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The High-Power *X*-Band Planetary Radar at Goldstone: Design, Development, and Early Results

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***Abstract*—Selected critical microwave components for a 400-kW very-long-pulse (several hours) *X*-band radar system are discussed from theoretical and practical viewpoints. 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 National Aeronautics and Space Administration/Jet Propulsion Laboratory 64-m-diam reflector antenna at Goldstone, CA.**

I. INTRODUCTION

THE 64-m-diam antenna at Goldstone, CA (Fig. 1), operated by the Jet Propulsion Laboratory (JPL) for the National Aeronautics and Space Administration [1], is equipped with a rotatable asymmetric hyperboloidal subreflector that permits the use of multiple feed systems at the Cassegrain focus. The subreflector can be precision indexed to a fixed number of positions (presently five) to allow each feed to properly illuminate the main reflector. Proper illumination is here defined to mean that each feed, in turn, produces a spherical phase front emanating from the prime focus, indistinguishable from that of a perfectly symmetric feed system except for minor amplitude illumination imbalance. Because the spherical phase fronts from the various feeds are not degraded, perfect axial pointing of the overall system is maintained among the feeds and no paraboloid "scan loss" is incurred; the minor amplitude imbalance inherent in this multiple feed system does cause a negligible (< 0.01-dB) illumination loss. In addition, two of the feeds are capable of simultaneous operations through a dual-reflector system consisting of a dichroic plate and ellipsoidal reflector; these two feeds typically operate simultaneously when the hyperboloid is indexed for the dichroic plate position [2].

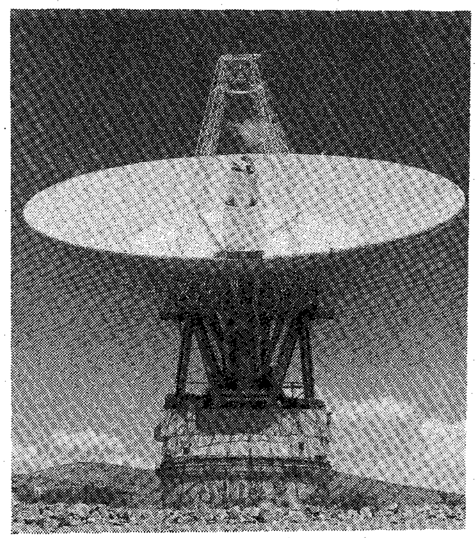

Fig. 1. The 64-m-diam antenna at Goldstone, CA.

For *S*-band frequencies, the feed that operates through the ellipsoidal reflector (Fig. 2) is diplexed for simultaneous

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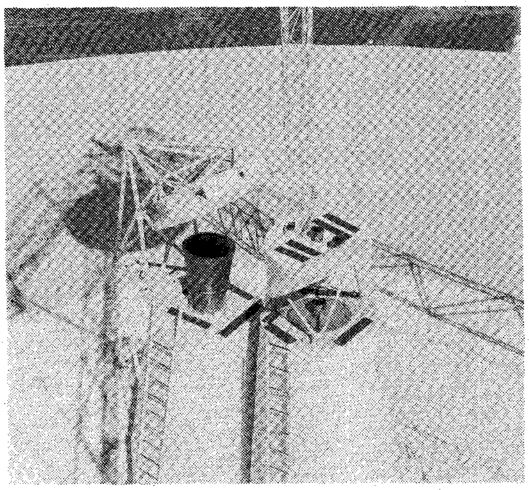

Fig. 2. The multiple feed system.

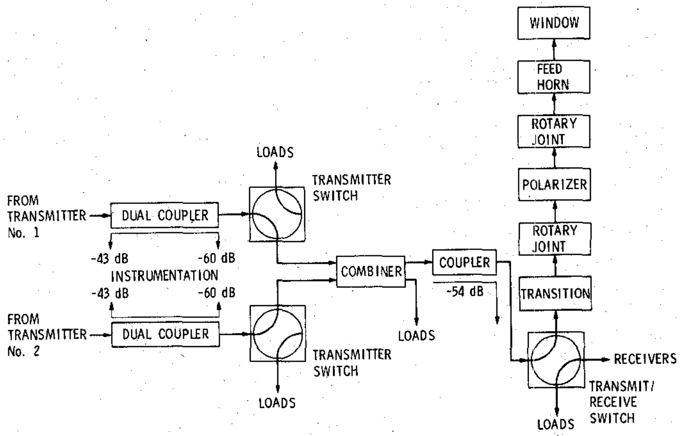

Fig. 3. Block diagram of radar system high-power components.

