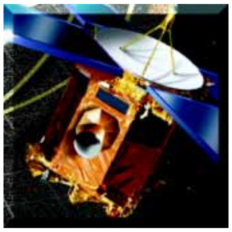

The NEAR Spacecraft RF Telecommunications System

Robert S. Bokulic, M. Katherine E. Flaherty, J. Robert Jensen, and Thomas R. McKnight

An X-band telecommunications system developed for the Near Earth Asteroid Rendezvous (NEAR) spacecraft represents an unmatched combination of performance, innovation, and cost-effectiveness for a deep space mission. It centers about two redundant X-band transponder systems that provide the command, telemetry, and tracking functions. Despite a tight development schedule, a significant amount of new technology has been used in the system. Included in the design are the most recent developments in transponder hardware, an X-band solid-state power amplifier (a deep space "first"), and efficient microstrip patch antennas. During spacecraft emergencies, a microstrip fanbeam antenna is used as part of a unique Earth acquisition algorithm. Postlaunch measurements have verified that in-flight performance closely matches predicted performance.
(Keywords: Deep space transponders, Fanbeam antenna, NEAR, Patch antenna, Solid-state power amplifier, Telecommunications, X-band.)

INTRODUCTION

The telecommunications system design for a typical deep space probe is driven by mission design. Not only does the distance between the spacecraft and Earth vary, but the geometrical relationships among the spacecraft, Earth, Sun, and destination object(s) also vary, making the antenna pattern requirements highly dependent on mission design.

The Near Earth Asteroid Rendezvous (NEAR) mission profile calls for a cruise period of 3 years, including a solar conjunction in February 1997, a flyby of the main belt asteroid Mathilde in June 1997, a major trajectory correction maneuver in July 1997, and an Earth swingby in January 1998. Having accomplished these milestones, NEAR will rendezvous with the asteroid 433 Eros in January 1999 and eventually go into orbit around it.

The spacecraft is designed for simplicity by configuring the high-gain antenna (HGA) and solar panels so that they are nongimbaled and pointed along the same axis. This arrangement is made possible because the mission trajectory design keeps the Sun–probe–Earth (SPE) angle within 40° for most of the mission (Fig. 1).

The NEAR telecommunications system had to simultaneously satisfy the goals of low power, low weight, low cost, and an extremely short delivery schedule (27 months from start to launch). The primary requirement was to provide a science data return

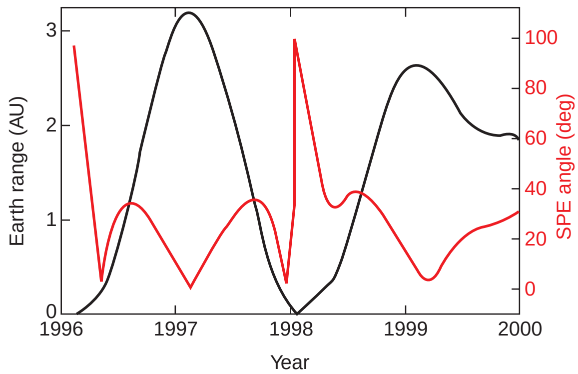

Figure 1. Earth range and Sun–probe–Earth (SPE) angle for the NEAR mission.

of at least 85 megabits/day from the asteroid. This equates to a downlink data rate of at least 2.9 kbps, assuming one 8-h deep space network (DSN) pass per day. The telecommunications system also had to be fully redundant and provide a dependable command link and a high-quality Doppler tracking capability. The DSN 34-m high-efficiency and beam waveguide antennas were baselined for all phases of the mission except critical periods and emergencies, during which the 70-m dishes would be used.

TELECOMMUNICATIONS SYSTEM DESIGN

For the NEAR telecommunications system (Fig. 2), the X-band frequency region (7.2-GHz uplink/8.4-GHz downlink) was chosen over S-band to maximize the data rate and tracking capabilities and to minimize the size of the HGA feed. Redundant, state-of-the-art transponder systems (discussed in the next section) are central to the design. These systems are connected to several antenna types to provide a variety of coverage patterns for the mission (Fig. 3).

