Design Concepts of a 1-MW CW X-Band Transmit/Receive System for Planetary Radar

Arthur J. Freiley, *Member, IEEE*, Bruce L. Conroy, Daniel J. Hoppe, and Alaudin M. Bhanji

Abstract—**The conceptual design of the 1-MW *X*-Band Transmit System for the Goldstone Solar System Radar represents the next step in the quest to expand planetary radar explorations. The radar transmitter requirements are summarized. The characteristics and expected performance of the major elements are discussed, including the klystrons, power amplifiers, microwave transmission lines, feed systems, beam power supply, heat exchanger, phase stable exciter, and the monitor/control system. An assessment of the technology development needed to meet the system requirements is given, and possible areas of difficulty are outlined.**

I. Introduction

RADAR has been used as a tool for the remote exploration of our solar system since 1946, when the first echoes from the moon were detected. Since this humble beginning, ground-based radar observations have been performed on the planets Mercury, Venus, and Mars and its moon Phobos, the Galilean satellites, the rings of Saturn and its moon Titan, and numerous near-Earth asteroids and comets [1]–[5]. The performance of these Earth-bound instruments has improved through the years by a factor of approximately 10^{12} since the first lunar observations were detected. Such great gains in sensitivity have been achieved by extraordinary improvements in antenna size, low-noise cryogenically cooled receiving systems, high-speed digital signal processing, and higher power transmitters at higher frequencies.

Currently, the Goldstone Solar System Radar (GSSR) Project has two radar systems in operation on the NASA/JPL 70-m shaped Cassegrain antenna at Goldstone, CA (Fig. 1). The first is an *S*-band system capable of radiating 400 kW (+86 dBm) while alternately receiving returns with a 16-kelvin receive system. The second is a newly upgraded *X*-band system capable of radiating 450 kW (+86.5 dBm) while alternately receiving its returns with a 14-kelvin receiving system. With the digital data processing techniques also applied, the overall dynamic range is in excess of 350 dB.

The 70-m antenna features a number of different feed systems to support the NASA unmanned deep space exploration programs as well as the radar feed systems. These feeds include an *S*-band diplex/*X*-band received system and an *L*/*C*-band receive system—both for deep space mission support, a *Ka*-band receive-only system for radio astronomy, and the two radar systems. The antenna is equipped with an asymmetric subreflector that can be precisely indexed to properly illuminate the main reflector with any of the feeds, located in the feedcone structure in the center of the main reflector. The *X*-band aperture efficiency is 75%, which corresponds to an antenna gain of 74.5 dBi. The antenna is fully steerable to any target above the horizon and has the capability to blind point to an accuracy of 3 to 5 millidegrees.

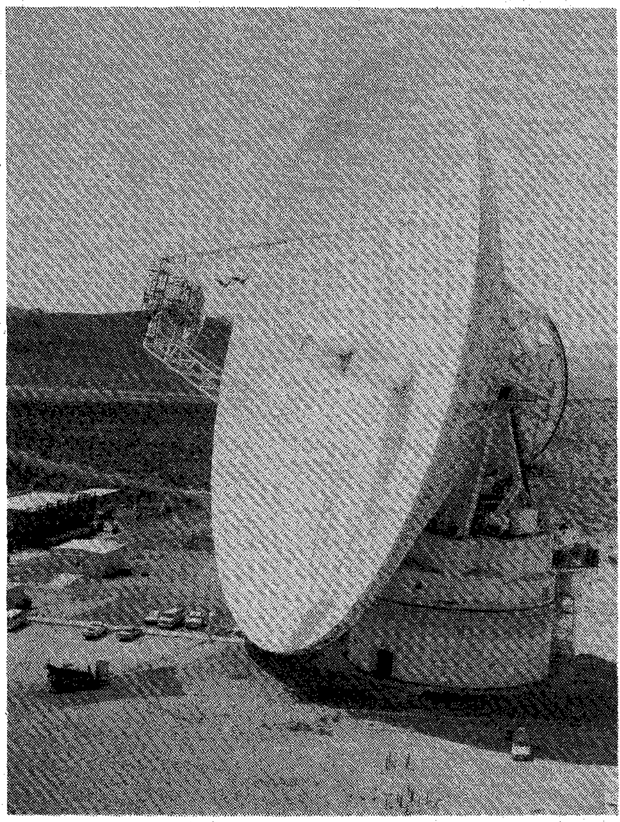


Fig. 1. 70-m shaped Cassegrain Antenna at Goldstone, CA.

The next improvement in capability of the radar program will come from the development of the 1-MW CW *X*-band radar transmitter. At the Jet Propulsion Laboratory the conceptual design has been initiated to expand the present *X*-band transmitter capability from 450 kW to

Manuscript received May 30, 1991; revised November 15, 1991. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors are with the Jet Propulsion Laboratory, 149-200, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

IEEE Log Number 9107473.

0018-9480/92$03.00 © 1992 IEEE

1 MW (90 dBm) CW with improvements in stability and operability. This system will extend the dynamic range of the *X*-band radar system by 3.5 dB.

II. Transmitter System Requirements

The transmitters used for radar astronomy systems differ from conventional radar systems in that they require high average power, rather than high peak power, over the bandwidth [6]. It is also important that these transmitters be coherent in order to determine the phase relationships of the returned signals, and they must have high phase stability if coherent measurements are to be made over long periods of time. The transmitter also must be capable of modulation via a variety of modulation programs, while maintaining the phase and amplitude fidelity and pulse-to-pulse stability required for pulse-compression systems incorporated in the radar.

The above requirements illustrate that high power alone will not provide the desired CW radar transmitter capabilities. If this were the case, it might be more easily obtained with an oscillator rather than an amplifier. In addition to the advantage of having dynamic control of amplitude and phase, the appeal of using an amplifier is that it eliminates the need for phase-locking an oscillator to its control signal.

Based on the above requirements, the *X*-band radar transmitter specifications are given in Table I.

