NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-390

Cost Effectiveness of Spacecraft Pointing Antennas

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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Abstract

This memorandum presents an analysis of the minimum telecommunication cost for data return at planetary distances using pointing antennas. The system analyzed concerns only the related communications downlink portions of a spacecraft and the Deep Space Network ground stations and Space Flight Operations Facility. A solar-cell-powered spacecraft using either a programmed pointing or RF tracking antenna is assumed. Based upon the assumptions made, spacecraft RF tracking antennas are shown to be more cost effective than programmed pointing antennas for the return of greater than 10^{10} bits of data from Mars or greater than 10^{8} bits from Jupiter. The results of the analysis are sensitive to certain cost and performance assumptions, which are discussed in the memorandum.

Cost Effectiveness of Spacecraft Pointing Antennas

I. Introduction

A. Background

The first successful planetary probe, *Mariner II*, which encountered Venus in 1962, used an optical sensor antenna pointing system originally developed for the *Ranger* spacecraft. During that mission, the earth presented a bright target that was used by the optical tracking system to keep the spacecraft antenna pointed.

During the later (1965) *Mariner IV* mission to Mars, the earth was a darker and less fully illuminated pointing source. However, it was discovered that the flight trajectory was such as to allow the use of a body-fixed antenna on the spacecraft. A shaped antenna with a broad beam in the ecliptic plane would permit communications to be maintained as the look angles to earth from the spacecraft changed along the flight trajectory around encounter. Although the body-fixed antenna is certainly more reliable than an articulated pointing system, it was gain limited, and a communications greyout period existed on the downlink between the time the trajectory distance diminished the hemispherical low-gain antenna signal and the time the spacecraft orientation allowed the high-gain antenna to be pointed back at earth near encounter.

A two-position body-fixed antenna was used on the 1967 *Mariner V* flight to Venus to enhance occultation data. However, the antenna experienced a communication blackout before encounter while using the Deep Space Network (DSN) 85-ft antennas.

The *Mariner 1969* spacecraft, designed to fly by Mars, will use a 40-in.-diameter packaging area-limited, body-fixed antenna. Because of the trajectory changes, the communications system operating at the planned low data rate will lose 4 dB in gain due to pointing losses during the time of data return.

The significant point of the above discussion is that, in the future, much higher-gain antennas will be required to send back greater amounts of information from the planets. The higher-gain antennas will have correspondingly narrower beamwidths and thus will require pointing systems to keep the narrow beam pointed to earth for efficient communications. For voyages away from the sun, where earth optical pointing is insufficient, antenna pointing can be effected by either a passive stored-program pointing system on the spacecraft if the spacecraft is three-axis stabilized (at present by use of optical sensors for the sun and Canopus), or by an active RF tracking system requiring a pilot signal from earth.

Conceptually, the stored-program system is simpler to implement; however, the pointing accuracy obtainable is less than with the active RF tracking system. This report will attempt to determine the operating conditions and performance regions in which the two types of pointing systems are most cost effective.

B. Method of Analysis

The study will present estimated production costs rather than estimated development costs for the spacecraft equipment, since the amortization of spacecraft development costs is not well understood at present.

The transportation costs (Ref. 1) for lifting the spacecraft to escape velocity, taken to be \$1000/lb, were not considered for either pointing system, as they were found to be negligible compared to the solar panel and antenna costs. Additionally, the transportation and data storage costs affect each pointing system equally and thus do not influence the location of a cost minimum with respect to spacecraft gain-power product or antenna size.

The questions of loss of science weight and mission reliability or the need to repeat a mission (Ref. 2) are rather cursorily treated by estimating the cost of a mission as twice the production cost of a single spacecraft.

First, the spacecraft downlink system cost will be minimized for any particular gain-power product. This involves the determination of what combination of antenna gain and transmitter output results in the minimum cost for the desired gain-power product.

Next, the ground station operating costs for the return of a total number of bits of data will be factored in to minimize the overall data return costs. This involves the determination of the bit rate that can be obtained for a range of spacecraft gain-power products based on the communication range, performance requirements, and Deep Space Instrumentation Facility (DSIF) configuration. Then, for a given total bit requirement, the time needed to transmit back the data at each bit rate can be determined. This time is used to compute the cost of using the DSN. The optimization results when the cost of operating the DSN is weighed against the cost of providing a given gain-power product at the spacecraft in establishing an overall minimum cost.

Once the optimization is complete, the size of each system component is uniquely determined for a given total bit requirement. The optimum antenna size and transmitter power level, which are the components we are specifically interested in, can then be obtained for the total bit requirement.

An analytic solution to the above problem is possible; however, a graphical solution was made in order to develop a better portrayal of the sensitivity of various factors.

II. Spacecraft Downlink System Cost

A. Cost of dc–RF Subsystem

The spacecraft downlink system is subdivided into two subsystems. The first is called the dc–RF power subsystem (Fig. 1). A solar panel is used to provide raw dc for powering the RF portion of the spacecraft downlink. The downlink transmitter uses redundant exciters, power supplies, and final amplifiers. A constant

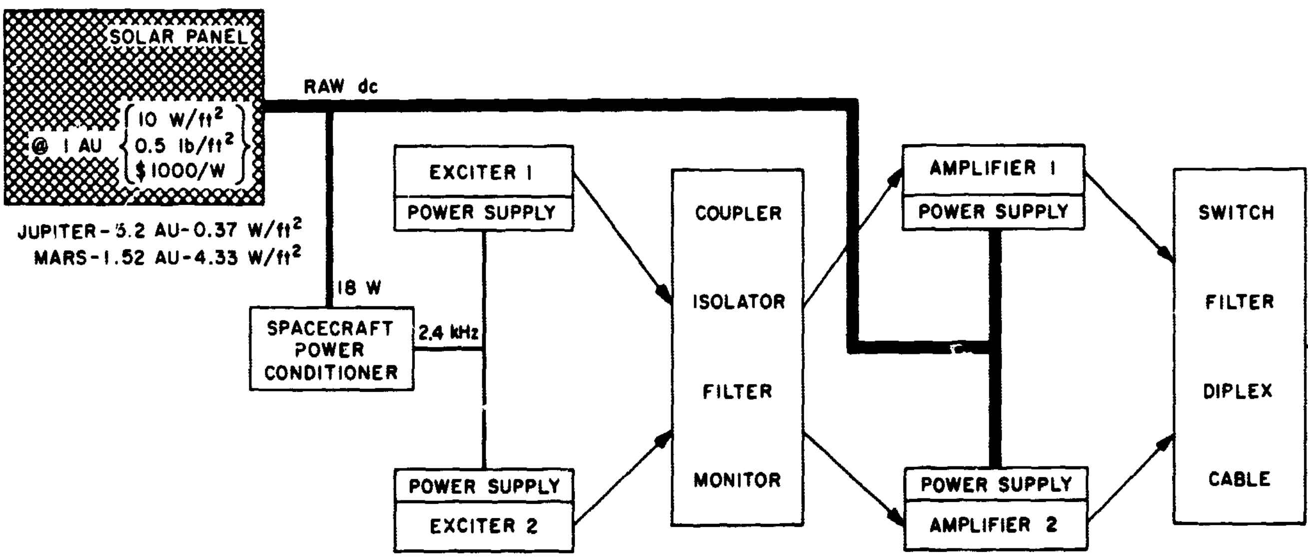

Fig. 1. Diagram of dc–RF power subsystem

power drain of 18 W is assumed for the exciters. The power drain for the final amplifiers varies with the desired output RF power.

