Potential Reduction of DSN Uplink Energy Cost

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DSN earth stations typically transmit more power than that required to meet minimum specifications for uplink performance. This article presents the results of a study of energy and cost savings that could result from matching the uplink power to the amount required for specified performance. The Galileo mission was selected as a case study.

Although substantial reduction in transmitted energy is possible, potential savings in source energy (oil or electricity) savings are much less. This is because of the rising inefficiency in power conversion and radio frequency power generation that accompanies reduced power output.

The work described in this report is part of a continuing study intended to guide future development and management of the DSN in the changing environment of space exploration.

I. Introduction

DSN earth stations typically transmit more power than that required to meet minimum specifications for uplink performance. The reason for this is the operational simplicity of selecting from one or two power settings, each of which can be used for a lengthy period of time. Excessive power also provides an additional margin of safety in performing the required uplink functions. If the uplink transmitter power was always adjusted to the minimum needed, a saving in electric energy would be expected. This report is the result of a study to assess the potential saving. Motivation for the study was the rapidly escalating energy cost at DSN stations.

To determine the potential cost savings that could result from more careful management of uplink power, the required power over the life of a mission was compared with the power that would be expected to result from station operation that is typical of past practice. The Galileo mission was selected as a case study.

Electric power for the earth station transmitter comes from either a commercial source or from diesel generator sets. The potential saving in transmitted power was converted to savings in electricity billings or fuel costs by considering the efficiencies of intervening equipment: transmitter power amplifier, motor/generator, and for the fuel oil case, the diesel generator.

II. Required Uplink Power

A. Uplink Modes

Four functions are performed via the uplink:

(1) Transmission of spacecraft commands.

(2) The uplink portion of turnaround ranging.

(3) The uplink portion of two-way doppler tracking.

(4) The provision of a carrier reference for downlink telemetry.

These functions may be required singly or in combination.

B. Required Uplink Power

For each mode or mode combination there is a required input power at the spacecraft receiver. A selected set of modes and their corresponding power requirements are shown in Table 1 (Ref. 1). These modes were selected for analysis because they are representative of the range of required power and because they are expected to be extensively utilized. To relate the receiver input power to the corresponding earth station transmitter power, it is necessary to consider the antenna gains, space loss, and various atmospheric losses and noise temperature effects. The parameter with the largest variation during a mission is the space loss, which is proportional to the distance squared.

To determine the variation of required transmitter power during the Galileo mission and as a function of mode and antenna size, it was found convenient to first compute the power for a single mode and antenna. The −120-dBm and 34-m case was selected and the result is shown in Fig. 1. Power profiles for other levels of received power are related to this curve by an appropriate multiplication factor. Data for the curve were computed by means of telecommunications design control tables and graphs (see Appendix).

By considering the difference between the -120-dBm value and the other required powers shown in Table 1, it is then simple to create the family of curves shown in Fig. 2. Taking into account the higher gain of the 64-m antenna, Fig. 3 was prepared. Note that Fig. 1 is in terms of kilowatts, while Figs. 2 and 3 are in terms of dBW. The logarithmic scale of Figs. 2 and 3 is needed to show meaningful relationships between mode power requirements; the lower power curves would be lost on the kilowatt scale of Fig. 1.

C. Typical DSN Operation

Based on past experience it may be assumed that earth station transmitter power to support Galileo would be adjusted to 10 kW for the first 300 days and then 18 kW until the end of mission. This typical operation is shown in Figs. 1, 2 and 3.

D. Comparison of Typical and Required Energy

The area under each curve in Figs. 1, 2 and 3 is representative of the number of kilowatt days needed for that mode or mode combination. The energy for the assumed typical DSN operation is

$$10 \times 300 + 18\,(1480 - 300) = 24{,}240 \text{ kW days}$$

The energy to provide -120 dBm at Galileo from a 34-m station was obtained by "counting the squares" under the curve in Fig. 1 and is 14,900 kW days. Energy required for the other modes was obtained by adjusting the value for the -120-dBm, 34-m case by an amount taken from Table 1. For example, the command mode requires 1/7.9 (9 dB) less power, or 3050 kW days. The ratio of required power to typical (assumed) power is presented in Table 2. Remember that the energy and energy ratios determined so far are for the transmitter radio frequency output, not the electric or fuel oil energy that must be purchased. To estimate the dollar value of net energy savings, the efficiency of generating the transmitted power must be considered. In addition, there is a minimum practical RF power from DSN transmitters, and this factor must be included when determining potential savings.

III. Transmitter and Power Source Efficiencies

In the previous section it was shown that uplink RF power can usually be reduced from typical values while still meeting required link performance. It is, however, the reduction of source power and hence energy cost that is the subject of this study. How much power is saved at the source when the RF power is reduced? In this section we consider the efficiency of the typical end-to-end power system which drives the 20 kW RF klystron transmitter. Figure 4 shows the power system, Ref. 2. Diesel generators and/or commercial power provide a 60-Hz source which drives a motor/generator (M/G). The 400-Hz voltage generated by the M/G is converted into dc, which in turn drives the klystron. During uplink transmissions, basic support equipment for the klystron must remain on at all times. This equipment includes a heat exchanger (18 kW dc); cathode, control and monitoring instrumentation and safety devices (2 kW); and the magnet (6 kW). In all, this amounts to 26 kW dc, which cannot be reduced, regardless of the output RF power of the klystron amplifier.

