one-half of a transponder for a two-year lease for continuous television broadcast. This exception was approved by the directing body of INTELSAT as a one-time event. This leads to the complex policy question: "Could NASA also be granted an exception from these restrictions for purposes of data distribution for the Landsat Follow-on Program?" The answer to this is possibly, but not probably.

Examination of this question must proceed at two levels. First, INTELSAT must be petitioned by the signatories of the countries involved for a ruling allowing an exception to current INTELSAT regulations. There would be many legal and political implications of such an exception, and its deliberation is likely to drag out for a lengthy period of time. The final decision would be based on a vote of major INTELSAT signatories. Even if this exception is ever granted, only half of the problem has been solved. At this point, COMSAT will have been granted the lease of a transponder (or some fraction) for $3M/year, specifically for NASA's application. But presently, the FCC and the Office of Telecommunication Policy forbid COMSAT from leasing service directly to the public (NASA).

There have been two instances in the past in which COMSAT has been allowed to rent directly to a customer for reasons of national interest. One of these was a DOD link to Southeast Asia several years ago, and the other was a NASA link necessary for the Apollo program. In both of these cases, the exceptions were terminated after a short period of time, and the customers (government agencies) were forced to deal with one of the outlet carriers (RCA, Western Union, ATT, ITT) for reasons of unfair competition. Therefore, NASA would probably be required to approach one of the outlet carriers for this transponder rental. Since both COMSAT and the outlet carrier are profit-making organizations, it has been estimated that at a minimum, the transponder rental fee would double, without even including additional fees for the required earth station, peripherals, etc.

Therefore, although it is clear that communications satellites are technologically the most efficient method of transmitting large quantities of data internationally, current international agreements and regulations have priced it out of consideration. One possible alternative to this situation is for NASA to put up its own transponder, either on a new spacecraft, or as part of an existing program. It is not clear at this time whether or not arrangements would still have to be made with INTELSAT under these conditions.

For domestic data transmission, satellites offer a very attractive alternative. It is estimated that a transponder, capable of relaying 40-60 Mbps, could be leased for $100K/mo, with a $750K ground station required at each end of the link. In addition, arrangements could probably be made for use of a domestic communications satellite for data transmission to Canada.

3.2 TERRESTRIAL DATA TRANSFER

Terrestrial data transmission will be employed for various portions of the transmission links if satellites are used. Data transfer links from White Sands to a DOMSAT facility, from DOMSAT facility to processing or production facility, or to an INTELSAT gateway facility, will be required.

A wideband data channel operating at 1.5 Mbps is available from the telephone company for digital data transmission. Costs for this service are:

1.	Intercity Service	\$64/mi/mo. 50/mi/mo. 40/mi/mo.	1st 200 miles Next 300 miles any additional
2.	Access Lines/Modems	\$700/location	
3.	Intracity Service	\$60/mi/mo.	

Some typical transmission links and their approximate costs are:

White Sands - Washington, D.C.	\$90,000/mo.
White Sands - San Francisco	\$55,000/mo.

As can be readily seen, the shorter the transmission distance, the less the cost, while the DOMSAT link is independent of the transmission distance.

Microwave links are another alternative terrestrial data transmission system. A rough cost estimate for a 10 Mbps system would be \$100K/terminal at each end with repeaters (\$100K each) spaced approximately every 30 miles.

3.3 DATA RELAY METHODS - SUMMARY

The main characteristics of a data relay system are the cost and associated time delay. Estimates of these parameters have been given for each potential transmission method. When definitive system requirements can be specified, for a specific LUT these costs can be determined precisely, and cost/timeliness trades performed.

The key to selection of a specific transmission method is the allowable time delay. If a 2 or 3 day delay is acceptable, then data transmission via commercial carrier offers a much less expensive alternative. To address this question, the time delay associated with other portions of the ground data handling system must also be known. For example, since a 2 - 4 day delay associated with the data correction processing is likely, 2 or 3 day data relay delay becomes significant.

4.0 DIRECT DATA TRANSMISSION TO LOCAL USER TERMINALS

An obvious alternative to the relay of data from LFo, through the U.S., to the LUT is for the direct transmission of data from LFo to a ground receiver at the LUT. In consideration of such an alternative, several factors must be evaluated for impact on the LUT design:

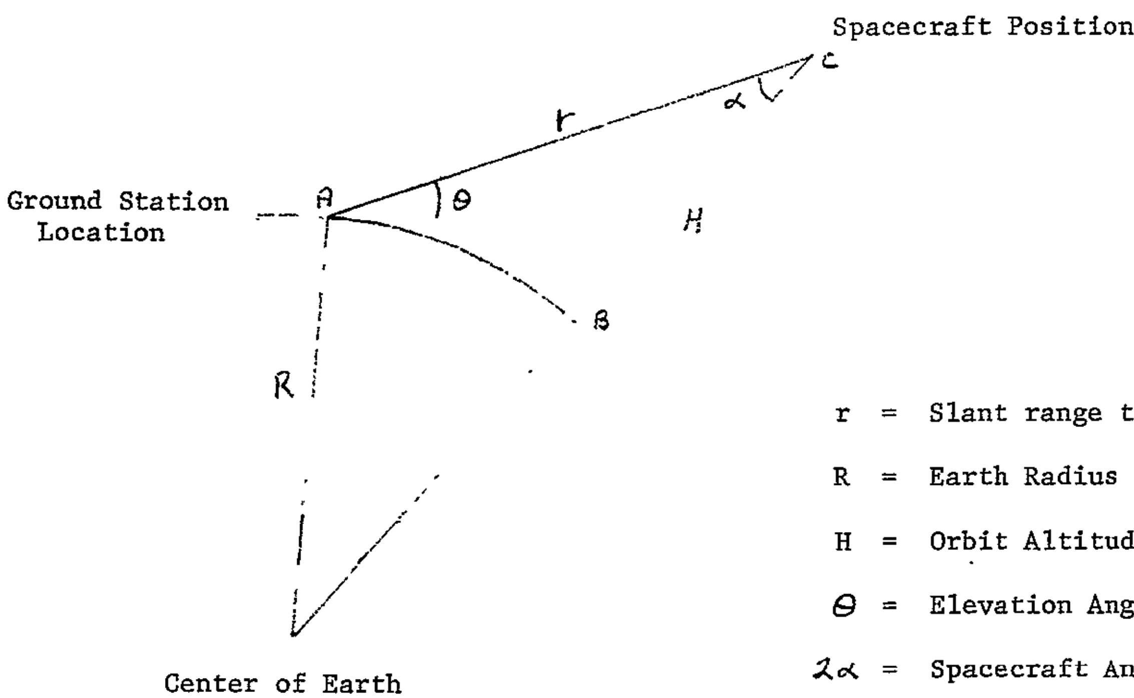
- Use of Ku-band as a carrier frequency.
- Impact of high data rate (120 Mbps) on communications link margins.

Each of these factors will be analyzed in this section of the report.

4.1 GEOMETRICAL CONSIDERATIONS

Of primary concern to the operator of a direct readout station is the coverage zone he may achieve from his station. This zone is expressed as the distance, drawn as a great circle, of the limit of coverage from the direct read-out station, and is called the coverage zone radius.

Figure 4-1 relates the coverage zone radius to the geometry of spacecraft antenna angle, ground antenna elevation and slant range from the direct readout station to the spacecraft.



r = Slant range to spacecraft

R = Earth Radius

H = Orbit Altitude

θ = Elevation Angle

2α = Spacecraft Antenna Beamwidth

$\widehat{AB}$ = Coverage Zone Radius

Figure 4-1. Spacecraft - Direct Readout-Station Geometry

The geometric relationships between the parameters of interest are given by

$$\sin\alpha = \frac{R \sin(\pi/2 + \theta)}{R + H} \quad (1)$$

$$\widehat{AB} = R\,(\pi/2 - \alpha - \theta) \quad (2)$$

$$r = \frac{R \sin(\pi/2 - \alpha - \theta)}{\sin\alpha} \quad (3)$$

It can be seen that the primary parameters of spacecraft antenna beamwidth, slant range to spacecraft, and ground antenna elevation angle can each be expressed as a function of coverage zone radius by manipulation of these relationships. These parameters are plotted in figures 4-2, 4-3, 4-4 for both orbit altitudes of interest.

4.2 COMMUNICATIONS LINK ANALYSIS

The establishment of a communications link at a given frequency, carrying a given data rate, is dependent on three primary parameters: the Effective Isotropic Radiated Power (EIRP) of the transmitter; the sensitivity, expressed as Gain to Temperature (G/T) ratio, of the receiver; and signal losses in the path between transmitter and receiver. Successful extraction of data (information) from the received signal also depends on the efficiency of components, such as demodulators, following the receiver.

The analysis of the communications link required for each of the cases considered was performed in three stages. First, the EIRP available from the spacecraft was computed, based on a set of assumptions about the spacecraft transmitter and antenna, and was plotted as a function of achievable coverage zone radius. Second, the

