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Microwave Power Transmitting Phased Array Antenna Research Project Summary Report

Richard M. Dickinson

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Space Administration

Jet Propulsion Laboratory
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FOREWORD

In 1973, the Jet Propulsion Laboratory was requested by NASA's Office of Applications, and subsequently by their Office of Energy Programs, to investigate the technology associated with the concept of beamed microwave power. Wireless power transmission is a key technology of satellite power systems that are proposed for importing, via conversion to microwave beam, the nearly continuous sunlight energy existing in geosynchronous orbit.

In 1975, supported by JPL-managed contracts with the Raytheon Company, a small-scale laboratory demonstration of beamed power was conducted. This experiment achieved an end-to-end dc efficiency in power transmission of 54% for approximately 1/2 kW transmitted over a 1.4-m range. The laboratory test demonstrated that there were no fundamental physical limitations to achieving greater than 50% end-to-end beamed power efficiency.

A further test of a larger area rectenna conducted at Goldstone, California, in 1975 yielded an output of over 34 kW of dc power, recovered with a combined RF collection-conversion efficiency of 82.5% at a wireless power transmission range of 1.54 km. The reception-conversion (RXCv) rectenna array had an area of 24 m², compared to the m² area in the previous lab test, and was used in conjunction with an existing 26-m-diameter antenna equipped with a 400-kW CW klystron operated at a reduced output power level. A large fraction of the beamed power spilled around the edges of the RXCV array due to a limited-focus capability of the transmitting antenna and the RXCV's limited size. Nevertheless, it was conclusively demonstrated that the small array receiving rectenna performance test results achieved in the lab could be accurately scaled upward to large-area, long-distance planar rectenna arrays in the field.

The technology investigation next turned toward the proposed satellite power systems' power transmitting phased arrays. Could antennas of up to 1-km diameter, composed of up to 10⁴ subarrays operating at S-band (2.45-GHz) RF frequencies, and radiating up to 6 GW or more be phase controlled accurately enough to be continuously pointed toward a single spot 37,500 km away on the Earth's surface, while maintaining the tightly bunched beam necessary for efficient energy transport? To answer these and other questions, the key elements of the proposed pilot-beam-steered, retrodirective power array were to be evaluated in a proposed instrumented field test at Goldstone. A program to carry out such a field test was initiated in September 1975. A preliminary program plan was prepared; a conceptual design of an experimental retrodirective power array and testing system were defined; and limited breadboard model tests were conducted. In the autumn of 1977, however, the microwave technology program was redirected and the phased array antenna test project was discontinued. This report presents the microwave power transmitting phased array (MPTX) project objectives and approach, and the design and limited breadboard test results achieved before the project was terminated. The insights and developments obtained in this technology investigation may prove useful for future satellite power system studies and assessments.

EXECUTIVE SUMMARY

An initial design study and the development results of an S-band RF power transmitting phased array antenna experiment system that was to be implemented by the Jet Propulsion Laboratory for NASA are presented. The array was to be designed, constructed, and instrumented to permit wireless power transmission technology evaluation measurements. The planned measurements were to provide data relative to the achievable performance in the state of the art of flexible-surface, retrodirective arrays, as a step in technology evaluating the Satellite Power System (SPS) concept for importing to Earth, via microwave beams, the nearly continuous solar power available in geosynchronous orbit.

As currently proposed, the approximately one-kilometer-diameter SPS planar transmitting array antenna would effectively be a flexible-surface RF radiator when considered in terms of the normally required overall surface tolerances (on the order of millimeters) necessary for high beam-power efficiency. Such flexibility would result from material limitations coupled with the requisite large diameter. However, by use of the retrodirective array technique and a unique phase reference distribution scheme, it is, in principle, possible to electronically compensate for the resulting flexible-surface RF path length phase errors. A small model, flexible-surface array incorporating high-power, dc-to-RF converters, pointed by use of a low-level pilot beam and instrumented for detailed performance measurements was to be built to assess the capabilities of the applicable technology.

This report presents details of the microwave power transmitting phased array (MPTX) design, instrumentation approaches, system block diagrams, and measured component and breadboard characteristics achieved before the project was discontinued.

The principal accomplishments of the project were in the following categories:

A. Design

1. An experimental demonstration and a rigorous technology verification test were designed for evaluating the beam-forming and beam-pointing accuracy of a pilot-beam steered, retrodirective, power transmitting array operating on a flexible surface.
2. An end-to-end electric power transmission test system employing high-power S-band microwaves was designed.
3. A preliminary design of a subsystem for monitoring microwave phased array rms phase error performance was generated.
4. A design solution was fostered for distributing a precision phase reference over a large flexible array aperture via a tree-branching network that employs the retrodirective

principle for self-compensation of transmission line length changes.

The resulting unique phase reference distribution and phase conjugation scheme yields exact array antenna beam pattern redirection -- there is no angular squint of the different-frequency, power-beam pattern relative to the pilot beam, (which is normally present in principal frequency-offset retrodirective array schemes).

5. Both dual pilot-beam tests and simultaneous dual-power beam tests were designed.
6. A simple approach with which to demonstrate a coding scheme for the pilot-beam signal was devised.

B. Development

1. Detailed Design Requirements for a scaled-model, RF power transmitting phased array and its instrumentation were generated.
2. Turn-on and turn-off sequences for RF power transmitting phased arrays were developed.
3. A procedure was developed for phase trimming of individual phased array subarrays relative to a central phase reference subarray.
4. High-power, microwave phased array safety considerations for personnel and equipment were identified.
5. A work breakdown structure and schedule for implementing the MPTX were developed, and the required resources were scoped.

C. Demonstrations

1. Phase-locked loop conjugation over a compensating cable length was demonstrated.
2. The thermal sensitivity and stability of the electronic phased array power components were established; their amplitude, frequency and phase responses were measured under thermal operating conditions.
3. A cost effective RF power converter subsystem design was achieved, by incorporating a modified form of the mass-produced consumer microwave oven magnetron. The modification consisted of phase injection locking and cleanup of the RF output spectrum by removing the filament excitation after tube turn-on.

4. It was demonstrated that an efficient dual-power level array is feasible by use of an injection-locked magnetron that, when turned-off, allows the low-level injection-locking signal to be transmitted past the inert high-power oscillator with low loss.
5. A two-element, X-band retrodirective array with phase-locked loop conjugation employing a reference transmitted over a phase path length compensating distribution line was demonstrated.

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Particular thanks are extended to Mr. Ralph Chernoff for the Active Retrodirective Array, Mr. Richard Kolbly for the magnetron experiments, Mr. Michel Schwartz for the slotted waveguide antenna, and Mr. Ed Finnegan for the discussions on power supplies.

This investigation was performed under the program guidance of Mr. Simon Manson of the Solar Energy Division, Office of Energy Programs, Office of Aeronautics and Space Technology, and with the technical direction of Mr. Sam Fordyce of the Office of Applications, NASA Headquarters.

ABSTRACT

An initial design study and the development results of an S-band RF power transmitting phased array antenna experiment system that was to be implemented by the Jet Propulsion Laboratory for NASA are presented. The array was to be designed, constructed and instrumented to permit wireless power transmission technology evaluation measurements. The planned measurements were to provide data relative to the achievable performance in the state of the art of flexible surface, retrodirective arrays, as a step in technically evaluating the Satellite Power System (SPS) concept for importing to Earth, via microwave beams, the nearly continuous solar power available in geosynchronous orbit.

This report presents details of the microwave power transmitting phased array (MPTX) design, instrumentation approaches, system block diagrams, and measured component and breadboard characteristics achieved before the project was discontinued.

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SECTION I

INTRODUCTION

A. MICROWAVE BEAM CONTROL

A key element of the Satellite Power System (SPS) technology (Ref. 1-1) is the microwave beam control subsystem. Its safety performance and efficiency effectiveness are prime concerns in considering a wireless power link from the orbiting spacecraft to the surface of the Earth.

Not only must the radio frequency (RF) beam be accurately pointed toward the target rectenna, but also the beam shape and amplitude must be controlled for safety and to maintain low sidelobes and high beam efficiency. High-beam efficiency means that a majority of the energy radiated from the antenna is contained within a small-diameter beam, to minimize both the transmitter and rectenna areas.

Low sidelobes are necessary far from the rectenna to minimize radio frequency interference (RFI). Near-in sidelobes must be low for biota safety.

These desirable beam characteristics are not mutually exclusive, but engineering compromises are necessary in the array design parameters to balance the competing characteristics of the functional requirements.

Considerations of the beam pointing accuracy, the beam safety scheme, its reaction time, the pointing control degradation or failure characteristics, the control of the energy distribution within the beam, levels of RF radiation outside of the main beam, the subsystem longevity and required maintenance, turn-on characteristics, and turn-off characteristics are all performance parameters or characteristics that need to be known with reasonable accuracy before a commitment to handle up to 6 GW or more of RF energy emanating from a remote spacecraft can be contemplated.

B. MPTX PROJECT OBJECTIVE

The objective of the microwave power transmitting phased array (MPTX) project at JPL was to provide measured information about the technology of the microwave power transmitting phased array proposed for the SPS. Of particular interest is the determination of the degree of accuracy with which an RF phase reference could be distributed over a large, mechanically flexible antenna structure and the accuracy of performing the associated RF phase conjugation of the reference signal and a received pilot-beam signal, when in the presence of the noise that accompanies high-power RF generation. (A detailed discussion of active retrodirective array antenna fundamentals and the added requirements for high-power transmission are contained in Appendix A.)

SECTION II

PROJECT APPROACH

A. MPTX CONCEPT

A functional block diagram of the proposed MPTX concept is shown in Fig. 2-1. The three major blocks of equipment are the power transmitting array, the existing power receiving or reception-conversion (RXCV) array (Ref. 2-1), and the control and status monitoring equipment. The block diagram is designed to permit the measurements and to investigate the operational sequences and events listed in Table 2-1. The entries in the table are based on the SPS array discussion in Appendix A.

The ultimate proof of concept for the pilot-beam steered retro-directive array on a flexible surface was considered to be that the array main beam pointing could be maintained on the RXCV pilot transmitter even though the array subarrays were moving about. To that end, Fig. 2-2 shows the proposed techniques of supporting the individual subarrays to allow positioning for simulating certain test configurations or to promote the flexible mechanical support condition.

Figure 2-3 is the artist's drawing of the overall view of the proposed MPTX configuration, showing the relative positions of the MPTX and RXCV arrays, along with inset details of the rear of a typical subarray and the front edge of the slotted waveguide RF subarray radiator. The MPTX array would have to be located rather close to the RXCV array to promote high beam-power transfer efficiency, since the proposed project budget would not allow large antenna diameters at either end of the system.

The planned period of performance for the project was three years, from September 1975 to September 1978. The milestone schedule for executing the project is shown in Fig. 2-4. Figure 2-5 is the work breakdown structure.

Details of the MPTX system design were to be developed on the basis of breadboard and prototype experiments. It was planned that a small, two- or three-element, low-power version of the pilot-beam receiver-transmitter subarray phase-control circuitry would be constructed by JPL and tested with the selected power tubes. From these breadboard results would come the detailed specifications for various elements of hardware such as receivers, power amplifier modules, instrumentation packages, etc. These would be procured either singly or in groups to yield a prototype subarray for further testing. Based in part on the prototype test results, detailed design specifications and requirements could be prepared and used to contract for producing the final MPTX production hardware. JPL was to perform the final hardware installation at Goldstone, the integration, checkout, and the testing and data reduction.

The total project cost over the three-year period was estimated at approximately \$2 million. The project contingency in the MPTX effort would be to produce fewer or more total subarrays, depending on the developing project cost history, as was successfully employed in the previous RXCV project.

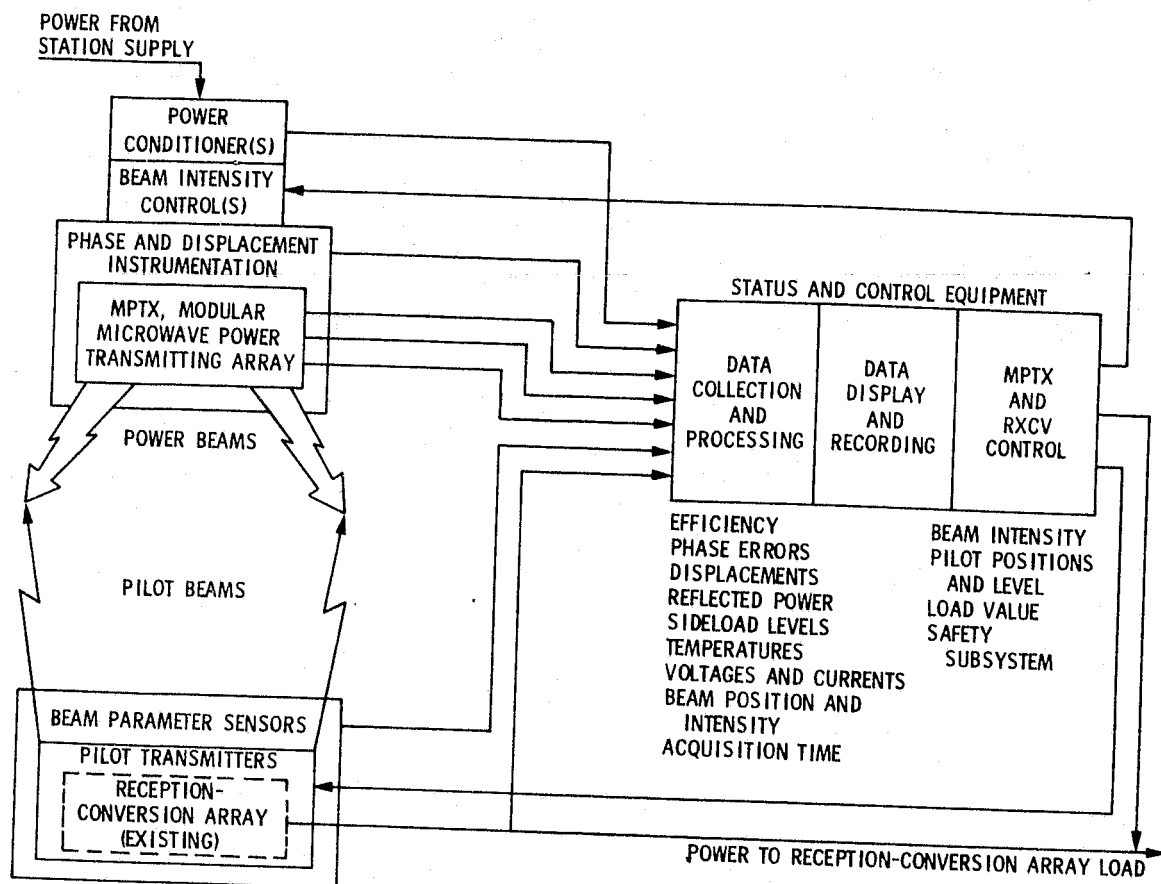


Figure 2-1. MPTX Functional Block Diagram

Table 2-1. Tests to be Conducted With a Modular Transmitting Array

-
1. On-axis (and elsewhere) power density of the emitted energy when the phased array is operating in an unphased mode (pilot beam absent, uncoded, or of very low level)
 2. Time to synchronize vs. pilot signal level
 3. Effects of multiple pilots
 4. Effects of failed elements
 5. Amplitude quantization effects
 6. Time to desynchronize vs. pilot signal level
 7. Performance vs. rms and peak phase errors and correlation regions
 8. Start-up and shut-down techniques and transients
 9. System performance with simulated control system delays
 10. Phase alignment and phase trim techniques
 11. Interstice effects
 12. Polarization performance
 13. Mutual coupling effects
 14. Load reflection effects
 15. Movable backup support structure effects
 16. Pilot tracking accuracy and rates
-

B. MPTX DESIGN REQUIREMENTS

A copy of the MPTX design requirements is given in Appendix B. A detailed table of performance monitored parameters, the associated measurement ranges and their tolerances is given. Requirements are included for personnel safety, dual-pilot and power-beam capability, positionable pilot-beam transmitter locations, dual power level capability for checkout and alignment at a low-power level, and harmonic and spurious radiation output levels among others. Requirements for testing, quality assurance provisions and a weather summary for Goldstone are also included in the document.