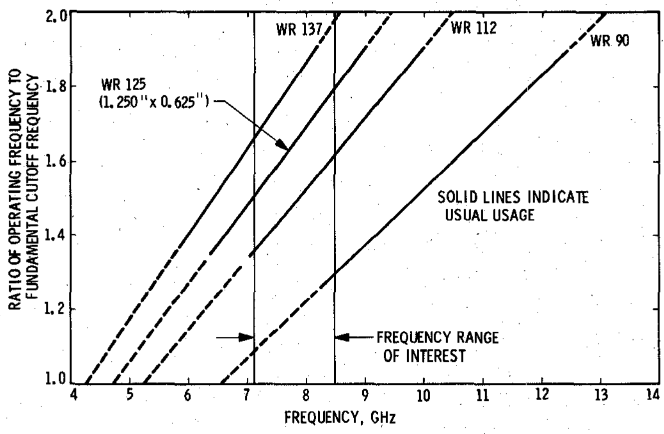

Fig. 4. Waveguide mode considerations.

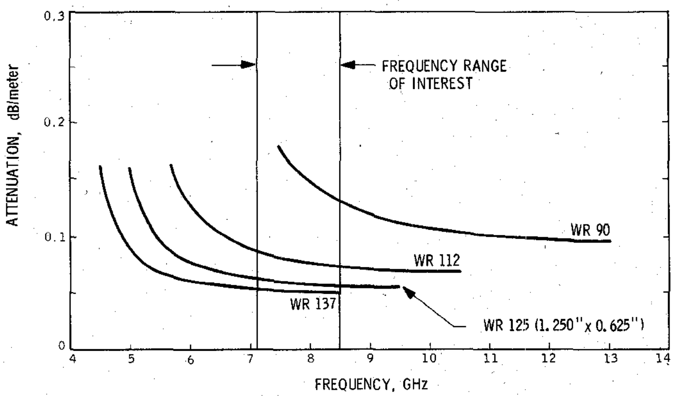

Fig. 5. Waveguide attenuation.

transmitting and receiving, has complete polarization diversity, and includes an optional very-low-noise listen-only mode. Three *S*-band transmitters are arranged to operate through this feed: 1) A 20-kW CW transmitter for routine spacecraft communications near 2.1 GHz; 2) a 400-kW CW transmitter for special communications situations; and 3) a 400-kW CW R & D transmitter operated near 2.4 GHz that is used primarily for planetary radar.

Below the dichroic plate is the *X*-band receive-only feed typically used in the dual-frequency (*S*- and *X*-band) spacecraft communications mode. This feed is presently being updated to include selectable RCP/LCP polarization diversity.

Located within the third conical structure seen in the background of Fig. 2 are three more feeds. The small dual horn is a *K*-band receive system that includes one focused and one skewed or off-axis horn for a cold-sky reference useful in radiometry. The center horn is a wide-band *X*-band receive-only feed for R & D and radio science use and provides a second radar receiving feed.

The fifth feed is the 400-kW *X*-band radar system [3]. To avoid a special vacuum tube development program, two modified amplifier klystrons, each capable of delivering 250 kW CW, were selected to operate into a hybrid combiner (Fig. 3) with a single waveguide carrying the total power to a single-aperture feed system. Limitations in the local dc power available prevent the dual klystron transmitter from generating more than about 400 kW of RF output. Since the gain of the antenna is approximately 72 dB at 8500 MHz, the *X*-band radar system has an effective radiated power of about 6×10^{12} W [4].

