COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Communication System Design for
an MM-Drag Probe Link on Manned
Mars Flyby Missions

TM- 68-2034-1

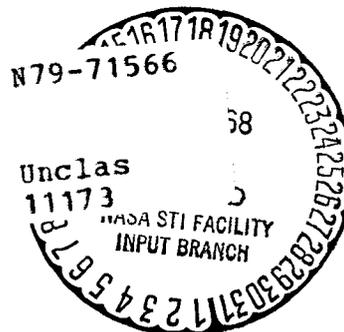DATE- February 15, 1968

FILING CASE NO(S)- 720

AUTHOR(S)-R. K. Chen

FILING SUBJECT(S)-
(ASSIGNED BY AUTHOR(S)- Planetary Communications

ABSTRACT

A conceptual design for a communication system serving a Mission Module and an Atmospheric Drag Probe on Manned Mars Flyby missions is formulated. The system serves two basic functions; namely, (1) transmission of 24 kilobits of scientific data from the probe to the Mission Module in 10 seconds and (2) periodic or continuous range and range-rate tracking of the probe from the Mission Module.

A method of optimally utilizing the RF transmitter power from both space vehicles is outlined as well as the weight of the communication system as a function of communication distances and the frequency of tracking operation. A typical system would utilize the available communication system existing in the Mission Module for communicating with Earth via a 30-foot antenna and 150 watts of transmitter power. A complementary communication system on the probe would weigh approximately 40 pounds and would be capable of operation over a maximum communication distance of 4×10^5 nm. This includes approximately 22 hours of tracking operation.

SEE REVERSE SIDE FOR DISTRIBUTION LIST

DISTRIBUTION

NASA Headquarters

W. W. Boyes, Jr./MTY
A. J. Calio/SY
P. E. Culbertson/MLA
J. H. Disher/MLD
F. P. Dixon/MTY
R. W. Gillespie/MTE
P. Grosz/MAL
M. Gruber/MTV
W. L. Haberman/MTY
E. W. Hall/MTG
J. L. Hammersmith/MTP
W. J. Hamon/MTP
D. P. Hearth/SY
H. Hornby/OART/MO
T. A. Keegan/MA-2
D. R. Lord/MTD
M. W. Molloy/SL
B. G. Noblitt/MTY
M. J. Raffensperger/MTE
L. Reiffel/MA-6
A. D. Schnyer/MTV
R. A. Summers/MTY
P. R. Swan/OART/MS

MSC

J. H. Boynton/FA4
C. Covington/ET23
D. E. Fielder/FA4
H. C. Kyle/EB
G. C. Miller/ET23
R. W. Moorehead/EB2
M. A. Silveira/EA2
W. E. Stoney, Jr./ET
P. Vavra/EB
J. M. West/AD

MSFC

H. S. Becker/R-AS-DIR
J. W. Carter/R-AS-V
R. J. Harris/R-AS-VP
F. L. Williams/R-AS-DIR

KSC

J. P. Claybourne/DE-FSO
R. C. Hock/AA
N. Salvail/DE/FSO

ERC

R. C. Duncan/S

LRC

W. R. Hook/600.300

ARC

L. Roberts/M (2)
J. S. White/FST

JPL

W. G. Breckenridge/343
T. W. Hamilton/312

Bellcomm

F. G. Allen
G. M. Anderson
A. P. Boysen, Jr.
J. P. Downs
D. R. Hagner
P. L. Havenstein
W. G. Heffron
J. J. Hibbert
W. C. Hittinger
B. T. Howard
D. B. James
C. M. Klingman
J. Kranton
K. E. Martersteck
H. H. McAdams
R. K. McFarland
J. Z. Menard
I. D. Nehama
G. T. Orrok
J. T. Raleigh
I. M. Ross
R. L. Selden
P. S. Schaenman
R. V. Sperry
W. B. Thompson
J. M. Tschirgi
J. E. Volonte
R. L. Wagner
J. E. Waldo
All Members, Dept. 2034
Department 1023

BELLCOMM, INC.
1100 SEVENTEENTH STREET, N.W.   WASHINGTON, D.C.   20036

COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Communication System Design for an MM-Drag Probe Link on Manned Mars Flyby Missions

FILING CASE NO(S)- 720

FILING SUBJECT(S)-
(ASSIGNED BY AUTHOR(S)- Planetary Communications

TM- 68-2034-1

DATE- February 15, 1968

AUTHOR(S)-R. K. Chen

ABSTRACT

A conceptual design for a communication system serving a Mission Module and an Atmospheric Drag Probe on Manned Mars Flyby missions is formulated. The system serves two basic functions; namely, (1) transmission of 24 kilobits of scientific data from the probe to the Mission Module in 10 seconds and (2) periodic or continuous range and range-rate tracking of the probe from the Mission Module.

A method of optimally utilizing the RF transmitter power from both space vehicles is outlined as well as the weight of the communication system as a function of communication distances and the frequency of tracking operation. A typical system would utilize the available communication system existing in the Mission Module for communicating with Earth via a 30-foot antenna and 150 watts of transmitter power. A complementary communication system on the probe would weigh approximately 40 pounds and would be capable of operation over a maximum communication distance of 4×10^5 nm. This includes approximately 22 hours of tracking operation.

SEE REVERSE SIDE FOR DISTRIBUTION LIST

DISTRIBUTION

COMPLETE MEMORANDUM TO

CORRESPONDENCE FILES:

OFFICIAL FILE COPY
plus one white copy for each
additional case referenced

TECHNICAL LIBRARY (4)

NASA Headquarters

W. W. Boyes, Jr./MTY
A. J. Calio/SY
P. E. Culbertson/MLA
J. H. Disher/MLD
F. P. Dixon/MTY
R. W. Gillespie/MTE
P. Grosz/MAL
M. Gruber/MTV
W. L. Haberman/MTY
E. W. Hall/MTG
J. L. Hammersmith/MTP
W. J. Hamon/MTP
D. P. Hearth/SY
H. Hornby/OART/MO
T. A. Keegan/MA-2
D. R. Lord/MTD
M. W. Molloy/SL
B. G. Noblitt/MTY
M. J. Raffensperger/MTE
L. Reiffel/MA-6
A. D. Schnyer/MTV
R. A. Summers/MTY
P. R. Swan/OART/MS

MSC

J. H. Boynton/FA4
C. Covington/ET23
D. E. Fielder/FA4
H. C. Kyle/EB
G. C. Miller/ET23
R. W. Moorehead/EB2
M. A. Silveira/EA2
W. E. Stoney, Jr./ET
P. Vavra/EB
J. M. West/AD

MSFC

H. S. Becker/R-AS-DIR
J. W. Carter/R-AS-V
R. J. Harris/R-AS-VP
F. L. Williams/R-AS-DIR

KSC

J. P. Claybourne/DE-FSO
R. C. Hock/AA
N. Salvail/DE/FSO

ERC

R. C. Duncan/S

LRC

W. R. Hook/600.300

ARC

L. Roberts/M (2)
J. S. White/FST

JPL

W. G. Breckenridge/343
T. W. Hamilton/312

Bellcomm

F. G. Allen
G. M. Anderson
A. P. Boysen, Jr.
J. P. Downs
D. R. Hagner
P. L. Havenstein
W. G. Heffron
J. J. Hibbert
W. C. Hittinger
B. T. Howard
D. B. James
C. M. Klingman
J. Kranton
K. E. Martersteck
H. H. McAdams
R. K. McFarland
J. Z. Menard
I. D. Nehama
G. T. Orrok
J. T. Raleigh
I. M. Ross
R. L. Selden
P. S. Schaenman
R. V. Sperry
W. B. Thompson
J. M. Tschirgi
J. E. Volonte
R. L. Wagner
J. E. Waldo
All Members, Dept. 2034
Department 1023

SUBJECT: Communication System Design for an
MM-Drag Probe Link on Manned Mars
Flyby Missions - Case 720

DATE: February 15, 1968

FROM: R. K. Chen

TM- 68-2034-1

TECHNICAL MEMORANDUM

I.   Introduction

An atmospheric drag probe (ADP) has been proposed for manned Mars flyby missions in the 1970's and beyond. The scientific objectives of the probe and its interactions with the other probes that will be deployed during the same mission have been described [1], [2]. Previous results in a communication system design study for a manned Mars flyby mission [3] cannot be applied to the ADP-mission module (MM) link because of the severe and unique environment that will be encountered by the ADP. This memorandum addresses the specific problems in the communication system design for the ADP-MM links in the transmission of scientific data from the ADP to MM and tracking of the ADP from the MM.

The RF characteristics of the probe environment that will be encountered by the ADP are discussed briefly in Sec. II. Sec. III provides various system designs for the ADP to MM data link and establishes their system requirements. The design of the tracking link is discussed in Sec. IV and also its system requirements. Section V presents a model for system selection and areas where system improvement may be possible. The tracking system analysis and the detail formulation of its system parameters are included in Appendix A.

II.   Drag Probe RF Environments

The RF characteristics of the probe environment referred to here are those that influence the performance of the ADP-MM communication link, these are:

1.   RF Blackout from Entry Plasma - The drag probe deployed from the MM on a Mars flyby mission will enter the sensible atmosphere of Mars at approximately 10 km/sec. Without any braking from a retro-rocket, the deceleration of the probe would be accomplished by the drag characteristics of the probe through aerodynamic shaping. The end result is the generation of heat about the probe body which in turn generates a plasma sheath about the probe body as well.

Because of the uncertainty of the density profile of the Mars atmosphere and the lack of definitive information on its constituents, very little can be said about RF blackout conditions. The only information available at this time is derived from the study made by Langley Research Center (LRC) for the Voyager program. It has been determined, with high confidence, that for a blunt body vehicle, S-band frequencies will not be blacked out at probe velocities of 15,000 ft/sec regardless of the altitude and the mixing ratio of gas

constituents (a mixture of CO_2, N_2, and A.)[4] The upper velocity boundary where S-band blackout begins is yet to be determined.

2. Doppler Frequency Shift - The doppler frequency profiles of the ADP-MM link for various Mars flyby missions have been computed by Mr. H. H. McAdams of the Planetary Studies Department at Bellcomm, Inc. Figure 1 shows the doppler frequency profiles of two typical missions which represent the bounds of expected doppler range for most Mars flyby missions.

3. Multipath Effects - The multipath phenomenon is not new to communication, however, the severity of the problem will depend on the surface characteristics of the Martian terrain which is not well known. The best one can do at this point is to allow sufficient design margin in the communication system for possible degradation effects.