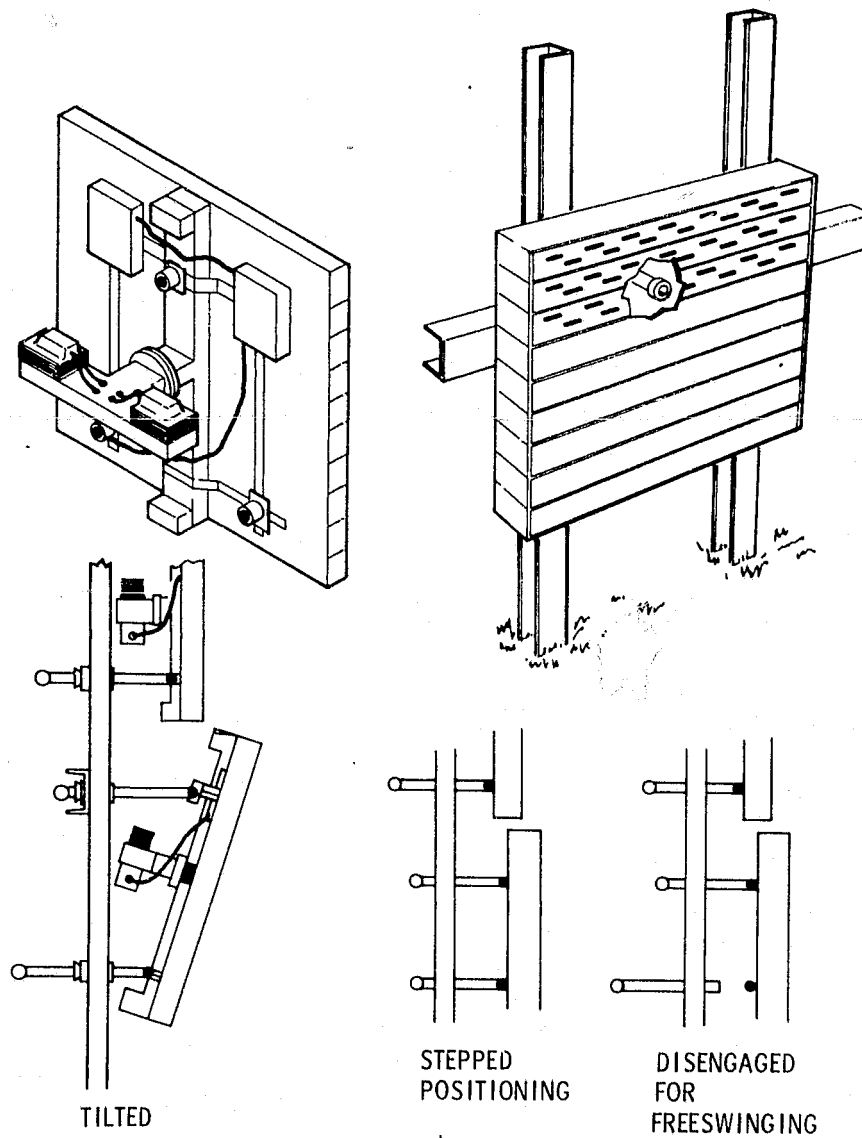


Figure 2-2. MPTX Subarray Support Fixture Concept

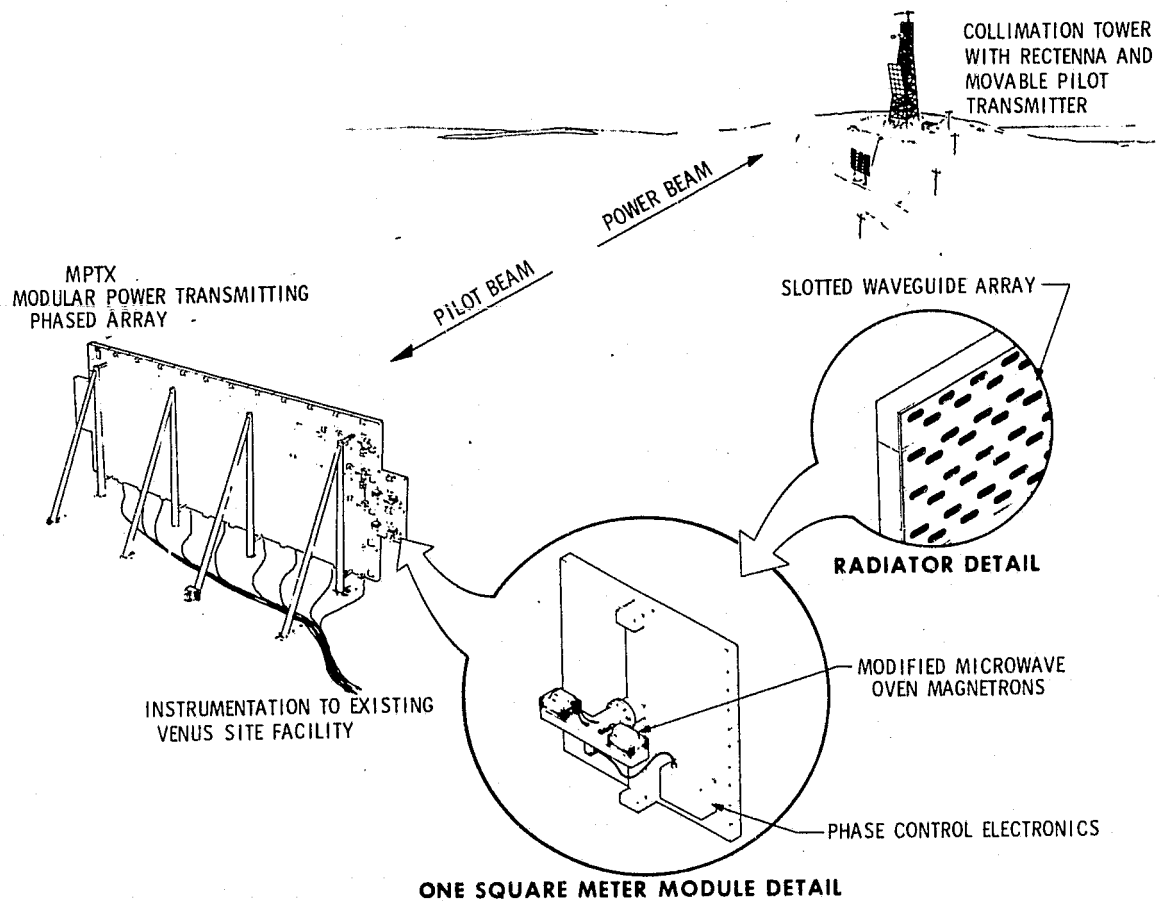


Figure 2-3. Artist's Concept of MPTX Verification Test

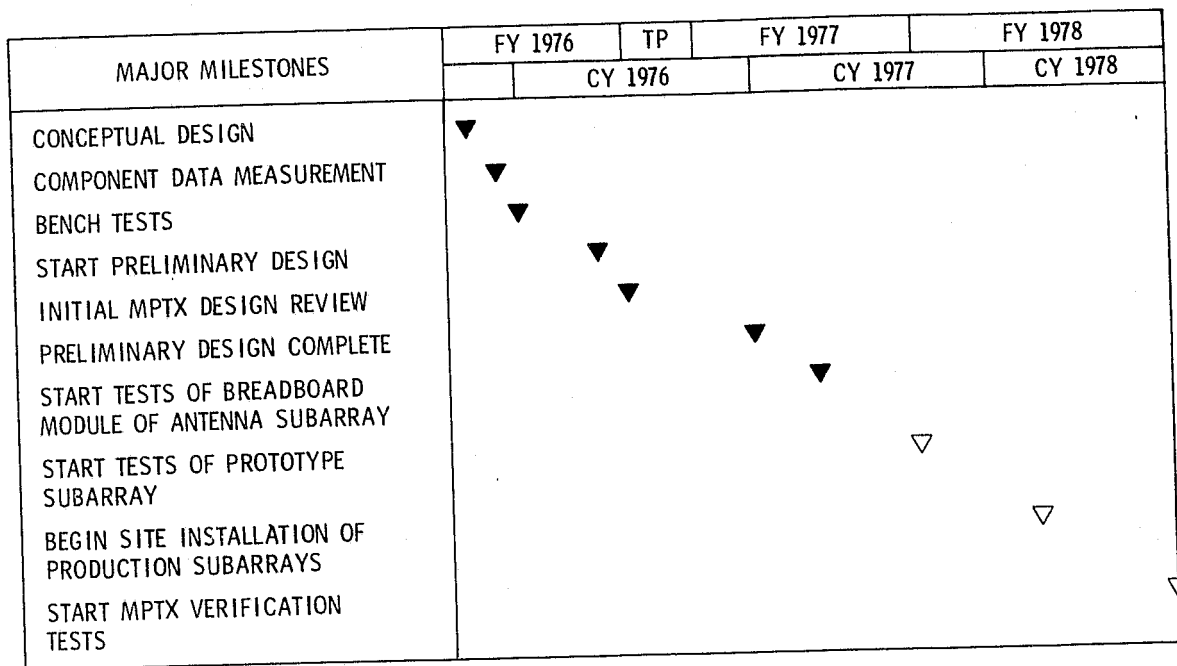


Figure 2-4. MPTX Project Milestone Schedule

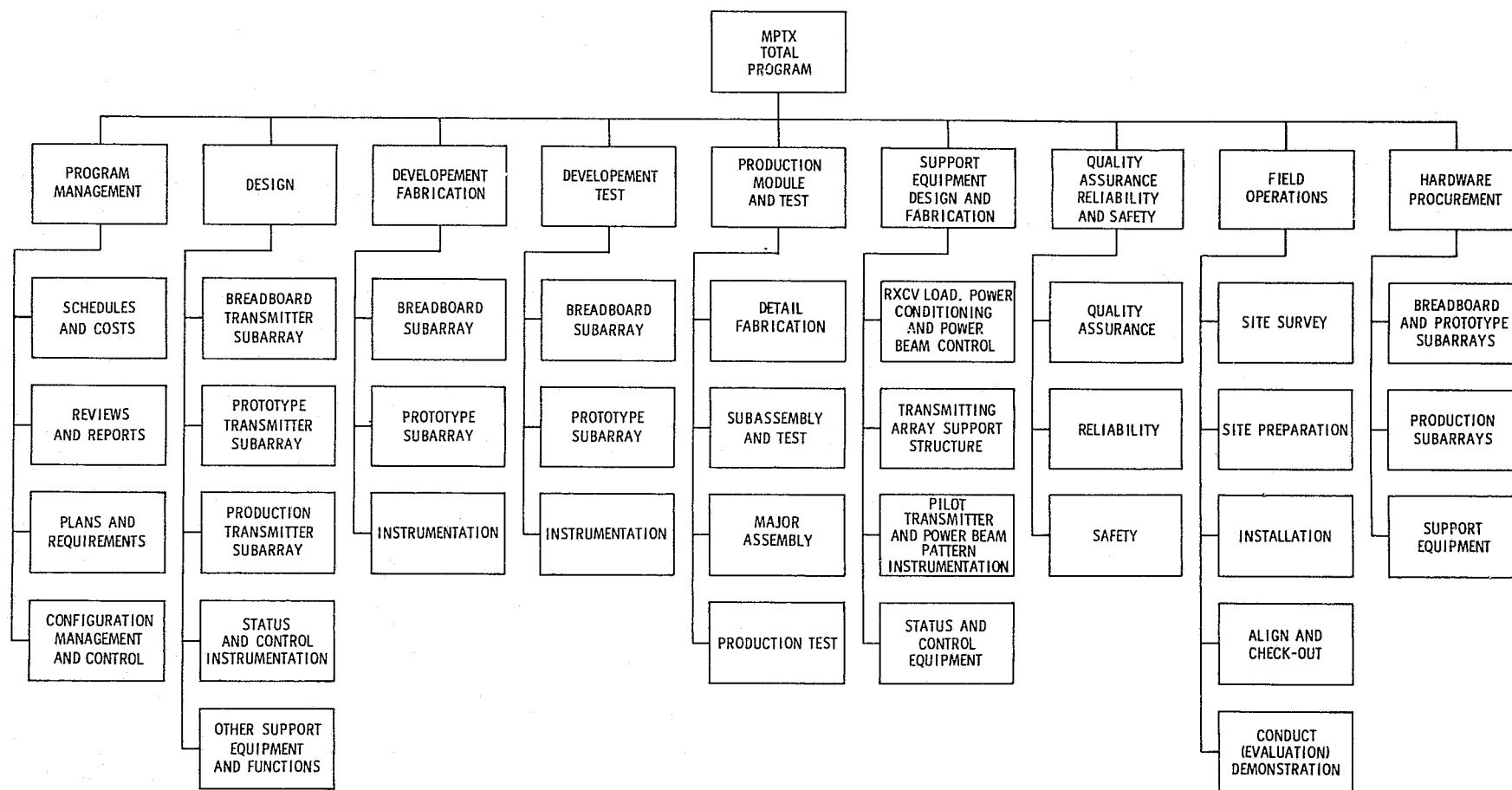


Figure 2-5. MPTX Project Work Breakdown Structure

SECTION III

PRELIMINARY MPTX DESIGN CONSIDERATIONS

A. PILOT-BEAM SIGNAL-TO-NOISE RATIO

The array device that affects the aperture amplitude distribution fidelity is the dc-to-RF converter. Its amplitude may be modified by tube gain degradation, increased noise output, or failure. The aperture phase distribution may be modified by the phase reference distribution accuracy, the phase conjugator fidelity, or the pilot-beam receiver signal-to-noise ratio (SNR). Significantly, the high-power dc-to-RF converter noise can thus affect both the amplitude and phase distribution accuracy in the array aperture. For this reason, it was deemed that to perform accurate, power-phased array technology investigations, it would be necessary to use high-power converter tubes in any test configuration! Low-power-level tests of a mainly receiving-only phased array could possibly be altered to introduce simulated noise to evaluate the array beam-steering adequacy, but there would always be some large degree of uncertainty in the test result because of questions about the degree of simulation accuracy. Thus, a design requirement for the MPTX would be the use of high-power (≥ 1 kW) RF tubes.

B. KLYSTRONS

Klystrons were the premier continuous wave (CW) high-power tubes available at the beginning of the MPTX project. The klystron amplifier tube can be readily phase controlled by varying the phase of the low-level input RF drive signal. Each cavity of the klystron may add about 15 to 20 dB of gain. Nevertheless, the complexities of the associated equipments for the proper operation and protection of the tube, along with the tubes' prices for the limited quantities required for the MPTX, were too expensive, amounting to approximately \$7,000 for an air-cooled, 2-kW klystron in quantities of 32 to 64.

C. MAGNETRON POSSIBILITY

In considering alternatives, the consumer market microwave oven magnetron was very tempting because the approximately 1-kW tube, blower, and unfiltered power supply could be obtained for around \$100 each! This low price results from the quantity production economies of scale.

Nevertheless, the magnetrons would require careful operating equipment design also, particularly as regards phase control since they are power oscillators, having only an output RF connection. Also, the magnetrons had a reputation for quite large noise components in their RF spectrum output.

A brief investigation by injecting a low-level RF signal into the magnetron's directly heated cathode was performed, without success. A test was conducted with injection locking via use of a circulator, which

was successful. In fact, with the magnetron filament turned off after oscillations have begun, the injection-locked output signal yielded dramatic results in terms of reduction in the normally large noise spectrum about the carrier frequency (see Fig. 3-1).

Thus, if certain parameters of the magnetron could be adequately controlled, such as the rest frequency, output load impedance stability, temperature, supply voltage and current, and magnetic field strength, the output RF phase of the injection-locked magnetron could be adequately controlled for use as the power tube in the phased array performance evaluation.

D. INJECTION-LOCK DESIGN

The equation in Fig. 3-2 shows the magnitude of the RF phase error between the output high-power RF signal and the low-level injection signal as a function of the magnetron operating parameters. Q_L refers to the bandwidth of the loaded oscillator. The smaller value means that the load is more tightly coupled to the magnetron output. A design Q_L of approximately 20 with an injection power, P_{inj} , of 5 W was contemplated. An overall rms phase error in the array of less than 10 deg was the design goal. The magnetron phase error was budgeted for ± 7 deg maximum, which was felt to be achievable via a selection of oscillators for best free-running frequencies, reasonable power supply regulation, and allowance for time for temperature stabilization after turn-on.

To couple the injection-locking signal into the magnetron, and to achieve a degree of isolation between the low-level injection-locking driver amplifier and the high-power magnetron, requires a high-power circulator. The circulator, as the name implies, separates the input and output signals by circulating each one in the same direction around the microwave ferrite and waveguide structure of three ports: magnetron, lock amplifier, and load. Each input signal fed into a port traverses to the next port and exits, in the ideal case. Because of the high-power level, it is generally necessary to water-cool the ferrite above 1 kW.

E. WATER COOLING PROBLEMS

Water cooling requires a source of water, control of water quality or purity, and pumping not only for flow, but also for achieving the head or pressure necessary to lift the water to the circulators. Means must be provided also to prevent the suction resulting from a lower elevation leak from collapsing the tubing or other plumbing. Finally, the water subsystem must be winterized to prevent freezing during cold weather.

Thus, it was desirable on the one hand to keep the RF power level low to avoid use of the cooled, high-power circulators. On the other hand, it was desirable to design for a high RF power level to facilitate a better approximation to the ultimate SPS array design, and to allow location of the MPTX at a long range from the rectenna to magnify any

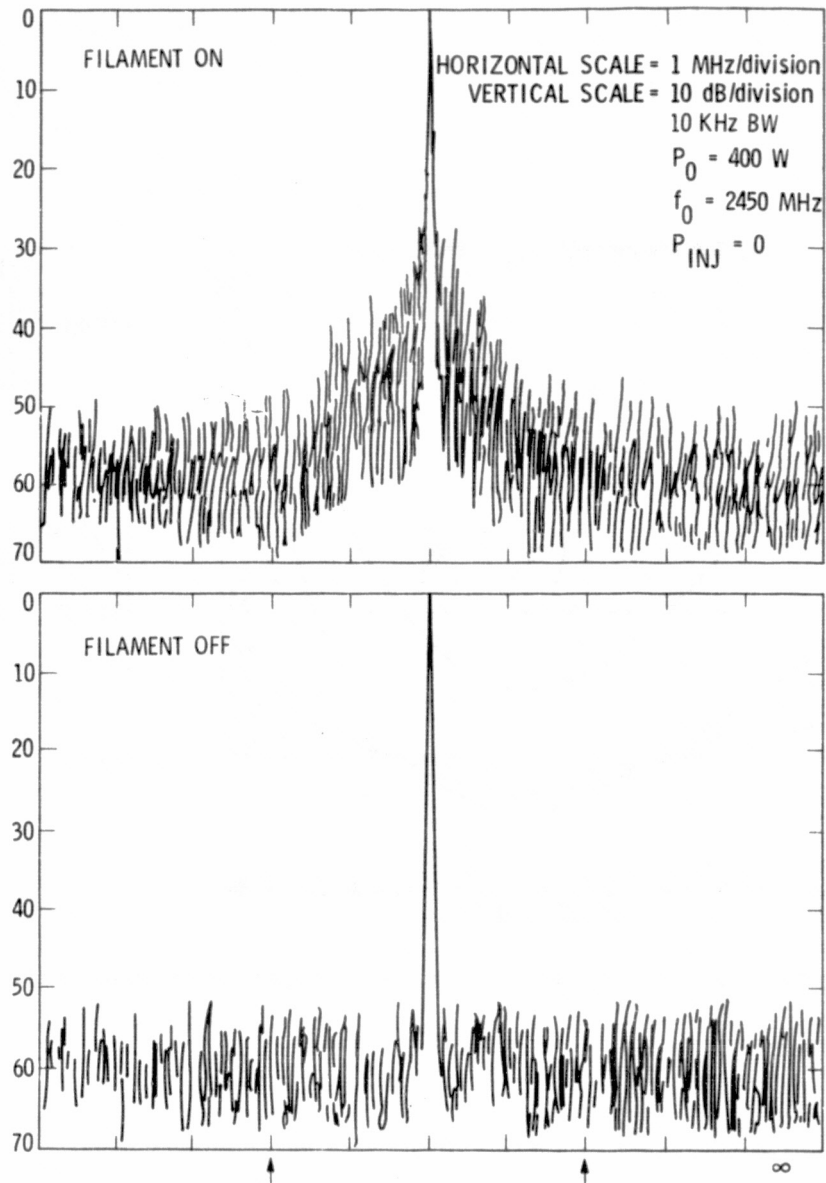


Figure 3-1. Consumer Microwave Oven Magnetron Spectrum With and Without Filament Voltage Applied

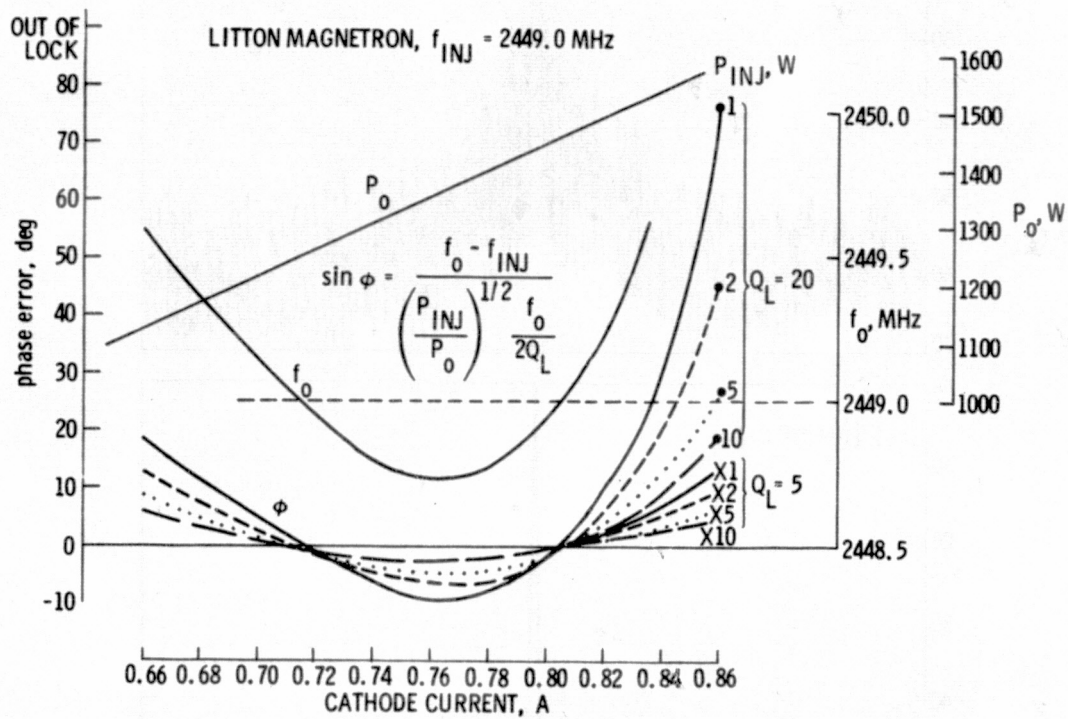


Figure 3-2. Injection-Locked Magnetron Characteristics

RF-beam mispointing by yielding large displacements of the beam centroid on the rectenna.

A brief investigation was conducted into the use of an alternate microwave combiner, a magic T or microwave E-H junction T, to combine the outputs of a pair of matched magnetrons, while providing a somewhat isolated input for the injection-locking signal. The T would admit a higher RF output power per subarray without the requirements for a high-power circulator, but at the expense of having to further screen and select magnetrons to match their output levels in pairs. The degree of isolation afforded the injection-locking input signal is a function of the amplitude balance, phase balance, load impedance, and supply voltage similitude of response by the magnetrons. Also, since the injection-locking signal splits equally between the magnetrons located on the arms of the T, the injection-locking signal amplifier must be twice the amplitude of the single magnetron configuration.

Project termination occurred before completing the final trade-off evaluation of the T versus the circulator.

F. ARRAY TURN-ON

An initial planning consideration was the turn-on of the array. That is, since the objective of the project is power transmission, how, at what rate, and in what sequence, is the power to be applied to the array? What responses are to be monitored, what commands to be given, and what controls to be applied to safely proceed from no output to full-power output?

Obviously, the power should not be instantly switched on. The transients to the primary supply, the repercussions to the array equipment, and the switch stresses would be severe. The array must be gradually brought on line, as with any other large power device. The considerations were whether to have a single common power supply operating from the station source, or to have individual supplies for each subarray. Because of the very-low impedance of the magnetrons at initial turn-on, coupled with the sudden starting characteristics, it was decided to pursue the individual supply approach. The individual supplies would provide the isolation between subarray magnetrons, without which there could be serious oscillations or power surges among the subarrays.

The basic options were either to connect all the RF power amplifiers to the single supply and gradually bring up the common supply voltage, or, alternatively, to switch on, in sequence, individual supplies for each subarray. In the former case, assuming the phase control is working, the array pattern is fully formed at initial turn-on. The beam shape stays the same while the beam intensity increases in a continuous fashion. In the latter case, which was destined to be selected because of the required magnetron isolation, the beam shape will vary as the subarrays are switched on line. This mode of turn-on would probably have been satisfactory for the MPTX, but may not be adequate for the SPS. Nonetheless, we considered what sequence would be best to minimize the RF power flux density magnitude and the time duration that the transient RF energy

existed outside the normally operating, fully-formed beam condition. The recommended scheme consists of sequencing the subarray turn-on from the central subarray outward, while maintaining as symmetrical a condition (that is alternating subarray turn-on from one side of the growing active array to the other) as possible. Thus, the beam, in a stepwise fashion, continuously focuses tighter, or narrows in beamwidth, while the beam intensity increases in steps.

G. SAFETY

The MPTX safety considerations ranged from keyswitch control of the primary power supply, to personnel fences, RF power monitors and warning signs proposed for surrounding the array. The array was to be supported about 2 m above the local terrain as added personnel protection; this would allow both visibility underneath the array and removal from the immediate area of the high voltages, hot components, and the intense RF energy. Detailed visual surveillance and audible and visual warnings were to be supplied also.