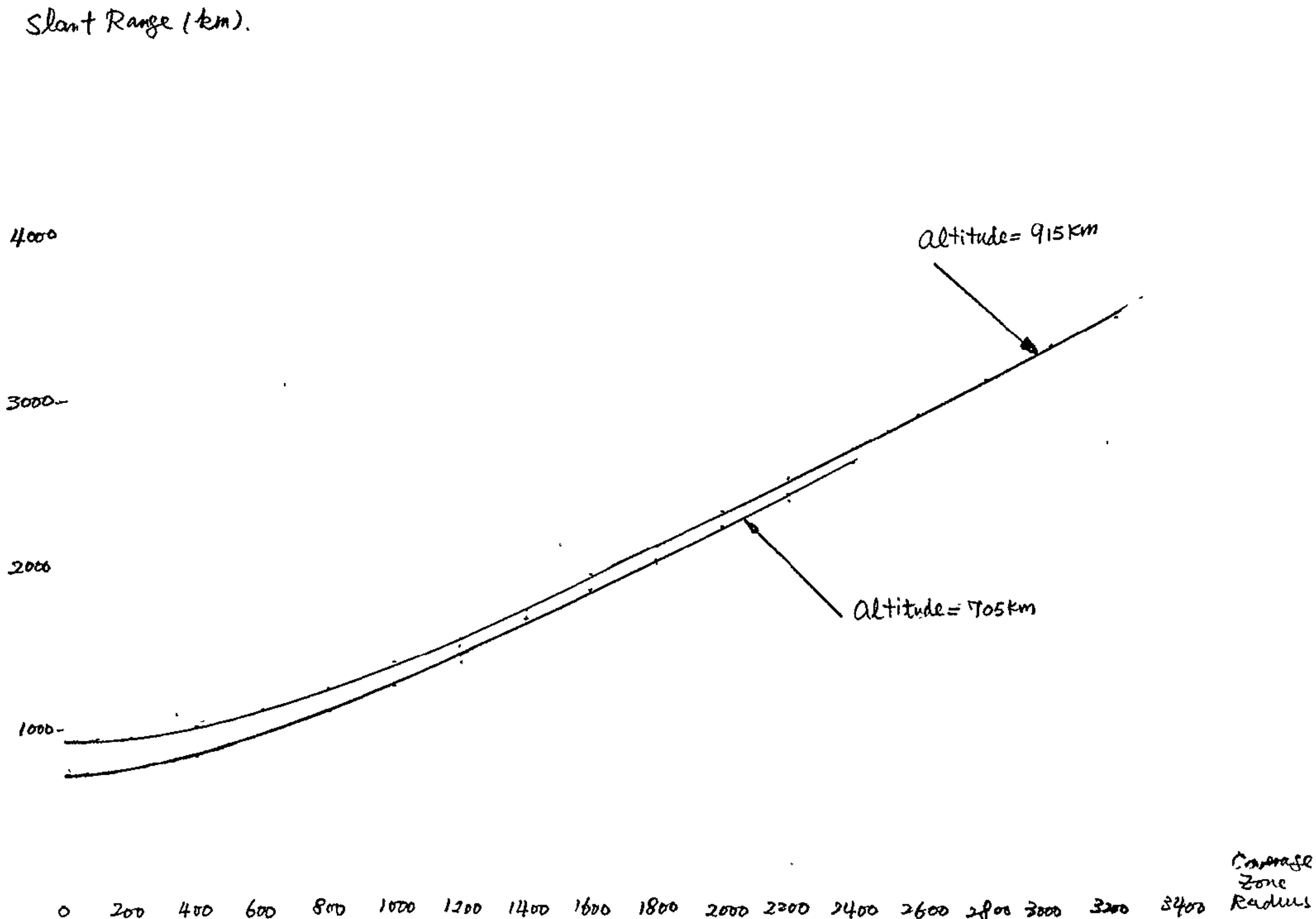


Figure 4-2. Coverage Zone Radius (km) vs. Slant Range

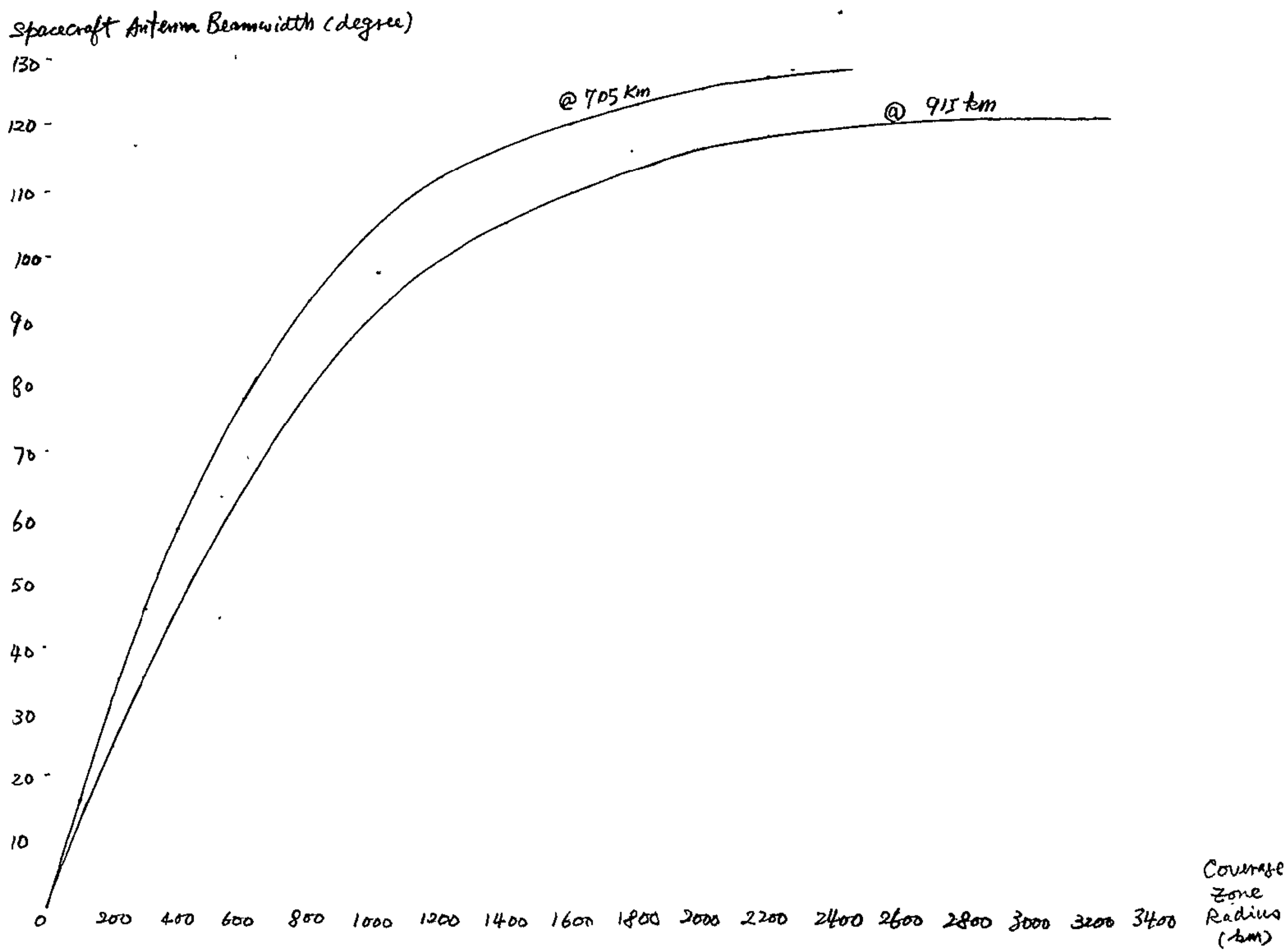


Figure 4-3. Coverage Zone Radius (km) vs. Antenna Beamwidth

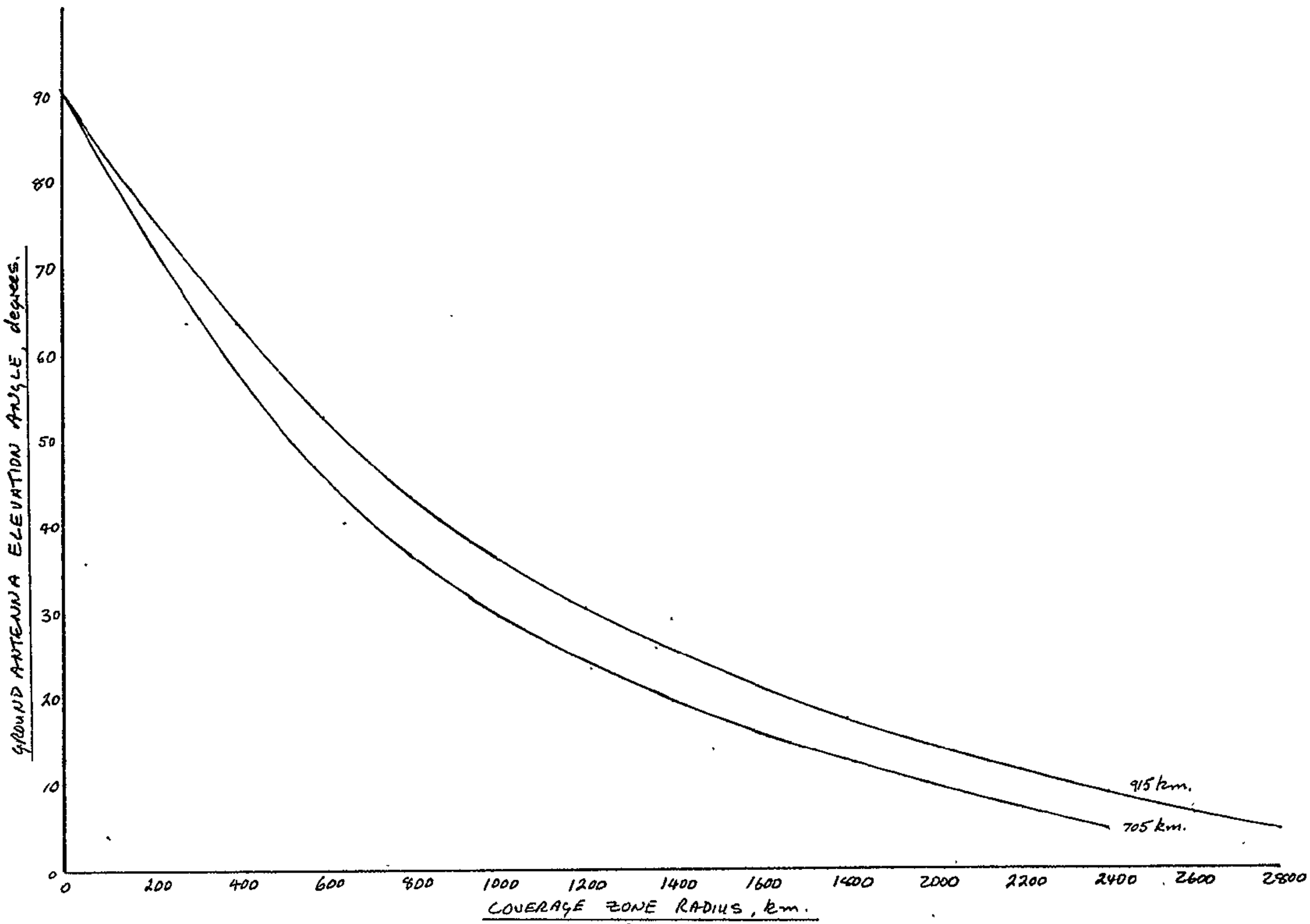


Figure 4-4. Ground Antenna Elevation Angle vs Coverage Zone Radius

EIRP required, based on a set of assumptions about a typical direct readout station receiver/antenna configuration and losses expected in the path between spacecraft and direct readout station, was computed and plotted, again as a function of coverage zone radius. Finally, the plots were compared to determine the coverage zone radius achievable, based on the assumptions made.

4.2.1 COMMUNICATION SYSTEM ASSUMPTIONS

The primary assumption made which relates to the spacecraft transmitting system is that the spacecraft antenna is fixed, with a beamwidth sized such that it just covers the achievable coverage zone radius at the 3 db points, and that the antenna beam is unshaped. In addition, a limit of 15 watts (11.8 dBw) was assumed for the available transmitter power.

For the direct readout station receiving system it was assumed that the antenna would be a 10 meter (33 ft.) diameter dish, similar to those currently used in existing Landsat receiving stations. When typical losses due to surface tolerance and antenna efficiency factors are taken into account, the antenna gain is assumed to be 58 dB. This, when combined with a system noise temperature of 263^{o} K, which is at the practical limit of current technology, results in a receiving system sensitivity (G/T) of 33.8 dB/^{o}K.

In addition, for purposes of assessing the path losses between transmitter and receiver the most optimistic case was assumed, with no allowance for losses due to rain.

The validity of these assumptions is discussed in a later section (Sec. 4.5) of this report.

4.2.2 SPACECRAFT EIRP AVAILABLE

For the assumed spacecraft antenna the gain is given by

$$GT = 10 \log \left[\frac{2}{1 - \cos \alpha} \right]$$

for a perfect antenna with 100% efficiency and beamwidth of 2α. For a practical antenna, however, the efficiency of the antenna and the shape of the beam (difference in intensity from center to "edge") must be considered. For this analysis, a 50% efficiency was assumed, and the "edge" of the beam is defined as the point where the intensity is 50% of the peak (center of the beam). Thus, converting these factors to dB, the gain becomes

$$G_T = 10 \log\left[\frac{2}{1 - \cos\alpha}\right] - 6 \text{ dB}$$

It is further assumed that the hardware chain from the transmitter tube to antenna has a loss of 1 dB thus, since

$$\text{EIRP} = \text{Transmitter Power} + \text{Antenna gain} - \text{losses}$$

the spacecraft EIRP is given by

$$\text{EIRP} = 10 \log \left[\frac{2}{1 - \cos\alpha}\right] + 4.8 \text{ dBw} \qquad (4)$$

using a transmitter power of 15 watts (11.8 dBw)
The EIRP available from the spacecraft as a function of achievable coverage zone radius is plotted in Figure 4-5.

4.2.3 PATH LOSSES

For this analysis only two sources of path loss were considered: the free space loss due to the distance (slant range) of the spacecraft from the direct readout station antenna, and the atmospheric attenuation. Signal attenuation by rain was not considered for the initial (most optimistic) analysis.

The free space loss is given by

$$L_S = 20 \log \left[\frac{\lambda}{4\pi R}\right]$$

where: λ is the carrier wavelength.

R is the slant range between the spacecraft and the receiving antenna.

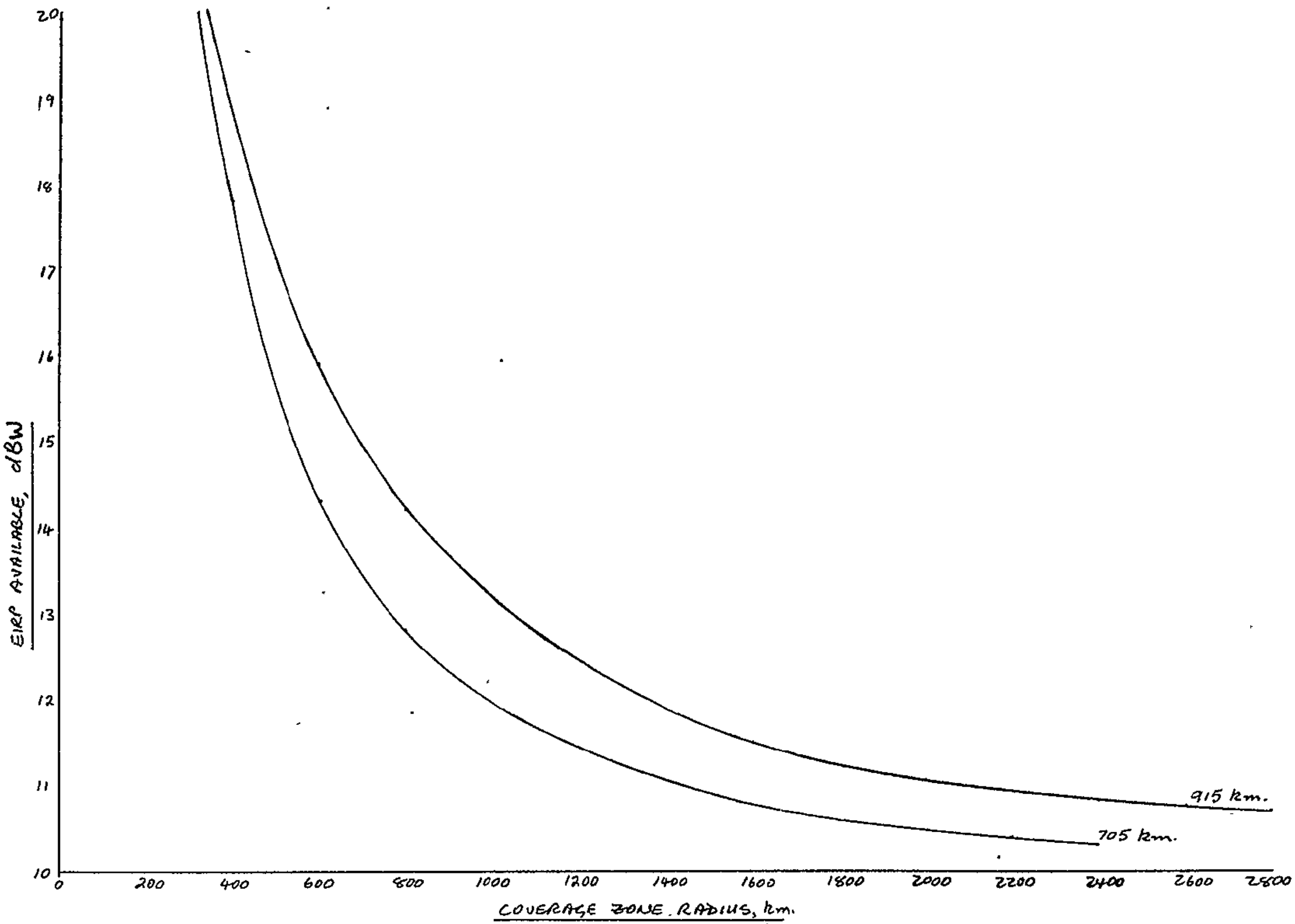


Figure 4-5. EIRP Available from LFo Spacecraft as a Function of Achievable Coverage Zone Radius

Atmospheric losses are the result of attenuation due to oxygen and atmospheric water vapor. For a "standard" atmosphere these losses are shown in Figure 4-6.

The total path losses as a function of coverage zone radius are plotted in Figure 4-7. (The apparent incongruity of a crossover for the curves for the two altitudes is a result of rapidly increasing atmospheric attenuation at low elevation angles of the ground antenna.)

4.2.4 SPACECRAFT EIRP REQUIRED BY DIRECT READOUT STATION

For a given direct readout station configuration, a minimum EIRP must be transmitted by the spacecraft, at a given slant range, to establish a communication link and permit demodulation of the data carried on the link.

The required EIRP can be expressed as

$$\text{EIRP required} = L_S + L_A + L_P + B + \left(E_b/N_o\right) + 10\log(DR) + \text{System Loss} + \text{Equipment margin} - (G/T).$$

Where L - free space loss

L - atmospheric loss

L - pointing and polarization loss = 0.7 dB

B - Boltzmann's constant = -228.6 dB

E_b/N_o - Energy per bit per noise density required for 10^{-5} bit error rate = 9.9 dB

DR - Data rate in Hz

System loss - detection and demodulation losses = 3 dB

G/T - Antenna/receiver sensitivity = 33.8 dB

Equipment margin = 3 dB

By combining parameters which do not vary as a function of coverage zone radius, the EIRP required can be expressed as

$$\text{EIRP required} = \text{Path loss} + 10\log(DR) - 245.8\text{ dB} \qquad (5)$$

Table 4-1. Spacecraft EIRP Calculations

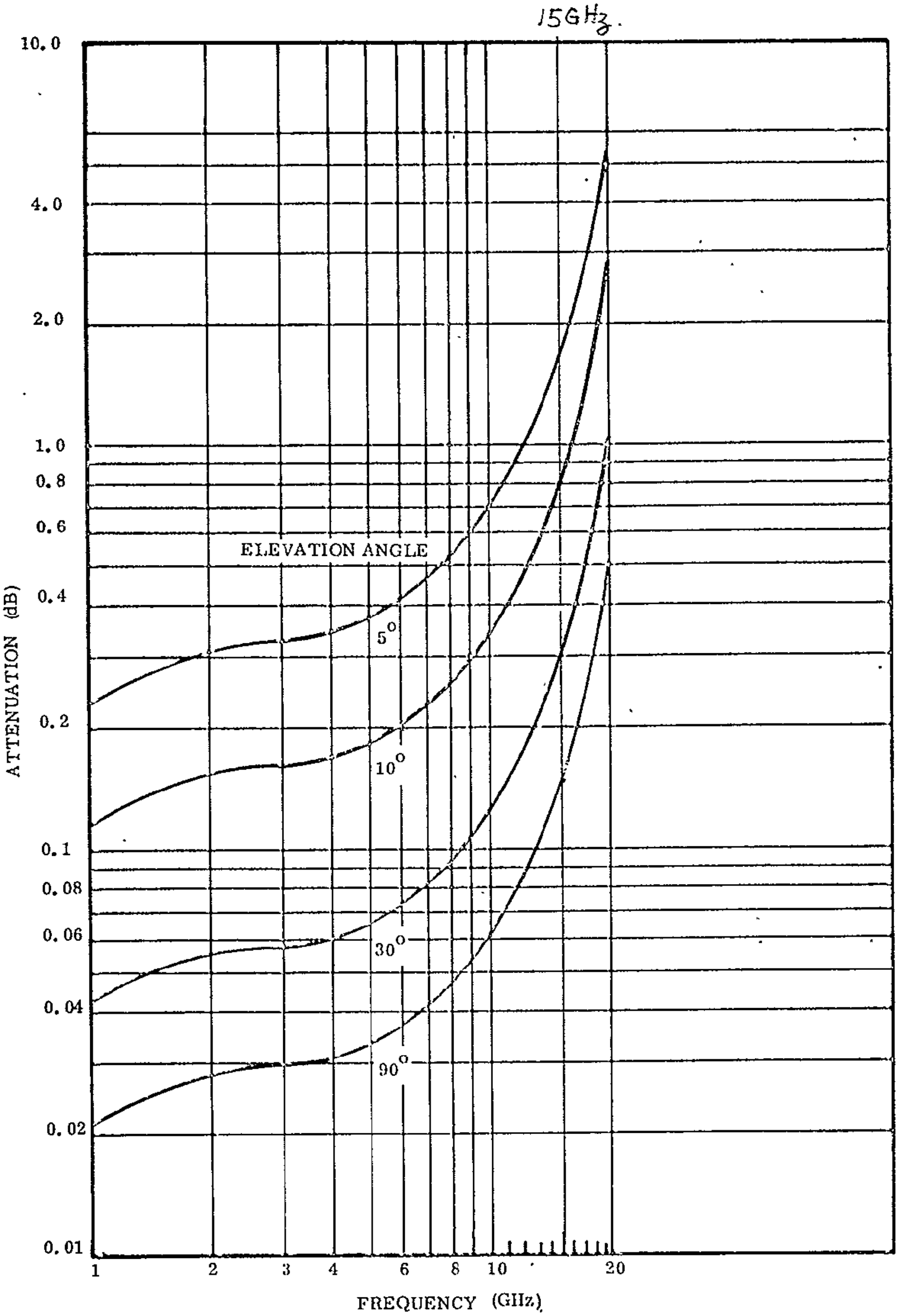


Figure 4-6. Attenuation Due to Oxygen and Water Vapor. From CCIR Documents of the XIth Plenary Assembly, 1966, Vol. 4, pp. 234-255

