PHASED ARRAY ANTENNA FOR SPACE SHUTTLE ORBITER

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ABSTRACT

The National Aeronautics and Space Administration is developing a distributed phased array antenna at the Lyndon B. Johnson Space Center as a possible upgrade for the Space Shuttle Orbiter S-band phase modulation communications system. The antenna consists of an eight-element transmit section, eight-element receive section, and a single L-band receive element. The antenna design is constrained by the existing Orbiter system and space environment. The solution to the interface design problems led to an antenna system which provides improved link margins and yet supports previous operational configurations. This paper describes the system development, antenna hardware, and the interface considerations which led to the final design.

1. INTRODUCTION

The S-band phased array antenna is being developed to provide a proof of concept for a possible upgrade to the quad antenna currently being used for the S-band phase modulation (PM) communication system on the Space Shuttle Orbiter. The Orbiter has historically exhibited less than desirable link margins with this system, and a phased array antenna is one solution to this problem. The phased array antenna also uses solid state components, which do not have the arcing problems of the current antenna.

The current antenna consists of two crossed dipole antennas that can be switched to produce two beams. The Orbiter has four of these antennas mounted in the forward fuselage (Fig. 1), hence the name "quad antennas." Depending on which quadrant the signal is in, the antenna system utilizes one of the four antennas in one of the two beam positions, during normal operation. The current antenna thus limits the Orbiter to eight beam positions for full spherical coverage. Antenna coverage is at least 3 dB

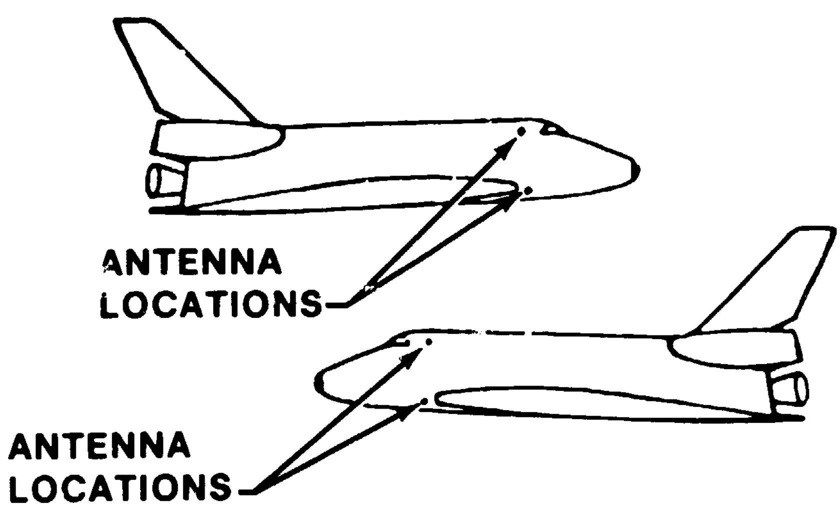

Fig. 1 S-band quad antenna placement on Space Shuttle Orbiter.

for only 50% of the sphere. Because the power is generated via a traveling wave tube amplifier before distribution to the antennas, the switches at the antenna locations to control the beam position are mechanical. These switches have demonstrated arcing problems on past Orbiter missions.

2. SYSTEM DEVELOPMENT

The original phased array antenna system design was a passive phased array with no active components at the array level. An active component is defined as one requiring direct current (dc) power to operate, such as an amplifier. The addition of active amplifiers for both transmit and receive functions significantly improved the calculated link margin of the phased array antenna and also allowed the power amplifier and preamplifier to be removed from the S-band PM system. This concept had been investigated previously, but the heat load at the antenna was too high to be dissipated passively. A new design was initiated in 1984 because of advances in amplifier technology that promised a reduced heat load, making the possibility of flying an active array again feasible.