Personnel safety considerations for the potentially intense (up to 300 mW/cm^2), perhaps lethal, beam in front of the array at close range, and even when unfocused, deserve the most serious considerations; because the phased array is electronically-pointed, one cannot tell where the RF beam is directed (as one can with a parabolic reflector, for example).

Fencing of the entire reservation in which the beam, with a total flux density exceeding 10 mW/cm^2 , could be potentially directed would be quite expensive, but might be less costly than the alternative of video surveillance monitoring. The beam safety techniques discussed in Ref. 3-1 would have been applicable to the MPTX, in particular the technique of low-power level initial surveying of both transmit and receive arrays for purposes of monitoring resting avians, for example.

The normal OSHA required protective railings and kick plates around the elevated array would be installed. Lightning protection and grounding for the exposed array would also have been required.

H. PROPOSED TEST RANGE

The artist's sketch of the proposed test range is shown in Fig. 2-3. The insets depict the dual magnetron power amplifiers, employing the injection-locked magic T configuration, mounted on the rear of the slotted waveguide radiators.

SECTION IV

THE MPTX ARRAY

A. POWER DENSITY AND POWER OUTPUT

The MPTX was to be designed to produce a peak microwave flux density of about 150 mW/cm^2 in the center of the existing RXCV so as to yield approximately 25 kW of dc output power. Figure 4-1 shows the beam power transfer efficiency versus the parameter τ as shown in Fig. A-5, but with annotations for the RXCV test, the proposed SPS operating point, and the laboratory test that achieved 54% dc-to-dc efficiency overall. An estimated MPTX value is plotted for the assumed transmitting area of 32 m^2 (the lower contingency planned area for only 32 each, 1-m^2 subarray RF radiator), the RXCV receiving area of 24 m^2 , a wavelength of 12.236 cm (2.45 GHz), and separation of 132 m.

The RXCV receiving flux density of 150 mW/cm^2 is much larger than the SPS planned peak flux density of 23 mW/cm^2 , as the RXCV was designed to achieve as high an output power level as the state of the art in 1975 would allow, and power level scaling effects could readily be accommodated in the test results.

B. RANGE

It was also deemed unnecessary to exactly scale the SPS range in obtaining measurements to determine the transmitting array pointing accuracy. The phased array antenna can readily focus a beam in the near or far field of the overall array. Accurate measurements of the pilot signal SNR and the array rms phase errors along with the resulting beam pointing errors on the RXCV could be used to extrapolate to the SPS ranges. Given the RXCV area of 24 m^2 and the SPS design τ value of 1.734, and a range that is 4.5 times the ratio of the transmitting antenna diameter squared divided by the wavelength ($4.5 D^2/\lambda$), the array range would be only 11.5 m with an area of only 0.245 m^2 . Thus the MPTX scaling was based upon achieving approximately 80% beam transfer efficiency only. Figure 4-2 shows the allowable range as a function of the transmitting array area for the design requirement.

C. POWER INPUT

Because the RXCV subarrays are configured for a uniform density of illumination, and the MPTX will produce a tapered distribution of energy over the RXCV aperture, the power transmission efficiency will be less than optimum. Additionally, since the MPTX will consist of a finite number of subarrays at discrete power levels, and the rectenna is not contained within a regular outline because of one (budget-trimmed) missing subarray, the ideal transmitting aperture taper cannot be achieved, and thus the net power transfer efficiently will be less for this reason also. Hence, somewhat greater than 32 kW of radiated power would be necessary to achieve the 25-kW dc output.

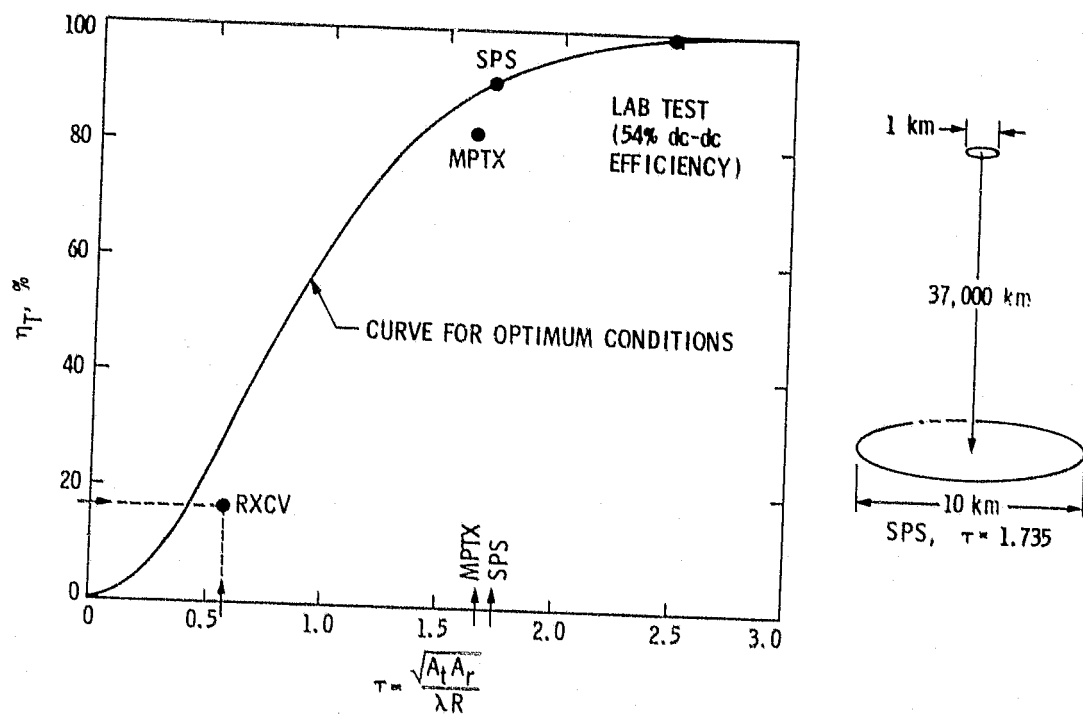


Figure 4-1. RF Power Transmission Efficiency Versus Parameter τ

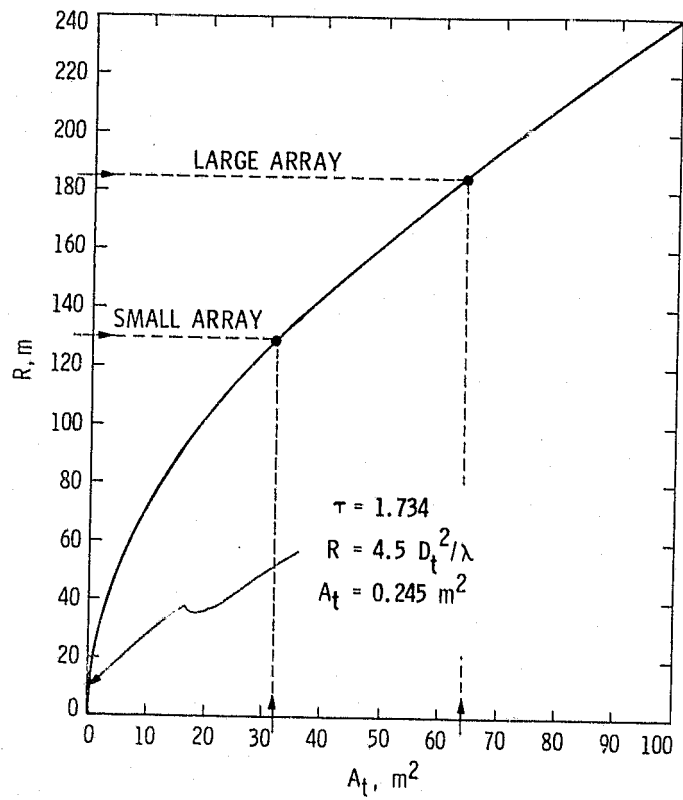


Figure 4-2. Range Versus Area of Transmitting Array

D. TEST SITE

The RXCV subarrays could be rearranged or removed and reconfigured to better approximate a desired geometric outline at a more desirable range. However, by leaving the RXCV on the Goldstone Venus Station Collimation Tower, the project expense would be less, and one could conduct tests of simultaneous illumination by the MPTX and the existing Venus Station transmitter that was used for the original RXCV tests. This would allow collecting performance data on the concept of dual illumination of a rectenna from simultaneous SPSSs.

E. SUBARRAYS

The MPTX design for the array attempted to incorporate as many subarrays in the array as possible. (The electronics cost per subarray constrains the result, however.) A large number of subarrays was desired to run tests whose results are derived on a statistical basis. For example, if the subarrays are randomly phased as a result of a very weak or absent pilot signal, the on-axis power density on the RXCV should decrease because the total array beamed energy would be spread uniformly within the envelope of an individual subarray and add only arithmetically instead of vectorially at the RXCV.

With perhaps only 32 subarrays in the array, it was debated whether or not it would be cost effective to attempt to taper the power density over the transmitting array. The tradeoff was the extra cost of producing the various power level subarrays and providing spares or having all uniform subarrays versus the marginal increase in system efficiency due to the rather coarse amplitude quantizing steps. The subarrays were rather arbitrarily set at 1 m^2 in area, so as to be of fairly high gain, but yet small enough to be handled readily.

The geometrical distribution of the subarrays in Fig. 2-3 arises as follows: The mainly vertical arrangement of the RXCV requires the MPTX to be mainly horizontal, as the RF beamwidth for a phase-coherent aperture (as contrasted to, for example, a flashlight) is inversely proportional to the width of the aperture in that plane. Hence the narrow beamwidth required in the horizontal plane requires a wide transmitting array dimension horizontally. Conversely, the larger allowed beamwidth of the RXCV vertical plane can be satisfied with a smaller vertical height of the MPTX. For safety reasons and to minimize multipath foreground reflections, the subarrays were to be mounted with their lower edge approximately 2 m above the local terrain.

The optimum arrangement of a large array consisting of 64 subarrays would be a 5×12 format with two additional subarrays on either end as shown in Fig. 2-3. The two subarrays on either end would approximate a taper in the horizontal plane due to the spatial tapering. An array of only 32 elements would probably be simply a 4×8 format arrangement of subarrays with no taper. The later to be an alternative in case of higher than anticipated development costs.

F. CIRCUITS

The mixer version of the MPTX is shown schematically in Fig. 4-3. The frequency spectrum of the dual pilot-beam signals employed to reduce the receiver front-end complexity is shown. Braces are indicated around the major subsystems of receivers, conjugators, regenerators and transmitters. The "Z" shaped signal connection lines are represented in that fashion to indicate the flexible interconnections allowed between the three subarrays shown as the reference subarray, the typical remote subarray, and the ultimate subarrays.

Figure 4-4 shows a more detailed block diagram of the injection-locked magnetron subarray proposed for the MPTX. The multiplexing operation for separating the low-level incoming pilot-beam signal from the outgoing high-power beam signal is shown as a power circulator, the lower level circulator to protect the injection locking-signal amplifier and the pilot-signal bandpass filter. The latter would probably also incorporate a power signal frequency reject section.

The times N frequency multiplier operates on the IF signal that results from the phase conjugator operating on the down-converted pilot signal and the reference signal. The multiplier output is divided between the injection-locking-signal amplifier input and the incoming pilot signal mixer's local oscillator inputs. Since the pair of pilot signals will be downconverted with the same local oscillator signal, the local oscillator (LO) may be incoherent, and thus each subarray's injection-locking signal may function as the LO to convert the coherent pilot signals to IF.

The injection-locking-signal amplifier raises the level of the frequency-converted, phase-conjugate signal to the level required for pulling the phase of the magnetron power oscillator to that of the multiplier output. If necessary, the output-radiated RF signal could be sampled at the output of the slotted waveguide antenna and compared in phase to that of the multiplier output to include more of the high-power components in the overall phase control loop. Any phase error could be applied to a correction phase shifter at the amplifier input.

The terminated circulator on the output of the injection amplifier is designed to absorb any of the high-power magnetron output signal that may leak down that path, as well as any power signal components reflected from the pilot-signal filter.

The coupling adjustment indicated on the magnetron output is an RF matching section designed to allow adjustment of the loaded Q of the magnetron (see Fig. 3-2). The current-limited power supply would incorporate provisions for reducing or turning off the magnetron's filament after initial turn-on to have a clean output spectrum. There is sufficient secondary emission to maintain the output power level, and the reduction in total electrons evidently reduces those contributing only noise to the output.

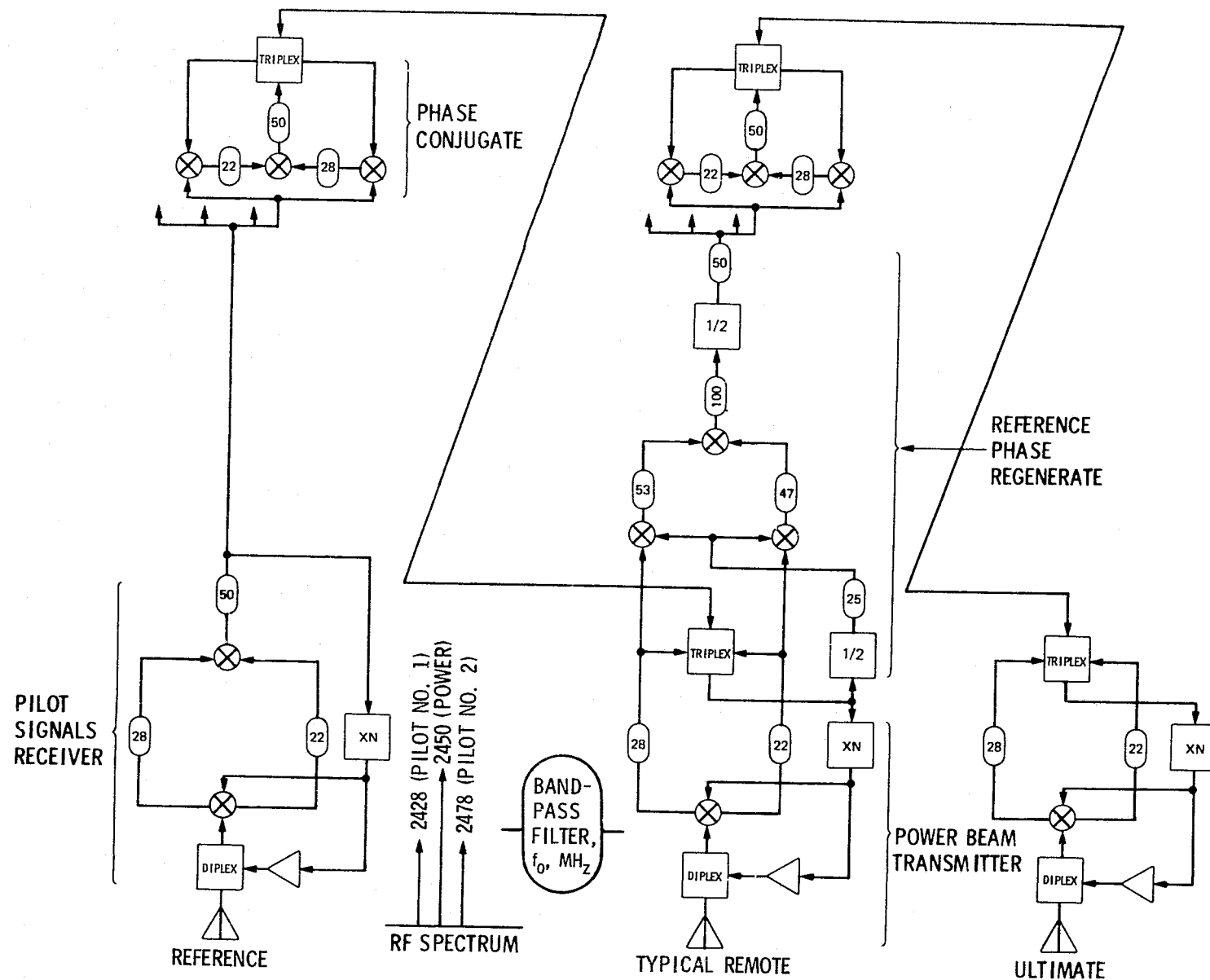


Figure 4-3. Mixer Version of MPTX Active Retrodirective Array

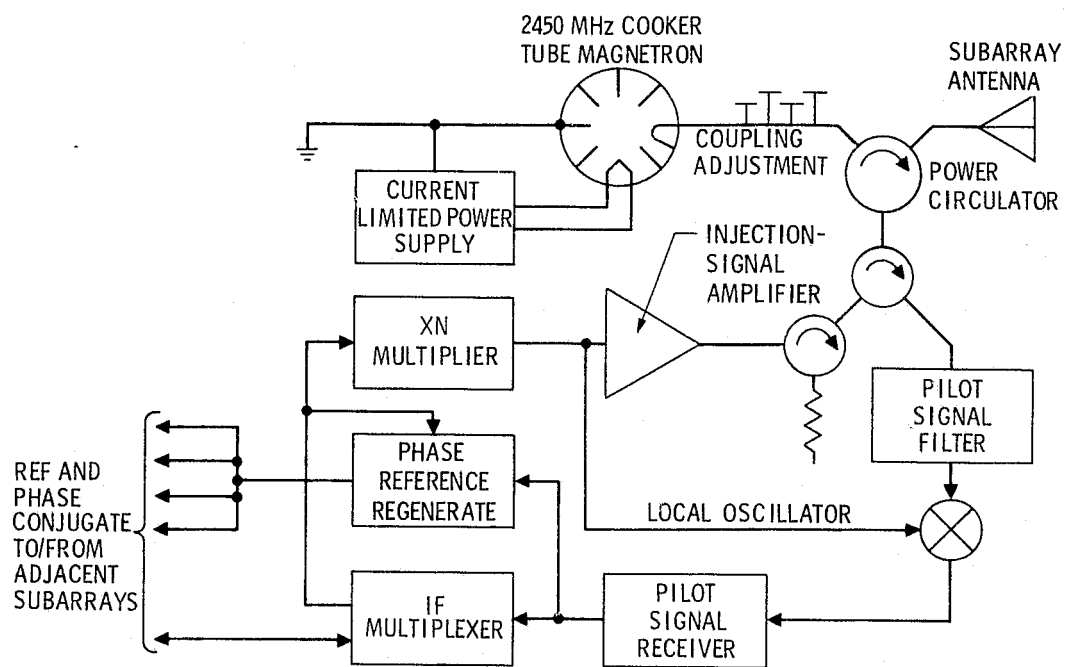


Figure 4-4. MPTX Injection-Locked Magnetron Subarray

SECTION V

THE PILOT TRANSMITTER

The pilot transmitter frequency spectrum is shown in Fig. 4-3. It was planned to employ unmodulated carriers that were 22 MHz below and 28 MHz above the S-band microwave oven center frequency of 2450 MHz. The pilots could be conveniently generated by suppressed carrier modulation of a 25-MHz tone on a microwave carrier centered between the two pilot signals at 2453 MHz. The "effective" coding of the pilot in this case would be to require two microwave signals, coherently related, and of the proper frequencies, to bring forth, via focusing, the power beam from the array.

Many elements of the typical subarray found in Fig. 4-4, such as filters, circulators, multipliers and injection amplifiers, could also be used in the pilot transmitters. In fact, it was considered to employ switched pilot transmitters in a controlled, stepped sequence to simulate pilot-beam transmitter movement, rather than to mechanically move about a single transmitter. The switched pilot transmitter could also produce rapid, effective pilot movements to allow testing of the rates of dynamic power beam movement in following the pilot motion. The pilot transmitters were to be designed to allow a large enough range of movement to sweep the MPTX array first sidelobes across the center of the RXCV. The intervening first null depth and the side lobe level would yield additional information concerning the phase-error status of the MPTX.

The pilot-beam transmitting antennas were to be of small physical cross section to block as little of the RXCV receiving area as possible. Conversely, a large area is desired for greater directivity to minimize the effects of multipath transmission (reflections from the intervening terrain between RXCV and MPTX arrays).

A. BEAM-CENTER LOCATION

The planned scheme for locating the centroid pointing location of the power beam in response to the pilot beam, or in the absence of the pilot signal, was via use of the subarrays of the RXCV. Figure 5-1 from Ref. 5-1 is reproduced here to show the monopulse pointing resolution of the RXCV. Given approximately the same relative beam shape as that resulting from the Venus Station antenna, the RXCV monopulse performance should have been adequate to resolve the beam-center location within about 22 centimeters, which is equivalent to 130 m in the full-scale SPS beam center.

An alternative beam-center location scheme would be to diplex the pilot-beam transmitter antennas, and to arrange them in a monopulse format to yield high angular resolution.

