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FINAL REPORT

PHASE III

EXECUTIVE SUMMARY

VOLUME I

(NASA-CR-160536) A GROUND BASED PHASE CONTROL SYSTEM FOR THE SOLAR POWER SATELLITE. EXECUTIVE SUMMARY, VOLUME 1, PHASE 3 Final Report (LinCom Corp., Pasadena, Calif.) 51 p HC A04/MF A01 G3/44

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ABSTRACT

This report provides a summary overview of the SPS reference phase control system as defined in a three phase study effort. The first part of this report, Sections 2 to 5, summarizes key results pertinent to the SPS reference phase control system design. These results are a consequence of extensive system engineering tradeoffs provided via mathematical modeling, optimization analysis and the development/utilization of a computer simulation tool called SOLARSIM. The second part, Section 6, of this report provides a summary overview of the major components and results of the three phase study (Refs. 1-4). In addition, a summary of a ground base phase control system study (Ref. 4, Vol. IV) is provided in Section 5.

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1.0 INTRODUCTION

A critical requirement for the proposed Solar Power Satellite (SPS) Concept is the ability to beam and focus microwave energy to an a priori chosen spot located on the Earth's surface from a geostationary orbit of 38,000 KM, with a 90% + transmission efficiency. The phase control problem, i.e., controlling the phases of the power amplifier output signals over the large transmitting antenna area so that a coherent beam can be formed and properly pointed, has been undertaken by LinCom Corporation since 1977 under a contract to JSC. Our earlier efforts (Phase I and II) were involved with the definition and the selection of a reference phase control system. Currently in Phase III, we are involved primarily with the performance evaluation of the SPS reference phase control system through the continued development of SOLARSIM--a computer program package that allows parametric evaluation of critical performance issues using a combined computer simulation and analytical approach. In addition, a ground based phase-control concept is also investigated as an alternate approach to the SPS phase control problem. Specifically, our efforts are devoted to the following tasks:

Task 1. Pilot Signal Parameter Optimization/Analysis

Task 2. Power Transponder Analysis/Modeling and Interference Evaluation

Task 3. Solar Simulation (SOLARSIM) Program Development

Task 4. Phase Control System Optimization/Tradeofffs

Task 5. Ground Based Phase Control System Evaluation

This executive summary of accomplishments and pertinent results is organized into five parts. The SPS concept and the reference phase control system investigated in our Phase I and II efforts are reviewed in Section 2. The next section is devoted to the analysis and selection of the pilot signal and power transponder design (Tasks 1 and 2). The SOLARSIM program development and the simulated SPS phase control performance (Tasks 3 and 4) are treated in Section 4. In Section 5 the ground based phase control system is evaluated as an alternate phase control concept. Section 6 is a summary overview of the three phase study (Refs. 1-4).

2.0 THE SPS CONCEPT AND THE REFERENCE PHASE CONTROL SYSTEM

Figure 2.1 illustrates the major elements required in the operation of an SPS system which employs retrodirectivity as a means of automatically pointing the beam to the appropriate spot on the Earth. From Figure 2.1 we see that these include: (1) the transmitting antenna, hereafter called the spacetenna, (2) the receiving antenna, hereafter called the rectenna, and (3) the pilot signal transmitter. The rectenna and pilot signal transmitter are located on the Earth. The purpose of the spacetenna is to direct the high-power beam so that it comes into focus at the rectenna. The pilot signal, transmitted from the center of the rectenna to the spacetenna, provides the signal needed at the SPS to focus and steer the power beam.

As seen from Fig. 2.1 the SPS phase control system is faced with several key problems. They include: (1) path delay variations due to imperfect SPS circular orbits, (2) ionospheric effects, (3) initial beam forming, (4) beam pointing, (5) beam safing, (6) high power amplifier phase noise effects, (7) interference (unintentional and intentional),

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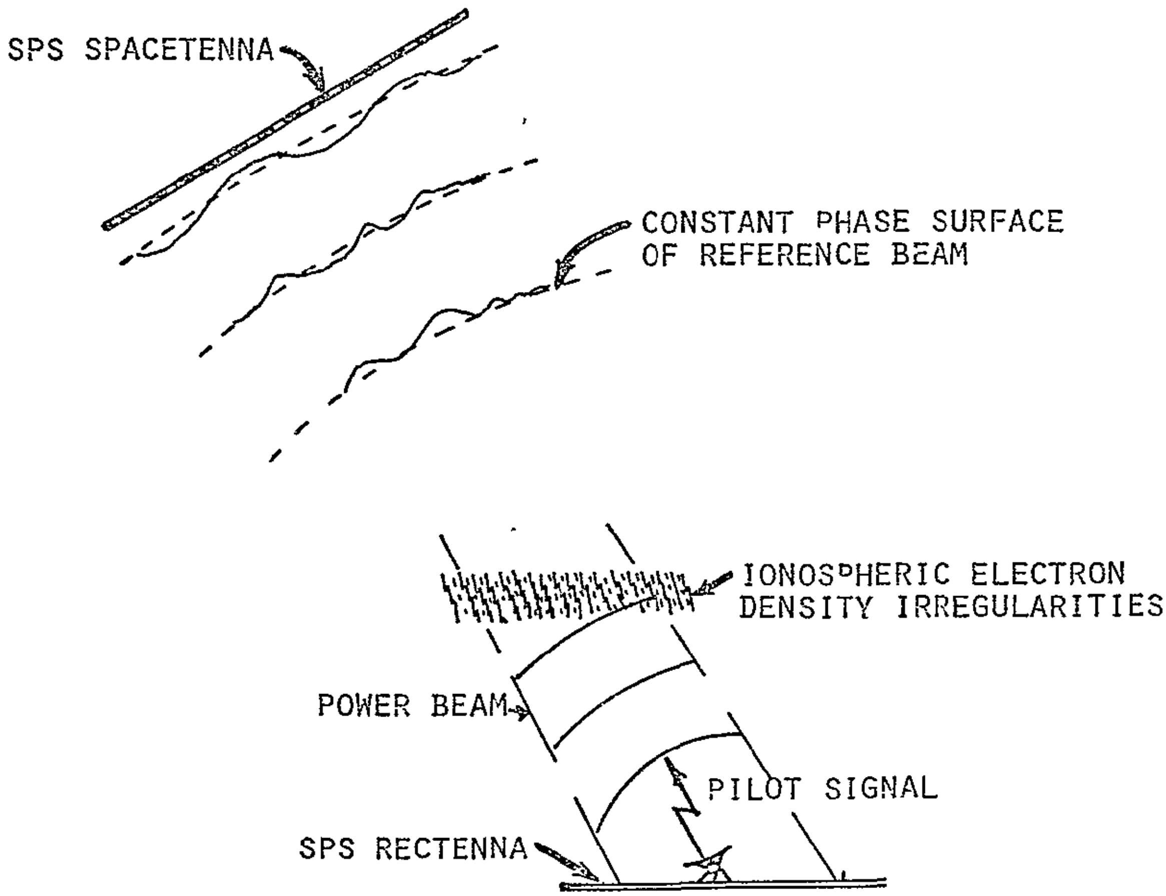

- PATH DELAY VARIATIONS
- IONOSPHERE EFFECTS
- INITIAL BEAM FORMING
- BEAM POINTING
- BEAM SAFING
- PHASE NOISE (HPA)
- INTERFERENCE
- SELF-JAMMING

Figure 2.1. Space Based Solar Power Satellite and Earth Based Energy Collection System Concept.

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etc.

2.1 SPS Transmitting System Concept

From the system engineering viewpoint, the SPS transmitting system which incorporates retrodirectivity is depicted in Fig. 2.2. As seen from Fig. 2.2 the SPS Transmission System consists of three major systems: (1) The Reference Phase Distribution System, (2) The Beamforming and Microwave Power Generating System, and (3) The Solar Power to Electrical Power Conversion System.

2.1.1 The Retrodirective Phase Control System Concept

To achieve retrodirectivity, the microwave power transmission system requires an on-board Phase Control System (Figure 2.2) phase-locked or synchronized to pilot signal transmitted from the center of the ground based retenna. One major purpose of the Phase Control System is to coherently reconstruct the instantaneous frequency and phase of the received pilot signal and use this to generate and distribute a set of constant phase conjugation reference signals. This set of signals is used to advance the phase of the pilot signal received at each spacetenna element by an amount equal to the phase delay accumulated on the uplink.

2.1.2 Beamforming and Microwave Power Generating System Concept

To form a coherent, high power microwave beam a cooperating Microwave Power Generating System is required, see Fig. 2.2. One of its main functions is that of delivering large amounts of microwave power to the radiating subarrays, Refs. 5,6. By taking advantage of the retrodirective feature of the active phased-array the power generated by the high power amplifiers is automatically returned (transponded) to the direction from which the pilot signal came. Thus the SPS system directs

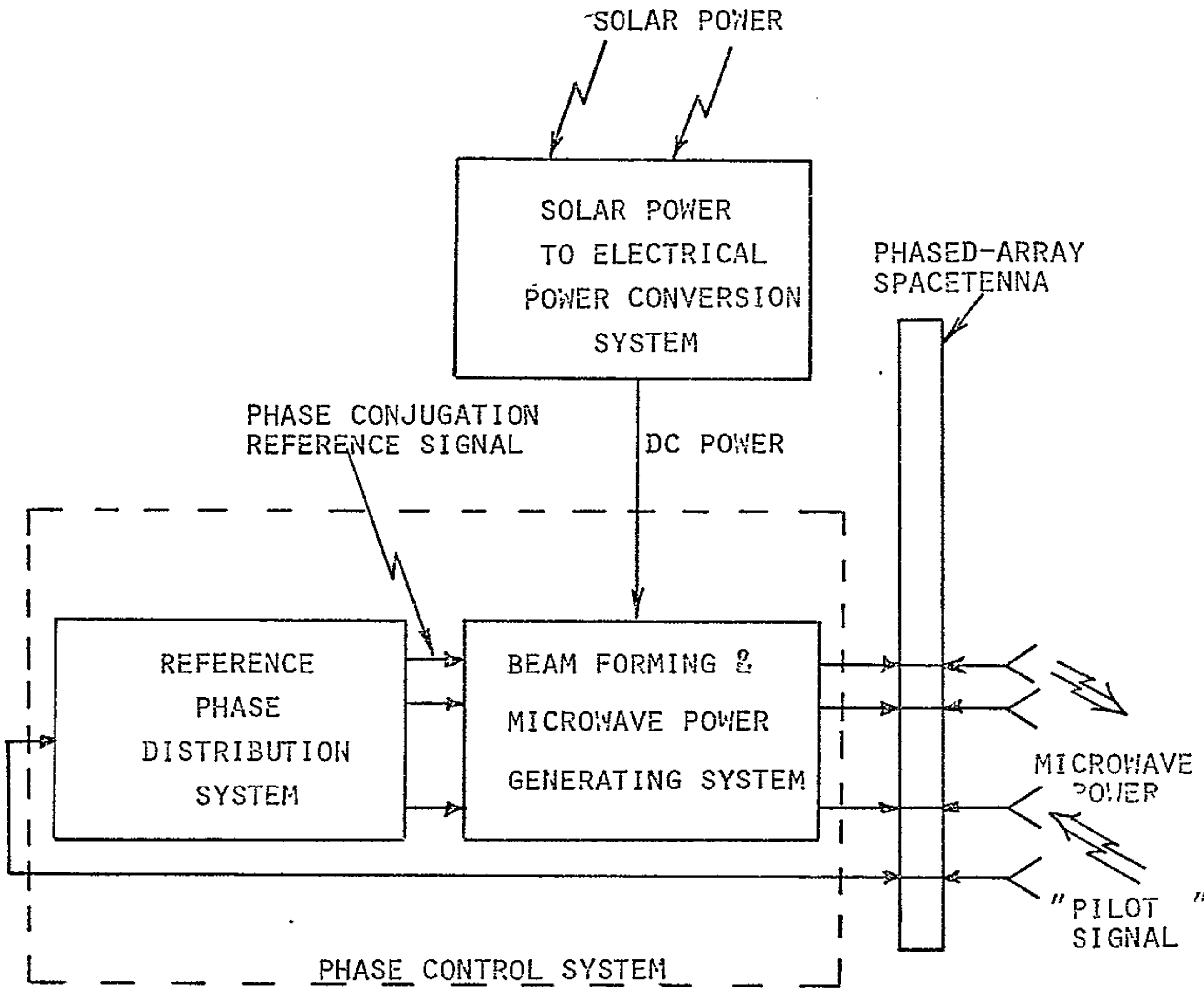

Figure 2.2. Solar Power Satellite (SPS) Transmission System (Phase Conjugation).

the power generated by the Space-Based Energy Station to the Earth based rectenna.

