Development of a New 20kW CW Transmitter for 34-meter Antennas of NASA's Deep Space Network

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Abstract—A next generation of 20kW dual-band (S/X) transmitters was developed for NASA's Deep Space Network (DSN) 34m Beam Waveguide (BWG) Antennas. Innovations include additional X-band communication capability for High Earth Orbit (HEO) missions, new control algorithms, automated calibration, improved and expanded monitoring and diagnostics, reduced cabling, and improved maintainability.

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1. INTRODUCTION

NASA Mars missions require additional DSN support in the next two years and beyond. Most support will be provided using 34-meter Beam Waveguide Antennas. The existing antennas that support X-Band uplink are equipped with 4kW transmitters and those that support S-Band uplink have 20kW transmitters. The 4kW X-Band transmitters do not provide enough power for reliable uplink communication in emergency situations; the S-Band transmitters were implemented about 10 years ago and are being replaced to maximize commonality of equipment across the various antennas at a DSN complex. Support of the planned Mars missions and other critical DSN support requirements in late-2003 through early-2004 requires building and installing three 20kW S-band transmitters and six new 20kW X-band transmitters.

The new design is partially based on innovations described in [1] and proven by several years of successful operation of 20kW X/S-band transmitters implemented at the 70-meter antennas. The transmitters for 70-meter antennas retained the previously-designed cabling, analog control panels, and a legacy computer interface, which provided smooth transition from one transmitter generation to another. The new transmitters fully implement Ethernet communication between main subassemblies where it is necessary and economically reasonable. Manual control, light indications, and electronics circuit adjustments are minimized, deferring this task to the computer controller. The latter uses an

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inexpensive industrial computer assembled in a high-voltage power supply cabinet. There are also a few other configuration changes in the transmitter caused by differences in the layout of BWG and 70-meter antennas. The X- and S-band power amplifier cabinets have identical interfaces to the high-voltage power supply and now include all necessary instrumentation. The footprint of the new 20kW X-band power amplifier is approximately the same as the existing 4kW power amplifier. The newly designed S-band power amplifier is about 30% smaller than the old one and provides more conveniences for service and repairs. Maximum commonality between X-band and S-band power amplifier achieved by using identical sets of instrumentation, magnet and filament power supplies, filament transformers and rectifiers, and water manifolds including all instrumentation, cables, etc. The new power amplifier interface provides all safety features and information flow with dramatically reduced cabling. All of this significantly reduces costs of design, production, and lifetime support of transmitters

2. Transmitter Description

Technical parameters

The newly-developed transmitter delivers 20kW Continuous Wave (CW) power to the BWG feedhorn in the frequency range 7145-7235 MHz (X-band) and 2020-2110 MHz (S-band). Power in HEO range (7190-7235 MHz) may be limited for some antennas by high VSWR in the X/X/Ka feed (which was not designed for HEO uplink). The transmitter output power fluctuations are less than 0.1dB for 12H of operation. Low phase noise and low radiation beyond the assigned bandwidth imposed by uplink requirements are also met.

The transmitter consumes about 100 kW of power from the 60 Hz power grid. The water-cooling circuit is closed-loop and does not need any additional water supply. External transmitter assemblies like the Heat Exchanger and Motor-Generator are designed to withstand extreme temperature conditions recorded at the DSN complexes. The transmitter is controlled remotely and does not require operator presence during normal operation. In case of failure, most of transmitter subassemblies may be replaced in several minutes.

Major assemblies (See Figure 1)

The transmitter consists of the following major components:

- X-Band Power Amplifier (PA) Assembly
- S-Band Power Amplifier Assembly (for 3 of 6 stations)
- X-Band Water Manifold Assembly
- S-Band Water Manifold Assembly (for 3 of 6 stations)
- Water Manifold Switching Assembly (for 3 of 6 stations)
- Heat Exchanger (HE)
- High-Voltage Power Supply (HVPS) with embedded controller
- Motor Generator (MG) Assembly
- Motor-Generator Controller Assembly
- Warning Light Control (WLC) Assembly

The X-band PA is located in BWG antenna pedestal and provides amplification of the X-band exciter signal to any desired level between +53 and 74 dBm.