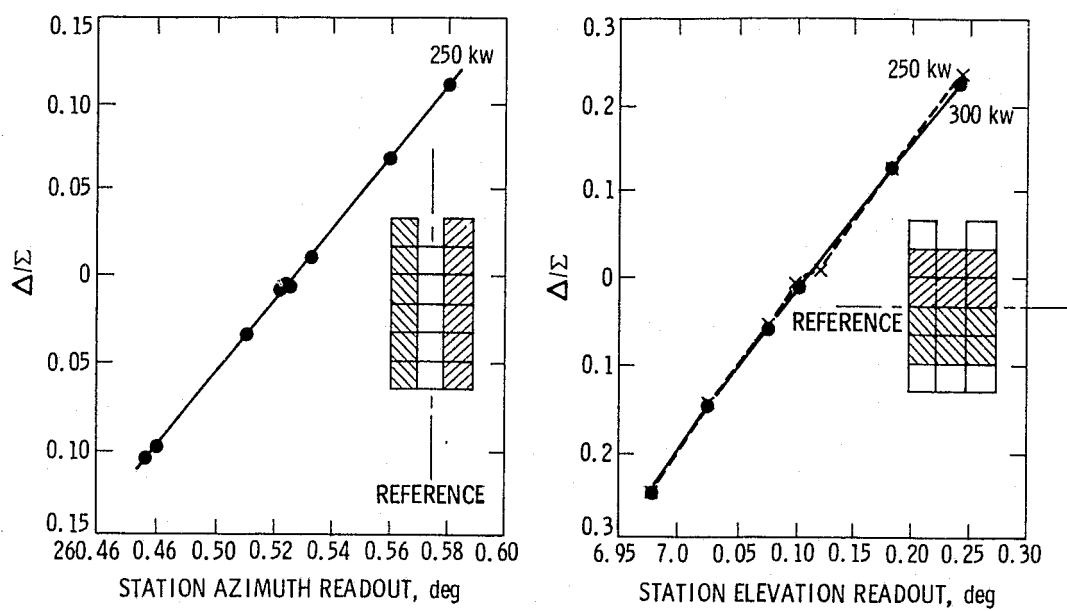


Figure 5-1. RXCV Monopulse Performance

B. OVEN MAGNETRON EVALUATION

The potential economies to be afforded by the use of the consumer microwave oven tube were attractive. However, certain data had to be obtained relative to design factors affecting the phase error between the low-level injection-locking signal coming from the subarray conjugator, and the output-radiated, high-power signal out of the magnetron. Also, the amount of noise in the output power spectrum of the magnetron that remains in the bandpass of the pilot signals would need to be determined.

A key design feature necessary for achieving good phase stability with a modest amount of injection-locking power is the ability to obtain a low-output coupling Q . From the calculated data of Fig. 3-2, a loaded Q , Q_L , value on the order of 20 would be required to achieve less than 10 deg peak phase error with only a 5-W injection-locking signal level. The test configuration shown in Figs. 5-2 and 5-3 was used to measure the magnetron-loaded Q and other parameters.

The experiments were designed and conducted by Richard Kolbly at Goldstone's Microwave Test Facility. Table 5-1 lists the typical operating parameters associated with a Litton L-5001 magnetron, based upon data reduced from tests of six different units. To allow for load impedance changes with temperature and other unforeseen design contingencies, it was tentatively decided to choose the injection-locking power at 10 W.

Table 5-1. Litton L-5001 Magnetron Typical Injection-Locked Operating Parameters

Center frequency, f_0	= 2450 MHz (selected to within ± 250 kHz at 34°C)
Loaded Q , Q_L	= 24 (adjustable multiscrew tuner)
Injected power, P_{inj}	= 10 W (for less than 10 deg rms phase-error design)
Output power, P_{out}	= 1540 ± 200 W
Supply voltage, V_b	= 3600 ± 100 V
Supply current, I_b	= 725 ± 35 mA
Thermal frequency sensitivity, $\Delta f(T)$	= $200 \text{ kHz}/^\circ\text{C}$
Current phase sensitivity, $\Delta\phi(I_b)$	= $1/4 \text{ deg}/\text{mA}$ at 725 mA

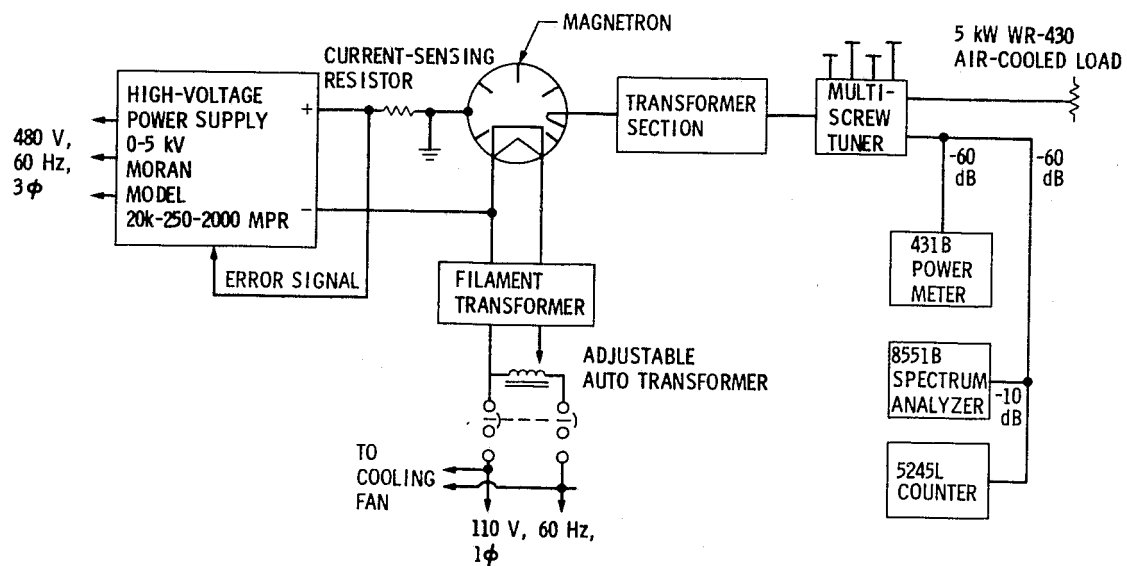


Figure 5-2. Magnetron Test Configuration Block Diagram

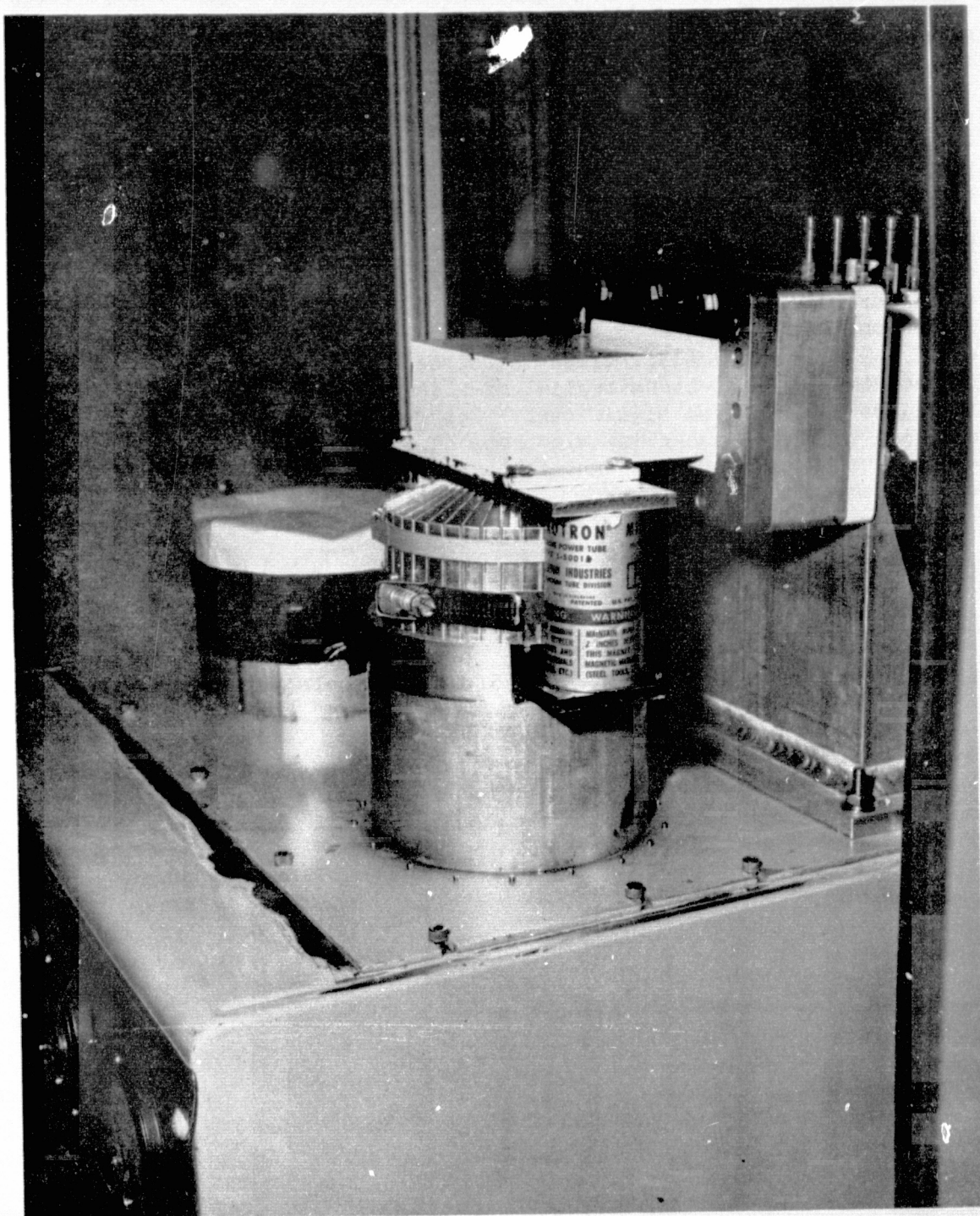


Figure 5-3. Microwave Test Facility Magnetron Test Setup

The magnetron was matched into WR-430 waveguide, and a multiscrew tuner was used to load the magnetron. Quarter-wave choke sections were required in the filament leads to reduce leakage of RF. The power supply must be current limiting because of the very-low impedance presented by the magnetron. It was tempting to consider using the unfiltered half-wave rectifying power supplies that are normally employed with the oven application, as it appeared that the magnetron RF output could be perhaps adequately phase locked over most of the conduction period with acceptable phase error. However, as the rectennas were not designed for pulsed RF operation, and the RFI problem would be worse during the transient portions of the power supply cycle, it was decided that a filtered dc supply should be employed. Table 5-2 shows the measured harmonics and incidental modulation resulting from the power supply consisting of paralleled power tetrode tubes for regulators. Part of the quiet performance of the injection-locked oscillator is due to the nature of the injection-locking phenomenon (Ref. 5-2), in particular, close in to the carrier; however, the reduction in the wide noise spectrum typical of a free-running magnetron, as shown in Figure 3-1, is also significant. The reasons for the quieting, in addition to less loose-noisy electrons participating in the basic energy conversion process, are thought to be perhaps better bunching and less end-cap emission.

Table 5-2. Measured Injection-Locked, Filament-Off
Magnetron-Harmonics and Incidental Modulation

Second harmonic	-55 dBc (decibels below the carrier)
Third harmonic	-66 dBc
Fourth harmonic	-67 dBc

Power supply incidental modulation (detector ambient noise in 200 Hz bandwidth = -84 dBc)		
Frequency component, Hz	AM, dBc	FM, dBc
60	-68	-58
120	-58	-62
240	-62	
360	-64	

Using a modified Pound discriminator detector for looking within 20 kHz of the carrier, the magnetron spectrum appears no different than the injection-locking signal spectrum.

A crucial test of the magnetron adequacy was conducted by employing a sample of the output signal from the injection-locked magnetron, with filament off, to act as the local oscillator signal for the MPTX breadboard receiver. The magnetron noise was low enough that no phase error could be detected in the pilot receiver output.

Discussions with various other engineers concerning the operating of the magnetrons without filaments on after initial turn-on brought mixed results. Some said the tube life may be shortened by vane tip erosion, leading to frequency change due to the secondary emission. Others said it may lead to longer tube life. For the MPTX application, longevity was not a prime design requirement, as most of the experimental data could be obtained in a few hundred total operating hours.

An experiment was conducted to determine if the magnetron rest frequency could be readily controlled via biasing the magnetic field to balance out the frequency change with temperature. The magnetrons have permanent magnets, so a trim coil of 300 ampere turns was wound around the pole pieces. Approximately 6 MHz of frequency change could be effected via the trim coil. A closed-loop control was not completed. The design is not difficult. The resulting performance improvement of the magnetron should be an advantage in a changing thermal environment.

Since it was desirable to have a dual-power level capability from each subarray, the insertion loss presented to the injection-locking amplifier output was measured with the magnetron inert. Less than 1-dB insertion loss was measured at the antenna input connector relative to the magnetron injection input level. The inert magnetron must represent a low-loss reactive termination for the circulator. This characteristic would allow the subarray to operate efficiently at the two power levels corresponding to either the injection-locking amplifier output, or the magnetron output power level.

SECTION VI

THE SUBARRAY RF RADIATOR ANTENNA

The requirements for the MPTX subarray radiator are: linear polarization to match the RXCV vertical dipoles, power handling capability for up to about 3 kW, bandwidth to accommodate the pilot tones, uniform aperture distribution of the RF power, stable input impedance well matched to contribute only a small amount of reflected power toward the receiver and injection lock amplifier, and high efficiency. Weight was not of prime importance, but the radiator was desired to be strong enough to support the high-power components. Also, as will be discussed in Appendix A, the subarray radiators must tile the array plane with only a small gap to permit relative motion.

Slotted waveguide resonant arrays of waveguide stacked side by side and fed by a common feed distribution guide across the rear surface were selected as the antenna type. The design requires precision in execution, but is rather straightforward once the mutual coupling of the adjacent slots is properly accommodated. The feed guide coupling apertures for equal power split are also a precision design, and somewhat difficult to achieve mechanically. Folded short circuits must be employed to reflect the proper impedance to the edge waveguide couplings. The fabrication and construction techniques for minimizing the radiator cost represent the greatest challenge in the design.

A comparison test of close-coupled power transmission efficiency was suggested for the production test of the manufactured subarrays, rather than full antenna pattern sets. Hence, the first antennas would receive the usual full-pattern documentation, but after a known pair was established, subsequent antennas would be rotated into position in a fixed short range, high RF power would be applied, and the resulting transmission efficiency compared to the two known antennas' performance under the same conditions. Any difficulties in tuning, voltage standing wave ratio (VSWR), leakage, or conductive loss would be readily apparent.

The approach to designing the antennas as pursued by Michel Schwartz of JPL, was to construct a frequency-scaled model employing available materials at 8.8217 GHz. A single length of WR-90 waveguide was developed with mirror image planes attached to each side of the guide to simulate the infinite array so as to model the adjacent waveguides slots mutual impedance effects. This mirrored guide was used to determine the optimum slot displacement from the guide centerline to achieve the correct slot conductance.

Figures 6-1 and 6-2 are photographs of the front and rear of the X-band scaled model of the subarray radiator. On the prototype and production units, the feed guide extensions would be folded back so that the subarrays could be closely juxtaposed to avoid grating lobes in the array pattern. The edge blocks with mounting holes would also be incorporated on the rear surface of the prototype antennas.

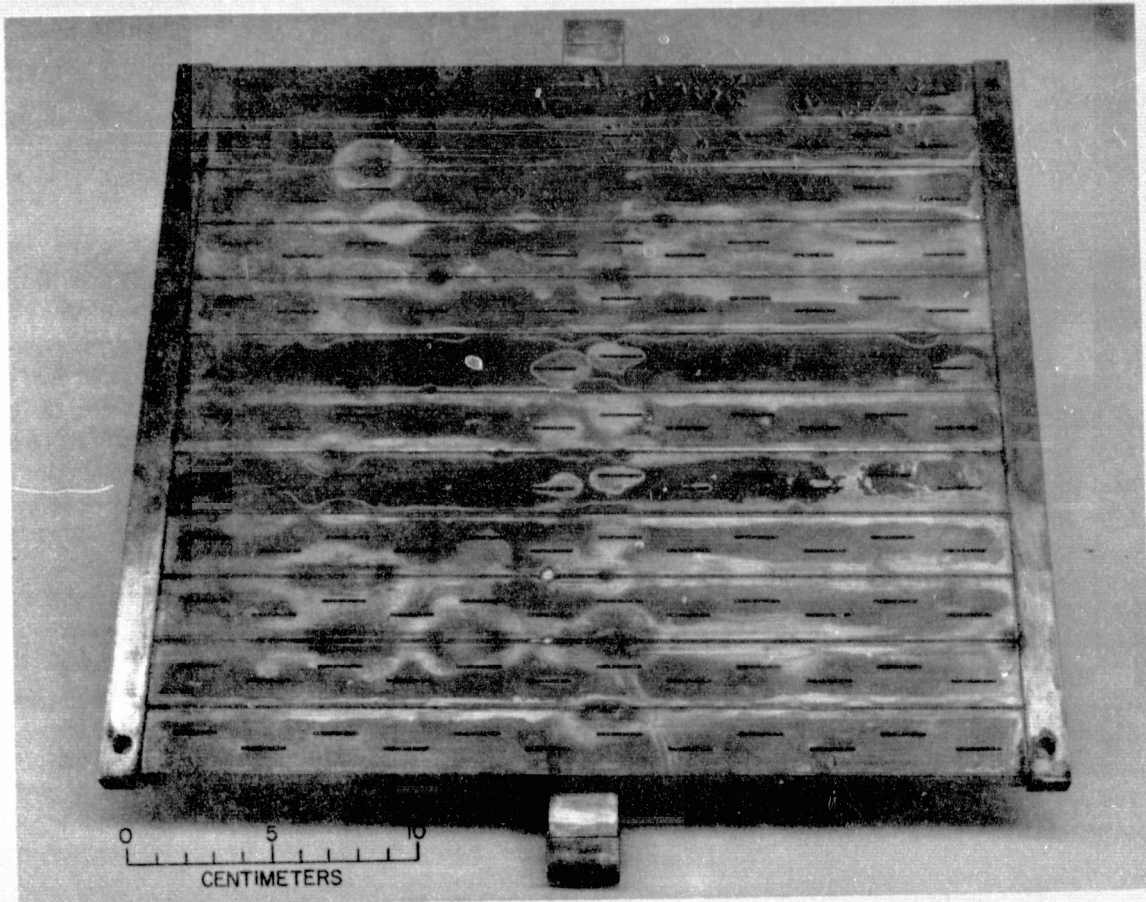


Figure 6-1. Radiating Face of X-Band Scaled Model of MPTX
Slotted Waveguide Antenna

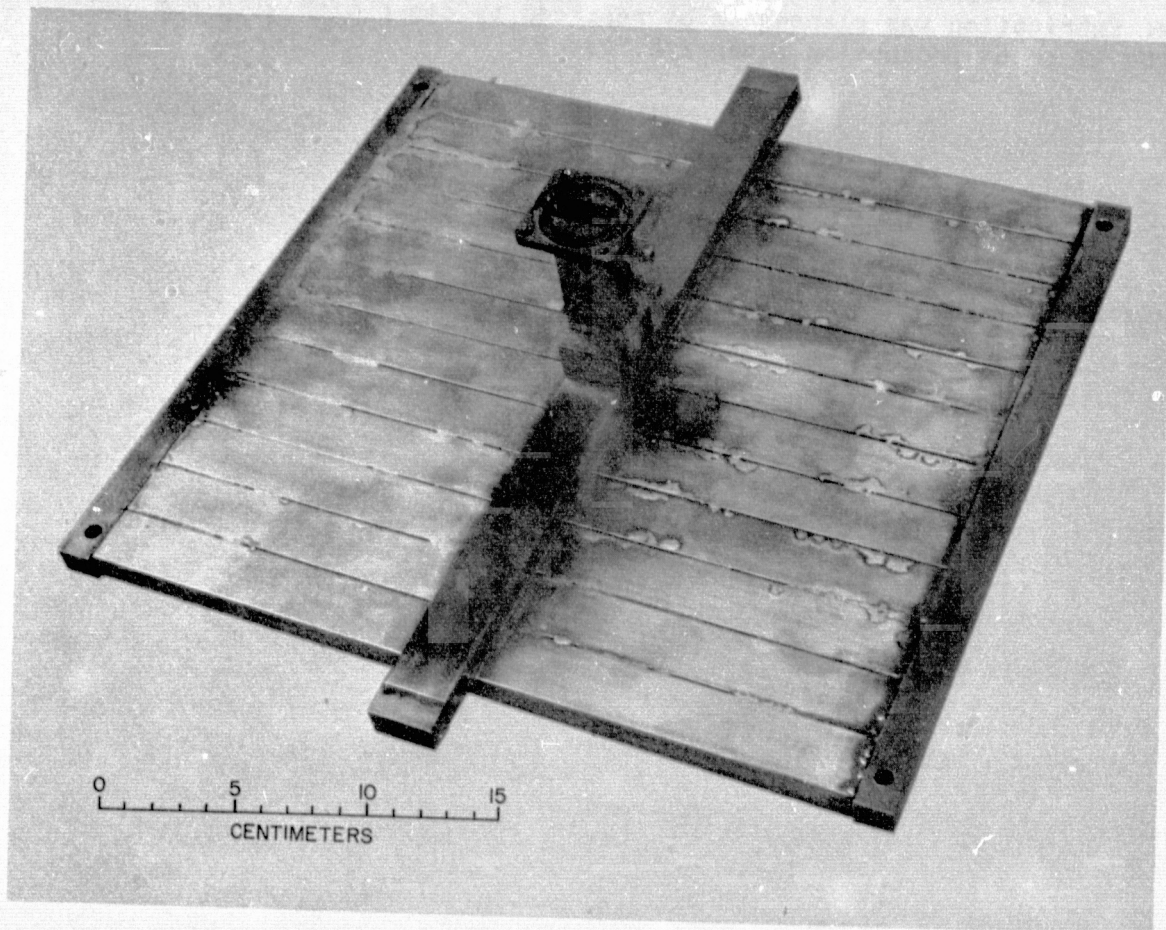


Figure 6-2. Input and Feed Waveguide Side of MPTX Slotted Waveguide X-Band Antenna Model

For the X-band scaled model, the input waveguide matching screws yielded an input impedance VSWR of less than 1.2 to 1. The first cut breadboard yielded an aperture efficiency of 72 to 74%. Machining tolerance effects and slight adjustments in radiating and coupling slot design would be expected to significantly improve the VSWR and aperture efficiency performance at S-band. The aperture covering or thin radome skin is necessary on Earth to prohibit entry of rodents, insects, bird droppings, rain, snow, dust, tumbleweed parts, and leaves.

