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SPS PHASE CONTROL STUDIES

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1.0 INTRODUCTION

To properly point and form the SPS microwave power beam, the outputs of the power amplifiers in the transmitting array must be phased in a specific and coherent fashion. The purpose of the SPS phase control system is to bring this about reliably.

A number of different phase control schemes can be, and have been, envisioned. The one selected for the SPS baseline system is a retrodirective CW phase conjugating system using a spread spectrum uplink signal and a reference phase signal that is distributed via fiber optics. The basis of this selection is relative technical simplicity and requisite assurance of success.

The operational principle of the retrodirective phase control system is that if a signal $E_{Received}$, described by

$$E_{Received} = \cos (wt + \emptyset_{ref} + \emptyset_{rec}) \qquad (1)$$

is received, a phase conjugated signal

$$E_{Transmitted} = \cos (wt + \emptyset_{ref} - \emptyset_{rec}) \qquad (2)$$

is transmitted. If this is done all over the transmitting aperture, the resulting beam will leave in the inverse direction of the incoming pilot beam.

Problematic technical aspects in implementing the scheme above are that the received and transmitted frequency spectra are dissimilar and that the reference phase $\emptyset_{ref}$ against which the received phase $\emptyset_{rec}$ is measured must be the same all over the transmitting array. (Regarding tolerable systematic phase shift, it may be noted that a phase shift of 3×10^{-2} radians will scan the beam approximately 40 meters.)

Transmitter noise, receiver noise and pilot beam power determine how close the pilot beam frequencies of the spread-spectrum uplink can be to the downlink. Studies at Boeing and elsewhere have yielded values for this offset in the range of 5 to 50 MHz. In the case of the most recent Boeing pilot link study, the network of considerations used was as shown on Figure 1, yielding the characteristics of the final system as a function of transmitting frequency notch filter cutoff frequency f_c, pilot beam receiving aperture and desired signal to noise of the received pilot signal shown on Figure 2.

For accurate pointing it is important that the received pilot signal be scaled to generate the transmitted downlink signal instead of merely translated. I.e., if the downlink frequency is f_0, the pilot frequency is $f_0 + \Delta f = \omega/2\pi$ and the received field is given by Equation (1), the downlink should be:

$$E_{transmitted} = \cos \left[f_o \, (f_o + \Delta f)^{-1} \, (\omega t + \emptyset_{ref} - \emptyset_{rec}) \right] , \qquad (3)$$

instead of

$$E_{transmitted} = \cos \left[(\omega - 2\pi\Delta f)t + \emptyset_{ref} - \emptyset_{rec} \right] . \qquad (4)$$

The reason for this is that if frequencies are not scaled but translated by some amount Δf, the transmitted beam is incorrectly steered off the pilot beam axis by an amount W. W depends on the transmitting aperture tilt θ, the range of R and the transmitting frequency f according to the "squint" formula:

$$W = R\,\theta\,\Delta f\,f_0^{-1}\,. \tag{5}$$

For the baselined spread spectrum pilot signal Δf is effectively 0.

Selection of the specific spread spectrum uplink signal scheme and the decoding of the uplink at the receiver is pending further study of ways to mitigate ionospheric and tropospheric distortions of the uplink wavefront. The basic problem is that the index of refraction in the beam propagation path depends on the atmospheric pressure, composition, temperature and the degree of ionization; and in the troposphere the index of refraction increases with increasing density while in the ionosphere the opposite is true. A secondary problem is geometry: if there is only a single pilot beam just a small central portion of the propagation path through the troposphere and ionosphere is sampled. Finally, the effects of the power beam on the temperature and density of the ionosphere must not interfere with phase control or beam pointing.

The effect of phase errors on the transmitted beam is to distort the wavefront. The effect of average phase errors can be treated as a function of position in classical optical fashion to get beam offset, defocusing, astigmatism, distortion and similar quantities. The effect of random RMS phase errors $\bar{\delta}^2$, assumed not a function of position, is to reduce the main beam efficiency by the factor

$$\eta_{random} = e^{-\bar{\delta}^2} \tag{6}$$

Because in general there is a residual on-axis $\bar{\delta}^2$ over a single phase controlled area proportional to that area, the above equation qualitatively illustrates the reason for the recent change in the baselined level of phase control from the subarray level to the klystron power module level. The approximately factor of 10 average decrease in phase controlled area contributed to a smaller effective $\bar{\delta}^2$. The revenues from the extra received power of the now more efficient power beam over a satellite lifetime were found to adequately compensate for the increased phase control system cost. Other benefits associated with phase control to the module level include increased pointing accuracy and decreased waveguide tuning mismatches.

