Power Combining Considerations for Prometheus TWTAs

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Introduction

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NASA and L-3 have, however, jointly developed a 100 W, 32 GHz TWT[1], and are currently developing a 180 W TWT that should be extendable to 250-300 W with a subsequent iteration. By combining four of these 250 W devices, the required 1 kW output can be obtained while still using devices (TWTAs) that have a long heritage of successful space-borne deployment. JIMO is planning to perform the combining spatially using a cluster antenna (i.e., multiple emitters)[2]. This approach offers several advantages over waveguide combining or a single high power device as initially considered; among them are the possibility of electronic beam steering and reduced susceptibility to multipaction and/or RF breakdown. Figure 1 is an artist's conception illustrating a four-cluster antenna.

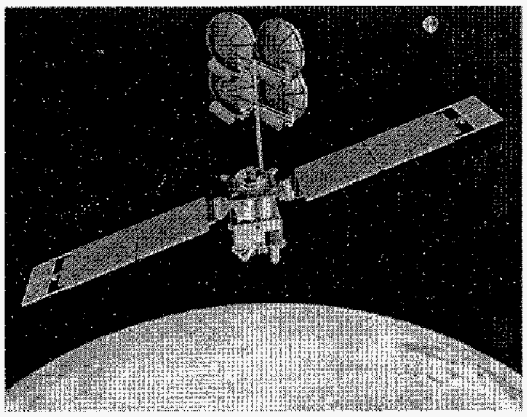

Figure 1. Artist's conception of a cluster antenna on Mars Global Surveyor

Maximum power output obviously requires minimization of phase and amplitude errors in the four signal paths. This paper presents a quantification of the expected combining errors due solely to effects within the TWTAs themselves (i.e., ignoring other potential errors in the signal paths) and attempts to predict the expected result from the combination of four devices.

Analysis of Spatial Power Combining

For the spatial superposition of four carriers of differing magnitudes and phases, electric field as function of time is

$$E(t) = A \sin(\omega t) + B \sin(\omega t + \phi_1) + C \sin(\omega t + \phi_2) + D \sin(\omega t + \phi_3)$$

where the magnitudes of the four carriers are given by A, B, C, and D, and the phases of carriers two, three, and four are referenced to the phase of the first carrier. Power is proportional to the mean squared electric field computed over one cycle by

$$< E^2 > = \int_0^T E^2(t)dt \Big/ \int_0^T dt$$

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Nominal power occurs when all carriers are of equal magnitude, A, and all relative phases are zero, which gives

$$< E^2 >_{nom} = 8 A^2$$

We will express the change in relative power output due to variations in phase and amplitude as

$$P_{rel} = < E^2 > / < E^2 >_{nom}$$

If we normalize the magnitude of three of the carriers relative to the first such that

$$B = bA, \ C = cA, \text{ and } D = dA$$

then the variation can be expressed as

$$P_{rel} = (1/8) [\ \tfrac{1}{2} (1 + b^2 + c^2 + d^2) + b \cos \phi_1 + c \cos \phi_2 + d \cos \phi_3 + bc \cos (\phi_1 - \phi_2) + bd \cos (\phi_1 - \phi_3) + cd \cos (\phi_2 - \phi_3) \ ]$$

To estimate the effects of these variations on the combined output power, we must first estimate the possible range of the phase errors and amplitude variations.

Expected Range of Phase and Amplitude Variations from TWTAs

Phase errors and amplitude variations in a TWTA derive primarily from two effects. The first is cathode voltage and/or current changes in the TWTA power supply, also known as the electronic power conditioner or EPC, due to aging and drift effects. If the EPC allows the cathode voltage to change, the phase of the TWT will change by an amount given by cathode phase pushing factor which is typically on the order of 1°/volt. Additionally, voltage and/or current changes will directly affect RF output power. The second primary effect is gain changes in the TWT as the tube ages[3]. Neither of these underlying effects can be modelled from first principles, but they can be estimated from empirical observations obtained over many years of TWTA production and life testing. These estimates for EPC aging and drift effects are the same values used for EPC worst case analyses and are well-accepted throughout the industry. TWT gain changes with life are less well known and are therefore subject to greater uncertainty.