The soldered copper waveguide construction material and technique of fabrication was planned to be replaced by dip-brazed aluminum for the 32 or 64 production subarrays.

SECTION VII

THE ACTIVE RETRODIRECTIVE ARRAY (ARA) BREADBOARD

As a check of the retrodirective array mechanization for operation on a flexible surface array, Ralph Chernoff of JPL designed and constructed a two-element model at X-band to make cost effective use of existing microwave hardware. The breadboard block diagram is shown in Fig. 7-1. The system employs a phase-locked loop to perform the phase conjugation instead of the mixer only version as shown in Fig. 4-3, as proposed for the final MPTX. Two tones for the pilot signal are employed to reduce the cost of the pilot receiver front end. For the high signal-to-noise ratio (SNR) achievable with either the breadboard or the ultimate MPTX, this is quite effective, particularly since the front end was also successfully operated in a test with an injection-locked magnetron as the incoherent local oscillator.

Because of the high-frequency multiples associated with the X-band breadboard, serious problems were encountered in the areas of component thermal stability and VCO crystal purity. The breadboard was quite valuable also in pointing up problems of am-to-pm conversion, wherein variations in signal amplitude when passed through nonlinear devices result in conversion of the amplitude changes into phase changes not originally present in the signal.

The breadboard hardware development also pointed up the need to refrain from frequency mixing operations wherein the harmonics in one signal may be present or reconstituted in the other signals also present at the mixer. Detailed frequency compatibility analysis is mandatory for the active retrodirective as in any other high-quality phase receiver, and particularly for the high RF power applications. The coupling line between the multiplexers must also be of high quality. That is, the multiplexing filters must be well matched to the coupling line, or else the multiple reflections will distort the phase information that has to be transmitted unambiguously in either direction.

Similarly, any multipath between the pilot transmitter and the subarray receivers can lead to phase distortion due to the difference between the pilot and power signal frequencies. This frequency difference accounts for the multiple signal paths not being identical. The array will respond with multiple beams to each of the images of the pilot transmitter represented by the multipath reflecting regions or surfaces, which appear different at the different frequencies generally. This should not be a problem for the SPS directive subarrays, but requires careful design for the MPTX. Nevertheless, for the small, two-element array employed in the breadboard active retrodirective array at X-band, the standard gain horns used as radiating elements were not quite directive enough, as shown in the antenna patterns of Fig. 7-2. Adjacent buildings at the antenna range provided the reflectors for multipath propagation.

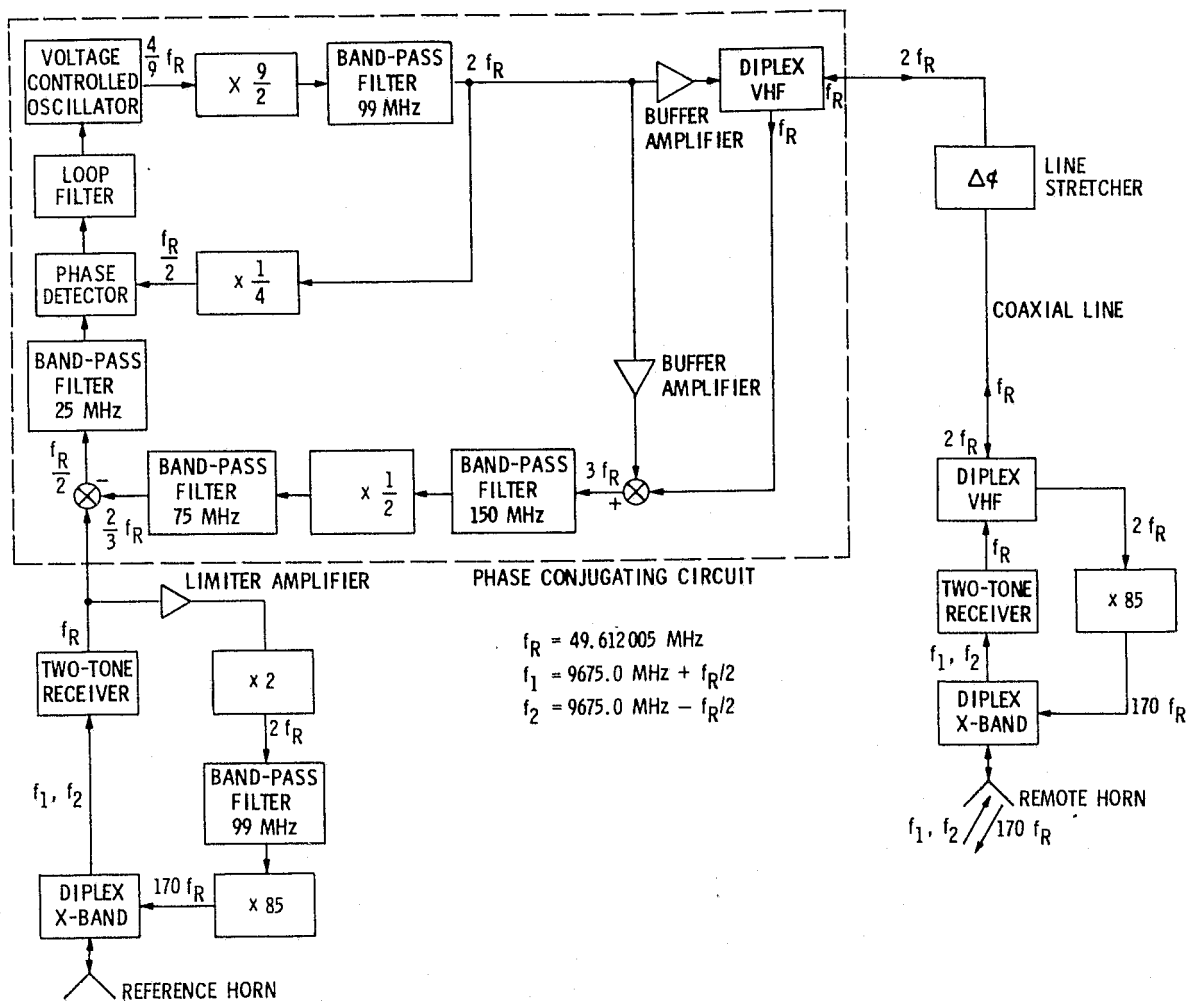


Figure 7-1. Chernoff's Active Retrodirective Array Block Diagram

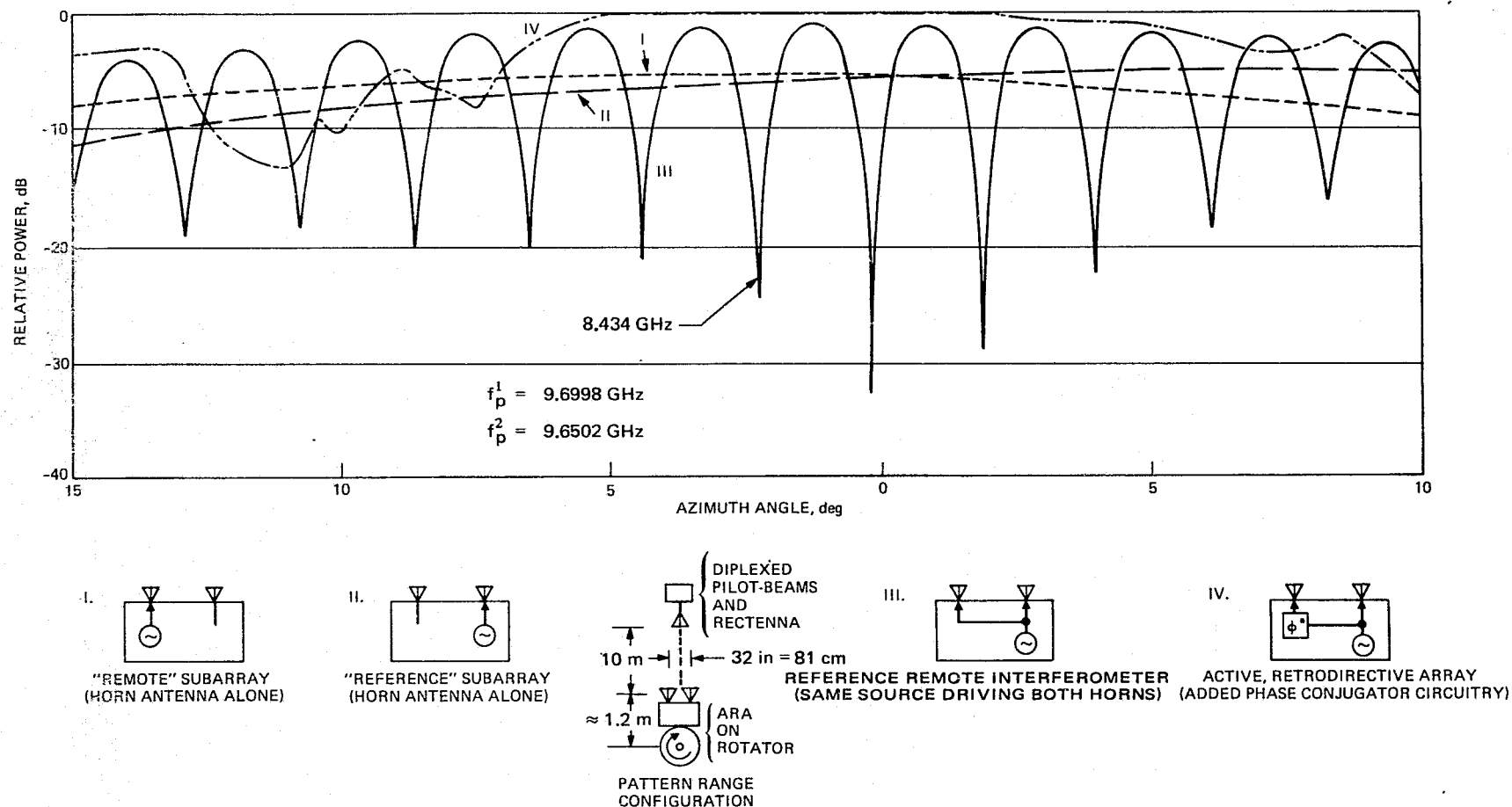


Figure 7-2. Retrodirective Array and Subarray Antenna Patterns

Figure 7-3 shows the range configuration, with the thermally-insulated box containing the two-horn antenna element array mounted on the antenna positioner. The diplexed pilot-beam transmitter and power-beam receiver are housed in the upright equipment rack. The liberal use of RF absorbing material was additionally required to dampen head-on multiple reflections because of the limited range length. Figure 7-4 shows the equipment distribution in the thermal box. The waveguide diplexing filters and frequency multipliers are the largest objects. The remainder are amplifiers, mixers, and filters for performing the phase conjugation. It is expected that a final production version of such circuitry could be executed in microstrip and custom integrated circuits (IC's) to reduce the size and cost for quantity production.

A detailed description of the Chernoff array, its characteristics, performance and analyses of various error sources is given in Ref. 7-1.

As the two-element array did not incorporate the phase reference reconstruction circuit, we are indebted to Richard Booth and Dr. William C. Lindsey of LinCom for pointing out in a technical discussion that the dividers in the circuits can suffer from phase ambiguities. That is, there is a problem of synchronizing all of the dividers in the various subarrays so that they all function alike, for example, when power is applied; furthermore, means must be taken to assure that the dividers do not drop a bit, or are resynchronized if they do.

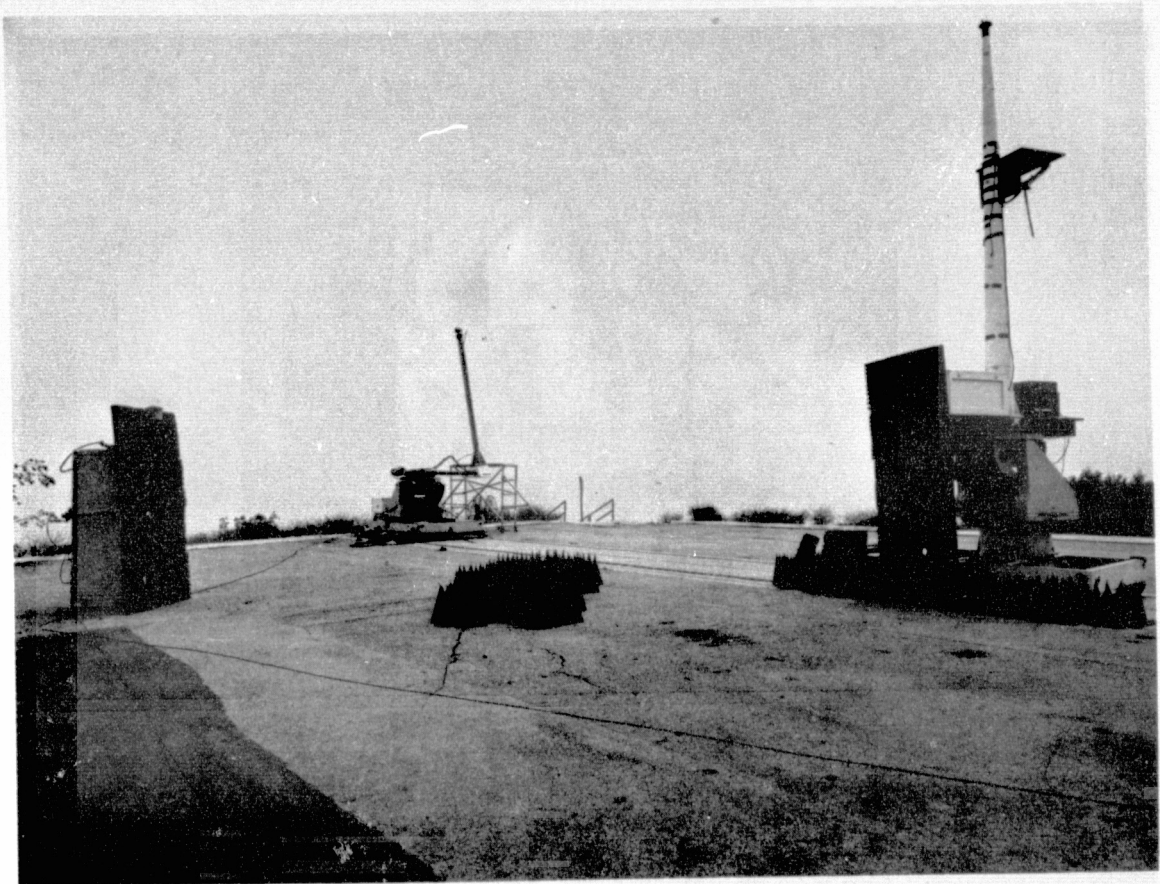


Figure 7-3. Active Retrodirective Array Range Configuration

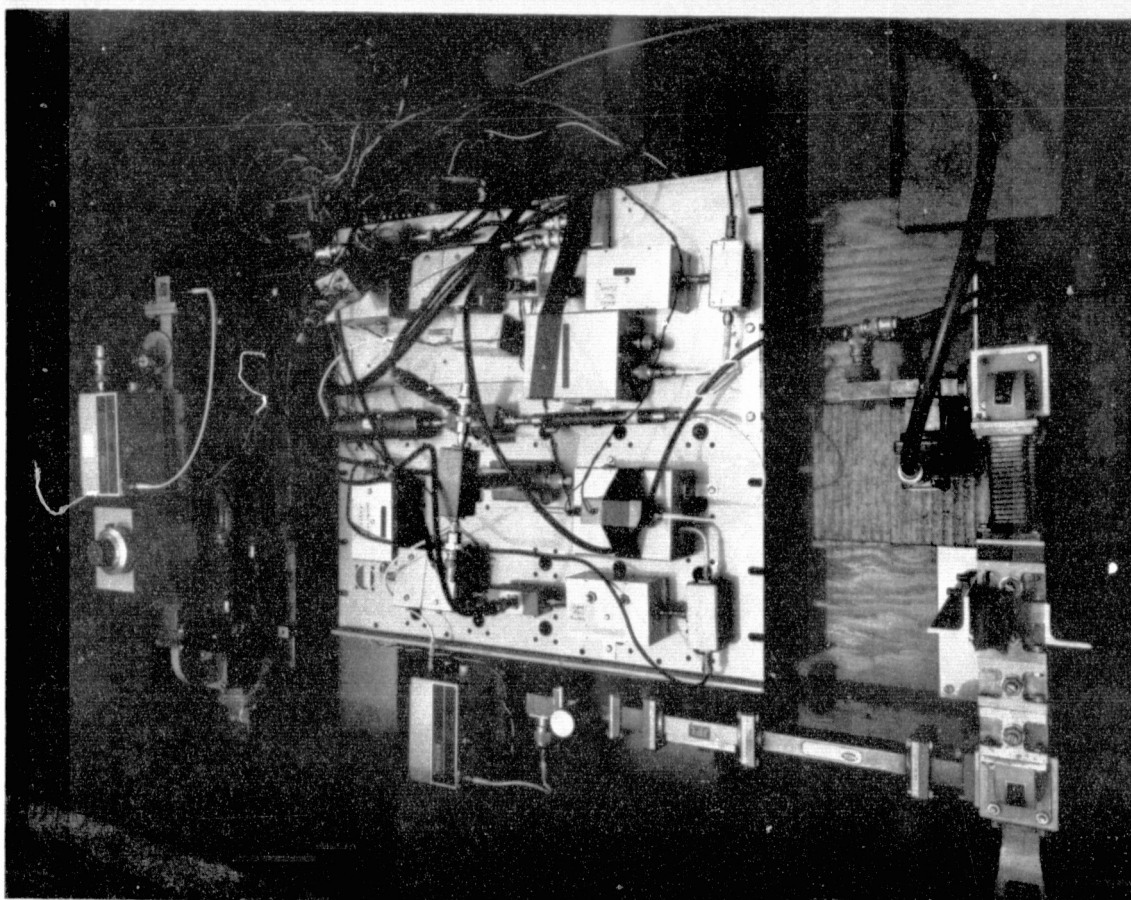


Figure 7-4. Active Retrodirective Array Electronics Inside Thermal Enclosure

SECTION VIII

THE MPTX ARRAY INSTRUMENTATION

The MPTX instrumentation includes controls for the various elements of the MPTX and the RXCV, including its dc load, the means for inputting a stimulus to the system, data collection, processing, output display, and recording of responses.

The main control functions are the selection of the number, position, and amplitudes of the pilot transmitters. The significant response is the resulting position or positions of the power beam or beams radiated from the MPTX on the RXCV, in connection with the rms phase error of the subarrays. For a single pilot beam in the center of the RXCV, the efficiency of dc-to-dc power transmission is also of prime interest.

As was previously discussed, the beam centroid position on the RXCV could be calculated by using monopulse techniques on the RXCV subarray outputs. A computer routine would determine the error in beam pointing by comparison with the known pilot-beam transmitter antenna positions. Coded commands would be sent over landline to the pilot transmitters where decoders would then turn on the appropriate units and set the requisite output levels depending on the desired SNR condition to be obtained at the MPTX receivers.

Assessing the MPTX array phase error is a particularly difficult measurement. At the surface of a sphere centered on the pilot transmitter and passing through the reference array position, the phase of each subarray's RF signal must be compared to that radiated from the reference subarray. The root of the mean-squared phase differences is a measure of the overall array performance at the time of sampling. Achieving the geometrical requirements for the required RF signal sampling is next to impossible. An imaginary sphere transparent to RF, yet supportive of the required instrumentation, does not exist. Thus, the measurement must perforce be made inside the array electronics, which consequently will suffer from the degree to which the sample point is remote from the actual radiation from a subarray.

