AUTOMATIC ANTENNA SWITCHING TECHNIQUES

H. DEAN CUBLEY

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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H. Dean Cubley

NASA-Manned Spacecraft Center
Houston, Texas

SUMMARY

A development program is described that has as its purpose the optimization of the communications antenna performance of the orbiter portion of the Shuttle vehicle. The basic configuration of the communications antennas on the Shuttle is discussed in view of the presently anticipated communications requirements. The design problems associated with the placement of Shuttle antennas and the possible effects of interference between antennas are explored. A proposal is made that some type of switching system for antenna control must be a basic part of any Shuttle design. The basic types of antenna control systems are reviewed with emphasis on their applicability to the Shuttle requirements. The results of an extensive comparative analysis of all of these basic systems and certain of their hybrid combinations are presented. The development of engineering models of some of the most interesting of these antenna control systems is discussed in relation to their adaptation to the Shuttle requirements. The present MSC in-house test program being conducted on these engineering models is discussed, and some of the results of these tests are presented. A summary of the additional planned development and testing objectives of this program is presented.

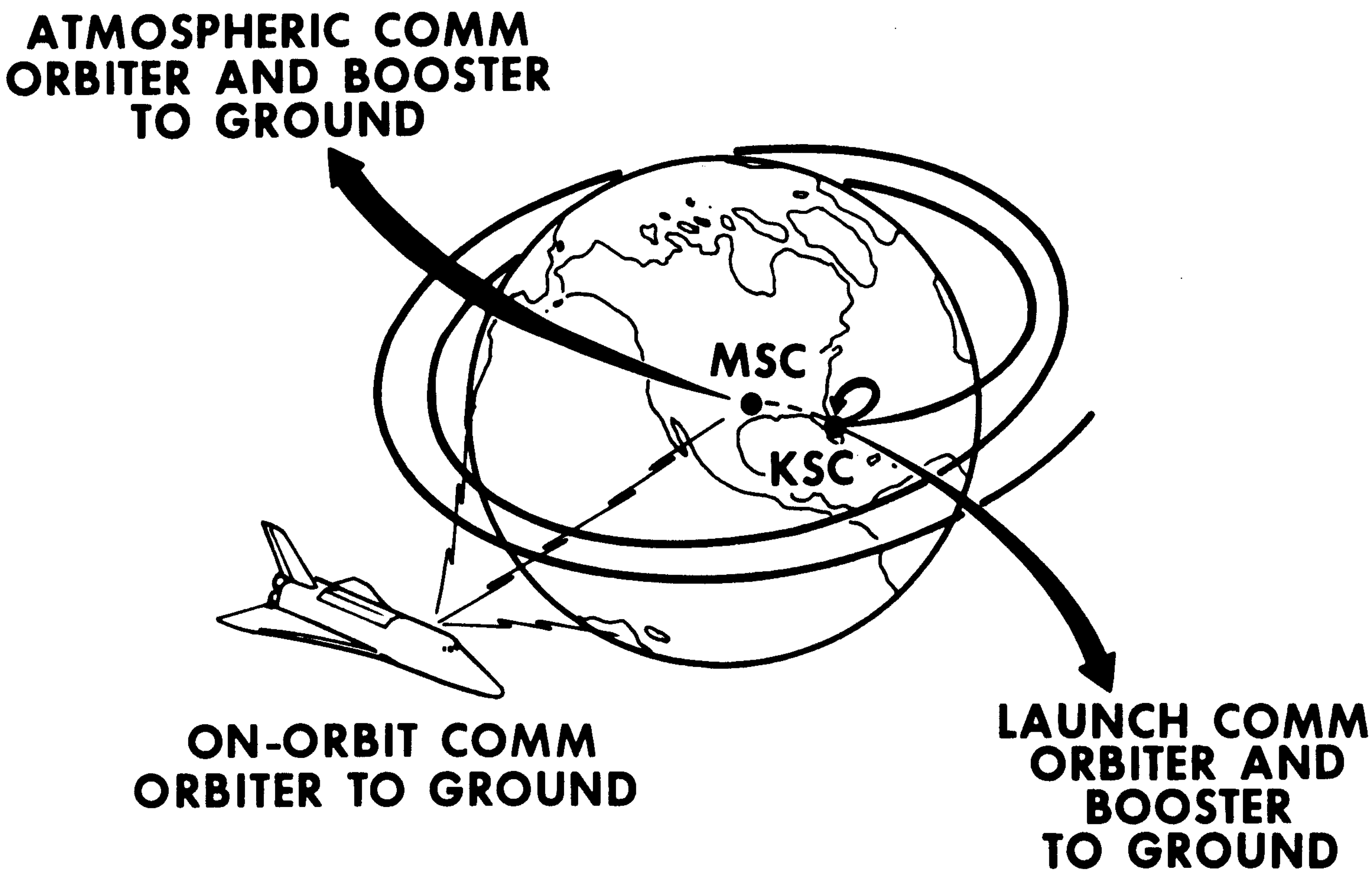
INTRODUCTION

The design of the Shuttle orbiter stage communications system must contain a sufficient number of antennas to provide the necessary pattern coverage to fulfill the Shuttle mission without constraints on the orientation of the vehicle. Because of the thermal heating of the Shuttle during reentry and the requirement for multiple mission usage, the placement of these antennas is not optimum from a coverage standpoint. The result of these conflicting requirements is a Shuttle antenna system that requires some means of logical selection of the best set of spacecraft antennas at each point in the Shuttle mission. The means of this antenna selection can take various forms depending on the mission requirements and the degree of sophistication available in the antenna selection system. The most basic selection system is manual selection by a Shuttle crew member. However, this technique will require an excessive amount of crew time. The more sophisticated techniques range from semi-automatic and automatic RF tracker techniques to complete antenna control by an onboard computer.

SHUTTLE BASIC COMMUNICATIONS REQUIREMENTS

The basic communications requirements of the first generation of Shuttle vehicles will consist of three separate phases. The first phase will consist of the relatively short range communications between the launch site and the orbiter and booster stages during and shortly after launch. The second phase of communications will consist of those transmissions between the orbiter and booster and down-range ground stations prior to the attainment of orbit. The final phase of communications will consist of transmissions between the orbiter stage and the various global ground stations after attainment of orbit. Because of the very low orbits planned for the orbiter stage, a large range of look angles to the various ground stations will be encountered. This variation in look angles will require repeated selection of the appropriate communications antennas in order not to have loss of communications.

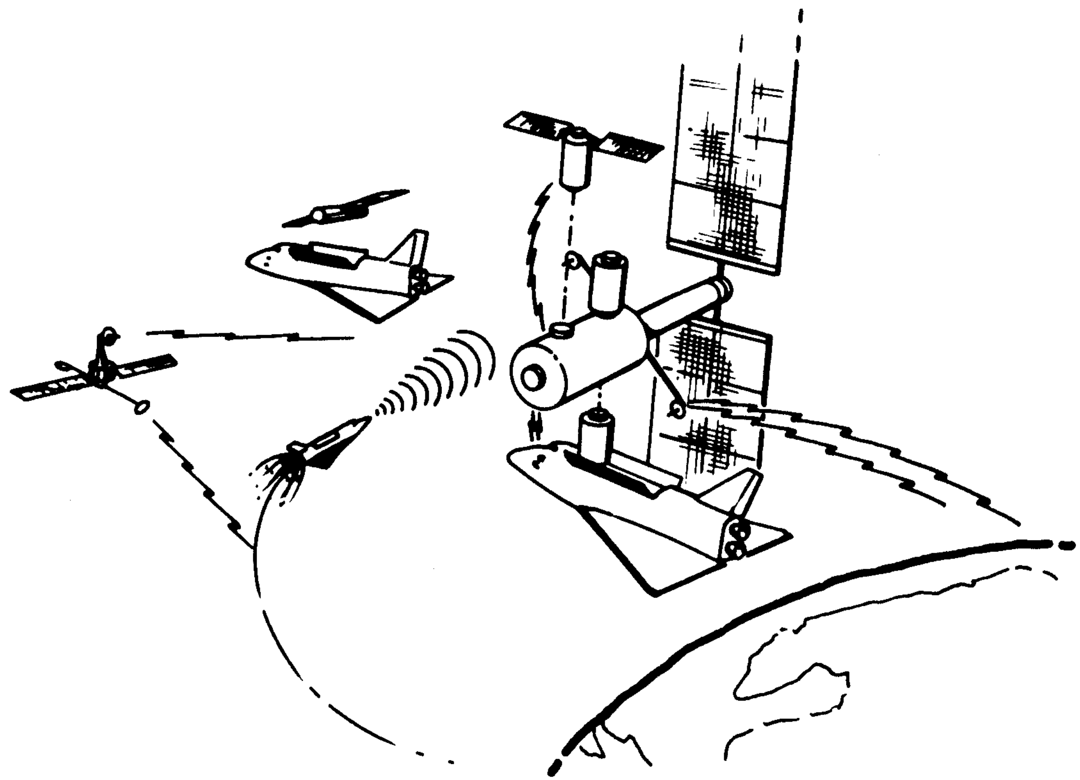
SHUTTLE BASIC COMMUNICATIONS REQUIREMENTS



SHUTTLE ADVANCED COMMUNICATIONS REQUIREMENTS

The more advanced Shuttle missions will encounter the same basic problems of antenna selection as those of previous missions. However, for Shuttle missions supporting other manned vehicles such as the space base, additional antenna selection requirements are encountered. Because of the more complex look-angle geometry between a Shuttle vehicle, a space base, and several ground stations, the selection of the appropriate antennas for all the required communications links will consume a large portion of the time of one Shuttle crew member if accomplished manually. In addition, as logistic requirements for the space base become greater, there is the likelihood that even more than one Shuttle may be in orbit at a given time. This will undoubtedly necessitate even more communications requirements, with the resultant increase in antenna switching operations.