Using the 180 W 32 GHz TWT that is under development (the L-3 999HA) as a

proxy for a future 250 W TWT, we applied these estimates of power supply drift and TWT gain changes to a model of that TWT created using the Naval Research Laboratory TWT design code, CHRISTINE 3-D[4] to determine the predicted effect on TWTA phase shift and power output. We also assumed that the input RF drive levels would be adjusted to maintain the TWTAs close to saturation. We analyzed two cases:

The first case considered was for a five year TWTA lifetime; this reflects the probable JIMO mission usage. The 32 GHz link will only be used to transmit science data gathered once the spacecraft reaches the Jovian moons. The TWTAs may be periodically turned on for health checks during the Earth-Jupiter cruise phase of the mission; but in general, there will be no need for any high-rate data transmission during this time frame. The second case considered was for a 20 year TWTA lifetime; this represents the maximum TWTA lifetime that can be reasonably conceived for any mission.

We assumed that the underlying EPC variations and TWT aging parameters are random and normally distributed. Our modeling then predicted relative phase variations of ±8.6° for the five year case and ±20.6° for the 20-year case. Predicted amplitude variations were +0.068 dB ± 0.02 dB and +0.13 dB ± 0.03 dB, respectively. The slight net increase in output power is due to TWT gain changes (and assuming that the EPC has a servo loop to hold cathode current constant). There is also a net change in TWT phase shift, but this constant phase offset of all four devices will not affect power combining and can be ignored.

Resulting Power Combining Losses

What will actually ensue for any four power-combined TWTAs can only be statistically predicted by a distribution function of possible outcomes based on the phase and amplitude variations just discussed. Consequently, we performed a Monte Carlo analysis of the power combining losses from four TWTAs using the expression above for relative power as a function of these phase and amplitude variations. Histograms of the results of five million trials are shown in Figure 2 for the two TWTA lifetimes. The histograms have been normalized to occupy unity area and, as such, can be interpreted as relative distribution functions of the expected combining losses.

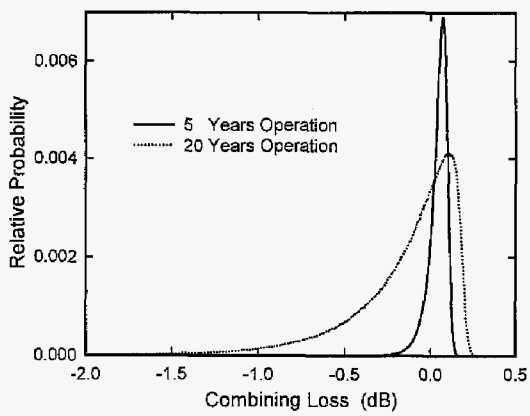

Figure 2. Histogram of Monte Carlo trials

Table 1 is a tabulation of the results showing the best case, worst case, mean, and standard deviation of the results. Note that the worst-case result tabulated is a single result of five million trials and really should be considered to be just an artifact of the calculation, not something expected to occur in practice.

Of more interest for determining link margin and availability is the cumulative distribution function of the simulations,

i.e., the integral of the distribution functions shown in Figures 3a and 3b.