III. The Transmitter System

As shown in Fig. 2, the transmitter will include a power supply that converts 2400-V, 3-phase, 60-Hz primary power to direct current at up to 51 kV with a power limitation of 2.25 MW for the four klystron amplifier beams. The frequency synthesizer-based exciter and the buffer amplifier will provide an input signal to these klystrons, and each of the four klystrons will provide approximately a 50-dB power gain. The automated transmitter control will perform monitoring and control of all functions. Protective devices (interlocks) will prevent damage to equipment by removing voltage and in some cases drive power in the event of a malfunction. The liquid-to-air 2.5-MW heat exchanger will be used to cool the amplifier, the power supply, various auxiliaries to the transmitter, microwave components of the transmitter, and microwave components of the transmission line. The following paragraphs describe each of the above components in greater detail.

A. Exciter

Fig. 3 shows the proposed configuration of the exciter portion of the 1-MW radar, which is based on an HP 8662A synthesizer [7]. The synthesizer uses the 10-MHz reference signal from a hydrogen maser to produce a phase-coherent output at 640 MHz, and a phase-coherent variable-frequency signal from 10 kHz to 640 MHz with 0.1-Hz resolution, or from 640 to 1280 MHz with 0.2-Hz resolution. The 640-MHz signal can be picked off and mixed with the variable frequency output. For the transmitter, the variable-frequency output is set to 830 MHz and mixed with 12 times the 640 MHz to produce 8510 MHz. In the receive configuration, the variable frequency is set to 505 MHz and mixed with 12 times the 640 MHz

TABLE I
1-MW *X*-Band Radar Transmitter Specifications

Parameter	Specification
Frequency	8.51 GHz
Bandwidth	20 MHz (−1 dB) 6 MHz (normal usable range)
RF output power	1 MW CW (+90 dBm)
RF stability	±0.25 dB over one planetary transmit/receive cycle
Incidental AM	60 dB below carrier at all modulating frequencies above 1 Hz
Phase stability, $\Delta f/f$	10^{-15} (1000 sec)
Incidental PM (jitter)	< 1° peak to peak
Transmit period	30 s min to 10 h max
Modulation:	
Phase Modulation	Biphase, 40-dB carrier suppression, dc to 20 MHz
Frequency Hopping	±2 MHz every few seconds
Frequency Ramping	±2 MHz in 200 ms
Group Delay Dispersion	10 ns over 6-MHz bandwidth
Polarization	
Transmit	RCP or LCP (one polarization at a time; cross polarization < −25 dB)
Receive	RCP and LCP simultaneously

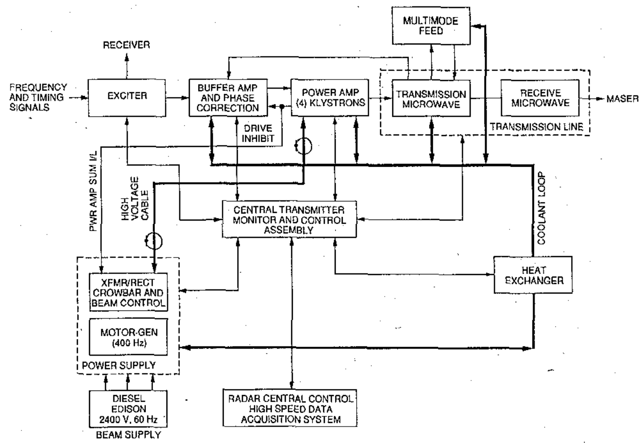


Fig. 2. 1-MW *X*-band radar transmitter block diagram.

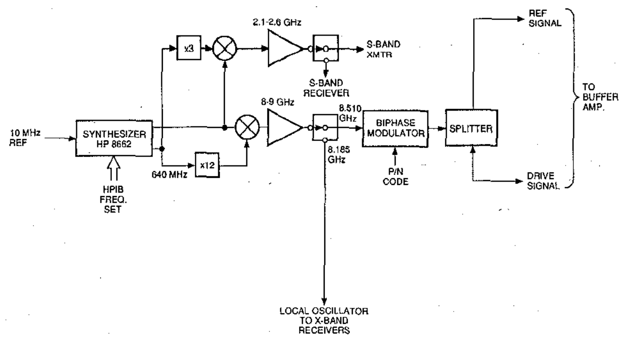


Fig. 3. Exciter.

to produce a signal at 8185 MHz, which could be used as the first local oscillator in the receiver. A similar system, using 3 times 640 MHz, is used for the S-band exciter and also could be used as a first local oscillator for an *S*-band receiver.

Reduction of phase noise is a major concern in the exciter design. By mixing the output of an extremely low-noise, high-frequency synthesizer with low multiples of a clean, fixed frequency oscillator, total phase noise should be reduced by more than 20 dB from that produced by the more standard methods of using a high multiple of a low-frequency synthesizer.

Provisions are made for biphase pseudo-noise modulation, frequency hopping, and continuous frequency sweep for Doppler cancellation. The frequency hopping is accomplished by sending frequency step commands to the synthesizer on an IEEE-488 interface. Doppler cancellation is done through a combination of a coarse frequency, set through the IEEE-488 interface, and an analog voltage at the search oscillator input. Phase noise modulation is done directly with the biphase modulator at the output frequency.

A power divider is included in the exciter, providing separate outputs for the phase reference system and klystron drive system in the buffer amplifier.

B. Buffer Amplifier

The functional block diagram for the buffer amplifier is shown in Fig. 4. For the first choice of transmission line arrangements (see Section III-D), phase-tracking loops and electronic polarization control are provided in the buffer. The phase-tracking loop uses a voltage-tracking controlled phase shifter in the drive path of each klystron to compensate for phase changes in klystrons and microwave components. A sample of the output from each klystron is taken as close to the feedhorn as possible and compared to the reference signal. Symmetry in the waveguide paths from the final splitter is still required to prevent differential phase shifts between the horn inputs.

Because the feed system uses two klystrons to drive the inline inputs to the horn and the other two klystrons to drive the orthomode inputs, polarization control is achieved by the phase shifter after the first splitter in the buffer amplifier. Phase shifts of ± 90 degrees yield righthand or lefthand circular polarizations. Other phase shift values produce various elliptical polarizations. A corresponding phase shift must be introduced in the phase correction loop, but in the case of switching from righthand circular to lefthand circular polarization, this can be done with an inverting amplifier after the phase detector. For the waveguide-based system, no special electronic control is required in the exciter. In both cases, a solid-state amplifier for each klystron provides the required 2 W of drive power.