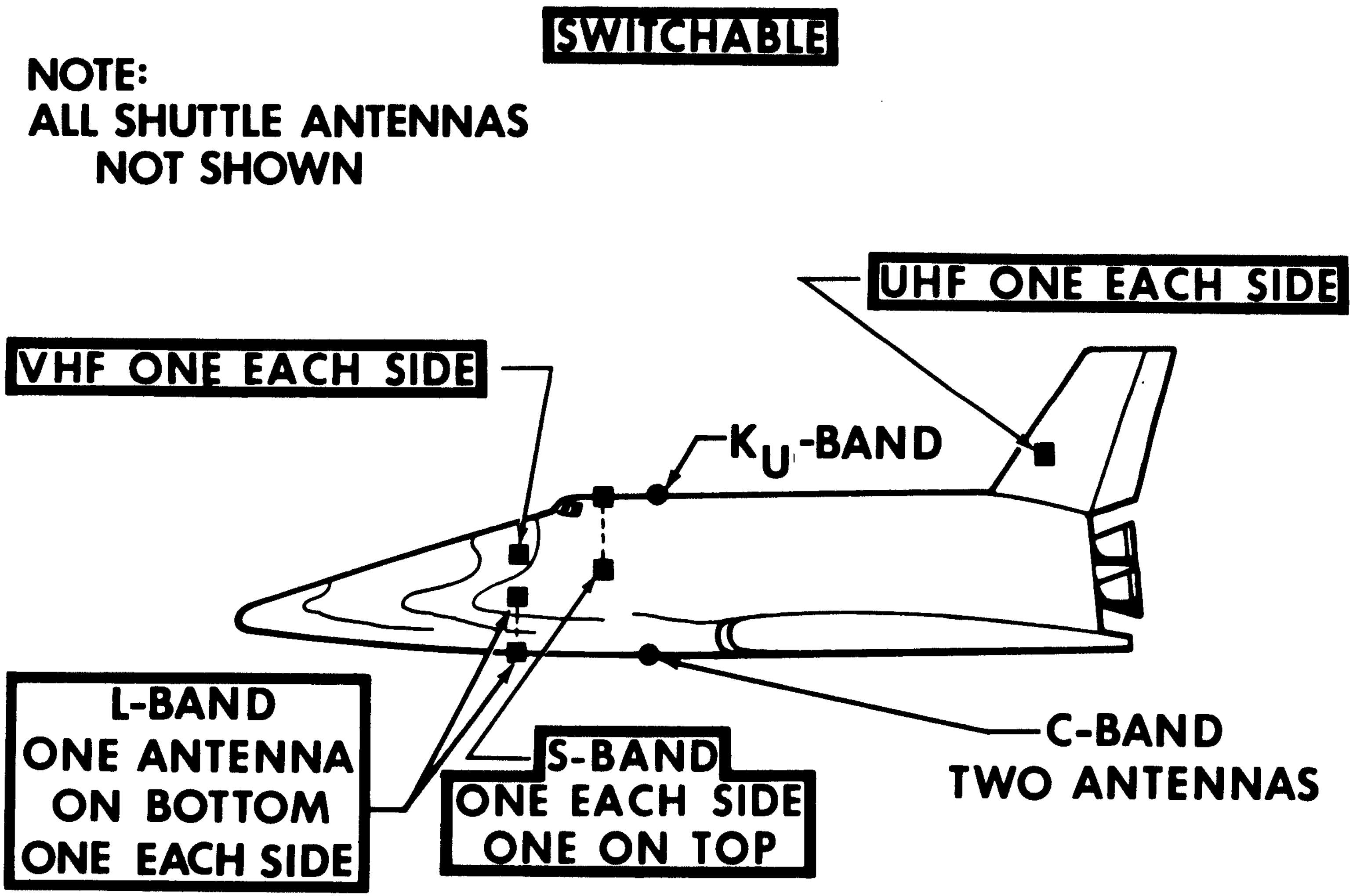
SHUTTLE ADVANCED COMMUNICATIONS REQUIREMENTS



SHUTTLE COMMUNICATIONS ANTENNA LOCATIONS

The obvious solution to the Shuttle antenna selection problem is to design a Shuttle communications antenna system with the minimum number of antenna elements. The nature of the Shuttle communications requirements necessitates almost complete coverage in the plane perpendicular to the longitudinal axis of the vehicle. Two antennas located on opposite sides of the Shuttle forward of the crew compartment represent the best choice for all the communications requirements. Unfortunately, this location also imposes severe heating levels on the antenna elements. The most logical choice for a compromise antenna location is shown in the accompanying figure. The basic communications frequencies are S-band, VHF, and UHF. The S-band antenna system consists of three antennas located directly behind the crew compartment. One of these S-band antennas is located centrally on the top of the vehicle to provide coverage above the Shuttle. The other two S-band antennas are located on opposite sides of the Shuttle to provide coverage both below and to each side of the vehicle. The VHF system consists of one antenna located on each side of the vehicle slightly forward of the crew compartments. The UHF antenna system consists of one antenna located on each side of the Shuttle vertical stabilizer tail assembly.

ANTENNA LOCATIONS

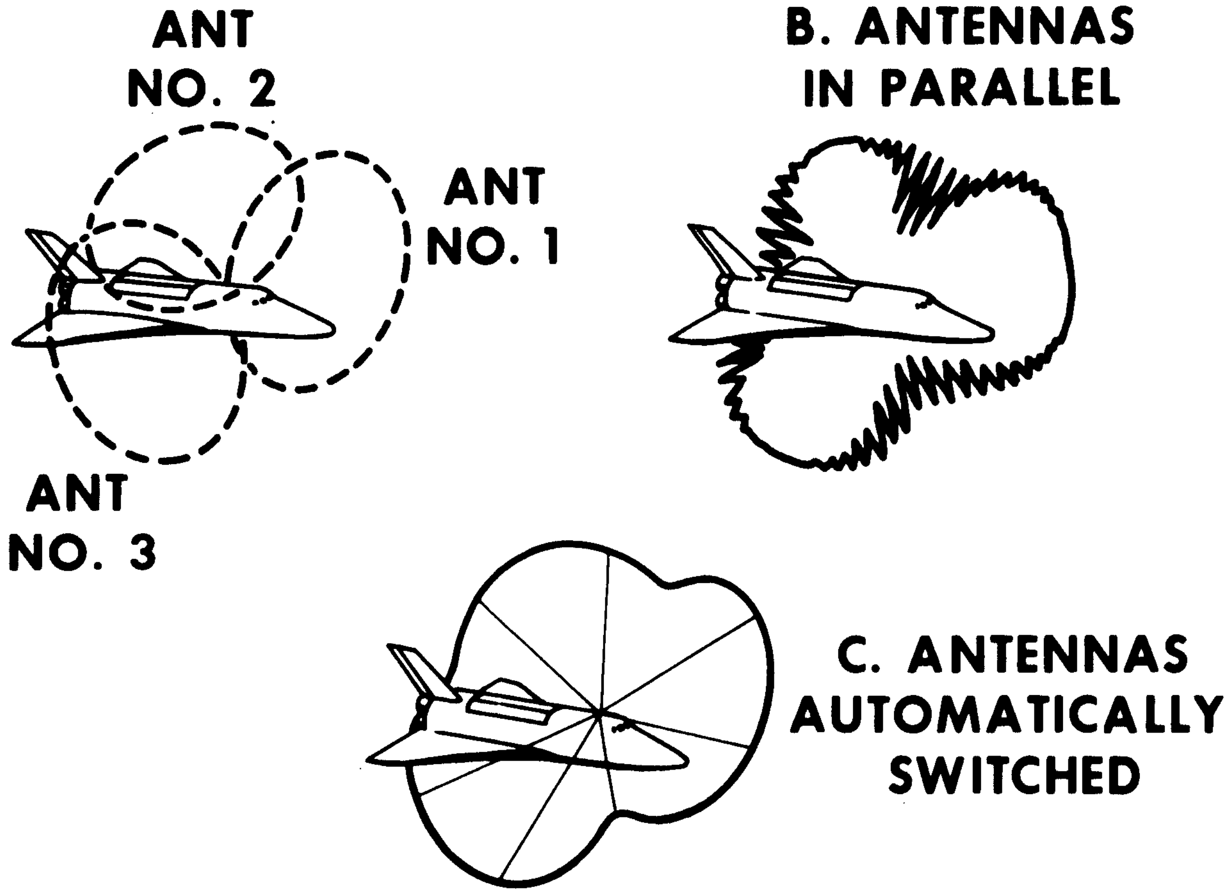


SHUTTLE ANTENNA INTERFERENCE PATTERNS

As an example of the type of pattern coverage expected from the Shuttle antenna system, consider the various antenna configurations shown in the accompanying figure. The S-band antennas previously described are the basis for this figure. The first part of this figure illustrates the typical shape of each of the individual S-band antenna patterns in the plane perpendicular to the Shuttle longitudinal axis. It should be noted that these patterns provide a large amount of overlapping coverage. This particular type of antenna pattern is required in order to minimize the total number of antennas required for complete coverage. One method that has been proposed to provide the required coverage is to connect all three antennas in parallel and thus eliminate the need for antenna switching. The result of such an arrangement is shown in the second part of the figure. One can see that the interference between the various antennas results in very deep nulls over a major portion of the composite pattern. By contrast, the composite pattern obtained by the use of any automatic switching system is shown in the third portion of the figure.

