A 400 kW LONG PULSE X-BAND PLANETARY RADAR

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Abstract

Selected critical microwave components for a very long pulse (several hours) X-band radar system are discussed from a theoretical and practical viewpoint. Included are the special-sized waveguide and flanges, hybrid power combiner, couplers, switches, polarizer, rotary joints, feedhorn and radome. The system is installed on the NASA/JPL 64-m diameter reflector antenna at Goldstone, California.

Introduction

In order to secure better data on the rings of Saturn in preparation for planned spacecraft missions to the vicinity of that planet, the 64-m antenna at Goldstone, California, operated by JPL for NASA (Ref. 1), has been equipped with a 400-kW X-band radar system. With an antenna gain of approximately 72 dBi, the antenna system has an effective radiated power of about 6×10^{12} W. Since no readily available klystron tubes could deliver the required power, two modified tubes are operated in-phase into a hybrid combiner with a single waveguide carrying the signal to a single aperture feed system.

Waveguides

It was apparent that the waveguide system would be highly stressed. In order to maximize the chances of reliable operation and to avoid the complications of exotic dielectric gases if at all possible, a special waveguide size was designed for the band covering the radar frequency of 8495 MHz and a future JPL frequency near 7150 MHz. Figure 1 shows the mode considerations for the new waveguide (called WR-125) compared to standard waveguides in this frequency band. WR-137 is seen to be overmoded for a frequency of 8495 MHz, and WR-112 would be highly stressed, especially at 7150 MHz. Figure 2 shows the attenuations of the same waveguides.

Accepting the theoretical breakdown of air as 3×10^6 V/m, the WR-125 waveguide would fail at 2500 kW. In the actual system, since no harmonic filtering is present, impedances are not perfectly matched, and thorough cleanliness cannot be guaranteed, a derating factor of about 0.28 is considered appropriate, reducing the maximum power to about 700 kW.

After passing through a transition, the waveguide becomes circular with a diameter of 1.369 in. A practical derating factor for this waveguide is estimated to be 0.40, so that this guide should support some 2.5 times the power of the rectangular guide. The polarizer, rotary joints, and feedhorn throat are designed in the circular guide, with all other components being rectangular.

All components are made from OFHC copper and the waveguide tubing is specially drawn with a wall thickness of 0.125 in. The flanges are solid brass, completely flat-faced, and finished to 16 μ in. with flatness held to 0.0005 in. The finished flanges are at least 0.375 in. thick and are assembled without gaskets of any kind. A special procedure involving lapping, cleaning and very light silicone greasing has been written to insure field reliability (Ref. 2).

Cooling

A major problem in a very-high-power continuous wave (CW) system is that of applying the cooling fluid to all components in an efficient manner. Following years of S-band practice at JPL, the waveguides are cooled by ducts consisting of WR-90 waveguide soldered onto both broad walls. This results in 42% of the surface being directly exposed to water flow, with conduction through the thick side walls cooling the remaining surface.

A severe problem arises at the flanges. Because of the necessity of allowing clearance for the flange hardware, the cooling ducts end about 1.8 in. from the flange face. This resulted in excessive temperatures (exceeding 300°F) and system shutdowns after 2 to 3 h of continuous transmission when operated with warm or room-temperature water available for ground testing. However, when mounted on the antenna, the system operates on chilled (about 60°F) water from an air-conditioning system. Under these conditions, no further shutdowns due to waveguide overheating occurred. Nonetheless, it is clear that the flange cooling is marginal, and improved cooling ducts which extend a copper heat-sink toward the flange have been successfully tested and will be incorporated into future components.

In testing the efficiency of various cooling modifications, a technique was developed that avoided excessive use of the transmitters for hours of routine temperature data. Electric heaters were placed inside connected waveguide sections, and controlled wattage was applied to simulate the power dissipated at 500 kW of microwave power (over 150 W per linear inch of waveguide). Operating the test pieces with temperature probes at various water flow rates for different cooling modifications readily indicated which changes were trivial and which were worthy of further investigation.

Testing of many components was also accomplished using a traveling-wave resonator, although stable power levels were limited to about 300 kW because of the same flange heating problem. This caused the resonator to detune so rapidly at higher power levels that manual operation of the tuners could not track the changing resonant frequency. Application of the improved cooling techniques is expected to alleviate this problem and allow power levels up to 600 kW to be maintained.

In the complete antenna-mounted radar system, 11 water circuits each carrying a nominal 2 GPM are used to cool the waveguide components alone. The transmitters, water loads, etc. all require large amounts of additional water.

Hybrid Combiners

Two hybrid power combiners of the 3-db sidewall coupler design were developed by Varian Associates. Figure 3 shows the unbrazed combiner with the top wall removed. The water cooling passages may be seen, including the holes that provide flow through the waveguide walls and the posts that determine the iris length. Another pair of covers (not shown) seals the passages and provides the input/output connectors.

No problems have occurred in the operation of the combiners in either balanced or unbalanced modes. The transmitters have been operated at independent amplitude and phase settings without difficulty. Isolation of the combiner exceeds 40 dB, and the VSWR is 1.015.