The end-to-end efficiency of the system depends on three efficiency factors.

A. Klystron Amplifier Efficiency

The klystron is operated in saturation at all times so as to prevent amplitude instabilities. Below 2 kW it is not possible to saturate the tube and so the klystron is not operated below this level. For the saturated condition, the beam power efficiency as a function of beam voltage is shown in Fig. 5. For 20-kW RF, the beam power efficiency is typically 43%. The klystron efficiency as a function of RF output is shown in Fig. 6.

The relationship between RF power and the beam voltage is

$$P_{RF} = \eta K V^{5/2}$$

where $K = 0.825 \times 10^{-6}$, V is the beam voltage in volts and η is the beam power efficiency.

The total klystron amplifier efficiency is

$$\frac{P_{RF}}{\dfrac{P_{RF}}{\eta} + 26\,kW}$$

These relationships determine the data shown in Table 3 and Fig. 6.

B. Motor/Generator Efficiency

Motor/generators like those at DSN sites work at a combined efficiency of 86% when the motor and generator each operate at a typical 93% efficiency. Using Refs. 3 and 4, a typical efficiency curve has been constructed and is shown in Fig. 7.

C. Efficiency of Converting 60 Hz Power to RF Output

The end-to-end efficiency from a 60-Hz source to RF output is shown in Table 4 and in Fig. 8.

D. Diesel Generator Efficiency

Either commercial power or on-site diesel generators may act as the 60-Hz source for the motor generator sets. There are 500-kW and 750-kW diesel generators at the DSN sites. Fuel consumption for these is nearly linear with electric power output and is approximately 1.9 gallons per kW-day for a 500-kW generator, 1.8 gallons per kW-day for a 750 kW generator. In this article, 1.9 gallons per kW-day will be used for calculation of cost savings.

IV. Estimated Energy and Cost Saving

In the example discussed earlier, the DSN was assumed to operate at 10 kW RF (12.1% total M/G plus klystron efficiency) to day 300 of the Galileo mission and then at 18 kW RF (19.2% total efficiency) for the remainder of the mission. The energy required for this case is

$$300 \text{ days} \times \frac{10}{0.121} = 24{,}800 \text{ kW days}$$

$$(1480\text{-}300) \text{ days} \times \frac{18}{0.192} = 110{,}600 \text{ kW days}$$

Total energy for typical operation = 135,400 kW days.

If the transmitter were to operate at the 2-kW minimum level for the mission duration, the total power would be $2 \times 1480 \div 0.029 = 102{,}100$ kW days.

Galileo will not operate continuously in any one mode for the entire mission. The potential for energy savings depends on the mix of modes. To estimate an aggregate energy saving, it is necessary to assume a mix. For example, a mission profile at a 64-m station might include:

Mode	Days	% of mission days
Doppler	800	54
Command	380	26
Carrier reference	300	20

By referring to Fig. 2 or 3, depending on the antenna to be used, an average power for the majority of the mission may be estimated for each mode. The source energy required for each mode to be used during the mission according to the assumed profile is then

$$E_{mode} = \text{days of mode operation} \times \text{average power} \div \text{efficiency}$$

The minimum allowable value for the average power is 2 kW.

The accuracy of this calculation depends upon the assumption that use of each of the several modes is more or less uniformly distributed over the life of the mission, and upon the estimate of the average power. Net savings are not very sensitive to these assumptions because of the linear relationship between efficiency and RF power output. A more elegant calculation is therefore not warranted. Table 5 shows the results of calculations for the assumed mix of modes, expressed in terms of gallons of fuel oil and kW-days of commercial power. Also shown are dollar savings at estimated 1985 rates.

V. Discussion

The study of potential savings in uplink energy cost was motivated by the observation that required performance margins are substantially exceeded in many instances. As shown in Table 2, less RF power could be used while meeting Galileo performance requirements. Depending upon the uplink mode, power reduction of 40 to 99% could be enjoyed, compared to typical past practice.

In reality, the potential for dollar and energy savings is much less. This is because of the efficiency with which 60-Hz souce power is converted to RF output power. The overall efficiency is roughly proportional to output power: along with reduced power we have reduced efficiency. This is the result of decreasing klystron and motor-generator efficiencies that accompany decreases in output power. An additional factor is the fixed power overhead required to operate the amplifier regardless of RF output.

The nature of the klystron amplifier is such that there is a minimum output power below which saturation cannot be obtained. Saturated operation is needed for typical DSN applications, and is obtainable only above 2 kW. Even when the link doesn't need it, 2 kW must be generated, at the expense of 26 kW of support power.

Table 6 compares the percentage savings in RF and source energy for the selected mix of Galileo mission modes studied in this report. The difference between the energy required for assumed typical DSN profile (10 kW for 300 days and 18 kW for the remainder of the mission) and that needed for the 2-kW minimum for the same length of time is 135,400 - 102,100 = 33,300 kW-days. The potential savings over mission life cannot greatly exceed this value.[1] Accordingly, since the spread between typical and minimum energy is relatively small, the potential for savings is not critically dependent upon the mix of modes that could or would be used during the Galileo mission. For the mix chosen in the Galileo study, the savings is 29,200 kW-days at a 34-m station and 32,700 kW-days at a 64-m station.

The analysis presented above presumes a single mission, Galileo, being supported continuously by means of stations at the U.S. and overseas DSN sites. Additional savings could accrue if other missions were supported by these stations during periods when Galileo was not in view.