SHUTTLE ANTENNA INTERFERENCE PATTERNS

A. INDIVIDUAL ANTENNAS



POSSIBLE SHUTTLE ANTENNA CONTROL TECHNIQUES

The possible antenna selection and switching techniques available to the Shuttle designer range from a simple mechanical switch to a system completely controlled by an onboard computer. The mechanical system consists of a switch that allows a crewman to select any one of the Shuttle antennas. The basis for his selection may be a preplanned sequence or a general knowledge of the look angles to the receiving station. A degree of sophistication may be added to the selection process if the switching is accomplished automatically, based on some knowledge of the signal strength being received from the remote station. All such switching systems may be termed RF track control systems. The most simple of the RF track control systems is the phase quadrature tracking system. This system may be used to phase the signal arriving from the various Shuttle antennas such that they may be connected in parallel without experiencing the interference nulls. A slightly more sophisticated RF system is the cochannel switching system. This system periodically connects the various antennas to the receiver and samples and compares the signal strength. The antenna with the strongest signal strength is then connected to the receiver until the selection process is repeated at the next sampling time. One disadvantage to this system is that the received signal must be periodically disconnected from the receiver in order to permit the required sampling. The most sophisticated RF system is the separate channel switching system. This system is the same as the cochannel system, except that the sampling is accomplished in a parallel fashion through the use of a secondary receiver. The ultimate in antenna control may be accomplished through the use of a small computer to select the proper antenna based on either a preprogrammed trajectory or possibly on inputs from the Shuttle guidance system.

POSSIBLE SHUTTLE ANTENNA CONTROL TECHNIQUES

- MANUAL CONTROL BY CREWMAN
- RF TRACK CONTROL SYSTEMS
  - PHASE QUADRATURE TRACKING SYSTEM
  - COCHANNEL SWITCHING SYSTEM
  - SEPARATE CHANNEL SWITCHING SYSTEM
- COMPUTER CONTROLLED SELECTION BASED ON GUIDANCE SYSTEM INFORMATION

PHASE QUADRATURE TRACKING SYSTEM

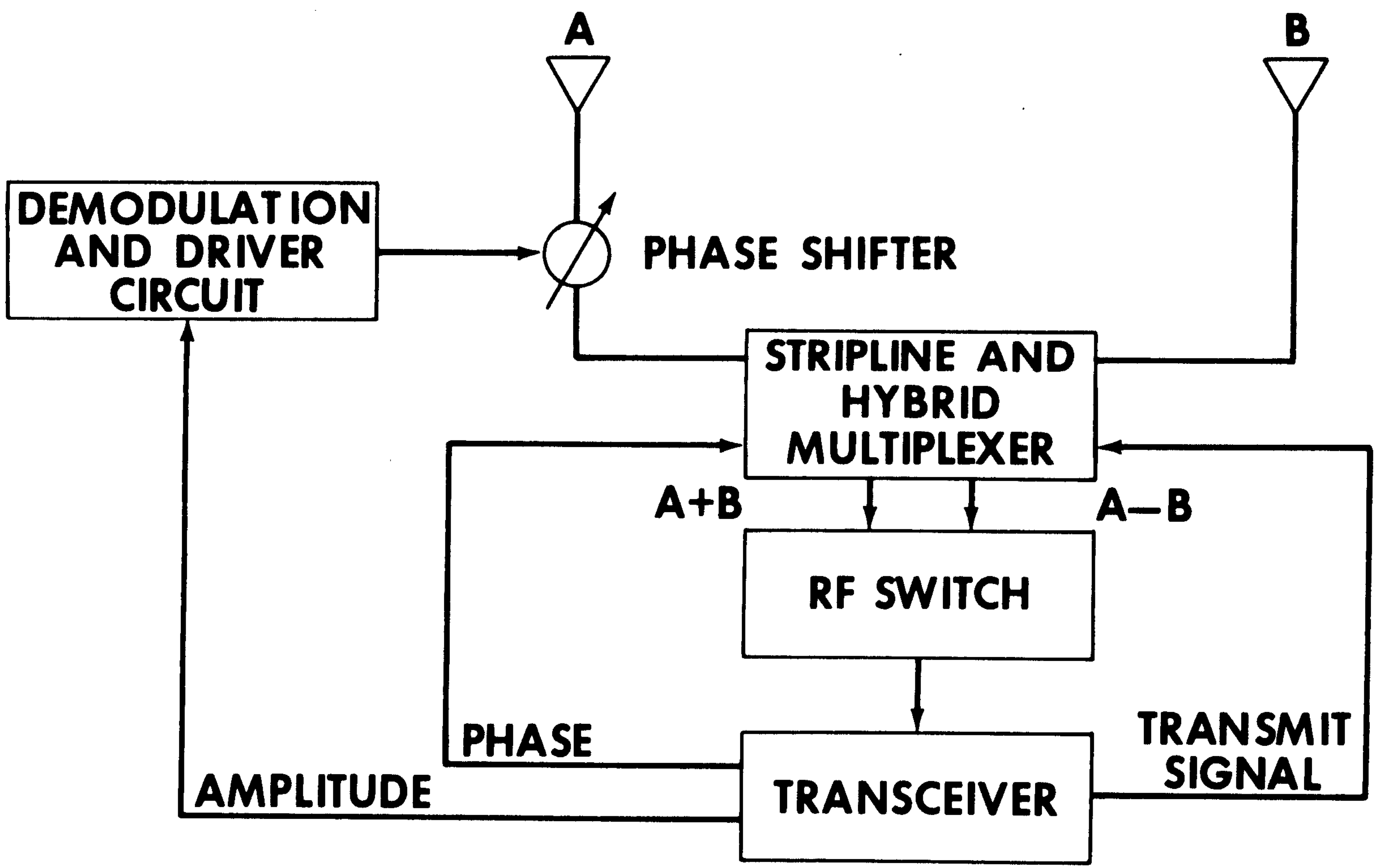
An antenna-array, phase quadrature tracking system automatically adjusts the phase relationship between the input signals appearing on two widely spaced parallel-connected antenna elements in the array. An optimum signal is delivered to a transceiver in the control system when a quadrature-phase relationship is achieved between the two input signals.

In the basic system, the two input signals in a single array are combined to form the absolute sum and difference values of the signals. The sum and difference signals are then time multiplexed through an RF switch at 10-millisecond intervals and processed to form a single multiplexed output which is applied to an amplitude detector in the receiver. The detector senses amplitude variations in the multiplexed signal and generates an output control voltage proportional to the deviation from the ideal quadrature-phase condition. The control voltage is applied to a feedback loop in a variable phase shifter circuit that automatically adjusts the relative phase of the two antenna signals until amplitude modulation ceases in the multiplexed signal (i.e., until the two antenna signals are locked in phase quadrature). The control loop continuously adjusts the relative phase of the two antenna signals to maintain the optimized signal input condition.

The RF switching operating in the multiplexing stage creates a phase modulation of the two input signals which is dependent upon the relative amplitude of the signals received on each of the antenna elements. The signal combining and multiplexing operations, including the RF switching, are accomplished by means of a stripline hybrid circuit which reduces the number of components in the antenna system.

When the antenna tracking system operates in the transmitting mode, power is delivered to the antenna element which will provide the maximum gain between the transmitting array and the receiving station. The automatic selection of the antenna element with the proper phase relation provides a substantially omnidirectional antenna coverage with a minimum number of antenna elements. The complete system is lightweight and sufficiently compact to permit its use in a Space Shuttle communications system.