The initial 1984 phased array antenna design called for a 16-element active array. The design included a microprocessor controller for selecting the antenna beam and setting the phase shifters. Each element would be part of an electronic chain consisting of a phase shifter, a circulator after the phase shifter to isolate the transmit and receive paths, a high power amplifier (HPA) for the transmit path, an isolator to protect the output of the HPA, a second circulator to isolate the transmit and receive paths at the antenna port, the antenna element, a filter for the receive path, and a low noise amplifier (LNA) for the receive path. Each phase shifter would be connected to a 16-way power divider to bring the combined signals to the single radiofrequency (RF) port which presently exists in the quad system configuration.

Further system studies identified microstrip antenna elements as the best element candidate because of the low profile. The only disadvantage was an inherently narrow bandwidth which would not cover the entire band from 1.7 to 2.3 GHz. A study of alternate system configurations led to the concept of separating the transmit and receive functions in the array, thereby removing the requirement for the two circulators. The narrow bandwidth of the microstrip element also protects the receive path, which deleted the requirement for a filter, since the isolation between transmit (2.2175 and 2.2875 GHz) and receive (2.0419 and 2.1064 GHz) is now provided by the system configuration. The reduced area of the individual transmit and receive arrays is compensated for by the reduction in path loss due to the removal of the circulators and filters. A single element at 1.75 GHz was designed to cover the requirement for 1.7767 and 1.8318 GHz for the Space Ground Link System. A triplexer is included to combine the transmit, S-band receive, and L-band receive on the single RF port.

The eight-element receive and transmit subarrays are oriented so that there are four elements in the roll plane and two elements in the pitch plane. This placement allows for three beams across the pitch plane (180° from nose to tail) and seven beams across the roll plan (45° from the top to side or side to bottom). The three-bit phase shifters result in a phase resolution of 45°, which results in 21 beams per antenna (Fig. 2) or 84 beams per Orbiter. The narrower beamwidths significantly improve the directivity and, therefore, gain of the antennas. The phased array antenna has a calculated gain of 13 dB on boresight and 9 dB when scanned ±90° off boresight, which does not include element gain. The effective isotropic radiated power of the antenna will vary from 26.7 dBW on boresight to 24 dBW when scanned 70° from boresight. Antenna coverage is calculated to be 10 dB over 85% of the sphere.

A schematic of the array is shown in Fig. 3. The radiating elements, triplexer, and microprocessor controller were designed and fabricated in-house. The HPA's, LNA's, power divider/combiner and phase shifter subassembly, and active limiter were purchased. The operating temperature range for all components was specified as -25° to +65° C, and the nonoperating temperature