To attempt the measurement at the output microwave frequency is also fraught with difficulty and expense, for it would require the distribution with precision, of a microwave RF signal to each subarray. Since this is the same problem as the particular array scheme under test is attempting to solve, an alternate approach is mandatory. If the subarray phase-error drift rate is slow enough, the subarrays null depth (when paired with the reference subarray and an appropriate 180-deg phase shift is introduced) may be used to derive a measure of the phase error. A microprocessor-driven digital command sequence may be able to perform a controlled sequencing rapidly enough through the limited number of subarrays. To prevent the thermal transients that would accompany the turning on and off of each magnetron, the subarrays are instead driven with an injection-locking signal that is noise modulated for all except the subarray under test. This action could be accommodated by individual control of the phase-trim input signals to each of the subarrays.

A block diagram of the proposed instrumentation system is shown in Fig. 8-1. Assessing the elemental contributions to the overall MPTX rms phase error would be accomplished by use of a common phase reference at the intermediate frequency (IF) distributed to all the subarrays and to the multipliers of the pilot transmitter input chains. The reference instrumentation phase signal would be designed to be nominally at the identical frequency of the MPTX subarray IF, so that a change in the master instrumentation reference signal frequency would change the entire array frequency proportionally. Figure 8-1 shows the instrumentation phase reference applied to one side of a subarray's instrumentation mixer whose output is labeled " $\Delta\phi$ ".

There is also an input stimulus to the phase-error measuring system labelled "phase trim". Phase trim can also be used to adjust the subarray radiated phase for the initial alignment sequence.

The steps for determining the reference phase reconstruction and distribution circuits contribution to the rms phase error of the array are first, to switch a calibrated IF phase shifter into the central subarray reference IF line so that each subarray is stepped through a programmed sequence of phase steps. As the introduced phase steps are not communicated to the pilot-beam transmitters, its signal will be unaffected in phase, and thus will act as the reference when downconverted and conjugated in each individual subarray reference. For each introduced phase step, the " $\Delta\phi$ " for each subarray is then recorded. Since all steps should be the same at each subarray, statistics on the variations in all of the outputs can be machine derived for a measure of this particular array rms phase-error contribution. An additional test can be developed by now placing the step phase shifter into the reference instrumentation line going to the pilot transmitter while tying the reference subarray IF to the instrumentation signal instead of the normal pilot signal. This, too, will cause every subarray to have the same input phase shift, and again the array rms phase errors may be derived by analysis of the " $\Delta\phi$ " responses. The tests can be conducted with both high and low power radiated from the array so as to determine any power amplifier SNR degradation due to noise in the receiver pass bands. In fact, the master oscillator could be tuned slightly and the rms phase-error measurements repeated to determine the optimum operating frequency for the ensemble of magnetrons. The instrumentation computer would be provided with software for calculating the array performance as a function of various states, transient conditions, temperatures, and pilot signal levels.

The acquisition time, for example, would have to be defined as given in the Design Requirement: "The time interval from turn-on of the pilot-beam transmitter until the RXCV dc load power has reached 90% of the final steady-state dc output power".

Additional instrumentation outputs from a typical subarray, such as temperature, and voltages, and currents, are indicated in Fig. 8-1. A controlled switch at each subarray power supply is necessary for interlocking with the RXCV for self-protection, the phase-trim sequence, simulating failures, and for conducting on-off transient studies.

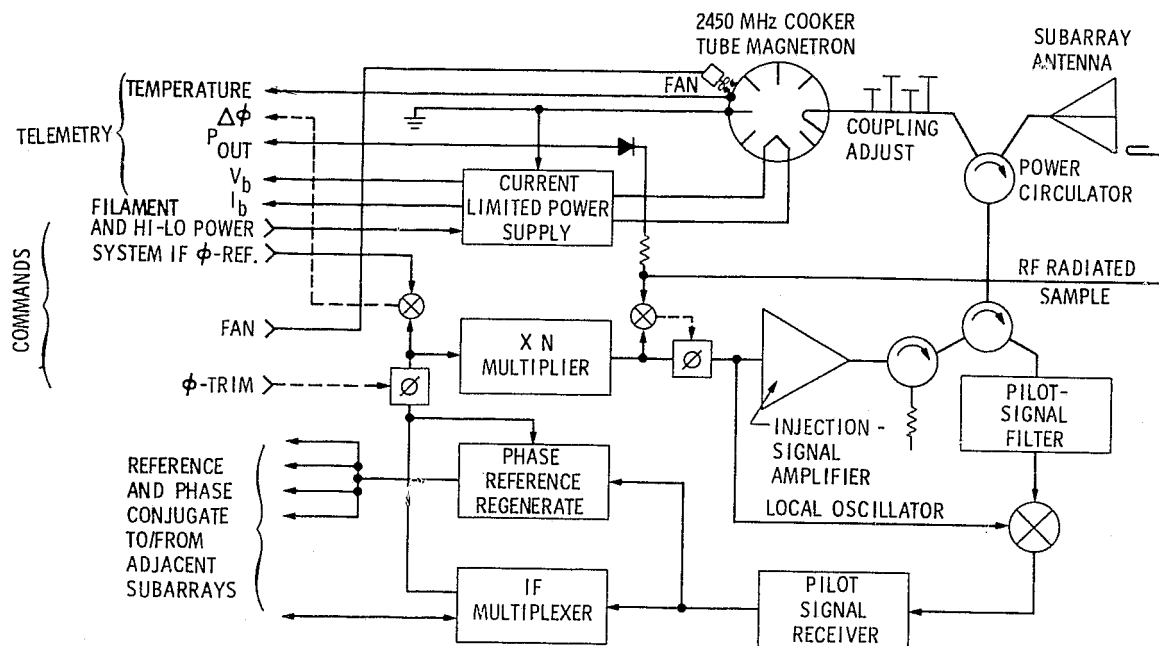


Figure 8-1. MPTX Injection-Locked Magnetron Subarray Instrumentation

Detailed instrumentation available with the RXCV for varying its load and for measuring and recording its performance parameters is given in Ref. 5-1. The MPTX processing, recording, and display instrumentation was not designed completely, because the interfacing equipments were not as yet adequately designed in detail. However, from the data requirements it was estimated that fully one third of the project cost would be in the instrumentation.

The following is a list of experiment parameters that can be controlled to evaluate the array performance:

- (1) Pilot signal: amplitude, position, and frequency.
- (2) Subarray mechanical: pointing and displacement.
- (3) Subarray electronic: RF power level, simulated failures, magnetron temperature (fan control), magnetron RF spectrum (filament control), and phase trim.

SECTION IX

RESULTS

The project conceived a rigorous demonstration test for the pointing accuracy and system efficiency evaluation of a proposed scheme for operating a phased array from a flexible surface, which will be required for the SPS technology. The planning development scoped the resources required for the initial development of an S-band, 32- to 64- element array of 1-m² area subarrays, radiating on the order of less than 100 kW, and heavily instrumented, at around \$2 million 1975 dollars. Although the final MPTX was not constructed, and the project really only proceeded through a portion of the breadboard phase, considerable results were achieved in terms of advancing the state of the art in microwave power transmission technology, as follows:

- (1) The design of an end-to-end microwave high-power test system resulted in the conception of a procedure, implementation circuitry, and instrumentation subsystem for continuously monitoring the rms phase error of a phased array antenna; turn-on and turn-off sequences for power subarrays; establishment of the magnitude of potential problems associated with crystal stability, thermal stability of components, multipath propagation, and amplitude-modulation-to-phase-modulation (am-to-pm) conversion; and a technique for subarray phase trim.
- (2) Preliminary breadboard test results demonstrated phase-locked loop conjugation over a compensating cable length, verified cleanup of the spectrum of a crossed-field magnetron by both phase injection locking and reducing the filament voltage to zero after turn-on, and demonstrated that an efficient dual-power-level subarray is possible via coupling the injection-locking amplifier signal through the magnetron circulator with the magnetron dc excitation voltage removed.
- (3) A subarray module design using the low-cost consumer microwave oven magnetron was achieved. This is considered a resourceful approach to a limited budget project and may have potential value for full-scale SPS design. The transmitter module hardware could also function as the heart of the pilot-beam transmitters because of the demonstrated feasible use of the relatively close-in pilot tone frequencies. The dual-pilot tone pointing system design allows for an inexpensive receiver.
- (4) The project fostered the design solution of a technique for distributing a precision phase reference over a large flexible array aperture via a tree network that employs the retrodirective principle for compensating for transmission line length changes. Also, the tree reference phase compensation scheme, when used in connection with particular phase-locked loop or mixer versions of phase conjugators, results in exact array antenna beam pattern redirection - there is no squint due to the normally employed frequency transponding.

The breadboard test results in the tables and figures, along with the detailed Design Requirements in Appendix B have potential utility for SPS system studies and further microwave power transmission technology developments or applications.

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

The power beam from an SPS will have to be accurately controlled to permit pointing always within the proposed rectenna boundaries, with the degree of precision required for efficient transfer of beamed power and with sidelobe levels low enough for biota safety and RFI prevention. Such control is necessary for economic viability of a satellite power system. The work described in the present report can contribute to the future design of test facilities for evaluations of antenna control systems to meet these requirements.

In the process of carrying out the preliminary portion of the MPTX design and breadboard tests, we have uncovered and sharpened our outlook on some unknown and previously hazy technical problem areas regarding the phase control system and hardware limitations as discussed in the text and cited in the results. The ultimate design task and its achievement will not be easy, but this author feels that, in view of the results to date, there is a basis for expectation that it will be possible to accurately point and control the SPS microwave beams with high efficiency by the late 1980s. Continued analysis and verification experiments are required. Assuming that continued investigation yields convincing analysis and demonstrations that SPS power can complete economically and environmentally with projected 1980s' alternate electric power sources, then ground-based tests of power phased array pointing such as the MPTX, should be conducted before undertaking low-Earth-orbit technology tests.

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APPENDIX A
POWER TRANSMITTING RETRODIRECTIVE ARRAY
DESIGN CONSIDERATIONS

This appendix contains a discussion of the SPS array requirements that are necessary to put into perspective the rationale in the MPTX approach. A discussion of portions of basic antenna theory as applied in particular to the requirements of highly-efficient power transmission (as contrasted to simply achieving high angular resolution for example) is in order also. A discussion of the details of retrodirective phased arrays is then necessary to set the stage for abstracting the MPTX model array design requirements and instrumentation areas, range of measured parameters, and accuracy requirements.

SECTION A-I

THE ARRAY DESIGN PROBLEM

A. MATERIALS LIMITATIONS

The SPS S-band transmitting antenna is proposed to be on the order of 1-km diameter. To achieve with precision the desired beam characteristics with a continuous surface, the equivalent surface accuracy would have to be on the order of millimeters over the antenna aperture. The SPS array design is complicated by limitations in construction materials and fabrication techniques for structures possessing such exacting desirable properties, particularly when applied on such a large scale. The spacecraft's geosynchronous orbit environment, its motions as it station keeps and tracks the Sun, the despun transmitting array forces, the properties of the construction materials, and the resulting structural deflections would lead to unacceptable RF pathlength or phase errors in the radiated energy from different portions of the antenna if the surface were continuous. Accordingly, the use of subarrays, rather than a monolithic surface, has received consideration.

B. SUBARRAYS

To periodically relieve the accumulation of strain in the transmitting antenna surface, the aperture could be periodically interrupted with a small gap so that the RF radiating surface is discontinuous and would thus consist locally of individual tiles filling the apertures, termed subarrays, which would approximate the desired continuous uniform current sheet radiating surface of the array. A flexible backup support structure as depicted in the cross-section schematic of Fig. A-1, would be necessary to maintain the subarrays in global or overall array position. The individual subarrays must then have their radiated RF phase controlled to correct for flexing in the underlying support structure.

The individual subarray's RF apertures must be made small enough to keep the phase errors produced by their surface deflections due to the operating environment within acceptable bounds. Current estimates are on the order of 10 m for rms phase errors over the subarray aperture of the order of only several degrees at 2.45 GHz. The retrodirective array technique (Ref. A-1) may then be extended to provide the means for controlling accurately the individual subarray phases.

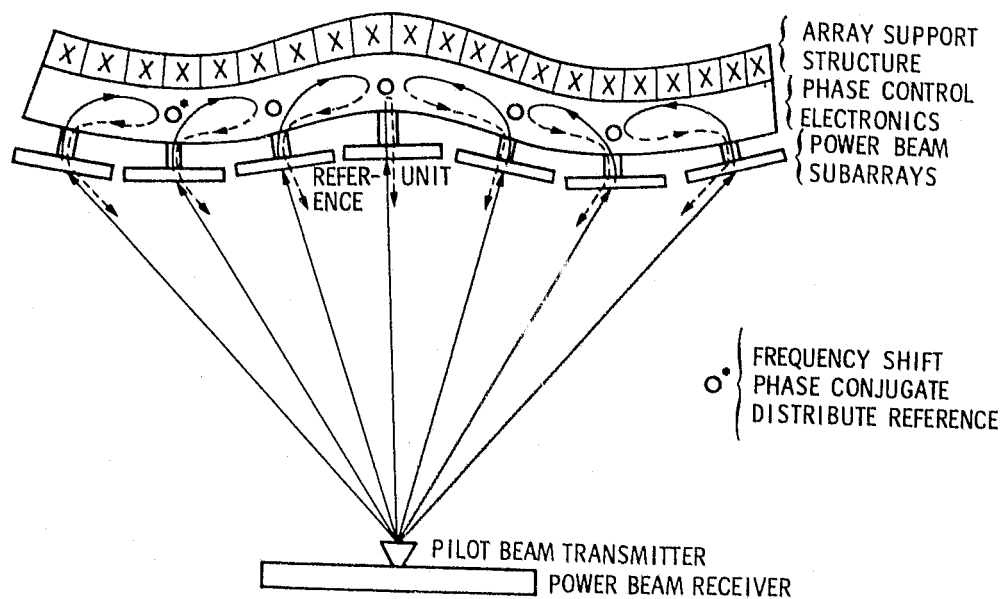


Figure A-1. Pilot-Beam-Steered Phased Array Cross-Section Schematic

C. PHASE ERROR SOURCES

It is necessary that the phase of the radiated RF power signal of each subarray be automatically varied in the proper amount as the subarray is subjected to both mechanically and electrically induced RF pathlength or phase changes. The sources of the phase variations are as follows:

- (1) Backup support structure deflections due to:
 - (a) Temperature differentials.
 - (b) Gravity gradients.
 - (c) Solar pressure.
 - (d) Lunar tides.
- (2) Waveguide propagation velocity changes due to:
 - (a) Temperature differentials.
 - (b) Propagation media dielectric changes.
- (3) Pointing errors of the array antenna due to:
 - (a) Spacecraft station keeping attitude control limit cycles.
 - (b) Earth pointing tracking motion errors of the array relative to the spacecraft.
- (4) Noise in the phase control subsystem electronics due to:
 - (a) Internal spacecraft RF noise sources.
 - (b) External RF noise sources.

SECTION A-II

RETRODIRECTIVE ARRAY PRINCIPLES AND REQUIREMENTS

The retrodirective array principle, as the name implies, means that the downlink power signal issuing from the spacecraft antenna is conveyed or redirected over the same path, but in the opposite direction to a low-power-level uplink signal emanating from a "pilot" signal transmitter located at the center of the power receiving rectenna array on Earth. By causing the pilot- and power-beam signals to traverse the same path between spacecraft and Earth, a desirable self-correcting feedback loop or automatic servo system is thereby created, which tends to maintain the power beam pointing at its rectenna target.

The magnitude and correct sign of the required phase-error correction to be applied to each individual subarray is continuously determined by comparing the received phase of the pilot signals at each subarray to a common reference signal at each subarray. Generally the reference signal derives from one selected of several redundant, designated subarrays, located near or at the center of the transmitting array. One of the redundant subarrays would become the reference for maintenance purposes, or in case of a failure. The problem of accurately distributing the reference signal over the flexible array were early recognized as a serious limitation to the retrodirective technique as applied to the large SPS array. Prior-art antennas employed much steel and concrete, and air conditioned control of phase-reference distribution transmission lines, which would be inappropriate for the SPS environment.

If one knows where a particular subarray is located electronically relative to the other subarrays in an array, it is an easy matter to simply calculate and command the proper state of RF phase for pointing the beam, or for correcting structural or thermally-induced electronic phase errors. However, such is not the case for a structurally flexible, 1-km diameter S-band antenna in orbit. Hence, some means other than conventional commanded phase steering must be devised and employed to determine and perform the proper phase control.

A. PHASE CONJUGATION

At the central reference subarray electronics location, the conditioned reference signal is divided among several circuits for phase conjugation. The phase conjugator is a three-terminal circuit device that accepts the reference and the pilot signals as inputs, and outputs a signal whose phase will become the phase of the RF power signal to be radiated from the corresponding appropriate subarray. The correct conditioned power signal phase relative to the reference is the conjugate (i.e., equal in magnitude but opposite in sign) of the phase of the corresponding subarray pilot signal relative to the reference.

The term "conditioned signal" refers to the processes that occur within the pilot-signal receivers and that consist of decoding and converting from the higher frequency RF to a lower frequency (termed IF or intermediate frequency), or vice versa, along with properly adjusting the signal amplitudes. The conditioning must be accomplished without erroneously altering the phase of the signals.

B. TRANSPONDING SIGNALS

It should be pointed out that the pilot- and power-beam signals cannot be at the same frequency for a continuously operating or continuous wave (CW) array. (A pulsed power transmitting array that could time-share a single frequency has not yet been determined to be an advantage for purposes of high-efficiency, base-load power transmission.) The identical frequency condition would result in the array oscillating and not forming the desired beam due to its inability to separate its own high-power output signal from the low-level pilot signal if at the same frequency.

Additionally, a corresponding problem exists relative to noise at the pilot-signal frequency generated inadvertently by the power-signal dc to RF converters. Thus, the array must transpond or change the uplink pilot beam signal to a different, separate frequency signal for the power beam. The transponding is accomplished via the frequency division in the subarray pilot-beam receiver and the frequency multiplication in the injection-locking signal generation process.

C. PHASE REFERENCE DISTRIBUTION

Because the centrally located subarrays have short transmission line pathlengths to the reference subarray, and because the conjugator circuits of adjacent subarrays are located in nearly the same identical temperature environment at the reference subarray, errors in the phase conjugating process are by design quite small. However, not all of the approximately 10^4 subarrays envisioned are able to be close to the central reference subarray, and, furthermore, not all the 10^4 phase conjugators can be located in the same thermal environment. Hence, a method of distributing the phase state of the central reference subarray to each subarray conjugator is required.

D. RECONSTRUCTED PHASE REFERENCE

A three-branching technique (Fig. A-2) has been conceptualized by Ralph Chernoff of JPL (Ref. A-2), wherein at one of the adjacent subarrays a sample of the inbound pilot signal and a sample of the corresponding outbound power signal are conditioned and mixed, thereby causing the phase error and its correction to essentially balance, and to result in yielding a signal whose phase varies as the central phase reference. Thus, the static phase of the reference subarray is thereby reconstructed at a remote subarray. The remote reconstruction process is not perfect, but the added noise or phase error at each reconstruction point or branch can be designed to be acceptably low at the array edge subarray conjugators. For truly random added noise at each reconstruction, the total phase noise error would increase only as the square root of the number of intermediate branch points. For example, to serve 10^4 subarrays with six adjacent subarrays at each branch point would require, at most, only six intermediate reconstructions. Thus, the phase error at the array edge subarray would be less than 2.5 times the error near the array center.

E. TECHNICAL ADVANCE

Using as much of the incoming pilot signal transmission line as practical to also distribute the phase reference via reconstruction at a remote conjugator location (thereby cancelling out any transmission line length changes, and thus allowing the separation of the subarrays electronically as well as mechanically) represents a significant advance in the array art! Previous retrodirective arrays were limited in size by requiring rigid interconnecting transmission lines maintained as absolutely phase stable for purposes of reference phase distribution.