Table 1 shows the assumed output powers, efficiencies, and costs for various transmitter output powers. The output power available to the spacecraft antenna was attenuated by an assumed 1.5 dB in the switching, filtering diplexing, and cable losses between the final amplifier output and the antenna input.

Table 1. Cost assumptions for dc–RF power subsystem[a]

Electrostatically focused amplifier output, W	Efficiency	Price per tube, $ × 10³	Price per power supply, $ × 10³
5	0.30	15	8
10	0.32	19	9
20	0.33	20	10
50	0.35	22	12
100	0.45	25	15

[a]Production (not development) costs per flight for program with one flight spacecraft and 100% spares (i.e., cost per flight = 2 × cost of 1 set).
Redundant exciter and power supply = $126,000.
Coupler-isolator-filter monitor-switch-diplex = $15,500.
Output loss = −1.5 dB.
Amplifier power supply efficiency = 0.85.

The costs shown in Table 1 are production, not development, costs for a program with one flight spacecraft and 100% spares (i.e., cost per flight = 2 times cost of one set). Figure 2 shows a curve fitted to the points obtained from Table 1 for the cost of the dc–RF power subsystem at Mars distance as a function of transmitter output at the antenna input. The fitted curve was a cubic equation.

The bend in the lower portion of the curve is due to the essentially fixed cost for the exciter power and subsystem components. The rapidly rising portion of the curve is caused by the fact that, for large transmitter outputs, the cost is essentially the cost of the solar panel power; for example, to double the output power, double the solar panel area is required. For the Mars case, 100% solar panel spares were assumed.

Figure 3 shows the cost curve that was fitted to data for a Jupiter mission. Fifty percent solar panel spares were assumed for this mission because of the greatly increased cost of obtaining the required power from the more distant sun.

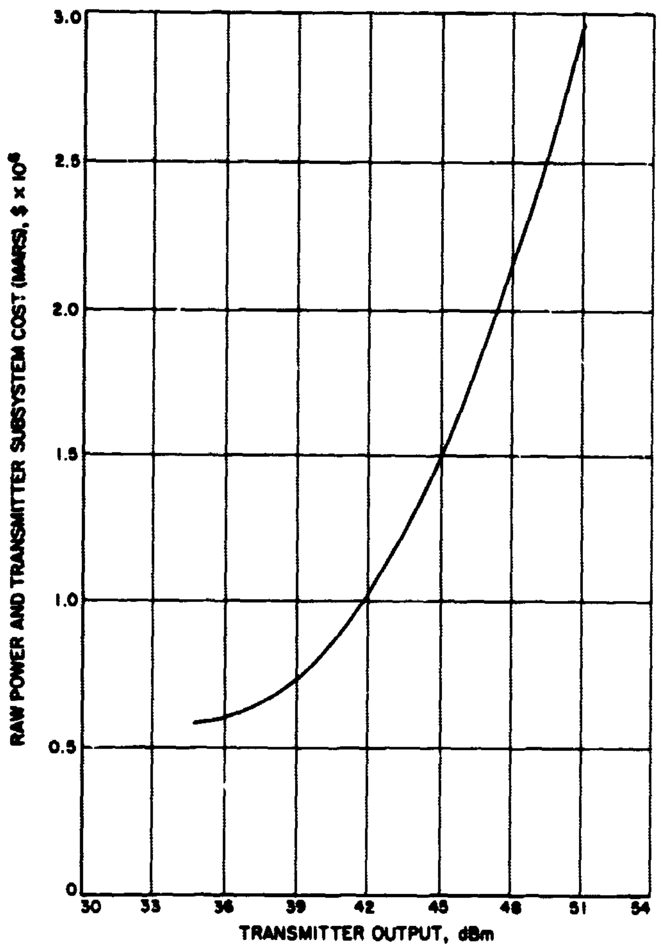

Fig. 2. Mars spacecraft dc–RF power subsystem cost

B. Pointing Antenna Subsystem Cost

The second subsystem consists of one of two types of pointing antennas. Figure 4 shows the tracking antenna subsystem and the programmed antenna subsystem. The tracking antenna subsystem was assumed to be able to point the beam in the direction of earth with sufficient accuracy to keep the combined loss due to the errors in beam pointing and to the tracking system components to less than 0.25 dB. The programmed antenna subsystem was assumed to be capable of pointing the beam to the earth to within ±1 deg of the boresight.

Figure 5 shows the gain at S-band as a function of antenna diameter for the tracking and programmed antennas. The upper curve indicates the boresight gain available from either antenna. The boresight gain minus 0.25 dB is shown for the tracking antenna on the second curve. The third curve presents the gain for a constant 1-deg offset for the programmed antenna. It can be seen