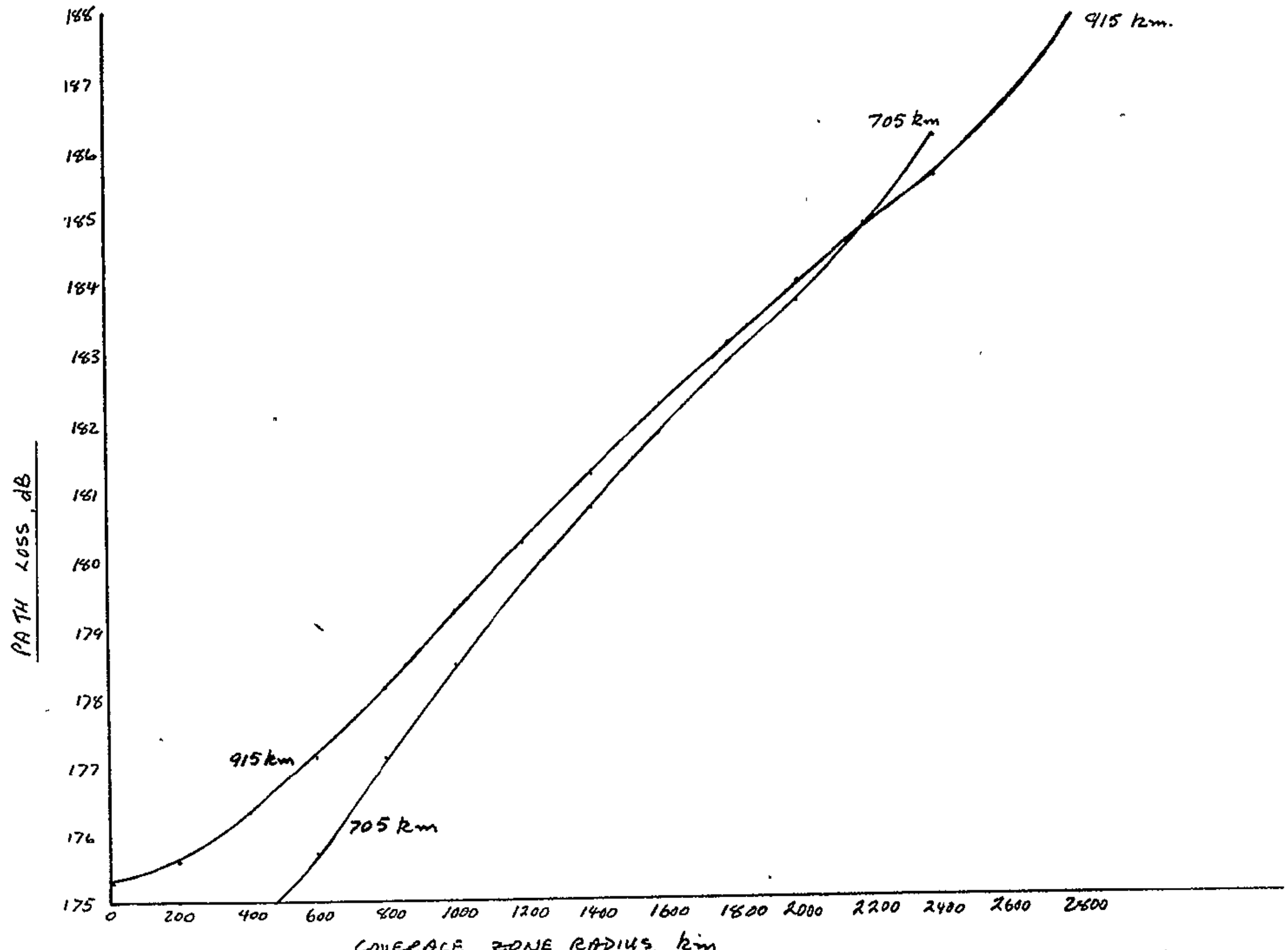


Figure 4-7. Path Losses from Spacecraft to Ground Antenna vs. Coverage Zone Radius

The path losses are derived from Figure 4-7, and the EIRP required for each data rate at each of the altitudes are plotted as a function of coverage zone radius in Figures 4-8 and 4-9.

4.3 ACHIEVABLE COVERAGE ZONE RADIUS

By comparing Figure 4-6, EIRP available, with Figures 4-8 and 4-9, EIRP required by the direct readout station, the achievable coverage zone radius may be determined.

The comparison is plotted on Figures 4-10 and 4-11, and from these figures it can be seen that the achievable coverage zone radius (the radius where the EIRP available equals the EIRP required) is as shown in Table 4-2.

Table 4-2. Achievable coverage zone radius.

Data Rate	705 km Orbit	915 km Orbit
9 Mbps	2300 km	2700 km
15 Mbps	2300 km	2200 km
70 Mbps	———	1150 km
120 Mbps	1000 km	900 km

It is also useful to plot the effective link margin (the difference between the EIRP available and the EIRP required) as is shown in Figures 4-12 and 4-13. These curves show how much additional power (or gain) must be included in the link to achieve a specific coverage zone radius. In addition, these curves may be used to estimate the achievable coverage zone radius in the presence of additional losses in the link (due to rain, less sensitive receiver or lower EIRP output from the spacecraft, etc.).