PHASE QUADRATURE TRACKING SYSTEM



COCHANNEL SWITCHING SYSTEM

The operation of the system is based on fixed sampling and dwell periods generated by timing circuits in the switch logic. During the sampling period, each antenna is connected in sequence to the receiver. The AGC samples are held in the logic, and at the end of the sampling period, the logic switches to the antenna which provided the largest signal for the dwell period of communication on the selected antenna. In a marginal gain situation, information may be lost during three-fourths of the sampling period. For comparison with other sampling methods, an equation may be written for the information transfer efficiency in percent when at least one antenna is capable of reception is

$$I_1 = 100 \times \left[1 - K_1 t_s/(t_s + t_d) - t_r/t_R\right], \text{ percent}$$

K_1 = a dimensionless constant = 0.750

t_s = sampling period, seconds

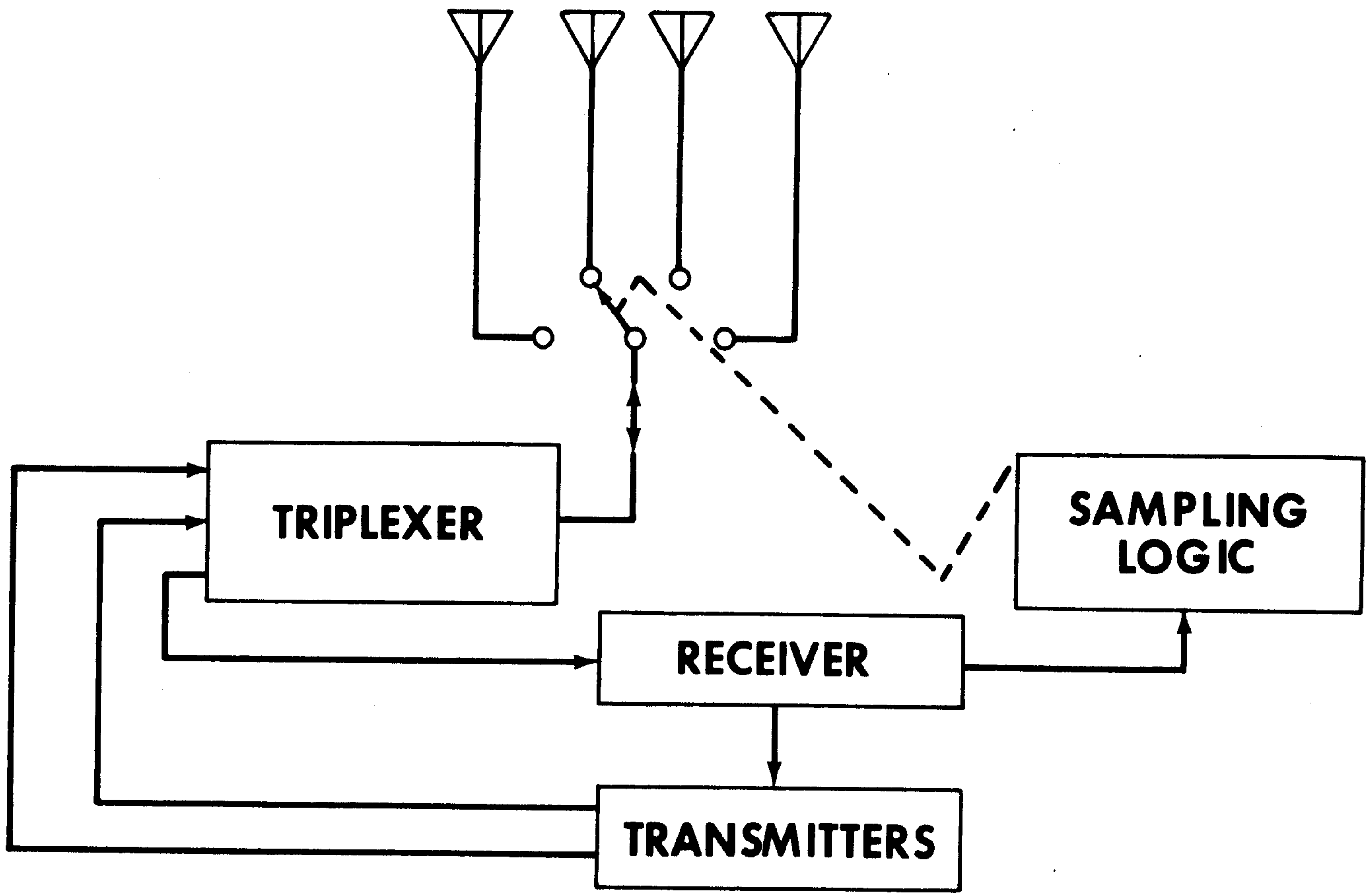
t_d = dwell period, seconds

t_r = time during dwell period in which signal is lost due to rotation

t_R = seconds per revclution

K_1 is determined by the gain margin and antenna directivity. t_r is a function of gain margin, antenna directivity, and roll rate. Additional refinement may be added to this system by including threshold and/or rate logic such that the sampling period becomes a function of the signal strength and/or the rate of change of signal strength.

COCHANNEL SWITCHING SYSTEM



SEPARATE CHANNEL SWITCHING

In separate channel switching, the sampling process is continuous in the sampling and control channel. The optimum antenna can be selected during each sampling period. If at least one antenna is capable of reception, information will be lost only during the marginal crossover period. The loss will occur four times per revolution of the spacecraft and have a maximum duration of $0.75t_s$. The loss of information can then be expressed as

$$\text{Fraction of information lost} = 4(0.75t_s/T_1)$$

T_1 = roll period, seconds

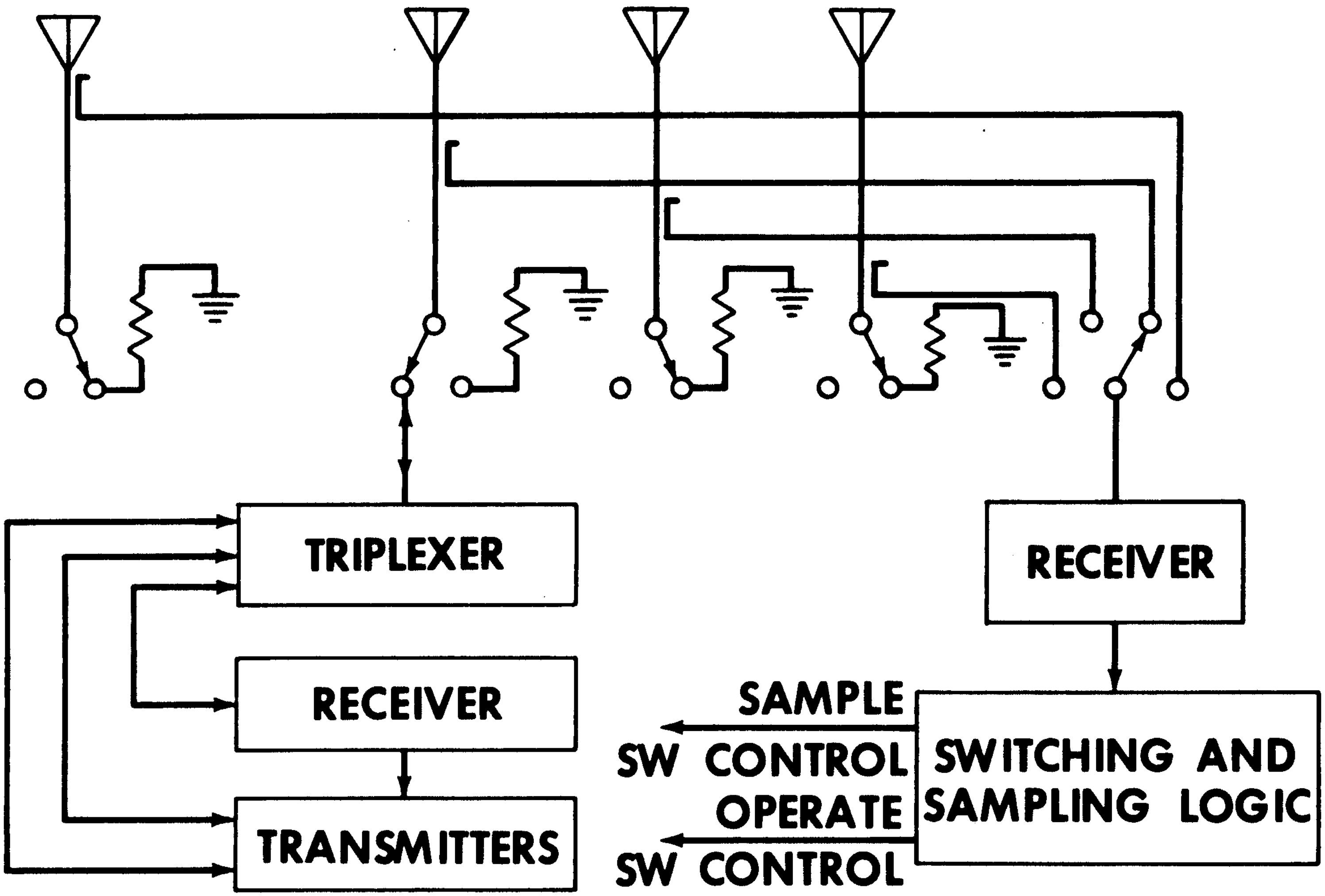
The intelligence transmission efficiency is then

$$I_2 = 100(1 - 3t_s/T_1) \text{ percent}$$

Practically speaking, in comparison to the cochannel switching system, the intelligence transmission efficiency can be taken as 100 percent, except for submarginal transmission conditions.