2.1.3 Reference Phase Distribution System and Microwave Power Generating System Interface

The phase conjugate reference signals generated by the Reference Phase Distribution System are coherently distributed to Phase Control Centers (PCCs) located on the SPS. From these PCCs, the signals are then distributed and used to drive the set of phase conjugate circuits associated with the Beam Forming and Power Generating System, Figure 2.2. These procesors, which contain the phase controlled high-power amplifiers operating in unison, automatically form the high power beam by causing advancement in the phase of the power amplifier output signals. This advancement is such that the accumulated phase on the downlink signal equals the phase accumulated on the uplink signal.

2.2 Reference System SPS Pilot Waveform

The reference system SPS pilot waveform utilizes: (1) NRZ command modulation, (2) split phase, direct sequence pseudo-noise or spread spectrum modulation, BI-ϕ-DS. This combined data-code modulation is used to bi-phase modulate (BPSK) the RF carrier. Multiple access in the SPS network is to be achieved via code divison multiple access techniques (CDMA). Thus the baseline SPS pilot waveform is characterized via four modulation components summarized by the symbols:

$$\underbrace{\text{NRZ}}_{\text{Command Modulation}} / \underbrace{\text{BPSK}}_{\text{RF Carrier Modulation}} / \underbrace{\text{BI-}\phi\text{-DS}}_{\text{Spread Spectrum Modulation}} / \underbrace{\text{CDMA}}_{\text{Multiple Access Modulation}}$$

A functional diagram indicating the mechanization of the pilot transmitter is shown in Fig. 2.3. As illustrated the data clock and code clock are coherent so that the uplink operates in a data privacy format. The purpose of the spread spectrum (SS) code generator is several fold. First it provides link security, second it provides a multiple access capability for the operation of a network of SPSs, see Fig. 2.4, and third, the anti-jamming protection is provided for both intentional radio frequency interference (RFI) and unintentional RFI such as those arising from a neighboring SPS on the adjacent orbit. Proper choice of this code modulation will also provide the needed isolation between the uplink and the downlink, since a notch filter can be placed around the carrier frequency at the SPS receiver input to blank out the interferences without destroying the uplink signal (see pilot signal spectrum in Fig. 2.3). The selection of the PN code parameters to achieve the code isolation and processing gain required will be addressed in Section 3.

2.3 Reference Phase Control System

The reference phase control system concept was presented in detail in Ref. 2; its major features are summarized in this section. Based upon earlier study efforts (Refs. 1,2), a phase control system concept has been proposed which partitions the system into three major levels. Figure 2.5 demonstrates the partitioning and represents an expanded version of Fig. 2.2. The first level in Fig. 2.5 consists of a reference phase distribution system implemented in the form of phase distribution tree structure. The major purpose of the tree structure is to electronically compensate for the phase shift due to the transition path lengths from the center of the spacetenna to each phase control center (PCC) located in each subarray. In the reference system, this is

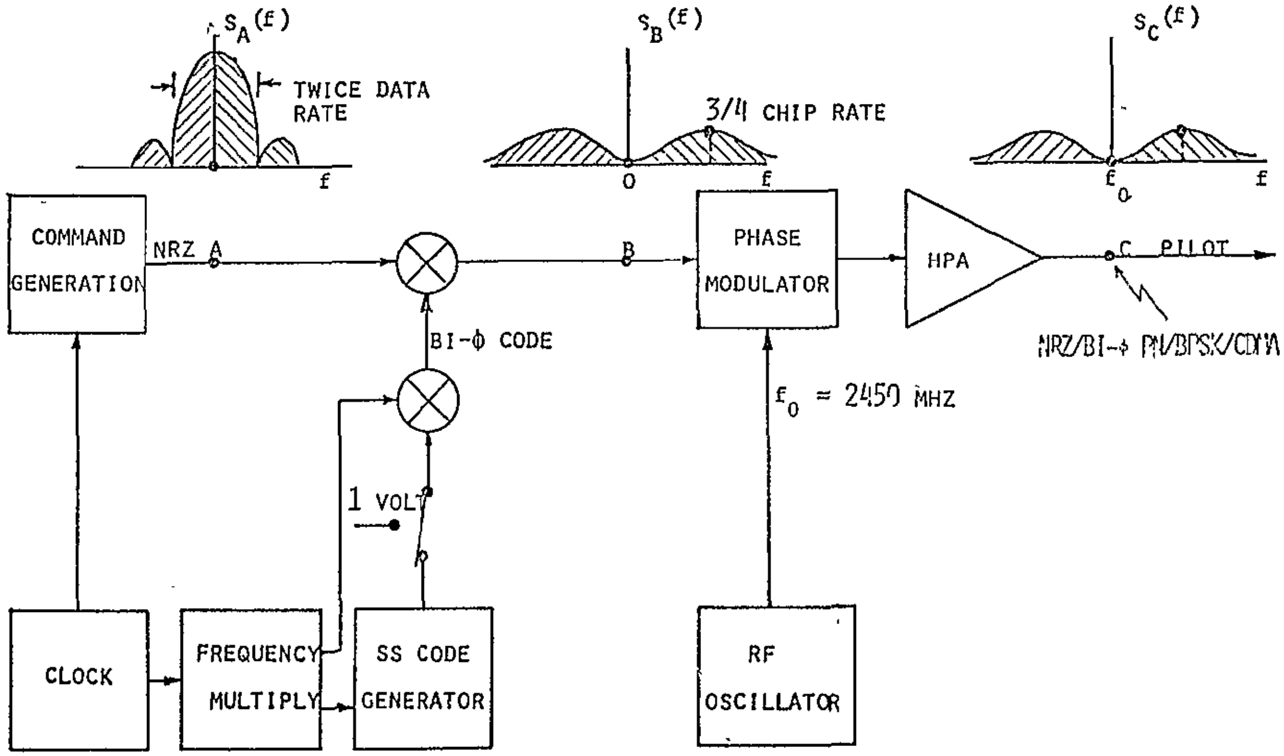

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Figure 2.3. Reference System Pilot Signal Transmitter Functional Diagram.

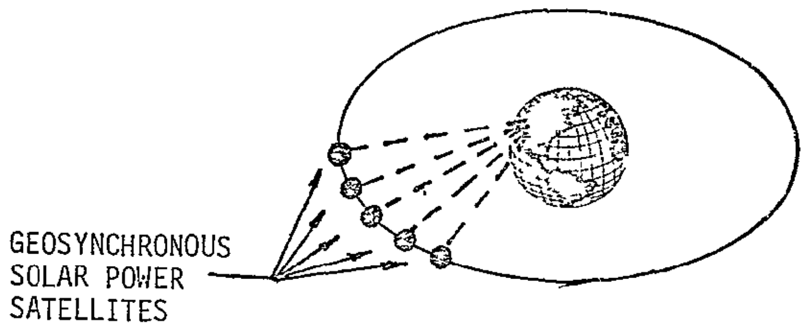

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Figure 2.4. SPS Network Scenario.

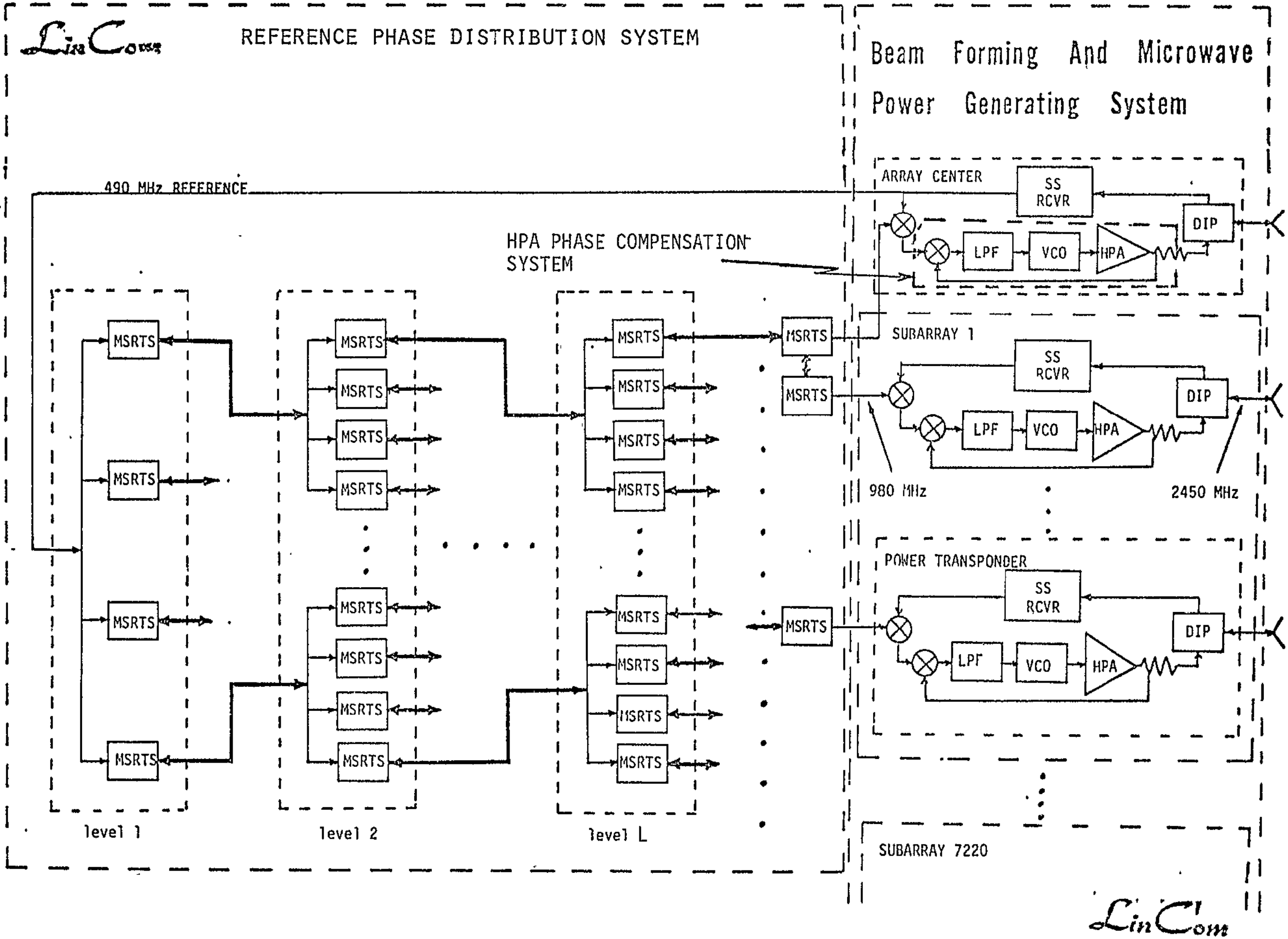

Figure 2.5. Reference Solar Power Satellite Transmission System.

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accomplished using the Master Slave Returnable Timing System (MSRTS) technique. Fig 2.6 illustrates the functional diagram associated with the MSRTS technique. The detailed mathematical modeling and analysis is provided in Ref. 3. Based upon extensive tradeoffs using SOLARSIM and appropriate analysis during the Phase II study, a four level tree is selected to be the reference phase distribution system configuration.

The second level is the Beam Steering and Microwave Power Generation System which houses the SPS Power Transponders. This transponder consists of a set of phase conjugation multipliers driven by the reference phase distribution system output and the output of a pilot spread spectrum receiver (SS RCVR) which accepts the received pilot via a diplexer connected to a separate receive horn or the subarray itself. The output of the phase conjugation circuits serve as inputs to the third level of the phase control system. The third level of phase control is associated with maintaining an equal and constant phase shift through the microwave power amplifier devices while minimizing the associated phase noise effects (SPS RFI potential) on the generated power beam. This is accomplished by providing a phase-locked loop around each high power amplifier.

2.4 Reference System SPS Power Transponder

In addition to distributing the constant phase reference signal over the spacetenna, a method for recovering the phase of the received pilot signal is required. Figure 2.7 represents the functional diagram of the SPS power transponder. This includes the pilot signal receiver, phase conjugation electronics and the high power amplifier phase control system.