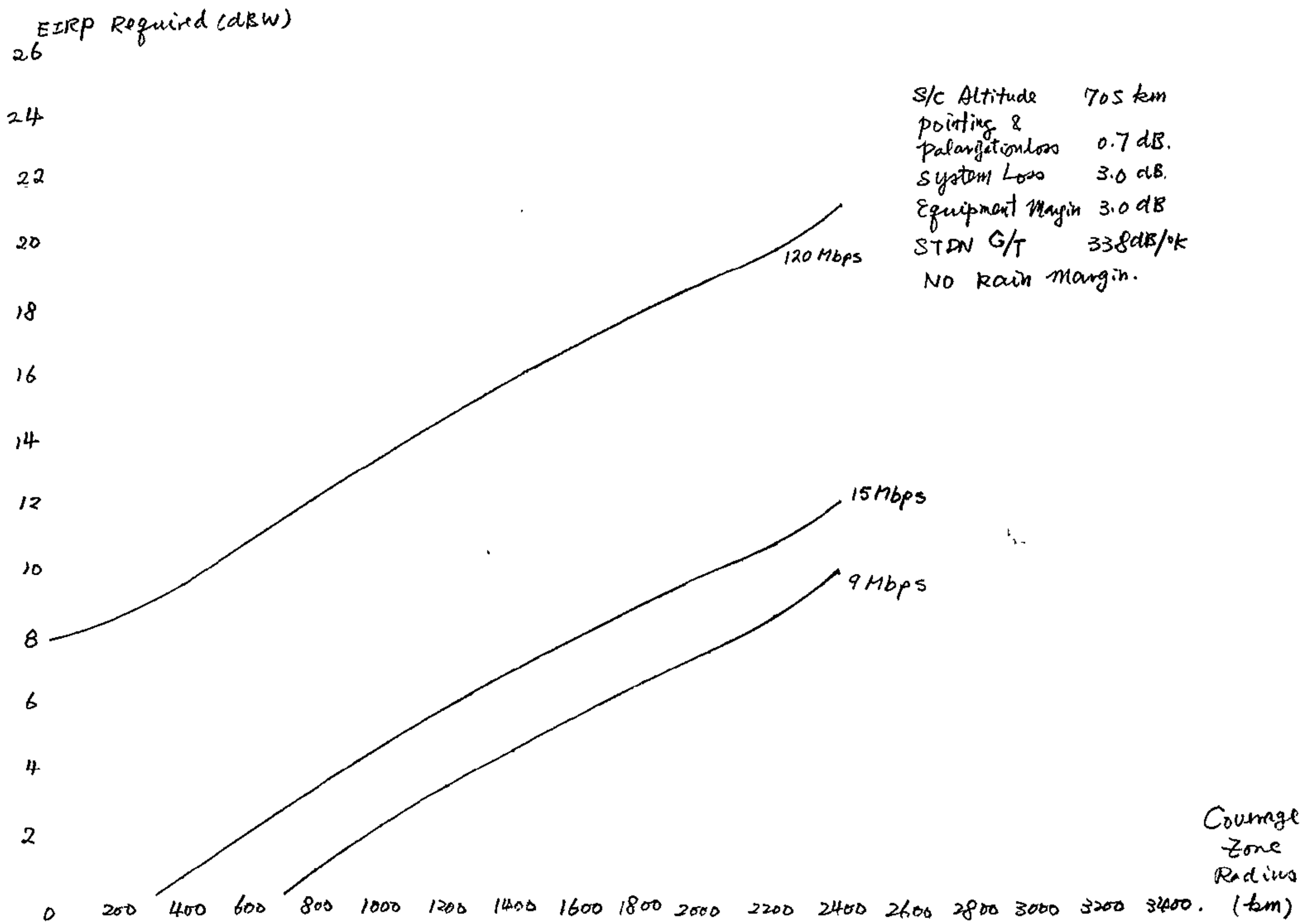


Figure 4-8. Coverage Zone Radius vs. EIRP Required

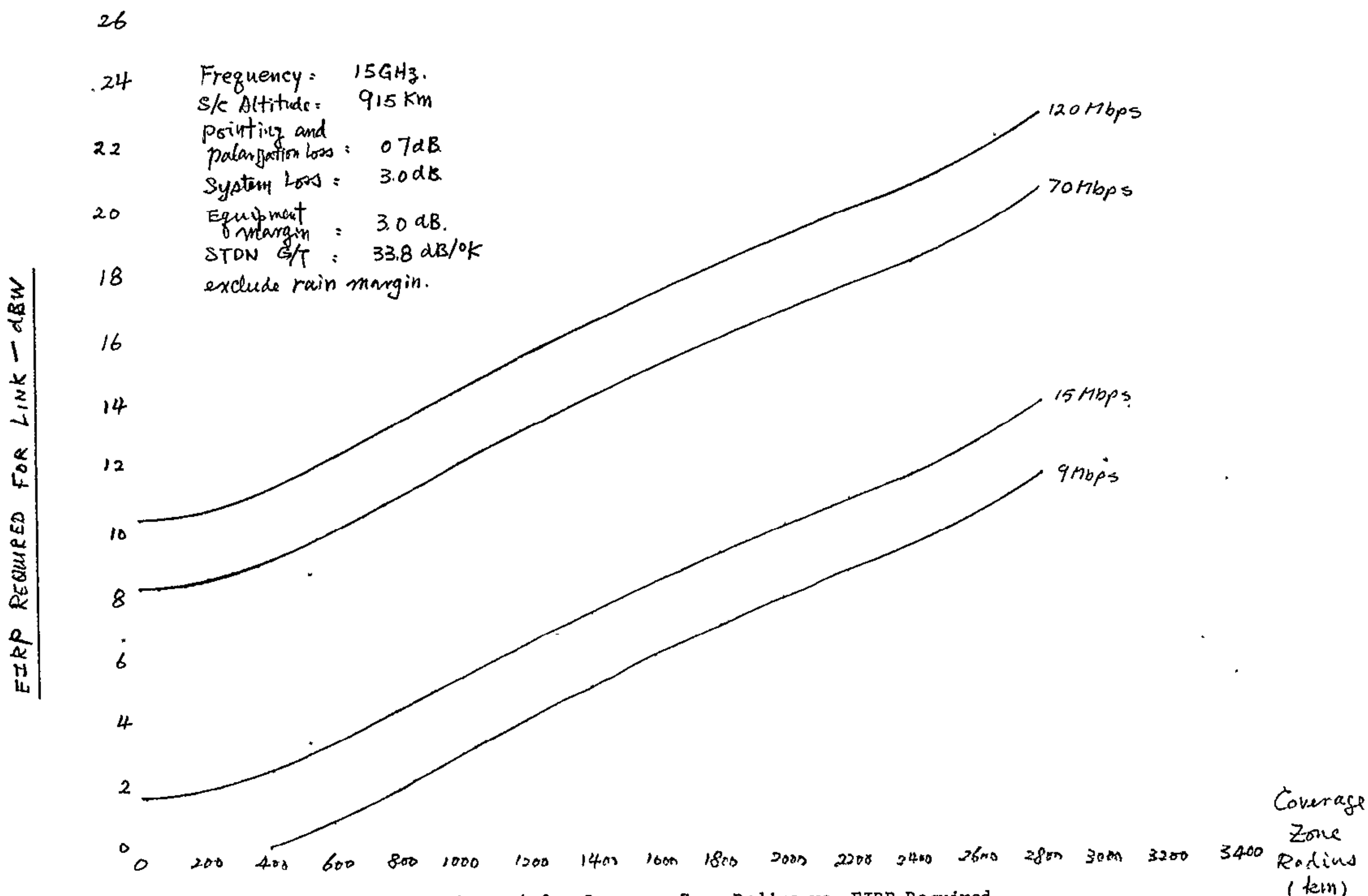


Figure 4-9. Coverage Zone Radius vs. EIRP Required

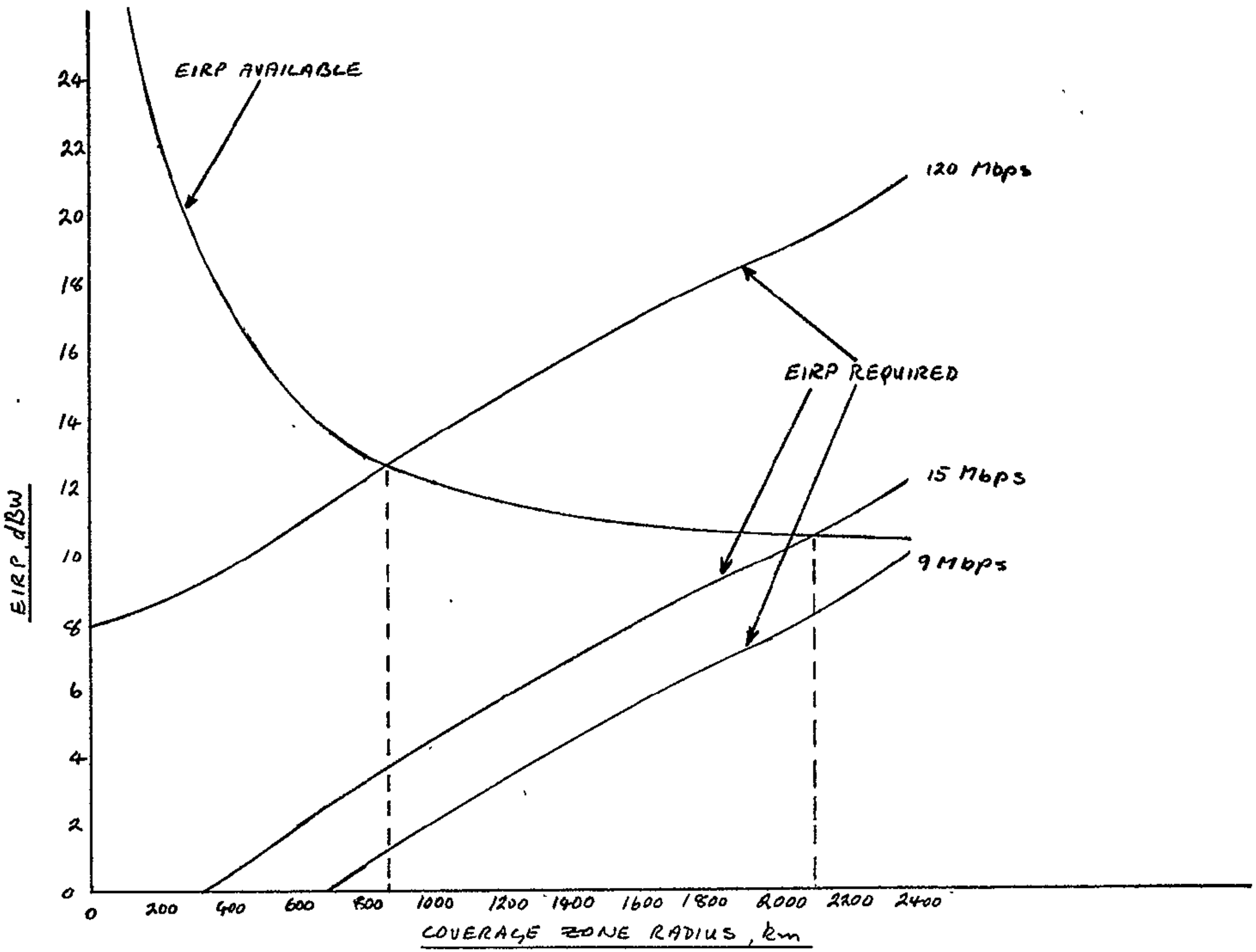


Figure 4-10. Achievable Coverage Zone Radius for 705 km Orbit

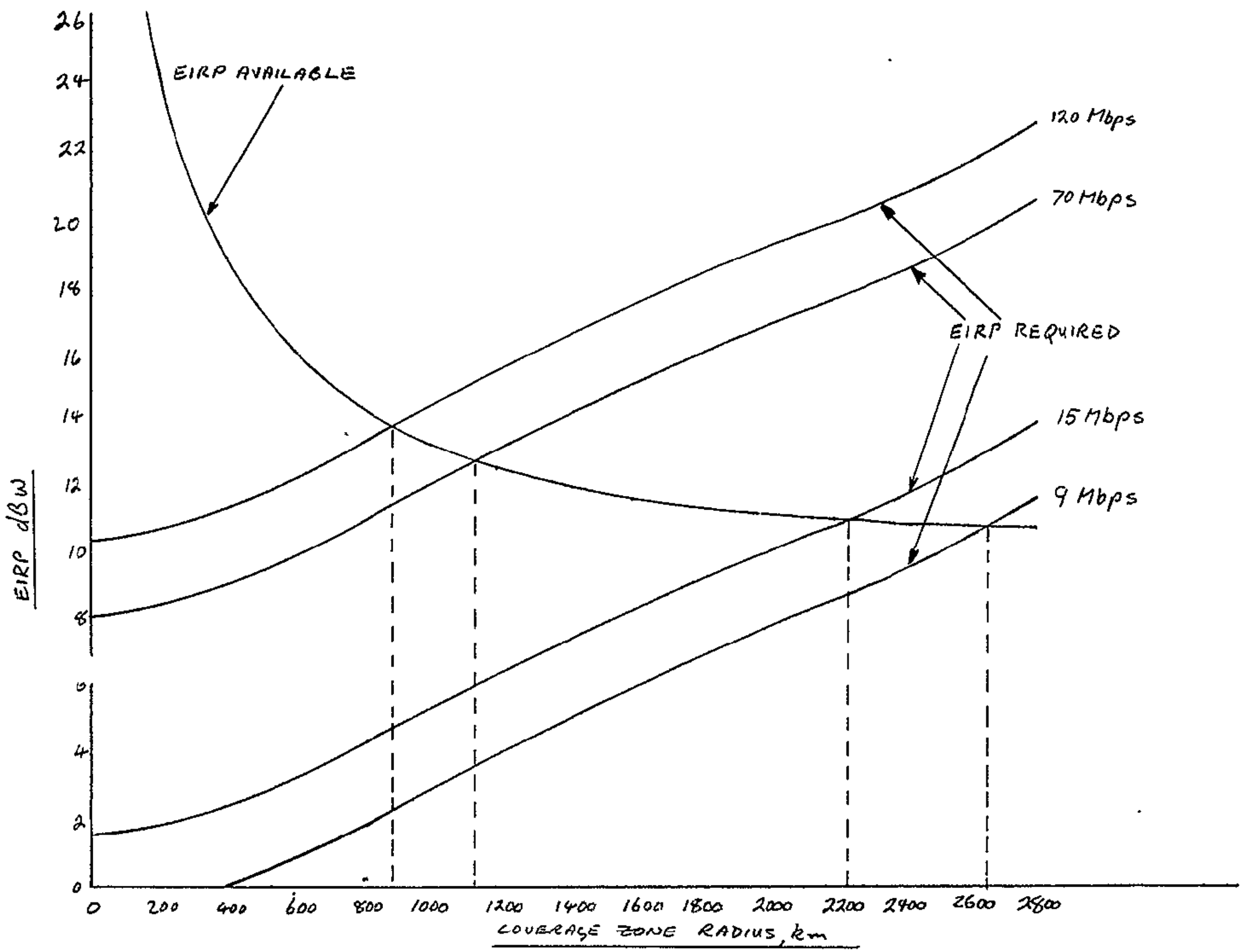


Figure 4-11. Achievable Coverage Zone Radius for 915 km Orbit

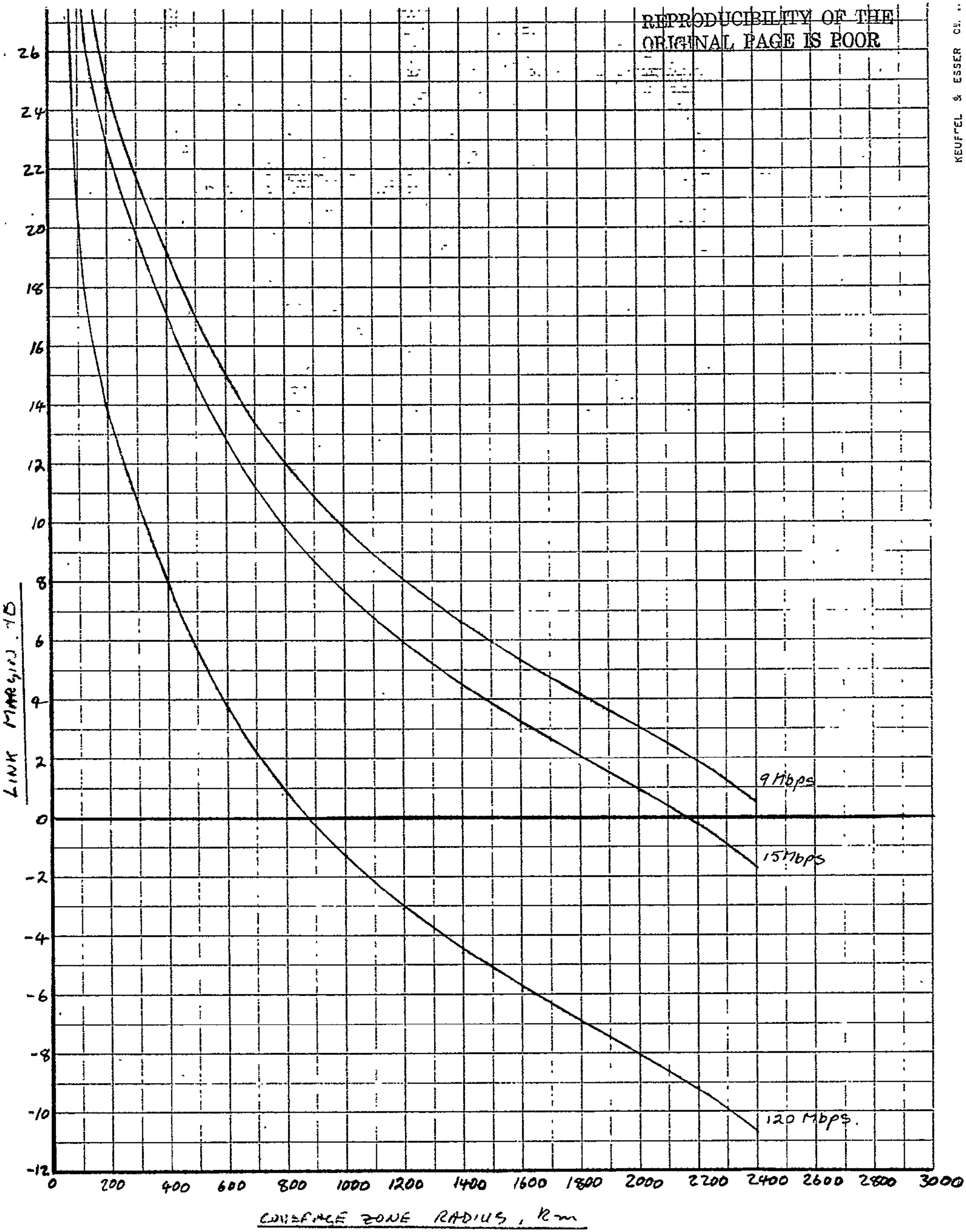


Figure 4-12. Link Margin vs. Coverage Zone Radius for 705 km Orbit

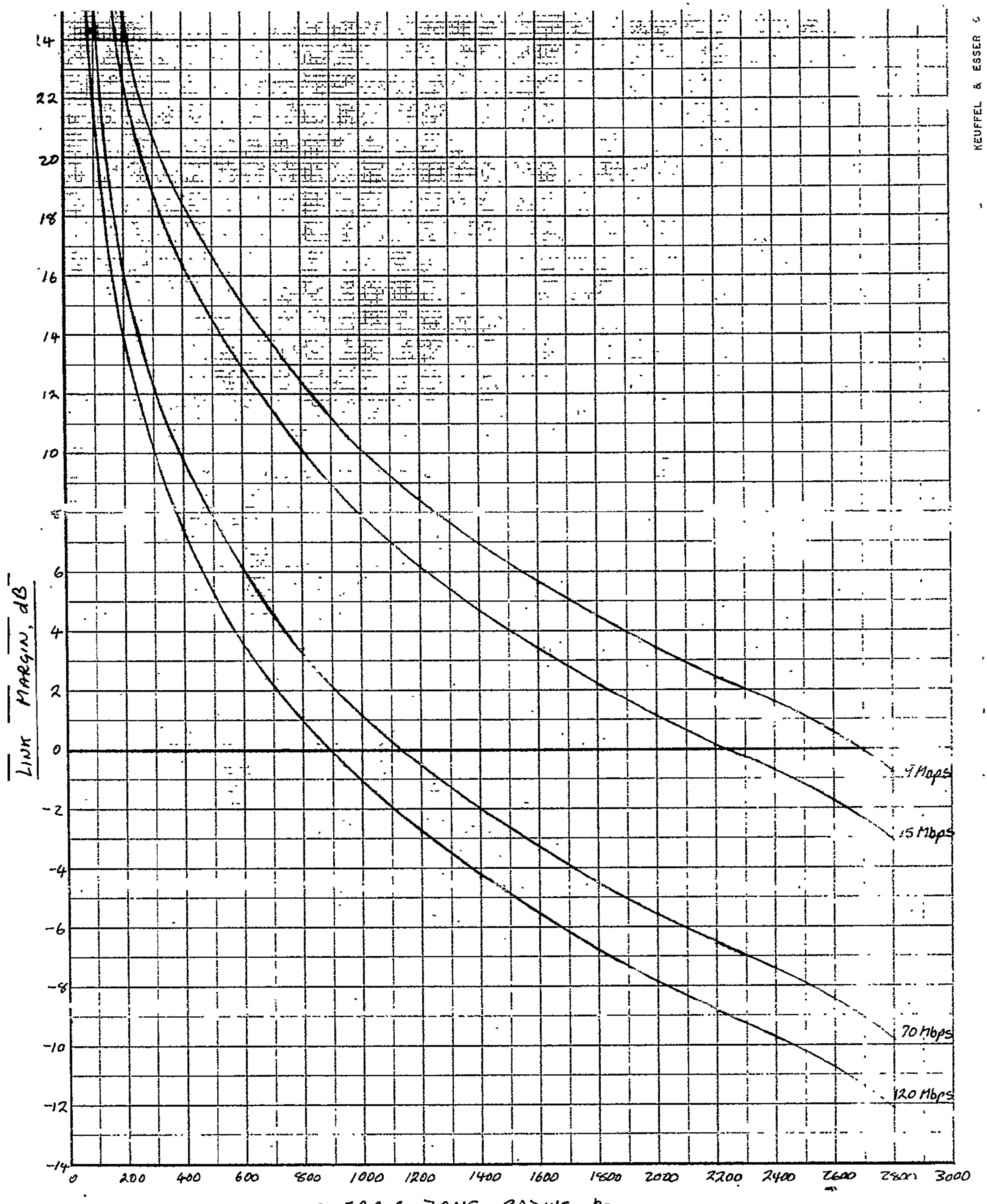


Figure 4-13. Link Margin vs. Coverage Zone Radius for 915 km Orbit

4.4 DISCUSSION

As has been shown, the use of a Ku-band communications link with broad-beam, fixed transmitting antenna onboard the Landsat Follow-on Spacecraft will have a significant impact on the coverage zone radius achievable from a direct readout ground station, even for a "most optimistic" analysis.

This section will provide a discussion of various factors affecting the achievable coverage which are not treated analytically.

4.4.1 ATTENUATION BY RAIN

The analysis, to this point, has ignored the effects of attenuation by rain of the signal transmitted by the spacecraft.

The exact effect of rainfall attenuation on the ability of a direct readout station to acquire data directly from the LFo spacecraft will, naturally, depend on the rainfall rate and the extent of rainfall around the receiving antenna at the time of overflight of the LFo spacecraft. An extensive amount of statistical data must be collected, for each ground site, in order to perform a thorough analytical prediction of data losses due to rainfall. Thus, prudent design practice is to include a fixed margin in communications link calculations which is representative of the attenuation which may be expected. Typically, a figure of 7 dB is used for Ku-band communications links, which corresponds to a rain-fall rate of 15 mm/hour in the path through the atmosphere with the ground antenna at a 30 degree elevation.

Thus, for the link characteristics used in this analysis, it will be seen, by reference to Figures 4-12 and 4-13, that a significant reduction in coverage zone radius will occur should it be raining at the time of the LFo spacecraft over-flight and should such an attenuation be present in the link.

4.4.2 SIGNAL ACQUISITION AND TRACKING

The signal beamwidth of a 10 meter diameter dish antenna, used at Ku-band, will be less than 0.1^{o} (3 dB beamwidth). Thus, the antenna must be positioned such that the line of sight from it to the spacecraft is less than 0.1^{o} from the antenna boresight for the signal from the spacecraft to be acquired. In addition, it is necessary to maintain position accuracy of better than 0.02^{o} in order to maintain tracking of the spacecraft during its pass. With current technology, and especially with the technology used in current foreign direct readout stations, it is doubtful that these accuracies can be achieved.

A further complication in the tracking of the LFo spacecraft is the problem of the zenith pass. The usual pedestal for direct readout stations used for Landsat 1 and 2 data acquisition is an Elevation over Azimuth mount. This type of mount suffers from the problem of requiring extremely high slew rates for spacecraft passes which are overhead or nearly overhead. For current systems, using S-band, the broader beam angle of the antenna permits the use of a programmed follower which enables tracking to be maintained. Because of the narrow beamwidth of the antenna when operated at Ku-band, this technique is not practical and, in consequence, a different mount type (several times more expensive) must be used which does not suffer from this deficiency.

4.5 VALIDITY OF DESIGN ASSUMPTIONS

4.5.1 SPACECRAFT DESIGN

Assumptions regarding LFo spacecraft EIRP are derived from the LFo spacecraft design baseline with the exception of the antenna gain characteristics.

A simplified analytical model was used for antenna gain as a function of half power bandwidth since no measured data is available. It is expected that, in any case, the gain values used are within $\pm$ 1dB of what would be achieved by a practical broad-beam Ku-band antenna.

A possible modification to this assumption would be to assume some form of beam shaping, as is used on the S-band antennas on Landsat 1 and 2 to boost power at the "edge" of the beam at the expense of the beam center. The implications of this alternative are discussed in Section 4.6.2.

4.5.2 DIRECT READOUT STATION ANTENNA/RECEIVER DESIGN

Several assumptions have been made regarding the direct readout station antenna/receiver design, however, since values for system losses, margin and E_b/N_o are based on typical prudent engineering values, the major assumptions which should be discussed are those of antenna diameter and system noise temperature.

Considering first the question of antenna diameter, Figure 4-14 shows the variation in system G/T as a function of antenna size. It can be seen that doubling the antenna diameter, from 10 meters to 20 meters, will provide a G/T increase of 6 dB. As has been discussed in section 4.4.2, however, an antenna diameter of 10 meters is considered to be at the limit of current technology for Ku-band tracking and communications with low earth orbit spacecraft. A 20 meter diameter antenna will further compound the difficulties alluded to in section 4.4.2, even if it could be built for a reasonable cost. Increasing antenna diameter is, thus, not practical, and use of 10 meters as an "optimistic" value for antenna diameter is a reasonable choice.