Part of the received signal is diverted to the sampling receiver. The transmission loss can be kept less than 1 dB. The nominal gain with respect to the cochannel system for the ground-to-air link can then be taken as -1 dB.

SEPARATE CHANNEL SWITCHING



COMPARISON OF POSSIBLE SHUTTLE AUTOMATIC ANTENNA SWITCHING SYSTEMS

An analytical comparison of the various candidate Shuttle antenna control systems was conducted to assess the various operational parameters of each such system. In addition, several hybrid systems were investigated to provide a better understanding of the various system tradeoffs. In general, this analysis revealed that the simple and adaptive switching techniques provide the highest percentage of coverage using the 3-dB pattern level as a basis for comparison. These particular systems also have the lowest rotational losses and the highest relative gain factors. However, the information transfer efficiency of these basic cochannel type of switching systems is quite low because of the requirement of periodic interruption of information flow to accomplish the antenna selection process. The separate channel switching system has a somewhat lower receive gain than the cochannel systems as a result of the need for part of the signal to be coupled to the second receiver. The percent coverage for this system is very high, and the rotational losses are quite small since antenna comparison may now be conducted on an almost continual basis. The most interesting parameter for the separate channel switching system is the information transfer efficiency which is essentially 100 percent regardless of the vehicle rotational rate. Unfortunately, the price that must be paid for the use of the separate channel switching system is the added weight, power, and complexity of the second receiver. The various phasing systems that were considered have in general a somewhat lower gain than the switching systems due to the fact that all of the antennas are always connected to the receiver in parallel. Also, the 3-dB coverage for these systems is somewhat lower than the switching systems. The information transfer efficiency of the phasing systems can be made very good with the proper choice of phasing angle depending on the particular application required.

RF AUTOMATIC ANTENNA SWITCHING TECHNIQUES

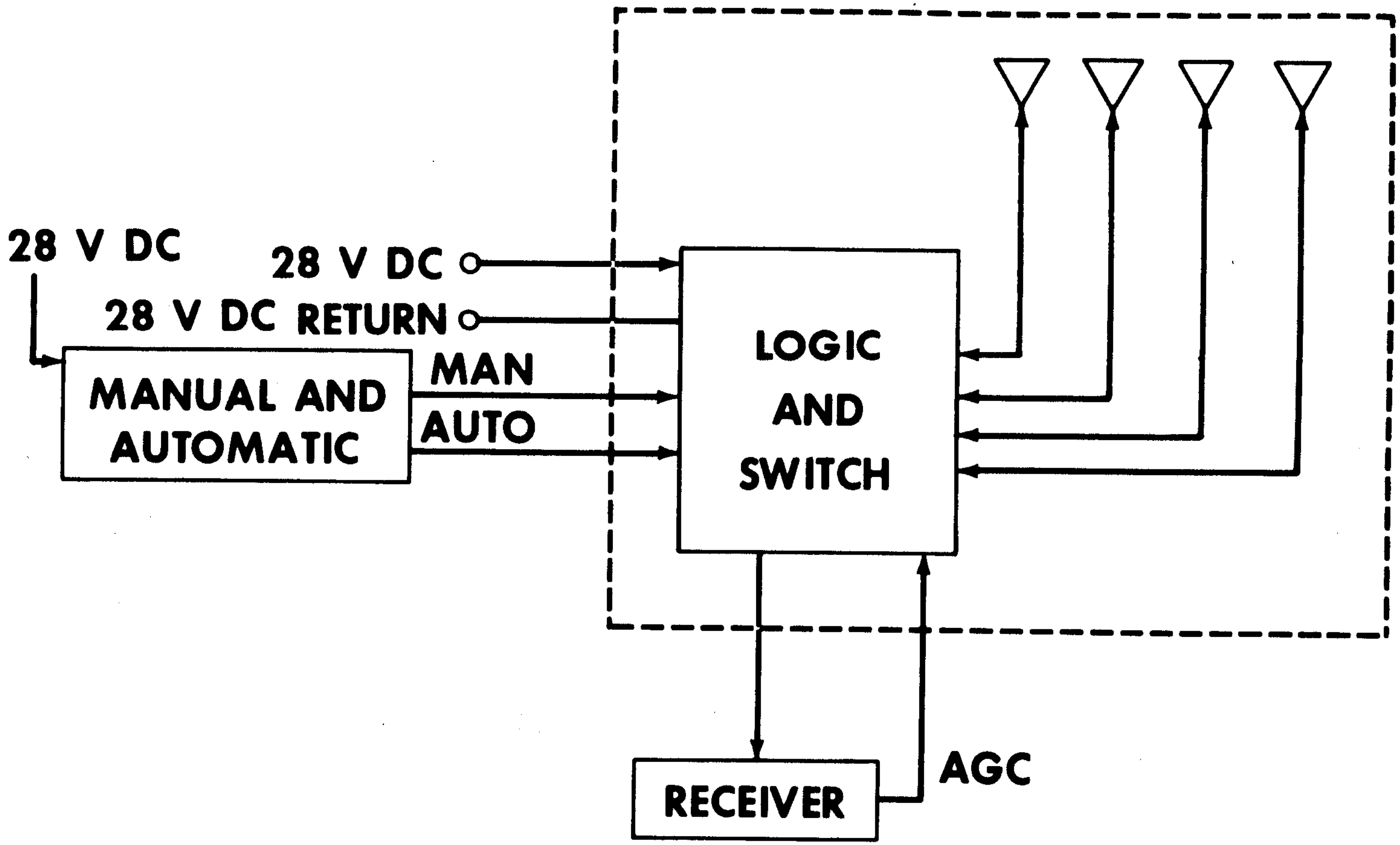
SYSTEM	THRES-HOLD	RECEIVE GAIN	TRANSMIT GAIN	COVER-AGE	TRANSMIT NULL DEPTH	ROTAT-IONAL LOSS 9 DEG/SEC	ROTAT-IONAL LOSS 36 DEG/SEC	MAX XMSN LOSS	INFORMATION TRANSFER EFFICIENCY									SIZE AND WEIGHT	MTBF
									9 DEG/SEC			18 DEG/SEC			36 DEG/SEC				
									MARGIN			MARGIN			MARGIN				
									3 dB	6 dB	12 dB	3 dB	6 dB	12 dB	3 dB	6 dB	12 dB		
		dB	dB	PERCENT	dB	dB	dB	dB	PERCENT			PERCENT			PERCENT			RELATIVE UNITS	RELATIVE UNITS
SIMPLE SWITCHING	NO	0	-0.7	100	-2.5	-1.5	-6.7	-9.2	95	95	95	0	95	95	0	0	95	1.0	1000
SIMPLE SWITCHING	YES	0	-0.7	100	-2.5	-1.5	-6.7	-9.2	95	95	100	0	95	100	0	0	100	1.05	950
ADAPTIVE SWITCHING	NO	0	-0.7	100	-2.5	-1.5	-6.7	-9.2	97	98.5	99.5	94	97	98.5	89.5	94.5	97	1.2	830
ADAPTIVE SWITCHING	YES	0	-0.7	100	-2.5	-1.5	-6.7	-9.2	97	98.5	100	94	97	100	89.5	94.5	100	1.25	800
SEPARATE CHANNEL SWITCHING	--	-1	-0.7	100	-2.5	-0.4	-1.7	-5.2	100	100	100	100	100	100	100	100	100	2.2	450
0 DEG PHASING SIMPLE SWITCH	YES	.6	-3.4	71	-12	0	0	-12	95	95	95	95	95	95	95	95	95	2.05	490
0 DEG PHASING ADAPTIVE SWITCH	YES	.6	-3.4	71	-12	0	0	-12	100	100	100	100	100	100	100	100	100	2.25	440
90 DEG PHASING SIMPLE SWITCH	YES	-2.5	-3.2	78	-8.5	-0.5	-5	-13.5	95	95	95	0	95	95	0	95	95	2.05	490
90 DEG SEPARATE SWITCH	--	-3.5	-3.2	78	-8.5	0	-5	-14.5	100	100	100	100	100	100	0	100	110	3.2	310
90 DEG PHASING ADAPTIVE SWITCH	YES	-2.5	-3.2	78	-8.5	-0.5	-5	-13.5	95	95	100	0	95	100	0	95	100	2.25	440
135 DEG PHASING SIMPLE SWITCH	YES	-7.5	-3.1	95	-7.5	-8.5	-8.5	-16	0	0	95	0	0	95	0	0	95	2.05	490
135 DEG PHASING ADAPTIVE SWITCH	YES	-7.5	-3.1	95	-7.5	-8.5	-8.5	-16	0	0	100	0	0	100	0	0	100	2.25	440

MSC SYSTEMS EVALUATION HARDWARE - BLOCK DIAGRAM

The automatic system presently being tested consists of a cochannel sampling system based on fixed sampling and dwell periods generated by timing circuits in the switch logic. During any one sampling period, AGC samples are stored in the logic circuits, and at the end of the sampling period, the logic switches to the antenna which provided the largest signal.