In the mechanization of the SPS power transponders, two receiver

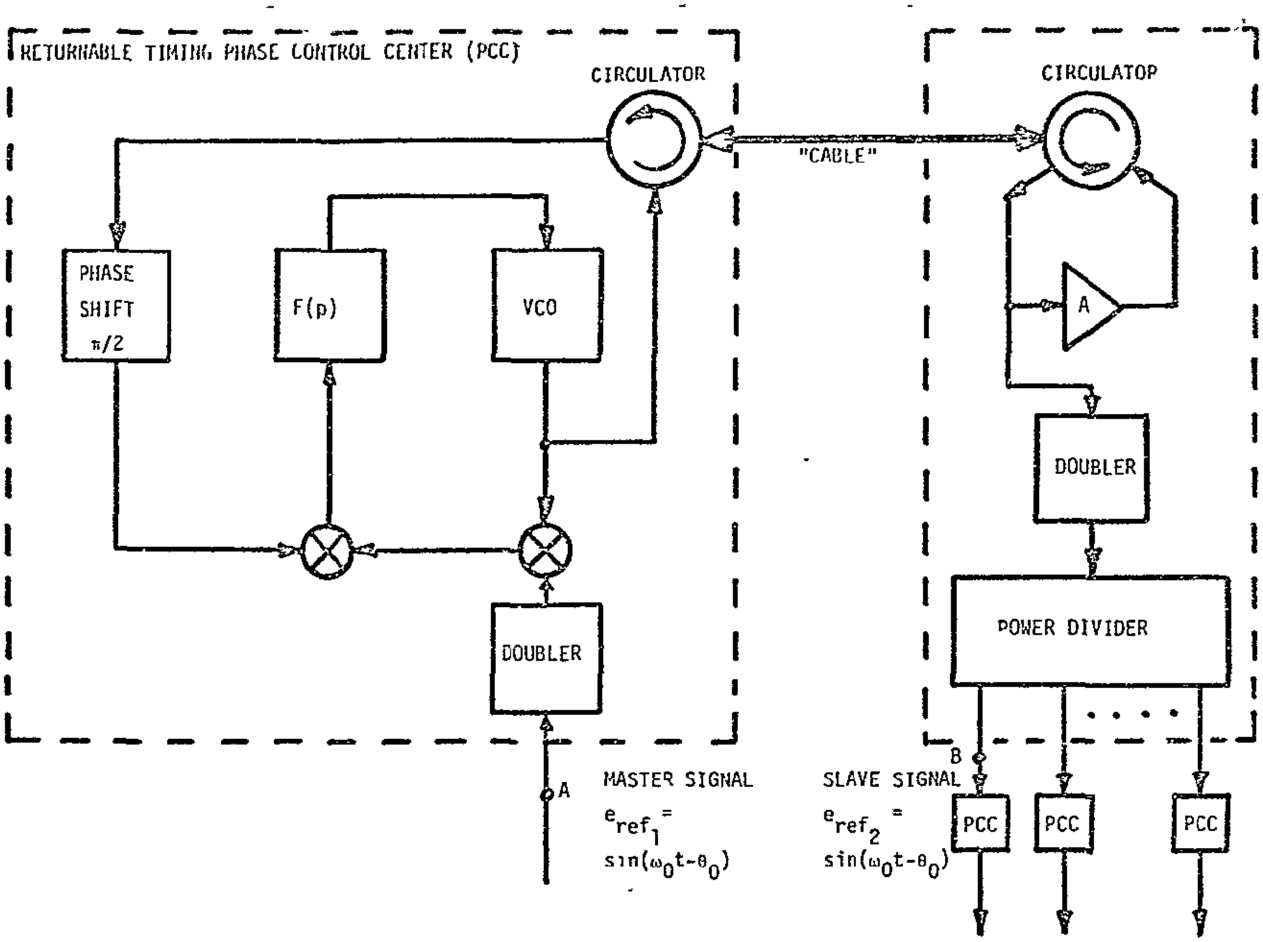

Figure 2.6. Master Slave Returnable Timing System (MSRTS).

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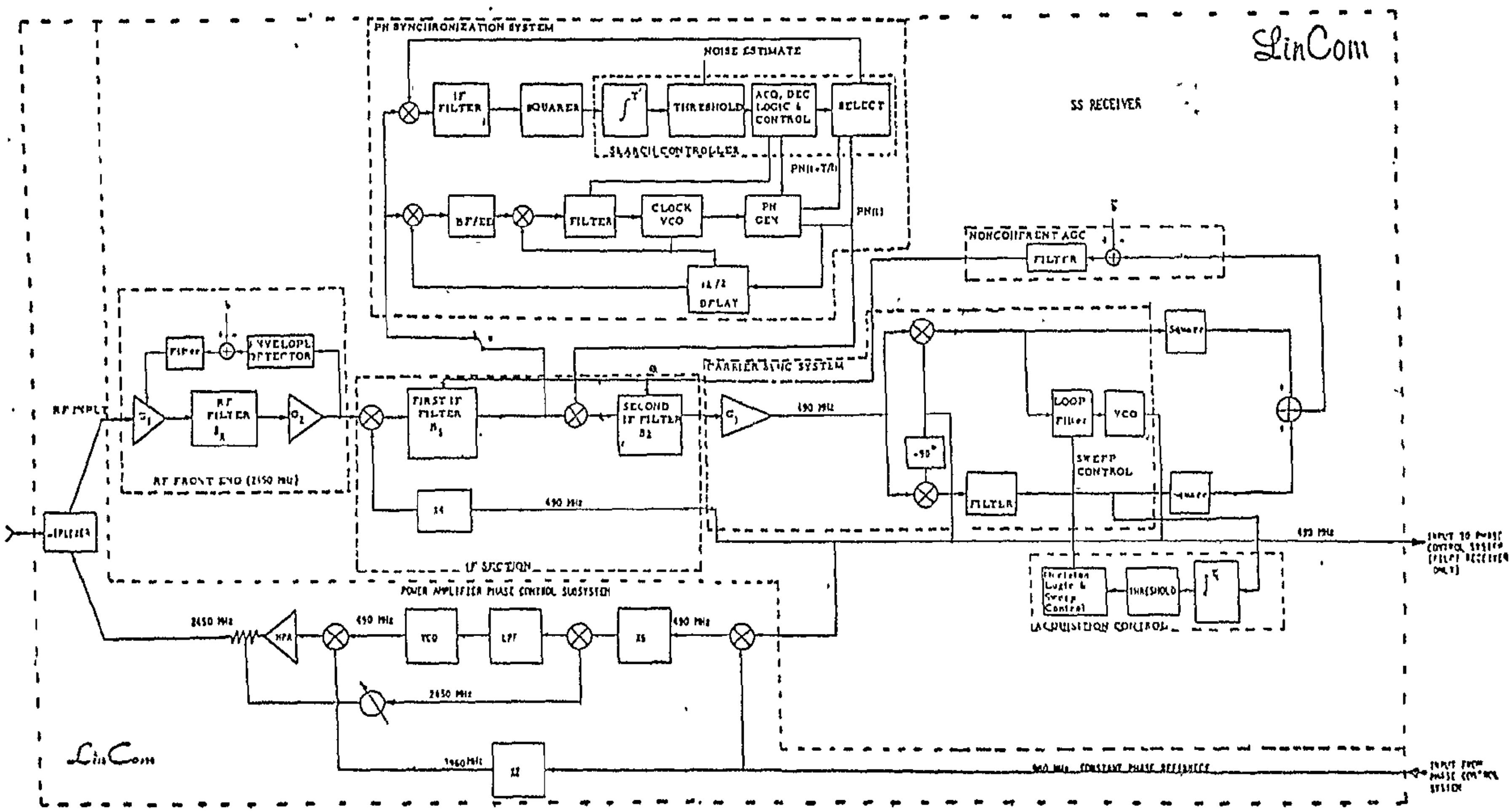

Figure 2.7. Central SPS Power Transponder Located at Spacetenna Center.

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"types" will be required; however, most of the hardware will be common between two receivers. One receiver, the Pilot Spread Spectrum Receiver, is located at the center of the spacetenna or the reference subarray. It serves two major functions: (1) acquires the SS code, the carrier and demodulates the command signal, (2) provides the main input signal to the Reference Phase Distribution System, see Figure 2.7.

The second receiver "type" will be located in the Beam Forming and Microwave Power Generating System, see Figure 2.8. Its main purpose is to phase conjugate the received pilot signal and transpond power via the j-th spacetenna element, j = 1,2,...,101,552.

In the case that data transmitting capability is not implemented for the pilot signal, the Costas loop in Figs. 2.7 and 2.8 can be replaced by a CW loop. This avoids the need for provisions to resolve the associated Costas loop induced phase ambiguity.

3.0 PILOT SIGNAL DESIGN AND POWER TRANSPONDER ANALYSIS

The key technical problem areas concerning the reference phase control system design and specifications are the SPS pilot signal design and power transponder analysis. Figure 3.1 illustrates the radio frequency interference (RFI) scenario.

The interferences are generated by different mechanisms: (1) self jamming due to the power beam leakage from the diplexer/circulator; (2) mutual coupling from adjacent transponders, (3) thermal noise and (4) interference from adjacent SPSs. The signal and interference spectrum at the input to the SPS transponder is depicted in Fig. 3.1. In general, the combined phase noise interference from the power beams consists of a coherent and a noncoherent term. Depending on the mechanization of the antenna structure and diplexer/circulator