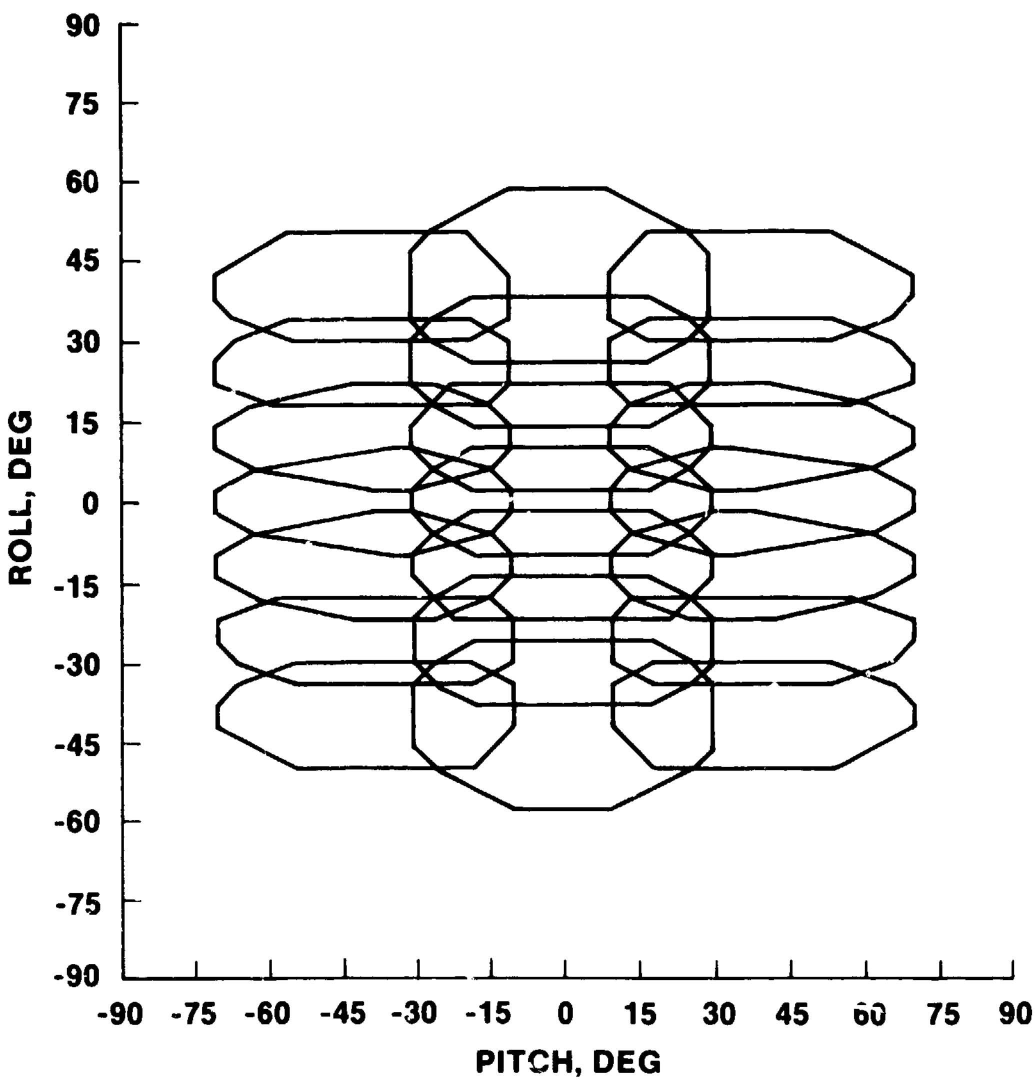

Fig. 2 Three dB gain contour.

range was specified as -65° to +100° C. The array components are discussed individually in the following section.

3. ARRAY COMPONENTS

The radiating elements for the S-band phased array antenna consist of 17 microstrip elements: 8 transmit, 8 receive, and 1 L-band receive for the Space Ground Link System frequencies. Each element is designed as a rectangular microstrip patch with a corner feed. The two orthonormal modes thus excited provide right hand circular polarization. The antenna elements are fabricated from a 0.3175 cm thick Rogers 5880 duroid substrate. Element spacing in the pitch plane is every 0.47 wavelength and in the roll plane is every 0.56 wavelength. The layout is shown in Fig. 4. Element voltage standing wave ratios (VSWR's) range

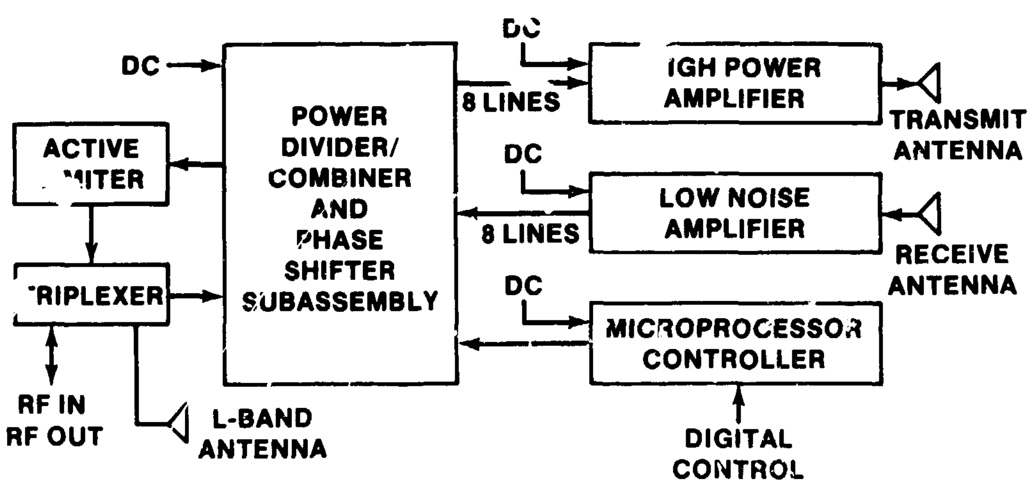

Fig. 3 Phased array antenna schematic.

from 1.15:1 to 1.5:1. The peak gain of the elements ranges from 4.4 to 7.3 dB.