It should be noted that each of the environmental conditions discussed above by itself does not cause complications to the communication system design, however, the total combination plus their uncertainties become problematic. Consequently, the system design is separated into two parts, namely: (1) the tracking system that is used for the period between ADP and MM separation to the beginning of RF blackout (assuming it does exist), and (2) the data transmission system from the ADP to the MM that is used between the period of ADP emergence from RF blackout to impact.

The amount of scientific data collected by the ADP and the data transmission rate from the ADP are provided by Mr. McAdams and summarized in Table I. It is assumed that all data will be recorded during probe descent and the RF blackout period. The data playback will take place after the probe emerges from blackout to the time of impact. The available transmission time is estimated to be ten seconds.

III. Data Transmission System from ADP to MM

Under ordinary circumstances, the most efficient modulation method for data transmission would be coherent PSK (PCM/PM). The implementation of a receiver on the MM would require that frequency lock be maintained between the ADP transmitter and the MM receiver.

Considering the uncertainties of the ADP environments discussed previously, it is highly probable that the RF blackout will cause the system to drop out of frequency lock, a frequency reacquisition will then be needed after the ADP emerges from blackout before any data can be transmitted to MM. Since the available time period for data transmission after RF blackout is uncertain, planning on the use of a coherent PSK system at this time is very risky.

A non-coherent frequency-shift-keying (FSK) system is considered next. In order to achieve the ideal performance of a FSK system, which is approximately 4 dB poorer in performance than a coherent PSK system, one needs to know the exact frequency of the signal at the receiver input. Alternatively, a more complex receiver is required to compensate for the uncertainty in frequency. This could be in the form of automatic frequency control or multiple filter channels, etc. Several analyses have been made on "non-ideal" FSK receivers which are usually referred to as "wideband FM receivers". These receivers employ wider bandwidth than that necessary to detect the information being transmitted. The excess bandwidth is necessary to accommodate the doppler frequency and oscillator instabilities. For the case considered here, the receiver has two main channels, one for each symbol transmitted (mark or space). The bandwidth of each main channel is approximately 77 kHz (65 kHz doppler frequency, $\pm 1 \times 10^{-6}$ oscillator stability, and 2.4 kHz bit-rate-bandwidth). Two different detection methods which have been analyzed in Ref. 5 are considered. The first one uses an envelope detector and the second uses comb filters followed by envelope detectors, one for each of the filter channels. The second method essentially subdivides the receiver bandwidth into a number of bit-rate-bandwidth channels (32 for each symbol in this case). Each channel can be thought of as an independent receiver operating in parallel with the others.

In the following, the relative performance of the four receivers mentioned are compared. The criterion used for the comparison is the required signal-to-noise density ratio (S/N_0) for a transmission rate of 2.4 kilo-bits per second (kbps) and 10^{-3} maximum bit error rate (BER).

Receiver	Signal Power to Noise Spectral Density Ratio, S/N_0, in dB-Hz (10^{-3} BER-2.4kbps)
1. Coherent PSK	40.8
2. Ideal non-coherent FSK	44.8
3. Wide-band FSK using comb-filters	47.4 (Ref. 5)
4. Wide-band FSK using envelope detectors	49.0 (Ref. 5)

It is clear from the listing above that, depending on the choice
of modulation method and receiver design, an eight to one
difference exists in the performance requirement which, in this
case, means an eight to one difference in the RF transmitter
power level at the ADP. Further improvement in performance can be
obtained by using coding techniques. For instance, the use of
M-ary FSK (MFSK) technique with M=4, which implies sending a
discrete frequency tone for every two bits of information uniquely
combined, would better the performance of receiver No. 4 above by
1.4 dB and receiver No. 3 by approximately 2 dB[5]. However, the
use of MFSK would further complicate not only the receiver design
but the transmitter design as well.

From the performance requirements established above,
the transmitter power required at the ADP can be calculated as a
function of communication distance by using the one-way transmission
equation, expressed as:

$$P_t = \frac{6{,}000 \ f^2 \ d^2 \ M \ (S/N_0) \ K \ T_{eff} \ L_{syst}}{G_t \ G_r} \qquad (1)$$

where: f = RF frequency in MHz

d = communication distance in nm

M = circuit margin required

(S/N_0) = Signal-to-noise spectral density ratio required

K = Boltzman's constant = 1.38×10^{-23} joules/°K

T_{eff} = effective noise temperature receiving system

L_{syst} = Combined system losses

G_t = transmitting antenna gain

G_r = receiving antenna gain

P_t = transmitter power in watts

N_0 = noise spectral density = $K \ T_{eff}$ in watt/Hz

The system parameters that are assumed for the ADP-MM communication
link are summarized in Table II. The MM parameters are taken from
Ref. 3 and the ADP parameters are estimated. The ADP antenna
information is obtained from Mr. McAdams, and is assumed to be a
simple spiral with beamwidth of 60° and 5 dB gain. The wide beam-
width is necessary so that the antenna beam of the probe will be
pointing in the general direction of the MM throughout the probe's
trajectory.

Substituting the assumed parameters into (1):

$$P_t = 1.86 \times 10^{-14}(S/N_0)\, d^2 \qquad (2)$$

or expressed in terms of dB:

$$P_t = (S/N_0) - 137.9 + 20 \log d \qquad (3)$$

The results of P_t required for various receiver designs are given in Fig. 2.

IV.   Tracking System

The range and range-rate tracking of the ADP from the MM between the time of separation of the ADP from the MM and its arrival at Mars (before RF blackout) will be accomplished by a coherent S-band system similar to the one developed and proposed for Apollo related programs[6]. Briefly, the two-way doppler frequency shift of the RF carrier provides the range-rate information, and the difference in phase of a two level psuedo-noise (PN) code* is used for the range measurement.

The range code is transmitted on a sub-carrier rather than the main carrier, such as in the Mark I system used for the Apollo USB system, to avoid the code spectrum interference to the main carrier channel. A two level code sequence is chosen as it provides an efficient method of achieving large unambiguous range measurement without the corresponding increase in code acquisition time. The implementation of the hardware is relatively simple and its performance is also adequate for the needs considered. A more detailed description of the PN code design is given in Ref. 6; for the MM-ADP ranging application, the bit period of the PN code is increased by a factor of ten over that described (Ref. 6) to 160 usec. in order to provide an unambiguous range capability of approximately 400,000 nm. The performance requirement for the range tracking system can be expressed as follows:[7]

$$S/N_0 = 30,000/T_{int},$$

---

*A two level PN code is one made up of two independent PN sequences combined logically to provide a composite code equal in length to the product of the lengths of the two component sequences.

where T_{int} is the integration time needed (in seconds) to acquire the range code. Assuming 60 seconds as the maximum code acquisition time, the performance requirement for the ranging channel would be:

$$S/N_0 = 27.0 \text{ dB-Hz.}$$

The equipment accuracy for ranging is estimated to be 500 ft.

The heart of the system design is the phase lock loop (PLL) in the ADP and MM. The PLL's serve two important functions:

1.   They generate replicas of the received RF carriers to facilitate doppler frequency extraction, and therefore, measurement of the range-rate between the ADP and MM.

2.   In addition, the replica frequencies generated are also phase coherent with the received carriers. Therefore, the replica at the MM can be used as the reference frequency for coherently demodulating the received signal (in this case, the ranging channel).

The discussion on the design of the PLL's is given in Appendix A. It is shown that the performance requirements of the range-rate channels (carrier) are:

$$(S/N_0)_c \text{ at ADP} = 36 \text{ dB-Hz, and}$$

$$(S/N_0)_c \text{ at MM} = 37.5 \text{ dB-Hz.}$$

The equipment accuracy for range-rate is estimated to be 0.33 ft/sec, and the two-way frequency acquisition time is approximately 11 sec.

Since a two-way coherent system is involved, the performance of the ADP to MM link (down-link) is affected not only by the parameters associated with the down-link but those of the MM to ADP link (up-link) as well. Consequently, the straight forward one-way transmission equation used previously cannot be applied. The two-way link performance analysis is given in Appendix A; a summary of the analysis is given here.

1.   The doppler rate between the MM and ADP, and the allowable frequency acquisition time determine the design of the PLL's in both the MM and ADP.

2.   For a given PLL design, the minimum performance is determined for the carrier channel which provides the range-rate information.

3. The required maximum unambiguous range to be measured, the range-readout resolution desired, and the allowable range code acquisition time primarily determine the design of the PN range code and the range receiver.

4. For a given PN range code and receiver design, the minimum performance of the ranging channel is determined.

5. An optimized system is proposed in which the range and range-rate channels for both up and down links reach their minimum performance criteria simultaneously.

6. To meet the optimized design criteria, the up and down link modulation indices are related as shown in Figure 5.

7. For every given up-link transmitter power, a corresponding down-link transmitter power, as shown in Fig. 6, must be used to satisfy the optimization criteria.

8. At a fixed distance, an infinite set of up and down link transmitter powers can be used to meet the minimum performance requirements depending on the up-link modulation index chosen. This effect is shown in Fig. 7, curves (2) and (3).

The conceptual design of the tracking system in simplified block diagrams is given in Figures 3 and 4. The pertinent parameters of the system are summarized in Table III. The analytical results given in Fig. 7 obviously do not provide a clear cut answer in terms of the transmitter power required for the MM and ADP as discussed in item 8 above. Additional tradeoffs concerning the overall design of the MM and ADP should be made to consider the weight, prime power, and the probe deployment strategy which ultimately determine the maximum communication distance. However, a careful examination of Fig. 7 with some simple assumptions provides significant results that will ease the overall vehicle design trade-off. This is duscussed in the following.

A previous study[3] concluded that, for the MM to Earth communication, the effective radiated power (ERP) needed at the MM is 65.6 dBW. With a 30 ft antenna on the MM, the transmitter power needed is approximately 150 watts. It is reasonable to assume that the same transmitter and antenna can be used for MM-ADP communication as well. To illustrate the utilization of Fig. 7, the normalized power vs. distance for 150 watt transmitter power is also plotted on Fig. 7 as curve (1). A distance vs. ADP transmitter power require-ment can be obtained by using the following procedures with 4.10^5 nm as the communication distance for illustration:

1.   From curve (1), the normalized up-link transmitter power, (P_{tu}/d^2) at that distance is 9.4×10^{-10} watt/nm^2.

2.   Curve (2) indicates the optimized up-link modulation index (θ_u) to be 1.13 radians at $P_{tu}/d^2 = 9.4 \times 10^{-10}$ watt/nm^2.

3.   From curve (3), the required down-link normalized power (P_{td}/d^2) at $\theta_u = 1.13$ is 1.4×10^{-10} watt/nm^2.

4.   The down-link transmitter power is:

$$P_{td} = 1.4 \times 10^{-10} \times (4 \times 10^5)^2 = 22.4 \text{ watts.}$$

The results are shown in Fig. 8. Similarly, MM transmitter power values of 300 watts, and 75 watts are also presented in Fig. 8 for comparison; two conclusions can be made readily, namely:

1.   For every up-link power value, there is a communication distance beyond which the down-link power requirement increases rapidly.