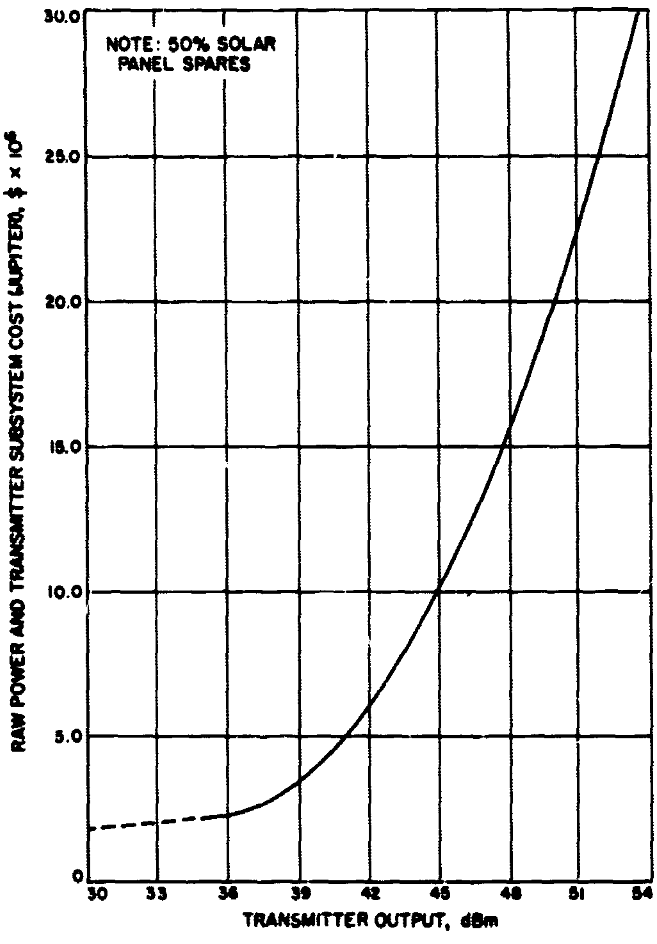

Fig. 3. Jupiter spacecraft dc–RF power subsystem cost

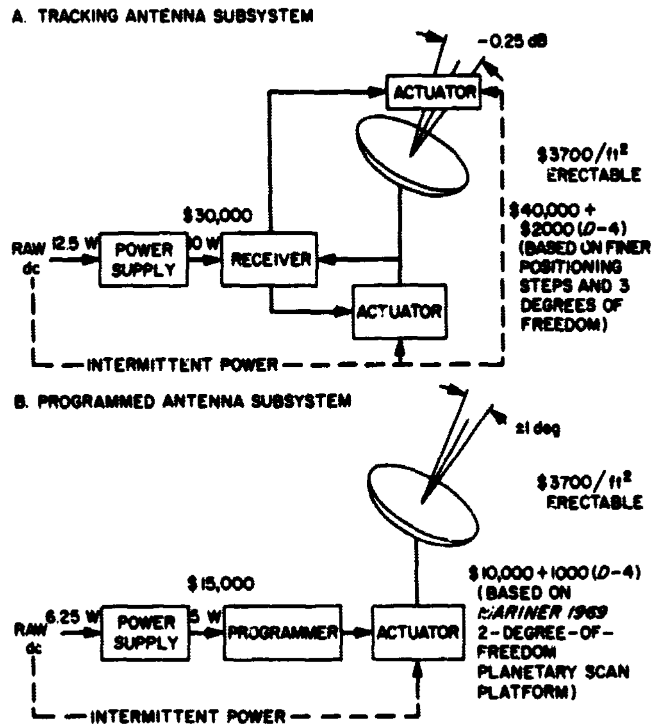

Fig. 4. Pointing antenna subsystems

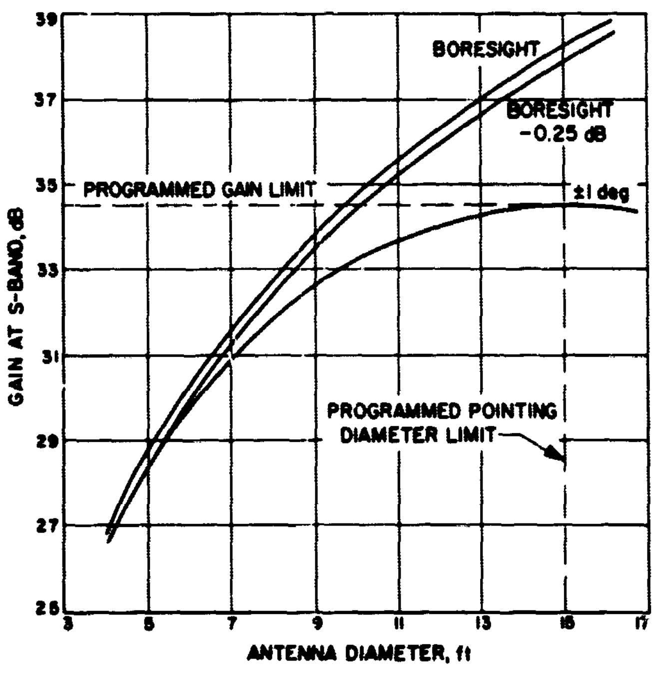

Fig. 5. Pointing antenna gain

that the ±1-deg programmed pointing antenna has a gain limit. As the diameter continues to increase, a point is reached at which the gain begins to decrease at 1 deg away from the boresight because of the increasingly narrower antenna beam. Table 2 shows the assumed uncertainties that lead to the ±1-deg programmed pointing limit.

Table 2. Pointing accuracy assumptions

Error source	Error, deg
Uncertainty in sun sensor null location	± 0.25
Attitude control limit cycling	± 0.25
Mechanical boresight location	± 0.25
Electrical boresight location	± 0.10
Thermal structural deflections	± 0.15
Programmed pointing limit	± 1.00

C. Minimum-Cost Gain-Power Product

The curves of Fig. 6, which show the cost of producing a given dBm gain-power product on the spacecraft as a function of the programmed antenna diameter, were produced using the cost data on the two spacecraft subsystems. To obtain larger gain-power products from antennas with small diameters and low gains, the transmitter output must be increased and is the controlling factor. Therefore, the cost rises rapidly, primarily because of the expense of the larger solar panels required to produce the increased output power. For larger antenna diameters, the cost increases because of the cost of the antenna. In the latter case, the transmitter output required to produce a given gain-power product is small. The balance between dc-RF subsystem cost and antenna cost are indicated by the minimum cost locus shown in Fig. 6. Scattered along the minimum cost locus are the powers required to yield the indicated gain-power product. The power is referred to the transmitter tube output. Also indicated in Fig. 6 is the fact that a 63-dBm gain-power product from the spacecraft could yield a 16,200 bps data rate back to earth from Mars distance.

Figure 7 shows data similar to those of Fig. 6 but for the case of a tracking antenna. It is to be noted that there is no diameter limit as for the programmed antenna. The ultimate diameter limit would depend upon the surface accuracy of the tracking antenna.

Figure 8 is a plot of the minimum cost loci of Figs. 6 and 7 as a function of spacecraft gain-power product.