II. Waveguides

Early in system planning it was apparent that the waveguides necessary for this system would be very 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 possible future deep space uplink band near 7150 MHz. Fig. 4 shows the mode considerations for the new waveguide (called WR-125) compared to standard waveguides in this frequency band. The WR-137 waveguide is seen to be overmoded for a frequency of 8495 MHz, and WR-112 would be highly stressed, especially near 7150 MHz. Fig. 5 shows the attenuations of the same waveguides. The WR-125 waveguide has a 2:1 aspect ratio and an inside wide dimension of 31.8 mm.

If the theoretical breakdown of air is accepted as 3×10^6 V/m, the WR-125 waveguide will fail at 2500 kW for standard temperature and pressure. In the actual system, since no harmonic filtering is present, impedances are not perfectly matched, sea-level conditions do not prevail (the altitude at Goldstone exceeds 1000 m), and thorough cleanliness is always problematic, a derating factor of about 0.40 is considered appropriate, indicating that the maximum practical power is about 1000 kW.

After passing through a transition, the feed waveguide is cylindrical with an inside diameter of 34.8 mm. The theoretical breakdown level for this waveguide is 4400 kW. Using the same derating factor, this guide can in practice support 1800 kW, or nearly twice the power ability of the rectangular guide. The polarizer, rotary joints, and feedhorn throat are designed in the cylindrical guide, with all other components being in the rectangular waveguide.

All components are made from oxygen-free high-conductivity (OFHC) copper, and the rectangular waveguide tubing is specially drawn with a wall thickness of 3.2 mm. The flanges are solid brass, completely flat faced, and finished to 0.4 μm with flatness held to 0.01 mm. The finished flanges are a minimum of 10 mm thick. This flange system is assembled without gaskets of any kind. A special procedure involving lapping, cleaning, and very light silicone greasing has been developed to ensure field reliability, including corrosion prevention, with good results [5].

III. Cooling

A major problem in any ultrahigh-power CW system is that of applying the cooling fluid to all components in an adequate and efficient manner. Following years of *S*-band practice at JPL, the waveguides are cooled by ducts consisting of ordinary WR-90 waveguide soldered onto both broad walls. This results in 42 percent 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 WR-125 flanges. Because of the necessity for allowing clearance for the flange hardware, the cooling ducts end about 45 mm from the flange face. This design results in excessive spot temperatures (exceeding 150°C) and system shutdowns due to arcing after 2–3 h of continuous transmission when the system is operated with warm or room-temperature water available for ground testing. However, when the system is antenna mounted, it operates on chilled (about 15°C) water from an air conditioning system. Under these conditions, no further shutdowns due to waveguide overheating have occurred. Nonetheless, it is clear that flange cooling is marginal, and improved cooling ducts which extend a copper heat sink toward the flange have been shown to reduce the flange temperatures by 30°C. It is recommended that some modification of this type be incorporated into future components.

In testing the efficiency of various cooling modifications, a technique was developed which avoids excessive use of the transmitters for hours of routine temperature data. Electric heaters are placed inside connected waveguide sections (Fig. 6), and controlled wattage is applied to simulate the power dissipated at 500 kW of microwave power (about 6000 W/m 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 under actual operating conditions.

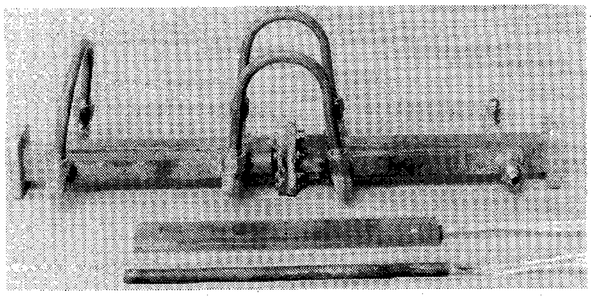

Fig. 6. Waveguide cooling test pieces: heater (front); heater within copper waveguide insert (center); modified cooling parts (rear).