The estimate of potential savings is based on the normal operating characteristics of existing DSN stations. These characteristics include maximum and minimum values of transmitter power. It has been shown that uplink functions can often be accomplished with less than the minimum power available from existing DSN transmitters. The saving that could result from the use of new, low-power transmitters, or from use of existing exciters without further amplification, is not treated in this report.

The maximum required power is usually determined by the need for spacecraft command under emergency condition. While normal operations may suggest the use of lower power transmitters, the emergency capability must be maintained. More economical means of providing this capability were not examined and are beyond the scope of this report.

[1] Because the efficiency values used in the study are approximate, computed energy consumption for some mode mixes may be less than that estimated for the 2-kW case.

Acknowledgments

Thanks are due Jim Taylor and John Rider for their suggestions regarding this study.

References

1. Taylor, F. H. J., Section 339, private communication.
2. Rayburn, J., Section 333, private communication.
3. "Standard Handbook for Electrical Engineers," editor A. E. Knowlton, 7th Edition, McGraw-Hill.
4. "Standard Handbook for Electrical Engineers," editors D. G. Fink and H. W. Beaty, McGraw-Hill, 1978.
5. Data from Utility Cost Analysis (FY 81-85), DSN Goldstone Complex, supplied by S. Friesema, Section 420.

Table 1. Power required at spacecraft receiver input

Uplink mode	Required power, dBm
Carrier tracking for doppler[a]	–142
Command	–129
Command plus ranging	–128
Carrier reference for telemetry[b]	–120

[a] S up, S down.
[b] S up, X down.

Table 2. Ratio of required transmitter power (kW days) to typical DSN practice (24,240 kW days)

Mode	Ratio	
	34-m Antenna	64-m Antenna
Carrier tracking for doppler	0.004	0.001
Command	0.077	0.022
Command plus ranging	0.097	0.028
Carrier reference for telemetry	0.615	0.178

Table 3. Klystron RF power out vs efficiency (RF power/total power)

RF power, kW	Total power consumed by klystron amplifier, kW	Efficiency (RF power/total power), %
2	33.6	6.0
4	38.6	10.4
6	43.4	13.8
8	47.6	16.8
10	51.5	19.4
12	55.8	21.5
14	60.1	23.3
16	64.4	24.9
18	68.7	26.2
20	72.6	27.6

Table 4. End-to-end efficiency from 60-Hz power source to RF output

RF power, kW	Klystron efficiency, %	Motor generator efficiency, %	Total efficiency, %
2	5.9	25	2.9
4	10.3	35	5.6
6	13.8	44	7.9
8	16.8	49	10.2
10	19.4	52	12.1
12	21.4	58	14.4
14	23.2	61	16.1
16	24.8	64	17.7
18	26.2	67	19.2
20	27.6	71	21.0

Note: Of the fixed 26 kW needed to support the klystron amplifier, 18 kW comes directly from the 60-Hz source and not through the motor/generator. The total efficiency is therefore not a simple product of the klystron and motor generator efficiency values given in the table.

Table 5. Potential source energy savings at 34-m and 64-m stations for selected profile of three Galileo mission modes

Antenna station	Electricity or fuel required	Electricity or fuel expended for 10-kW/18-kW profile	Saving	Cost[a] saving, $
34m station:				
Diesel generator	201,700 gal	257,300 gal	55,600 gal	94,300
Commercial power	106,200 kW-days	135,400 kW-days	29,200 kW-days	95,700
64m station:				
Diesel generator	195,000 gal	257,300 gal	62,300 gal	105,700
Commercial power	102,700 kW-days	135,400 kW-days	32,470 kW-days	107,500

[a]Estimated 1985 costs: \$1.696/gal; \$0.137/kWh. (Ref. 5)

Table 6. Comparison of RF and source energy savings

Antenna station	Potential RF saving, %	Estimated source energy saving, %
34 m	78	22
64 m	87	24