2.0 BASELINE PHASE CONTROL SYSTEM DESCRIPTION

The baselined phase control system, illustrated on Figure 3, consists of 101,552 klystron module level power amplifier phase control subsystems, as shown on Figure 4, and an 816-2/3 MHz reference phase distribution network of fiber optical cables and master slave returnable timing system repeater units as shown in Figure 5.

The reference phase distribution tree (to be described in more detail in the next section) has four levels culminating at the klystron module with no more than a 1:36 output branching, and constitutes most of the physical and operational (but not functional) complexity of the system. Its purpose is to provide identical phase reference phase signals to all klystron modules for use in conjugating the pilot to get the power downlink.

The klystron power amplifier phase control subsystems contain the phase control system's functional complexity insofar as they each receive and decode the spread spectrum pilot link signal, make any necessary corrections, conjugate it using the 816-2/3 MHz reference phase signal from the phase distribution tree and actively compensate for phase shifts suffered in the power amplifier and waveguide feed networks.

Fiber optic cabling was chosen over conventional coax for the reference phase distribution because of its lower mass, lower signal attenuation, and the fact that it has no short circuit failure mode. It also has lower phase delay and costs less. However, the phase delay variations are not low enough to eliminate the need of feedback (i.e., returnable timing systems) on all but the subarray (Level 4) reference phase control tree level. At the lowest level the length is so short that temperature induced variations in phase shift are judged to be tolerable.

NASA-funded technology development work at Boeing is currently developing 980 MHz fiber optic transmitters and receivers for SPS use. The expected successful completion of these and their demonstration with a 1 km cable should substantially verify that fiber optic technology can distribute the reference phase.

3.0 BASELINE SYSTEM RELIABILITY AND REDUNDANCY

It is clear that any reference phase control system that refers phases to central points has critical links when system reliability is considered. Because of this, the most central units in the reference system have been made redundant and autonomous.

The baseline transmitting array has three autonomous master reference phase receivers, which each transmit a reference phase signal via separate and redundant fiber optic cable links to each of twenty active Level 1 sector phase distribution units. (See Figure 7) These units select valid phase control signals and distribute them via redundant fiber optic cables to twenty Level 2 (group) distribution units. The group distribution units in turn tree the signal out further to 19 subarrays each. At the subarray, a last distribution unit sends the signal to each klystron module, where it is used as a reference for conjugation of the phase control pilot signal receiver output. The klystron is held in proper relation to the conjugated pilot beam signal by a control loop of its own that compensates for its internal phase shifts with temperature, time, and voltage.

An analysis of the basic reliability of the baseline configuration was performed by G.E. under subcontract to Boeing. The element reliabilities and basic configuration assumed are shown in Figures 7 and 8. For purposes of analysis the phase control system was considered as four segments. The first segment starts at the master reference receivers and continues through the sector reference distribution unit's selection switch SW_1. The second segment is from the output of SW_1 to the output of the subarray group signal splitter B_{19}. A third segment runs from this splitter through to the output of the subarray splitter B_{mn}. Finally, the last segment was analyzed from the B_{mn} output to the klystron input.

4.0 COSTS

Reference phase control system element costs, estimated by standard aerospace avionics cost estimating methodology from the computerized Boeing Program Cost Model data base. After estimation of the first unit cost on the basis of platform, function and service factors the costing methodology used was to discount the per unit cost on a 70% learning curve through the 1000th unit. After this was assumed to saturate and per learning unit costs were constant. Table I summarizes characteristics of the phase control system units on board subarrays, while Table II summarizes the segments of the reference phase distribution system at levels above the subarray level.

The primary results of the cost estimations are that the phase control system costs total well under $100 million and are dominated by the costs of the phase control pilot beam receivers. With more detailed reference satellite phase control system specifications there can be a requisite reduction in cost uncertainties. However, it should be noted that substantial (factor of two or more) reductions in phase control system cost are unlikely because current aerospace and electronic industry technology routinely deals with production runs such as those required for the SPS phase control system on equipment of comparable complexity.