2.   At communication distances less than 5×10^5 nm, the down-link power requirement is almost independent of the up-link power and has a slope of approximately 6.3 dB per octave with distance.

V.   System Selection

The conceptual communication design for the MM-ADP links can be summarized as follows:

1.   MM - The antenna system and the RF power amplifier system used for the MM-Earth communication links[3] is assumed to be adequate. The receiver design and the data processor design should be sufficiently flexible to meet the MM-ADP communication links with ease. The only unique subsystems for this application is the range code generator and the range receiver for the tracking function; conceivably, this equipment would be utilized during other phases of the mission where tracking is needed, such as Earth orbit assembly, and the rendezvous of the MM with the Mars Surface Sample Return probe (MSSR)[1][2]. From Reference 2, the nominal strategy for the deployment of ADP is as follows:

1.   MM-ADP separation occurs approximately 10 days before the MM pariapsis passage of Mars (t_0).

2.   The ADP's arrive at Mars between t_0-16 hrs. and t_0-24 hrs., which corresponds to a communications distance of approximately 2.6×10^5 nm to 4×10^5 nm.

Therefore, the use of 150 watt power amplifier is justified not only because it is available, but also by the fact that higher power from the MM would not help to reduce the ADP transmitter power appreciably, as indicated in Figure 8, for distances less than 6×10^5 nm, (approximately t_0-36 hrs.).

2.   ADP - The communication system on the ADP would consist of a coherent transponder for the tracking function, a digital storage device in conjunction with a data processor and a FSK modulator for scientific data transmission. The RF power amplifier is common to both tracking and data transmission functions, except a low power mode is used for tracking and a high power mode for data transmission. An onboard sensor would be needed for switching power levels.

From previous discussion and results presented in Figures 2 and 8, a model for selecting a communication system can be derived. Furthermore, this model is only needed for the ADP. The model would effectively relate the communication system weight and the maximum communication distance to be served. Needless to say, the weight estimated at present for a future system is speculative, as certain devices needed exist in the laboratories only. Therefore, it should be understood that the weight discussions to follow are not based on the "state of the art" but rather on anticipated technology of the next decade.

The weight of the communication system of the ADP can be divided into two general categories:

1.   Subsystems independent of communication distance, and

2.   Subsystems dependent to the communication distance.

The first category includes: transponder, storage device, data processor, and the FSK modulator. In the second category are: RF power amplifier, and prime power supply.

The estimated weights for the subsystems in category (1) are:

transponder	4 lbs.
data storage device	0.5 lbs. [8]
data processor and FSK modulator	1.0 lbs.
<u>Total category (1)</u>	<u>5.5 lbs.</u>

The data storage device envisaged is a digital device produced by LSI (large scale integration).

The estimated weights for the subsystems in category (2) are:

Prime power supply-silver zinc battery   90 watt-hr/lb [9]

RF power amplifier package (traveling wave tube type)

$$W = 5 \times P^{0.2} \qquad \text{for:} 1<P<20 \text{ watt}$$

$$W = 2.35 \times P^{0.45} \qquad \text{for:} 20<P<200 \text{ watt}$$

$$W = 0.65 \times P^{0.69} \qquad \text{for:} 200<P<1000 \text{ watt}$$

where W = weight of RF power amplifier package in pounds

P = RF power in watts.

The estimates made for the RF power amplifiers are based on a discussion with Mr. B. M. Kendall of Langley Research Center where a one kilowatt RF amplifier study is now in progress.* Fig. 9 shows the weight for RF amplifier tubes alone as a function of RF output power and also the complete RF power amplifier package which includes the high voltage power supply and other electronic components required for the tube operation. It should be mentioned that Mr. Kendall supplied most of the discrete points on the curve for the power amplifier packages, the estimated curves and weight ranges are estimated by the author. The possibility of using solid state high power RF amplifiers were also discussed; these devices, at present, are not as far along in their development as comparable power tube devices. Furthermore, solid state power efficiencies probably will be inferior to tube type devices; it is estimated that the power efficiency of the tubes will be 40%, while solid state amplifiers will exhibit about half as much. Therefore, only tube amplifiers are considered.

The total system weight can now be expressed as:

$$W_s = 5.5 + 5P_1^{0.2} + (P_1 T_1)/90\eta + (P_2 T_2)/90\eta \quad \text{for:} 1<P_1<20 \text{ watt}$$

$$W_s = 5.5 + 2.35P_1^{0.45} + (P_1 T_1)/90\eta + (P_2 T_2)/90\eta \quad \text{for:} 20<P_1<200 \text{ watt}$$

$$W_s = 5.5 + 0.65P_1^{0.69} + (P_1 T_1)/90\eta + (P_2 T_2)/90\eta \quad \text{for:} 200<P_1<1000 \text{ watt}$$

---

*The study is being accomplished by Varian Associates under a LRC contract.

where: W_s = total system weight in pounds

P_1 = power requirement for data transmission in watts (Fig. 2)

P_2 = power requirement for tracking system in watts (Fig. 8)

T_1 = data transmission period in hrs.

T_2 = total tracking period in hrs.

η = power efficiency of RF power amplifier.

To determine the value to be used for T_2 requires a detailed tracking analysis where accuracy requirements and the number of data samples needed would be determined from operational considerations.

Assuming the nominal probe deployment strategy of Ref. 2, T_2 will be some fraction of nine days depending on the duty cycle required for the tracking operation. In the following, the results obtained assuming duty cycles of 5%, 10%, 50%, and 100% are evaluated. The value of T_1 is obtained from Sec. I as 10 seconds, or 1/360 hr. Substitute these values into the weight equations:

$$W_s = 5.5 + 5P_1^{0.2} + 6aP_2 \qquad \text{for: } 1 < P_1 < 20 \text{ watts}$$

$$W_s = 5.5 + 2.35P_1^{0.45} + 6aP_2 \qquad \text{for: } 20 < P_1 < 200 \text{ watts}$$

$$W_s = 5.5 + 0.65P_1^{0.69} + 6aP_2 \qquad \text{for: } 200 < P_1 < 1000 \text{ watts}$$

where: a = duty cycle of tracking operation.

The prime power weight for data transmission, $P_1 T_1 / 90\eta$, is omitted as it is very small in comparison with the other terms in the equation. Combining the weight equations with the RF power requirements presented in Figures 2 and 8, a weight vs. distance relation can be derived, which is given in Figure 10.

From Fig. 10, it is seen that when a large duty cycle is assumed for the tracking operation, the data transmission method chosen is inconsequential from the total system weight standpoint. With low duty cycle for tracking operation, the choice of data transmission method becomes more critical. Curves 3 and 4 in Fig. 10 represent coherent PSK and ideal FSK modulation methods which, as previously discussed in Sec. II, are difficult to realize. These curves are provided for comparison and indicate the upper limit in

theoretically attainable performances. Curves 1 and 2 in Fig. 10 represent the wideband FSK modulation methods that appear attractive because of the expected RF environment for the ADP mission. The weight differences between these two methods are relatively slight; as expected, the heavier system, which is the one using an envelope detector[5], is also the simpler system to implement.

System improvement may be possible in several areas, some of these are:

1.   Reduction in the receiver temperature for ADP. A solid state preamplifier is chosen for the analysis here because of its simplicity. Future low noise amplifier technology may evolve so that a light weight parametric amplifier may be possible.

2.   A lower threshold requirement may be considered for the PLL on the ADP during frequency acquisition operation. It has been claimed that if a _a priori_ knowledge of the doppler frequency exists, the PLL threshold can be reduced by 3 dB.

3.   When more is known of the RF blackout characteristics for Mars atmosphere entry, it may be possible to use S-band or higher frequencies for data transmission without interruption. If these higher frequencies obviate the blackout phenomenon the use of coherent PSK for data transmission becomes attractive and would provide a considerable weight reduction, as shown in Fig. 10, when the duty cycle of the tracking operation is low.

4.   Improvement in the energy density (watt-hr/lb) of the bettery would provide a considerable savings in total system weight. More exotic devices, such as zinc-oxygen primary battery fuel cell hybrids have the potential to provide 120-150 watt-hr/lb.[9]

On the other hand, if the multipath environment near Mars proves to be worse than the 6 dB performance margin allowed in this analysis, the system weight would have to be increased accordingly.
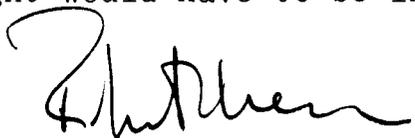
2034-RKC-dlb   R. K. Chen

Attachments
  Tables I - III
  Figures 1 - 10
  Appendix A
  References

Instrument	Range		Quantity	No. bits/instrument/sec	No. of Sec	Total Bits
Accelerometers	Axial	0-400g	2	70	20 stored + 10 RT	
		0-40g	2	70	" " " "	
		0-4g	2	70	" · " " "	
	Transverse	0-100	2	70	" " " "	
		0-20	2	70	" " " "	21,000
Temperature	50°-350°K		2	7	10 RT	140
Pressure	0-50 mb		2	7	20 stored + 10 RT	420
Mass Spectrometer	6 Channels $O, H_2O, O_2, A, CO_2, N_2$		1	6 bits/channel/sec	10 RT	60
Radiometer	4 spectral lines C, CN, C_2, N_2^+			Records peak intensity and time of peak for each line		56

Total Data Bits   ~22,000

+ 10% for synchronization   2,000

Total bits to be transmitted in ten seconds   24,000

Bit rate   2400 bits/second

Table I   Estimate of Scientitic Data To Be Collected by Atmospheric Drag Probe

Table II

Assumed Parameters for One-Way Data Transmission

Mission Module

    Antenna Gain   44 dB at 2.3 GHz (30 ft dish)

    RF Losses   3.0 dB

    Receiving System Noise Temperature
      (uncooled parametric amplifier-120°K
        Sky noise - 20°K
        Mars noise - 10°K)   150°K

Atmospheric Drag Probe

    Antenna Gain   5.0 dB

    RF Losses   1.5 dB

    Pointing and Polarization Loss   3.0 dB

    Receiving System Noise   900°K
      Temperature (Solid State
        Amplifier)

    Performance Margin Required   6.0 dB

Table III

Parameters for Tracking System

All parameters in Table II apply.