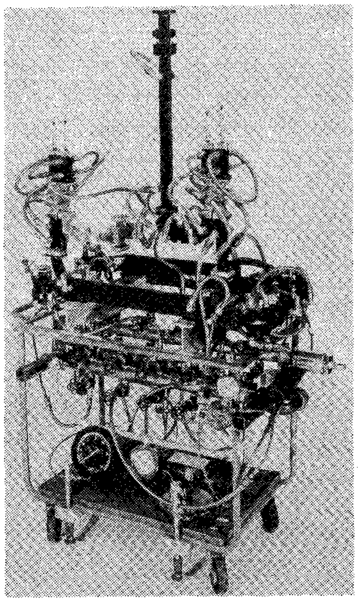

Fig. 7. Traveling-wave resonator.

Testing of many components was also accomplished using a traveling-wave resonator (Fig. 7), although stable power levels were limited to about 300 kW because of the same flange heating problem. Thermal expansion 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 for thorough testing of future components.

In the complete antenna-mounted radar system, 11 water circuits, each carrying a nominal 10 l/min, are used to cool the waveguide components alone. The transmitters, water loads, etc., all require large amounts of additional coolant.

IV. Hybrid Combiners

Two hybrid power combiners of the 3-dB sidewall coupler design were developed by Varian Associates. Fig. 8 shows an unbrazed combiner with the top wall removed. The water cooling passages may be seen, including the

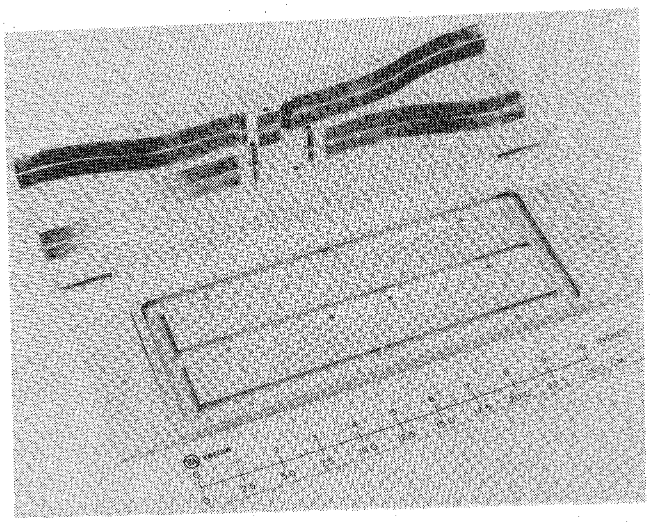

Fig. 8. Hybrid combiner.

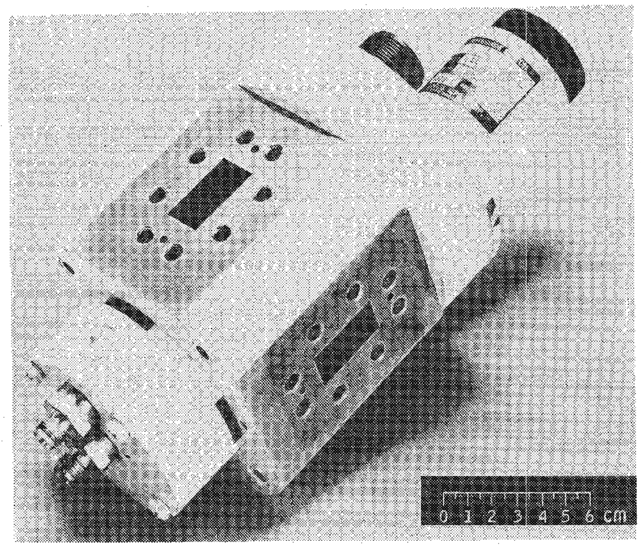

Fig. 9. Waveguide switch.

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 water connectors. The waveguide flanges are added after machining of the brazed assembly.

No problems have occurred in the operation of the combiners in either balanced or unbalanced modes. A phase control in the exciters permits the combiner to operate as a switch, with all or any part of the output power being terminated in water-cooled loads. 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. The expected power handling capacity of this unit is 700 kW (total).