The S-band PA is also located in BWG antenna pedestal and provides amplification of the S-band exciter signal to any desired level between +53 and 74 dBm.

X- and S-band water manifold assemblies are located near the corresponding power amplifiers and distribute water to the different cooling circuits in the respective PAs, provide instrumentation for water flow and temperature control, collect discharged water, and return it to the heat exchanger.

The water manifold switching assembly is located near the S-band PA and directs water to the X- or S-band PA, depending which of them is in use. This assembly is installed only at the stations equipped with the both X- and S-band PAs.

The heat exchanger is located at ground level outside the antenna pedestal and supplies temperature regulated water to the transmitter.

The high voltage power supply assembly is located in the antenna pedestal and provides regulated DC power to the klystrons. This assembly includes the computer controller, protective circuits, interface for controlling all major assemblies, and interface for transmitter remote control.

The motor-generator is located in an outside shelter at ground level. It converts 3-phase 60 Hz power from the grid to the regulated 400Hz power supplied to the primary of HV transformer in the HVPS. The MG-controller, which is located in the same shelter, provides protection and control for the MG.

The warning light controller activates safety warning lights when the transmitter is radiating or when high voltage is on.

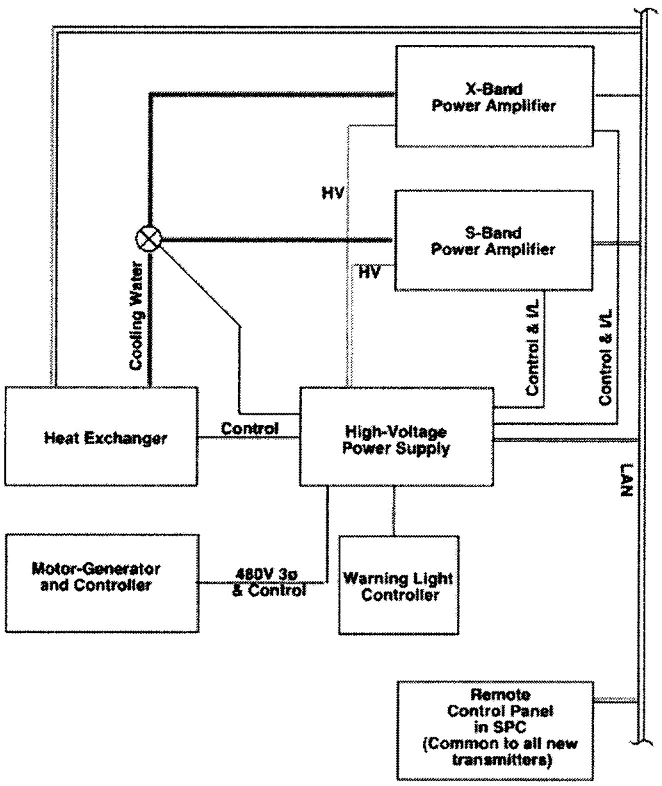


Figure 1. Block Diagram of 20KW S and X-Band Transmitter

3. Innovations and Performance

Innovations

The new BWG transmitter was designed after several years of successful operation of the 70-meter Uplink transmitters and implements most of the innovations discussed in [1]. It also implements quite a few new improvements, providing more reliable operation, easier service, a more modern interface, and full compatibility with the rest of the Deep Space Communication complex equipment. At the same time most of the functionally outdated or performance-limiting elements were excluded.

X-band klystron amplifier

The Klystron amplifier tube used in the X-band portion of the BWG transmitter has a 90 MHz bandwidth covering the Deep Space and HEO frequency range. The mechanical dimensions of the tube and its major electrical parameters are identical to the ones for the previously used narrow band tubes. The tube is located at the very bottom part of the X-PA rack, which makes replacement work much easier and allows simplification of the waveguide stack structure. In addition, the location also segregates the instrumentation from most of the cooling water supply in the event of a broken hose in the klystron cooling circuits.