Table 1. Summary statistics of combining losses (dB) from Monte Carlo simulation

	5 Year	20 Year
Best case	0.20	0.29
Mean	0.05	-0.11
Std. Dev	0.01	0.10
Worst case	-0.82	-4.5

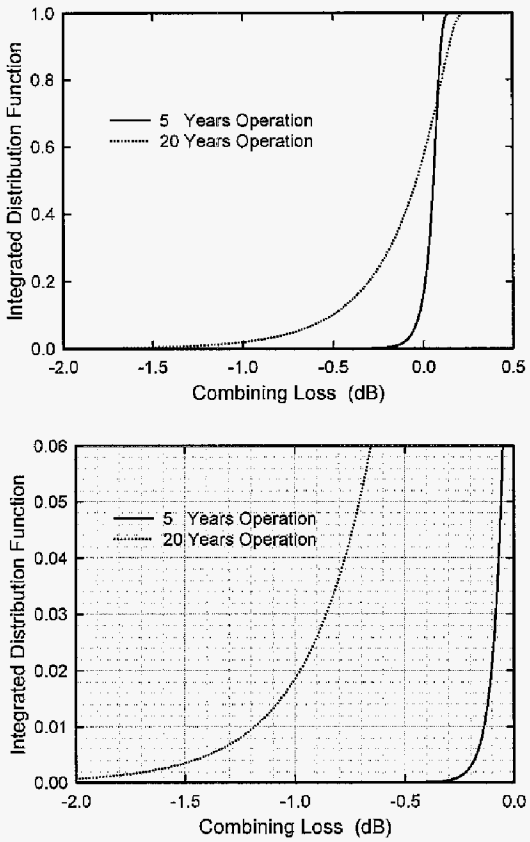

Figure 3a & b. Cumulative distribution function with high loss region expanded

This shows that 95% of the time the loss will be no worse than 0.06 dB for the five years of operation and no worse than 0.7 dB for the 20 years of operation. Link calculations are typically based upon 99% availability. At this level of confidence, the loss will be no worse than 0.14 dB over five years of operation and no worse than 1.2 dB over 20 years of operation. Thus over five years of operation at the 99% confidence level, the output power from four power combined 250 W TWTAs can be estimated to be at least 968 watts.

Conclusion

We have developed a model that statistically predicts the expected total power resulting from spatially power combining the output of four TWTAs. Due to the inability to control phase and amplitude variations of the TWTAs, we predict a mean combining gain of about 0.05 dB over five years of operation and a loss of 0.1 dB for 20 years of operation. Link budget analyses, however, are concerned with the availability of the link; and thus the distribution function of the combining loss is a more meaningful measure of the effects. Our modelling predicts that for the five years of operation required for JIMO, the loss should be no worse than 0.14 dB 99% of the time and no worse than 0.7 dB for a mission requiring 20 years of operation. These losses are purely due to variations within the TWTAs themselves. Other elements in the transmit chain will also contribute to combining errors and must also be considered for any overall link budget calculations.

References

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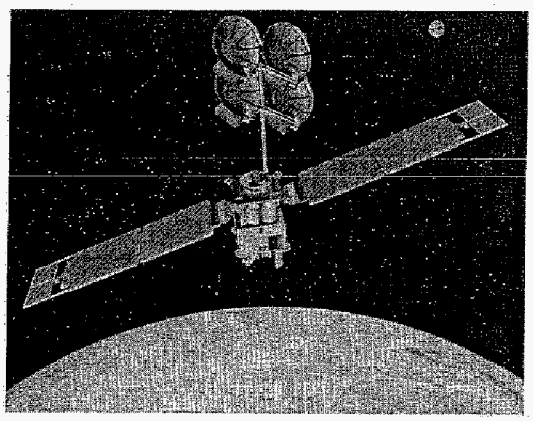

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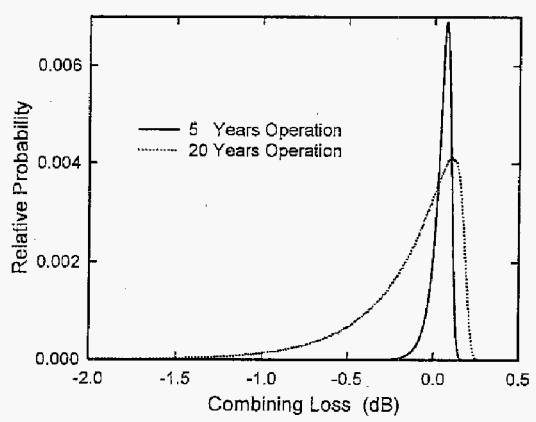

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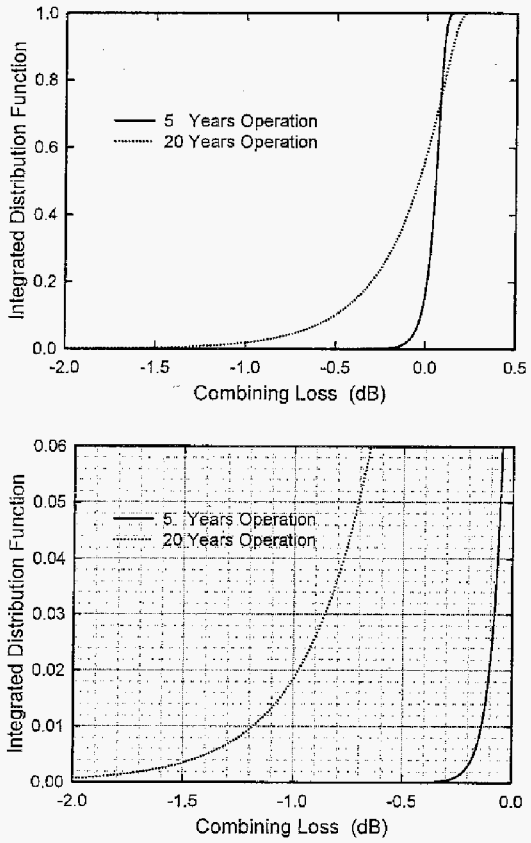