Mission Module

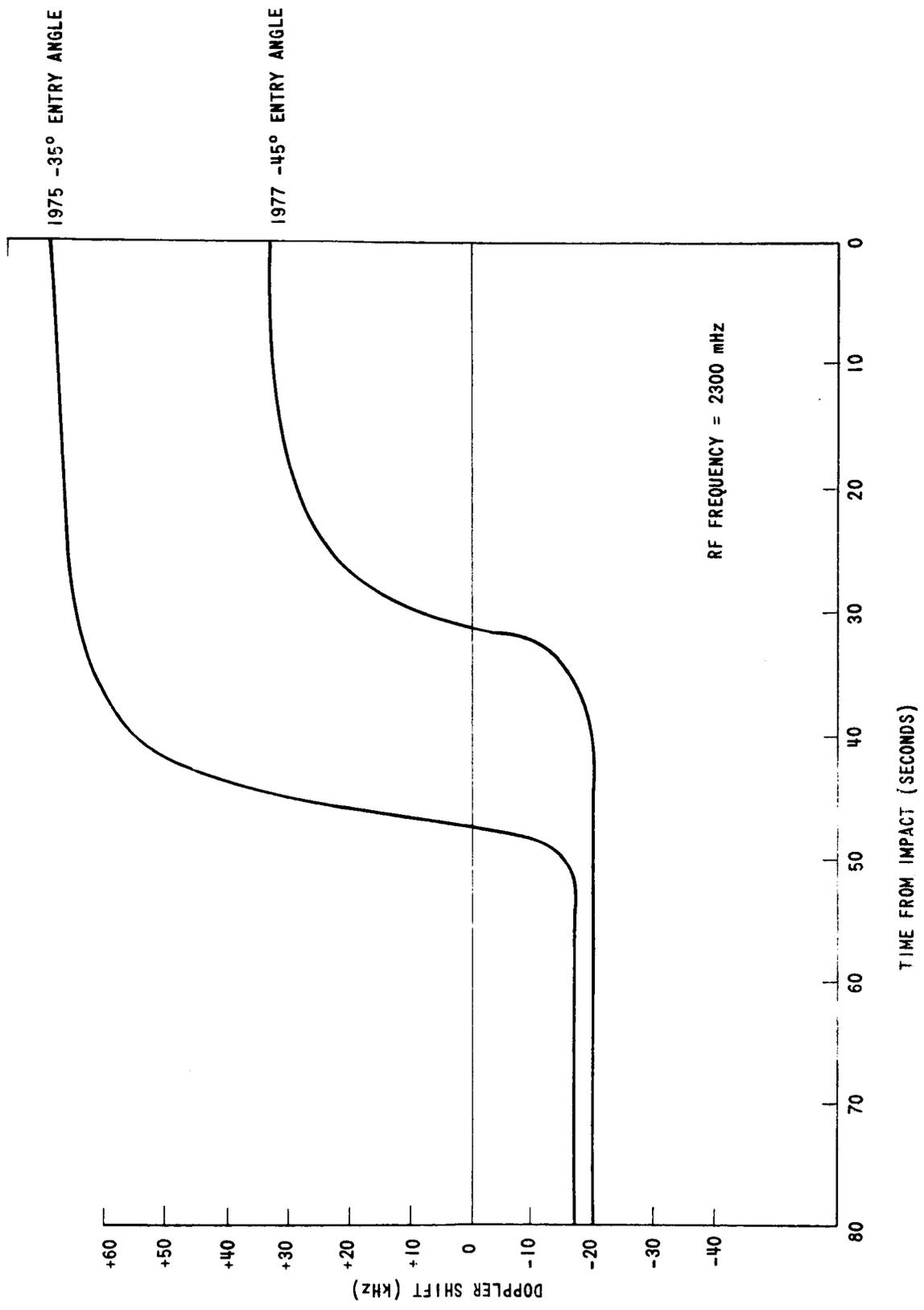|	
Limiter Bandwidth, ranging channel, B_{Rd}	15 kHz
Limiter Bandwidth, carrier channel, B_{Rd}	14 kHz
PLL Threshold Bandwidth, $2B_{Lo}$	280 Hz
Carrier channel performance requirement at limiter input $(S/N)_{cd}$	−3.4 dB
Ranging channel performance requirement at limiter input $(S/N)_{Rd}$	−13.8 dB

Atmospheric Drag Probe

Limiter Bandwidth, ranging channel, B_{Ru}	15 kHz
Limiter Bandwidth, carrier channel, B_{cu}	10 kHz
PLL Threshold Bandwidth, $2B_{Lo}$	200 Hz
Carrier channel performance requirement at limiter input $(S/N)_{cu}$	−3.4 dB

1975 -35° ENTRY ANGLE

1977 -45° ENTRY ANGLE

RF FREQUENCY = 2300 mHz

TIME FROM IMPACT (SECONDS)

DOPPLER SHIFT (kHz)