The triplexer for the S-band phased array antenna is required to separate the transmit, receive, and L-band receive paths. This triplexer consists of a common RF port for the antenna RF connector, a circulator to separate transmit and receive, a matching network to combine the received signal from the S-band LNA's and the L-band element, bandpass filters for each receive frequency, and isolators for each receive frequency (Fig. 5). The isolators and circulator provide channel isolation, and the circulator also reduces the insertion loss in the transmit path

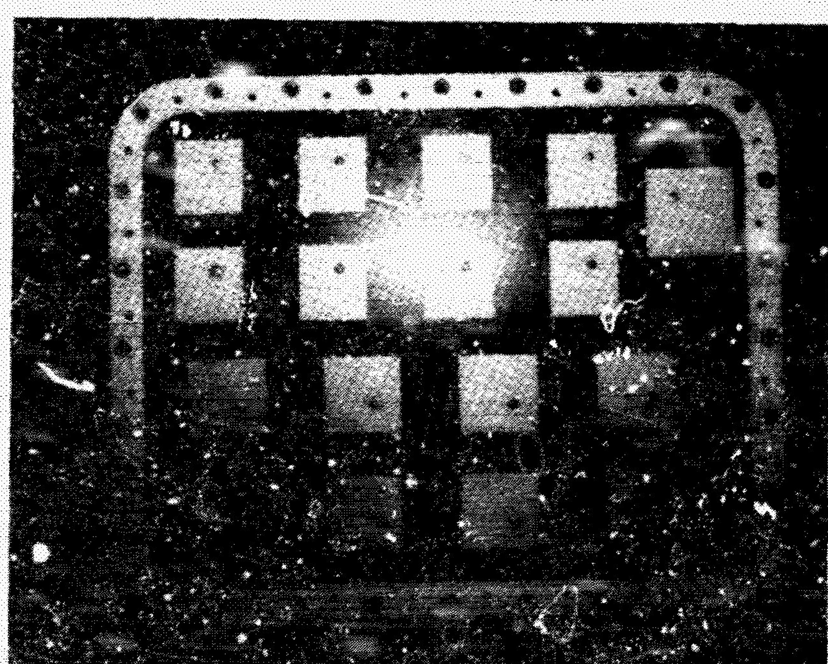

Fig. 4 Radiating aperture layout.

and therefore improves the transmit link margin. A transmit bandpass filter is included, because the initial design did not include the circulator, and transmit signals were therefore required to go through the matching network. With the addition of the circulator, the transmit bandpass filter is no longer required and is therefore connected to a 50 ohm load. For each path, the VSWR's are 1.13:1 or better, and the highest insertion loss is 2.9 dB between the common output and the S-band receive input, which does not significantly degrade the link margin since this loss is after the LNA's in the receive path. Isolation is 75 dB from the common input to the receive inputs and greater than 20 dB from the receive inputs to the transmit output.