Buffer amplifier

The new X-Band tube has lower gain compared with the older narrowband tube. This required the development of a new 5W solid-state buffer amplifier (SSA). It was decided to provide this SSA with water cooling, which reduced the size of the buffer amplifier assembly to half that of the old system. A heat sink with cooling passages is connected in series with the electromagnet cooling circuit and supplied with 45 deg.C water from the heat exchanger. Special temperature compensation circuitry stabilizes the buffer amplifier gain when the water temperature is below 45 deg.C during system start-up.

Power meter calibration

One of the disadvantages of the 70-meter transmitters was the need for periodic calibration of the commercial power meters. It was accomplished by manual connection of the power sensors to the power meter calibration port and performing the routine recommended by Agilent, the meters' manufacturer. This operation required access to the remote transmitter and could only be performed during the scheduled maintenance time. Manual connecting, zeroing and calibration of the two dual channel power meters required a one to two hours of maintenance time.

The new power meter assemblies in the BWG transmitters are equipped with remotely-controlled (via the transmitter controller) coaxial switches, which sequentially connect each power sensor to the meter calibration port. This operation is performed automatically during the initial start-up of the transmitter. It also can be performed upon operator request from the computer controller or any of the maintenance computers on the transmitter LAN. The operation completes automatically in about 30 seconds. The default position of switches is configured for operational measurements, so the introduction of these new elements did not affect the reliability of the transmitter. At the same time the accuracy of the power measurements and availability of the transmitter were significantly increased.

Filament supply circuit

The X- and S-band klystrons in the BWG transmitter are supplied with DC filament voltage to eliminate one of the sources of the low-frequency phase noise. Both PAs are equipped with a 400 Hz current-limiting filament transformer and rectifier that were designed to satisfy the requirements of both klystrons. This results in a significant reduction in the size of S-band transformer and provides common spares for transmitters.

Magnet supply circuit

The 20kW dual-band DSN transmitters implemented on the 70m antennas had a common linear power supply for both X-band and S-band electromagnets. This required an additional magnet current-range switching assembly, switching of current measuring shunts, custom cables to handle the relatively high currents (up to 20A), and switching of high current cables between X- and S-band PAs. The new BWG X- and S-band PAs are equipped with GPIB-controlled switching magnet power supplies located in cabinets close to the respective electromagnets. This arrangement not only reduces the number of custom-designed components and cables, it significantly increases availability of the transmitter because a fault in one of the supplies does not prevent the other PA from operating.

Remote AC power controller

The 70-meter 20kW transmitters are equipped with network (Ethernet) controlled power switches. Sometimes those switches hang-up, and require about two minutes for self-recovery. This problem was eliminated completely in the BWG transmitter by using a 28VDC signal to control an intermediate relay in the power distribution assembly.

Cabling

The 70-meter 20kW transmitters retained all traditional multiconductor cables (about 400 wires) needed to support the legacy interface. The new BWG transmitters are using dual fiber-optic cable for communications with the controller. Each PA is connected to the HVPS with high-voltage cable to provide beam voltage for klystron tube. The low current 28VDC signals: two wires for device loop, two wires for hard-wired interlock, and 28VDC return (ground), are the only wires needed to control the power amplifier. The legacy interface is retained only for external antenna interlock, heat exchanger, warning light controller, and motor-generator controller to keep those major assemblies interchangeable with previously-fielded units.

Computer Control Software

All DSN transmitters are controlled from remote signal processing centers via closed networks. In previous implementations, a computer system (hardware and software) performed low-level control of the transmitter (e.g., setting klystron beam voltage and drive to achieve a user-specified power) as well as high-level functions (e.g., interfacing to DSN operations and supplying monitor data to spacecraft customer. This all-inclusive system created significant problems in operation. For example, an initial calibration of a transmitter would take almost 8 hours to construct a reference table that the software used later to make setting beam voltage and drive faster. Even with this table, the old system would take several minutes to arrive at the proper combination of beam voltage and drive.