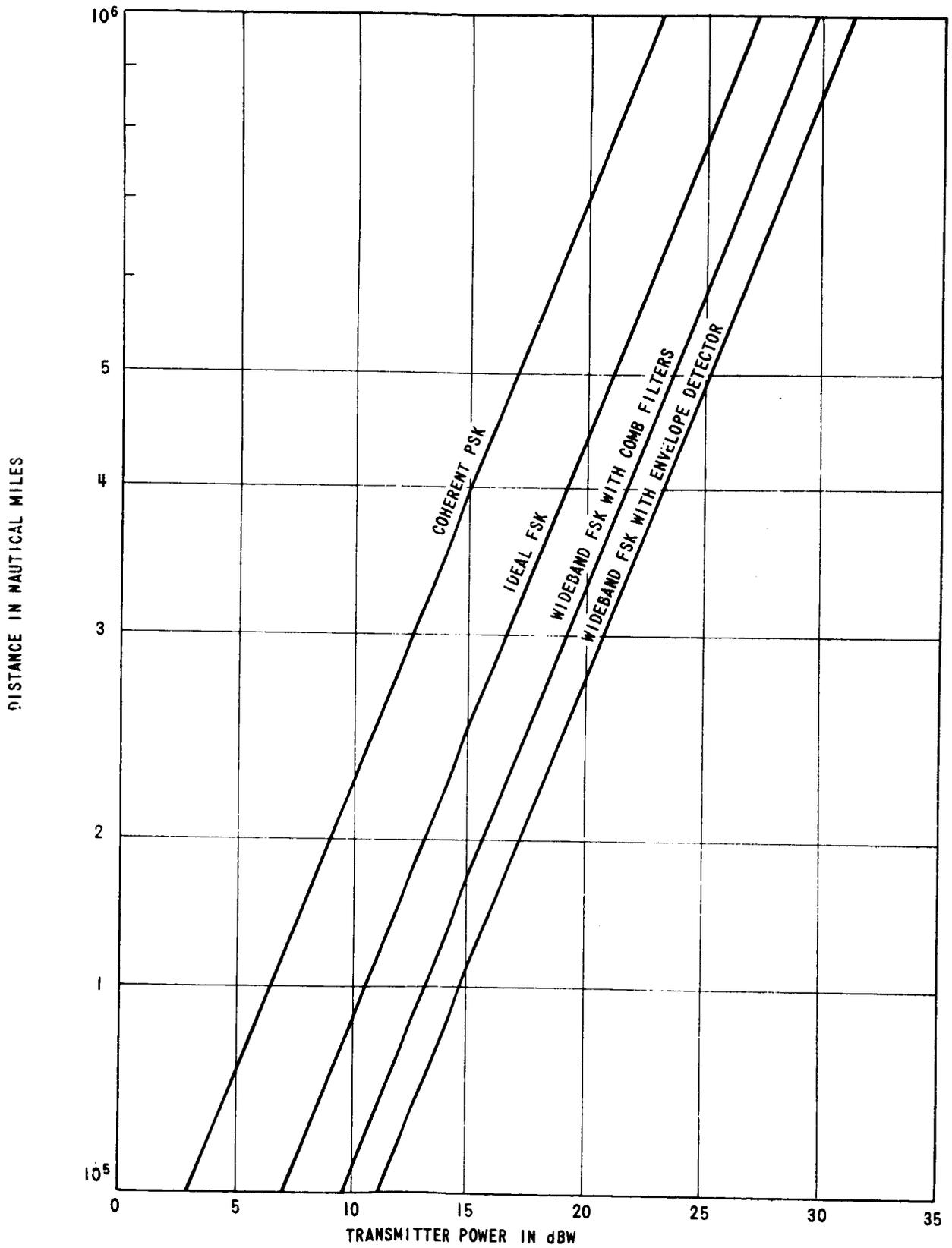FIGURE 1. DOPPLER FREQUENCY PROFILE FOR ADP-MM LINK

FIGURE 2 - ADP TRANSMITTER POWER REQUIREMENT FOR ONE-WAY DATA TRANSMISSION
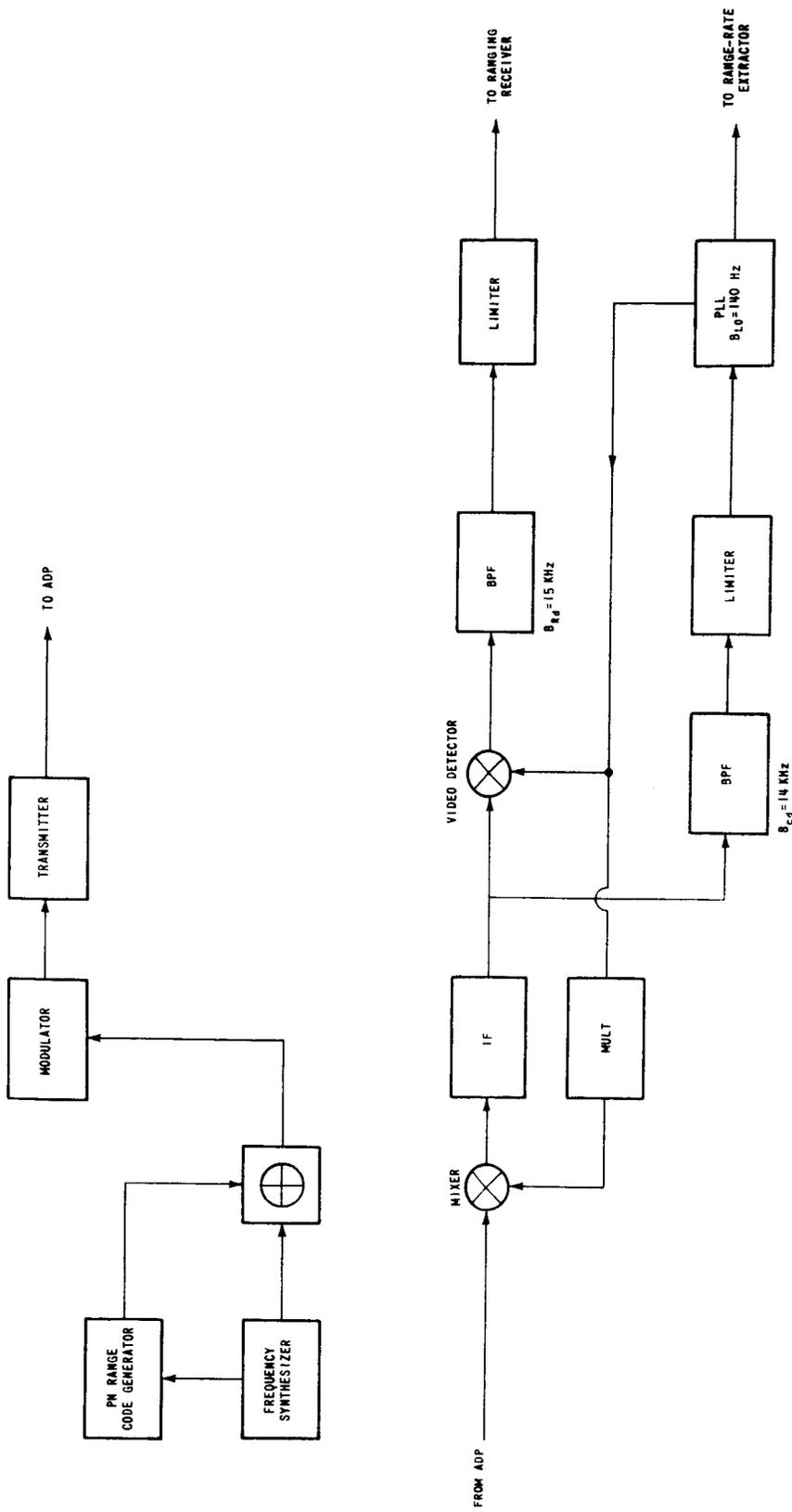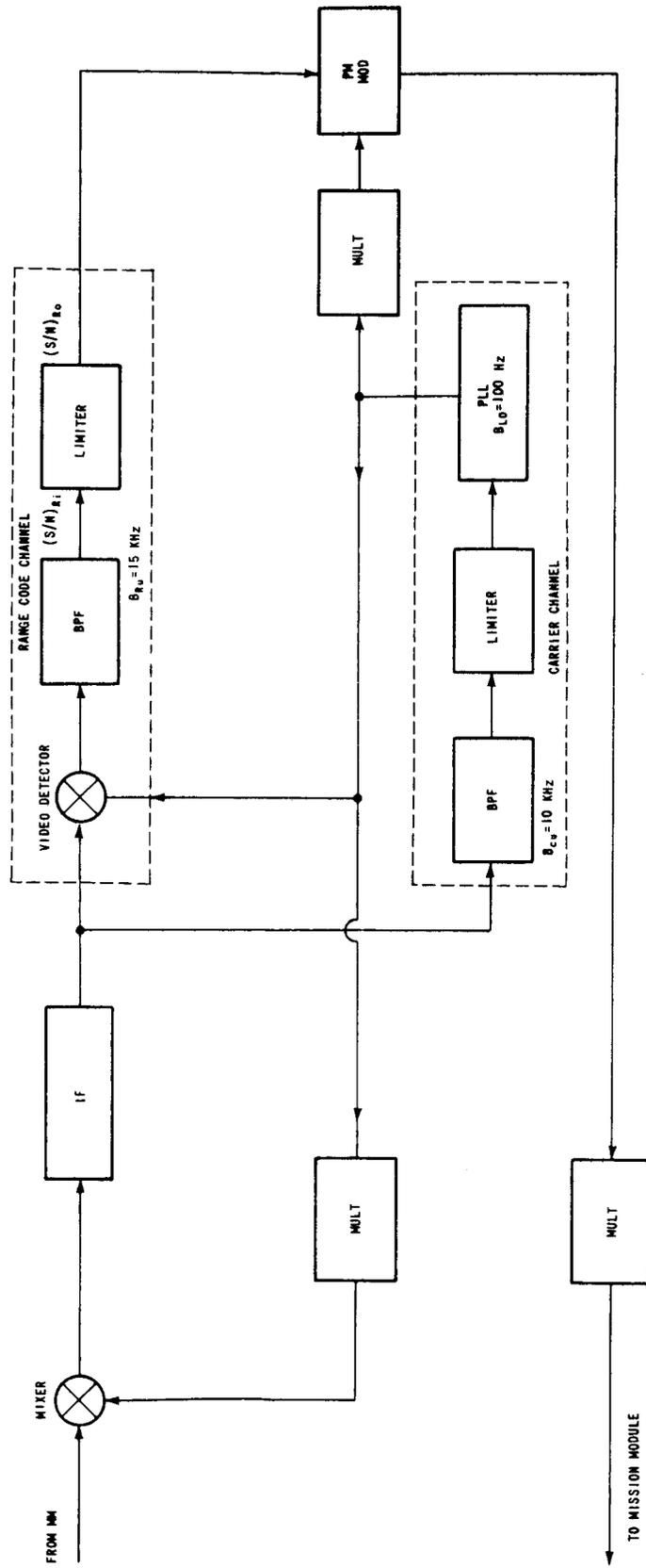
FIGURE 3 - TRACKING SYSTEM FOR MM

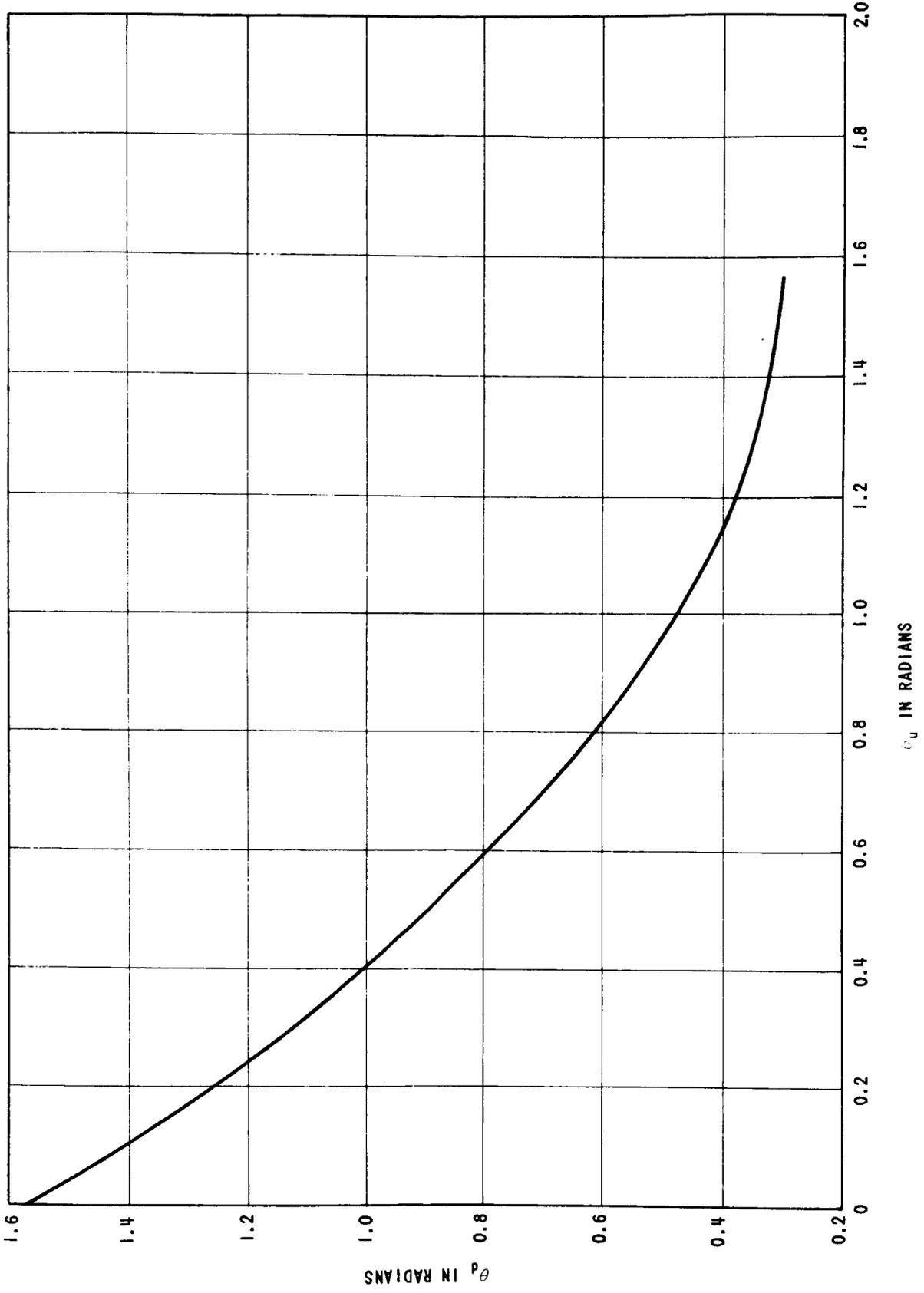FIGURE 4 - TWO WAY COHERENT RANGE & RANGE RATE TRANSPONDER FOR ATMOSPHERIC DRAG PROBE