With regard to the system noise temperature, the value selected of 263° K is also considered "optimistic" but reasonable.

System noise temperature is made up of components due to sky noise, thermodynamic temperature of the antenna, losses between antenna and receiving amplifier (paramp), and paramp noise temperature. Sky noise and thermodynamic temperature of the antenna result in a value of $\sim 100^{\circ}$ k effective noise temperature which cannot be reduced. Antenna feed and waveguide contribute approx-

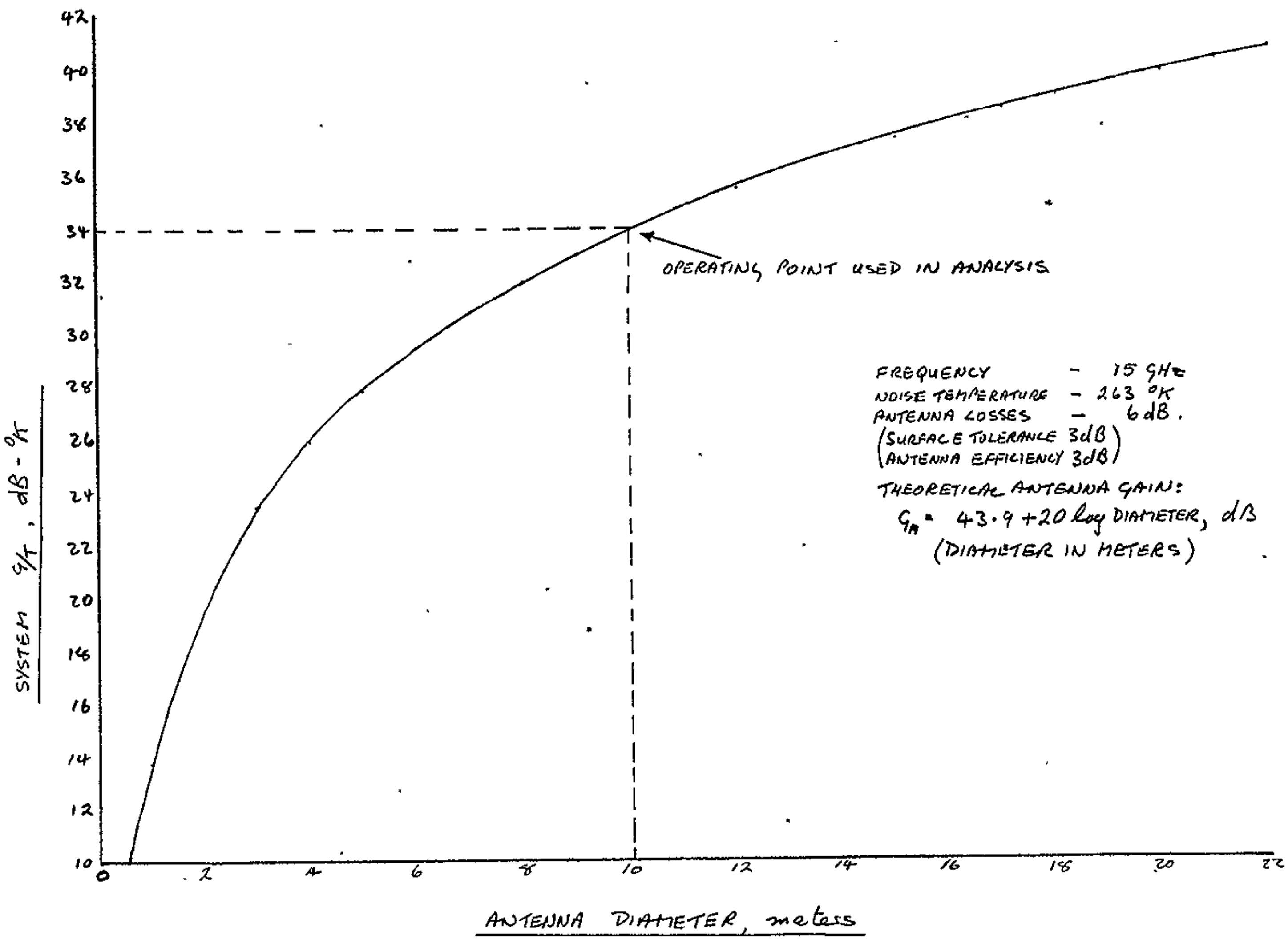


Figure 4-14. Variation of System G/T as a Function of Antenna Diameter

imately 85° K due to inherent losses, for a total effective noise temperature at the antenna port of the paramp of 185° K.

Paramp technology, using cooled amplifiers, can achieve effective noise temperatures in the 50° K region, thus, the most optimistic value of system noise temperature which may be obtained is approximately 235° K. Use of this value would provide an increase of 1 dB in G/T, but for a practical system the value of 263° K used is felt to be somewhat more representative of what would be realistically achievable.

It could, of course, be argued that the antenna diameter could be reduced slightly (to ~8 meters in diameter) which, with a concurrent decrease in effective noise temperature, would result in essentially the same system G/T with some reduction in tracking and acquisition problems. This would not, however, alter the link calculations or provide any significant increase in achievable coverage zone.

4.6 ALLEVIATION OF IMPACT

Previous sections of this report have established the impact of LFo baseline spacecraft design on coverage zone radius. As a point of comparison, Figures 4-15 and 4-16 show the achievable coverage zones for a representative selection of current and planned direct readout stations for the two altitudes of interest, based on 5° minimum antenna elevation and 30° minimum antenna elevation angles. The 30° minimum antenna elevation corresponds to the coverage zone radius achieveable for the 120 Mbps Thematic Mapper data link at 705 km altitude, and the 70 Mbps link at 915 km altitude.

An obvious conclusion to be drawn from the analysis presented in section 3 is that, in order to increase the achievable coverage zone radius, either the sensitivity of the receiving system (G/T), or the EIRP of the spacecraft, must be increased (or both).

To establish the magnitudes of the improvement required, inspection of Figures 4-12 and 4-13 shows that, for coverage to 5° minimum antenna elevation, an additional 10 dB must be included for a 705 km orbit, and an additional 12 dB must be included for a 915 km orbit, either by increasing the ground system sensitivity or by increasing spacecraft EIRP, or a combination of both. It should be noted that these values do not provide any additional margin to protect against attenuation by rain.

The sensitivity of the receiving system is expressed as the Gain-to-Temperature ratio (G/T) of the antenna/receiving amplifier, in dB.

Since antenna gain is a function of antenna diameter and efficiency, it is reasonable to assume that increasing either diameter or efficiency will result in an increase in G/T. It has been shown, however, (Section 4.5.2) that the assumed antenna design is at the limit of current technology. Also, since the efficiency is assumed to be that dictated by prudent design and engineering, it is clear that little improvement may be achieved by attempting to increase antenna gain.

FOREIGN LANDSAT GROUND STATION COVERAGE

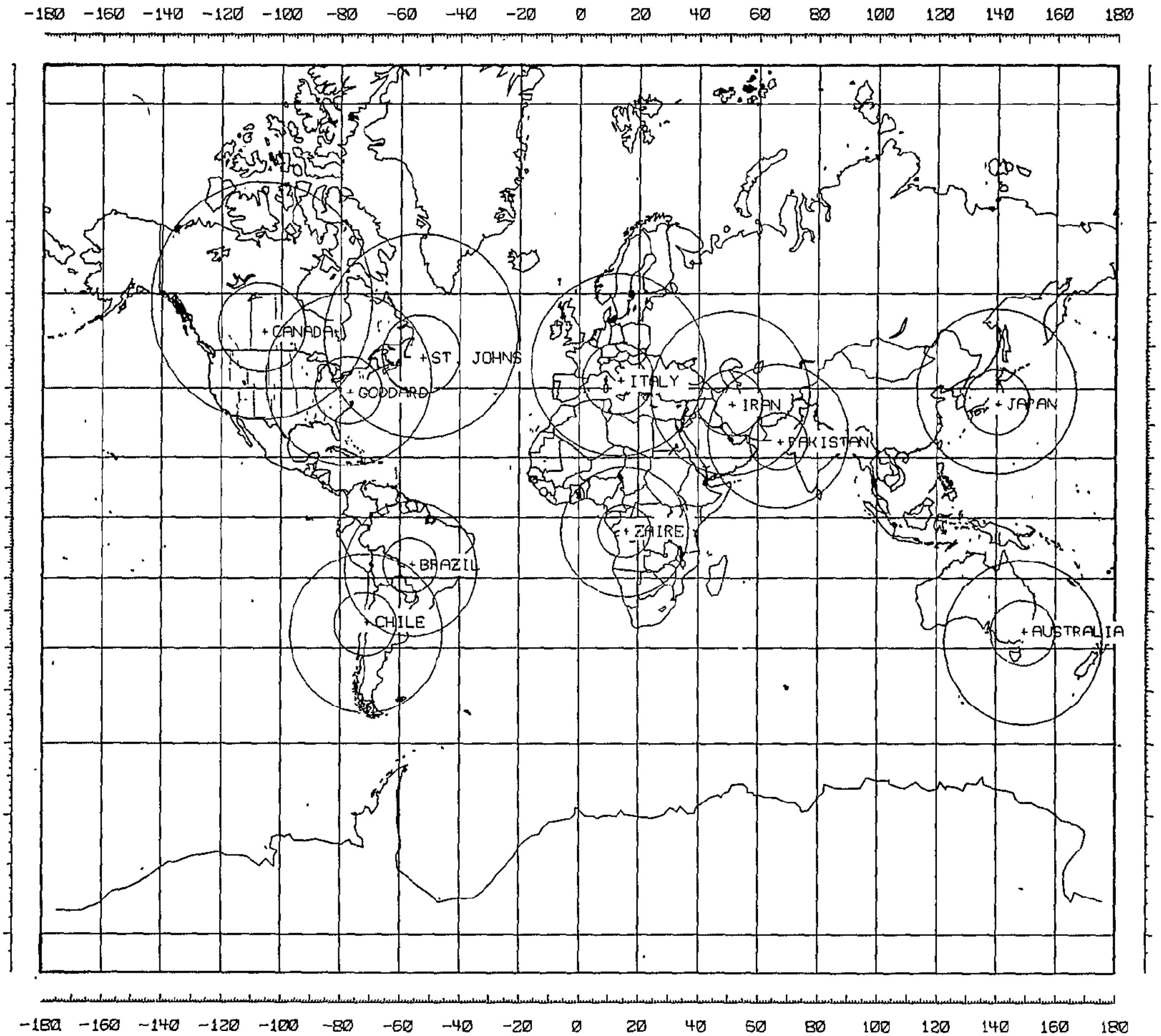


Figure 4-15. Global Current and Planned Coverage Zones - 705 km Orbit

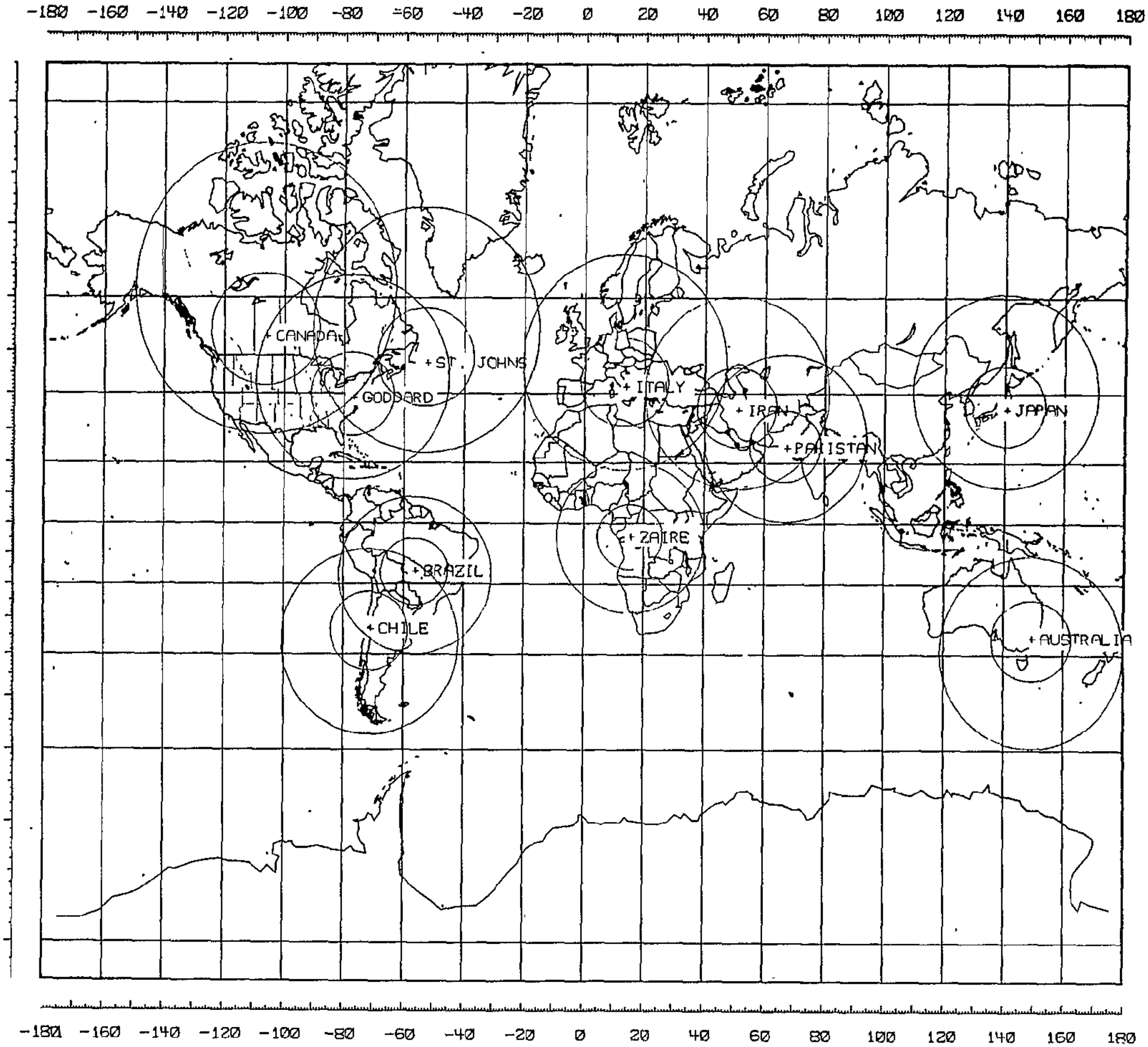


Figure 4-16. Global Current and Planned Coverage Zones - 915 km Orbit

Similarly, it has been shown, in section 4.5.2, that the assumed value of 263° K for system noise temperature is close to the limit of current technology.

The obvious conclusion to be drawn from the foregoing is that improvements in link margin cannot realistically be expected by changes in direct readout station design parameters.

Thus, the only alternative is to make an attempt to increase spacecraft EIRP. Methods of accomplishing this will be discussed, together with an assessment of inherent limitations and implications, in this section of the report.

4.6.1 TRANSMITTER POWER INCREASE

One alternative for increasing spacecraft EIRP is to use a higher power transmitting tube. For the LFo system under analysis here, which requires an additional 10 dB in EIRP, this means using transmitter power in the 150 - 200 watt range to provide full coverage of the maximum achievable coverage zone (to 5° minimum ground antenna elevation).

A single transmitter tube of this power level is probably not practical, however a 100 watt tube is under development for the General Electric Broadcast Satellite -- Experimental (BSE) program. The tube is, however, rather large, and since it has an efficiency of approximately 30%, will require some 300 watts of power input from the spacecraft power system.

Use of a single such tube would increase the achievable coverage zone radius to approximately 2000 km for the Thematic Mapper data rate (120 Mbps), and may represent a reasonable alternative if other methods cannot be implemented. It should be remembered, however, that even with such a transmitter there is still no rain margin in the link, and the direct readout station will still require the somewhat optimistic design characteristics assumed earlier.

4.6.2 INCREASE SPACECRAFT EIRP BY ANTENNA BEAM SHAPING

The other alternative for increasing the EIRP from the spacecraft is increasing the antenna gain.