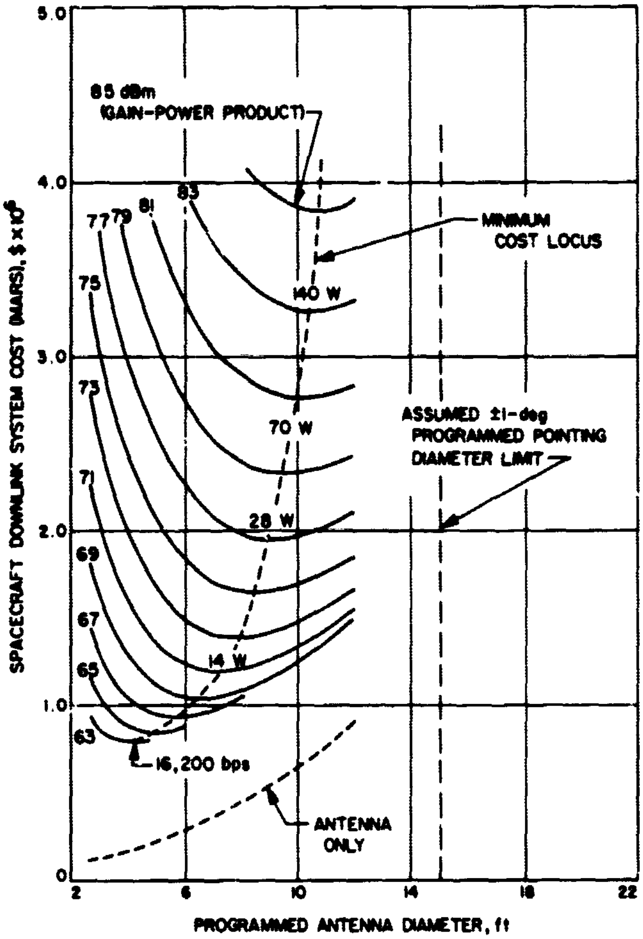

Fig. 6. Mars programmed antenna downlink cost

The cost difference between the programmed antenna pointing system and the tracking antenna system is shown. It may be seen that the tracking antenna is more cost effective for spacecraft gain-power products greater than approximately 72 dBm.

Figure 9 shows data similar to those of Fig. 6, except that the spacecraft is at the planet Jupiter. Again the programmed pointing diameter limit is shown.

The data presented in Fig. 10 are the same as those of Fig. 7, except that Jupiter distances are used.

Figure 11 shows the programmed and tracking antenna minimum cost loci plotted as a function of the spacecraft gain-power product for Jupiter distances, together with the cost difference. The tracking antenna is cost effective for gain-power products greater than 70 dBm.