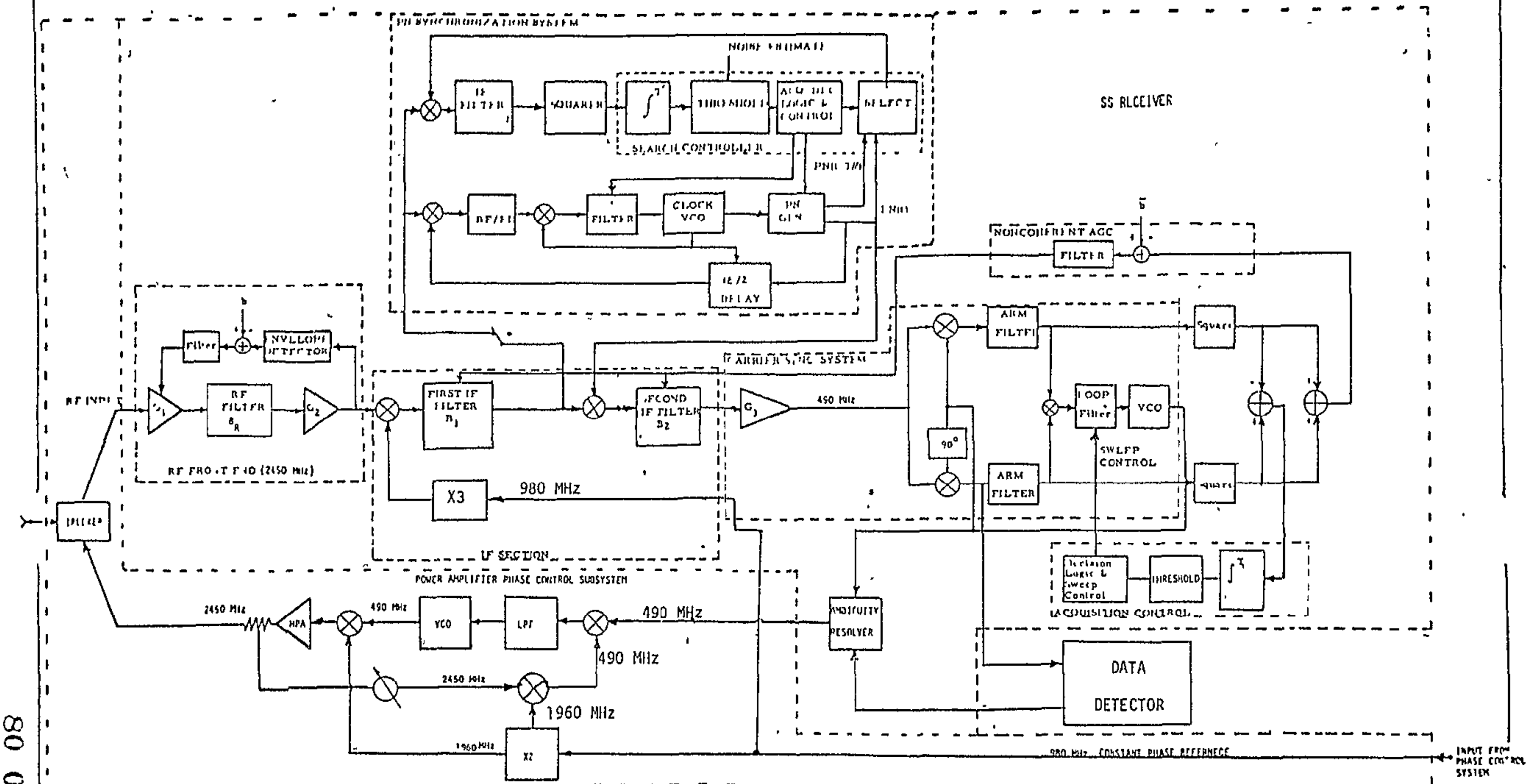

Figure 2.8. SPS Power Transponder

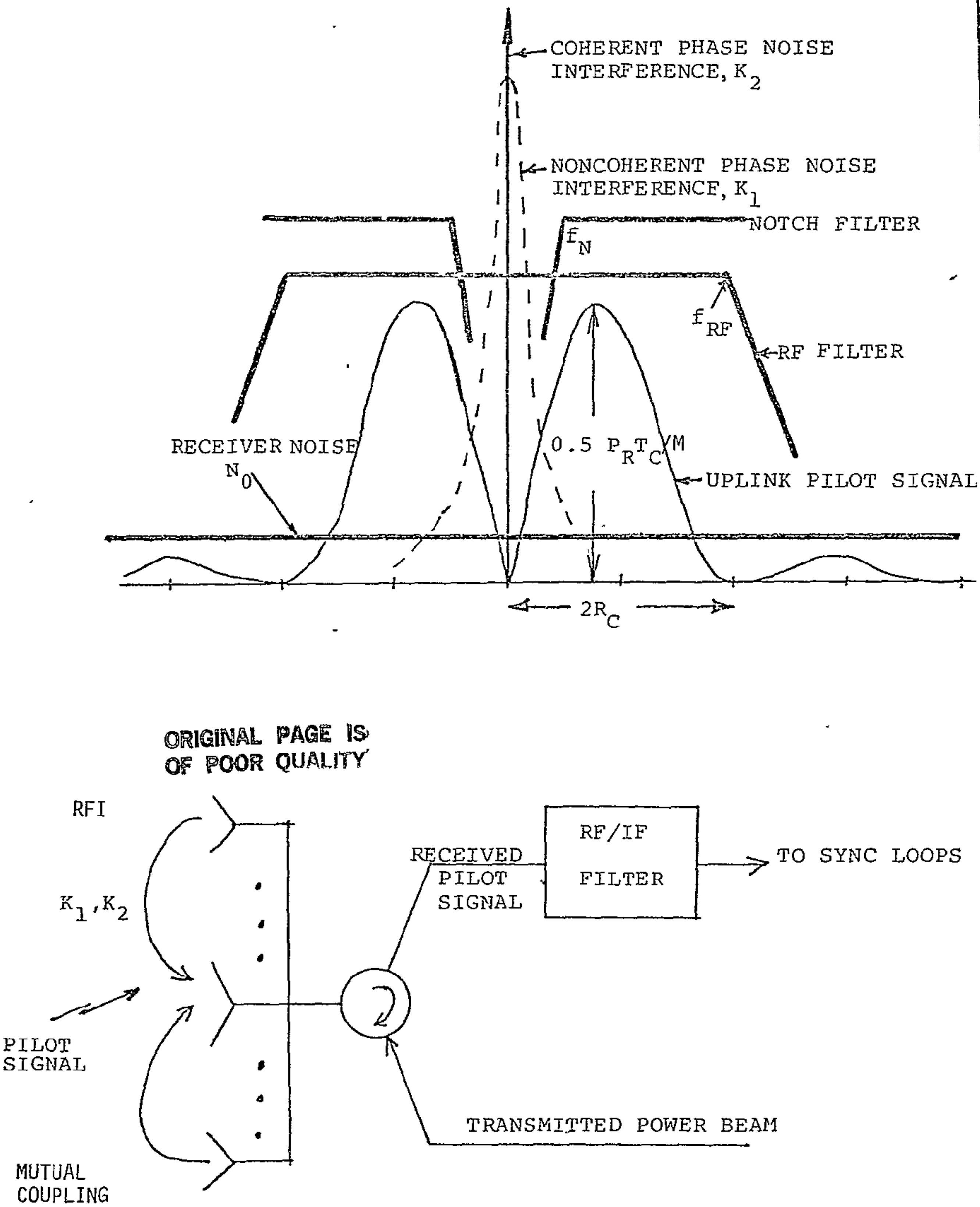

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Figure 3.1. Signal and Noise Spectrum into SPS Transponder.

characteristics, these terms are associated with gains K_1 and K_2. Note that the phase noise interferences are concentrated around the carrier frequency (2450 MHz). The uplink pilot signal on the other hand has no power around this frequency. Its power spectrum peaks at f $\sim$0.75 R_c, with a value proportional to the produce of the received power (P_R) and the PN chip rate (R_c), and inversely proportional to the PN code length (M). The parameters R_c and M are related to the processing gain of the PN spread signal and determines its interference suppression capability. The RF filter characteristic is mainly determined by the waveguide antennas, which have bandwidths ranging from 15 to 45 MHz depending on the array area. Our goal is to optimally select (1) the pilot signal so that it passes the RF filter with negligible distortions, and (2) a practical notch filter that rejects most of the phase noise interferences. When this is done, one can be assured that the reconstructed pilot signal phase after the sync loops is within a tolerable error for the retrodirective scheme.

3.1 Pilot Signal Parameter Selection

In order to optimally design and select the pilot signal parameters, the interference model and the requirements for the first IF filter/notch filter must be characterized. We have characterized analytically the power spectral density of the pilot signal as well as various sources of interference. Based upon this information, we are able to optimize the cascade of first IF (notch) filter and RF filter characteristics in the reference SPS transponder for interference rejection. We have also formulated a mathematical framework which serves as a basis where different tradeoffs can be made in terms of system parameters such as pilot signal transmitter EIRP, PN code requirements and chip rates. As a result, a computer program is developed to be included in the SOLARSIM package to perform tradeoffs of pertinent design parameters of the receiver portion of the SPS transponder. The phase error of the pilot phase tracking (Costas) loop is chosen to be the performance measure.

3.2 Power Transponder Analysis

Analytical models are developed for the SPS transponder tracking loop system that include: (1) the PN despreader loop, (2) the pilot phase tracking (Costas) loop and (3) the PA phase control loop. The phase reference receiver that feeds the phase distribution system is also modeled. Various sources of potential phase noise interferences are identified and their effects on the performance of the individual loops are modeled. In particular, a model of the phase noise profile of the klystron amplifier based on a specific tube measurement is introduced. Important implications on the PA control loop design are also addressed.

An analytical model for evaluating the overall performance of the SPS transponder is given. The phase fluctuation at the output of the transponder is shown to be directly related to the various noise processes through the closed-loop transfer functions of the tracking loops. These noise processes are either generated externally to the transponder circuitry such as ionospheric disturbances, transmit frequency instability, or externally such as receiver thermal noise, power beam interferences, data distortions, VCO/mixer phase noise and the phase variations introduced by the reference distribution tree. Even though the analytical method provides us with invaluable insights into the performance of the power transponder, a detailed computer simulation is deemed necessary to quantitatively investigate the interplays between the elements of the transponder.

3.3 Summary of Results

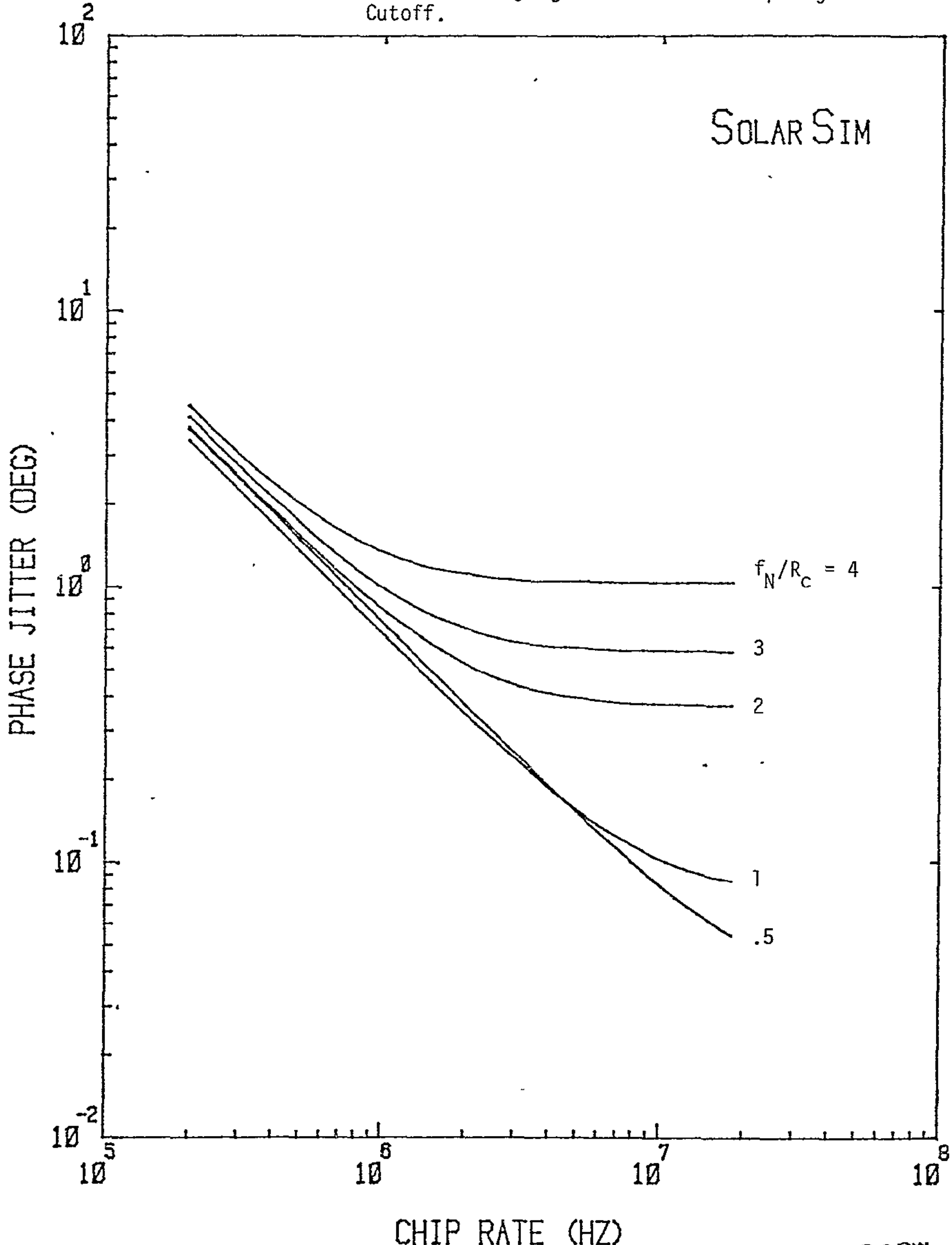
The important findings on the transponder design parameters and results based upon SOLARSIM and the analytical models discussed in Sections 3.1 and 3.2 can be summarized as follows:

- EIRP = 93.3 dBW
- PN Chip Rate ~ 10 Mcps
- RF filter 3 dB cutoff frequency ~ 20 MHz
- Notch filter 3 dB cutoff frequency ~ 1 MHz
- Notch filter dc attenuation ~ 60 dB
- PN Code period ~ 1 msec
- Costas loop phase jitter $\leq$ 0.1 deg for 10 Hz loop bandwidth
- Channel Doppler is negligible
- Klystron phase control loop bandwidth $\geq$ 10 kHz

In arriving at these design values, we have used extensively the capabilities of SOLARSIM to perform the necessary tradeoffs. Figure 3.2 represents a typical design curve generated via SOLARSIM and used to pick the RF filter 3 dB cutoff frequency. The details and other tradeoffs performed are documented in Vol. II of this report.

The preliminary results are generated using a tentative model of RFI with coupling coefficients $K_1 = K_2 = -20$ dB. Explicitly, we assumed that the transponder input sees a CW interference with power equal to 0.65 KW and a phase noise (1/f type) interference at about 20 W. Of course, when these values are changed significantly, our predictions have to be modified. For this reason, the development and verification of an acceptable model for the effects of mutual coupling on the phase

Figure 3.2. Effect of Varying Notch Filter Frequency Cutoff.