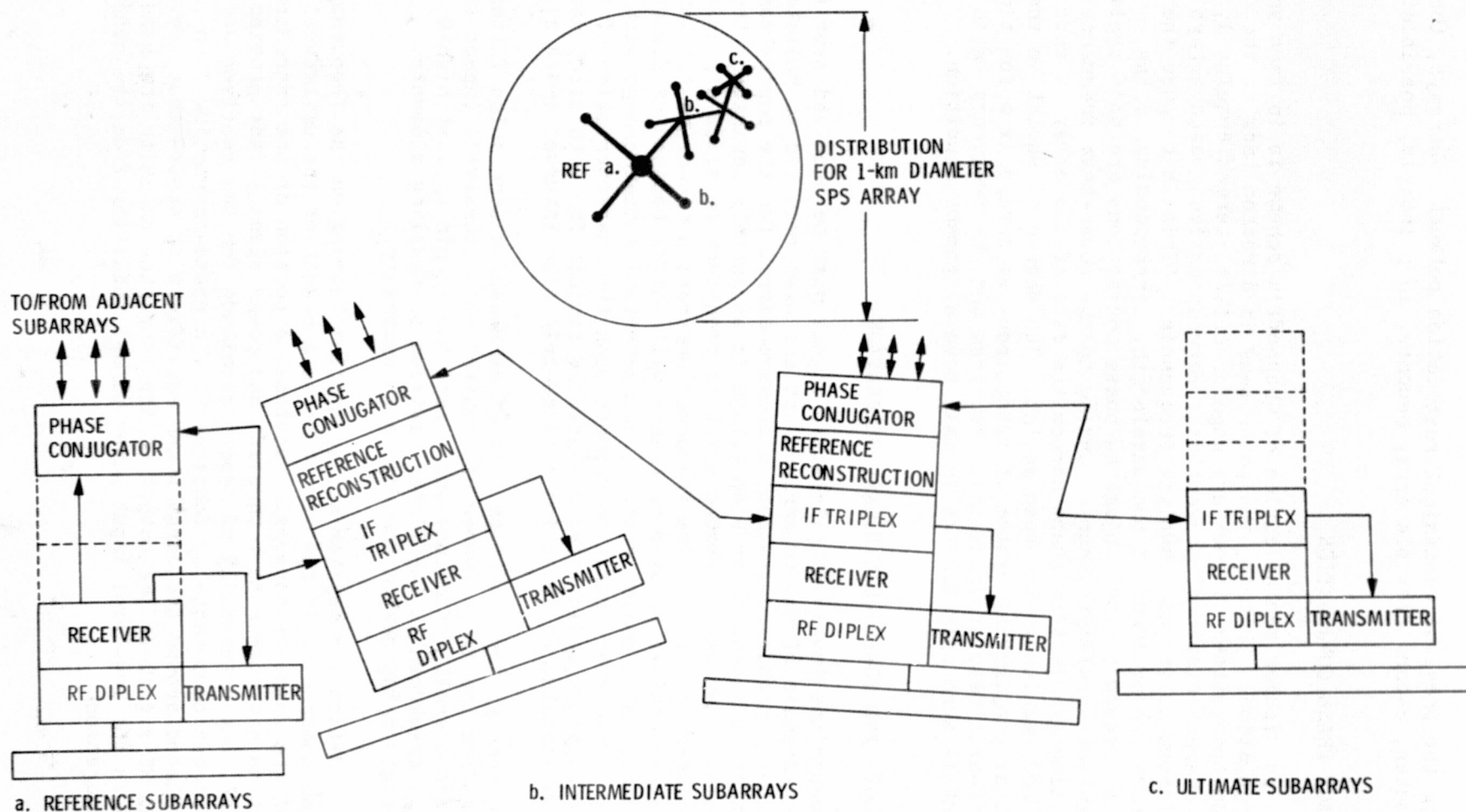


Figure A-2. MPTX Phase Conjugation and Reference Distribution

By freeing the previous mechanical restriction between subarrays, the 1-km diameter, S-band flexible array becomes, in principle, possible.

F. EXACT PHASE CONJUGATION

The particular mechanization of Chernoff's scheme is in fact an exact conjugation. That is, the power beam is directed back at the pilot-beam transmitter without any angular offset (termed "squint"), which is characteristic of conventional retrodirective phased arrays with different uplink and downlink frequencies. This is because the phase errors are measured at one wavelength, corresponding to the pilot-beam frequency; the conjugated phase corrections are then applied to a different wavelength, corresponding to the power-beam frequency. The resulting gradient of phase across the face of the array is thus improper and results in the beam squint. The degree of squint in the conventional conjugating system of retrodirective arrays is a function of the off-axis beam steering angle required and the frequency ratio. The squint is zero only for the on-axis beam alignment condition.

G. PILOT- AND POWER-BEAM SIGNAL SEPARATION

Because the low-level pilot-beam signal must be received over the very same antennas of the subarrays that are also required to radiate a tremendously higher-power-level microwave signal for the power-beam contribution, a potential problem exists in adequately separating the two signals. They can be spaced apart in frequency to allow diplexing filter discrimination, but the frequency separation cannot be too large, or the retrodirective array performance will suffer because of dispersion in the transmission media, that is, characteristics that change with RF frequency. The array operation depends upon the characteristics of the signal propagation media being essentially similar for both pilot and power beam signals, at least for a round-trip time interval ($\sim 1/4$ s).

Conversely, the insertion loss of narrow-band separation filters resulting from the large number of required resonators will impact the subsystem's overall efficiency and affect the margin against high-Q RF-voltage breakdown in the filter cavities or coupling elements. Another engineering design compromise is necessary.

An additional subsystem design problem bearing on the frequency separation compromise is the fact that as a result of the unilateral nature of the dc-to-RF conversion devices, a portion of the retrodirective path is not common to both pilot and power signals (the problem is similar, but potentially of lesser magnitude for the receiver and other selected components). Consequently, a phase-correcting loop must be placed around the large power amplifiers to assure that the amplified RF signal on the output of the converter exhibits the same RF phase as the low-level input power signal resulting from the conjugation operation.

H. SUBARRAY PHASE TRIM

Because the MPTX amplifiers and other devices may have different phase delays or age differently with time, or have to be replaced in scheduled maintenance, and due to the fact that the limited quantities of other microwave electronics for the subarrays cannot be economically produced or factory aligned with exact precision, provisions may be necessary in the subsystem subarray design for initial and perhaps periodic phase trimming of each subarray. The function of the phase-trim capability would be to assure that the RF power contribution from an individual subarray initially adds in the proper phase at the rectenna, independent of relative subarray deflections and for any attitude of the array at the time of assembly. The sum of the uplink and downlink RF signal paths (combined mechanical and electrical) must be modulo 2π identical in phase for each subarray. Because of its design, the subarray, once it is assembled, plugged into its position in the array, and then phase trimmed, would be nearly identical in phase-delay performance (for some given design length of time) to its neighbors as far as any known environmental phase drifts are concerned. The maximum phase-trim magnitude would be $\pm$ radians at either the pilot- or power-signal frequency, and the resolution required would be a function of the subsystem overall accuracy requirements.

I. PHASE TRIM TECHNIQUE

A technique for adjusting the phase-trim setting is to pair the subarray with another and to note the condition of the phase setting that yields a null or minimum of signal condition in a receiver diplexed to the pilot-signal transmitter antenna in the center of the rectenna. The proper operational condition phase for the subarray under test is exactly $\pm\pi$ radians from the phase condition that yielded a null. A condition of maximum received signal from the pair of subarrays could be used to achieve the correct phase-trim alignment directly; however, the phase setting for a maximum received signal condition is not as selective or precise as the phase setting for achieving a null condition, given that the two subarray power output levels are approximately equal. Subarray phase-trim calibrations for an amplitude-tapered array should proceed from the center subarray outward so as to minimize the effects of subarray amplitude differences.

J. SUBARRAY INTERSTICES

The limitations to the separated subarray approach as applied to the SPS antenna are determined by the allowable decrease in beam efficiency caused by the unfilled fraction of the array aperture. The beam-pointing accuracy is unaffected by the separated subarrays, but the loss in efficiency in the power in the main beam is in the ratio of the unfilled to the available apertures. The "lost" energy appears in increased sidelobes or more properly, grating lobes. The grating lobes are caused by a lack of radiated field components of proper phase opposition and amplitude at repetitive spatial angles determined by the subarray spacing dimension. The grating or unsuppressed lobe amplitudes

are determined by their spacing from the main beam and the subarray gap width.

K. BEAM SAFETY

Beamed power safety (Ref. 3-1) for the SPS transmitting array beam on or near the Earth is to be effected with electronic speed via randomizing the RF phase of the approximately 10^4 subarrays that tile the circular, 1-km-diameter array. This action will result in spreading the array's previously focused beam energy over a wide area, the wide beamwidth of a typical subarray. Thus, the flux density at the peak of the beam and nearby will decrease by the ratio of the subarray to array beam areas, or by a factor of approximately 10^{-4} . This approach will, however, result in an increase of flux density in areas outside the rectenna, but that condition need only last for the short period of time required to begin shutting down the RF output of the individual subarrays.

Because of the high (up to 20 kW/m^2) RF flux density near the transmit subarrays, the area on or near the transmitting array may be rendered safe only by turning off the power to the subarrays. Figure A-3 shows the RF flux density calculated along the beam axis for the proposed SPS transmitting array when focused. The ripples and the one large peak of flux density in the near field along the beam axis are due to various regions of the array being in or out of phase at that particular range.

The operational or emergency conditions requiring beam safety responses on Earth or in space have yet to be defined, and will depend upon the applicable regulations in effect at the time of SPS deployment.

L. BEAM SECURITY

The pilot signal will more than likely be coded to prevent unauthorized users from siphoning beamed power from the array. Depending on the pilot-signal receiver mechanization, the array is capable of forming multiple beams simultaneously. At low levels of pilot signal, the array output power could divide between the beams in the ratio of the amplitudes of the pilot signals. At high pilot-signal levels, the largest amplitude signal would saturate the receivers and thus tend to dominate the output power-beam amplitudes.

Multiple controlled (coded) beams may be desirable for load following or controlled, ramped-type switching between rectennas. Alternately, in addition to coding for security, the price of admission into the transmitting array pilot receiving system could be made large by requiring a high power level in the received coded pilot signals.

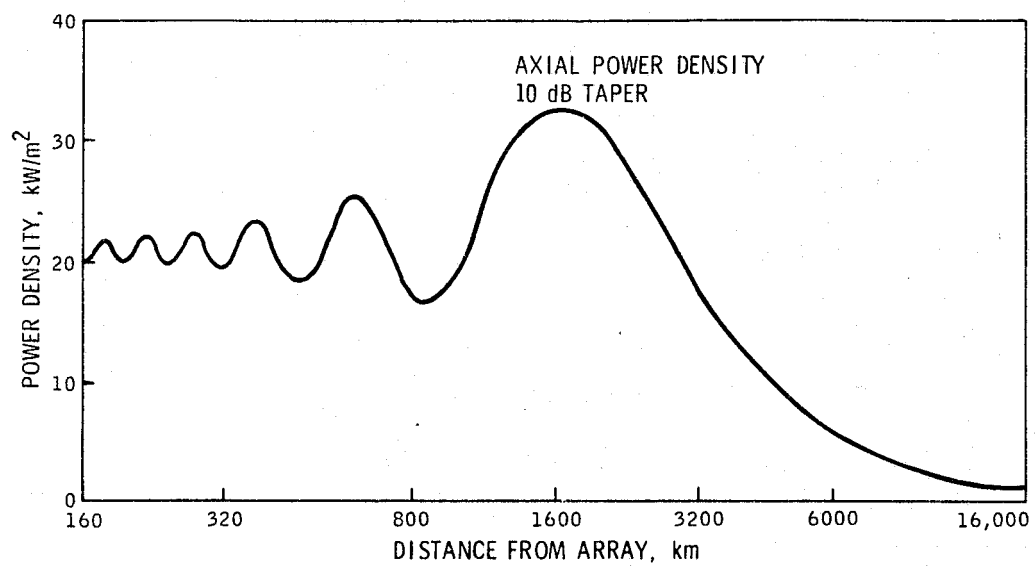


Figure A-3. SPS Transmit Array Near-Field Beam Intensity on Axis

M. BEAM TURN ON AND OFF

The beam amplitude must be capable of being changed in a controlled manner. For the above discussed beam safety condition achieved by randomizing the subarray phases, the action can be swiftly affected on the Earth by suppressing the pilot coding, or by dimming or dousing the pilot-beam amplitude. Aboard the spacecraft, the decoder could be commanded to disable, or the reference subarray output phase reference could be commanded to be dimmed or doused, with the backup references overridden. These actions will lead to a temporary transient RF condition outside the rectenna.

In cases other than a beam safety action, the normal turn-off sequence would probably be a somewhat more gradual dimming of the power beam while simultaneously maintaining the normal beam shape by turning down the subarray RF converter outputs.

Since turn-on will probably be effected by bringing on line a portion of the array at a time, there will thus be a wide and varying beamwidth-beamshape transient pattern condition until the total array is on and properly phased for normal functioning. The length of time to bring the total array on stream is unknown at present, but the turn-on transient pattern condition must be recognized and considered in the array subsystem design.

SECTION A-III

POWER TRANSMISSION ANTENNA FUNDAMENTALS

A. BEAM CONTROL

The microwave beam shape and pointing control is effected via control of the transmitting antenna aperture power amplitude distribution and the aperture phase distribution. The desired phase distribution results in beam focus on the rectenna center and is automatically produced by the retrodirective subsystem when properly operating. The phase distribution is a spherical phase front at the array, centered on the rectenna.

Generally, the desired overall antenna aperture amplitude or RF power flux density distribution is built into the array during construction, and provisions must be made for maintaining this distribution through the SPS environmental and operational changes (such as temperature, attitude control, and pointing), and throughout the design life (typically 30 years for a utility) of the satellite.

There exists an "optimum" distribution of power density across the face of the array. This optimum distribution must be faithfully approximated (by the stepped quantization resulting from the finite size and limited quantity of the subarrays, and the limited available power levels) to achieve low sidelobes and high-beam efficiency.

B. BEAM EFFICIENCY DESIGN

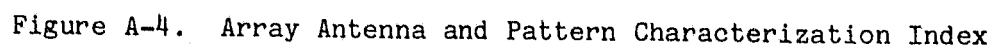
High beam efficiency represents an engineering design compromise. (High beam efficiency means that a majority of the energy radiated from the antenna is contained within a small-diameter beam, so as to minimize both the transmitter and rectenna areas.) The compromise arises as a consequence of the fundamental diffraction limit of finite-sized apertures (measured in wavelengths). The smallest achievable beam diameter from a given diameter antenna results in only about 87% of the transmitted energy being in that portion of the beam contained within the first nulls of the antenna pattern. (See Fig. A-4 for an antenna and pattern characterization index.) This particular pattern results from a uniformly illuminated aperture. That is, the RF power radiated per unit area of the transmitting antenna is the same all over the antenna. This is a desirable condition in one respect, in that only a single type of subarray is then needed to tile the plane of the array. However, the uniform aperture illumination leads to rather high sidelobes, which are about 1/50th of the peak power density or only 17.6 dB down from the peak intensity of the beam.

The opposite extreme design condition, a beam with extremely low-level sidelobes, requires a Gaussian distribution of energy across the array aperture, which requires an extremely large aperture and yet yields a comparatively wide beamwidth at the rectenna. The Gaussian approximation to the power density distribution in the transmitting array makes very inefficient use of the array, in that there are large areas at the edge of the array radiating quite low power-per-unit area.

C. OPTIMUM APERTURE DISTRIBUTION

The optimum conditions for the compromise between a radiated antenna pattern with no sidelobes and one with the majority of the energy in an acceptably small diameter beamwidth have been derived by Goubau and Schwering (Ref. A-3). The resulting efficiency of beamed power transport is shown in the design curves of Fig. A-5 as a function of the transmitting and receiving aperture areas, the wavelength, and the aperture separation distance. Also shown are the requisite aperture distributions for achieving the corresponding design efficiency. The high-efficiency optimum aperture distributions as shown in the figure tend to be truncated Gaussians. That is, the power density at the array edge is a small but finite fraction of the peak power density in the array center. The calculated antenna patterns as a function of various truncated Gaussian tapers are shown in Fig. A-6.

The subarray size is a factor in achieving the desired aperture taper. If the subarray size is made large, for example, the quantized approximation to the desired truncated Gaussian aperture distribution is poorer, which results in lower beam efficiency and higher grating lobes.



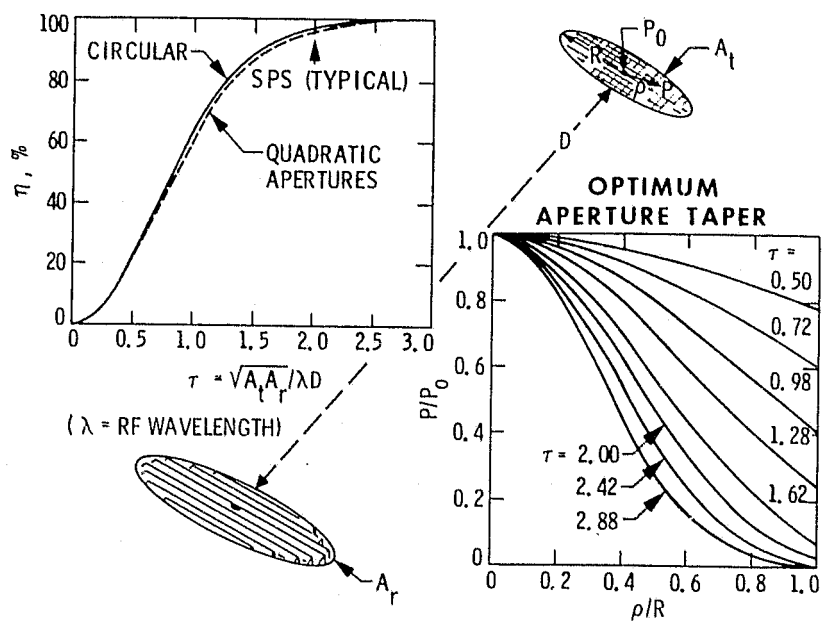


Figure A-5. RF Power-Beam Transmission Efficiency

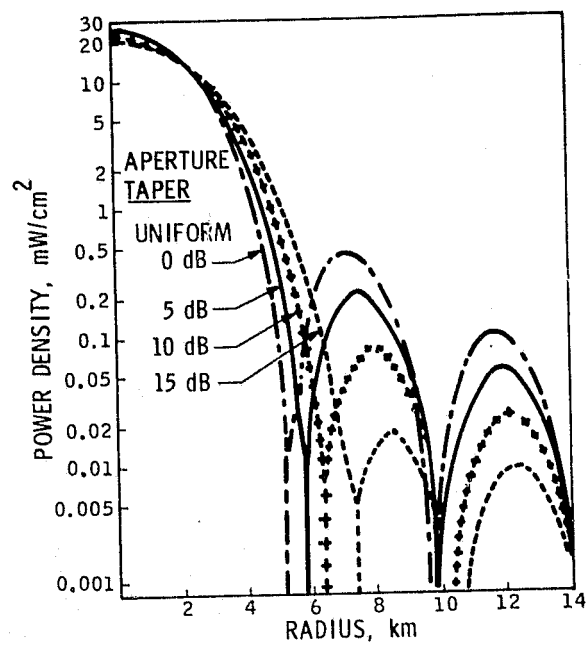


Figure A-6. Rectenna Power Density Distribution as a Function of the Array Aperture Truncated Gaussian Taper in dB

D. A POINT DESIGN PATTERN

Figure A-7 shows a calculated pattern of a proposed SPS array design for certain assumed operating parameters. The rms phase errors among the subarrays due to errors in the phase-control subsystem are assumed to be 10 deg. The errors in amplitude are assumed to be randomly distributed over the aperture and to have a standard deviation of ± 1 dB. There are also assumed to be randomly distributed subarray failures of 2% of the nearly 10^4 each 10-m^2 subarrays. The effect of the errors is to fill in the nulls of the array pattern and distribute some of the radiated energy out into an envelope bounded by the pattern of a subarray as shown.

Because of the attitude limit cycling of the array pointing, which is assumed to be $\pm$ one minute of arc, the subarrays are not pointed with their beam maxima toward the rectenna at all times. The retro-directive phase-control subsystem causes the individual subarray phases to change, causing the electrical peak of the beam of the array as a whole to steer on the rectenna pilot transmitter. This change of phase gradient across the array also causes low-level mirror images of the main beam and sidelobes to form in multiple directions around the array main beam. These are termed "grating lobes" and are normally suppressed by nulls of the subarray patterns where the array main beam is pointed normal to the plane of the array. The amplitude of the grating lobes is thus a function of the array-beam steering electrical angle. It is also a function of the order or repetition number away from the first grating lobe, and the degree of uniformity of the various subarray displacements, tilts, and amplitude and phase magnitudes.

The existence and regularity of the grating lobes can be thought of as equivalent to the multiple coincidences of aligned rows of trees in a regular orchard or troops in a parade formation that occur as one's line of vision moves relative to the rows or columns of trees or troops. Thus, for certain main-beam steering conditions, the resulting phase condition across the array also leads to multiple directions in space wherein the fields add up to a local maximum. A "worst case" example of the grating lobe consequences is next described.