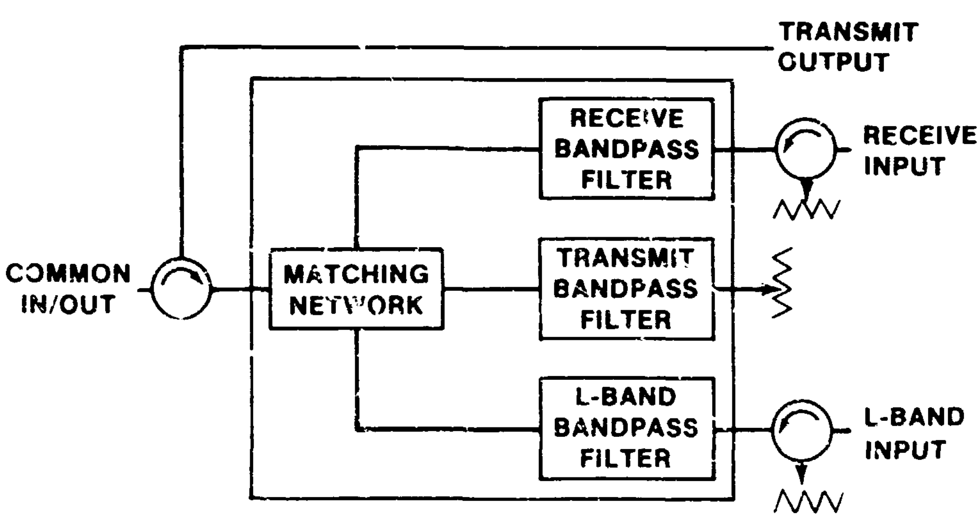

Fig. 5 Triplexer block diagram.

Isolation is greater than 48 dB from the transmit output to the receive inputs.

The microprocessor controller for the S-band phased array antenna sets the phase shifters based on the desired pointing angle and returns telemetry data. Roll and pitch angles are compared to a data list which determines the beam. The phase shifter bit pattern for this beam is then output to the phase shifters. The microprocessor returns telemetry consisting of the selected beam number, microprocessor health data, one of the HPA temperatures, and a flag for the HPA RF power levels. The data exchange occurs every 2 sec, which means that it takes 16 sec to poll all of the eight HPA temperatures.

The HPA's are placed in the transmit paths to raise the power just before the antenna elements. Each three-stage amplifier was specified to produce 7 W RF output at the transmit frequencies and be at least 30% efficient. When these amplifiers were tested at -25°, +23°, and +65° C, the highest temperature tended to produce a slightly low output power (6.62 W minimum, instead of 7 W). Efficiencies range from 32.0% to 42.5%. Circulators are included internally on the input and output of each HPA to allow the HPA to operate with a VSWR of any magnitude and phase, on either input or output. The HPA temperature and detected RF output power level are provided as dc voltages.

The LNA's are included in the S-band phased array antenna to reduce the noise figure and increase the signal-to-noise ratio. There are eight LNA's, one for each of the eight receive elements. The candidate LN' was placed in the Electronic Systems Test Laboratory Orbiter S-band PM receive configuration. The bit error rate was improved by 1 dB when the Orbiter S-band pre-amplifier was replaced with the candidate LNA. The LNA's for the array were therefore ordered with gain tolerances from 35.0 to 36.5 dB and a 1.5 dB noise figure. Actual test data show that the LNA's have noise figures of 1.28 dB maximum and a maximum VSWR of 1.8:1. The total power dissipated by all eight units is 9.62 W.

The 16 phase shifters, 8-way power divider, and 8-way power combiner for the antenna are integrated into a single subassembly that requires less volume and provides a lower insertion loss because of the direct connections from the phase shifters to the power divider and power combiner ports. Insertion losses are 12.9 dB maximum and VSWR's are 1.52:1 maximum. The minimum isolation is 18.7 dB.

An active limiter is inserted in the receive path of the antenna to protect the Orbiter S-band transponder from excess RF energy. The device limits the RF power to -25 dBm in the receive path between the power combiner and the triplexer and is reflective when limiting.

4. ORBITER INTERFACES

The existing cavity in the Orbiter must be used for the S-band phased array antenna, since fabricating new holes in the Orbiter structure and routing new cables would be too costly. The cavity was therefore defined as the maximum available envelope for the phased array. The current antenna does not utilize all of the cavity, so a study was performed to define the limits of the cavity. It was found that the cavity was smaller toward the front of the Orbiter, and that the upper and lower cavities differ. The antenna housing for the upper right antenna based on the cavity dimensions is shown in Fig. 6. All of the antenna components must be mounted in this housing, as shown in Fig. 7. The phased array antenna requires one more connector than the current antenna, so the connectors on the housing had to be placed to fit through the hole in the skin in the Orbiter during mounting.