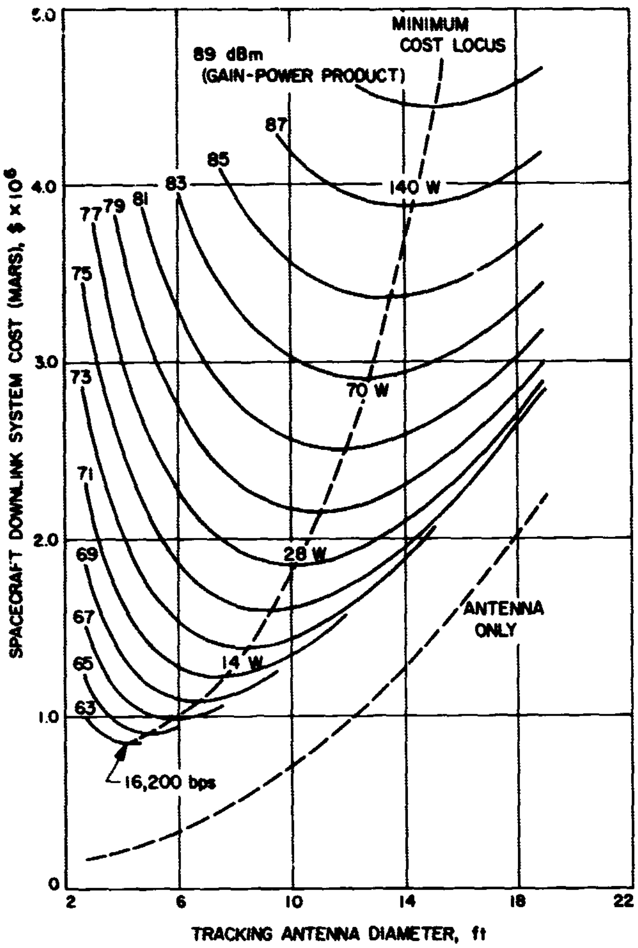

Fig. 7. Mars tracking antenna downlink cost

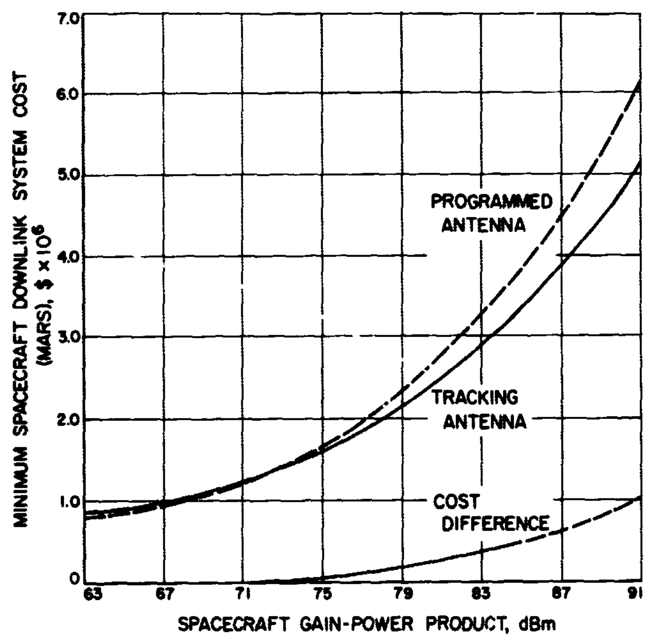

Fig. 8. Minimum-cost Mars downlink system

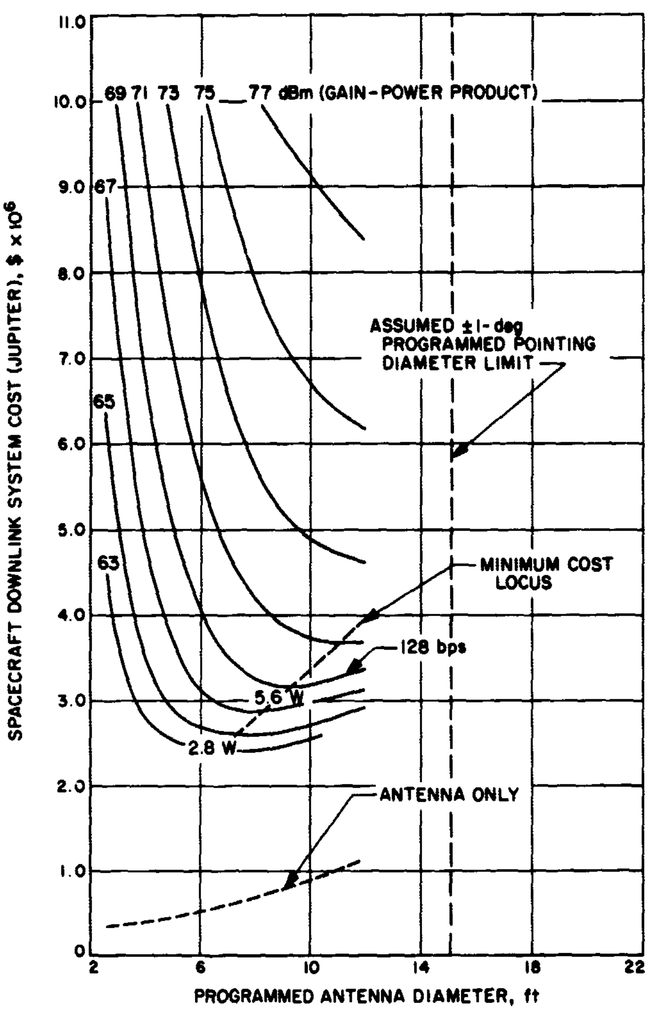

Fig. 9. Jupiter programmed antenna downlink cost

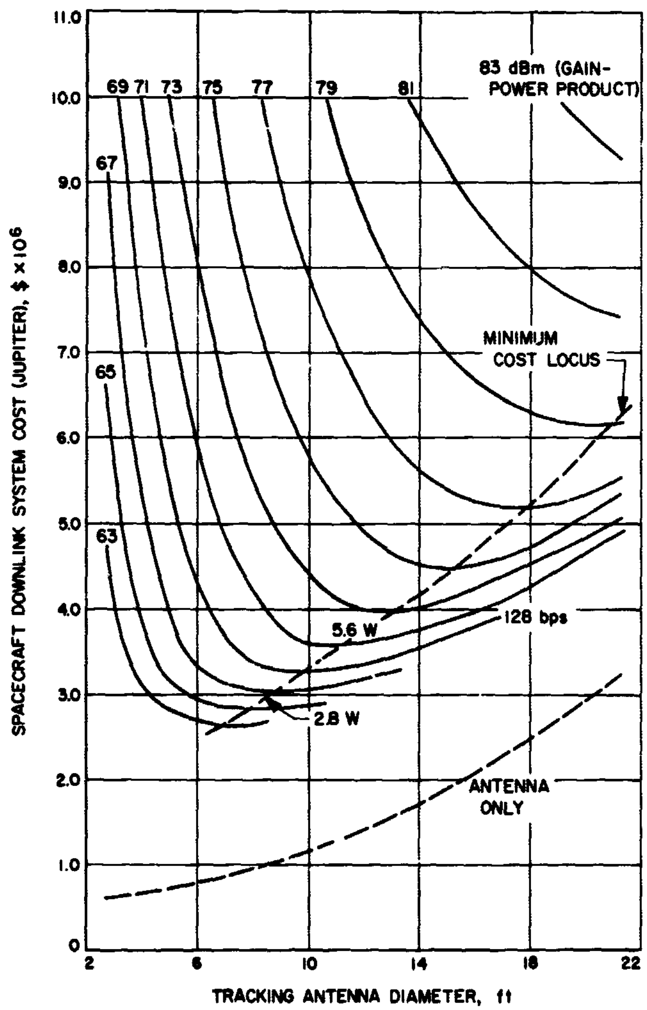

Fig. 10. Jupiter tracking antenna downlink cost

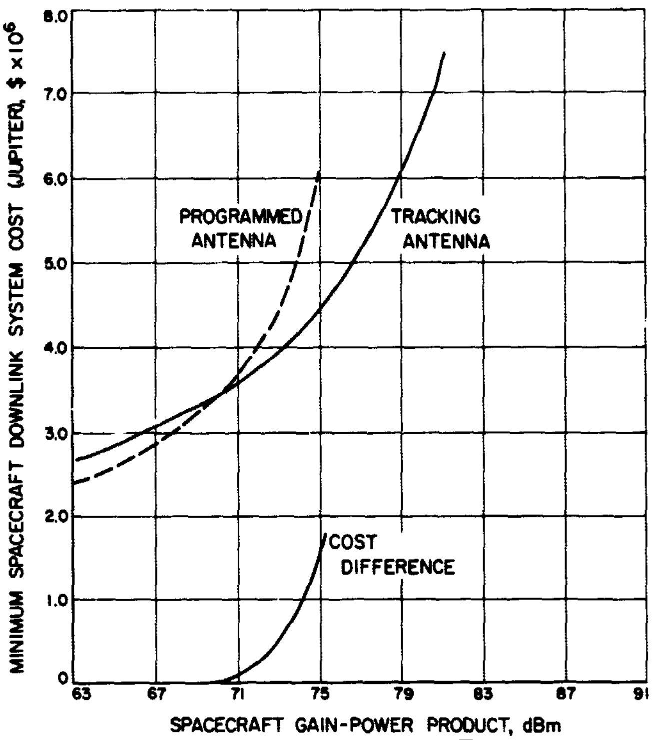

Fig. 11. Minimum-cost Jupiter downlink system

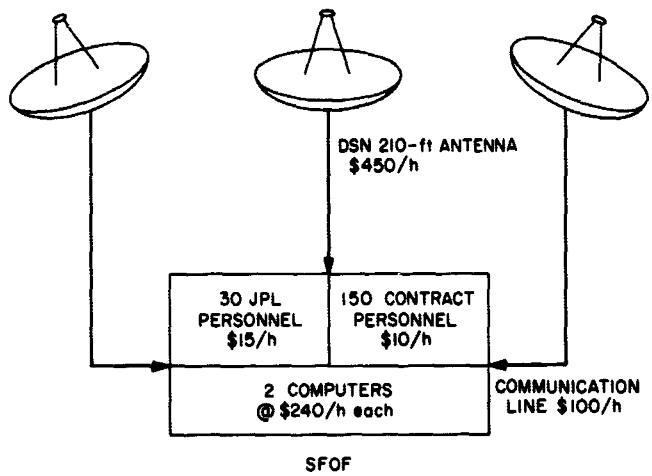

Fig. 12. DSN–SFOF block diagram

III. Ground Station Operating Cost for Data Return

A. DSN–SFOF Costs

Figure 12 shows the block diagram and costs per hour for a three-station network of 210-foot antennas for the DSN. Also shown are the costs for the Space Flight Operations Facility (SFOF) computers, personnel, and a communication line to the DSIF station. Table 3 lists the assumed DSN operating costs of $3 000/h for returning data.

B. Minimum-Cost Data Return

Figure 13 shows the combined DSN and spacecraft downlink cost as a function of the spacecraft gain-power product for various total numbers of bits to be returned from Mars. These curves were generated using the fact that a particular gain-power product on the spacecraft and a given level of performance on the ground can support a certain data rate back to earth. Returning a total number of bits at a fixed data rate implies use of the ground stations for a certain amount of time. The cost curves rise at low spacecraft gain-power products because the low data rate requires that the DSN stations be operated for a long time to return a fixed amount of data. The cost curves also rise at high gain-power products (the DSN is used for only a short time), which become exceedingly costly for the spacecraft. The minimum cost locus is shown intersecting the various total-number-of-bits cost curves. Also indicated is the cross-over point between the programmed pointed antenna and the tracking antenna at 72 dBm.