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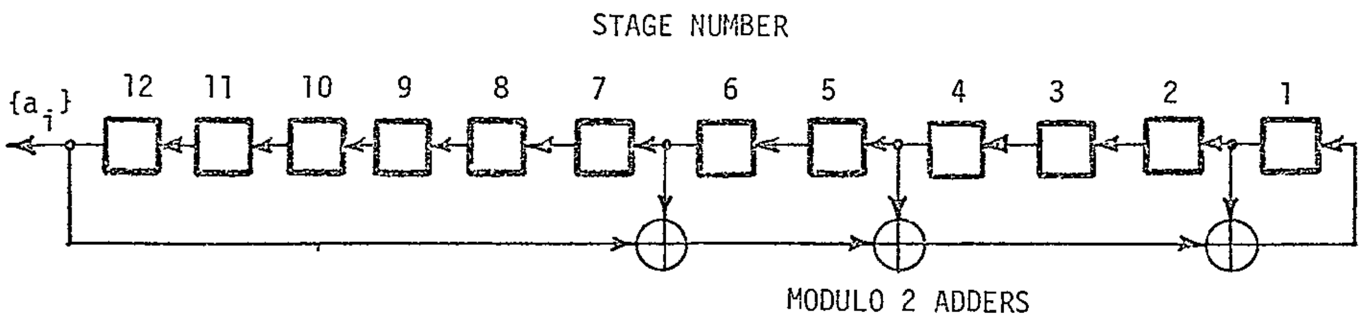
array antenna based upon the "near field" theory is extremely important and essential in the near future.

A maximum-length linear-feedback shift register sequence, i.e., m-sequences generated by a 12 stage shift register with a period equal to 4095 is recommended as the spread spectrum code. A typical code generator is given below:



In the code division multiple access situation, the theoretical optimal solution is to use the set of 64 bent function sequences of period 4095, enabling as much as 4095 simultaneous satellite operation of the SPS network. The bent sequences are guaranteed to be balanced, have long linear span and are easy to initialize. However, the set of maximum length sequence of period 4095 may suffice. This depends of course on the code partial correlation requirement and the number of satellites in the network. The design detail is discussed in Vol. II of this report.

At this point our results indicate that it is feasible to hold the antenna array phase error to less than one degree per module for the type of disturbances modeled in this report. However, there are irreducible error sources that are not considered herein and their effects remain to be seen. They include:

- Reference phase distribution errors
- Differential delays in the RF path

4.0 SPS PERFORMANCE AND SOLARSIM STATUS

Because of the complicated nature of the problem of evaluating performance of the SPS phase control system and because of the multiplicity and interaction of the problems as they relate to subsystem interfaces, the methods of analysis and computer simulation (analytical simulation) have been combined to yield performance of the SPS system. The result is the development of SOLARSIM--a computer program package that allows a parametric evaluation of critical performance issues. The current capabilities of SOLARSIM are highlighted in Table 4-1. The SOLARSIM program and its various subroutines have been exercised in great detail to provide system engineering tradeoffs and design data for the reference system. For example, a typical power pattern is depicted in Fig. 4.1. In what follows, we shall focus on the key results obtained from the program POWER TRANSFER EFFICIENCY.

4.1 Effects of System Jitters and Imperfections on the Power Transfer Efficiency of the Spacetenna

The system jitters and imperfections can be grouped into two main classes: (1) jitters arising due to spacetenna electrical components which include such effects as the amplitude jitter of the feed currents to the radiating elements of the spacetenna and the phase jitters of the feed currents originated from the phase control system and (2) jitters arising due to the mechanical imperfections of the spacetenna which include the subarray tilts (mechanical pointing error), tilt jitters and the location jitters. The location jitters include the transmitting and receiving elements and arise from the misplacement of the radiating elements.

4.2 Definition of Power Transfer Efficiency

The power transfer efficiency adopted is defined by:

Table 4-1. SOLARSIM Subroutine Package Capabilities.

SUBROUTINE NAME	PURPOSE
PONTING ERROR	Evaluation of the effect of phase error introduced by the phase distribution tree on pointing error
VARSUM	Evaluation of the effects of: •Subarray Tilts •Location Jitters •Phase Distribution System Error on spacetenna gain
POWER PATTERN	Evaluation of the power pattern as a function of: •Subarray Tilts •Current Amplitude Jitter •Phase Jitters •Location Jitters
POWER TRANSFER EFFICIENCY	Evaluation of power transfer efficiency or power pattern as a function of: •Subarray Tilts •Current Amplitude Jitter •Phase Jitters •Location Jitters
SIDR	Evaluates the reconstructed pilot phase error (rms) as a function of: •Pilot Signal Design Parameters •Link Budget •RF/Notch Filter Characteristics •Costas Loop Bandwidth

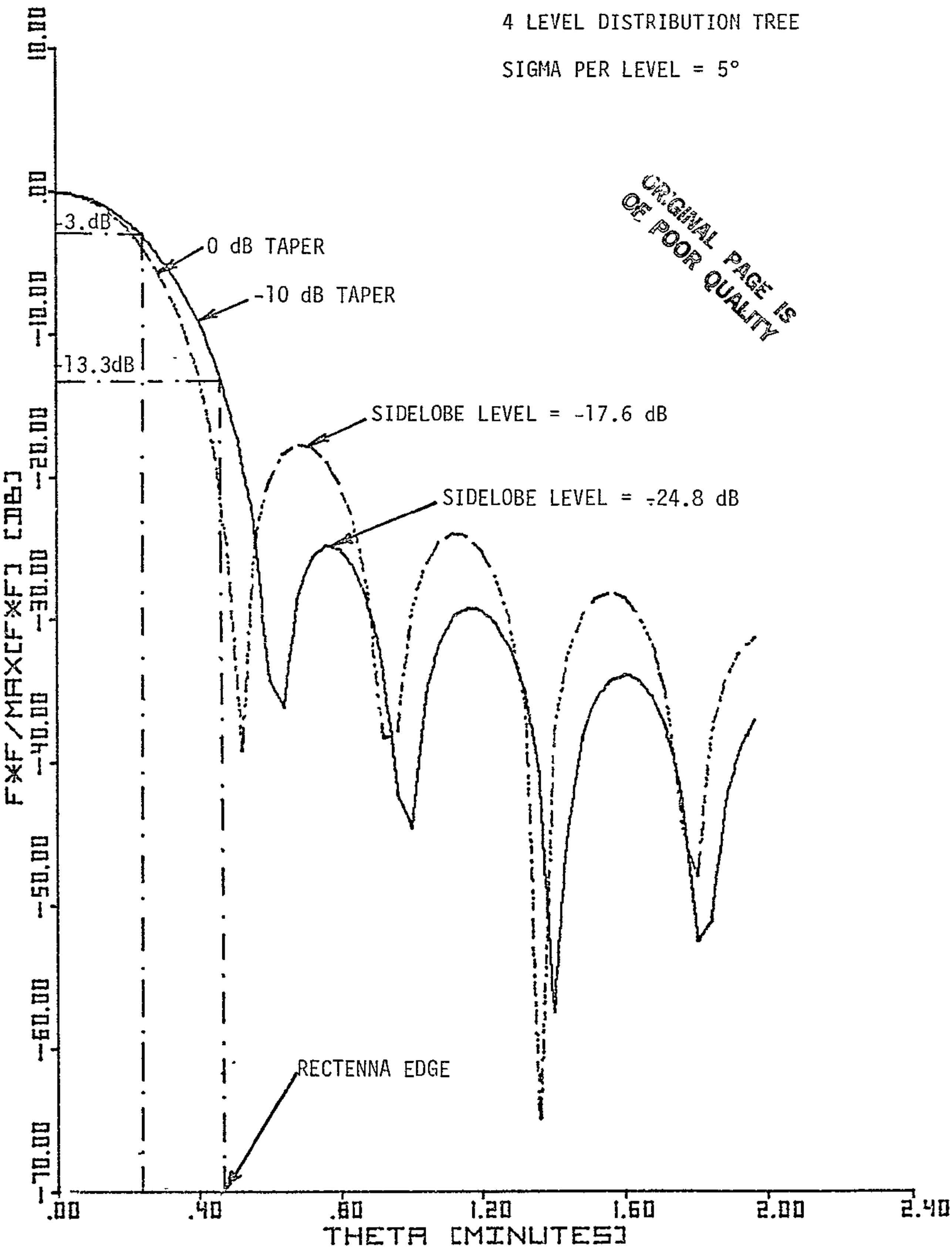


Figure 4.1. Power Pattern for 5° rms Phase Error.

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$$\text{POWER TRANSFER EFFICIENCY} = \frac{\text{Power Received by the 10 km Diameter Rectenna}}{\text{Total Power Radiated by the Spacetenna}}$$

Figure 4.2 makes the idea clear. The power transfer efficiency can be redefined as

$$\text{POWER TRANSFER EFFICIENCY} = \frac{\text{Power Output at Terminals A \& B}}{\text{Power Output at Terminals C \& D}}$$

This definition is convenient because the multiplying constants due to the propagation through the medium cancel out from the numerator and denominator. The computation of the denominator needs special attention since the average power pattern includes an "isotropic" term which is computationally difficult to account for if the individual (transponder) radiation phasors are not perfectly aligned in phase as a result of system jitters and imperfections. The present analytical approach alleviates this problem and is superior to the widely used Monte Carlo technique in this respect.

4.3 Effects of System Imperfections on SPS Efficiency

Figures 4.3 - 4.5 summarize the effects of the various system imperfections on the SPS power transfer efficiency obtained through SOLARSIM. In Figure 4.3, the power transfer efficiency is plotted against the total phase error produced by the SPS phase control system. For a mechanically perfect system with no location jitters and mechanical pointing errors or jitters (curve 1), the total rms phase error is restricted to less than 10^{o} at RF to yield a 90% efficiency. Curve 2 depicts the influence of the mechanical pointing error (assumed to be 10' with a jitter of 2') when the location jitters are absent. As can be seen from the figure, for a total phase error of 10^{o}.

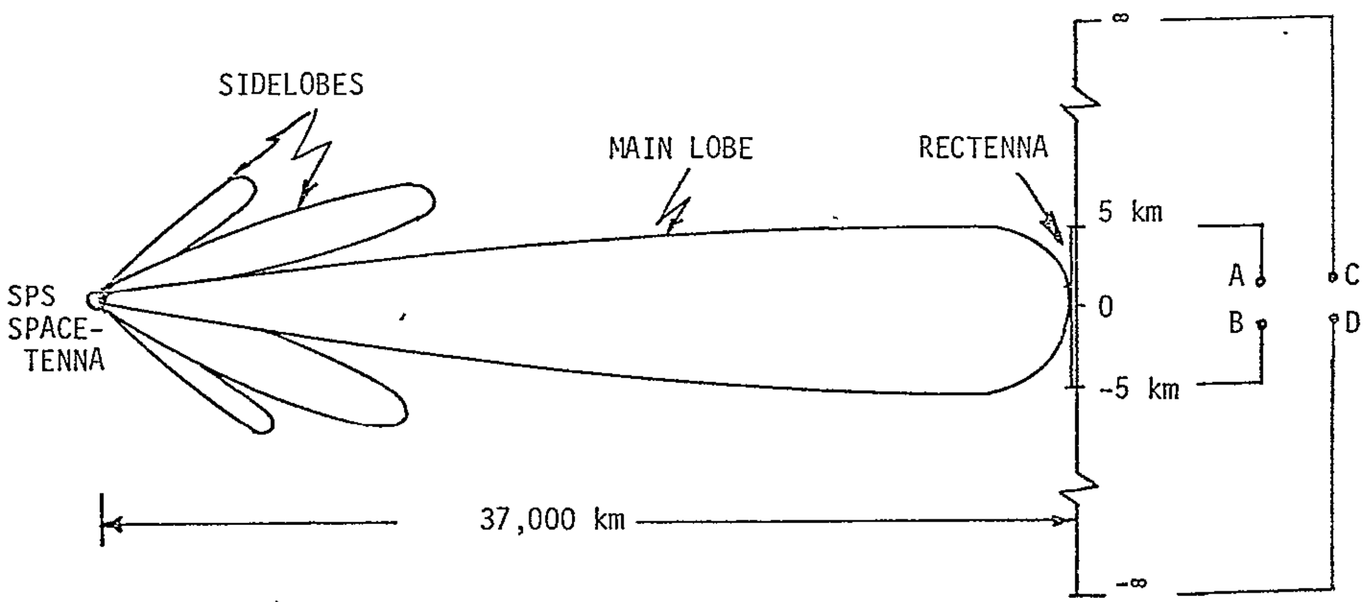

Figure 4.2. Geometry of the Power Pattern.