Some increase in gain may be achieved by shaping the beam of the broadbeam antenna assumed in the analysis, to boost the gain at the edge of the beam at the expense of the on-axis gain, as is done on current Landsat vehicles. This would, however, only result in an increase of 2 - 3 dB, and would thus extend the achievable coverage zone radius by, at most, 200 - 300 km.

While it is quite practical to provide such improvements, either by fixed element design or by use of an appropriate phased array, this degree of increase in achievable coverage zone radius is still not at the desired level.

4.6.3 INCREASE SPACECRAFT EIRP BY NARROWING ANTENNA BEAMWIDTH

The most desirable method of increasing spacecraft EIRP is by using a directional antenna with a narrow beamwidth. Figure 4-17 shows the on-axis gain of a Ku-band antenna as a function of beamwidth (an assumption of 50% efficiency is made).

From this figure it is apparent that significant increases in spacecraft EIRP are realizable by narrowing the beamwidth. A disadvantage of this approach is, of course, that a requirement exists for the transmitting antenna to be steerable, either mechanically or electrically, to maintain beam pointing towards the direct readout station.

A further complication is that the higher EIRP may violate flux density limits allowed for space to ground communications.

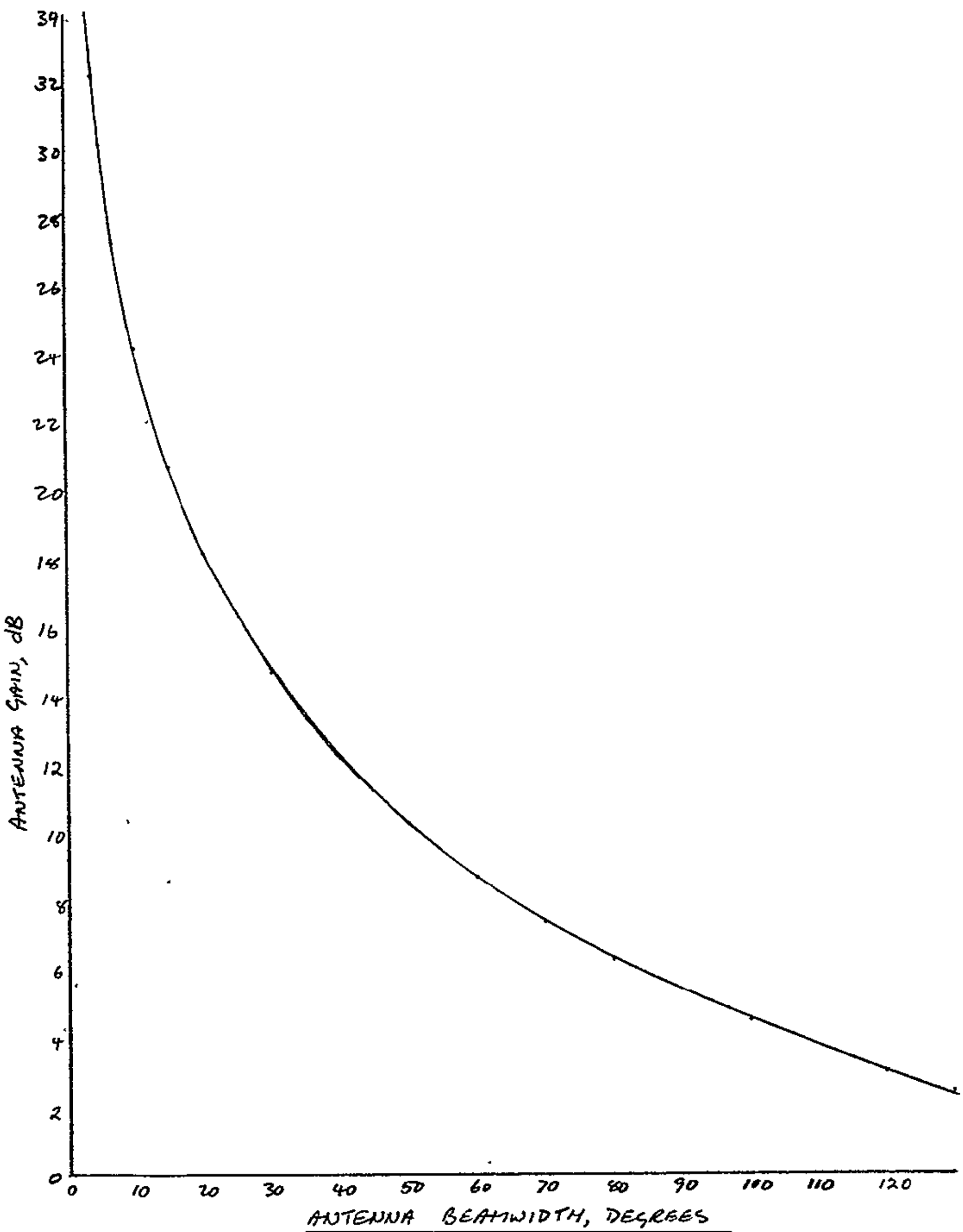


Figure 4-17. Antenna Gain vs. Beamwidth for 50% Efficiency

Advantages to be gained, however, are:

1) The achievable coverage zone radius may be extended to that corresponding to 5^{o} minimum ground antenna elevation.

2) Sufficient gain may be included in the transmitting antenna to permit the use of smaller ground antennas, which will result in a cheaper, more easily constructed, direct readout station antenna system.

For these reasons, it is believed that the incorporation of a narrow beam antenna on the LFo spacecraft is a desirable design feature, which will enhance the utility of the LFo system to operators of direct readout stations. The implications of such a design alternative are investigated further in subsequent sections of this report.

4.6.3.1 Antenna Steering Considerations

The narrow beam antenna on the LFo spacecraft must be steered within a 128^{o} cone to satisfy a full coverage zone radius requirement, and it is desirable that the pointing accuracy be maintained within 0.1 of the beamwidth.

The apparent angular velocity of the LFo spacecraft relative to a direct readout station is highest at zenith, and for a 705 km orbit is approximately 0.6 degrees per second. Thus, to maintain beam pointing accuracy within the 0.1 beamwidth figure stated, steering commands must be executed at a rate of

$$\frac{6}{\text{Antenna Beamwidth}} \quad \text{commands/second.}$$

For beamwidths on the order of 5 degrees this means a worst case of ~ 1 command / second (at zenith). This assumes, of course, that the antenna steering is commanded from the OCC and does not require closed loop tracking on the LFo spacecraft.

4.6.3.2 Antenna Beamwidth

Figure 4-17 has shown the antenna gain as a function of beamwidth. Since the LFo spacecraft is specified to have an altitude stability of 0.01 degrees, the pointing accuracy criterion dictates a minimum beamwidth of 0.1 degrees. This, however, will result in very severe design restrictions, requiring an antenna approximately 8 meters in diameter, and, in addition, represents an unnecessary increase in EIRP. Reference to Figures 4-12 and 4-13 indicates a requirement for an additional 10 - 12 dB of gain for 120 Mbps data links; if rain margin of 8 dB is included a value of 18 - 20 dB additional gain results. This can be accomplished using an antenna beamwidth of ~ 8 degrees.

Such an antenna beamwidth can readily be achieved using phased array technology, which offers the additional advantage of electrical beam steering, requiring no moving parts.

4.6.3.3 Flux Density Limitations

Power flux density at the earth's surface produced by emissions from earth expoloration, space research, and fixed satellites is regulated by International Telecommunications Union (ITU) as revised by the World Administrative Radio Conference (WARC), Geneva, 1971. The objective of these regulations is to control interference from satellite emissions with terrestrial radio communication service above 1 GHz. The power flux density limit is typically expressed as dB-watts per square meter in a 4 KHz bandwidth (nominal bandwidth of a SSB voice channel).

Flux density limits are not specified at Ku-band (14.5 to 15.35 GHz) by the current ITU regulations, probably because interference has not been common in this band due to low usage for terrestrial links.

In the absence of such limits, the values incorporated in the NASA specification for the TDRSS have been taken as typical values. These are shown in Table 4-3.

Table 4-3. TDRSS Flux density limits

Angle of arrival of signal above horizontal plane (degrees)	Maximum flux density in any 4 kHz band (dBw/meter^2)
$0 \leq \psi \leq 5^\circ$	- 152
$5^\circ \leq \psi \leq 25^\circ$	$-152 + \frac{\varphi - 5}{2}$
$25^\circ \leq \psi \leq 90^\circ$	- 142

(From TDRSS specification S-805-1, Revised June, 1975)

These flux density limits may be translated into an allowable EIRP for the LFo spacecraft, in consideration of its orbit altitude and the data rate required. The equation governing this is

$$EIRP_{MAX} = \text{Flux limit} + 10 \log (4\pi R^2) - 10 \log \left(\frac{BW}{4000}\right)$$

where:

R - slant range to the spacecraft, in meters

BW - Bandwidth required to carry the data rate, in Hz.

The LFo is expected to use QPSK modulation, which will result in a required bandwidth of one half the data rate. The governing equation becomes

$$EIRP_{MAX} = \text{Flux limit} + 10 \log (4\pi R^2) - 10 \log \left(\frac{DR}{8000}\right) \qquad (6)$$

The maximum allowable EIRP is plotted as a function of achievable coverage zone radius in Figures 4-18 and 4-19. Also shown, for reference, is the EIRP for a 0 dB gain antenna with a 15 watt transmitter and 1 dB losses between transmitter and antenna.

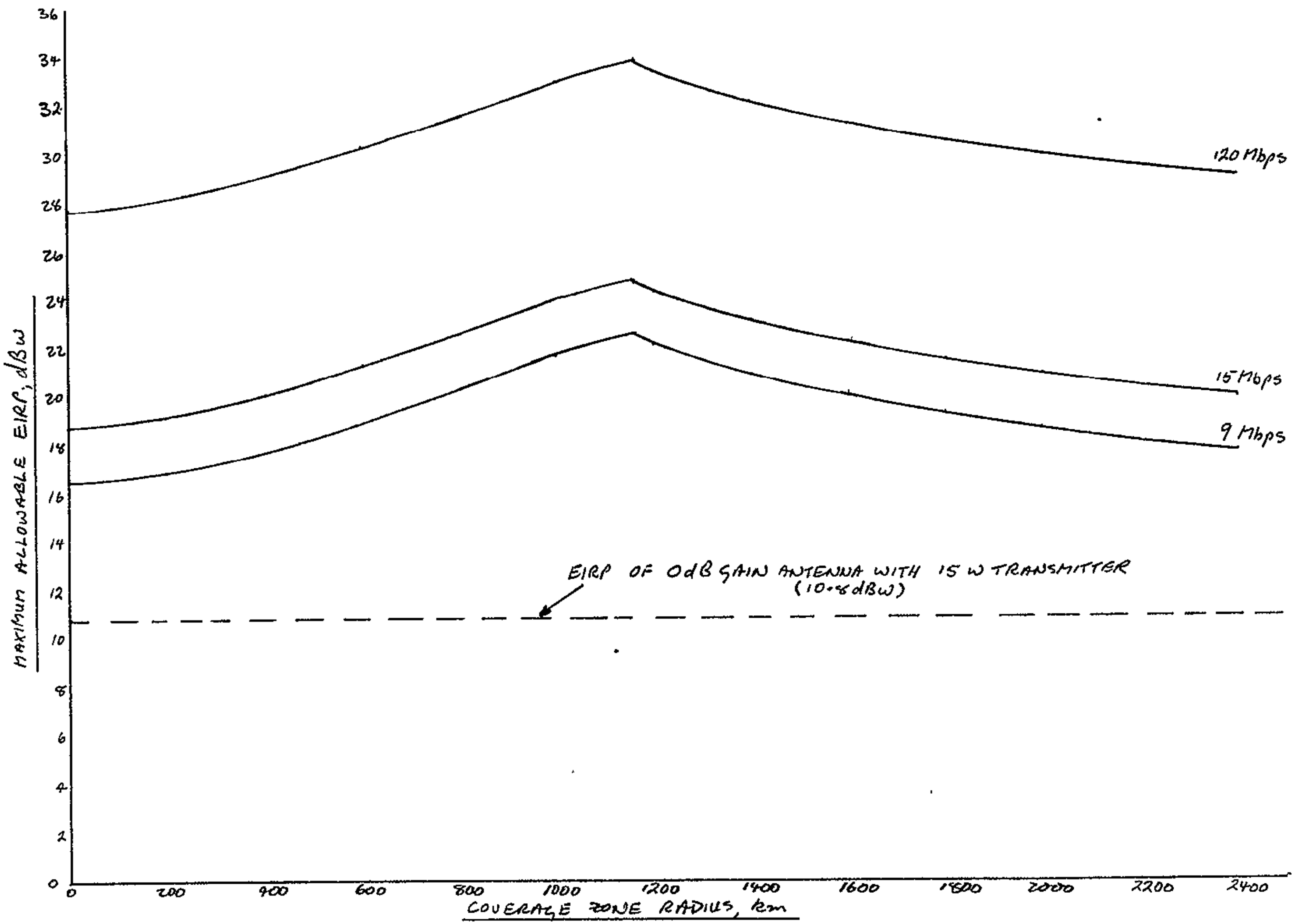


Figure 4-18. Maximum Allowable EIRP vs. Coverage Zone Radius for 705 km Orbit

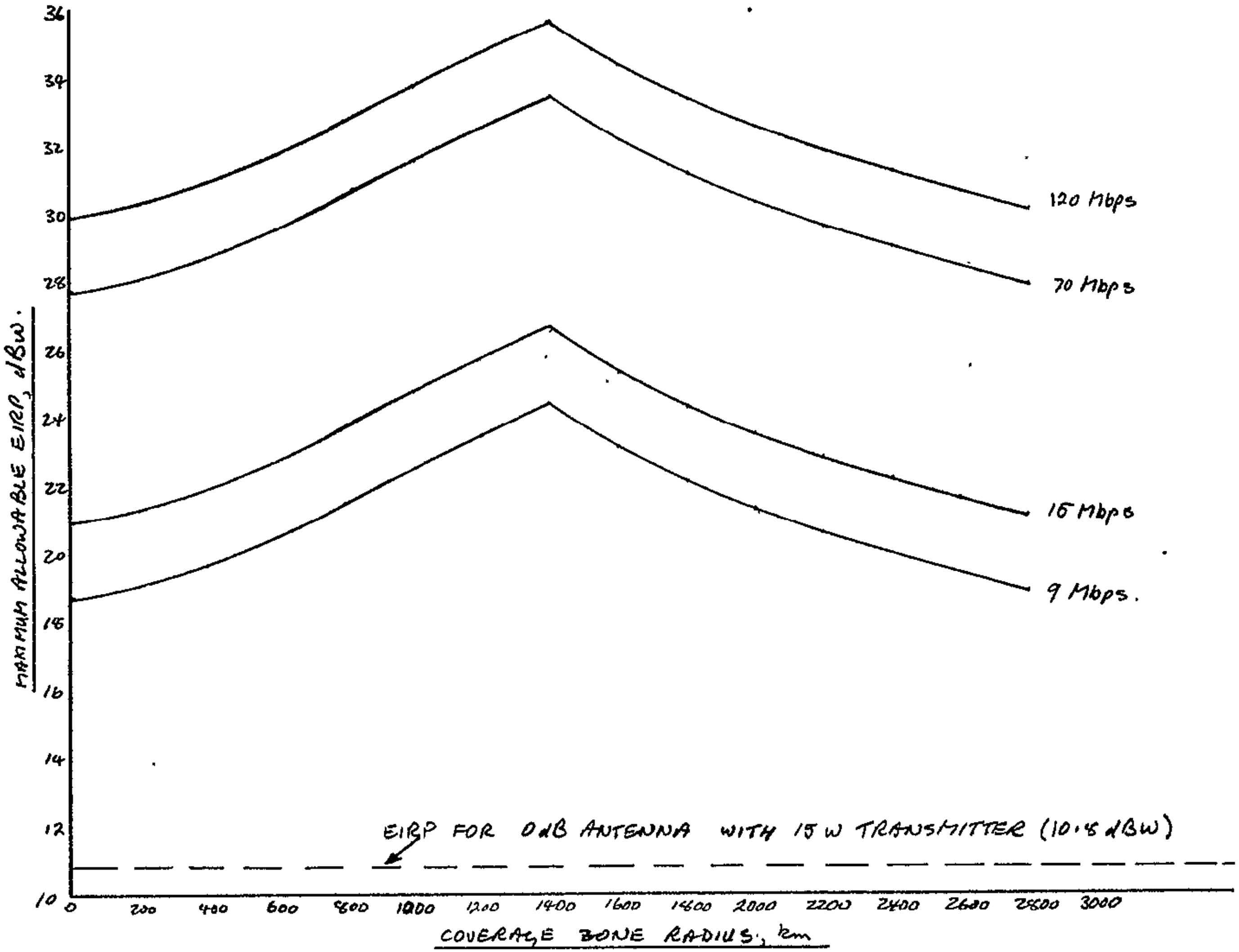


Figure 4-19. Maximum Allowable EIRP vs. Coverage Zone Radius for 915 km Orbit

From these curves it can be seen that up to 17 dB of gain may be included in the spacecraft antenna for a 705 km orbit, and up to 19 dB for the 915 km orbit, for a 120 Mbps data link, without violating the flux density limitations.