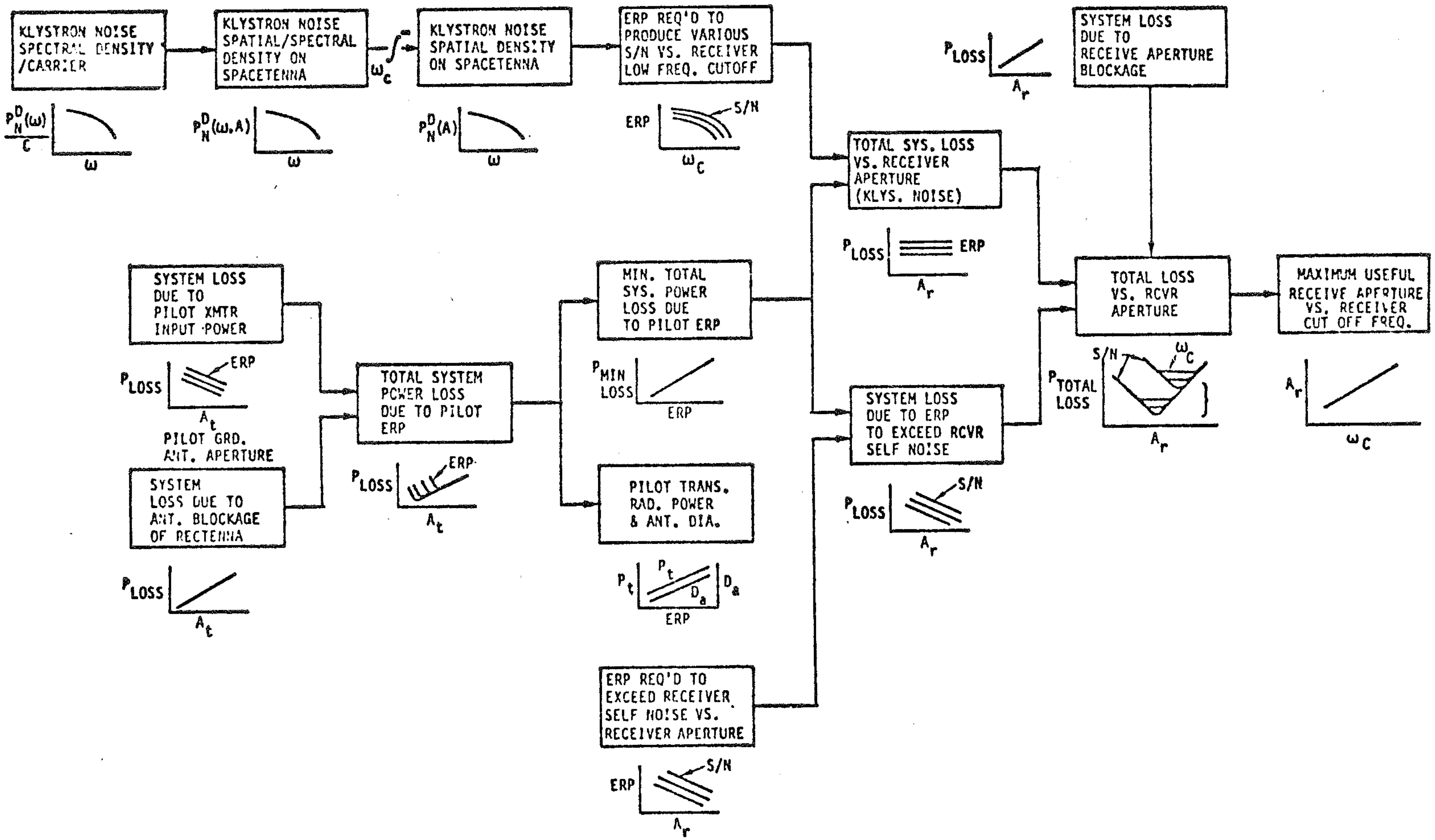

FIGURE 1. PILOT LINK ANALYSIS FLOW CHART

Table I. Intrasubarray Phase Control System
Production Cost Characteristics

Subarray Type	Number of Klystrons	Subarrays of This Type	PCR Mass (kg)	PCR Cost ($)	RPDS Mass (kg)	RPDS Cost ($)	Length Cable (m)	Cable Mass (kg)	Cable Cost ($)
1	4	1028	4.4	2240	1.0	595	33	3.7	73
2	6	1052	6.6	3360	1.0	595	49	5.4	108
3	8	612	8.8	4480	1.0	595	61	6.9	138
4	9	664	9.9	5040	1.0	595	72	8.0	160
5	12	900	13.2	6720	1.0	595	95	10.6	212
6	16	784	17.6	8960	1.0	595	132	14.5	290
7	20	628	22.0	11200	1.0	595	167	18.2	365
8	24	644	26.4	13440	1.0	595	197	21.6	433
9	30	632	33.0	16800	1.0	595	232	26.0	521
10	36	276	39.6	20160	1.0	595	296	32.5	649
TOTAL		7220	112 T	$57M	7 T	$4M		91 T	$1M

Table II. Intersubarray Phase Control System
Production Cost Characteristics

Item	No. Req'd.	Avg. Unit	Per SPS (M)
Master Reference Receiver and Reference Phase Transmitter	3	424K	1.272
Cables	60	4.6K	0.276
Slave Repeaters	400	25.1K	10
Level 2 Cables	380	2.5K	0.95
			$12.5M

Level 3 cables are common with
area-subarray data harness (see WBS 1.1.3)