Directional Couplers

Three multihole topwall couplers are used in the system. Two dual 60/43 dB couplers near the klyston output sense the forward and reverse power for each klystron. Near the feed, one 54 dB forward power coupler measures the combined power. Early testing of these couplers resulted in failure of the internal loads. A change of material corrected the problem and no further difficulties were encountered with the exception of one waveguide arc, which apparently started in the main line coupler due to dirt and was stopped by the combiner before system shutdown was triggered. Since cleaning and rework of the waveguides, no further arcs have occurred.

Switches

A new waveguide switch was developed for this project using various design features developed at S-band and for an earlier 150-kW X-band lunar radar system in WR-112 waveguide. The switch shown in Fig. 4 has a housing on the bottom of the stator that provides stationary water connectors for the rotor without permitting water to leak into the waveguide in the event of seal failure. This is accomplished by running a straight tube into the center of the rotor and allowing the water to return coaxially outside the tube. An extension of the rotor shaft itself returns the water to the housing where it is removed. A seal prevents the water from escaping around the rotor extension. Should this seal fail, the water simply leaks from passages between the housing and the stator. A second seal in the stator retains nitrogen gas pressure within the switch and prevents any leaking water from finding its way into the waveguide.

Three switches are used in the system. One of these operates at full power as the transmit/receive switch. The switches have isolations exceeding 100 dB and insertion losses of less than 0.013 dB.

Polarizer and Rotary Joints

The switchable polarizer converts the linearly polarized TE°_{11} mode into a right- or left-hand circularly polarized TE°_{11} mode by means of a quarter-wave plate. The mechanical design is somewhat unique in that waveguide flanges are avoided. Each end of the polarizer is designed to be one-half of a rotary joint as shown in Fig. 5. This allows water cooling to be applied to the rotary joints in an efficient manner. Were they to be constructed as separate assemblies as at S-band (where aluminum joints have operated successfully without water cooling at power levels up to 500 kW) it would be very difficult to apply the coolant without intentionally making the joints longer than microwave design requires. Thorough cooling is essential to provide trouble-free transmit/receive switching with mechanical clearances between rotating surfaces of only 0.005 to 0.010 in.

Transition

The mating half of the lower rotary joint is machined onto the tapered transition. The design for this unit was available from another program, where the uniform transition was chosen to avoid the introduction of higher modes into the feed system even though a multi-step transition would be possible and physically shorter. The transition is made by electron discharge machining of a solid copper rod using interior tooling made from a computer-generated tape and an automatic milling machine. Thorough cooling of this part simultaneously cools the lower half of the bottom rotary joint.

Feedhorn

The feedhorn is a corrugated design utilizing the HE_{11} hybrid mode (Ref. 3) that produces suppressed-sidelobe patterns. Large aluminum horns of this design have been in routine use at JPL at S-band power levels of 400 kW with water cooling provided only at the horn throat. For the present application, the two smaller sections of the four-section horn are made of OFHC copper and have water cooling jackets. The two larger sections are aluminum and are cooled by conduction to the lower sections, to the feedcone roof through the mounting flange, and to the air. The throat of the horn is designed to provide the mating half of the upper rotary joint.

Horn Window

To maintain a pressure of 5 to 8 oz/in^2 internal waveguide positive pressure, the horn is covered with a thin window, or radome. Original S-band practice was to use Mylar* of 0.003 or 0.005 in. thickness. Failures occurred only when the material became excessively dirty or power levels exceeded 300 kW.

In searching for a better material for both the 150-kW X-band lunar radar and 400-kW S-band systems, Kapton* was tested because of its excellent mechanical properties. Where thick Mylar would sometimes soften and perforate at high S-band power levels, Kapton of equal thickness maintained its strength despite the inevitable heating, especially near the center of the horn aperture.

It was calculated that the ratio of power densities in WR-125 waveguide to the centerline of the 7-in. X-band horn aperture is 33.1, so that the traveling-wave resonator greatly eases the problem of determining the failure levels for the horn windows. Tests of 0.003-in. Kapton in the resonator showed slight discoloration after 30 min at 45 kW. This corresponds to 1490 kW at the horn aperture. At 50 kW, test samples failed in 1 min, with considerable charring. Repeated tests with several samples of 0.003-in. Kapton gave consistent results, indicating that approximately 1500 kW is the horn window failure level for clean material. As shown by a field failure at only 300 kW, dirt can cause a substantial degradation of the laboratory level. A practical solution is to use even thinner Kapton (thicknesses are available down to 0.0005 in.), or take steps to maintain cleanliness, or both.

Conclusion

Having individually tested most of the components, the radar system was ground tested and then mounted on the 64-m antenna in December 1974. The system operated successfully and returned valuable data on the rings of Saturn. The system is presently in use supporting landing site selection on Mars for the 1976 Viking mission.

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*Trademark, E.I. Dupont de Nemours Co.

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3. Brunstein, S.A., "A New Wideband Feed Horn with Equal E- and H-Plane Beamwidths and Suppressed Sidelopes", Space Programs Summary 37-58, Vol. II, pp. 61-64, Jet Propulsion Laboratory, Pasadena, Calif., July 31, 69.