C. Power Amplifier

The power amplifier section of the transmitter contains four 250-kW CW klystrons. The requirements of high

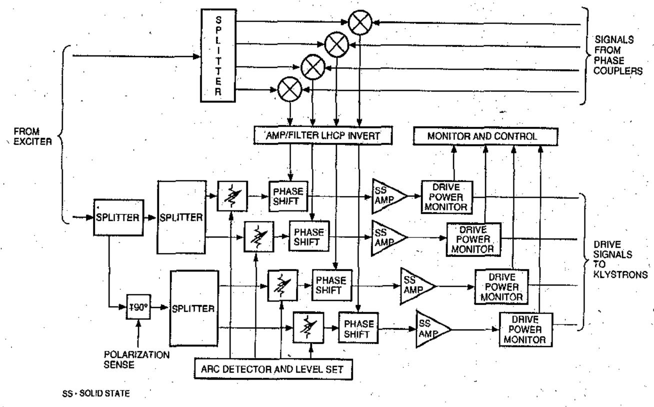


Fig. 4. Buffer amplifier.

power, high gain, efficiency, ease of modulation, and an output spectrum free from spurious signals and noise make a klystron linear-beam amplifier the natural choice for radars, as long as its narrow bandwidth, high operating voltage, and large size can be tolerated.

Early in 1986, Varian Associates was contracted by JPL to develop the state-of-the-art 250-kW CW klystron amplifier at 8510 MHz [8]. The design, development, and production was concluded with the delivery of two klystrons in May 1990. The characteristics of this tube, designated the VKX-7864A [3], are given in Table II. The weight of the klystron assembly is approximately 835 lbs: 465 lbs for the klystron itself, 270 lbs for the solenoid, and 100 lbs for the stand. Fig. 5 shows the klystron ready for installation in the high-power test bed at Goldstone, CA.

As part of the testing of the klystron, the phase modulation sensitivities were measured. These pushing factors from variations in any of the tube parameters such as beam voltage, drive power, body coolant, focus current, or heater voltage contribute to phase variations in the output signal and the production of unwanted discrete lines on the phase noise spectrum. The control and stability of these factors establish the requirements for the design of other elements of the transmitter. The phase linearity is another klystron parameter that becomes critical to this design. The phase linearity function with frequency and the variations from tube to tube must be within limits to allow successful combining of power from multiple tubes as required to produce 1 MW of radiated power.

As part of the power amplifier assembly, each klystron is provided with an arc detector at the window and a reverse power coupler for protection. In the event of a fault, these monitors will remove the RF drive before permanent damage can occur.

One of the critical elements of the klystrons is the focusing magnet. This device is a solenoid which surrounds the interactive volume and keeps the electron beam focused into a narrow beam between the electron gun and the collector. A control of better than 1% must be exercised to maintain high efficiency and low body current. This solenoid normally requires 200-V, 20-A dc power to provide the proper magnetic field.

TABLE II
CHARACTERISTICS OF VKX-7864A *X*-BAND KLYSTRON

Parameter	Specification
Frequency	8510 MHz
Bandwidth	20 MHz (1-dB points)
Output power	250 kW min
Beam voltage	51 kV
Beam current	11.2 A
Efficiency	45%
Gain (sat)	50 dB
Klystron weight	835 lb
Klystron height	5 ft
Pushing factors	
Beam voltage	<0.02 deg/V
Drive power	<-3 deg/V
Coolant temp	<-0.9 deg/C

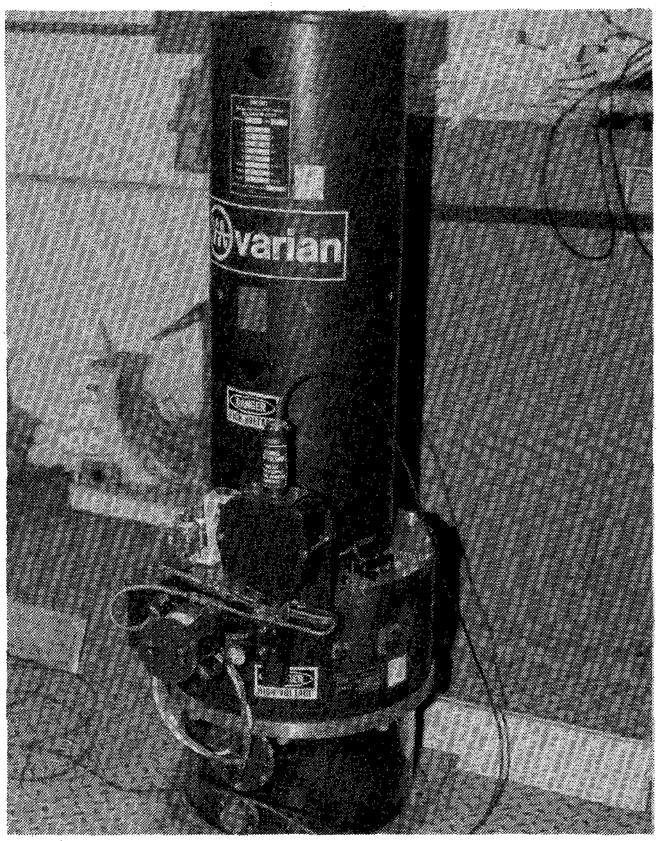


Fig. 5. 250-kW *X*-band Klystron.

The separate coolant manifold for each klystron will monitor and control flows, temperature, and pressure. This data will be routed to the data collection system, which is described in Section III-H.

The power amplifier, including the transmission line and feed system (described in the following section) will all be housed in the feedcone. The mechanical layout for one system is shown in Fig. 6.

D. Transmission Line

Three alternatives for the transmission line system are under consideration. The first system is shown in Fig. 7.