V. Directional Couplers

Three multihole topwall couplers are used in the system. Two dual 60-/43-dB couplers near the klystron 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 thermal failure of the internal loads. A change of material corrected the problem and no further difficulties have been encountered, with the exception of one waveguide arc, which apparently started in the main line coupler and was, interestingly enough, stopped by the combiner before system shutdown was triggered. Dirt was the suspected reason for the initial arc. Since cleaning and rework of the waveguides, no further problem arcs have occurred.

VI. Switches

A new waveguide switch was developed for this project using various design features developed at S band and for an earlier 150-kW CW X-band lunar radar system in WR-112 waveguide. The switch shown in Fig. 9 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 water circulation 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 waveguides and gaps and thus prevents any leaking water from finding its way into the waveguide.

Three switches are used in the system. One of these handles full power for the waveguide transmit/receive function. The other switches provide individual loads for each klystron and generally operate at one-half total power. Minor temperature rise problems are associated with the uncooled (except by conduction) stator in contact with previously mentioned 45-mm spacings from flange faces to cooling ducts, but these temperature rises do not detract from system operation. The switches have isolations exceeding 100 dB and insertion losses of less than 0.013 dB. The ultimate power-handling ability of the choked switch assemblies has not been calculated.

VII. Polarizer and Rotary Joints

The switchable polarizer converts the outgoing linearly polarized $TE_{11}{}^0$ mode into a right- or left-hand circularly polarized $TE_{11}{}^0$ mode by means of a quarter-wave plate. Each end of the polarizer is designed to be one-half of a rotary joint, as shown in Fig. 10. This design allows water cooling to be applied to the rotary joints in a fairly 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 and thus increasing the dissipation loss. Thorough cooling is essential to provide trouble-free transmit/receive polarization switching with mechanical clearances between rotating surfaces of only 0.1–0.2 mm.

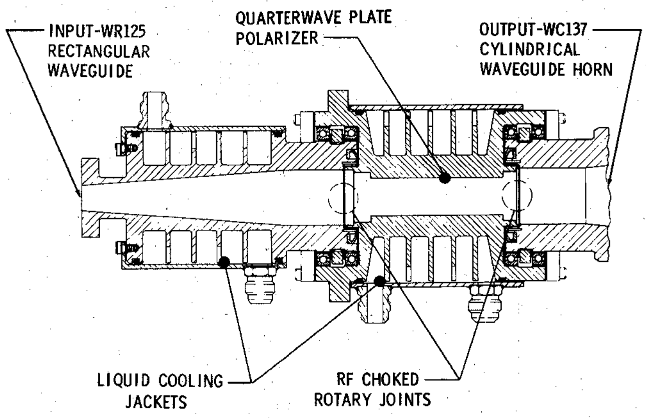

Fig. 10. Radar feed cross section.

Although radar system transmit/receive switching does not require it, polarization switching under full power is possible and has been reliably tested. The ultimate power-handling ability of the choked rotary joint assemblies has not been calculated.

VIII. 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 possible introduction of a breakdown situation due to unfiltered harmonics carried in higher order waveguide modes, though an available multistep transition would have been physically shorter and would have had lower loss. The uniform 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. The cross section of the transition changes gradually from a 2:1 rectangle to a circle with only a slight rounding of corners to correct for the rectangle diagonal being larger than the diameter of the circle. Thorough cooling of this part simultaneously cools the integral half of the adjacent rotary joint.

IX. Feedhorn

The 22.4-dB gain feedhorn is a corrugated design utilizing the dominant HE_{11} hybrid mode [6], which produces a high-quality beam. 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 a mounting flange, and to the air. The throat of the horn is machined to include the integral half of the upper rotary joint. Because of the hybrid mode generation, the breakdown level of the horn is difficult to calculate; it probably lies in the range of 1000–2000 kW.

X. Horn Window

To maintain a positive pressure inside the waveguides of about 0.3 N/cm^2 (8 oz/in^2) of dry nitrogen, the horn aperture is covered with a thin window, or radome. Original

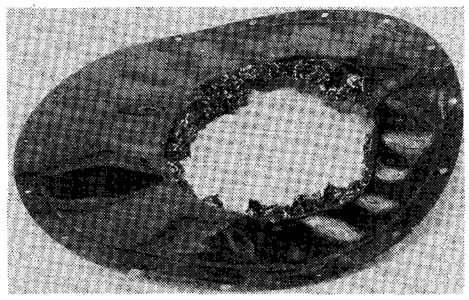

Fig. 11. Horn window failure.