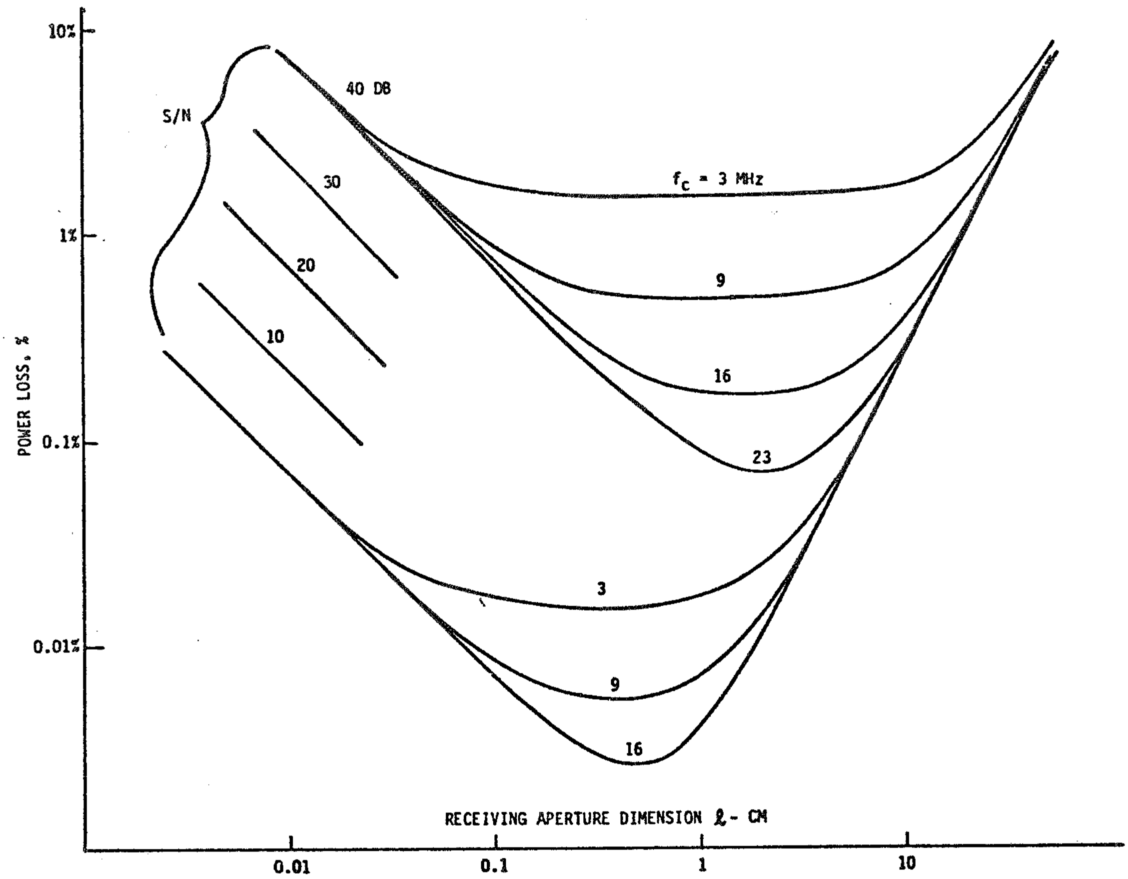

FIGURE 2. TOTAL SYSTEM LOSS VS. RECEIVE APERTURE.