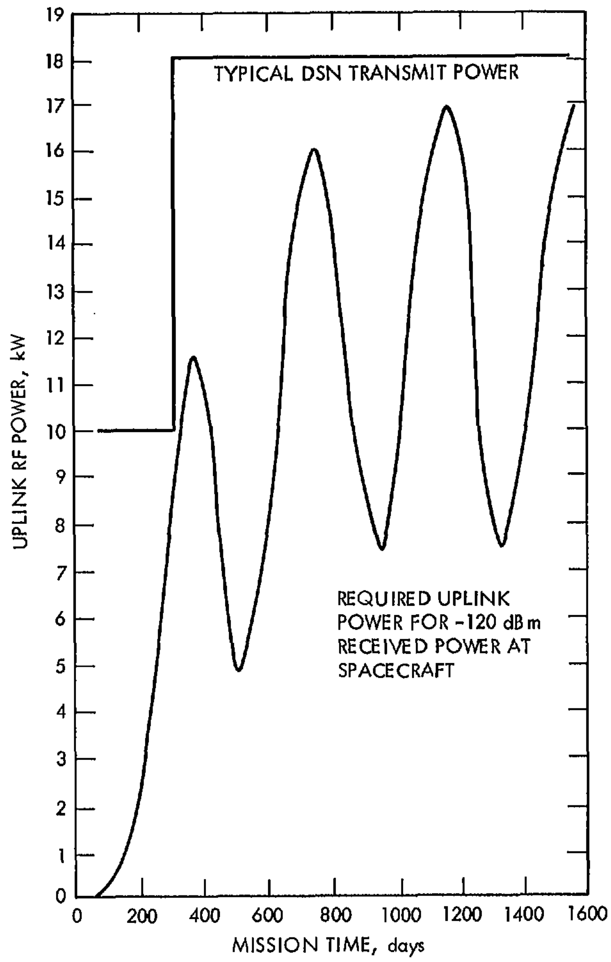

Fig. 1. Typical and required uplink power vs time for Galileo, 34-m antenna

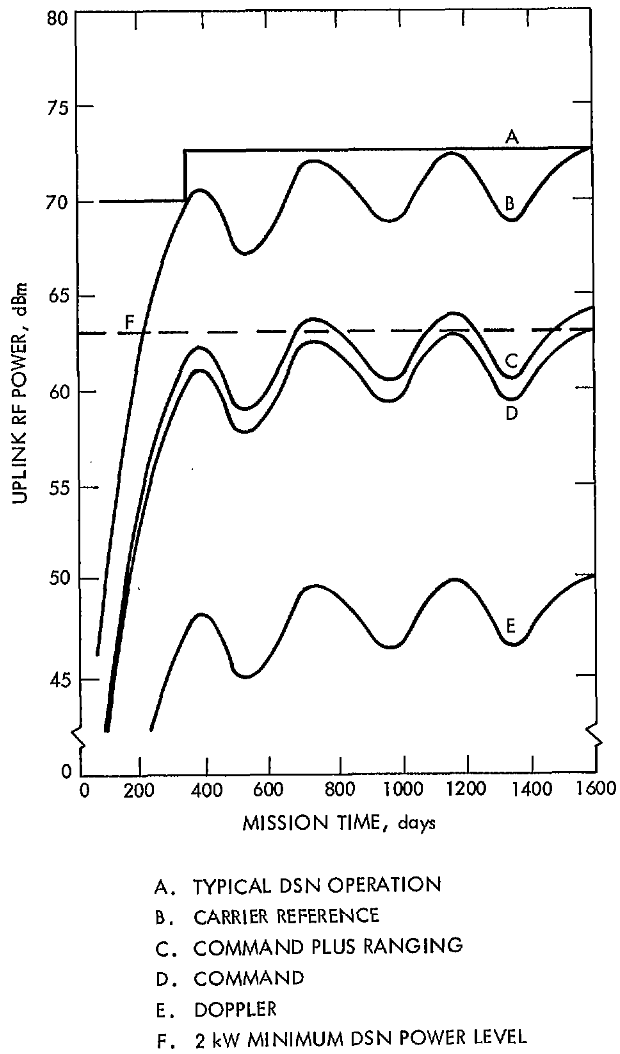

Fig. 2. 34-m uplink power vs time for typical DSN operation and for selected Galileo mode requirements

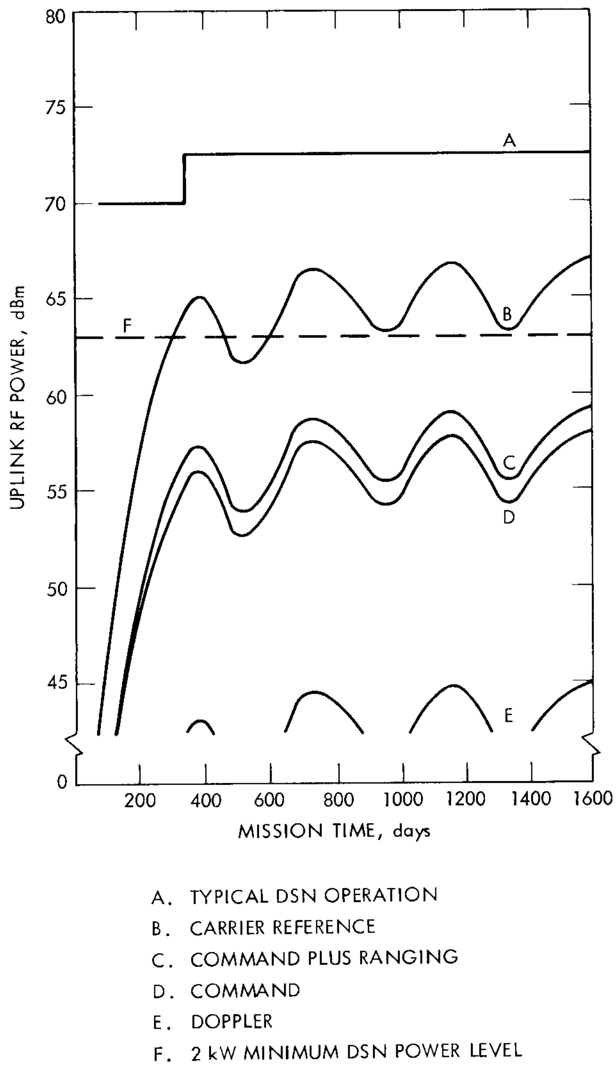

Fig. 3. 64-m uplink power vs time for typical DSN operation and for selected Galileo mode requirements