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Expected Range of Phase and Amplitude Variations from TWTAs

We first estimated the possible range of the phase errors and amplitude variations. These variations in a TWTA derive primarily from two effects. The first effect is phase pushing caused by cathode voltage changes in the TWTA power supply due to aging and drift in its component values. The second primary effect is gain change in the TWT as the tube ages[3]. These underlying causes cannot be predicted from first principles, but must be empirically determined.

Knowing the expected power supply drift and TWT gain changes, their combined effects on TWT phase shift and power output were modeled in the Naval Research Laboratory TWT design code, CHRISTINE 3-D[4]. This resulted in predicted maximum phase variations from +17° to -30° and maximum amplitude variations from +0.05 dB to -0.025 dB. We also assumed that the input drive levels would be adjusted to maintain the TWTAs close to saturation.

Resulting Power Combining Losses

These estimates are the maximum values of the expected variation. By definition, these errors are random and their exact values for any TWTA cannot be predicted in advance. What will actually ensue for any particular TWTA can only be statistically predicted by a distribution function of possible outcomes, and the distribution function of the possible combining losses for four

power-combined TWTAs is then determined by the distribution functions of the phase and amplitude variations.

If we assume that the distribution functions of the variations are Gaussian, then the above estimates of the maximum values can be equated to 3σ for each of the distributions. This allowed us to perform a Monte Carlo analysis of the power combining losses from the four TWTAs. A histogram of the results of one million trials is shown in Figure 1 which is an approximate graphical representation of the distribution function of the expected combining losses.

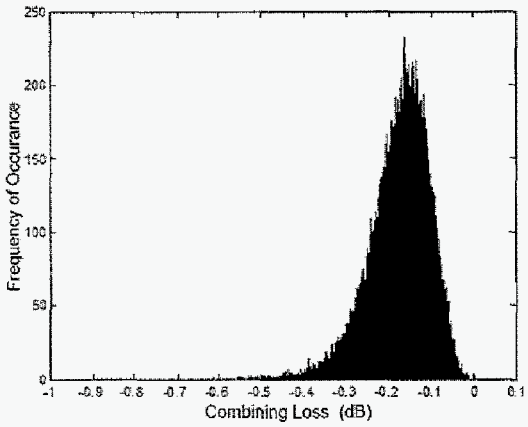

Figure 1. Histogram of Monte Carlo trials

The result is almost completely dominated by the effects of the phase errors. Table 1 is a tabulation of the results showing the least, worst, and average loss due to the two effects and the resultant combination.

Of more interest for determining link margins and link availability is the cumulative distribution function of the simulation shown in Figure 2, *i.e.*, the integral of the distribution function. This shows that 95% of the time the loss will be no worse than 0.3 dB, and that 99% of the time the loss will be no worse than 0.5 dB. Thus at the 95% confidence level, the output power from four power combined 250 W TWTAs can be estimated to be at least 891 watts.

These results will be discussed in detail at the Conference.

Table 1. Summary statistics of losses (dB) from Monte Carlo simulation

	Amplitude Error Only	Phase Error Only	Combined Effect
Least	+0.033	-0.015	-0.006
Mean	0.000	-0.183	-0.174
Worst	-0.013	-0.797	-0.786

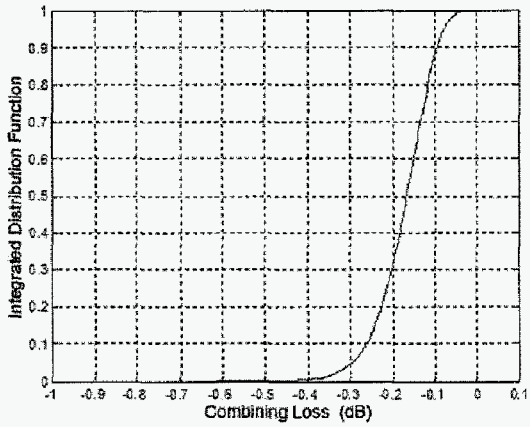

Figure 2. Cumulative distribution function

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