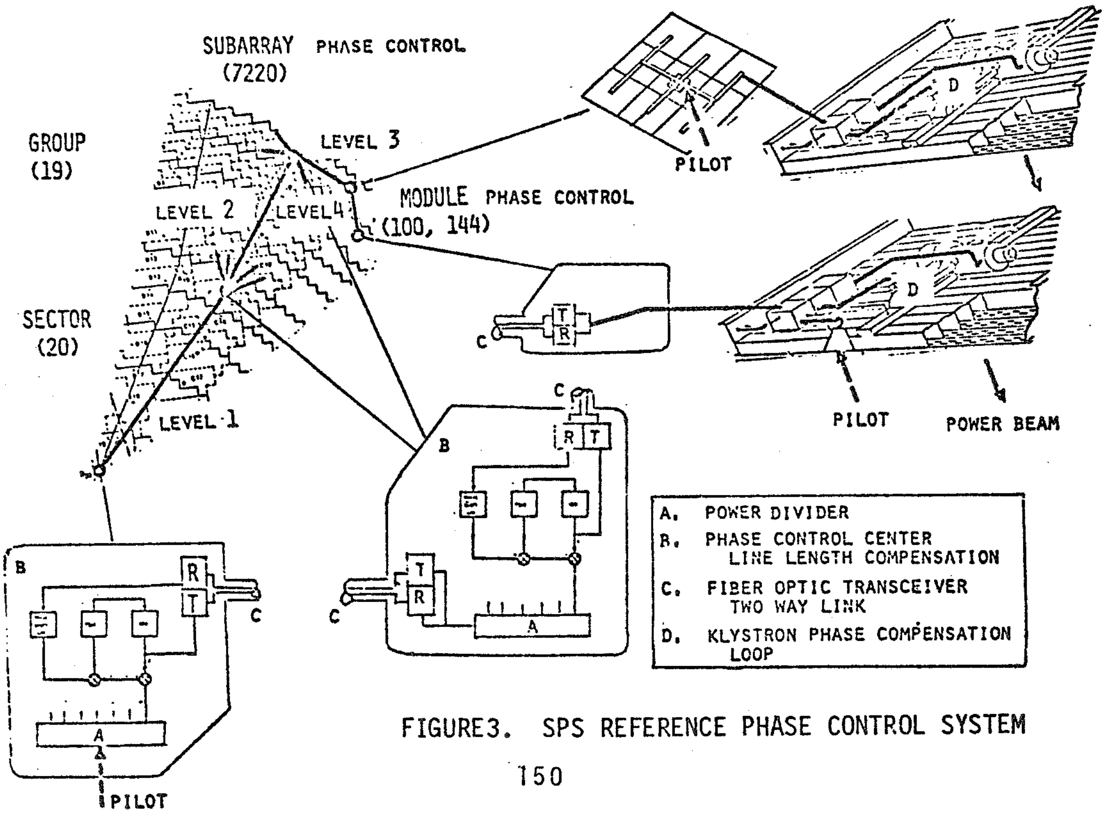

FIGURE3. SPS REFERENCE PHASE CONTROL SYSTEM

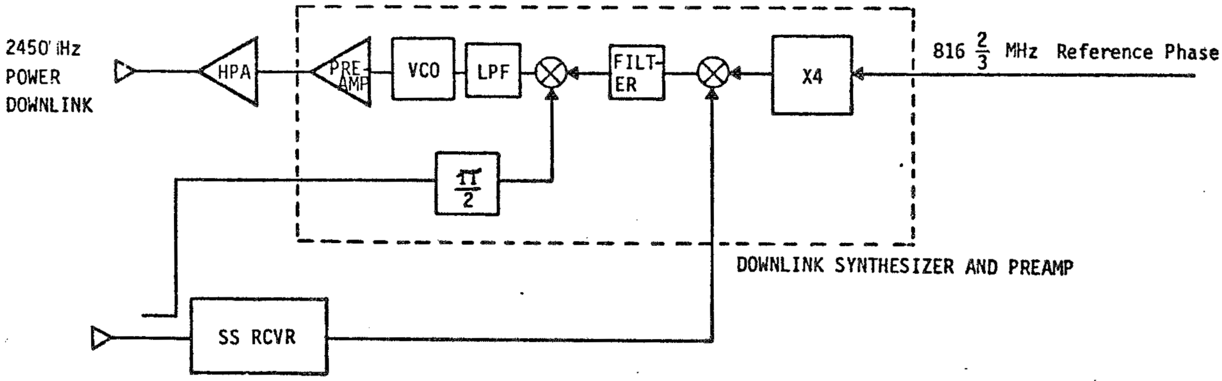

FIGURE 4. POWER AMPLIFIER PHASE CONTROL SUBSYSTEM

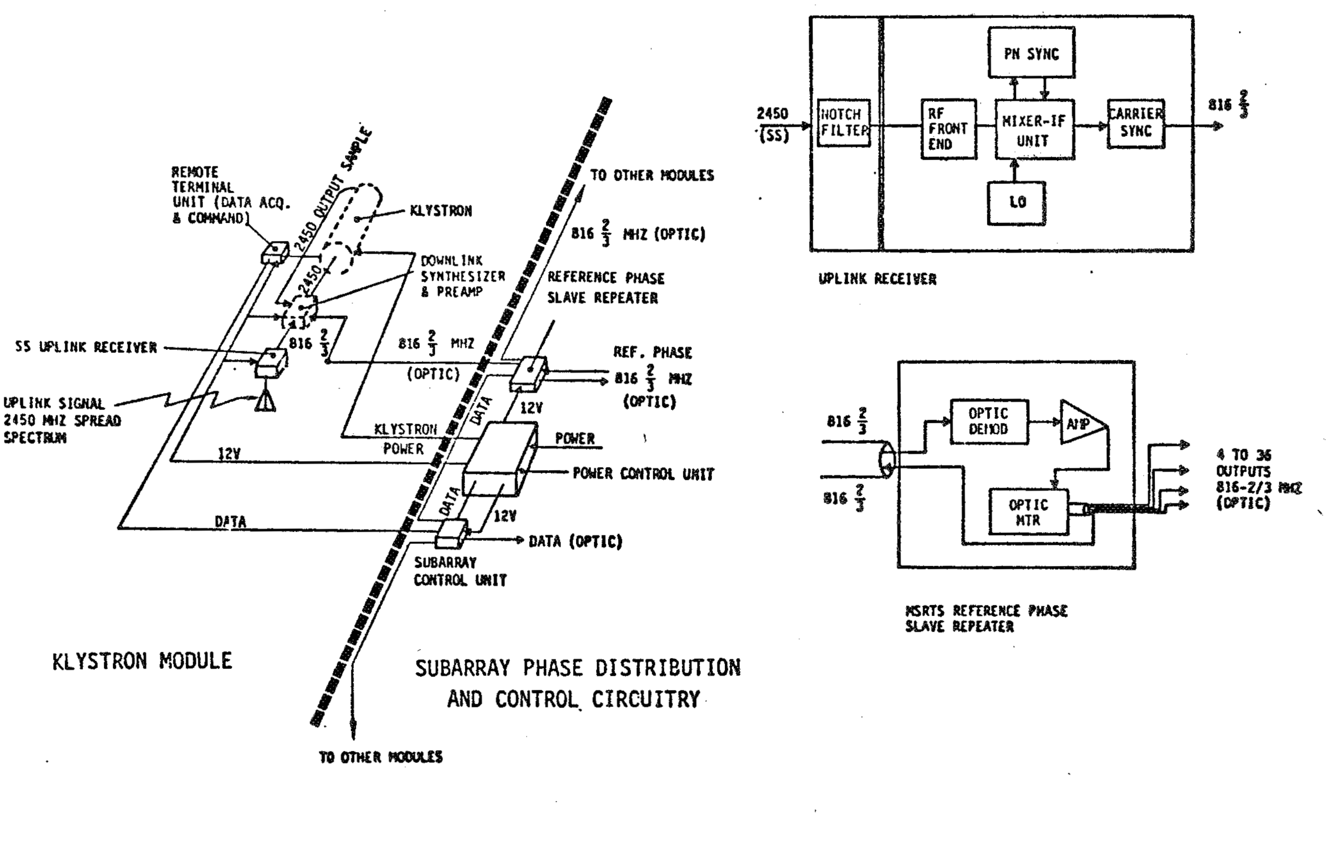