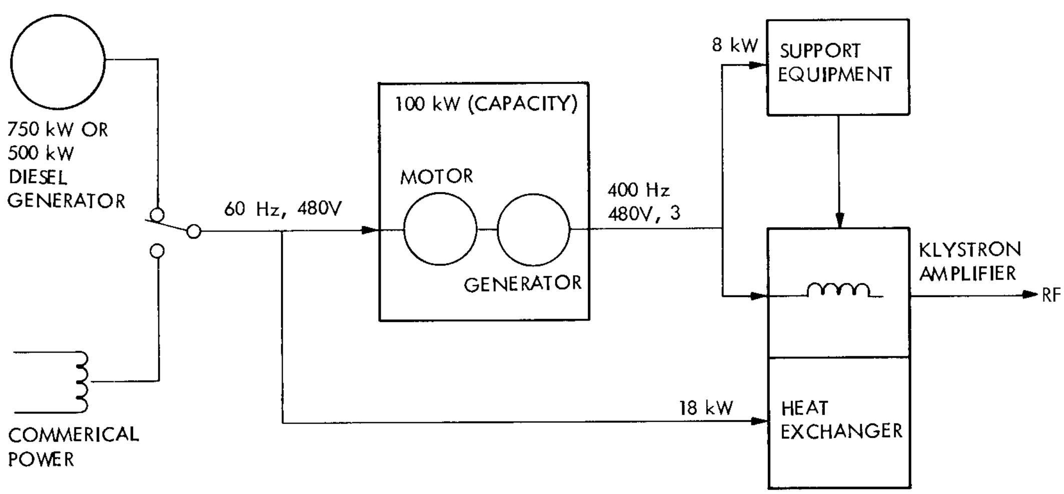

Fig. 4. End-to-end power flow diagram for Goldstone DSS 14/12

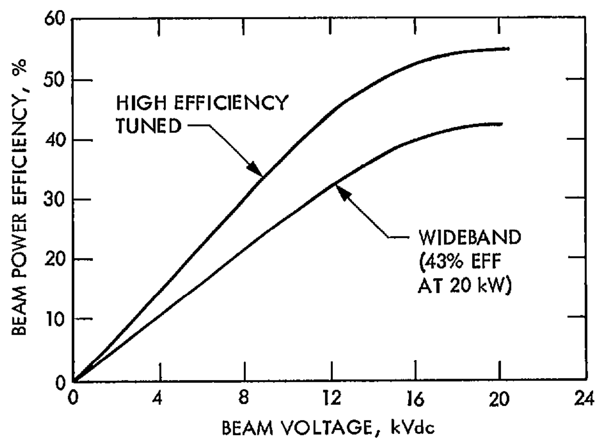

Fig. 5. Typical klystron beam power efficiency vs beam voltage

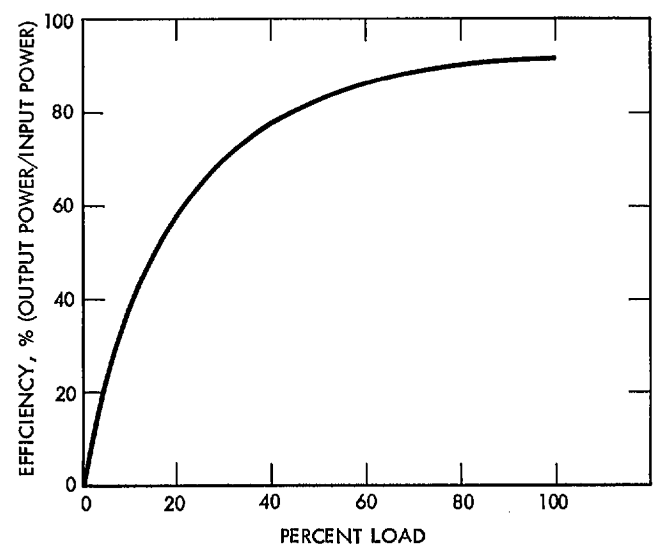

Fig. 7. Typical efficiency for 100-kW motor or generator

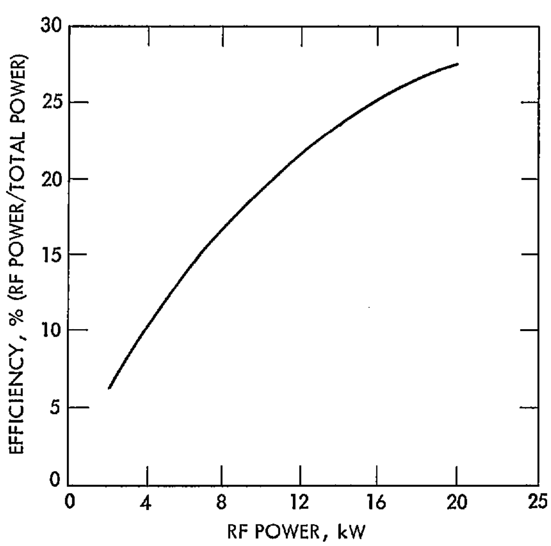

Fig. 6. Typical klystron efficiency vs RF power output

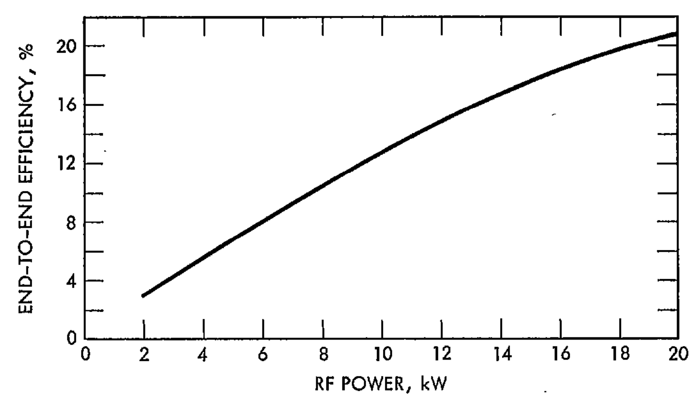

Fig. 8. End-to-end efficiency vs RF power output

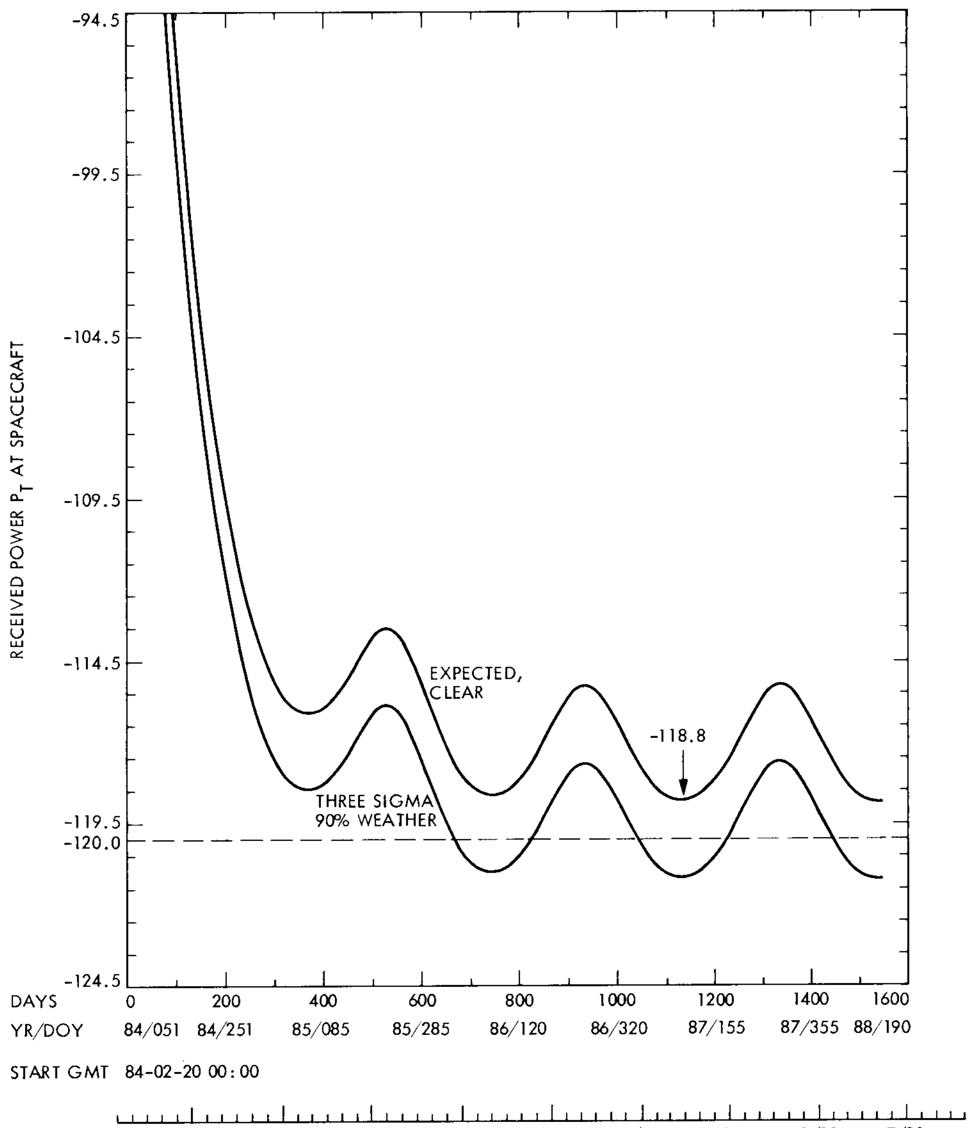

Fig. 9. Received power at spacecraft

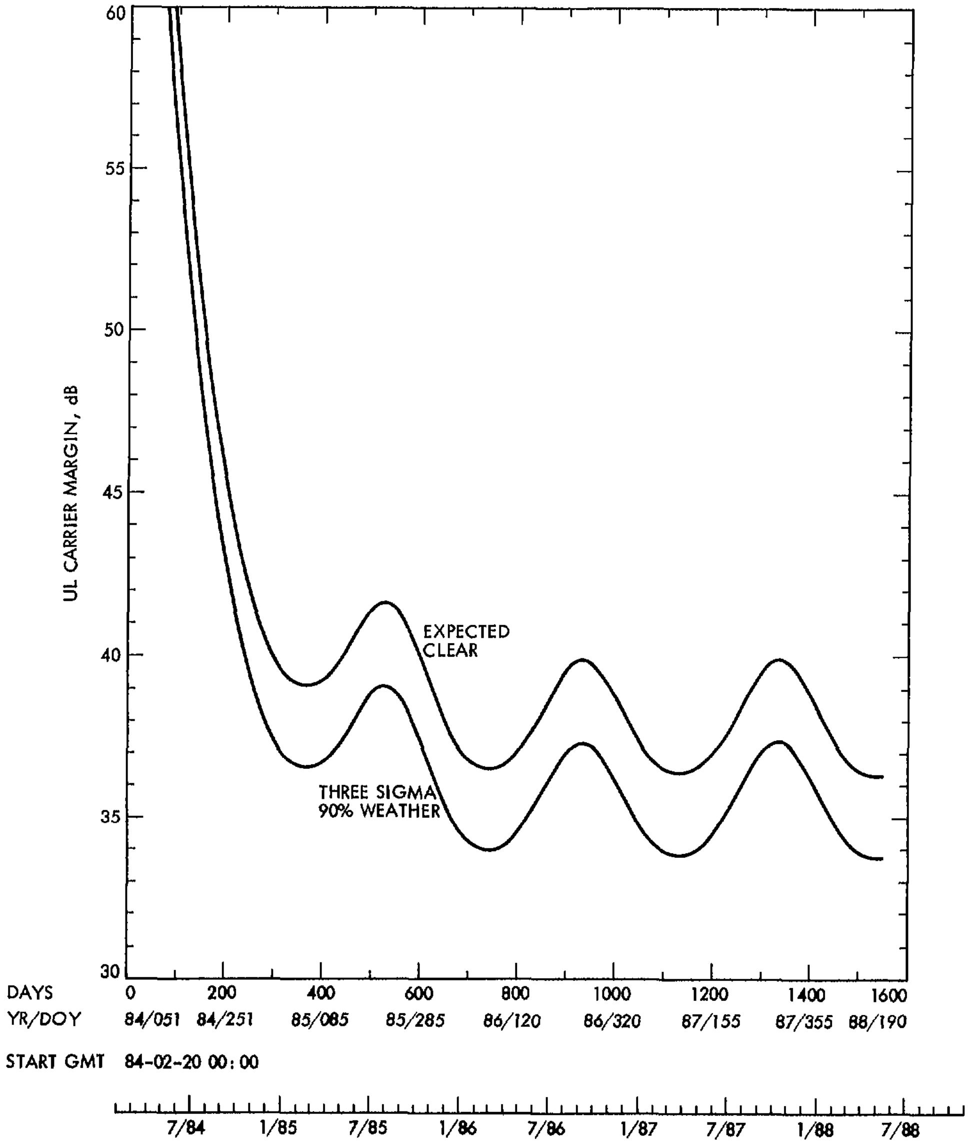

Fig. 10. Uplink carrier margin

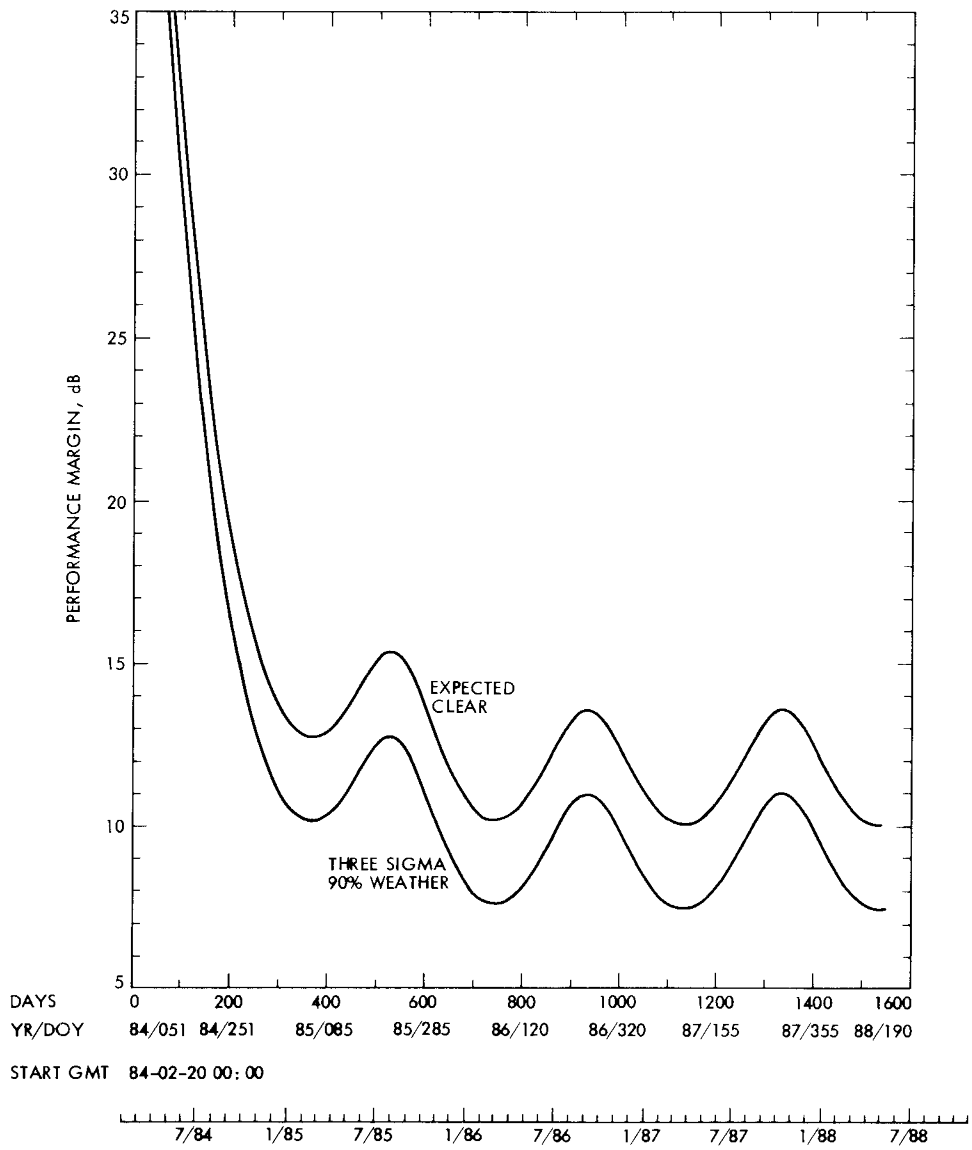

Fig. 11. Command performance margin

Appendix

Design Control Tables

Design Control Tables (DCT) are used to predict performance of a communications link. A DCT describes the link for a particular set of parameters at one point in the mission. Table A-1 is an example and is for the Galileo command link at Jupiter distance. To see the performance throughout the mission, certain