The system known as the OR logic cochannel logic commutation system (OLCLCS) performs the function of automatically selecting the antenna with the strongest signal input regardless of roll, turns, or other spacecraft maneuvers. Very basically, the OLCLCS consists of (1) a sampling circuit which samples the signal level of each antenna, (2) digital logic which performs the decision as to which one of the four antennas sampled has the strongest input signal, (3) and digital control circuitry which sets the RF switch to that antenna.

MSC SYSTEMS EVALUATION HARDWARE - BLOCK DIAGRAM



MSC SYSTEM EVALUATION HARDWARE - SYSTEM DESCRIPTION

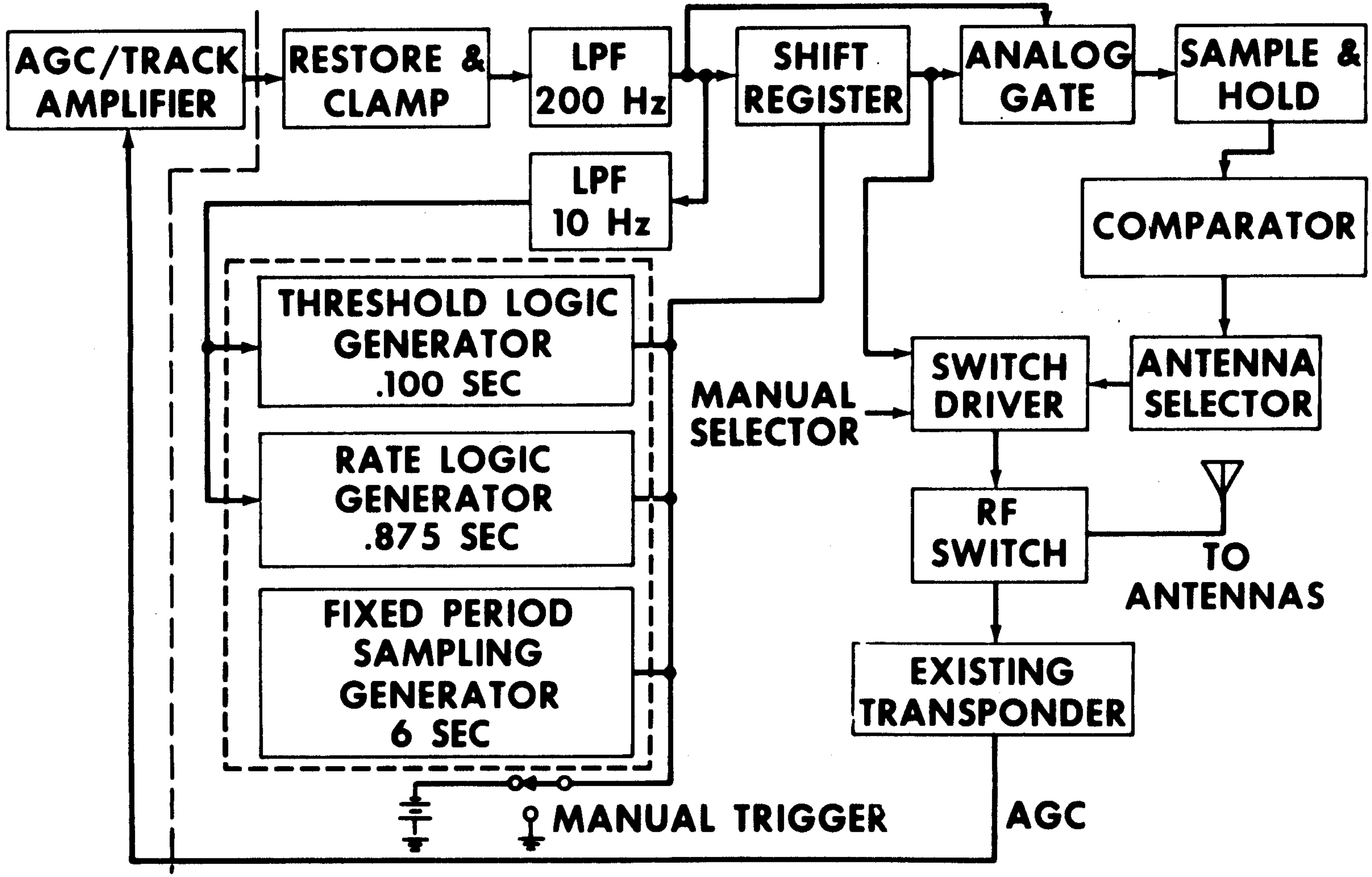
Initiation of sampling is caused by three timing circuits. The rate timing circuit is a function of the rate of decrease of the signal level on the selected antenna. A rate of voltage decrease of 0.042 volts/second will cause sampling every 0.875 seconds. This corresponds to a 6-RPM rotational rate. The level logic circuit causes sampling to occur at a maximum rate of 0.1-second intervals if the coherent amplitude detector voltage falls below a predetermined threshold. The fixed-time-interval logic causes sampling every 6 seconds.

In general, if the vehicle is not rotating, the fixed-time-interval logic causes fixed period sampling every 6 seconds. If the input signal is above the threshold setting and the vehicle is rotating at such a rate to cause a voltage decrease of 0.042 volts/second, then the rate timing circuit initiates sampling at 0.1-second intervals.

In addition, provisions are incorporated for a manual over-ride function to allow an operator to manually select the desired antenna.

MSC SYSTEM EVALUATION HARDWARE

SYSTEM DESCRIPTION



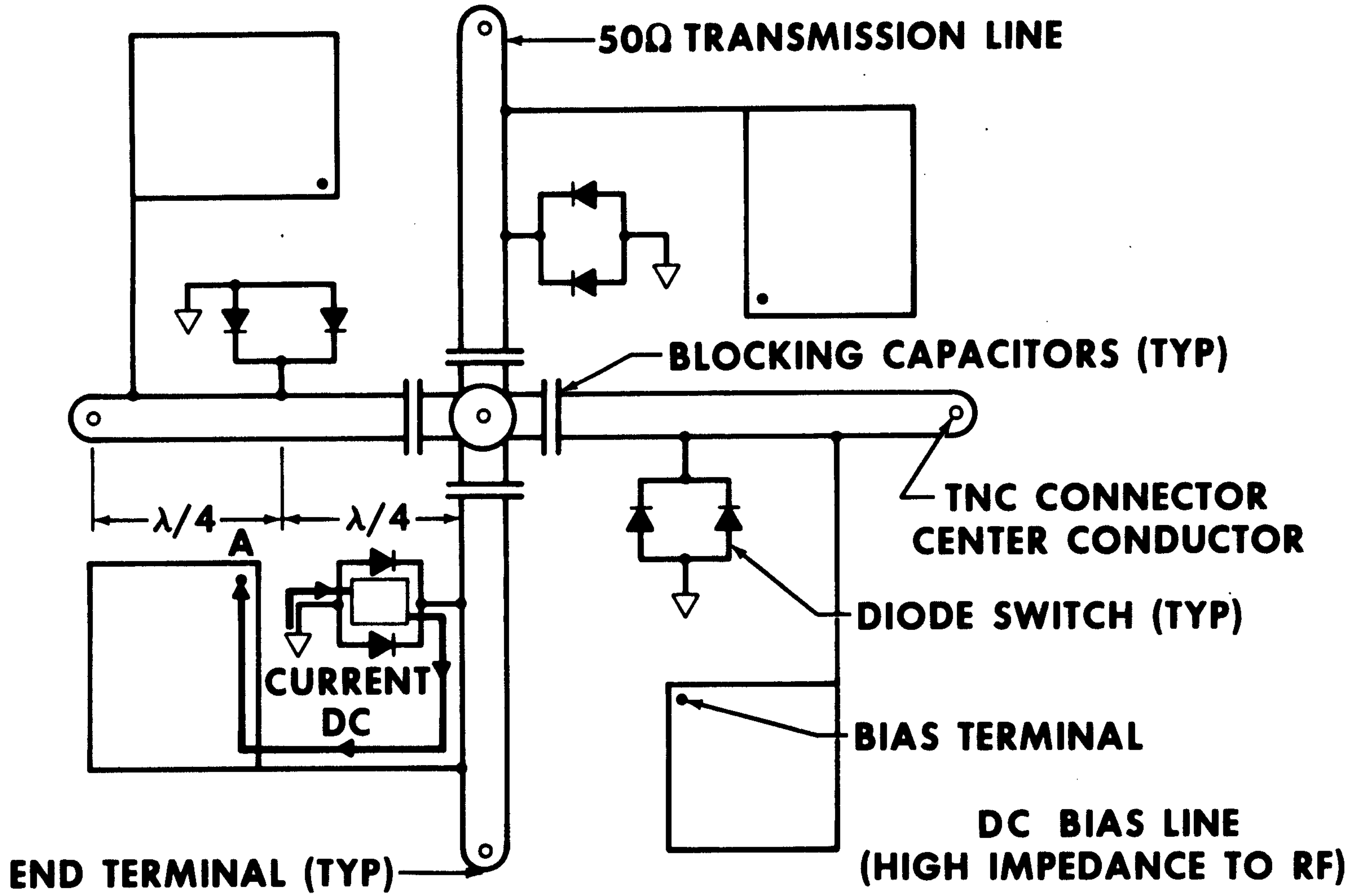
MSC SYSTEM HARDWARE - ANTENNA SWITCH

The antenna switch that is being evaluated for all Shuttle switching systems under consideration is a stripline device printed on dielectric boards and sandwiched between parallel conductive plates. It is composed of four orthogonal 50Ω transmission lines joined at a common junction. Attached to each transmission line is a switching diode, a high-RF impedance DC bias line, and an in-line blocking capacitor in front of the junction. The switching diodes are placed 90 electrical degrees from the common junction and the END terminal.