The software was partitioned into two sets: one that is concerned with high-level interfaces and communication with the operator and another that controls the transmitter hardware directly. The latter was implemented in the embedded controller in the high-voltage power supply. The interface between the two software entities provides an abstraction of transmitter for the high-level control software. (Nine commands: Power On/Off, High-Voltage On/Off, Interlock Reset, Saturated Operation On/Off, Set Forward Power, Stop Power Set, Enable/Disable RF Drive, Set Frequency, and Return All Values). At the same time, other elements in the interface (not used by the high-level control software) provide detailed information about the transmitter for maintenance personnel.

The physical implementation replaces two 85-conductor cables with an Ethernet cable. The embedded controller software detects loss of communication with the GPIB instruments (magnet and filament power supplies, two dual-channel power meters, and data acquisition unit), takes the transmitter to a safe state, and attempts to recover so long as control power is on. A separate hardware "watchdog" timer detects failures in the computer system and will cause the transmitter to shut down.

A SQL server is used to maintain calibration data and an event log as well as to store a variety of performance data once per minute. The calibration database retains a history of all changes to calibration parameters including date, time, values and comments. The current calibration data is converted to a local file for use by the embedded controller for reliability. The event log contains a record of all interlock occurrences and resets along with the data and time of occurrence. The SQL server is network-enabled and can be queried remotely given suitable access privileges.

The parameter logging function records the averaged value over the last minute of approximately 25 parameters. The parameters being logged is controlled by a parameter list in a text file. Even recording all parameters, the resultant files are relatively compact taking approximately TBD MB per hour of transmitter operation.

Saturation Algorithm

The embedded controller uses an algorithm to determine the optimum beam voltage and drive to achieve either saturated or non-saturated operation as directed by the high-level controller. The algorithm works as follows:

1. Set drive to a low level so that the klystron won't saturate at any voltage. (This is controlled by the calibration database.)
2. Set the beam voltage greater than necessary to produce the requested saturated power. (Also controlled by the calibration database.)
3. Raise the drive in steps to achieve the requested power. At each step measure the gain slope:

$$S = \left[\frac{(\Delta P_O / P_O)}{(\Delta P_I / P_I)} \right]$$

where

ΔP_O is the change in output power from the previous step,
P_O is the output power at the current step,
ΔP_I is the change in input power from the previous step,
P_I is the current input power, and
S is the slope which is:
1 for linear operation,

0 if saturated, and
<0 if over-saturated

4. If the output power at the current step is within 0.1 dB of the desired value and the slope is less than a database constant, the algorithm exits. Also, an error exit is taken if the slope is less than 0 since the klystron can be damaged by over-saturated operation for a long time.
5. Reduce the beam voltage and to back to step 3.

Setting power for unsaturated operation is the same, except the algorithm exits when the power is within 0.1 dB of the desired power, regardless of the slope.

The algorithm is robust in that it always converges if the starting drive is sufficiently low, the starting voltage is sufficiently high, and the hardware is capable of delivering the requested power in saturated operation. The algorithm is save in that decreasing voltage at a constant drive will never over-saturate. Increasing drive in small steps at a constant voltage allows over-saturation to be detected before it becomes dangerous to the tube. Experience has shown that the algorithm can converge to the desired power within three minutes without requiring the extensive pre-operation calibration previously needed.

Computer Hardware

The embedded BWG transmitter controller is located in the instrumentation bay of the HVPS cabinet. For local control it is equipped with a color display, keyboard and touch pad, CD-ROM and 3.5-inch floppy drive. Interface with the transmitter hardware is carried out via a 96-channel digital input/output board and an analog 16-channel input/2-channel output board.

The BWG controller is based on a relatively simple industrial computer rather than on an expensive and large VXI chassis. Two years of testing in a laboratory environment (which is similar to the controlled environment in a BWG antenna pedestal) showed that inexpensive industrial computers work reliably. Board replacement in the computer requires a very short time to change the hardware and for the board (via software) to perform an auto-calibration. Implementation of this controller allows significantly reduced maintenance and replacement costs.