performance parameters from the DCT are presented graphically. Figures A-1, 2, 3 are examples showing the received power, uplink carrier performance margin and command performance margin. The upper curve shows expected or mean link conditions. The lower curve takes into account a statistical estimate of weather effects plus the adverse tolerances of the link parameters. With approximately 99% confidence, the link will operate above the curve.

Each parameter listed in the DCT affects the link. By varying the bit rate, bit error rate, modulation index, coding, antenna size, transmitter power, and pointing error allowance the link performance will change.

The result of each DCT calculation is a performance margin. This margin is the amount by which the link varies from that required to give a specified performance. For the uplink power study the parameter of interest is the power required to just meet a specified required performance, not the margin resulting from a given uplink power. DCT results were adjusted accordingly. A new configuration, for example, 64-m rather than 34-m antenna, may be calculated from previous DCTs by adding the appropriate gain or loss into the table.

Table A-1. Galileo uplink carrier design control table

GALILEO CMD/34M/CLR DSGN/90PCT 2-SIG/RNG OFF/20 DEG MI
HGA, 1985 BASELINE, STANDARD CASE #2, RUN 11/11/81

EPOCH 85/120/00/00 SPACECRAFT 0 STATION 43

DATE 89-06-13 DOY 164 HH:MM 00:00 DAYS FROM EPOCH 1505 00:00

	DESIGN	FAV TOL	ADV TOL	MEAN	VAR
TRANSMITTER PARAMETERS					
1) RF POWER, DBM	73.00	.50	-.50	73.0	.04
POWER OUTPUT = 20.0 KW					
XMITR CIRCT LOSS, DB	.00	.00	.00	.0	.00
2) ANTENNA GAIN, DBI	55.30	.30	-.70	55.1	.08
ELEV ANGLE = 25.00 DEG					
3) POINTING LOSS, DB	.00	.00	-.10		
PATH PARAMETERS					
4) SPACE LOSS, DB	-278.16			-278.2	.00
FREQ = 2114.68 MHZ					
RANGE = 9.124+08 KM					
= 6.10 AU					
5) ATMOSPHRIC ATTNUATION,DB	-.11	.00	.00	-.1	.00
WTHR MODEL IS 810-5					
RECEIVER PARAMETERS					
6) POLARIZATION LOSS, DB	-4.25	1.22	-1.55		
7) ANTENNA GAIN, DBI	36.30	.30	-.30	31.9	.34
CONE ANGLE = .69 DEG					
8) POINTING LOSS, DB	-.18	.18	-.07	-.1	.00
9) REC CIRCUIT LOSS, DB	-1.90	.40	-.50	-2.0	.07