E. DESPUN ARRAY ERROR SCENARIO

In the unlikely instance wherein the properly coded pilot-beam integrity is maintained but the mechanical pointing is no longer maintained (i.e., the normal axis of the array is no longer directed at the rectenna, and begins sweeping westward at a clock rate), the geometrical pointing error relative to the rectenna will continuously increase and would normally cause the RF beam to sweep off the rectenna. However, the retrodirective array scheme would maintain a main lobe toward the rectenna whose amplitude would slowly decrease, while the amplitude of the grating lobes to the west of the rectenna would begin to rise in amplitude while staying fixed in position on the ground. For the example of Fig. A-7, the first grating lobe at 280 km from the rectenna would rise in amplitude to equal the diminished amplitude (now $1/2$ of normal) of the previous normal main beam in approximately

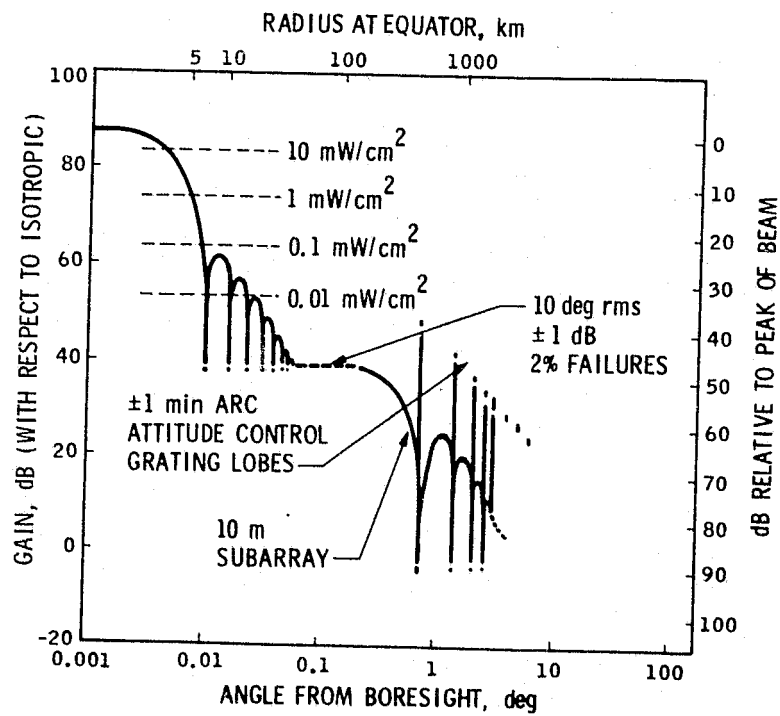


Figure A-7. Far-Field Pattern for a 10-dB Truncated Gaussian Aperture Distribution Array

100 seconds. The rise time and grating lobe position are a function of the subarray size. The grating lobes would each in turn, progressing westward, increase in amplitude toward the previous main-beam amplitude as the array mechanical beam axis passes their fixed spatial positions, until the subarrays are turned far enough in angle to begin suppressing the pilot signal as received from the rectenna. Thus, the array pattern would eventually decay into the randomized phase beam condition unless the despin failure was earlier detected and appropriate action instituted, which is more likely to occur.

APPENDIX B
DESIGN REQUIREMENTS

DESIGN REQUIREMENT

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DES. REQ. DM511337 REV. A
ISSUE DATE 17 October 1975
SUPERSEDING _____
DATED _____

MODULAR MICROWAVE POWER TRANSMITTING PHASED ARRAY (MPTX)

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RELEASED BY H. G. Homan DATE
Section 655

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1. SCOPE

1.1 Scope. This document covers the design requirements for an active, retrodirective, modular power transmitting phased array system (MPTX) to be used for advancing the state-of-the-art, performing technology demonstrations; investigations and experiments in microwave high power transmission. The MPTX system consists of the positionable, coded-pilot-beam transmitters, located at or near the microwave power reception-conversion array (RXCV), the transmitter power beam subarrays, the support and positioning structure, power conditioning, beam intensity control, array pattern, power transfer efficiency and phase control and measuring instrumentation and status monitoring, safety and control equipment.

1.2 Description. The MPTX subsystem described as follows will:

- a. Provide for personnel safety and equipment protection while operating.
- b. Provide for remote control positioning of pilot beam transmitters.
- c. Generate, code, radiate, receive and conjugate the phase of a low power level pilot beam microwave signal with the aid of a phase reference signal distributed over the power array.
- d. Efficiently convert station supply power into high power at a microwave frequency by use of phase injection locked magnetrons.
- e. Provide control subsystems for power beam intensity, pilot beam intensity and position and RXCV load value.
- f. Efficiently form and radiate a retrodirective microwave beam toward the pilot transmitters [the pilot transmitters are to be located in and near existing subarrays of a high power reception-conversion (RXCV) subsystem].
- g. Provide instrumentation, software and hardware to measure, display and record the phase relative to the reference phase,

the incident and reflected RF power, supply voltage and current, temperature and displacement of each of the modular, approximately 1.0 m^2 area slotted waveguide sub-arrays of the approximately 64 m^2 area transmitting array; the resulting power beam shape, position and side lobe levels; and the input power, output power, mean and standard deviation of the subarray phase errors and efficiency of the power transmission of the MPTX-RXCV system.

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue specified in the contractual instrument, form a part of this document to the extent specified herein:

SPECIFICATIONS

Jet Propulsion Laboratory

DOS-8913-GEN	Manufacturing Requirements DSN Cables and Harnesses, General Specification for
30606	DSIF Paint Standard
ES506015	Quality Assurance Inspection System Requirements for Electronic and Mechanical Equipment, Detail Specification for
FS507017	Identification and Marking Methods for Parts and Assemblies, General Specification for

PROCEDURE

Jet Propulsion Laboratory

DSIF-STD-1006	Standard Procedure, Painting or Thermal Coating DSIF Antennas and Supporting Structures
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3. REQUIREMENTS

3.1 Conflicting requirements. In case of conflict between the requirements of this document and requirements of any document referenced herein, the conflict shall be referred to the JPL contract negotiator and the JPL cognizant engineer for resolution.

3.2 Design. The MPTX shall safely and efficiently retrodirect over a minimum 200 m range, a controlled intensity beam of microwave power to a positionable, coded pilot beam transmitter location. The basic source of power is to be Goldstone station power which shall be efficiently and cost effectively converted into coherent 2450 MHz RF power for the power beam.

The MPTX subarrays shall be mechanically supported in the array such as to provide a fixed position relative to each other and alternatively by design to be free swinging within a restricted range of movement such that a dynamically compensating RF phase control system can be demonstrated to electronically correct for the mechanical displacements and maintain high power transmission efficiency.

The MPTX shall incorporate provisions for operating in a low power mode such as to allow measurement and check-out of phase accuracy and beam pointing and side lobes before as well as during high power transmission.

A functional block diagram of the MPTX subsystem and its interfaces is shown on Figure 1.

3.3 Materials, parts, and processes. Wherever possible fabrication techniques and components of demonstrated or proven quality, in particular connectors and cables shall be used. All materials, parts, and processes used in the design, fabrication, and assembly of the MPTX subsystem shall reflect the fact that the demonstration site (for reasons of personnel safety) is located in the MOJAVE DESERT. (See 6. for weather summary.)

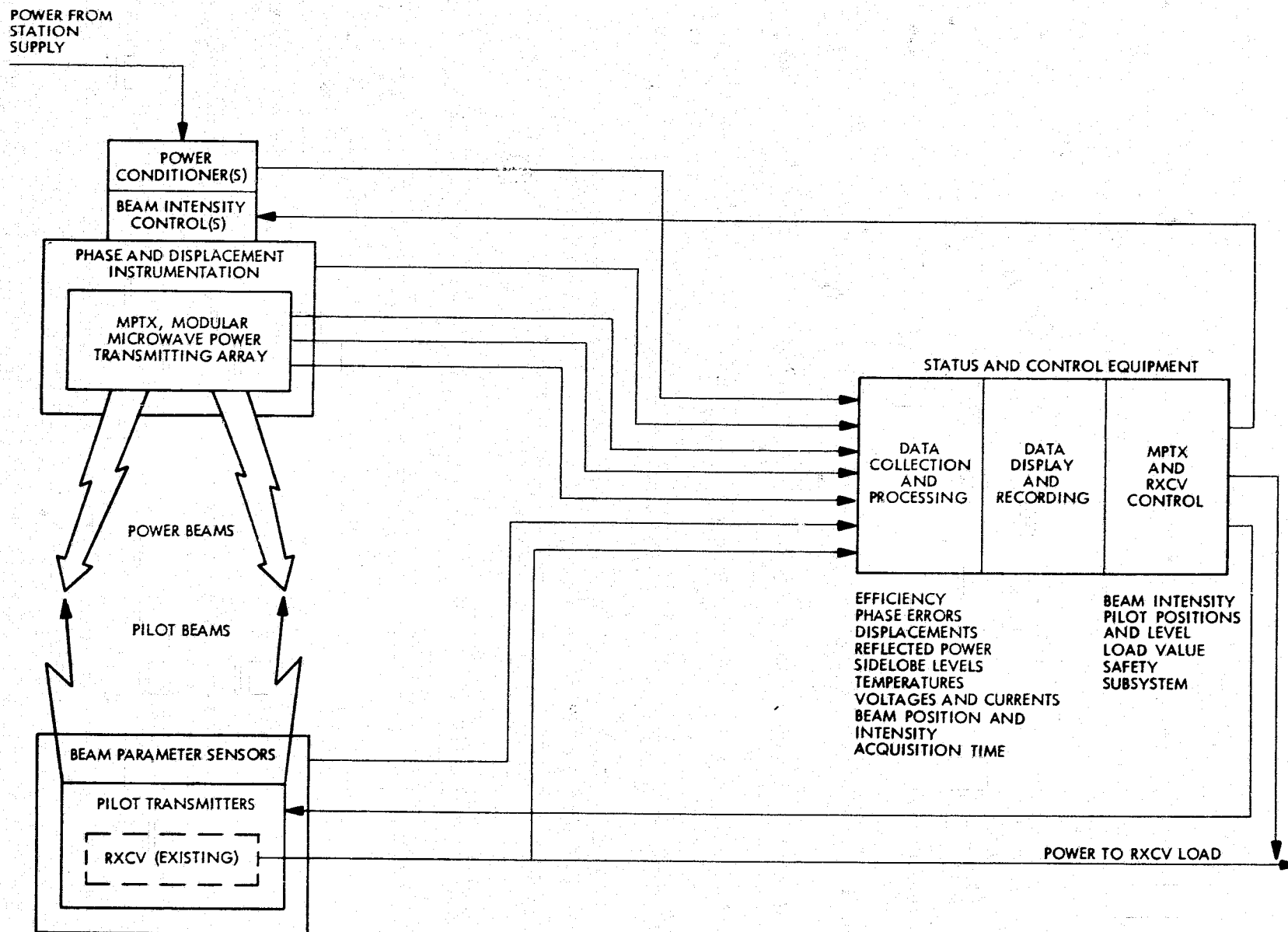


Figure 1. Functional Block Diagram

3.4 Cost. The target capital cost for the MPTX transmitting array shall be less than \$100 per watt of dc power delivered at the RXCV load output.

3.5 RF frequencies. The MPTX shall perform as specified herein when subjected to the specified frequency range and with proper pilot beam coding.

3.5.1 Pilot beam frequency and coding. The pilot beam transmitter frequency shall be 2390 ± 5 MHz and nominally coded in a manner to make it difficult for a "power freak" to misdirect the power beam. In any case, the loss of proper pilot beam coding shall cause random phase inputs to the transmitting subarrays and be interlocked with the system power supply.

3.5.2 Power beam frequency. The power beam transmitter frequency shall be 2450 ± 50 MHz.

3.5.3 Harmonic and spurious frequencies. All radiated harmonic or spurious outputs shall be less than one milliwatt at any frequency.

3.6 Dual power level capability. A scheme shall be provided to allow the MPTX transmitting array to operate in a low power transmitting mode such as to allow measurement and checkout of phase control accuracy, beam pointing and side lobe level before as well as during high power transmission operations.

3.6.1 High level output power. The maximum output dc power shall not be less than 20 kW

3.6.2 Input/output, protection/regulation. If at either end of the power transmission system where applicable, the input or output current, voltage or operating temperature or side lobe level or power beam main lobe position should exceed the acceptable operating parameter value by a predetermined amount, a subsystem control or override shall reduce or change the system state sufficiently to protect the equipment and personnel.

3.7 Efficiency. The goal of the ratio of dc output power at the RXCV load input connector (load input voltage x load input current) to input station supply power (supply input voltage x supply input current x power factor) shall be 0.4 or better under design optimum conditions for at least 20 kW output at the RXCV load.

3.8 Pilot beam subsystem. The pilot beam intensity at the power beam array shall not exceed 0.01 mW/cm^2 .

3.8.1 Pilot transmitter positionability. A scheme shall be provided to position the pilot beam transmitter such that the power beam may be caused to move in a horizontal plane across the RXCV array center so as to position the power beam from main lobe on the RXCV to first side lobe on the RXCV in at least five approximately equal angular steps.

3.8.2 Pilot SNR control. A scheme shall be provided to control the pilot SNR in approximately five each, 10 dB steps as well as the pilot beam off condition.

3.9 Transmitter subarray radiator mechanical displacement capability. A scheme shall be provided to mechanically support the transmitting subarrays such as to provide for:

- a. Setting the subarray mechanical boresight pointing direction relative to the RXCV within a cone of $1/2$ angle equal to $1/5$ of a subarray beamwidth and simultaneously,
- b. Setting the individual subarrays position such that the in-plane displacement of the subarray center relative to a designated reference subarray near the center of the transmitting array is capable of being positioned for a relative displacement of ± 1 wavelength in the direction of the RXCV, or,
- c. Unrestraining, within limits, the subarrays so as to be "free swinging" in the desert breeze within a restricted range of movement approximately equal to a. and b. above, but with the "average" boresight direction to be toward the RXCV.

3.9.1 Transmitter subarray rms surface position displacement and rms subarray phase error. A scheme shall be provided to determine with the aid of the system computer the individual transmitter subarray's rms surface position displacement and rms subarray phase error relative to a central, designated reference subarray near the center of the transmitting array.

3.10 Load variability. A scheme of RXCV load control shall be provided to allow the load to be varied from $2R_0$ to $R_0/2$ in at least 5 steps, one of which is R_0 , where R_0 is the approximately maximum power delivery load value.

3.11 Electromagnetic compatibility.

3.11.1 RF opacity. The level of the transmitted RF signal density at the nearest convenient point immediately to the rear of the boresight centerline of the subarrays of the MPTX transmitter subsystem shall be greater than 23 dB down from the front side output RF field density.

3.11.2 Testing. A MPTX transmitter subarray shall be tested to determine the harmonic and spurious radiated output levels.

3.12 Environmental requirements.

3.12.1 Design. The MPTX subsystem shall be designed to meet the goals specified in 3.6.1 and 3.7 when the subsystem is exposed to the Mojave Desert environment of sunshine, precipitation, wind up to 96 km/hr, (60 mph), sand, static charge accumulation, lightning, rodents and dust for a minimum of five years after installation. Surface temperatures may vary from -20° to 60°C . Cooling air in this environment may vary from -18° to 40°C at any relative humidity, and at pressures ranging from 0.79×10^5 to $1.01 \times 10^5 \text{ N/m}^2$.

The MPTX subsystem shall survive a 161 km/hr (100 mph) wind without permanent degradation.

The MPTX shall survive a non-operating storage temperature range of -30°C (-22°F) to 79°C (175°F) without permanent degradation.

The production approval ambient temperature range shall be -20°C (-4°F) to 60°C (140°F).

Over the type approval ambient temperature range of -30°C (-22°F) to 65°C (150°F) the MPTX efficiency shall not be less than 0.3.

3.12.2 Testing. The prototype MPTX subarray shall be subjected to the environmental tests listed in Table I to verify that the performance is in accordance with 3.12.1. The production MPTX subarrays shall be tested after assembly, before shipping to verify satisfactory performance relative to minimum requirements established based upon prototype test results. In particular, the mechanical and electrical interfaces including all controls and instrumentation shall be exercised.

Table I. RXCV Environmental Tests

Rain
Sand and Dust
Transportation Vibration
Transportation Shock
Sunshine (Ultraviolet)
High Temperature
Low Temperature
Actual Goldstone Installation

3.13 Performance monitoring instrumentation.

3.13.1 Performance monitoring. The functions listed in Table II shall be provided to evaluate the MPTX operating status. The cables and harnesses shall meet the requirements of JPL Spec DOS-8913-GEN or as defined at the primary design review. Acquisition time, is the time interval from turn-on of the pilot beam transmitter until the RXCV dc load power has reached 90 percent of the final steady state dc output power.

3.13.2 Temperature. The temperature shall be measured on the common heat sink near the magnetrons of the subarray.

3.14 Mechanical characteristics. The following criteria shall govern mechanical characteristics.

3.14.1 Modular element design. Provisions both mechanically and electrically shall be made in the MPTX and its support structure to yield a modular element design such that by replicating the 1.0 m² area slotted waveguide MPTX subarray and juxtaposing these elements, the MPTX subsystem shall be capable of forming a microwave power beam efficiently from over a larger area.

3.15 Identification and marking. The following criteria and JPL Spec FS507017 shall govern identification and marking.

3.15.1 MPTX subarray nameplate. A nameplate shall be affixed to each MPTX subarray, indicating at least the following information:

DEVICE NAME
MANUFACTURER
PROGRAM
MODEL NO.
SERIAL NO.*

*Consecutive from 001.

Table II. Performance Monitored Parameters and Characteristics

MPTX Parameter	Measurement Range	Tolerances
1. Power transmission efficiency	0-100%	$\pm 1\%$
2. Output dc power	0-35 kW	$\pm 1/2\%$
3. Input power	0-75 kW	$\pm 1/2\%$
4. rms surface position displacement	0-1 wavelength	± 0.1 wavelength
5. Pilot position	(in radians) ± 2 wavelengths / D_t^*	± 0.04 radian
6. Load value	0-2 R_o	$\pm 0.02 R_o$
7. Transmitter temperature	-30° to +200°C	$\pm 2^\circ\text{C}$
8. RXCV temperature	-30° to +79°C	$\pm 1^\circ\text{C}$
9. Load temperature	-30° to +100°C	$\pm 2^\circ\text{C}$
10. Beam pointing	(in radians) ± 2 wavelengths / D_t^*	$\pm \text{beamwidth}/30$
11. rms subarray phase error	0-1 radian	± 0.04 radian
12. Reflected RF power	0-200 W	± 2 dB
13. Transmitted beam intensity at the RXCV	0-150 mW/cm ²	$\pm 3\%$
14. Magnetron currents	0-400 mA	$\pm 1\%$
15. Magnetron voltages	0-5000 V	$\pm 1\%$
16. Acquisition time	0-10 s	$\pm 2\%$
17. Side lobe level	0 to -30 dB	± 2 dB
18. Coded pilot beam SNR	0 to 40 dB	± 2 dB

* D_t = "Effective" transmit array diameter, in wavelengths.

3.15.2 Finish. Finish and surface coatings shall comply with para. 3.3 of JPL Spec 30606, JPL Procedure DSIF-STD-1006 and provide as necessary for fire proofing or flame retardation, rodent protection, dust erosion resistance, corrosion resistance, high insulation resistance, protection from ultraviolet deterioration, and electrolysis inhibition while not impeding thermal dissipation.

3.16 Safety. The project shall meet or exceed all applicable federal, state and JPL safety standards and specifications.

3.16.1 Personnel non-ionizing radiation safety. A system of interlocks, warning devices, and the MPTX layout shall be configured to provide for maximum personnel non-ionizing radiation safety.

3.16.2 Safety warning. Any applicable safety warnings shall meet O.S.H.A. requirements.

4. QUALITY ASSURANCE PROVISIONS

4.1 Inspection and controls. A system of inspection and controls shall be implemented during assembly and test of the MPTX subarray prototype and prototype and production models in accordance with JPL Spec ES506015, to assure compliance with all policies and requirements specified herein (except that in JPL Spec ES506015 para. 4.14, first article inspection is limited to form, fit and function) and in the JPL-approved Quality Assurance Plan.

4.2 Rejection and resubmittal. Individual MPTX subarray models which do not meet all requirements of this document will be reviewed and may be rejected by JPL. Rework of the units will be permitted. Resubmittal of all rejected units shall be accompanied with details concerning the previous rejection and the action to be taken to correct the deficiencies.

5. PREPARATION FOR DELIVERY

5.1 Packaging. Subarrays of the MPTX subsystem shall be placed in a contractor-furnished shipping container and packaged in a manner to assure safe delivery to the test site at Goldstone.

6. NOTES

Goldstone Weather Summary by W. E. Ackerknecht
(1-24-74)

The Goldstone area is a desert region which has hot, dry summers and erratic winters. The winds are strong in the spring and very light in the late summer. Rainfall usually occurs in the winter, with occasional thunderstorms during the summer.

The average monthly temperature varies from about 5°C (+40°F) in December and January to about 28°C (+82°F) in July and August. Temperature extremes from -10°C (15°F) to 45°C (113°F) should be expected during the year. The year average temperature is about 17°C (65°F).

Winds are highest in April and May, while very little wind occurs during July and August. Wind velocities average over 12 mph in April and less than 5 mph in July. On the average the velocity will exceed 25 mph about five percent of the time. Gust factors (maximum short-time velocity/5 minute average velocity) of 1.2 to 1.3 are common, indicating that the wind is rather steady most of the time.

Rainfall at Goldstone usually occurs from November through April, averaging less than one inch per month and about 5.5 inches each year. The winter months usually have days of light rain (0.1 - 0.2 in. /day) and the summer months have a few days of light-to-heavy rain (.05 - 0.25 in. /day). There is usually at least a day or two of snowfall each winter, with heavy snows having occurred two out of the last three winters.

Relative humidity is generally low, averaging about 30 percent during the year. Monthly averages range from 40 percent during December-January to 20 percent during July. Very dry weather occurs occasionally during the summer.