If a negative DC bias is applied at point A, DC current is from ground, through the forward biased diodes, to point A. If the diodes are of high quality and driven with sufficient current, they present a very low impedance shunt across the 50Ω line. Theoretically, if the shunt impedance of the diode can be driven to zero, an infinitely high impedance will be reflected to both the junction and the end of the line. A positive bias placed at point A causes the diode to appear as a very high impedance shunt to any incident RF energy. The blocking capacitor blocks the DC current from the RF junction.

In normal operation, three of the bias points of the switch have a negative bias, and one (the switched port) has a positive bias. Thus, on the three arms with a negative bias, a high impedance is reflected to both the END terminal and the common junction, while the positively biased port is essentially a 50Ω transmission line.

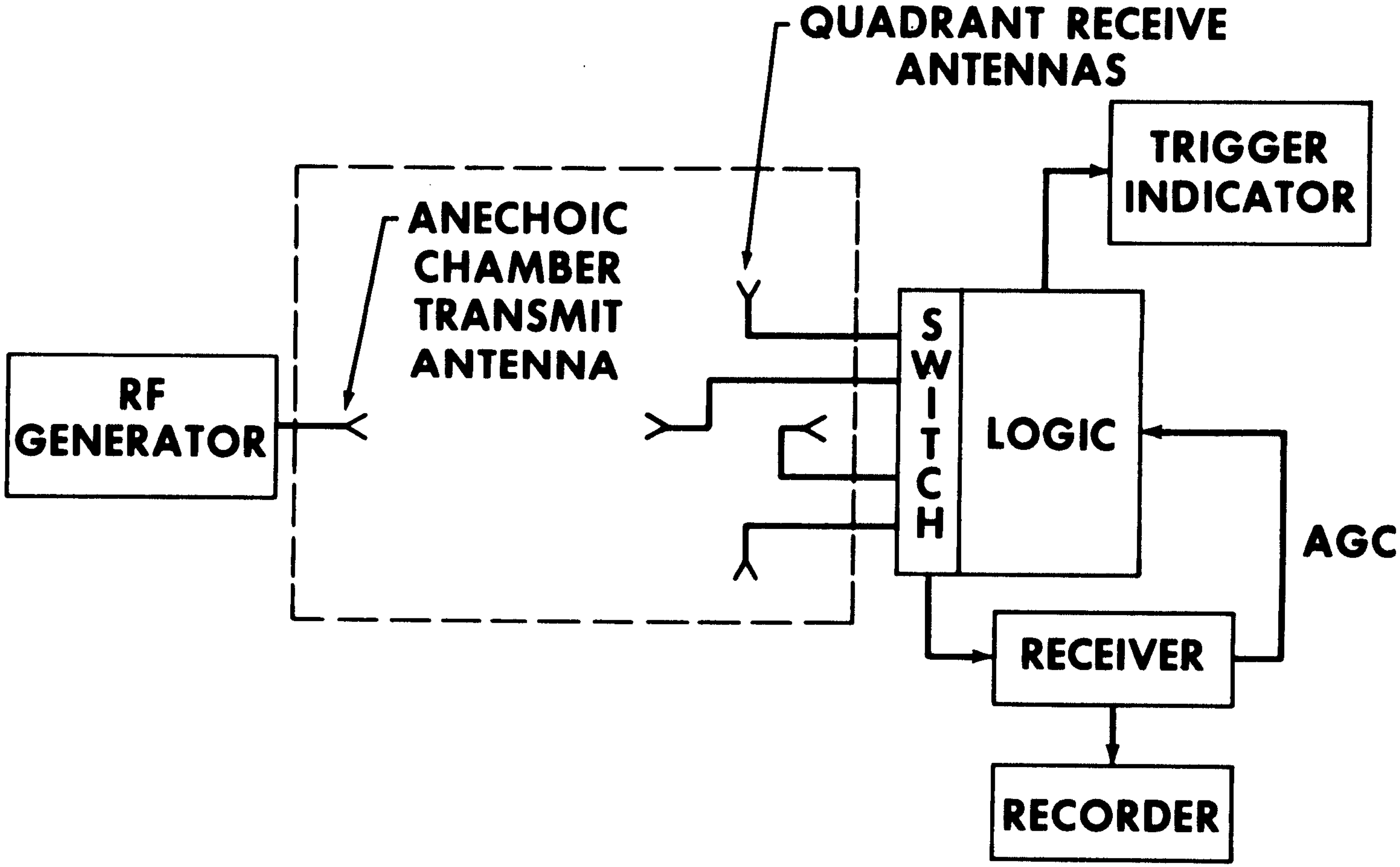
MSC SYSTEM EVALUATION HARDWARE - ANTENNA SWITCH



MSC SYSTEMS TEST PROGRAM - BLOCK DIAGRAM

All of the system evaluation tests being conducted at MSC on possible Shuttle candidate antenna control systems are being conducted in Building 14, anechoic chamber test facility. Each of the antenna switching systems is connected to the appropriate antenna configuration mounted on a positioner in the anechoic chamber, and complete radiation distribution plots of the composite antenna patterns are recorded for each test condition. The transmitter source antenna is located at such a position in the chamber that far field requirements are met for each test configuration. During the initial test phase of this evaluation, all the test configurations are at full scale, with the Shuttle antennas mounted on a wooden platform with only the essential parts of the Shuttle structure mocked up. Later tests will be conducted at 1/10 scale on a completely structured Shuttle orbiter mockup.

MSC SYSTEM TEST PROGRAM
BLOCK DIAGRAM



MSC SYSTEM TEST PROGRAM - TEST DATA

The MSC System Test Program is primarily devoted to accomplishing those data recording tasks that will identify the candidate systems of Shuttle antenna control systems that warrant further development. With this purpose in mind, all of the systems tests have been specifically tailored to Shuttle applications. To date, a considerable amount of data has been recorded on the cochannel switching system, with somewhat more limited data on the other candidate systems. The reason for this situation is that a cochannel switching system had been already developed under a previous development contract. This system was easily modified to fit Shuttle requirements and was a logical choice for the initial testing. Work is presently underway in the development of test units of the other candidate systems, and similar testing will subsequently be accomplished.

Data tasks that are presently being planned include the testing of scale models of the cochannel, separate channel, and phase quadrature control systems on a 1/10 scale model of the Shuttle orbiter. Also, the operation of the solid state switch design at all the frequencies and power levels of interest will be investigated. Lastly, the candidate systems will be investigated to determine the effects of each candidate system on the operation of the communications system as a whole.

MSC SYSTEM TEST PROGRAM

- DATA TASKS ACCOMPLISHED TO DATE
  - PATTERN DATA FOR COCHANNEL SYSTEM AT S-BAND
  - EVALUATION OF SAMPLING RATE REQUIREMENTS IN COCHANNEL SYSTEM
  - EVALUATION OF SOLID STATE SWITCH OPERATION AT S-BAND
  - EVALUATION OF RATE EFFECTS ON COCHANNEL SYSTEM OPERATION
  - EVALUATION OF MULTIPLEXER DESIGN FOR PHASE QUADRATURE SYSTEM
  - PATTERN DATA FOR PHASE QUADRATURE SYSTEM AT S-BAND