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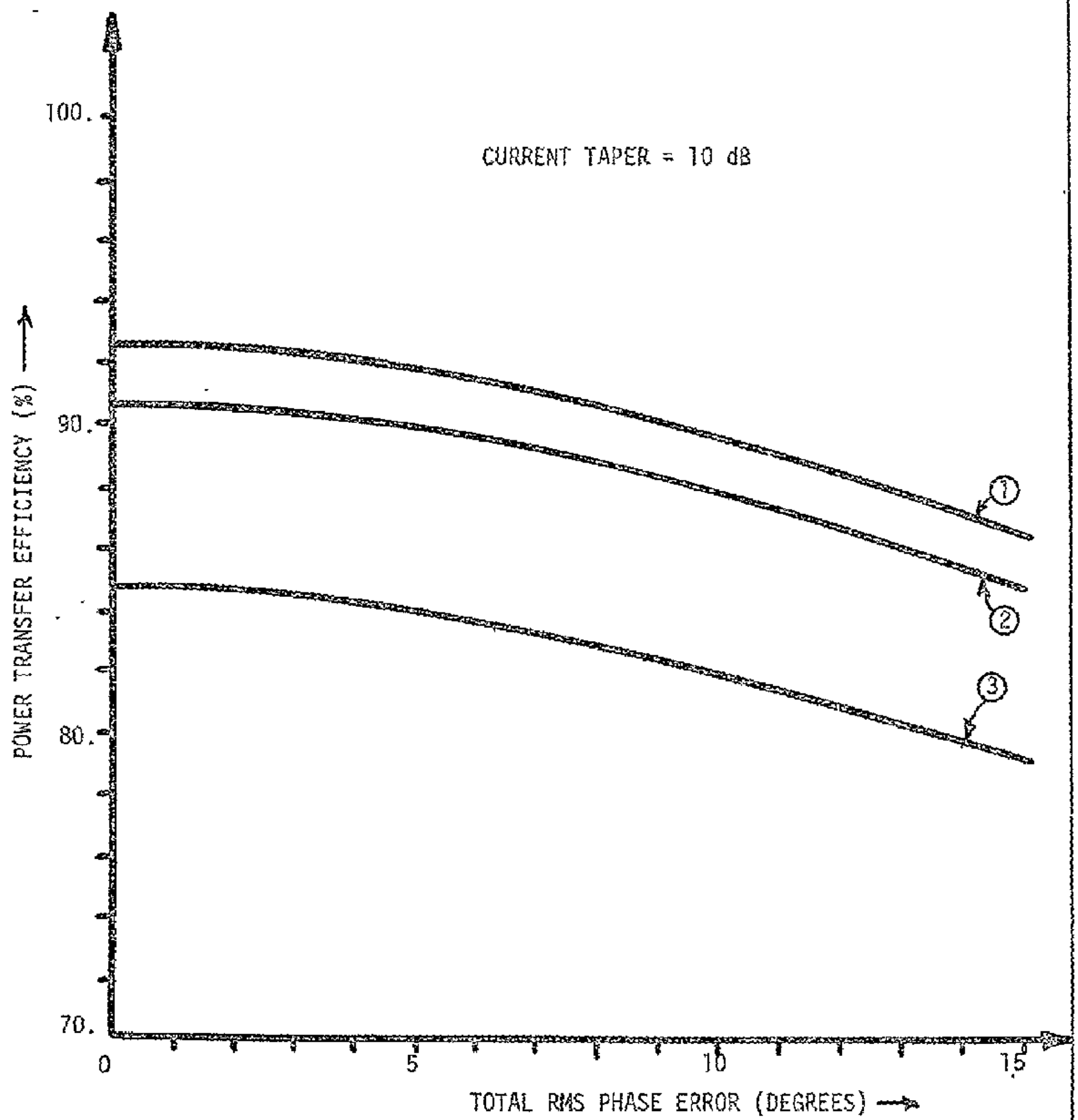

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① MECHANICAL POINTING ERROR (MPE) = 0, LOCATION JITTER (LJ) = 0, JITTER ON MECHANICAL POINTING = 0

② MPE = 10', LJ = 0, JITTER ON MPE = 2'

③ MPE = 10', LJ = 2% of λ, JITTER ON MPE = 2'

Figure 4.3. . Curves of Power Transfer Efficiency vs Total RMS Phase Error.

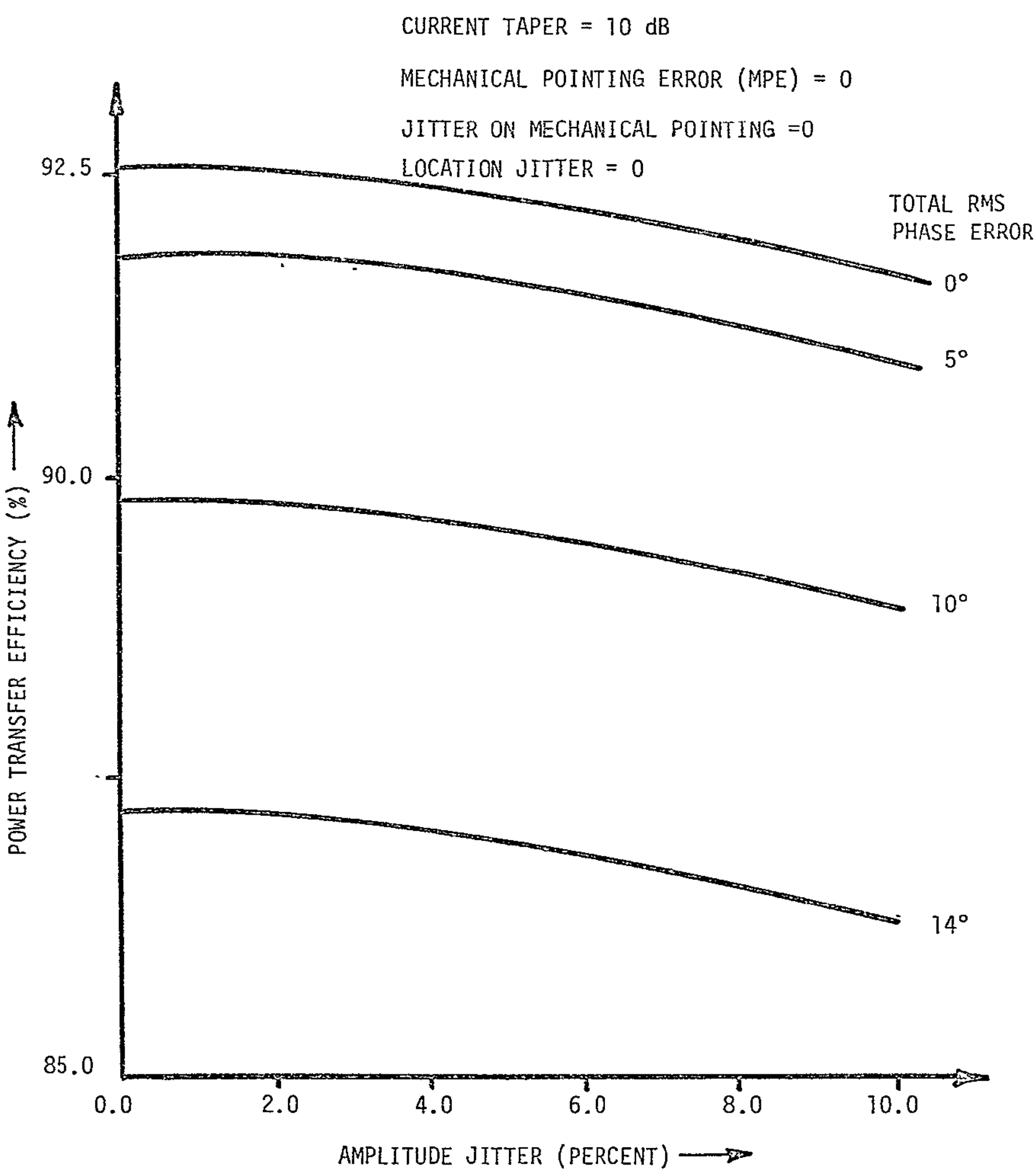

Figure 4.4. Effect of Amplitude Jitter on SPS Power Transfer Efficiency.

CURRENT TAPER = 10 dB

MECHANICAL POINTING ERROR = 0

JITTER ON MECHANICAL POINTING = 0

PHASE JITTER = 0

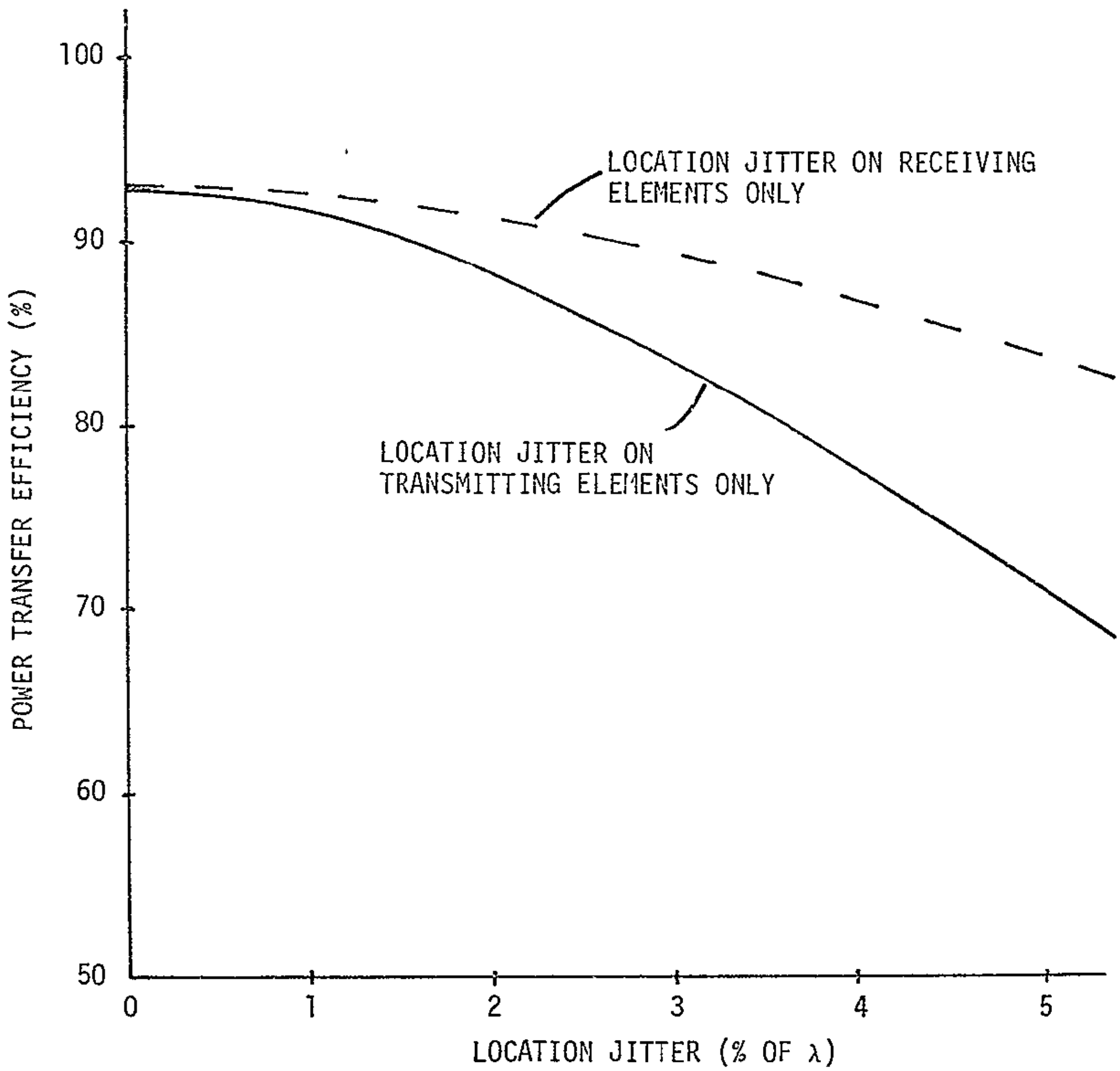

Figure 4.5. Effect of Location Jitters on the Otherwise Perfect SPS.

the power transfer efficiency of the spacetenna drops down to 87.3%. When the location jitters of 2% of lambda is added for the transmitting and receiving elements, this number drops down to 82.0% (see Curve 3). It is expected that the SPS system will operate in the region between Curve 1 and 3 . In this case, the power transfer efficiency will be less than 90% for a typical rms phase error of 10 degrees.