Acknowledgement

Among the many contributors to the project, special acknowledgement is given to R. B. Kolbly, who constructed and operated the traveling-wave resonator, and to D. E. Neff, who was instrumental in the design and testing of the feed subsystem. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

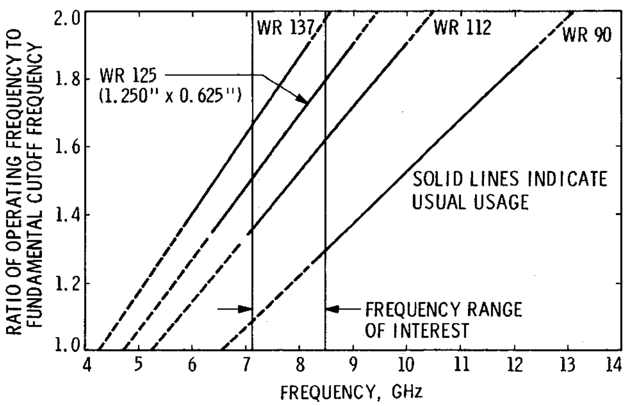

Fig. 1. Waveguide mode considerations

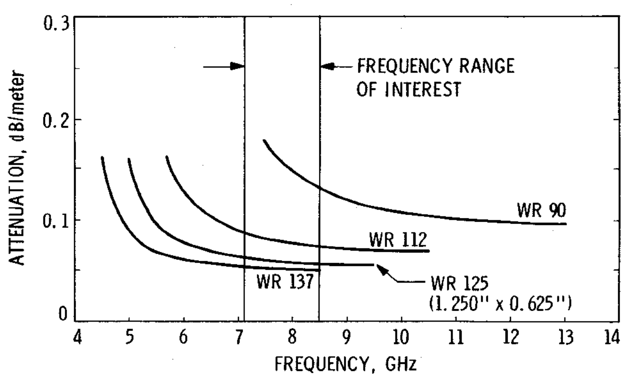

Fig. 2. Attenuation vs frequency

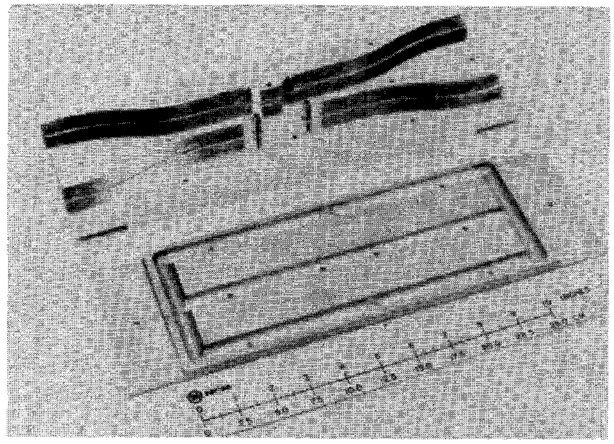

Fig. 3. Unbrazed combiner

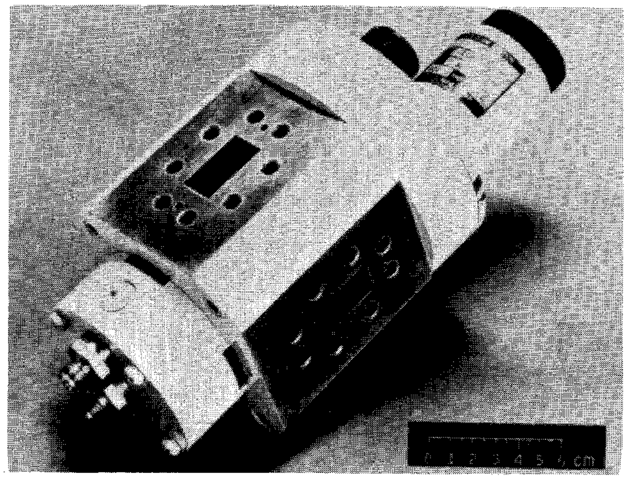

Fig. 4. Waveguide switch

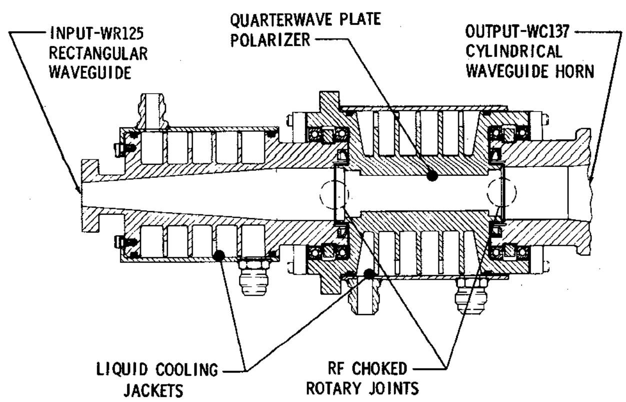

Fig. 5. X-band radar feed