Figure 14 also shows the combined DSN and spacecraft downlink cost as a function of spacecraft gain-power product for a Jupiter mission. The total number of bits for a given performance level are less in this case, and the cross-over point between the programmed pointing and tracking antenna systems is lower (70 dBm). It is to be noted that the cost curves for returning a total number of bits become very sensitive in regard to the location of the minimum overall cost.

Table 3. DSN operating cost per data return hour

210-foot station		Communication line		Computer		JPL personnel		Contract personnel		Rate
$450	+	$100	+	2 × $240	+	30 × $15	+	150 × $10	≐	$3000

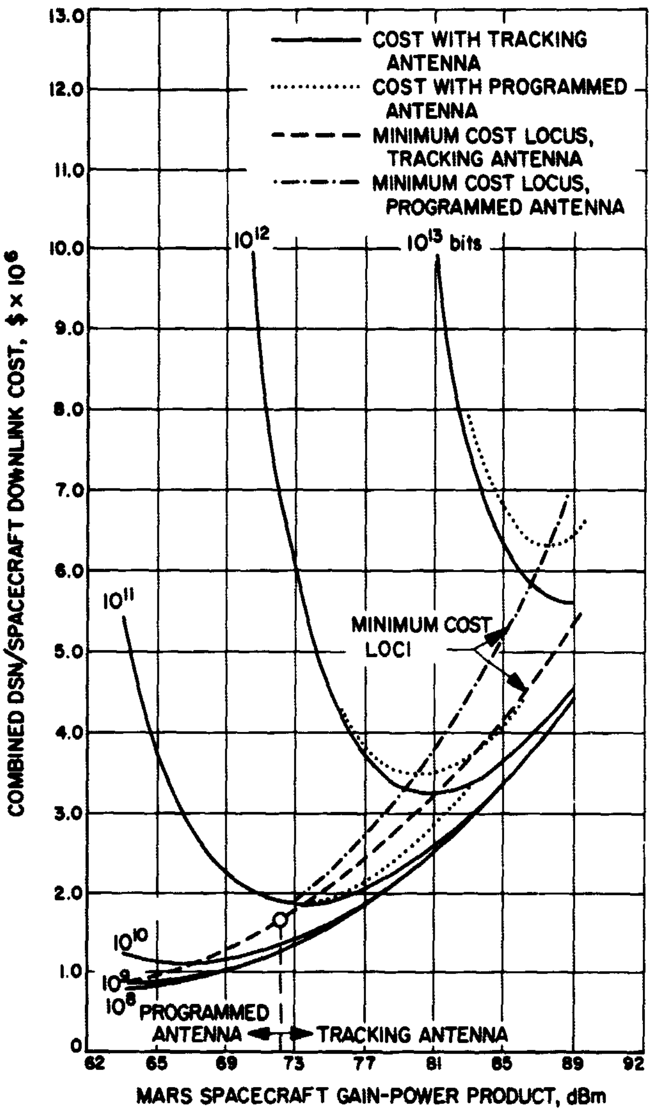

Fig. 13. Combined DSN–spacecraft downlink cost for data return from Mars

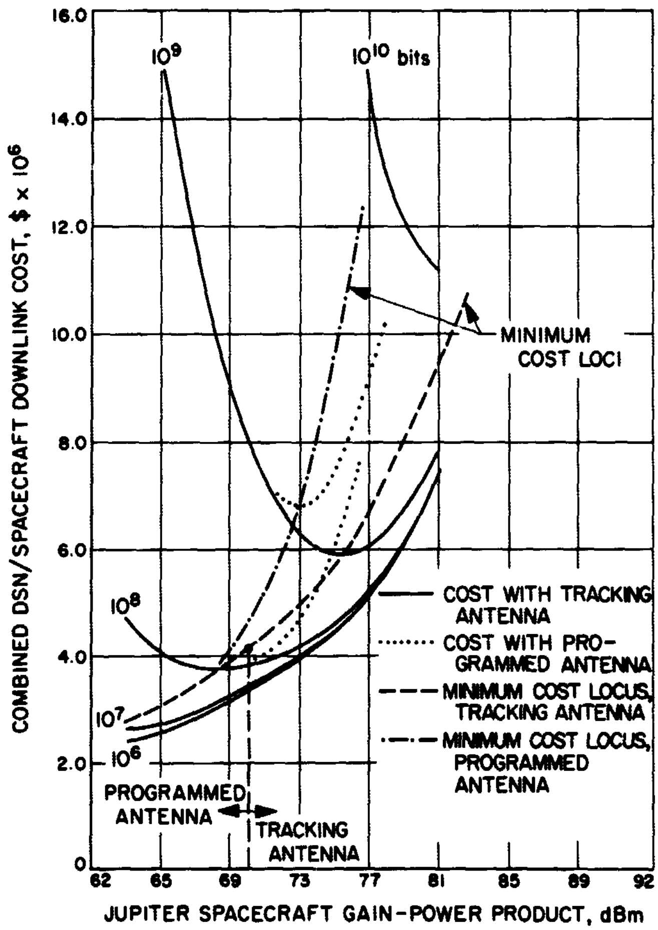

Fig. 14. Combined DSN–spacecraft downlink cost for data return from Jupiter

IV. Summary and Conclusions

A. Summary

Table 4 is a summary (made to graphical accuracy) of the significant data for return of a total number of bits at minimum cost. Shown are the DSN operating time, the spacecraft power output at the final amplifier, the antenna diameter, and the type of antenna. Data are presented for total bits returned from both Mars and Jupiter. As examples of what various total bits represent, the 21 *Mariner IV* low-resolution photos of Mars were 5×10^6 bits; the planned 27 high-resolution pictures of *Mariner 1969* will be 10^8 bits; and a *Lunar Orbiter* mapping photo sequence of the moon represents 10^{13} bits.

The critical assumptions used in this analysis are

(1) Solar power (advances in nuclear power sources may change the results of these data) and spares percentage for solar panel construction, which reflects heavily on the total cost and location of the minimum cost operating points.

(2) Erectable antennas, costed on a basis proportional to the square of the diameter. (Ground antennas tend to increase in cost as the 2.7 power of the diameter.)

(3) Availability of the network of 210s. (For example, can the 210 net be made available for the periods of time required for large total bit returns?)

(4) The ±1-deg programmed pointing limit, which could either increase or decrease as a result of additional uncertainties in this pointing scheme.

B. Conclusions

The results of this study are only a small portion of what is required for actual mission planning. Further refinements relating to data storage, development cost, better costing of erectable antennas as a function of diameter, and the cost of the raw dc power must be made to obtain costing information for actual design consideration. However, it is hoped that the approach used in this cost analysis may be useful for future design studies.

The appendix contains a listing of cost equations, the 1620 IBM computer programs that were generated to produce the curves presented in this memorandum, and computer program parameters.