4.3.1 Current Amplitude Jitter

The effect of the current amplitude jitter is shown in Fig. 4.4 for a mechanically perfect system. As can be seen from the figure, for an amplitude jitter of 5%, the power transfer efficiency of the mechanically perfect spacetenna with the current phase jitter of 0^o is 92.3%. This value drops to 91.63% for the total phase error of 5^o and to 89.57% for a total phase error of 10^o. One can conclude that the power transfer efficiency is relatively insensitive to the amplitude jitters.

4.3.2 Location Jitters

Figure 4.5 investigates the effects of location jitters on the power transfer efficiency of an otherwise perfect SPS. As can be seen from the figure, the degradation of efficiency is severe: for a location jitter on each radiating element of 2% λ the power transfer efficiency drops to 88.3%. As a comparison, Fig. 4.3 shows that for a rms phase error of 7^o (2% λ = 7.2^o) the efficiency is down to 91.2%. It is noticeable that the effect produced by location jitters on the receiving (conjugating) elements is comparable to the effect produced by the phase error. This is true because both these effects enter into the transmission system at the same physical point, i.e., the center subarray. On the other hand, power transfer efficiency is rather sensitive to the location jitter on the radiating elements.

5.0 GROUND-BASED PHASE CONTROL SYSTEM FOR SPS

A ground-based phase control system is studied as an alternative approach to the current reference retrodirective phase control system. This concept is evaluated in terms of its feasibility and implementation at the system engineering level. The main impetus behind this approach is to reduce the amount of spaceborne hardware required. Since the beam forming is accomplished by ground command, inherent protection against beam stealing and intentional interference of the system operation is provided.

5.1 Ground-Based Phase Control Concept

The ground-based phase control system achieves beam forming by adjusting the phases of the individual transmitters on board SPS. The phase adjustments are controlled by ground commands. To specify the correct amount of adjustments,the phases of the power beams from each individual transmitter arriving at the rectenna center must be measured, the appropriate corrections determined (to ensure that all power beams arrive at the same phase) and relayed to the SPS. The proposed scheme to be considered in this report is sequential in nature, i.e., the phase measurement is performed one at a time for each individual transmitter at approximately one second intervals (measurement time allocated is 10 μsec). The phase corrections are updated once every second. A 10-bit phase quantization for the corrections giving 0.35° resolution is envisioned. The uplink command data rate is on the order of 10 Mbps. The functional operation of the ground-based phase control concept is summarized in Fig. 5.1. As evident from the figure, the key issues that

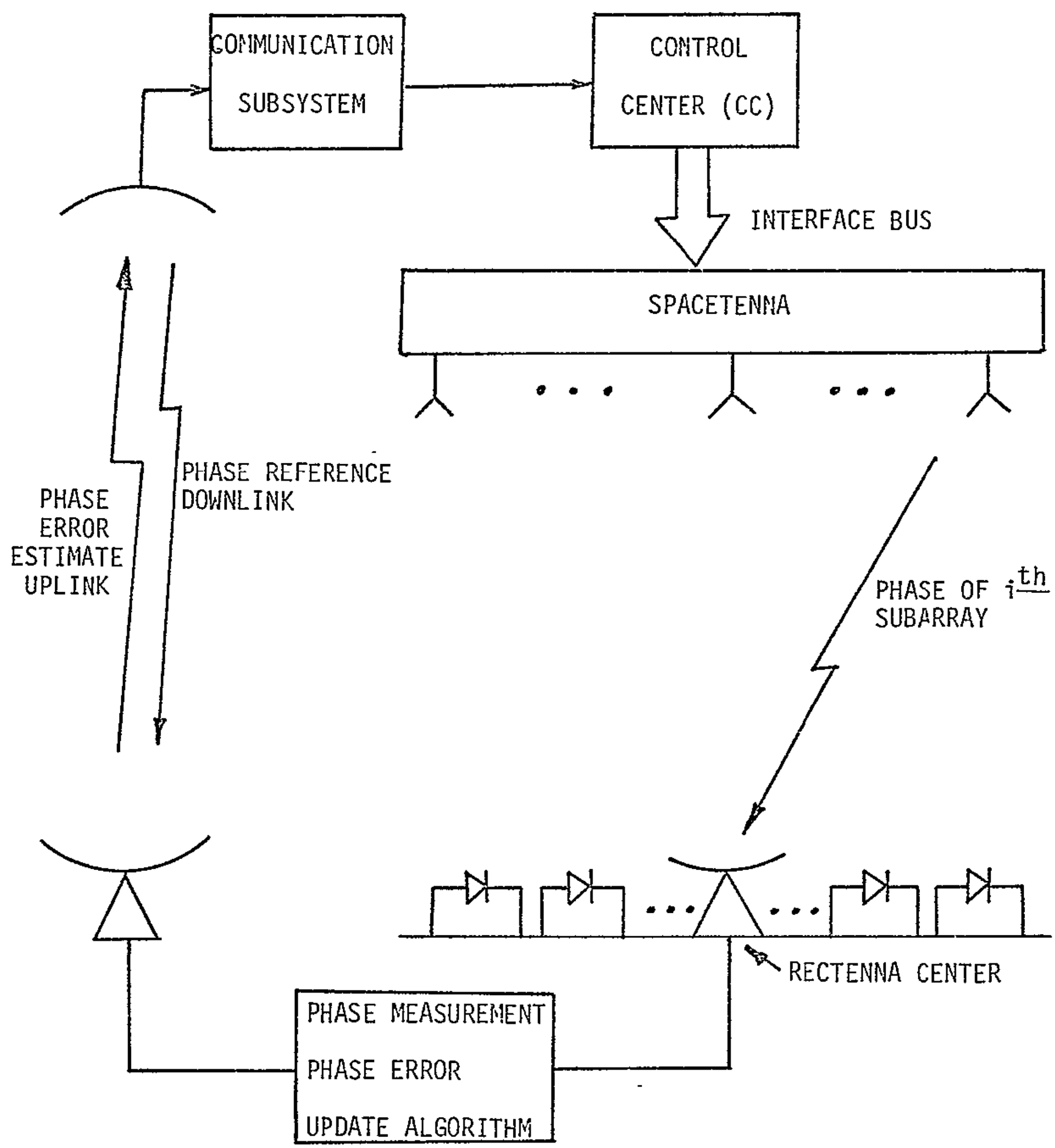

Figure 5.1. Ground Based Phase Control System Concept with Major Functional Blocks.

need to be addressed are:

(1) measurement waveform design and selection,

(2) phase measurement pilot reference design and selection,

(3) uplink phase corrections command link format and design, and

(4) system synchronization techniques.

The salient features of the ground-based phase control system are compared with the reference system in Fig. 5.2.

5.2 Baseline System for Ground-Based Phase Control

The implementation of the ground-based phase control concept is determined mainly by the phase control waveform designs employed. Based upon our waveform selections, functional subsystems to implement the ground-based phase control concept are identified and functionally represented. The resultant ground-based phase control functional block diagram is depicted in Fig. 5.3 and includes:

- Satellite Signal Processing
  - Time-Frequency Control
  - Processing Control Center
  - Signal Distribution Network
  - Processing Power Module
  - Downlink Pilot Transmitter
  - Uplink Command Receiver
- Ground Based Signal Processing
  - Pilot Beacon Receiver
  - Calibration Receiver
  - Phase Measurement Unit
  - Synchronization Unit
  - Phase Update Algorithm

REFERENCE SYSTEM	GROUND BASED SYSTEM
• REQUIRES LARGE AMOUNT OF SPACEBORNE ELECTRONICS	• REQUIRES LESS SPACEBORNE ELECTRONICS
• COMPLEX SPACEBORNE PROCESSING BUT SIMPLE GROUND SIGNAL PROCESSING	• COMPLEX GROUND PROCESSING BUT SIMPLE SPACEBORNE SIGNAL PROCESSING
• CORRECTS FOR IONOSPHERIC DISTURBANCES WITH CORRELATION TIME MORE THAN 0.25 sec	• CORRECTS FOR IONOSPHERIC DISTURBANCES WITH CORRELATION TIME MORE THAN 1.25 sec
• REQUIRES PN CODE FOR SECURITY	• SECURITY OF DOWNLINK
• INSTANTANEOUS CORRECTION FOR SPACETENNA MOTION	• SENSITIVE TO RATE OF CHANGE OF POINTING ERROR
• PERFORMANCE INHERENTLY LIMITED BY THE PHASE ERROR INTRODUCED BY THE PHASE REFERENCE DISTRIBUTION SYSTEM	• PERFORMANCE INHERENTLY LIMITED BY PHASE ERROR INTRODUCED BY THE DIGITAL PHASE SHIFTER
• DOES NOT CORRECT FOR DC PHASE OFFSETS BEYOND THE PHASE CONJUGATION POINT	• NOT AFFECTED BY DC OFFSETS INTRODUCED ANYWHERE ALONG THE SIGNAL PATH
• FAST START-UP	• SLOWER START-UP

Figure 5.22 Salient Features of the Ground Based Phase Control System and Their Comparison to the Reference Baseline System.

80 0057

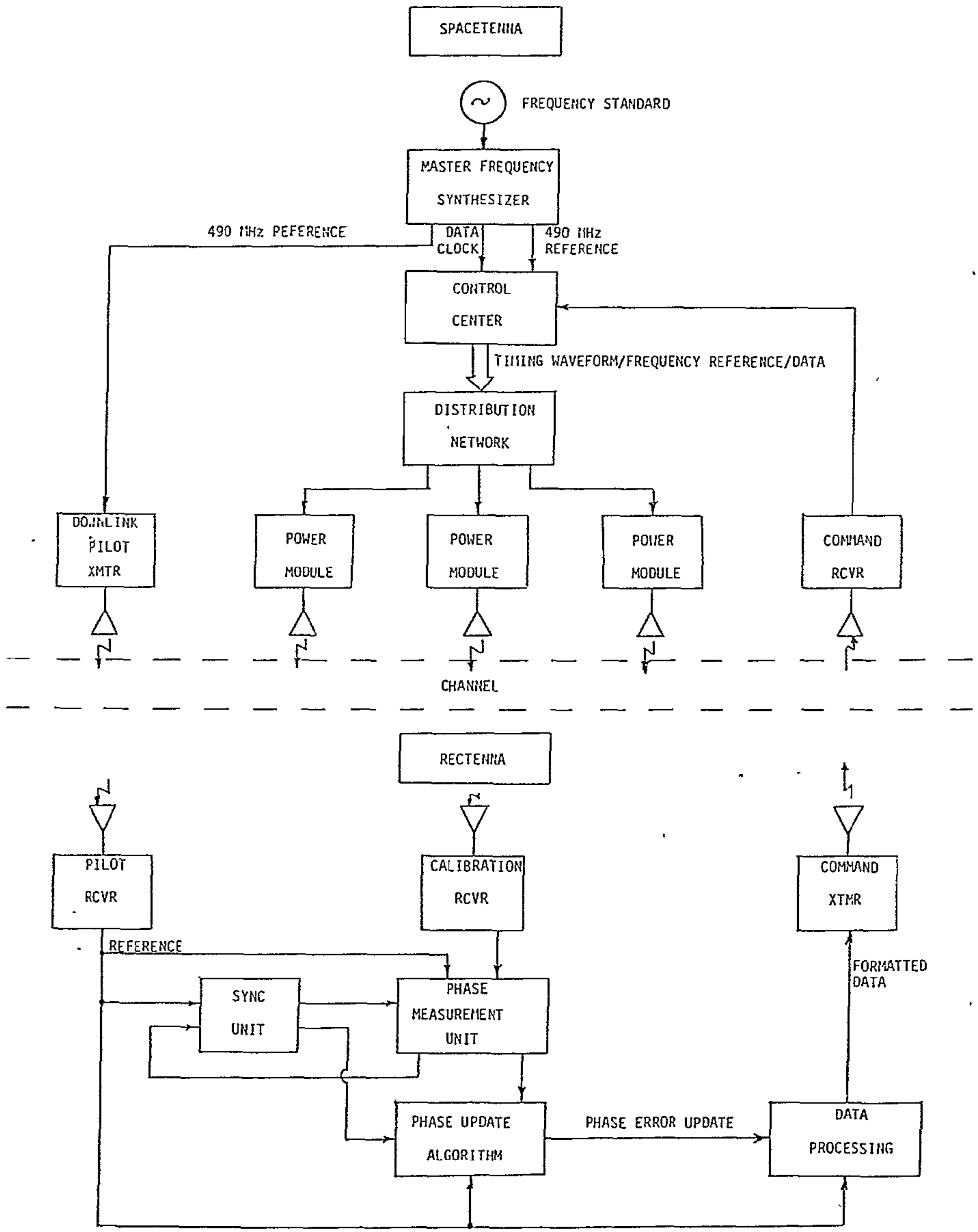

Figure 5.3. SPS Ground Based Phase Control Functional Block Diagram Showing System Timing Hierarchy. 80 0058

- Data Processing Unit
- Uplink Command Transmitter

The associated initial start-up procedure is also considered.