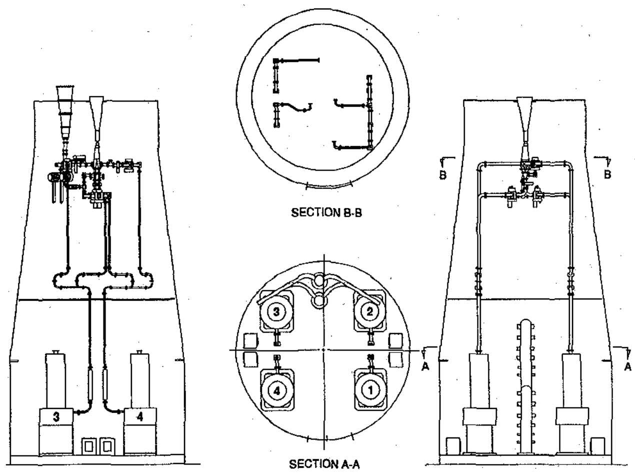


Fig. 6. Mechanical layout.

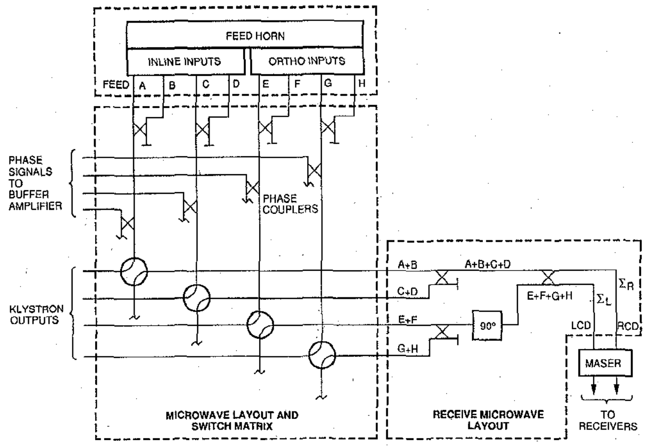


Fig. 7. Transmission line system (Option 1).

For this system, the 250-kW output from each klystron passes through a waveguide switch and directional coupler before being split into two 125-kW signals. Four of these signals (two pairs) feed the in-line ports of four orthomode junctions, while the other pair feeds the orthogonal ports. Thus, by adjusting the relative phase between the two pairs of klystrons, one of the two orthogonal linear polarizations, RCP or LCP, may be obtained (see buffer amplifier, Section III-C). The outputs of the four orthomode junctions then feed the four inputs to the multimode feedhorn (described in the next section). In this system, phase detectors and electrically controlled phase shifters will be used to adjust the outputs of each of the klystrons and to provide polarization control. The reliance on electronics reduces the complexity of the waveguide layout in comparison to the waveguide-based system described below.

Fig. 8 shows the waveguide-based alternative to the previous system. This system is similar to that used at the Haystack Hill Observatory in Westford, MA [9]. In this system, a series of splitters and combiners ultimately forms four identical signals. Each of the signals is composed of 25% of the power from each klystron, and all four are equal in amplitude and phase, independent of the

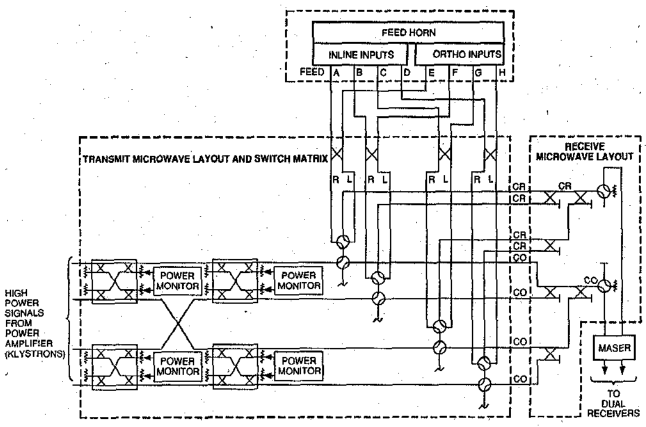


Fig. 8. Transmission line system (Option 2).

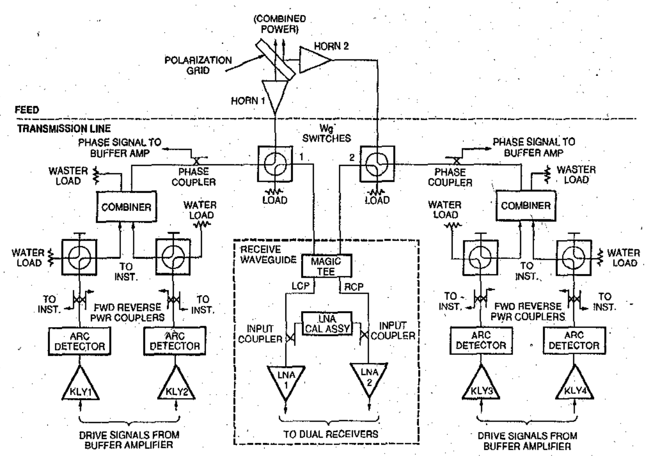


Fig. 9. Transmit/receive feed with transmission lines and power amplifier (Option 3).

four klystron outputs. Phase shifters are used in each of the drive lines to the klystrons in order to minimize the power in the waster loads. This adjustment is made once, and if klystron parameters or frequencies change during a track, only the waster-load power will change.

Polarization is changed mechanically through switches immediately before the orthomode junctions. Although this approach is complicated mechanically, it has the advantage that beam position and polarization purity are virtually guaranteed without the use of any electronics.

The third alternative being considered is shown in Fig. 9. In this configuration the signals from each pair of klystrons are combined. The phasing of the two klystron signals is monitored by the power in the waster load of the combiner. Phase adjustments are made to minimize the power in this load. The output of the combiner is a single waveguide carrying 500 kW to the feed. The signals from the third and fourth klystrons are also combined in a similar manner. Each of these 500-kW signals then drives corresponding orthogonally polarized feedhorns. A more detailed description of the feeds and power combining techniques is presented in the next section.

The final decision on which of the systems, or a combination thereof, will be used depends on how closely the four klystrons tubes can be matched in terms of phase, gain, and group delay versus frequency. Measurements of these parameters on the first two klystrons agree well and are well within the limits set to allow the combining of power from individual tubes. The effects of aging also must be considered to guarantee that the system will run reliably over the expected lifetime of the tubes with minimal adjustment.

For any of these systems, WR-125 waveguide is used as the high-power waveguide to avoid operation close to the higher-order modes in WR-137, which begins propagating at 8600 MHz [10].