Table 4. Summary of minimum cost for data return (graphical accuracy)

Mission	Total bits	Cost, $ × 10^6	DSN time, h	Bit rate, bps	Spacecraft transmitter output, W	Antenna diameter, ft	Antenna type
Mars	10^9	0.9	25	13,000	4.7	3.6	Programmed
	10^{10}	1.2	92	34,000	7.4	5.5	Programmed
	10^{11}	1.9	146	162,000	14.8	8.8	Tracking
	10^{12}	3.3	274	1,000,000	45.6	11.7	Tracking
	10^{13}	5.6	310	8,000,000	200.0	15.2	Tracking
Jupiter	10^7	2.6	107	26	2.0	5.8	Programmed
	10^8	3.8	215	128	5.3	9	Programmed
	10^9	6.0	400	688	7.6	15.6	Tracking
	10^{10}	11.0	860	3,200	12.6	25	Tracking

Appendix

Computer Programs

I. Cost Equations

Program A punches cards of dc-RF power subsystem cost vs dBm power output which are used in a general curve-fitting, curve-plotting program labeled DLN 60.

The equation for the dc-RF power subsystem cost for a particular gain-power product is

$$c = k_1 k_2 d^2 \left(k_3 + \frac{P}{\eta_1 \eta_2 \eta_3} \right) + k_4 (c_1 + c_2 + c_3) \qquad \text{(A-1)}$$

where

k_1 = solar panel cost per watt at 1 AU

k_2 = solar panel spares ratio

d = planetary distance from sun, AU

k_3 = exciter power drain, W

P = transmitter tube output power, W

η_1 = transmitter efficiency, dc-to-RF power conversion

η_2 = transmitter power supply efficiency, dc-to-dc conversion

η_3 = output RF circuitry efficiency

k_4 = RF subsystem spares ratio

c_1 = cost of exciters, power supplies, couplers, diplexers, switches, and monitors

c_2 = RF transmitter tube cost

c_3 = transmitter power supply cost

Program B shows the cubic equation coefficients and fitted cost curve data output from DLN 60.

Program C calculates antenna cost vs gain and diameter. The listing shown is for the RF tracking system. The cost equation is

$$c = k_1 k_2 \frac{\pi}{4} D^2 + c_1 + k_3 (D - 4) + k_4 k_5 d^2 \qquad \text{(A-2)}$$

where

k_1 = antenna cost per square foot of aperture area

k_2 = antenna system spares ratio

D = antenna diameter, ft

c_1 = tracking receiver cost and positioner constant costs

k_3 = positioner variable cost per foot of antenna diameter

k_4 = regulated solar power cost to receiver at 1 AU

k_5 = solar panel spares ratio

d = planetary distance from sun, AU

The tracking antenna diameter D as a function of antenna gain is given by

$$D = \frac{\lambda}{\pi} \; \frac{\sqrt{G}}{\eta_1 \eta_2} \qquad \text{(A-3)}$$

where

λ = wavelength

G = required antenna gain

η_1 = basic antenna aperture efficiency

η_2 = pointing system efficiency

The programmed pointing antenna system costs were calculated manually using Eq. (A-2) modified for programmer costs and power rather than receiver costs and power. The diameters required for a given gain value were obtained graphically from a plot of antenna beam shape given by

$$G = \eta \left(\frac{\pi D}{\lambda} \right)^2 \cos^4 \left(\frac{D\theta}{\lambda} \right) \qquad \text{(A-4)}$$

where

η = aperture efficiency

D = antenna diameter, ft

λ = wavelength

θ = programmed pointing angular accuracy

Program D combines the antenna gain and dc and RF power subsystem costs to provide plot cards of spacecraft system cost vs antenna diameter for various gain-power products.

Program E provides plot cards of total cost, including DSN costs vs gain-power product for various total bits.

The equation for the cost of returning a total number of bits, given by 10^u bits, is

$$c = c_1 + k_1 T_r \frac{\log_{10}^{-1}(u - B_r)}{\log_{10}^{-1} \dfrac{dBm - dBm_r}{10}} \qquad \text{(A-5)}$$

where

c_1 = spacecraft system minimum cost for gain-power product

dBm = spacecraft system gain-power product in dBm

k_1 = DSN–SFOF hourly cost rate

T_r = reference time required for telecommunications system to transmit 10^{B_r} bits, h

dBm_r = reference spacecraft gain-power product required to return 10^{B_r} bits in the time T_r

Equation (A-5) is based upon the assumption that in a given telecommunication system, a doubling of the gain-power product will support a doubled bit rate. Also, twice the required total number of bits to be transmitted will require twice the amount of time for transmission. Thus, transmission time (with respect to a reference transmission time, bits, and gain-power product) is directly proportional to the bit ratio for another total number of bits, and time is inversely proportional to the gain-power product ratio for another gain-power product.

II. Program Parameters

A. Program A

Variables

C(I) = dc–RF subsystem cost, $ × 10^6

PT(I) = transmitter tube output power, W

TE(I) = associated transmitter efficiency, units

TP(I) = associated tube cost, $ × 10^6

PP(I) = associated power supply cost, $ × 10^6

DBM(I) = associated transmitter output at antenna input

D = planet distance from sun, AU

SP = solar panel spares ratio, units >1

Coefficients and constants

0.001 = solar panel cost per watt, $ × 10^6/W

18. = exciter power drain, W

0.85 = amplifier power supply efficiency, units

0.70 = output circuit efficiency, units

2. = RF system redundancy factor, units

0.0470 = cost of exciters, power supplies, couplers, diplexers, etc., $ × 10^6

B. Program B

The X values are transmitter output in dBm to the antenna. The Y (data) values are cost in millions of dollars. The cubic equation coefficients of cost vs dBm are listed along with the standard deviation.

This program also provides an output plot of the fitted curve on the IBM plotter.

C. Program C

Variables

EFSUM = pointing loss, units (¼ dB ∼ 0.944)

DAU = planetary distance from sun, AU

SP = solar panel spares ratio

I = antenna gain, dB

G = antenna gain, units

D = antenna diameter, ft

CA = cost of tracking antenna subsystem, $ × 10^6

Coefficients and constants

0.43 = S-band wavelength, ft

0.55 = antenna efficiency, %

0.0037 = antenna cost per unit aperture area, $ × 10^6/ft²

2. = antenna cost per flight ratio, units

0.0700 = receiver and positioner basic cost, $ × 10^6

0.002 = positioner costs as a function of antenna diameter, $ × 10^6/ft

0.0125 = regulated solar power cost to receiver at 1 AU, $ × 10^6

D. Program D

Variables

CT(I) = total system cost, $ × 10^6

CA(I) = antenna subsystem cost, $ × 10^6

C(I) = dc–RF power subsystem cost, $ × 10^6

A(I) = antenna gain, db (not used)

D(I) = antenna diameter, ft

J = 23, 41 = antenna gain, dB

I = 35, 53 = transmitter output, dBm

I = 63, 89, 2 = gain-power product, dBm

Coefficients and constants

The coefficients of the powers of AI in statement 2 were obtained from Program B. The remainder of the program after statement 2 generates cards used as plot input data for DLN 60, Program B, for plotting only (not for curve fitting).