10) NOISE SPEC DENS, DBM/HZ	-167.92	-.23	.79	-167.6	.03
OPERATING TEMP, K	1170.00	-60.00	235.00		
HOT BODY NOISE, K	.00	.00	.00		
11) 2-SIDED THRESHOLD LOOP NOISE BANDWIDTH, DB-HZ	12.00	-.70	.60	12.0	.07
POWER SUMMARY					
12) RCVD POWER,PT,DBM (1+2+3+4+5+6+7+8+9)				-120.3	.53
13) RCVD PT/NO, DB-HZ (12-10)				47.3	.56
14) RANGING SUPPRESSION, DB	.00	.00	.00	.0	.00
15) COMMAND SUPPRESSION, DB	-.55	.10	-.10	-.5	.00
16) CARR PWR/TOT PWR, DB (14+15)				-.5	.00
17) RCVD CARR PWR, DBM (12+16)				-120.9	.53
18) CARRIER MARGIN, DB (17-10-11)				34.8	.63

Table A-1 (contd)

	DESIGN	FAV TOL	ADV TOL	MEAN	VAR
DATA CHANNEL PERFORMANCE					
19) DATA BIT RATE, DB BIT RATE = 32.0 BPS	15.05	.00	.00	15.1	.00
20) DATA PWR/TOTAL PWR, DB	-9.25	.68	-.82	-9.3	.09
21) DATA PWR TO RCVR, DBM (12+14+20)				-129.6	.63
22) ST/NO TO RCVR, DB (21-19-10)				23.0	.66
23) SYSTEM LOSSES, DB RADIO LOSS, DB DEMOD,DETECT LOSS, DB	-1.20	.40	-.40	-1.2	.03
24) ST/NO OUTPUT, DB (22+23)				21.8	.68
25) THRESHOLD ST/NO, DB	9.59	.00	.00	9.6	.00
26) PERFORMANCE MARGIN, DB (24-25)				12.2	.68
				3.0S = 2.48	