The electrically operated waveguide switches allow selection of the radar antenna or water loads of termination of transmitter output power. The water loads also will be used for calibrating the output power calorimetrically.

On receive, the klystrons are turned off and switches are rotated, connecting the receive waveguide to the feedhorn. Through a series of combiners, RCP and LCP signals are formed. These signals then enter the dual-channel maser, and finally the heterodyne receiver. In addition, the existing low-noise system (Fig. 10), which uses a separate corrugated horn for receiving, will be retained. The disadvantage of this receiving arrangement is that the antenna subreflector must be rotated between transmit and receive cycles. A further disadvantage is that only those observations with sufficient round-trip light times to allow the 30-to-60 second switching time can be observed using the low system noise temperature. The measurements of the receive system in the existing *X*-band radar indicate that the noise temperature is 14.7 kelvins.

Observations of targets with short round-trip light times will require the use of the integral receive system built into the transmit system (see Figs. 7, 8, and 9). These systems will offer switching times on the order of 0.5 seconds and system noise temperatures between 40 and 50 kelvins.

E. Antenna Feed System

The final element required in the transmission line for the radar system is the antenna feed, which will launch the transmitter power toward the subreflector of the antenna. The feedhorn should illuminate the subreflector efficiently and contribute minimum noise to the system noise temperature. The horn will be designed to meet or exceed the RF performance of the feedhorns presently in use, with the added feature of 1-MW capability.

Two alternative feed designs are under consideration; the first is depicted in Figs. 7 and 8 and the second is shown in Fig. 9. Experience indicates that conventional corrugated or dual-mode horns are not capable of handling the 1-MW CW power without breaking down at the small-diameter input section. It was also found that a rather large number of small horns arranged in a closely packed array would be required to illuminate the subreflector efficiently. Due to the complexity of this type of system, as well as the losses associated with the power

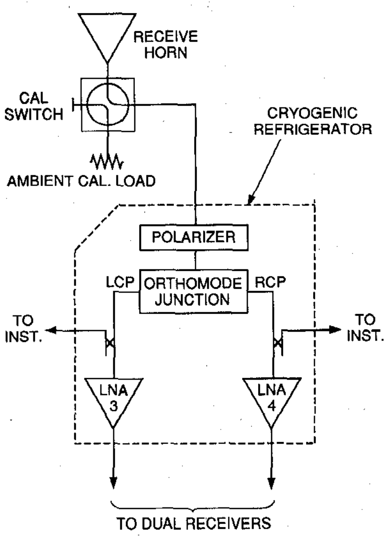


Fig. 10. Receive-only feed.

splitting components, the array concept was also rejected for the 1-MW system.

The first design option uses a multiflare rectangular horn [11]. Such a horn is well suited to the 1-MW system, since it possesses an excellent radiation pattern and has been used in other power applications.

The multimode horn is depicted in Fig. 11. Four square waveguides feed a large square chamber where the power is launched into a square multiflare horn. Since the larger chamber is oversized for the frequency of interest, the sum of the power in the four waveguides can be supported without breakdown. In the present case, each of the guides must support 250 kW, and the larger chamber 1 MW. Flare angle changes are used to generate the required higher-order modes for pattern symmetry.

The analysis of the horn is carried out using mode-matching methods [12] from which the overall scattering matrix of the horn is obtained. Using these results, the input match, as well as the far-field radiation pattern, can be predicted for arbitrary input levels and phases in the four input guides. Calculated radiation patterns for the horn at 8.51 GHz are shown in Fig. 12. Details of the design, analysis, and measured performance are presented in [13].

Estimates for the peak electric fields in the horn indicate that the maximum level (about 6.9 kV/cm) occurs in the four feeding waveguides, which are 0.95 in. square. This should be compared to the present 450-kW WR-125 waveguide system (about 9.0 kV/cm) and the theoretical limit for a 0.95-in. square waveguide, which is about 2.1 MW. Resonant ring tests [14] will be used to evaluate the power performance of orthomode junctions and the horn. Should arcing become a problem, backup approaches include evacuating areas of the horn or pressurizing them with a dielectric gas such as sulfur hexaflouride (SF_6).

The second feed approach is similar to the existing X-band system now in operation on the 70-m antenna at Goldstone. The power from each of two klystrons is combined and channeled to a single feedhorn illuminating the

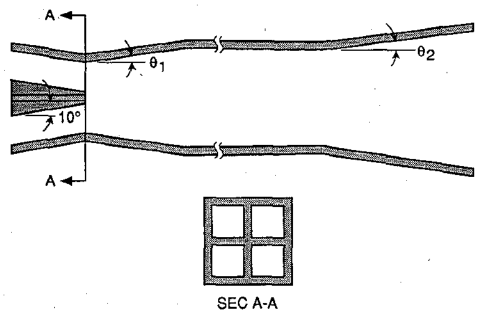


Fig. 11. 1-MW Multiflare Horn.

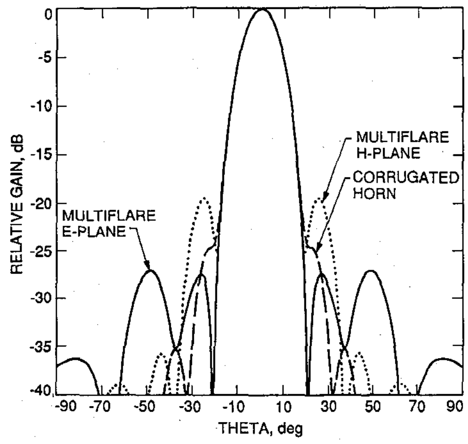
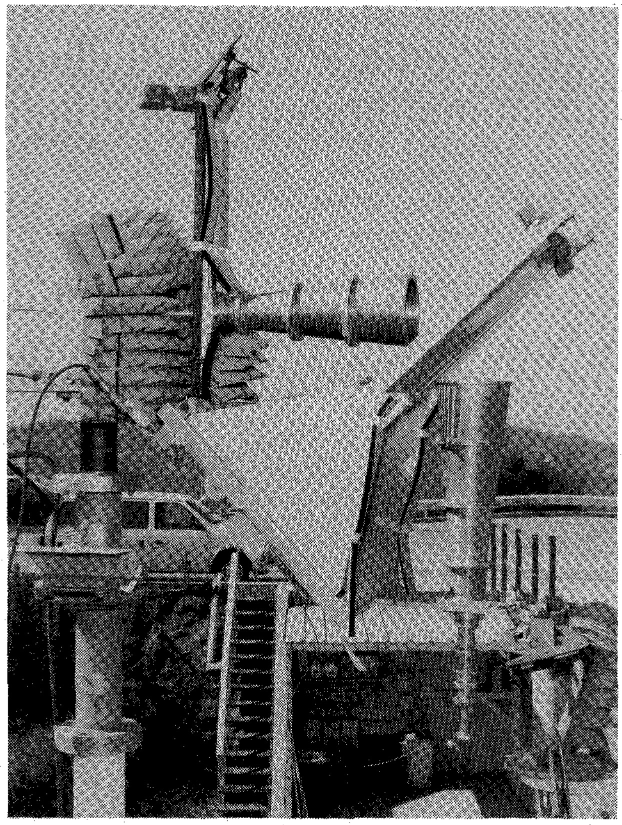