FIGURE 5. SUBARRAY CONTROL CIRCUITS

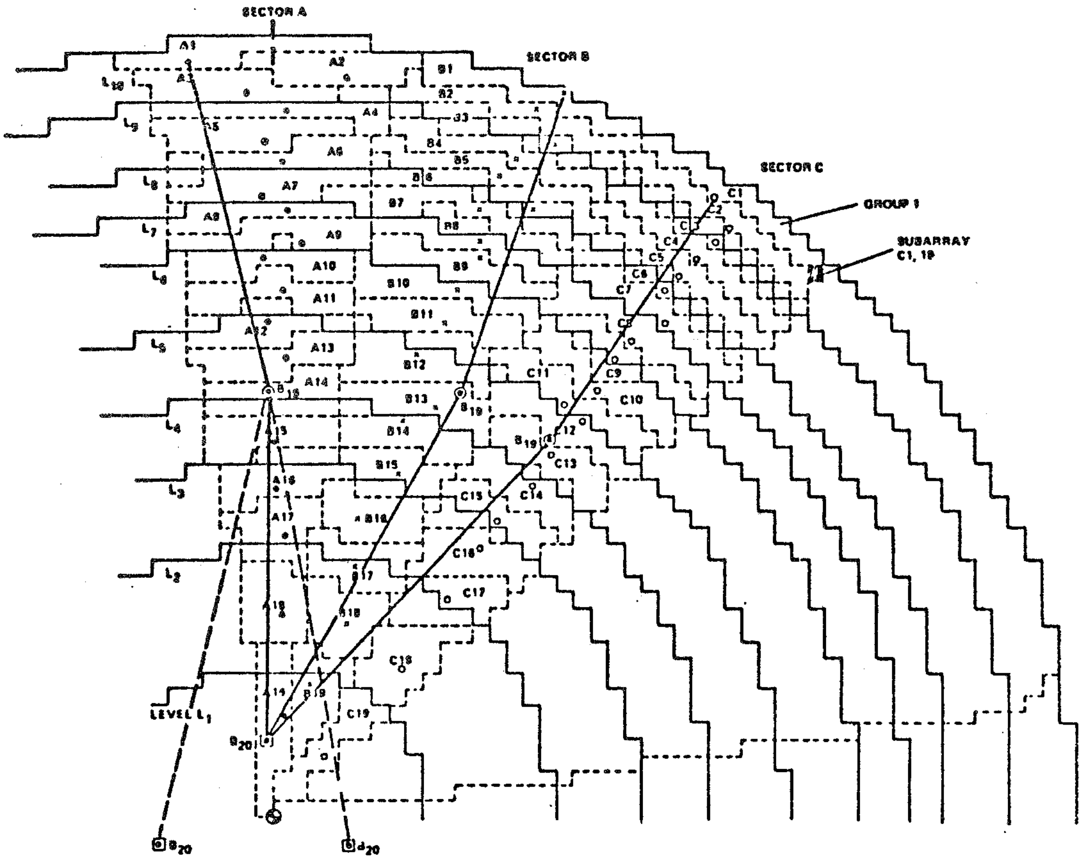

FIGURE 6. LOCATION OF REFERENCED PHASE REPEATER STATIONS OF SECTORS AND GROUPS

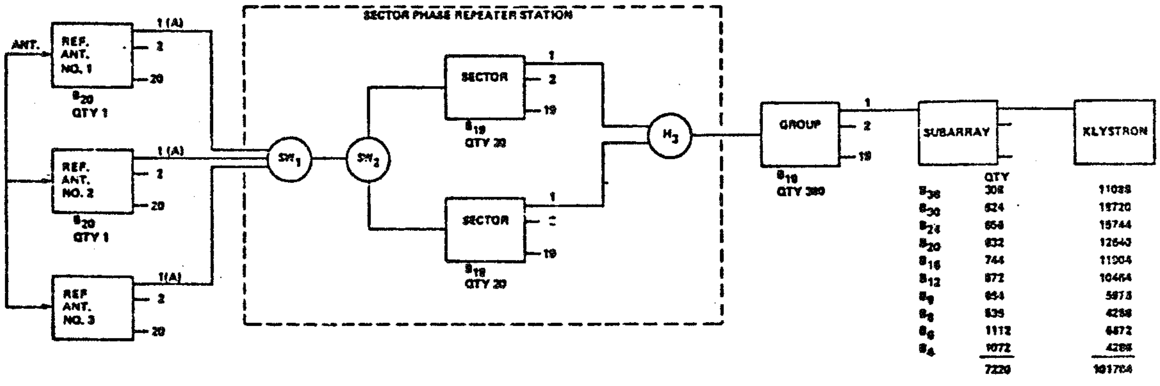