Thus, for the LFo program it appears that these flux density limitations are rather severe. In addition, reference to Figure 4-20 shows that the assumed values given in Table 4-3 correspond to the current ITU regulation for C-band operation.

To provide reliable service, terrestrial links at frequencies higher than C-Band (4 GHz) must necessarily provide increased carrier power margin to compensate for atmospheric and rain loss likewise provides an increase in tolerance against emissions from satellites, and it is therefore realistic to incorporate a relaxation of earth flux-density regulations with increased down-link frequency; this is in fact the case where ITU regulations exist for specific frequency bands.

The C-Band (3.4 GHz to 7.75 GHz) ITU limit, -152 dB W/meter^2/4 KHz at low arrival angles, results in an interference level 10 dB below the quiescent noise plateau of a terrestrial link receiving station with an antenna area of one square meter and a system noise figure of 6 dB; this interference level would result in a 0.5 dB CNR degradation of the station. Typically, a 10 dB increase in flux density is allowed for angles of arrival greater than 25 degrees because of the reduced side-lobe gain of the terrestrial link receiving antenna.

Thus, it is suggested that the flux density limits for Ku-band operation should be relaxed from those used in the TDRSS specification; a recommended set of levels which should be proposed to the 1977 WARC are shown in Table 4-4.

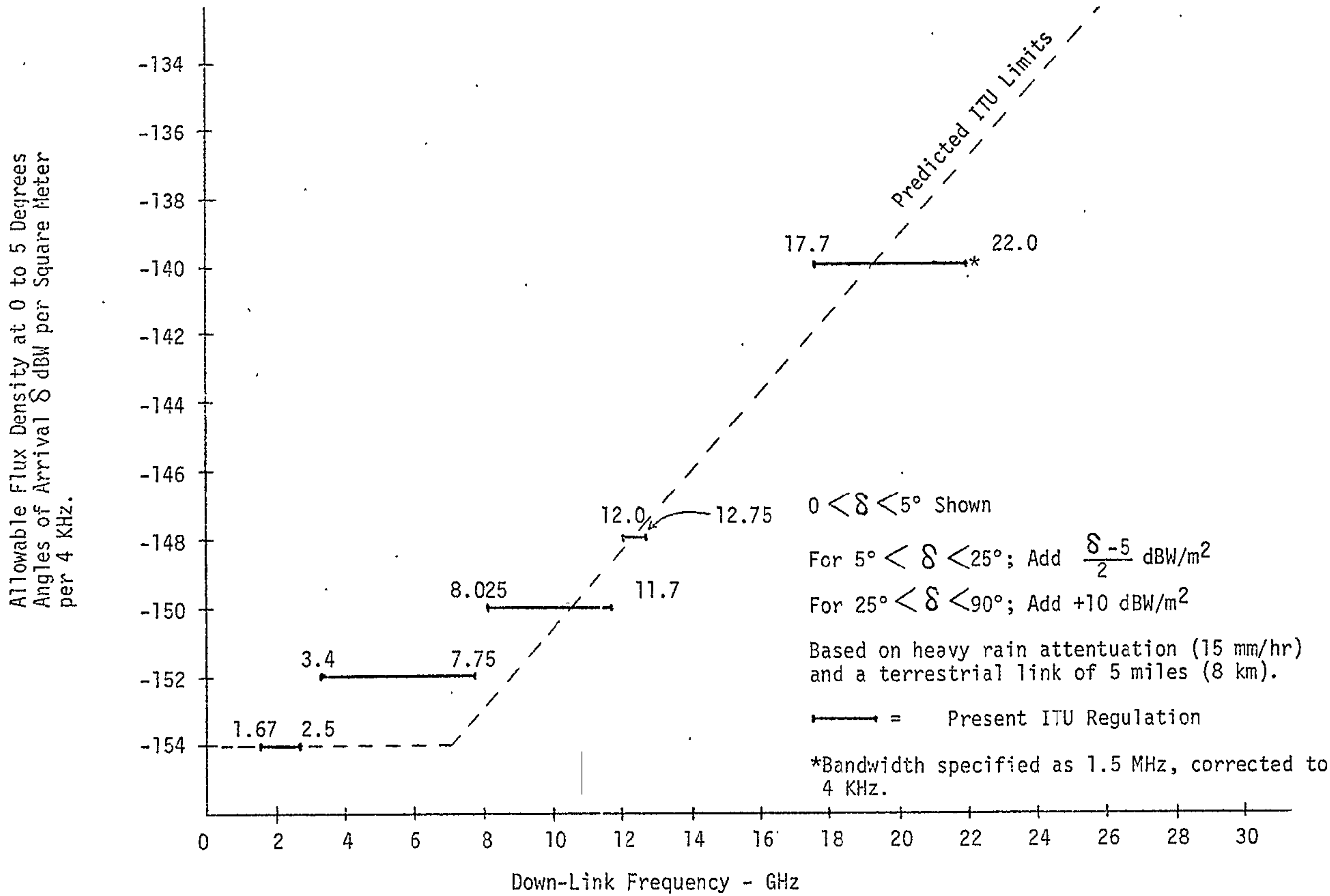


Figure 4-20. Predicted ITU Limits on Allowable Earth Flux Density

Table 4-4. Recommended Flux Density Limits

Angle of arrival of signal above horizontal (degrees)	Maximum flux density in any 4 kHz band (dBW/meter^2)
$0 \leqslant \varphi \leqslant 5^\circ$	-144
$5^\circ \leqslant \varphi \leqslant 25^\circ$	$-144 + \frac{\varphi - 5}{2}$
$25^\circ \leqslant \varphi \leqslant 90^\circ$	-134

These suggested limits relate to flux density which would be obtained under assumed free space propagation conditions.

Use of such values for flux density limits will provide an additional 8 dB of margin for the LFo system design, which may be traded off against a reduction in direct readout station G/T requirement.

4.6.3.4 Spacecraft EIRP and Direct Readout Station G/T Tradeoff Analysis

If the LFo spacecraft EIRP is increased, the Direct Readout station G/T may be reduced correspondingly.

From the basic link equation (equation 4)

$$\text{EIRP}_{\text{required}} = \text{Path losses} + \text{Pointing \& Polarization losses} + 10 \log (\text{Data Rate}) + E_b/N_o + \text{System loss} + \text{System margin} - G/T - 228.6$$

if we assume, as in Section 4.2.4,

E_b/N_o	9.9 dB
System losses	3.0 dB
System margin	3.0 dB
Pointing & Polarization losses	0.7 dB
No rain margin	

the tradeoff equation becomes

$$\text{EIRP}_{\text{required}} = \text{Path losses} + 10 \log (\text{DR}) - G/T - 212.0 \qquad (7)$$

Figures 4-21 and 4-22 shows plots of this equation for the different data rates and different orbit altitudes at the maximum coverage zone radius (corresponding to 5^o elevation of the direct readout station antenna). Also shown are the EIRP limits dictated by the flux density restrictions (assumed to be those recommended in Table 4-4).

4.6.4 SUGGESTED LFo SPACECRAFT DESIGN

In order to provide the capability for the development of a low cost direct readout station antenna/receiver system, it is suggested that the LFo spacecraft be equipped with a narrow beam steerable antenna which, with a 15 watt transmitter, will provide an EIRP just below the maximum consistent with flux density limits.

This will then permit direct readout station operators to assess their coverage zone requirements, to the maximum allowed by the orbit geometry, and size their ground antenna system accordingly.

To accomplish this, a spacecraft antenna of approximately 5 degree beamwidth providing a gain of 28 dB, using programmed steering by command from the OCC, is recommended. This will provide adequate EIRP for full coverage of the zone allowable by orbit geometry, using a 5 meter ground antenna, and allowing 7 dB margin for rainfall attenuation. Such a ground antenna is within the capability of current technology, and would alleviate many of the problems referred to in Section 4.5.2.

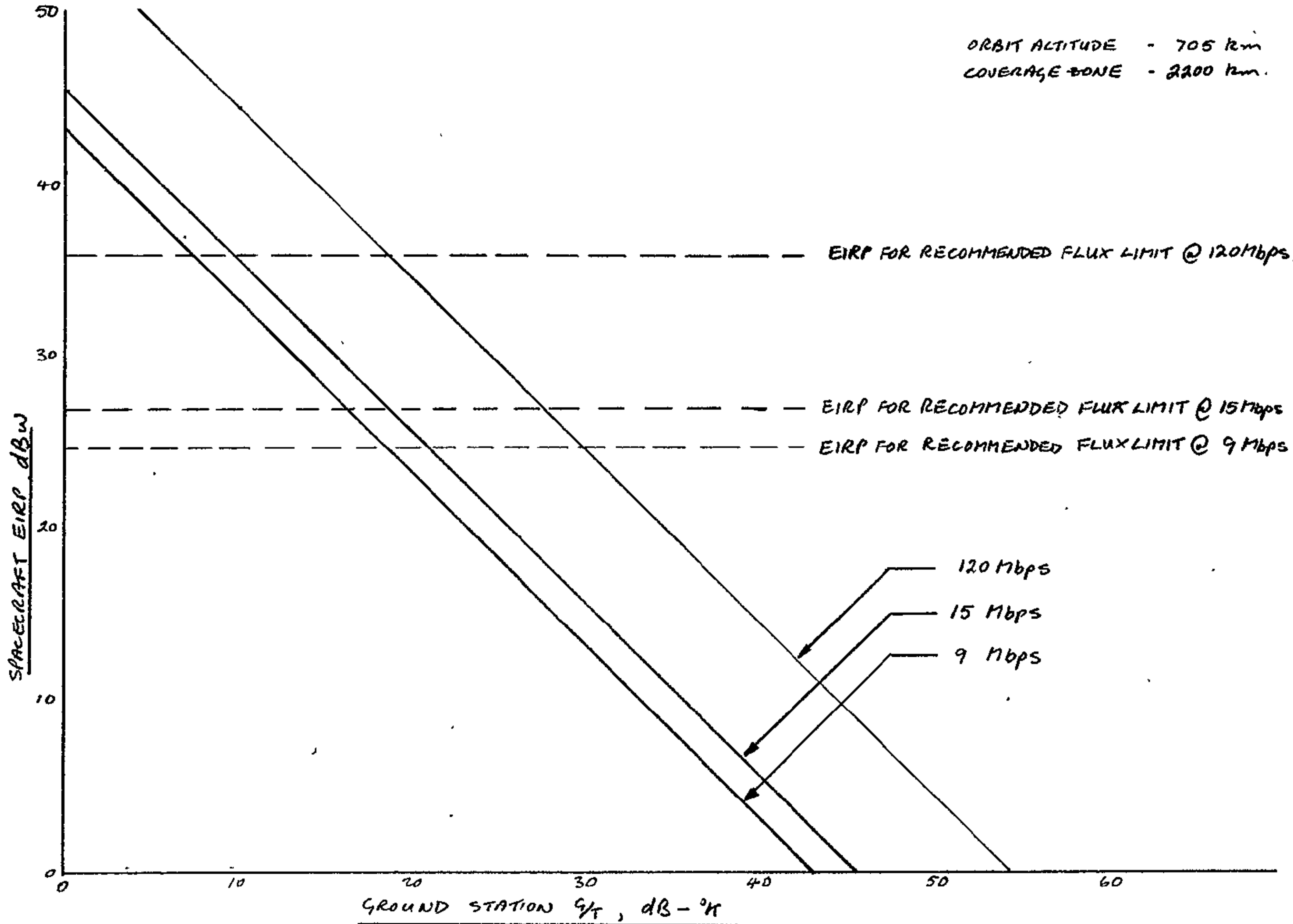


Figure 4-21. Spacecraft EIRP vs. Ground Station G/T Tradeoff for Orbit Altitude of 705 km

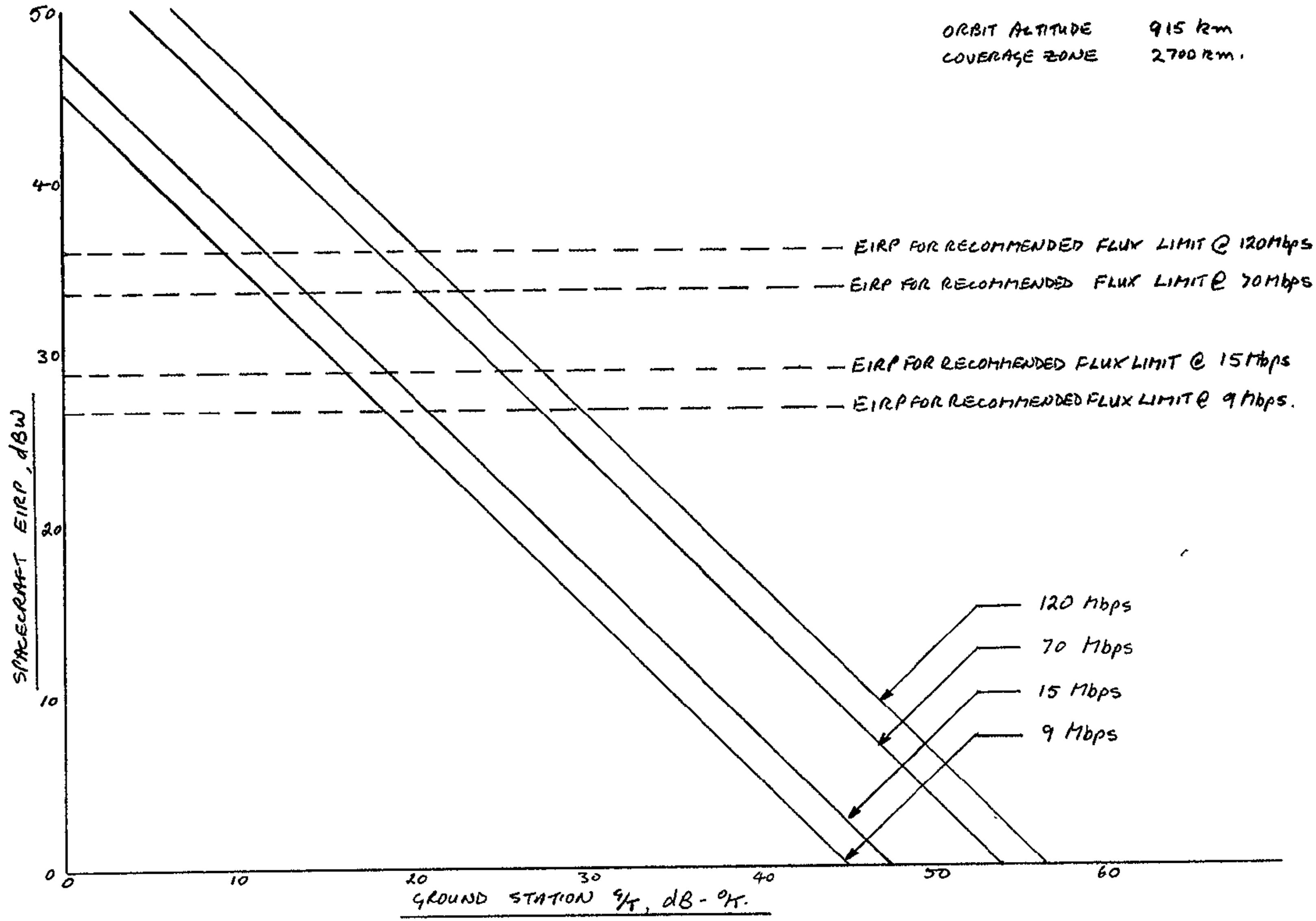


Figure 4-22. Spacecraft EIRP vs. Ground Station G/T Tradeoff for Orbit Altitude of 915 km

4.7 COMMUNICATION ANALYSIS

CONCLUSIONS AND RECOMMENDATIONS

The conclusions to be drawn from the analysis presented in this report are:

- Use of omnidirectional spacecraft antennas for direct readout of LFo data imposes severe restrictions on achievable coverage zone radius.
- Use of omnidirectional spacecraft antennas requires large (10 meter dia.) ground antennas which are at or beyond the limit of current technology, and are extremely expensive.
- The limitations on coverage and the ground antenna requirement may be alleviated by use of high gain, steerable antennas on the LFo spacecraft.
- Currently anticipated Ku-band flux density restrictions will reduce the effectiveness of such antennas by imposing a severe restriction on the amount of gain which may be incorporated.