The ground-based system envisioned employs satellite based frequency/timing reference with an IF frequency of 490 MHz. A 4-tone measurement scheme using frequencies at 2,450 $\pm$ 9.57 MHz and 2,450 $\pm$ 19.14 MHz is selected. Each power module devotes 10 μsec per second for phase correction measurement, representing a minimal loss in total power transmitted. Two frequencies are chosen for the downlink and one frequency for uplink; the downlink pilot signal center frequency is set at 4.9 GHz.

Our preliminary investigation indicates that the effects of power beam interference and thermal noise on the phase measurement error can be controlled to a tolerable level. The ground based system can also function if the ionosphere is nonturbulent in nature and the satellite's tilt rate is limited to 0.5 min/sec.

5.3 Limiting Factors of the Feasibility of Ground-Based Phase Control System

The feasibility of the ground-based phase control concept becomes unclear if the conditions on the ionosphere and the satellite motion are not met. As indicated in Fig. 5.3, the ground based phase control system can only correct for random phase fluctuations which have a correlation time that it large compared with 1.25 sec. The noise components which are faster than 1.25 sec is uncompensated for and result in a degradation on transmission efficiency. Unfortunately, measured ionosphere data which is suitable for the SPS system is not readily available. (Most data are concerned with spatial correlations rather than temporal correlations. Also, most data are measured from low orbit satellites rather than geostationary satellites). The other limiting factor is the statistical behavior of the random pointing error exhibited by the spacetenna. Again, the fast component of this error is not corrected for and it contributes to power transfer efficiency degradation. At this point, we feel that the development and specification of models for ionospheric phase disturbance and satellite motion is essential. It is hoped that our findings can serve as a guideline for any parallel efforts in studying these two factors.

There are other factors that serve as drivers to determine the performance of the ground based phase control system. They depend on projected technologies, e.g., the availability of low noise S-band ten bit digital phase shifters, and low noise, wide band (40 MHz) klystrons.

5.4 Further Directions

Further efforts for the ground-based phase control study shold be directed towards:

(1) Development of detailed subsystem analytical models.

(2) Tradeoffs for waveform designs and RFI analysis.

(3) Development of computer simulation/graphics capabilities for performance analysis and system evaluations and tradeoffs.

(4) Study of satellite data distribution system networking methodology.

(5) Detailed comparison with the retrodirective reference system.

(6) Evaluation of ionospheric effects of reference phase control system.

Finally, the hybrid phase control system concept deserves to be investigated as it appears to overcome certain shortcomings of the reference retrodirective and the ground-based phase control system.

6.0 SUMMARY OVERVIEW OF REFERENCE SPS PHASE CONTROL SYSTEM ANALYTICAL/SIMULATION PERFORMANCE STATUS

The section serves to document the evolution, important milestones and findings of the SPS Antenna Phase Control System Hardware Simulation Study undertaken by LinCom since 1977. This study has progressed from a definition phase to the present evaluation phase. Currently, we are also investigating alternative approaches to the reference phase control system.

A critical requirement for the proposed Solar Power Satellite (SPS) Concept is the ability to beam and focus microwave energy to an a priori chosen spot located on the Earth's surface from a geostationary orbit of 38,000 Km, with a 90%+ transmission efficiency. The phase control problem, i.e., controlling the phases of the power amplifier output signals over the large transmitting antenna area so that a coherent beam can be formed and properly pointed, has been undertaken by LinCom corporation since 1977 under a contract to JSC. Our earlier efforts were involved with the definition and the selection of a reference phase control system. From then on, we have been involved primarily with the performance evaluation of the SPS reference phase control system through the development of SOLARSIM--a computer program package that allows parametric evaluation of critical performance issues using a combined simulation and analytical approach. In addition, a ground based phase-control concept is being investigated as an alternative approach to the SPS phase control problem.

6.1 Phase I Status Summary

Phase control system techniques based upon the method of retrodirectivity (phase conjugation) and by Ground Control were reviewed as candidate phase control techniques during the Phase I study (Ref. 1). For the phase conjugation method the effect of frequency separation was addressed. The beam pointing error was quantified and evaluated as a function of subarray coordinates, angles of arrival of the transmitted pilot, frequency offset and antenna flexing. It was determined that for this scheme the beam squinting (pointing error) would be excessive unless the conjugated phase was corrected for a phase shift due to the frequency difference. A (two-tone) scheme for employing in effect the same frequency for the pilot and the power signal was developed to alleviate this problem. The method of phase control via ground control was addressed in principle and preliminary comparisons of the phase conjugation method with the ground control method were made from the viewpoint of media stability, power robbing, security and radio frequency interference (RFI).

In addition to a review of phase control techniques, various approaches to the key problem of generating, maintaining and distributing a coherent, reference phase signal over the antenna were suggested, mathematically modeled and analyzed with respect to their ability to minimize: phase error build-up, beam diffusion and beam steering phase jitter, "cable length" and to maximize power transfer efficiency. Phase control configurations were suggested which alleviate the need for layout symmetry.

In order to minimize the required cable length, phase build-up, beam diffusion and phase jitter, Phase Control Centers (PCCs) were introduced and special layouts were suggested. This leads to the philosophy of using the reference phase generated at each Terminal PCC to phase control the power amplifiers (PAs) located in the individual subarrays.

Configurations for interconnecting the PCCs and the PAs are suggested so as to minimize cable length, phase build-up, beam diffusion and phase jitter. The phase control configurations suggested, mathematically modeled and analyzed include: (1) Master Slave (MS), (2) Mutual Synchronous Configuration (MSC), (3) Returnable Timing (RTC), (4) Equational Timing (ETC), (5) Hierarchial Master Slave 1 (HMS1) and 2 (HMS2).

System analysis requirements for performance comparisons were also defined. It was established that an analytical simulation approach to determine the power transfer efficiency was needed to perform further analysis and system tradeoffs.

6.2 Phase II Status Summary

Based upon Phase I study efforts, a reference phase control system via the retrodirectivity concept was proposed. The conceptual design and/or baseline for the three major technical areas: SPS pilot signal modulation format, reference phase distribution and SPS power transponder were defined during the Phase II study. The reference system SPS pilot waveform utilizes: (1) NRZ command modulation, (2) split phase, direct sequence pseudo-noise or spread spectrum modulation, Bi-ϕ-DS. This combined data-code modulation is used to biphase modulate the RF carrier. Multiple access in the SPS network is to be achieved via code division multiple access techniques (CDMA).

The reference phase distribution tree consists of three major parameters and one functional building block. The parameters of the tree optimized include: (1) the number of levels in the tree, (2) the number of branches per level and (3) the interconnecting cable length.

The functional building block consists of the Master Slave Returnable Timing System (MSRTS) units which is an active phase compensation technique that is capable of transfering frequency and phase from a maaster to a slave clock which is geographically separated.

The SPS power transponder can be partitioned into the pilot signal receiver, phase conjugation electronics and the high power amplifier phase control subsystem. Its purpose is to recover the phase of the received pilot signal, perform the phase conjugation and transmit the required microwave power with the proper phase.

Two critical hardware development areas were identified in the reference phase control system. They include the spread spectrum pilot receiver and the reference phase distribution system components such as the MSRTS unit. Hardware development on these areas are currently underway at JSC.

In a parallel effort, SOLARSIM has been developed (Ref. 1). Program packages were developed for computing the following performance measures:

(1) Antenna element covariance matrix.

(2) Individual realization of random power pattern.

(3) Mean far field power pattern.

(4) Main beam gain losses.

(5) RMS pointing error.

(6) Tilt/mechanical error effects on gain with effect of conjugation at other than radiating element level.

(7) Main beam program transfer efficiency.

The SOLARSIM program was also demonstrated to be very useful as a general evaluation tool even though it has not been fully developed during Phase II. Examples of the more important findings were:

(1) Selection of a four-level phase distribution tree to reduce RMS pointing error.

(2) A 10 dB power taper reduces the sidelobe level by approximately 7 dB.

(3) With no phase control, the spacetenna appears to be an isotropic radiating element with a power density of 3×10^{-5} mW/cm^2 measured on Earth.

(4) The rms phase error of the phase control system should be limited to 10^o at the RF level.

(5) Phase conjugation at the power module level is required to reduce the system performance sensitivity to tilt effects.

6.3 Phase III Status Summary

The purpose of Phase III is to quantitatively address certain key technical tasks associated with the reference phase control system requiring further analysis and areas where computer simulation is still required to complete the system simulation capability. The key technical problems concerning the reference phase control system design and specifications are the SPS pilot signal design and power transponder analysis. The continued development of SOLARSIM is concentrated on updating the SPS system simulation capabilities. A ground-based phase control alternative is also addressed

The pilot signal design is analyzed to insure optimum performance with respect to the specific SPS environment. The associated power transponder is analyzed and an appropriate analytical model established to include the evaluation of the power transponder performance in the overall SPS simulation capability. Based on the analysis and system tradeoffs performed using the SOLARSIM, key parameters for the pilot signal and transponder design are specified. For the pilot signal, they include the uplink EIRP, the chip rate, and the PN code period. For the power transponder, they include the RF filter bandwidth, the notch filter bandwidth, dc attenuation and gain slope, the Costas loop bandwidth and associated phase jitter, the PN code loop jitter, and the PA (Klystron) phase control loop bandwidth.

During Phase III, the SOLARSIM program was continually expanded and modified by using more refined models and by incorporating newly developed softwares. A more meaningful performance measure, the system transfer efficiency which is defined as the ratio of the received power intercepted by the rectenna to the total radiated power, has been adopted. Using the SOLARSIM program, we have evaluated the sensitivity of SPS performance due to phase error systematic, random temporal effects and mechanical alignment accuracy (tilts). It is found that the SPS power transfer efficiency is rather sensitive to location jitter (waveguide surface tolerance) when the tilts are taken into effect.

During Phase III, a ground-based phase control system is also studied as an alternative approach to the current reference retrodirective phase control system. The ground-based concept is anticipated to simplify the spaceborne hardware requirement.

The implementation of the ground-based phase control concept is determined by the phase control waveform designs employed. In the ground based phase control system, three different waveforms are required in the design: (1) downlink frequency reference signal, (2) downlink subarray (power module) transmission and (3) an uplink phase error correction command signal. Based on our waveform selections, functional subsystems to implement the ground-based phase control concept are identified and functionally represented. The resultant ground-based phase control system includes:

- Satellite Signal Processing
  - Time-Frequency Control
  - Processing Control Center
  - Signal Distribution Network
  - Processing Power Module
  - Downlink Pilot Transmitter
  - Uplink Command Receiver
- Ground Based Signal Processing
  - Pilot Beacon Receiver
  - Calibration Receiver
  - Phase Measurement Unit
  - Synchronization Unit
  - Phase Update Algorithm
  - Data Processing Unit
  - Uplink Command Transmitter

The associated initial start-up procedure is considered.

Our preliminary investigation indicates that the effects of power beam interference and thermal noise on the phase measurement error can be limited to a tolerable level. The ground based system can also function if the ionosphere is nonturbulent in nature and the satellite's tilt range is limited to 0.5 $\widehat{\text{min}}$/sec. The feasibility of the ground-based phase control concept becomes unclear if the conditions on the ionosphere and the satellite motion are not met.

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