FIGURE 7. REDUNDANCY CONCEPT OF PHASE DISTRIBUTION NETWORK

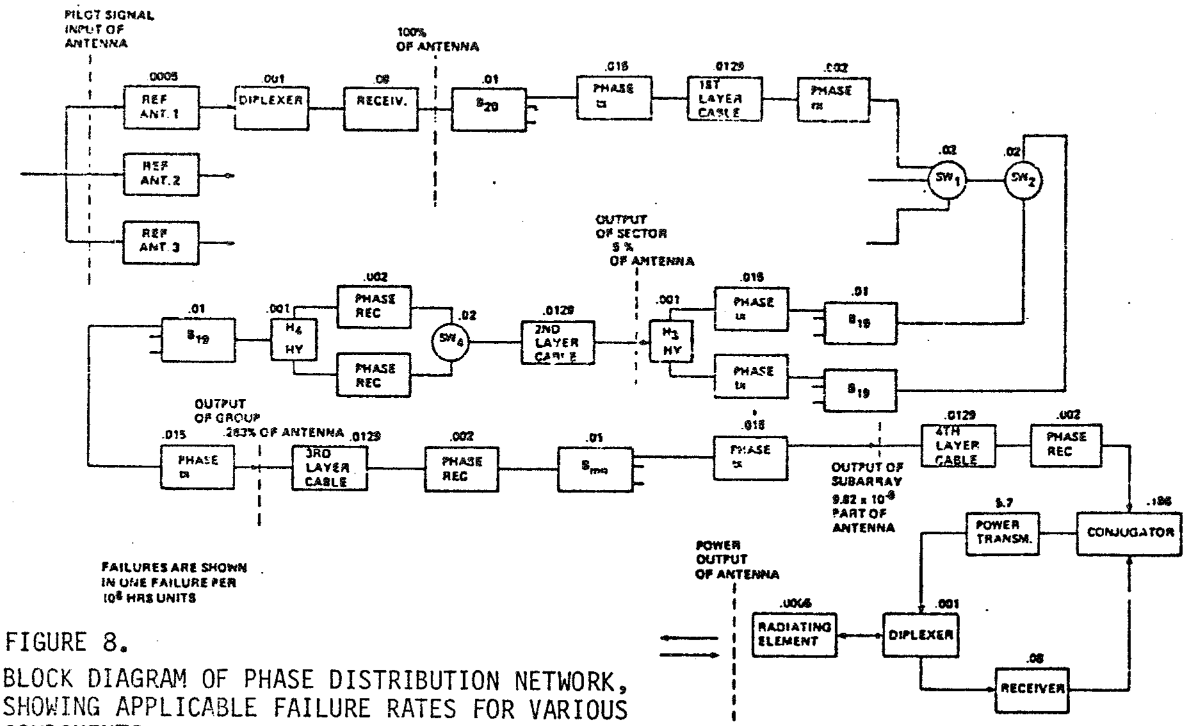

FIGURE 8.
BLOCK DIAGRAM OF PHASE DISTRIBUTION NETWORK, SHOWING APPLICABLE FAILURE RATES FOR VARIOUS COMPONENTS.