Fig. 12. 1-MW multiflare horn patterns at 8.51 GHz.

antenna. In the 1-MW version, each of these 500-kW signals from the transmission lines is channeled to one of two standard 22-dB corrugated feedhorns through a transmit/receive select switch. The two horns are physically orthogonal to each other and separated by the polarization grid. Fig. 13 shows the grid under test on the antenna range. This model consists of parallel bars spaced in such a manner as to allow a perpendicular linear signal to pass through virtually loss free and a parallel linear signal to reflect off the grid. The grid has been tested with a 500-kW signal in the transmission and reflection modes of operation. When one end of the grid element was allowed to expand due to temperature increase, the signal was able to pass through with no measurable effect on feedhorn gain or pattern. The reflected signal also showed no evidence of degradation. Peak temperatures of the grid were measured at 50° to 70° centigrade above ambient during the radiation tests. The temperature gradients across the grid were consistent with the Gaussian shape of the RF beam from the feedhorn.

The signal from the lower horn is polarized orthogonally to the elements of the grid, and passes through with little or no loss. The signal from the horizontal horn is polarized such that the signal is reflected off the grid. The result is the combining of the two orthogonal signals in front of the grid. With the correct phasing of these signals, a righthand or lefthand circularly polarized signal is radiated to the subreflector.


(a)

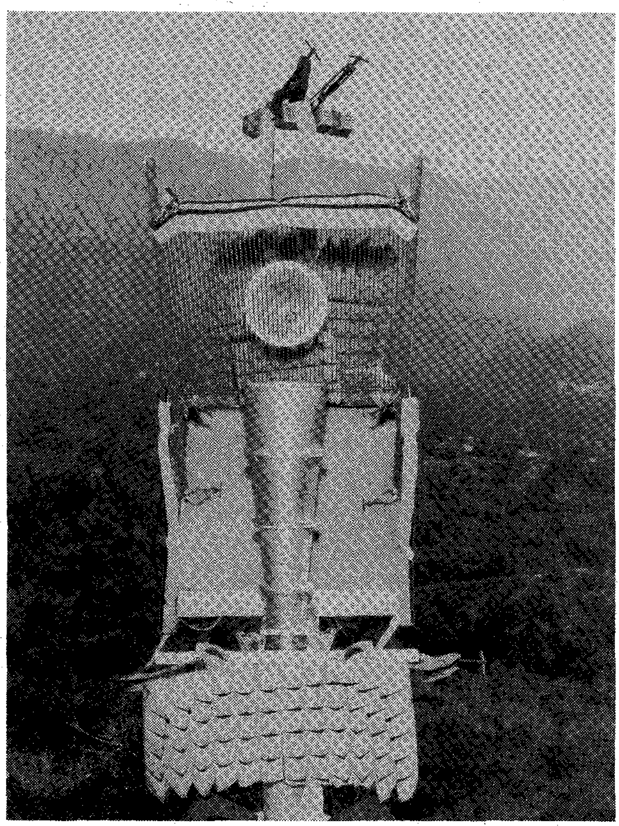

(b)

Fig. 13. Polarization grid under test on the antenna range.

The window at the aperture of each feedhorn is a concern at these high power levels. This window is used to maintain 4–6 ounces of positive pressure in the feed and transmission lines to prevent arcing from contamination in the system. The window is made of Kapton, a material known for its relative low loss and tensile strength but which has poor heat dissipation qualities. Special care is needed with the present system to prevent organic material from collecting on the window and creating localized heating. This heating can cause a failure of the window and contamination of the system.

Testing of a replacement quartz window with a thickness of 0.357 inches has shown certain advantages over the Kapton window. With 250 kW of RF energy the quartz material shows lower loss and better heat dissipation; as a result it operates at a lower temperature.

F. Beam Power Supply

A block diagram of the beam power supply is shown in Fig. 14. The 3-phase, 60-Hz power at 12.600 V is supplied to a commercial substation (Edison), which steps the voltage down to 2400 V. The power lines from the substation are run underground for the last mile before reaching the antenna site to prevent any interference that may be generated. Under critical operation, this 60-Hz, 3-phase, 2400-V power could be supplied by the diesel generators as well. This 2400-V, 60-Hz power is applied to the 4000-hp motor of the main motor/generator set.

This motor/generator set converts the 60-Hz power to 3-phase, 400-Hz, 2400-V power. The power is then conditioned by the transformer/rectifier, where the power is stepped up in voltage and rectified to supply 51 kV at 44 A dc to the four klystrons in the power amplifier. The design in this power supply will maintain output ripple under full load at less than 0.05%, and voltage regulation of 0.01%, with settling time of 200 ms.

This frequency conversion from 60 to 400 Hz might seem unnecessary, but it actually provides worthwhile technical and economic advantages. It isolates the power line from a crowbar of the dc supply and greatly simplifies line protection. It also isolates the supply from short-duration line voltage fluctuations and transients due to the large inertia of the rotating machines. The change from 60 to 400 Hz reduces all transformer and filter sizes and costs.