E. Program E

Variable

I = 6, 11 = exponents of 10 for total bits of data to be returned

Coefficients and constants

0.00274 = DSN–SFOF operating costs per hour, $ × 10^6/h

DBM = spacecraft gain-power product, dBm

C = spacecraft system minimum cost, $ × 10^6

HR = time required to return 10^8 total bits at spacecraft gain-power product reference DBT, h

DBT = spacecraft gain-power product reference, dBm

	For the return of 10^8 bits from	
	Mars	Jupiter
DBT	63	69
HR	1.7	215

III. Programs

Program A

```
C  MINIMUM DOWNLINK SYSTEM COST ANALYSIS - TRANSMITTER,POWER COST
C MARS CASE
      DIMENSION C(10),PT(10),TE(10),TP(10),PP(10),DBM(10)
      READ 1,D,SP
    1 FORMAT(2F10.2)
      DO 2 I=1,5
      READ12,PT(I),TE(I),TP(I),PP(I)
   12 FORMAT(4F10.2)
    2 CONTINUE
      DO 4 I=1,5
      C(I)=0.001*D*D*SP*(18.+((PT(I))/(TE(I)*0.85*0.70)))+(2.*
     1(0.0470+TP(I)+PP(I)))
      DBM(I)=     (4.34*LOGF(0.7*PT(I)))+30.
      PRINT14,DBM(I),C(I)
   14 FORMAT(6H DBM =,F10.2,2X,11H M DOLLARS=,F10.6)
    4 CONTINUE
      DO 5 I=1,5
      PUNCH15,DBM(I),C(I)
   15 FORMAT(F10.2,F10.6)
    5 CONTINUE
      END
```

Program B

```
     MARS


                     0        .85583930E+01
                     1       -.42145286E+00
                     2        .39309116E-02
                     3        .41391030E-04

STANDARD DEVIATION= .14573493E-01
```

X	Y(DATA)	Y(FIT)	DIFFERENCE	
35.43	.3986	.4015	-.00298030	1
38.44	.5318	.5172	.01464980	2
41.45	.7678	.7905	-.02271360	3
45.43	1.4226	1.4056	.01695330	4
48.43	2.0629	2.0688	-.00592560	5
35.43	.3986	.4015	-.00298030	1
38.44	.5318	.5172	.01464980	2
41.45	.7678	.7905	-.02271360	3
45.43	1.4226	1.4056	.01695330	4
48.43	2.0629	2.0688	-.00592560	5
35.43	.3986	.4015	-.00298030	1
38.44	.5318	.5172	.01464980	2
41.45	.7678	.7905	-.02271360	3
45.43	1.4226	1.4056	.01695330	4
48.43	2.0629	2.0688	-.00592560	5

Program C

```
C SPACECRAFT DOWNLINK COST ANALYSIS, ANTENNA GAIN
C DB VS. DIAMETER-TRACKING SYSTEM, EFSUM=SUM CHANNEL EFFICIENCY,114=.944
      READ 1,EFSUM,DAU,SP
    1 FORMAT(3F10.3)
      DO 4 I=23,40
      AI=I
      G=EXPF(0.2303*AI)
      D=(0.43/3.1416)*SQRTF(G/(.55*EFSUM))
COST
     0CA=.0037*(3.1416/4.)*D*D*2.+0.0700+0.002*(D-4.)+0.0125*DAU*DAU*SP
      PRINT 2,D,CA,AI
    2 FORMAT(8H DIAFT =,F10.2,2X,10H ANTMDOL =,F10.6,2X,5H DB =,F10.2)
      PUNCH 3,D,CA,AI
    3 FORMAT(1F10.2,2F10.6)
    4 CONTINUE
      END
```

Program D

```
COST ANALYSIS GAIN-POWER PRODUCT COMBINING ROUTINE -SPACECRAFT DOWNLINK
      DIMENSION CT(90),CA(90),C(90),A(45),D(90)
      DO 1 I=1,90
      CT(I)=0.0
   12 C(I)=0.0
    1 CA(I)=0.0
      DO 7 J=23,41
      READ 6,D(J),CA(J),A(J)
    6 FORMAT(F10.2,2F10.0)
    7 CONTINUE
      C(30)=1.67
      C(31)=1.77
      C(32)=1.83
      C(33)=2.0
      C(34)=2.15
      DO 2 I=35,53
      AI=I
    2 C(I)=.0001336*AI*AI*AI+.062697*AI*AI-4.8812*AI+90.554
      DO 8 I=63,89,2
      PUNCH 4,I
    4 FORMAT (I3)
      X=19
      Y=1
      Z=2
      PUNCH 3,X,Y,Z
    3 FORMAT (3I4)
      DO 8 J=23,41
      K=I-J
      CT(I)=CA(J)+C(K)
      QTC=10.0-CT(I)
      IF (QTC) 14,14,15
   14 CT(I)=10.0
   15 PUNCH 5,D(J),CT(I)
    5 FORMAT( F10.2,F10.6)
    8 CONTINUE
      END
```

Program E

```
C FINAL COST ANALYSIS PLOT DATA GEN
      DIMENSIUN DBM(50),C(50)
      READ 1,HR,DBT
    1 FORMAT(2F10.2)
      DO 3 J=1,10
      READ 2,DBM(J),C(J)
    2 FORMAT(F10.2,F10.6)
    3 CONTINUE
      DO 9 I=6,11
      PUNCH 4,I
    4 FORMAT(I3)
      L=10
      M=1
      N=2
      PUNCH 5,L,M,N
    5 FORMAT(3I4)
      BTE=I
      DO 9 J=1,10
      CTB=C(J)+0.00274*HR*(EXPF(2.303*((BTE-8.)-((DBM(J)-DBT)/10.))))
      QTB=15.-CTB
      IF (QTB) 15,15,16
   15 CTB=15.0
   16 PUNCH 8,DBM(J),CTB
    8 FORMAT(F10.2,F10.6)
    9 CONTINUE
      END
```

References

1. Potter, P., Merrick, W., and Ludwig, A., *Large Apertures and Arrays for Deep Space Communications,* Technical Report 32-848. Jet Propulsion Laboratory, Pasadena, Calif., Nov. 1965.

2. Tam, M., "Performance Margin and Cost Trade-Off for Spacecraft Telecommunication Systems Design," Space Programs Summary 37-45, Vol. IV, pp. 343–351, Jet Propulsion Laboratory, Pasadena, Calif., June 1967.