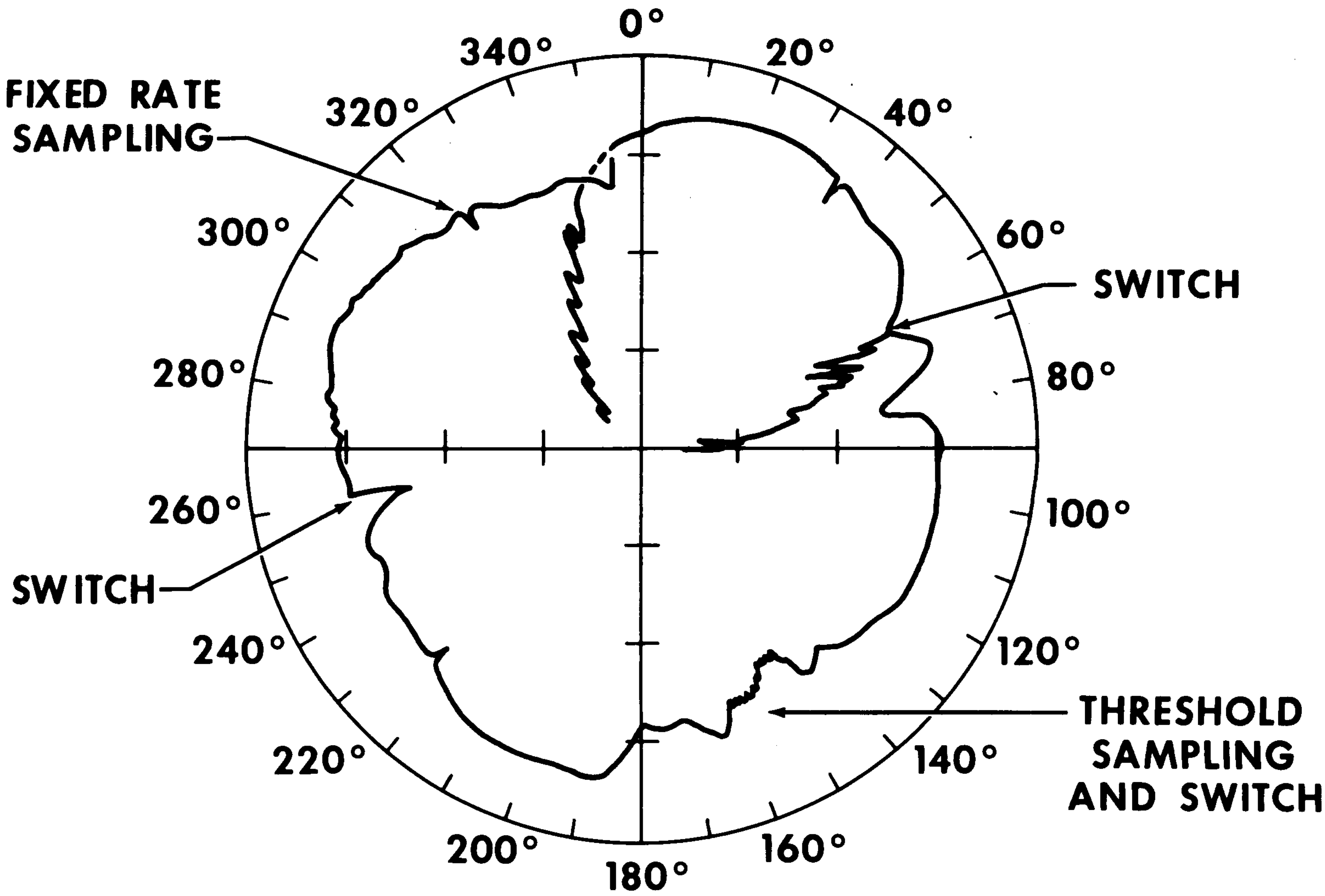
MSC SYSTEM TEST PROGRAM (CONT)

- TEST RESULTS SUMMARY
  - COCHANNEL SYSTEM PROVIDES ADEQUATE PATTERN COVERAGE BUT RESULTS IN A REDUCED COMMUNICATIONS TRANSFER EFFICIENCY COMPARED TO THE SEPARATE CHANNEL SYSTEM
  - SAMPLING RATES IN COCHANNEL SYSTEM MAY BE GREATLY REDUCED AND STILL SATISFY SHUTTLE PATTERN REQUIREMENTS
  - SOLID STATE SWITCH DESIGN APPEARS FEASIBLE FOR SHUTTLE APPLICATIONS
  - PHASE SHIFTER CHARACTERISTICS MUST BE FURTHER EVALUATED FOR THE BASIC PHASING SYSTEMS

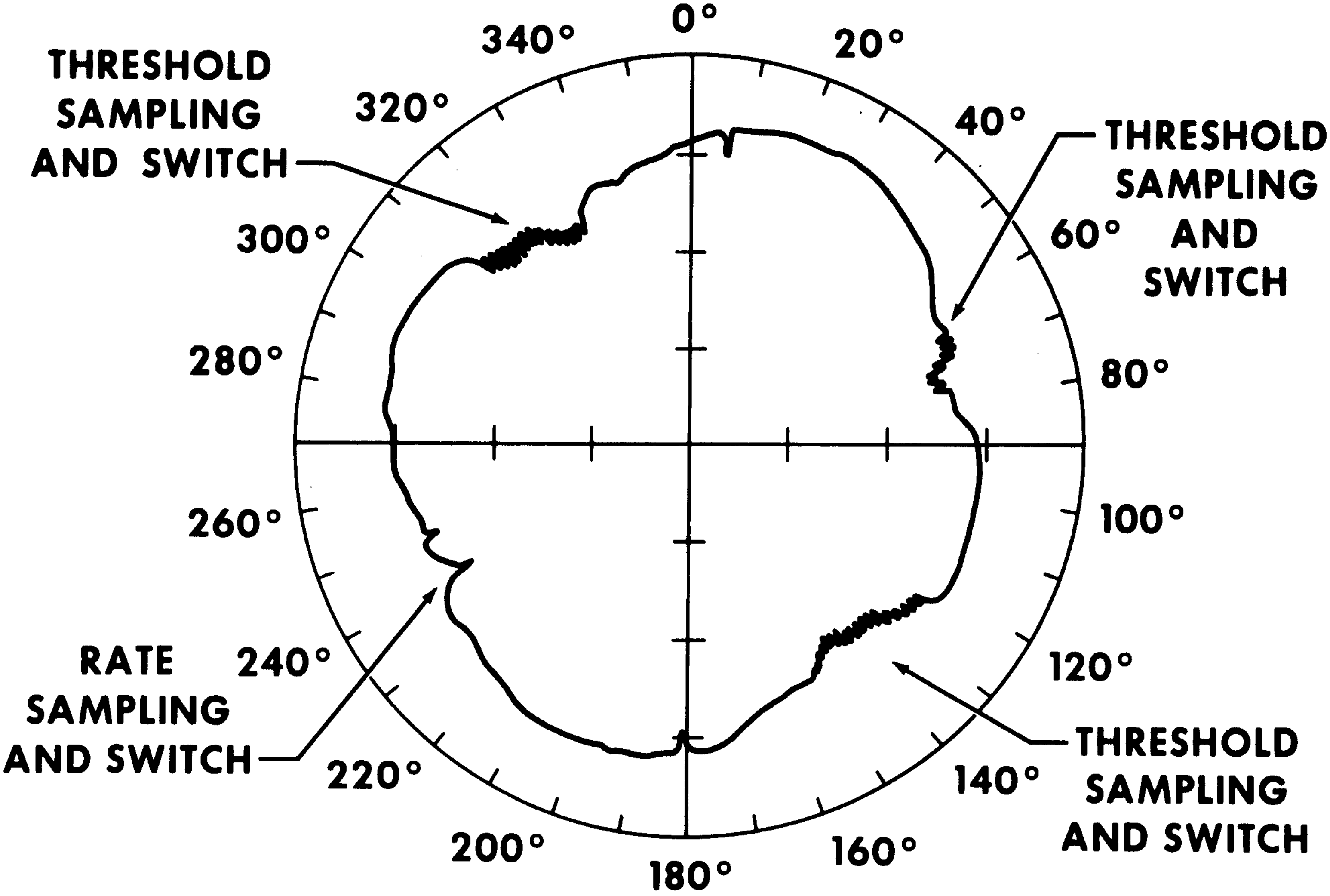
MSC SYSTEM TEST PROGRAM (CONCL)

- PLANNED TASKS
  - PATTERN DATA FOR COCHANNEL, SEPARATE CHANNEL, AND PHASE QUADRATURE SYSTEM AT 1/10 SCALE S-BAND ON SHUTTLE MOCKUP
  - EVALUATION OF THE EFFECTS OF THE ANTENNA SYSTEM ON THE COMMUNICATIONS SYSTEM AS A WHOLE
  - EVALUATION OF THE SOLID STATE SWITCH OPERATION AT HIGH POWER LEVELS AND AT LOWER FREQUENCIES
  - COMPLETE EVALUATION OF FACTORS SUCH AS WEIGHT, VOLUME, POWER CONSUMPTION, COMPLEXITY, MANUFACTURABILITY

MSC SYSTEM TEST PROGRAM - TEST DATA



MSC SYSTEM TEST PROGRAM - TEST DATA



CONCLUSIONS

The work that has been conducted to date indicates that the Shuttle requirements dictate some type of antenna control system to relieve the crew operational requirements. The preliminary analysis and testing indicate that several different control systems meet the basic Shuttle requirements. The desirability of one system over another will depend on the results of detailed testing of the complete Shuttle antenna system. Detailed testing of the Shuttle antenna system will be conducted on breadboard hardware as this hardware becomes available.