High voltage power supply

The control, interface, and indication systems of the HVPS were fully upgraded. Most of those upgrades were achieved by replacing the analog control interface by an digital interface and by transferring the functions of the outdated analog control panels and indicator lamps to the embedded controller. A 25% reduction in size (elimination of a separate transmitter control rack) and significantly reduced internal and external wiring was achieved. The new HVPS control system includes three operator-activated hardware switches where safety is a concern: run/safe (high-voltage off) switch, motor-generator inhibit switch, and emergency shut-off switch.

Heat Exchanger

The design of the heat exchanger has been upgraded because hardware (pumps and programmable logic controllers (PLCs)) used on previous versions of the heat exchanger are no longer available and because recent extremely cold weather at the Madrid, Spain tracking station caused several heat exchangers to freeze resulting in broken water lines and loss of tracking support. DSN operations strongly encourages the use of non-glycol coolants to prevent spilling of hazardous material in the event of a coolant line rupture; therefore, pure, de-ionized water is used for transmitter cooling.

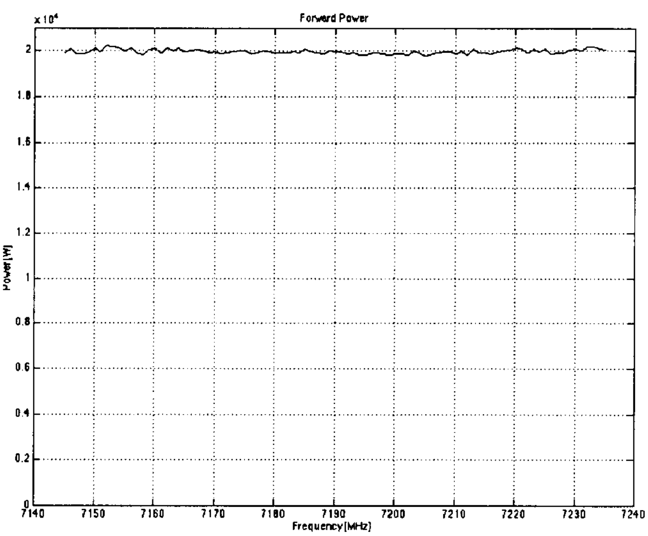
Investigation of various PLCs yielded the Siemens SIMATIC series as the only PLC capable of supporting extended temperature operation compatible with DSN requirements. The Siemens unit supports an Ethernet interface, so the control software was augmented to provide operating parameters for the heat exchanger to the embedded controller in the HVPS for logging. The controller provides regulation of transmitter cooling water at approximately 45 deg. C. When the transmitter is turned off, the PLC in the heat exchanger monitors ambient temperature and will start water circulating should the temperature fall within a few degrees of freezing. The heat generated by the pumps and friction in the piping is adequate to maintain the water throughout the system above freezing. As a backup, an auxiliary control card has been added to force the pumps to start when the ambient air temperature reaches –2 deg C should the controller fail to start them. In addition, the auxiliary control card will force the cooling fans to full speed should the temperature of the water start to rise above approximately 71 deg C.

PERFORMANCE

Initial test data for the transmitter shows the system to meet or perform better than its requirements. Data runs were performed in late September and early October 2002, just prior to delivery to the DSN site for installations. The following table and graph are indicative of the transmitters amplitude and phase stability. The following table shows the laboratory-measured performance compared with required performance.

X-Band Requirement	Measurement
Output Power 73 dBm +0/-1dBm	73±0.1 dBm
Power Output Stability	
10s: ≤0.1 dB	0.03 dB
60s: ≤0.1 dB	0.03 dB
100s: ≤0.1 dB	0.03 dB
1000s: ≤0.1 dB	0.04 dB
Saturated Stability ≤0.25 dB	
1 min	0.15 dB
10 min	0.16 dB
1 hr	0.17 dB