The recommendations which are made in the report are:

- The LFo spacecraft design should incorporate a high gain steerable antenna for LFo-to-ground communications.
- NASA should attempt to get agreement on flux density limits for Ku-band operation of values corresponding to those stated in this report.

5.0 TAPE RECORDER REQUIREMENTS

Acquisition of Thematic Mapper data in real-time will require a completely new generation of tape recording equipment. This required equipment will cause a fairly large cost increment for upgrading ground station service. The specifications for both the old and new recording equipment will be briefly examined.

5.1 ALTERNATIVE TAPE RECORDER SPECIFICATIONS

It is expected that the LUT will contain sufficient 20 Mbps tape recorders to receive LANDSAT C data to the extent that is desirable. However, in order to receive Thematic Mapper data in real-time, a higher bit recording rate is required than is available from the High Density Rate Recorders. For this purpose, High Data Rate Recorders are necessary.

The High Density Data Recorder is a tape recorder which records in a longitudinal format at data rates up to 20 Mbps and capacity up to 1.4×10^{10} bits of serial data. The unit will reproduce a serial data stream over a wide range of data rates and tape speeds and has full remote operation capability. It will accept standard IRIG-A time code modulated on a 10 KHz carrier as a separate, edge track data stream. The serial data is recorded and reproduced in the forward direction of tape travel, but time code is reproducible in both forward and reverse directions. Normal data input to the unit is in 8-bit bytes, and the machine uses NRZL coding. Units meeting these requirements are currently available and operational in the field.

The High Data Rate Recorder is a tape recorder which records and reproduces a single digital input data stream from 0.500 to 120 Mbps. Tape-track packing density is controlled by the number of tape tracks over which the incoming data is distributed; typically 28 or 42 tracks per machine. There are at least two unused tracks available for signals such as servo, time code, direct or FM recording. This recorder will operate in three modes. The first mode is up to 150 Mbps which is distributed to tape track formatters for inclusion of appropriate overhead to reconstruct the serial data upon playback. The second mode uses multiple synchronized data streams with a common clock fed directly to the track data formatters for recording which results in parallel digital recording capability. The third mode of operation is the analog domain with typical signals being low rate, spacecraft telemetry, servo-reference, time code, etc. that are FM or direct recorded.

The pertinent specifications for the High Density Data Recorder and the High Data Rate Recorder are presented in Table 5-1. A minimum of two 120 Mbps recorders, at a cost in excess of $0.6M, will be required in order for an LUT to record Thématic Mapper data at the full rate.

5.2 DATA DEMODULATION PRIOR TO RECORDING

A second alternative for the recording of real-time Thematic Mapper rates is to use a demodulator at the front-end of the system in order to split the data into lower bit rate data streams. This represents a lower cost alternative to a foreign user who has some number of 20 Mbps recorders, is not willing to spend the money for the higher data rate recorders, but still wishes to receive some real-time Thematic Mapper data.

The Thematic Mapper Decommutator Unit (TMDU) will accept 120 Mbps Thematic Mapper data and process the data stream to permit selection of any single band or any combination of single bands of Thematic Mapper data for recording on 20 Mbps recorders. A conceptual design for the TDMU is shown in Figure 5-1. Input Thematic Mapper data is continuously supplied to the data latches. The sync recognition circuitry determines data identity and causes synchronization of the latch controller with the input data stream. Once synchronized, the latch controller output automatically commands the latches to accept and pass on the computer selected words to the appropriate low data rate recorders. For example, if the LUT has two 20 Mbps recorders, he may opt to select the .63-.69 micron and the .74-.91 micron spectral bands from the bit stream and record them in real time. On a subsequent pass over the same area, he has the option of selecting the same or different spectral bands to be recorded.

The estimated cost for design and fabrication of one Thematic Mapper Decommutator Unit is approximately $250K.

SPECIFICATION	20 MBPS RECORDER	120 MBPS RECORDER
Number of tracks	14	42
Packing Density (kbits/in.)	17.5	26.0
Input Data Rates	500 Kbps-20 Mbps	500 Kbps-120/150 Mbps
Input Format	Serial NRZL & Clock	Serial NRZL & Clock
Input Levels	DTL/TTL	TTL or ECL compatible
Output Data Rates	$\frac{20\text{ Mbps}}{2^n}$ n=0, 5	Same as input
Output Format	Serial Data & Clock	Serial Data & Clock
Output Levels	DTL/TTL	"1" = 1 $\pm$.25 V, "0" = -1 $\pm$ .25 V
Operation	Full Remote	Full Remote
Start Time	5 sec.	8 sec.
Stop Time	5 sec.	5 sec.
Fast Forward/Reverse	180 - 240 IPS	240 IPS +
Vendor	Martin Marietta	3 bidders: M. Marietta/Honeywell Ampex CEC (Bell & Howell)
Cost	$67 - 70K	$225K - 300K
Est. head life (operating hrs.)	3000	1000
Est. tape life	no spec.	75 Reads

Table 5-1. Alternative Tape Recorder Specifications.

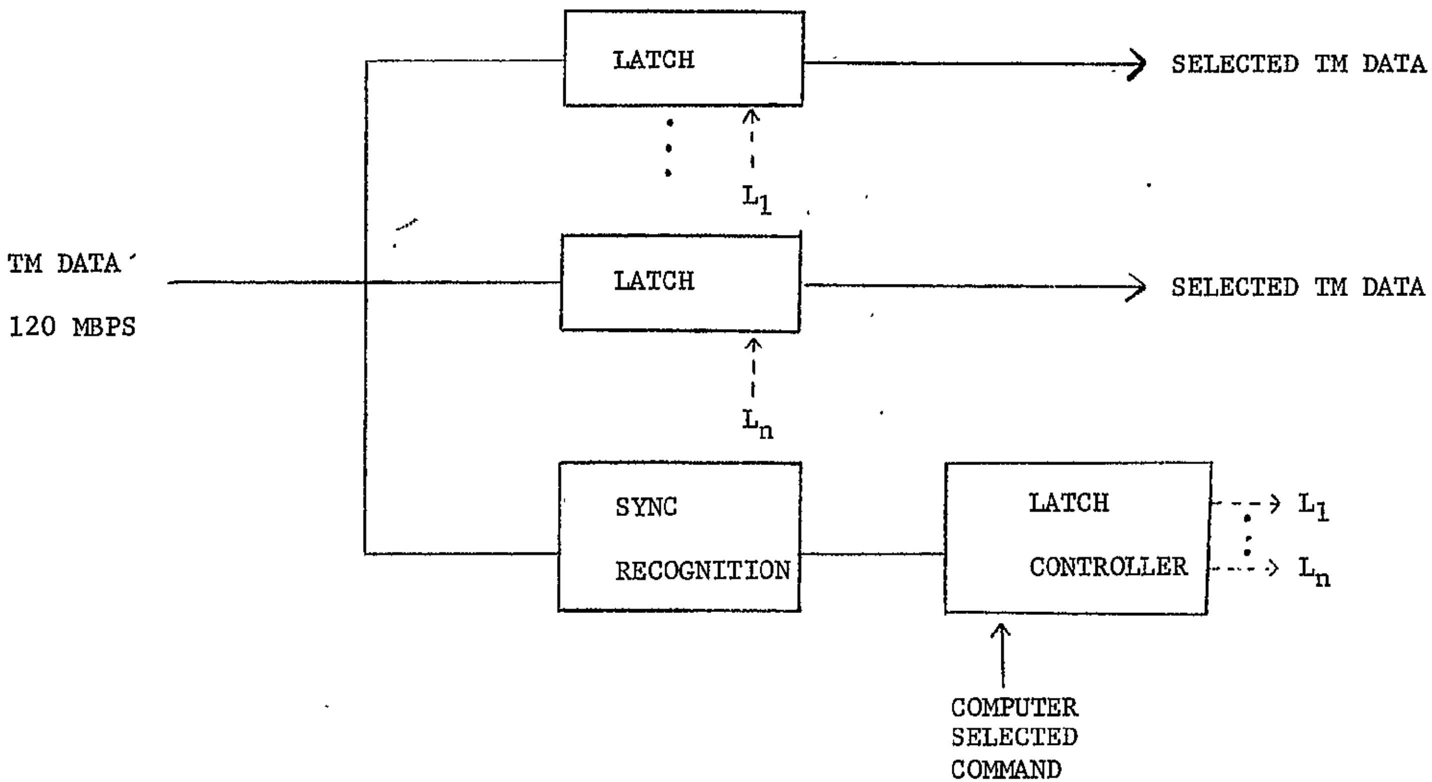


Figure 5-1.Block Diagram - Thematic Mapper Decommutation Unit

APPENDIX A - FOREIGN USER QUESTIONNAIRE

PREFACE

The United States National Aeronautics and Space Administration, NASA, is currently investigating future alternatives for its Earth Resources Program. In particular, consideration is being given to the spacecraft system which will follow the currently planned Landsat C; this sucessor spacecraft system is called the Landsat Follow-on.

There are several significant characteristics envisioned for the Landsat Follow-on that will cause it to be different from the Landsat 1, 2 and c series. One of the most visible differences is that the Landsat Follow-on will carry a Thematic Mapper as a new sensor, in addition to a Multispectral Scanner, MSS. The Thematic Mapper is an evolutionary advance over the MSS and will provide: more and different spectral bands, greater signal to noise performance, and finer spatial resolution. The result of these improvements is an increase in the data rate to 120M bits per second (compared to the current 15M bps for the MSS). This higher data rate will preclude existing ground stations from receiving and processing the new Thematic Mapper data.

NASA is currently considering several options with respect to the Landsat Follow-on which would affect the degree of impact on the foreign ground stations of the new system. In order to fully evaluate the potential impact of each system alternative, it is necessary to consider the current and planned foreign ground stations. To this end, NASA has prepared the attached questionnaire; the information thus received will assist NASA in evaluating the various system alternatives.

SECTION I GROUND STATION CONFIGURATION

1. Please describe existing LANDSAT ground station configuration and capability.

   a) Antenna:
      size
      surface tolerance
      mount type
      tracking accuracy
      location

   b) Feeds available (S-Band, L-Band, etc.)

   c) Receiver:
      number
      type
      noise temperature

2. Please describe any preprocessing performed on data <u>prior to</u> recording (Bit synchronization, demodulation, reformatting, geometric or radiometric correction, etc.).

3. Please describe recording and quick look display capability.

   a) Recording:
      recorder type (HDDT).
      data rate capability
      number of recorders available
      number of tracks
      type of recording (serial, parallel etc.)

   b) Quick look display capability:
      data rate limitations
      resolution

4. Please describe any <u>preprocessing</u> performed on data <u>following</u> recording on high density digital tape, exclusive of extractive processing or information extractions (radiometric or geometric corrections, resampling, reprojection, etc.

5. What coverage is routinely obtained:

   - average no. of scenes/day
   - Max. no. of scenes/day

SECTION II PREPROCESSING FUNCTIONS

1. Do you perform static or dynamic radiometric corrections?

2. Are the geometric corrections based on

   a. earth rotation
   b. sensor nonlinearities
   c. ephemeral data
   d. spacecraft attitude
   e. various map projections
   f. ground control points

3. Are the corrections performed in digital domain or are the coefficients applied to the output film device?

4. If output film device, what CCT input capability is desired?

5. If performed in digital domain what is your constraint on

   a. number of points for resampling
   b. resampling algorithm; e.g. nearest neighbor, $\frac{\sin x}{x}$ etc.
   c. amount of rotational capability

6. What is max throughput?

7. Is one band corrected at a time?

8. What are your output product
   - please describe in terms of

     - resolution
     - accuracy
     - production rate
     - format

SECTION III EXTRACTIVE PROCESSING FACILITIES

1. What preprocessing, if any, is routinely performed on data as received from the ground station prior to extractive processing?

2. Please describe the types of extractive processing equipment used in the analysis of LANDSAT MSS data.

   a) High speed general purpose computers
   b) Special purpose multipsectral image analysis systems
   c) Photographic image analysis systems
      - density slicing
      - color additive viewers

3. Please describe the preferred format for input of data to the extractive processing equipment (film, CCT, HDDT.)

4. Is film imagery of LANDSAT MSS data routinely used for interpretive purposes, or as a convenient display and information storage medium?

5. What is the typical throughput capability of the primary extractive processing facility?

6. Is all extractive processing performed at a central facility, or is it decentralized through Universities, discipline oriented organizations etc?

7. Please describe planned for projected additions, expansions or new extractive processing facilities for the 1976 - 1982 timeframe.

SECTION IV APPLICATION OF LANDSAT DATA

1. Please describe the general goals of your remote sensing program and the applicability of LANDSAT MSS data in the various discipline areas:

   Agriculture
   Forestry
   Land Use Mapping
   Rangeland Management
   Cartography
   Hydrology
   Mineral Exploration
   Environmental Monitoring

2. To what extent are these goals predicated on the routine use of LANDSAT MSS data, as opposed to a one time or infrequent coverage cycle which resulted or will result in acquisition of data not previously available?

3. Please estimate the probable percentage of utilization of available LANDSAT data, assuming acquisition of all data available at your current receiving site.

4. Please describe the use to which information generated from LANDSAT MSS data is put, and estimate the level of importance of LANDSAT data to related decision making functions.

SECTION V DATA REQUIREMENTS

1. Please describe the data requirements of your LANDSAT oriented remote sensing programs:

   Spectral characteristics
   Spatial resolution
   Amplitude resolution
   Repeat coverage cycle
   Preprocessing (radiometric and geometric corrections, mapping projection)
   Products used (film, CCT, etc.)

2. What is the greatest delay tolerable in receipt of data from any given overflight?

3. Do you forsee a requirement for data with significantly higher ground resolution (30m vs. 80m) and additional spectral bands over currently available LANDSAT MSS data? For what percentage of total coverage or data acquired?

4. Do you forsee a requirement for data with significantly higher radiometric capability than MSS; e.g. greater than 64 levels?

SECTION VI LANDSAT FOLLOW-ON IMPACT ASSESSMENT

1. Please describe your assessment of the impact of the LANDSAT follow-on program, especially with respect to the availability of Thematic Mapper (TM) data, on your programs.

2. Please describe your assessment of the desirability of compacted TM data to your program, and define methods by which you would prefer such compaction to be performed, e.g.:

   degrade spatial resolution
   eliminate one or more spectral bands
   reduce word size from 8 bits to 7 or 6 bits.

3. Please assess the impact on your program of relay of TM data through a U.S. based receiving and preprocessing facility, with precision preprocessed data products available ~1 week after overflight.

4. Please assess the desirability of communications satellite relay of raw or preprocessed TM data through a U.S. based receiving facility with data available within 24 hours of the overflight.

5. Would you be prepared to upgrade your receiving and recording facilities to handle full TM data transmitted direct to your receiving facilities on a Ku-band carrier (14-20GHZ) at a data rate of ~120 Mbps?

6. What is preprocessing thruput and/or output product generation requirements and actuals.

   - No. of uncorrected film images/day
   - No. of corrected film images/day
   - No. of uncorrected CCT's/day
   - No. of corrected CCT's/day

7. What is current (and desired) time delay from reception of imagery until output products are available to users for extractive processing?

8. Please describe methods of data dissemination from receiving site to extractive processing facilities (film, CCT, HDDT).

9. Please describe any planned or projected additions, upgrading, or improvements to existing receiving station facilities within the 1976-1982 timeframe.

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