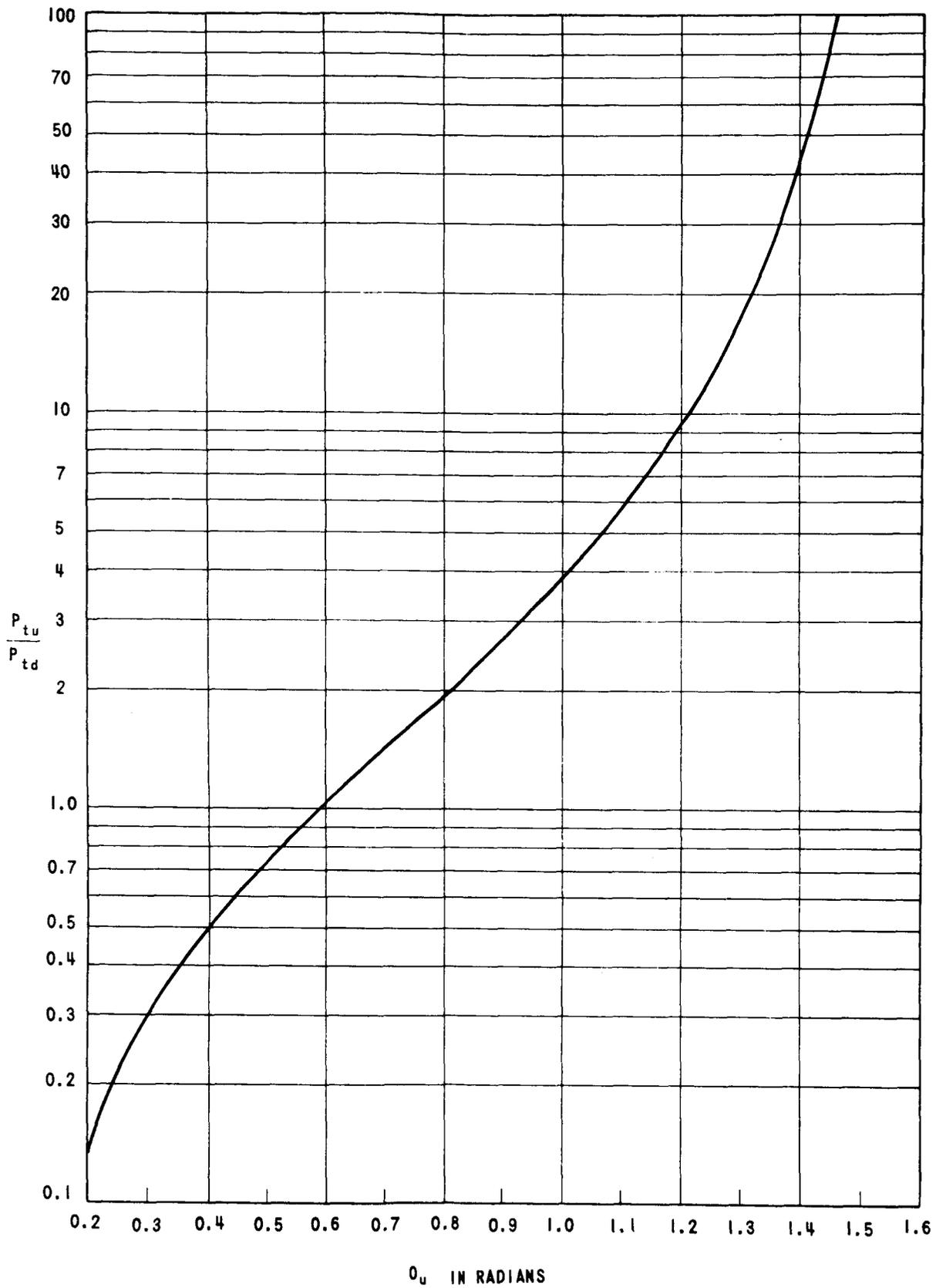FIGURE 5 - FUNCTIONAL RELATION OF OPTIMIZED UP AND DOWN LINK MODULATION INDICES

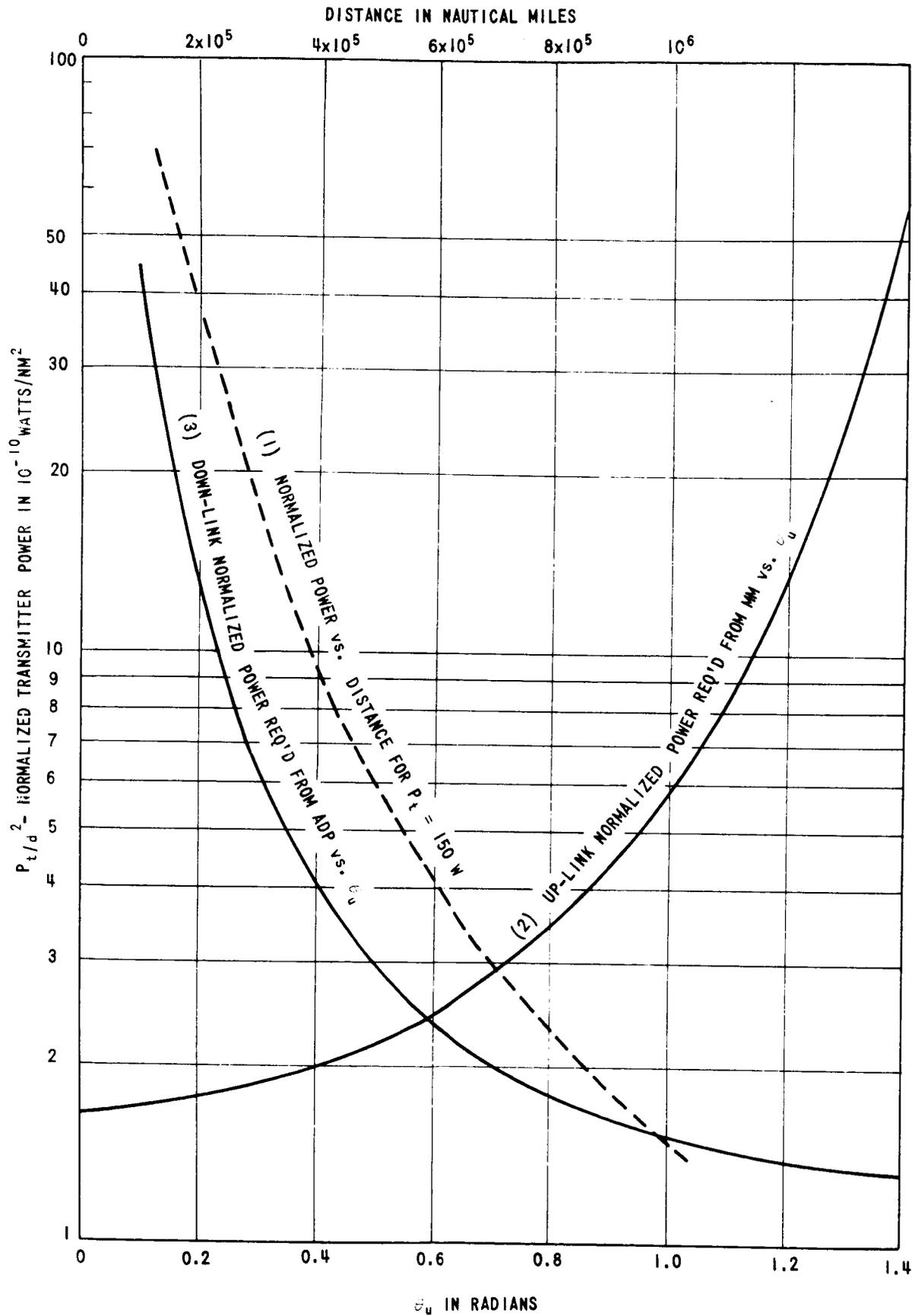FIG. 6 UP AND DOWN LINK TRANSMITTER POWER RATIO

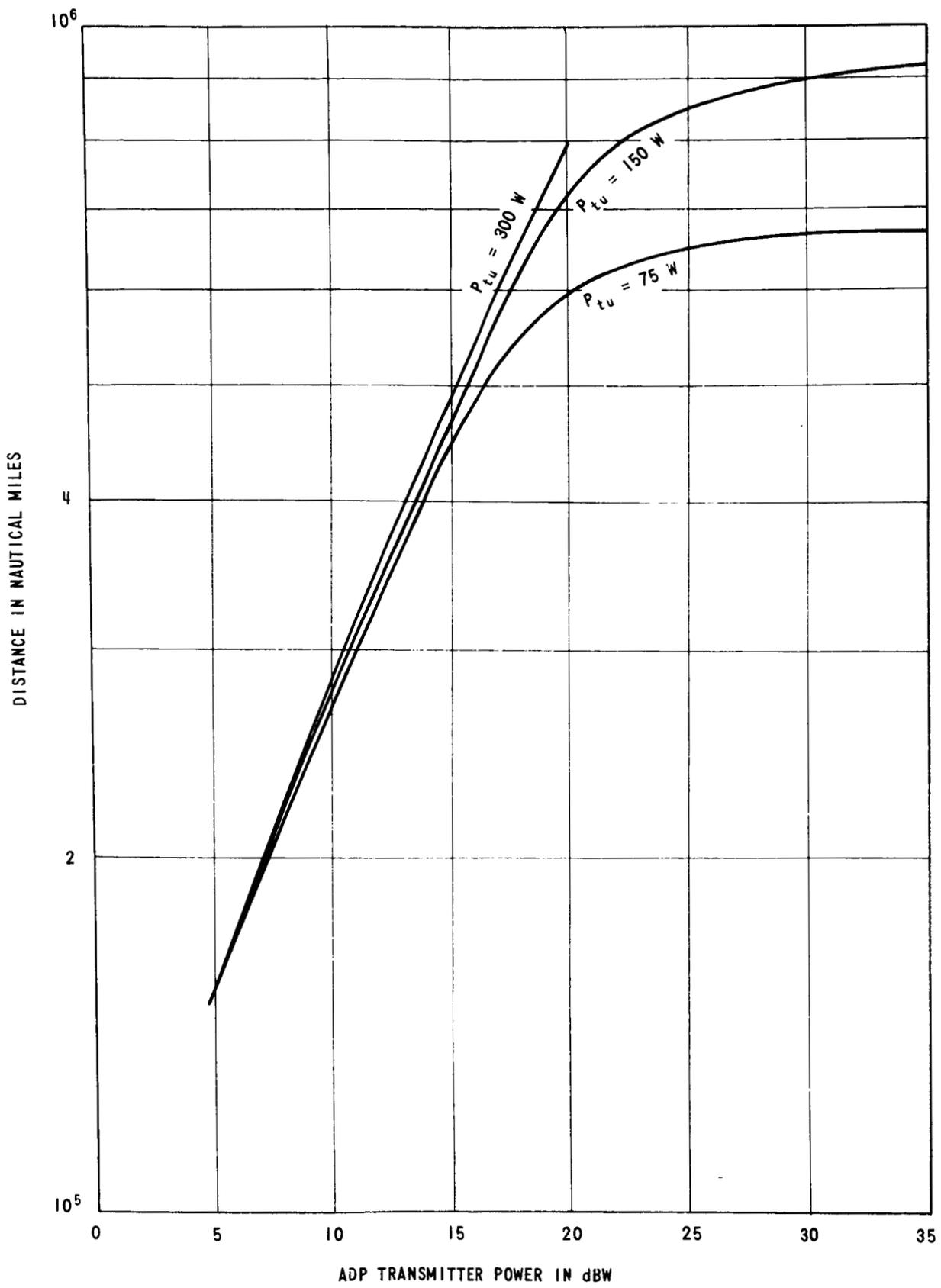FIGURE 7 - TRANSMITTER POWER REQUIREMENTS

FIGURE 8 - ADP TRANSMITTER POWER REQUIREMENT

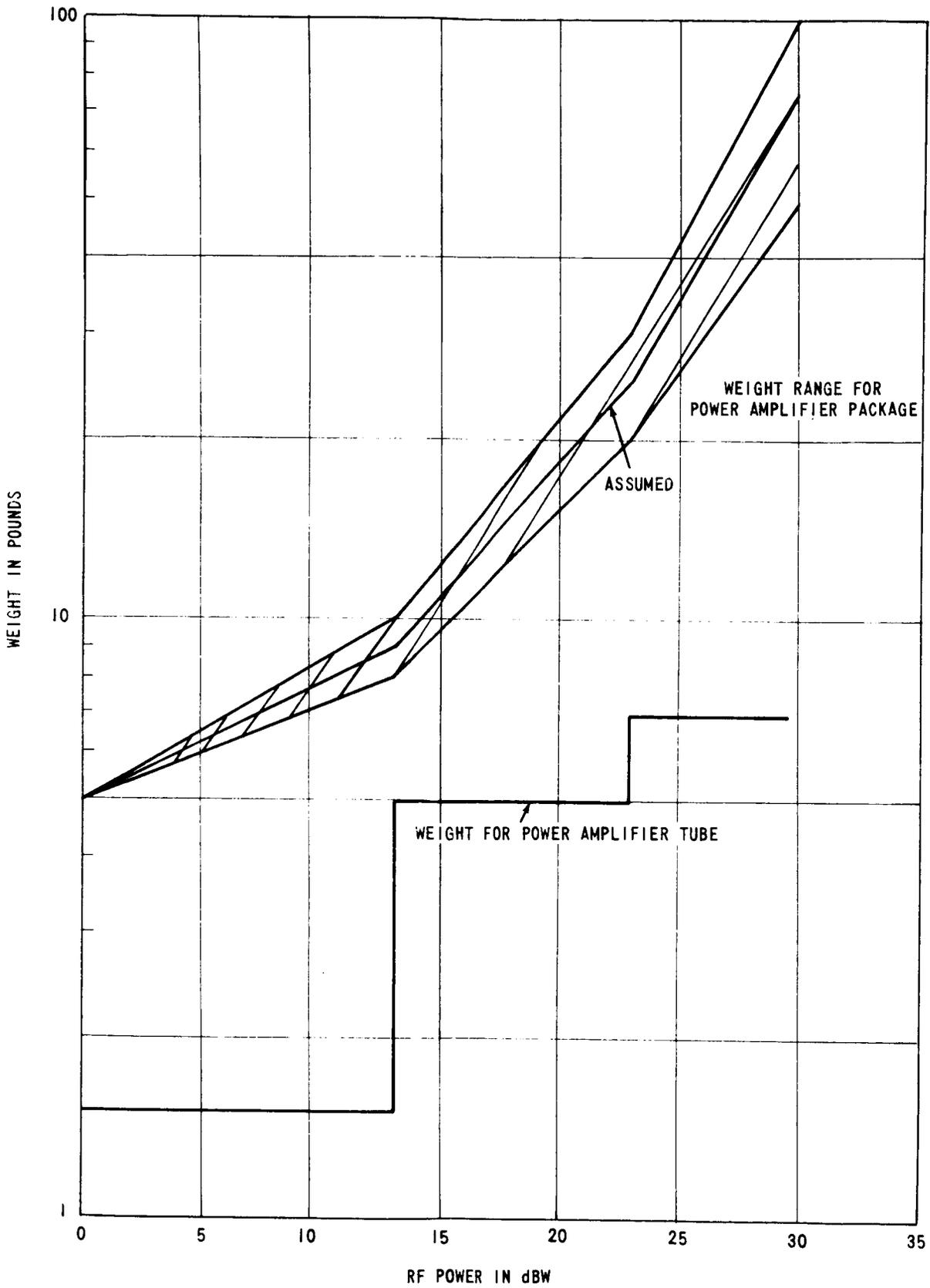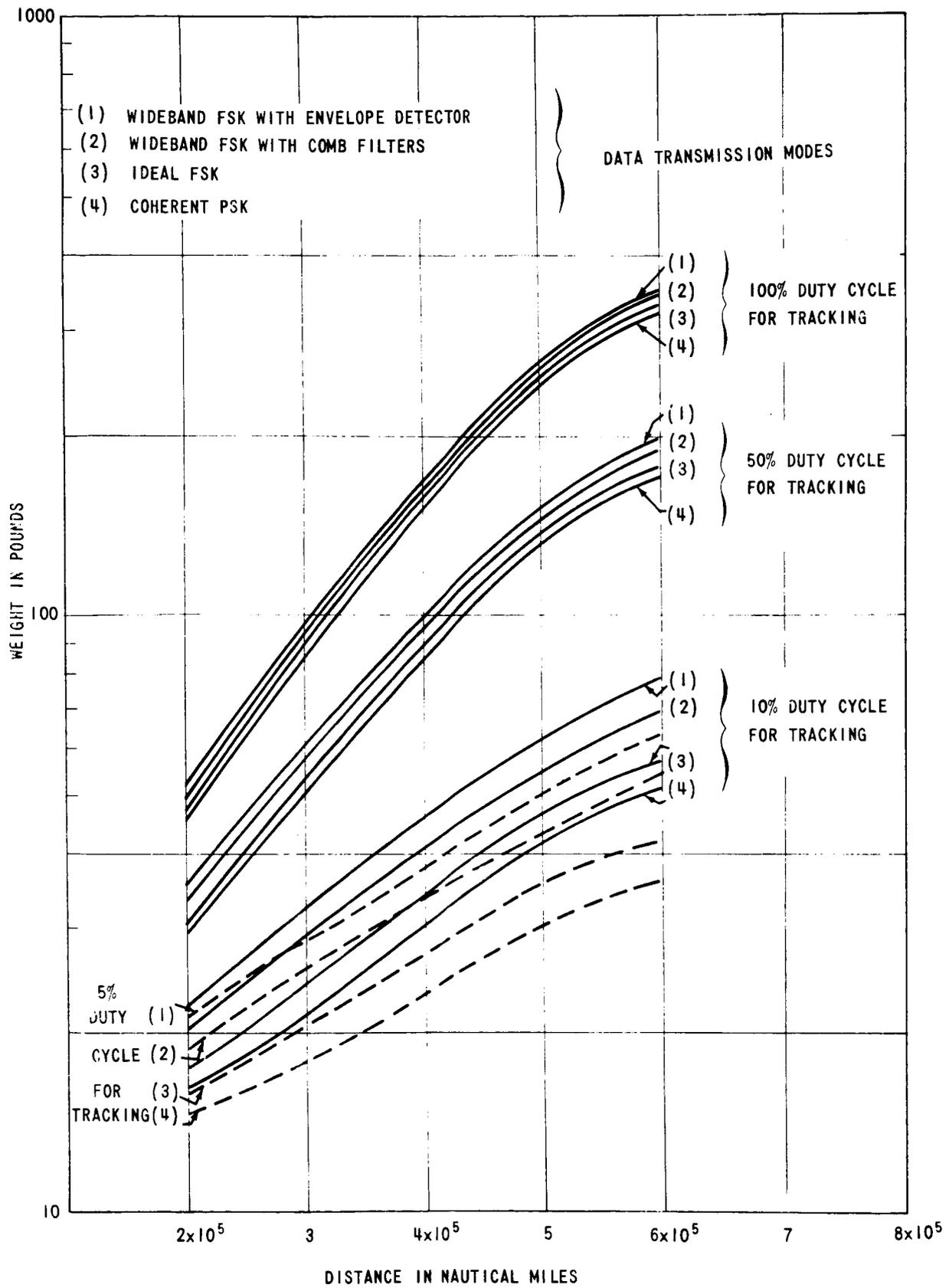FIGURE 9 - WEIGHT ESTIMATE FOR TUBE TYPE RF POWER AMPLIFIERS

FIGURE 10 - ADP COMMUNICATION SYSTEM WEIGHT

APPENDIX A

Two-way Coherent Tracking System Analysis

Figures 3 and 4 provide the simplified block diagrams of the system to be analyzed. The RF transmission equation can be expressed as:

$$P_r = \frac{P_t \, G_t \, G_r}{6,000 \, f^2 \, d^2 \, L_{syst}} \qquad (A-1)$$

where: P_r = total received power

P_t = transmitted power

G_t = transmitting antenna gain

G_r = receiving antenna gain

f = RF frequency in MHz

d = distance in nm

L_{syst} = Combined system losses.

P_r, the total received power, has to satisfy the communication channel requirements for range (ranging channel), and range-rate (carrier channel) functions as follows:

$$(S/N_0)_R = \frac{P_r \, L_r \, \alpha_r}{K \, T_{eff}}, \text{ and} \qquad (A-2)$$

$$(S/N_0)_c = \frac{P_r \, L_c \, \alpha_c}{K \, T_{eff}} \qquad (A-3)$$

where: $(S/N_0)_R$ = Signal-to-noise spectral density ratio required for the ranging channel.

$(S/N_0)_c$ = Signal-to-noise spectral density ratio required for the carrier channel.

L_c & L_R = the ratio of power in the carrier channel and ranging channel, respectively, to the total power received.

α_c & α_R = S/N degradation from the limiter stage of the carrier channel and ranging channel, respectively, it is approximated by $(1 + 2SNR_i)/(4/\pi + SNR_i)$, where SNR_i is the S/N at the limiter input.