Unsaturated stability ≤ 1dB	
1 min	0.29 dB
10 min	0.31 dB
1 hr	0.31 dB
Phase stability (Doppler Error)	
60s: ≤23 deg	0.13 deg
12 h: ≤295 deg.	2.64 deg
Group Delay Stability: ≤0.7 ns/12h	0.37 ns
Allan Deviation	
1s: 1.2 e-13	
10s: 1.7 e-14	1.70E-15
1000-3600s: 1.2e-15	4.00E-17
Phase Noise	
1-10Hz: -53dBc/Hz	-75 dBc/Hz
10 Hz-1.5 MHz: -63 dBc/Hz	-63 dBc/Hz



Conclusions

A new capability is now being implemented throughout the Deep Space Network that brings 20KW X-band uplink to the 34meter beam waveguide stations and an upgraded S-band capability as well. Enhanced commonality, simplified TCP/IP-based control interfaces are employed in this dual transmit capability as well as enhanced data capture and reporting capability. This system will improve the reliability, availability and maintainability of the DSN 34m Beam Waveguide transmitters consistent with the operational requirements of deep space communications missions sets and scenarios and in particular, for the upcoming Mars2003/2004 "overload" of missions expected and throughout this decade.

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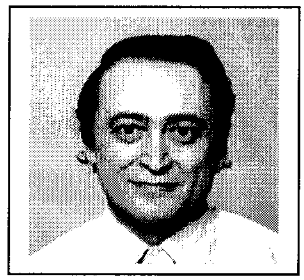
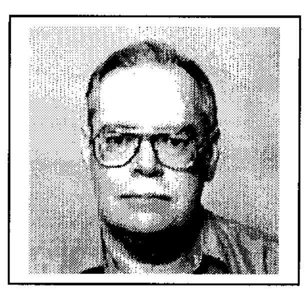
BIOGRAPHIES



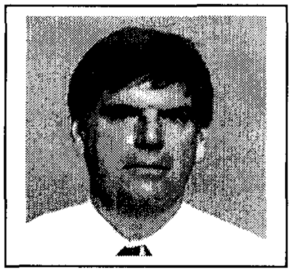
Yakov Vodonos received his BS degree in Electronics from Moscow College of Radio Equipment in 1965, MS degree in Physics and Mathematics from Moscow Engineering Physics Institute in 1971, and Ph.D. degree in Technical Sciences from Moscow Aviation Institute in 1992. In his position as a Senior RF and Microwave Engineer in the Ground Communication Section in JPL he is the Cognizant Development Engineer for the High-Voltage Power Supply portion of the transmitter described in this paper.
His previous experience includes work in the Isotope Products Laboratories (Burbank, CA) and in research institutes in Russia as a Senior Scientist in the area of low-temperature plasma, vacuum electron tubes, magneto-hydrodynamic (MHD) generators, and as a Lead Engineer for high power microwave generators, modulators, and other major assemblies for radars, particle accelerators, ion implanters, etc.
He is the author or co-author of two patents and of over 40 technical reports and journal articles, including five published in the USA.



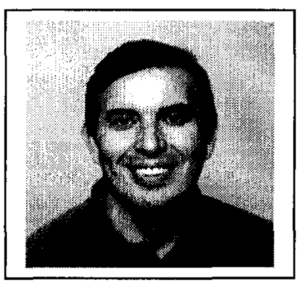
Bruce L. Conroy has received a B.S. degree from MIT, a M.S. degree from Caltech and a J.D. degree from Loyola University of Los Angeles.
He has been employed as a microwave engineer by the Jet Propulsion Laboratory since 1967.

Timothy Cornish received a B.S. degree in Electrical Engineering from Illinois Institute of Technology in 1995. He has been employed in private industry in the high power transmitter field for over 15 years in positions ranging from Design Engineer to Engineering Department Manager. During that time he was responsible for system engineering and project management in the development of the 4 kW X-band High Power Amplifier currently in use in the Deep Space Network 34m Beam Waveguide Stations.
Timothy joined the Jet Propulsion Laboratory in 2000 as a Transmitter Design Engineer in the Communications Ground Systems Section and is currently Subsystem

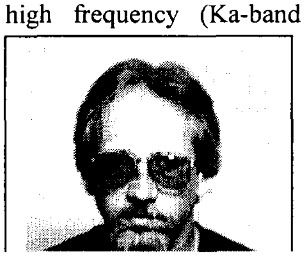
Engineer for the Deep Space Network Uplink Subsystem. In his position as Transmitter Design Engineer he was responsible for the design of the X-Band High Power Amplifier described in this paper.