The ability of the beam to remain ripple free and tightly regulated, and to settle in 200 ms, will require a unique and state-of-the-art feedback control circuit. The design is in progress and the first approach is being tested. The supply also must be capable of withstanding the stress imposed on it when an arc occurs in any klystron and all the power is removed in 10 microseconds from all the klystrons as part of the system protective interlocks.

G. Cooling System

The cooling system provides a 2.5-MW cooling capacity for klystrons, focusing magnets, high-power microwave components, water loads, feed, and the transformer rectifier, including the motor-generator clutch. Basically, the cooling system is a closed loop that consists of a heat

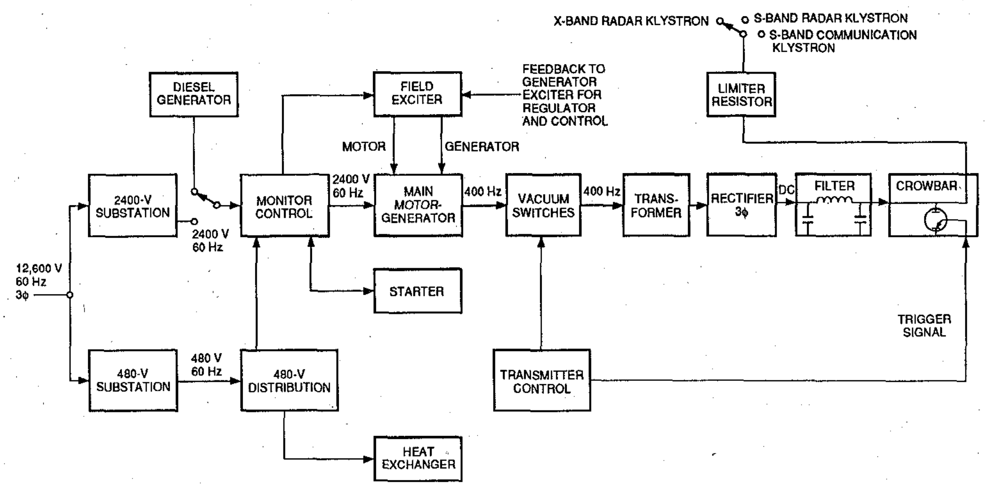


Fig. 14. Power supply block diagram.

exchanger, a distribution manifold, and all connecting piping. Coolant is circulated through the cooling system by the heat exchanger pumps. The coolant gains heat as it passes through the RF system (buffer amplifier, power amplifier, and microwave components) and loses heat as it passes through the heat exchanger. A purity loop is connected to the input of the heat exchanger to maintain the purity of the coolant. Resistivity of the coolant is maintained at 1–2 megohms.

As part of this transmitter modification, the pumps for the existing system will have to be upgraded, including replacing all of the 6-inch water lines, and a complex water-switching mechanism will have to be installed. The existing water-to-water heat exchanger will have to be changed to a liquid-to-air heat exchanger to improve the efficiency of the cooling system.

H. Monitor and Control

Operation of the 1-MW radar will be extensively automated. The control system will comprise an HP Industrial Vectra computer, two HP 38526 Data Acquisition and Control units, a frequency counter, and a multichannel power meter. All the instruments will be connected by an IEEE-488 interface bus, with a fiber optic extension between the control room and the feedcone area of the antenna at distance of 700 ft. The IEEE bus will also connect to the synthesizer in the exciter.

The monitor and control software will be written in Ada, a language especially designed for hardware control applications, and will make use of artificial intelligence principles to maximize the system functionality while maintaining a simple user interface. It will automatically keep long-term data logs to look for trends and predict failures before they can disable the radar. It will correlate data from different sources to distinguish between sensor problems and transmitter problems, and it will be able to calibrate the RF power calorimetrically to within 0.1–0.2 dB by precision measurement of the flow rates and temperature rises of the coolant in the water loads.

IV. Concerns

The general concepts presented here make it clear that a 1-MW radar transmitter will be a very complicated system, giving rise to several areas of concern. Of primary concern is the possibility of waveguide/feedhorn breakdown in a system using a standard 22-dB horn and waveguide. The system using the multiflare rectangular horn combines the full 1-MW of power inside the large throat section, thereby reducing the risk of arcing. The second approach sidesteps the problem of the full 1 MW in any waveguide at all by combining the power above the polarization grid. This approach also uses elements of the existing system that have been demonstrated at 450 kW.

The fundamental problem in the development of any of the high-power components is the lack of testing facilities capable of power levels well above the level of operation to ensure a safe power margin. In the development of this system, no 1-MW CW capability will exist until well into the program, when all four klystrons are delivered and operating as a unit. Resonant ring testing can be used for some components, but the most critical components, such as the feedhorn and the polarization grid, can be tested under full power only when the 1-MW capability exists in at least a test bed configuration.

Several areas of concern involve the 250-kW klystrons. Each system under consideration demands that the four klystrons have matched gain and phase characteristics over the band of interest. The tube-to-tube matching or repeatability must be determined. The first two tubes that have been delivered show promise, but time will tell if subsequent production of tubes will match as well. In order for each klystron to meet all requirements, the system must present a 1.05 to 1 VSWR. This will be a difficult requirement to meet.

The feedhorn window must be capable of handling 500 kW to 1 MW to meet the range of requirements described in this report. The Kapton windows are marginal. Quartz windows show promise but the final results and decisions depend on further development and testing with the high-power test facilities.

This transmitter system will be the most complicated transmitter in the field and will require special knowledge and care from the maintenance personnel at the site. Also of concern is the environment in which this system is to be installed. The present feedcone design offers limited space in which to install this system. To accommodate all radar functions and other radio astronomy equipment a larger feed module is recommended as an alternative to the cylindrical feedcone.

With the 1-MW radar system on the 70-m antenna the effective radiated power would be about 2.5 trillion watts and have a dynamic range of greater than 354 dB. This great sensitivity would allow the study of more distant astronomical objects with better resoluion than ever before. The asteroid program would benefit the most by increasing the number of small and distant objects than can now be detected by a factor of 4 to 7. Equally important is that many observations that are now only barely detected would be subject to much more refined observation and analysis. The determination of rotation and pole position, delay Doppler determination of figure, and high-resolution ranging for astrometrics would greatly benefit. The astrometrics program is especially important for the observation of newly discovered Earth-crossing objects to be sure they can be detected at the next apparition. Accurate ephemerides of these objects are essential to predict possible collisions with Earth.