Equations (A-2) and (A-3) can be altered to:

$$(S/N)_R = \frac{P_r \, L_R}{K \, T_{eff} \, B_R} \text{, and} \qquad\qquad (A-4)$$

$$(S/N)_c = \frac{P_r \, L_c}{K \, T_{eff} \, B_c} \qquad\qquad (A-5)$$

where: $(S/N)_R$ and $(S/N)_c$ are the signal-to-noise ratio required at the input of the limiter stage for the ranging channel and carrier channel, respectively.

B_R and B_c are the input noise bandwidth of the limiter stages of the ranging channel and carrier channel, respectively.

Since a two-way coherent system is involved, the down link (ADP to MM) performance is affected not only by the parameters associated with the down-link but those of the up-link (MM to ADP) as well. The exact analysis for the optimal design of such a system is not trivial and, to the best of our knowledge, has yet to be published. W. C. Lindsey of the Jet Propulsion Laboratory (JPL) has published several articles related to the subject matter[10][11][12] which provide some insight to the nature of the problems involved. A detailed treatment of the analysis is beyond the scope of the discussion here; instead, an approximate approach is used on the basis of reasonable assumptions which simplify the calculations for system evaluations.

The heart of the system design is the phase lock loops (PLL) in the ADP and the MM. They serve the following functions:

1.   They generate replicas of the received RF carriers to facilitate doppler frequency extraction, and therefore, measure the range-rate between the ADP and MM.

2.   In addition, the replica frequencies generated also maintain phase coherency with the received carriers. Therefore,

the replica in the MM can be used as the reference frequency for coherently demodulating the received signal (in this case, the ranging channel).