S-band practice was to use Mylar® of 0.08- or 0.13-mm thickness. Operations at 100 kW were totally reliable. Failures frequently occurred when the material became excessively dirty or when power levels exceeded 300 kW.

In the search 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 and its reported burnout-free use as an optical attenuator for modest laser applications. Whereas Mylar softened and perforated at high *S*-band power levels, Kapton of equal thickness maintained its strength despite dielectric heating, especially on the high-power-density feedhorn center line.

Calculations show that the ratio of power densities in the WR-125 TE_{10} mode waveguide to the center line of the 180-mm-diam HE_{11} mode horn aperture is 33.1; as a result, the traveling-wave resonator greatly eases the problem of determining the failure levels for feedhorn windows.[1] Tests of 0.08-mm 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 0.08-mm Kapton gave consistent results, indicating that approximately 1500 kW (or about 30 kW/cm^2 at the center) is the horn window failure level for clean material. As shown by one field failure at only 300 kW (Fig. 11), dirt causes a substantial degradation of the laboratory level. A practical solution is to use even thinner Kapton (thicknesses are available down to 0.013 mm), or take steps to maintain cleanliness, or both.

XI. Operating Experience

Following individual component testing, and in certain cases subsystem level tests, the complete third conical structure (feedcone) seen in Fig. 2 was ground tested before final mounting at the Cassegrain focus of the 64-m-diam antenna in December 1974. Such ground testing very effectively saves large blocks of antenna time (a commodity in constant short supply) which normally would have to be devoted to startup test activities. The antenna-mounted system returned valuable and timely data, on schedule, on the rings of Saturn which were in a unique face-on attitude

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[1] This apparently high ratio results because the highly tapered electric plane field of the HE_{11} mode effectively concentrates power on axis (by roughly an order of magnitude in intensity) compared with a uniform electric field device, such as a simple TE_{11} or TE_{10} mode horn. Approximately Gaussian illumination (in any plane) is provided by the HE_{11} mode horn.

(as viewed from Earth) during January 1975 [7]. After a few months of successful operations followed by several dormant months, the system was again brought on line in the second half of 1975. Klystron and waveguide problems combined to cause low power output and unreliable arcing operations, and a major overhaul was accomplished late in 1975. New klystrons were installed and protective circuitry improved. All waveguides were cleaned of suspected small-scale debris accumulation, and a few components were replaced as a result of extensive reflection tests. A new operations philosophy of a once-per-week minimum full-power "burn in" of at least 2–3-h duration was adopted. This burn in is considered necessary, on the basis of previous S-band experience, to the maintenance of clean waveguide conditions. Apparently, internal water vapor, dust, and/or other debris are eliminated by this procedure [8], [9]. With about five months experience to date, the overhaul and new operating technique are successful; typically one or two arcs occur during the first 15–30 min of use with complete freedom from arcs thereafter. The system has recently been used to support landing site selection on Mars for the 1976 Viking mission, in conjunction with alternating S-band radar surveys using the same 64-m-diam antenna.

XII. Conclusions

An important adjunct to support the NASA commitment to planetary radar astronomy is provided by the 400-kW X-band radar located at Goldstone, CA. Other solar system objects, including certain asteroids and some of Jupiter's moons, have also become available for study as a result of this development [10].

Important initial system decisions have proved sound. These include 1) use of a single transmission line rather than multiples, 2) operation of special waveguides at ultrahigh CW power without special dielectric gas insulation, 3) use of choked rotary switches and a rotary polarizer, and 4) all of the aforementioned in a system without harmonic control.

Wherever possible, estimates of component power-handling ability have been given. Substantial additional work will be required to extend present techniques to reliable 1000- to 1600-kW class equipment at X band; in all likelihood a few major departures from established methods will be needed to bridge the next gap if 3–6-dB additional power output becomes a requirement.

Acknowledgment

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