The phased array antenna is designed to be cooled passively, since it is impossible to route cooling lines to the antenna locations without modifying the Orbiter structure. The phased array antenna can dissipate a maximum of 94 W of heat using cooling straps tied to the frame of the Orbiter.

The phased array antenna requires pointing angles in roll and pitch to set the correct phase shifter bit pattern. This information is generated in the Orbiter antenna management software and can be routed to a multiplexer/demultiplexer (MDM). The phased array antenna interfaces with the MDM via a digital control line. Telemetry from the phased array antenna is also passed through the MDM.

The Orbiter has the capability of allowing the crew or ground control to select one of the existing eight antenna beams. To maintain this function, the phased array antenna has a mode which mimics the fore or aft beam of the current antenna if the

Fig. 6 Antenna housing for upper right phased array antenna.

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pointing angles are not present on the digital control line.

The current antenna has only 28 V dc power supplied to it. The phased array antenna requires a variety of dc power levels for its active components. Rather than convert the dc power at the antenna location and generate additional heat, the dc power is converted in the Orbiter avionics bay, and separate dc power lines are then routed to the antenna locations.

The phased array antenna requires less input power than the current antenna, since the power level is boosted at the antenna elements by the HPA's on transmit and the LNA's on receive. For this reason, the preamplifier and power amplifier in the S-band

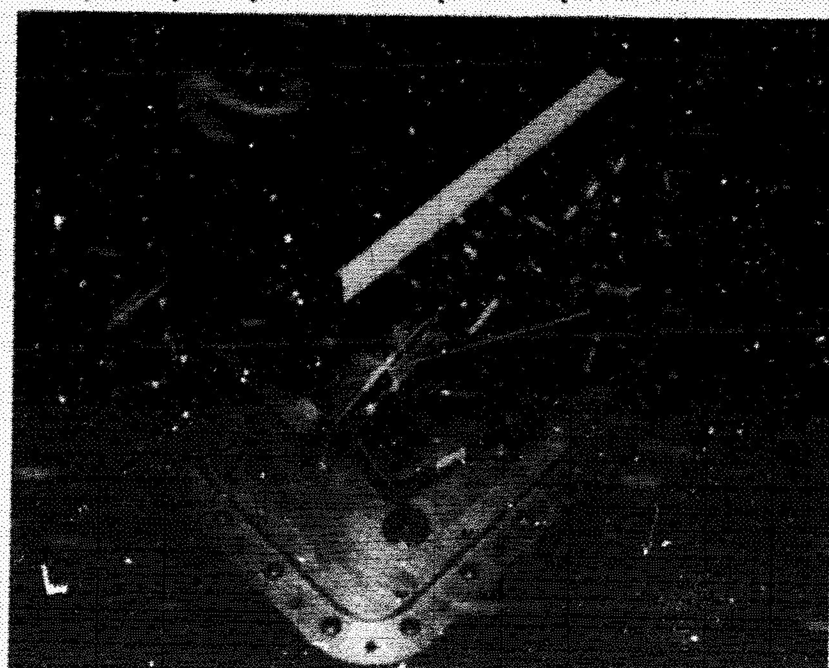

Fig. 7 Phased array antenna components mounted in housing with walls removed.

PM system can be removed for the phased array antenna system. This saves power and also leaves more room in the avionics bay for other avionics system components.

5. CONCLUSIONS

The phased array antenna will maintain a better link margin during all modes of operation than the current antenna and has produced a more efficient system requiring less power. The phased array antenna will provide 10 dB over 85% of the sphere, compared to 3 dB over 50% of the sphere for the current antenna. In addition, the arcing problem of the current antenna has been overcome and additional benefits of more room in the avionics bay will be achieved. Current estimates predict that the phased array antenna system will be half as expensive as the current antenna system.

Final assembly and testing is planned for the remainder of 1986 with environmental tests occurring in early 1987. The results of all these tests will then be presented to the Space Shuttle Projects Office with specifications for an operational system and final recommendations. The decision whether to retrofit the existing Orbiters or to include the phased array design on future Orbiters can then be made.