Currently, one of the most important observation targets is Titan. At best, we can do primitive detections of this moon, but the 1-MW transmitter will allow better imaging, more accurate cross-section measurements as a function of rotational phase, and estimates of the scattering mechanism involved in the reflection process. These improved observations are needed to help define the Cassini spacecraft radar that will image Titan at the end of this decade.

References

[1] S. J. Ostro, "Planetary radar astronomy," *Encyclopedia of Physical Science and Technology*, vol. 10, pp. 612–634, 1987.

[2] R. F. Jurgens, "Earth-based radar studies of planetary surfaces and atmospheres," in *Proc. IEEE IGARSS '81 Conf. on Remote Sensing*, Washington, DC, June 8–10, 1981, p. 519. Also see *IEEE Trans. Geosci. Remote Sensing*, vol. GE-20, pp. 293–305, 1982.

[3] S. J. Ostro, R. F. Jurgens, D. K. Yeomans, E. M. Standish, and W. Greiner, "Radar dectection of Phobos," *Science*, vol. 243, pp. 1584–1586, 1989.

[4] S. J. Ostro, D. K. Yeomans, P. W. Chodas, R. M. Goldstein, R. F. Jurgens, and T. W. Thompson, "Radar observations of asteroids 1986 JK," *Icarus*, vol. 78, pp. 382–394, 1989.

[5] J. J. Plaut, R. E. Arvidson, and R. F. Jurgens, "Radar Characteristics of the Equatorial Plains of Venus from Goldstone Observations: Implications for Interpretation of Magellan Data," GRL, 17, #9.

[6] S. A. Hovanessian, *Radar Detection and Tracking Systems.* Dedham, MA: Artech House, 1973, ch. 11, sect. 5, pp. 11–22.

[7] B. Conroy and D. Le, "Multipurpose exciter with low phase noise," *TDA Progress Report 42-97*, Jet Propulsion Laboratory, Pasadena, CA, pp. 169–174, May 15, 1989.

[8] R. Cormier and A. Mizuhara, "250-kW Klystron amplifier for planetary radar," *IEEE Trans. Microwave Theory Tech.*, vol. 40, no. 6, June 1992.

[9] W. North, "Haystack Hill long range imaging radar transmitter," in *Proc. 13th Pulse Power Modulator Symp.*, 1978, pp. 247–253.

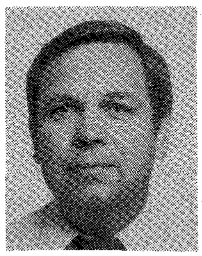
[10] H. R. Buchanan, "*X*-band uplink microwave components," JPL Tech. Report 32-1526, vol. XII, Jet Propulsion Laboratory, Pasadena, CA, pp. 22–24, December 15, 1972.

[11] K. R. Goudey and A. F. Sciambi, Jr., "High power *X*-band monopulse tracking feed for the Lincoln Laboratory long range imaging radar," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, no. 5, pp. 326–332, May 1978.

[12] J. A. Encinar and J. M. Rebollar, "A hybrid technique for analyzing corrugated and noncorrugated rectangular horns," *IEEE Trans. Antennas Propagat.*, vol. AP-24, no. 8, Aug. 1986.

[13] D. Hoppe, "A square multiflare horn with 1-megawatt CW power handling capability," *Microwave and Optical Technology Letters*, vol. 2, no. 11, pp. 400–404, Nov. 1989.

[14] D. J. Hoppe and R. M. Perez, "X-band resonant ring operation at 450 kW," *TDA Progress Report 42-93*, vol. Jan.-Mar. 1988, Jet Propulsion Laboratory, Pasadena, CA, pp. 18–26, May 15, 1988.



Arthur J. Freiley (M'72) was born in Ingelwood, CA on March 7, 1946. He studied at the California State Polytechnic University, Pomona, California where he obtained the B.S. degree in electrical engineering.

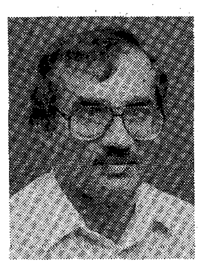
He joined the Jet Propulsion Laboratory in January 1970 where he has been active in the design and evaluation of large ground-based antennas for the NASA/JPL Deep Space Network (DSN). He has also served as the Cognizant Design Engineer for the Antenna Microwave Subsystem of the DSN. His current assignment is the Task Leader for the Megawatt Radar Transmitter development for the Goldstone Solar System Radar (GSSR).

Bruce L. Conroy received the B.S.E.E. degree from MIT in 1962 and M.S.E.E. from Caltech in 1963.

He joined the Jet Propulsion Laboratory in 1967 as an Engineer in the Spacecraft Transmitter Development group, designing frequency multipliers, amplifiers, filters and power combiners. Returning to night school in 1971, he received the J.D. degree from Loyola of Los Angeles in 1975. He joined the Transmitter Engineering Group in 1986 where he is involved the design of future transmitters, including the 1-MW *X*-band for planetary radar.

Daniel J. Hoppe received the B.S. and M.S. degrees in electrical engineering from the University of Wisconsin, Madison in 1982 and 1983, respectively.

He joined the Jet Propulsion Laboratory, Pasadena, CA, in 1984, where he is a Member of the Technical Staff. He is currently working toward the Ph.D. degree at the University of California at Los Angeles. His particular areas of interest are in electromagnetic theory and the numerical analysis of antennas and microwave components.



Alaudin M. Bhanji was born in Dar-es-salaam, Tanzania on February 14, 1951. He studied at the California Institute of Technology, where he obtained the B.S. and M.S. degrees in electrical engineering in June 1975, and 1976, respectively.

In 1975 he joined the Jet Propulsion Laboratory, Pasadena, CA, where he worked in the Laser Group engaged in research and development of Copper Halide Lasers. In 1979 he moved to the Transmitter Group at JPL, and became Technical Group Supervisor in 1988. The group develops high power ground based transmitters for deep space communication and planetary radar.