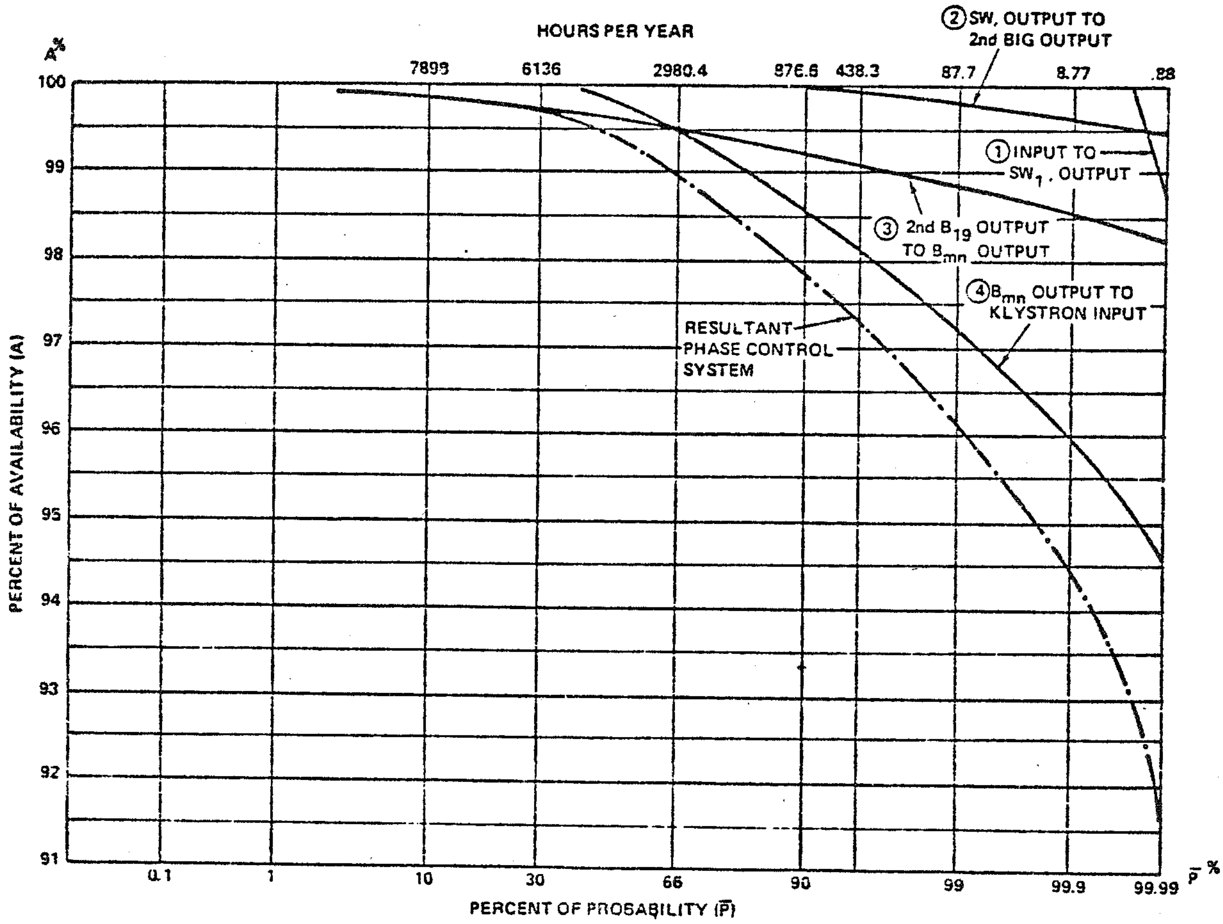

FIGURE 9. AVAILABILITY VS PROBABILITY FOR SPACE ANTENNA PHASE CONTROL SYSTEM FROM INPUT OF PILOT RECEIVE ANTENNA TO KLYSTRON DRIVE INPUT.