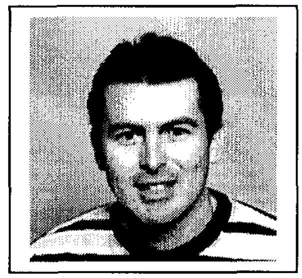
David L. Losh received the B.S. degree in physics from Case Institute of Technology, Cleveland, OH, in 1970, and the M.S. degree in computer science from University of Southern California, Los Angeles, in 1980. In his position as a Senior Telecommunications Engineer in the Communications Ground Systems Section, he is the Engineering Manager for the 20-kW transmitters described in this paper. Previous work at the Jet Propulsion Laboratory, Pasadena, CA, includes Task Manager for a microwave-powered aircraft to provide telecommunications services to sparsely populated areas and experiment director for a phased-array coherent microwave power uplink system.



Arnold Silva received the B.S. degree in 1981, from the California State University at Los Angeles, California and the M.S. degree from the California State University at Northridge, California in 1987, both in electrical engineering. In 1981, he joined the Transmitter Group of ITT Gilfillan and was involved in the design of high power modulators, power converters and control circuits for the company's major radar programs. While at ITT, he was project engineer for the development of the solid-state (FET based) modulators requiring the paralleling of hundreds of FET's in a high power pulsed radar application. From 1989 to 1993, he was employed as an Engineering Specialist of Whittaker Electronic Systems engaged in the design, simulation and analysis of radar transmitter systems and subsystems, for both classified and unclassified programs. His designs have involved development of very high power, low phase noise transmitters (pulsed and CW). In 1993 he joined the Jet Propulsion Laboratory as a Member of the Technical Staff in the Transmitter Engineering Group. He has designed ultra phase and amplitude stable high-voltage power subsystems and RF subsystems for the S-band and X-band Deep Space Network (DSN) klystron-based transmitter uplinks. These systems range in power from 200W CW up to 500 KW CW X-band systems. In December of 1997, he assumed position as Group Supervisor for the Transmitter Engineering Group and oversees a team of engineers involved in multifaceted aspects and thrusts in high-power high frequency (Ka-band through W-band) transmitter technology efforts.



Gregory McDowall has an AS degree in electronics. He has been with the Jet Propulsion Laboratory since 1996, where he works in the Transmitter Engineering Group of the Communications Ground Systems Section. He is the Cognizant Development Engineer for the 20 kW S-Band PA described in this paper. He is responsible for S-band transmitter developments ranging from 200 W to 400 kW. Prior to joining JPL, he was the transmitter subsystem engineer at the Deep Space Network (DSN) Goldstone tracking facility near Barstow, CA for twenty years. He also served in the U.S. Navy as an Electronic Technician (Radar), Second Class.



Juan J. Ocampo received his B.S. degree in electrical engineering in 1995, and M.S. degree in Communication and Microwave Engineering in 1998 from California State Polytechnic University, Pomona, CA. As an engineer at the Jet Propulsion Laboratory in the Communications Ground Systems Section, he has supported development and testing for the High-Voltage Power Supply discussed in this paper as well as an 800 W Ka-band transmitter to support Radio Science studies with Cassini. Previous work at JPL includes Cognizant Development Engineer for the 20 kW S-Band Beam Waveguide transmitters and design engineer for an X-Band QPSK modulator for spacecraft communications applications.

Antonio M. Santos attended University of Maryland and Johns Hopkins University.
Over the past 35 years, Tony has held positions at Johns Hopkins Applied Physics Lab and at Whittaker Electronics where he specialized in high-power transmitters for radar applications. In his work at JPL, he is the Cognizant Development Engineer for the Heat Exchanger described in this paper.