The operating environment and requirements dictate the design of the PLL's. Briefly, for the application needed here, the major design considerations are:

   1.   The expected rate of change of the doppler frequency between the ADP and MM, and

   2.   The acceptable length of time for achieving two-way frequency lock (acquisition).

      Without going into the detailed procedures for the design of PLL, which is also a non-trivial subject, material from References 13 and 14 is used to calculate the parameters of a second order PLL whose characteristics are compatible with the following RF link parameters taken from Fig. 1:

	ADP	MM
Maximum Doppler Rate	13 kHz/Sec	26 kHz/Sec
Maximum Doppler Range	20 kHz	40 kHz
Oscillator Drift (Assumed)	2×10^{-6} max.	2×10^{-6} max.

The range of doppler frequency is purposely restricted as we are assuming that the last range and range-rate reading would be taken sometime between 40-50 seconds before the ADP impacts the surface of Mars. This is dictated by the assumption that, during the same period, the onset of the RF blackout occurs. The parameters for the PLL's are:

	ADP	MM
Noise Bandwidth at threshold*$(2B_{Lo})$	200 Hz	280 Hz
Input Bandwidth of limiter stage (B_c)	10 kHz	14 kHz
Damping Factor at threshold (ξ_o)	0.707	0.707
Maximum rate of sweep frequency used for acquisition		8.3 kHz/sec.

The acquisition time for two-way frequency lock is approximately 11 seconds.

---

*Threshold is defined as S/N = 1 in $2B_{Lo}$ bandwidth.

For the determination of the maximum rate of change of the sweep frequency used for acquisition, it is assumed that a 6 dB signal-to-noise ratio exists in the PLL (SNR_L). It can be shown that the equivalent noise bandwidth ($2B_L$) of the PLL at this signal level is 2.55 times greater than its threshold bandwidth ($2B_{Lo}$). Therefore, for this particular PLL design, the performance requirements for the carrier channel are as follows:

For ADP

$$(S/N_0)_{cu} = SNR_L \times 2.55 \times 2B_{Lo} = 33 \text{ dB-Hz}$$

For MM

similarly, $(S/N_0)_{cd} = 34.5$ dB-Hz .

Since the noise in the up-link carrier channel will be turned around through the ADP transponder and will appear as modulation on the down-link carrier, each link individually will need to be 3 dB better in performance, which leads to the following channel requirements:

$$(S/N_0)_{cu} = 36 \text{ dB-Hz} \qquad \text{or} \qquad (S/N)_{cu} = -3.4 \text{ dB}$$

$$(S/N_0)_{cd} = 37.5 \text{ dB-Hz} \qquad \text{or} \qquad (S/N)_{cd} = -3.4 \text{ dB}$$

and from Sec. IV.:

$$(S/N_0)_{Rd} = 27 \text{ dB-Hz} \qquad \text{or} \qquad (S/N)_{Rd} = -13.8 \text{ dB}.$$

The only remaining performance requirement that has not been determined is the signal-to-noise spectral density ratio required for proper operation of the ranging channel at the ADP, $(S/N_0)_{Ru}$. This requirement taken with the carrier channel requirement dictates the allocation of transmitted RF power to the carrier and ranging channels. From equations (A-2) and (A-3) or (A-4) and (A-5), it is seen that parameters L_R and L_c play an important role in determining the transmitter power requirements. For a given design, these parameters are related to the modulation methods chosen and, in the case of a two-way coherent system, also relate to the signal-to-noise ratio at the signal turn-around point as seen in the following expressions:

$$L_{cd} = \cos^2 \theta_d \tag{A-6}$$

$$L_{Rd} = \sin^2 \theta_d \, L_s \tag{A-7}$$

$$L_{cu} = \cos^2 \theta_u \tag{A-8}$$

$$L_{Ru} = \sin^2 \theta_u \tag{A-9}$$

where: L_c & L_R are defined previously, the additional subscripts, u and d, denote the up-link and down-link differences.

θ's are the modulation indices for the range code subcarrier and the subscripts differentiate the up and down links.

The term L_s is assoicated with the limiter characteristics of the ranging channel in the ADP. It is the ratio of signal power at the limiter output (S_{Ro}) to the input signal power (S_{Ri}) of the limiter, and is approximated by:

$$L_s = \frac{S_{Ro}}{S_{Ri}} = \frac{(S/N)_{Ru}}{4/\pi + (S/N)_{Ru}} \tag{A-10}$$

where: $(S/N)_{Ru}$ is the signal-to-noise ratio at the input of limiter stage in the ranging channel of ADP.

Substituting equations (A-6)-(A-10) into equations (A-4) and (A-5):

$$(S/N)_{Ru} = \frac{P_{ru} \sin^2 \theta_u}{N_{0u} B_{Ru}} \tag{A-11}$$

$$(S/N)_{cu} = \frac{P_{ru} \cos^2 \theta_u}{N_{0u} B_{cu}} \tag{A-12}$$

$$(S/N)_{Rd} = \frac{P_{rd} \sin^2 \theta_d \, L_s}{N_{0d} B_{Rd}} \tag{A-13}$$

$$= \frac{P_{ru} \sin^2 \theta_u \, P_{rd} \sin^2 \theta_d}{N_{0d} B_{Rd} (4/\pi N_{0u} B_{Ru} + P_{ru} \sin^2 \theta_u)} \tag{A-14}$$

$$(S/N)_{cd} = \frac{P_{rd} \cos^2 \theta_d}{N_{0d} B_{cd}} \tag{A-15}$$

where: $N_0 = K\ T_{eff}$.

     The full impact of the interrelation between the up and down links is now clearly seen from equation (A-14). It is also apparent that four parameters, the up and down link modulation indices of the ranging subcarrier, and the up and down link transmitter power are subjected to tradeoff considerations. One of the criteria used for tradeoff is to optimize the modulation indices so that the division of power among the carrier and ranging channels would reach the minimum required performance simultaneously at a certain maximum communication distance for both links.

     The functional relation between the optimized up and down link modulation indices is obtained by combining equations (A-13)-(A-14) and (A-10)-(A-12):

$$\mathrm{Cot}^2\theta_d = \frac{\mathrm{Tan}^2\theta_u (S/N)_{cu} B_{cu} (S/N)_{cd} B_{cd}}{(S/N)_{Rd} B_{Rd} [4/\pi x B_{Ru} + (S/N)_{cu} \mathrm{Tan}^2\theta_u]} \quad . \tag{A-16}$$

Inserting the known parameters from Table III:

$$\mathrm{Cot}^2\theta_d = \frac{10\ \mathrm{Tan}^2\theta_u}{4.17 + \mathrm{Tan}^2\theta_u} \quad . \tag{A-17}$$

The results are given in Fig. 5, which shows that for a given up-link modulation index, the down-link modulation index must be that indicated for optimal performance of both up and down links.

     For every set of θ_d and θ_u, the required total RF received power, P_{rd} and P_{ru}, can be determined from equations (A-12) and (A-15). The received power is related to the transmitted power by equation (A-1). Combining these, the expressions for required transmitter power become:

$$P_{tu} = M\ \frac{(S/N)_{cu} N_{0u} B_{cu} 6{,}000\ f^2\ d^2\ L_{syst}}{G_t\ G_r\ \mathrm{Cos}^2\theta_u} \tag{A-18}$$

$$P_{td} = M\ \frac{(S/N)_{cd} N_{0d} B_{cd} 6{,}000\ f^2\ d^2\ L_{syst}}{G_t\ G_r\ \mathrm{Cos}^2\theta_d} \tag{A-19}$$

where M is the added margin.

Inserting the known values of the parameters from Table III into (A-18) and (A-19) yield:

$$P_{tu} = \frac{1.68 \times 10^{-10} d^2}{\cos^2\theta_u} \quad , \quad \text{and} \tag{A-20}$$

$$P_{td} = \frac{1.18 \times 10^{-10} d^2}{\cos^2\theta_d} \quad . \tag{A-21}$$

The ratio of equations (23) and (24),

$$P_{tu}/P_{td} = 1.42 \cos^2\theta_d/\cos^2\theta_u \quad , \tag{A-22}$$

provides the relative tradeoff criterion for the up and down link transmitter power. Equation (A-22) is plotted in Fig. 6 using the up-link modulation index as the independent parameter. The absolute transmitter power requirements for both up and down links are plotted in Fig. 7 as curves (2) and (3), again, using the up-link modulation index as the independent parameter. It should be noted in Fig. 7 that instead of power, a normalized parameter P_t/d^2 is used with the dimension of power per unit distance squared, watt/nm^2, this should not be confused with the well known power density term which also has the same unit but has an entirely different physical meaning.

BELLCOMM, INC.

REFERENCES

1. F. G. Allen, et. al., "Experiment Payloads for a Manned Mars Flyby Mission," Bellcomm Technical Report #TR-67-233-1, May 15, 1967.

2. E. M. Grenning, "Interim Mission Sequence Plan for the Encounter Portion of the 1975 Manned Mars Flyby Mission," Bellcomm Memorandum for File, June 15, 1967.

3. R. K. Chen and R. L. Selden, "Communication Systems Design for Manned Mars Flyby Mission," Bellcomm Technical Memorandum #TM-66-2021-8, July 29, 1966.

4. Private communication with Mr. P. W. Huber of Langley Research Center, October 26, 1967.

5. L. Schuchman, "Wideband Detection of MFSK Transmission in a Two-Path/Multipath Channel," Philco Ford Corporation, Technical Memorandum #SRS TM-119, July 14, 1967.

6. "LM Relay Experiment Study - Final Report," Motorola Company Report #3347-3, October 9, 1967.

7. R. K. Chen, "Preliminary Communication System Design for the Ascent and Rendezvous Phases of a Manned Mars Landing Mission," Bellcomm Memorandum for File, June 29, 1967.

8. Private communication with Mr. P. S. Schaenman of Bellcomm, December 15, 1967.

9. R. C. Shair, et. al., "A Review of Batteries and Fuel Cells for Space Power Systems," Journal of Spacecraft and Rockets, July, 1967.

10. W. C. Lindsey, "Optimal Design of One-Way and Two-Way Coherent Communication Links," IEEE Transactions on Communication Technology, August, 1966.

11. W. C. Lindsey, "Error Rates in Phase Coherent Systems with Band Pass Limiters," JPL Space Programs Summary, No. 37-45, Volume IV.

12. W. C. Lindsey, "The Effects of Radio Frequency (RF) Timing Noise in Two-Way Communication Systems," JPL Space Programs Summary, No. 37-32, Volume IV.

13. F. M. Gardner, "Phase Lock Techniques," John Wiley & Sons, Inc., New York, 1966.

14. R. C. Tausworthe, "Theory and Design of Phase-Locked Receivers," Volume I, JPL Technical Report No. 32-819, February 15, 1967.