The HGA is a 1.5-m-dia. dish intended to supply the science data return at the asteroid. Its pencil beam gives coverage whenever the spacecraft is pointed toward Earth. The fanbeam antenna has a medium-gain capability for portions of the mission when the distance to the Earth is large and the HGA cannot be pointed earthward. It has an important role in the recovery of the spacecraft during emergency situations. The low-gain antennas (LGAs) supply hemispherical coverage in the forward and aft directions for portions of the mission when the spacecraft is relatively near Earth. To save weight and minimize mechanical complexity, coaxial cabling is used for all RF interconnections instead of waveguide.

To minimize complexity, the mission uses a select set of bit rates: two uplink data rates (125 bps for normal operations and 7.8 bps for emergency operations) and eight downlink data rates (six between 1.1 and 26.5 kbps for normal operations using the HGA and two at 39.4 and 9.9 bps for cruise operations and safe-mode recovery using the fanbeam antenna). Once the spacecraft reaches the asteroid, the downlink data rate will vary from 4.4 to 8.8 kbps (Fig. 4). Occasional use of the 70-m DSN antennas will permit data dumping at

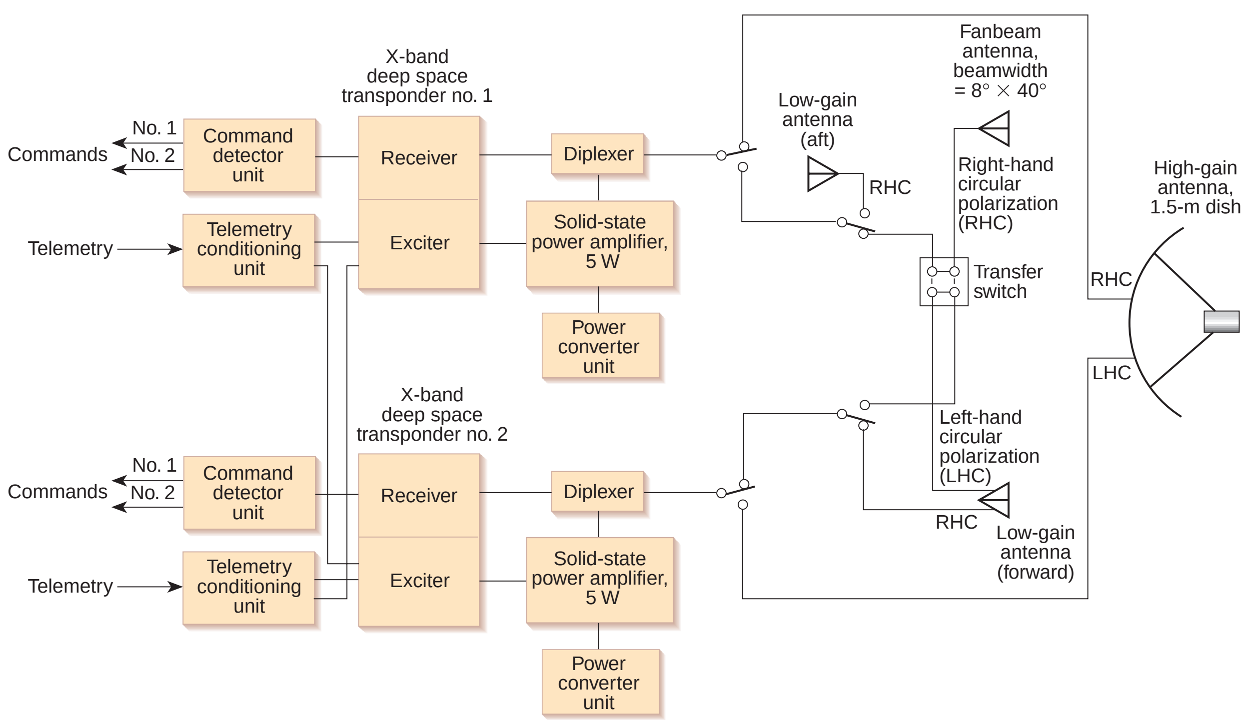

Figure 2. Block diagram of the NEAR telecommunications system (switches shown in cruise configuration).

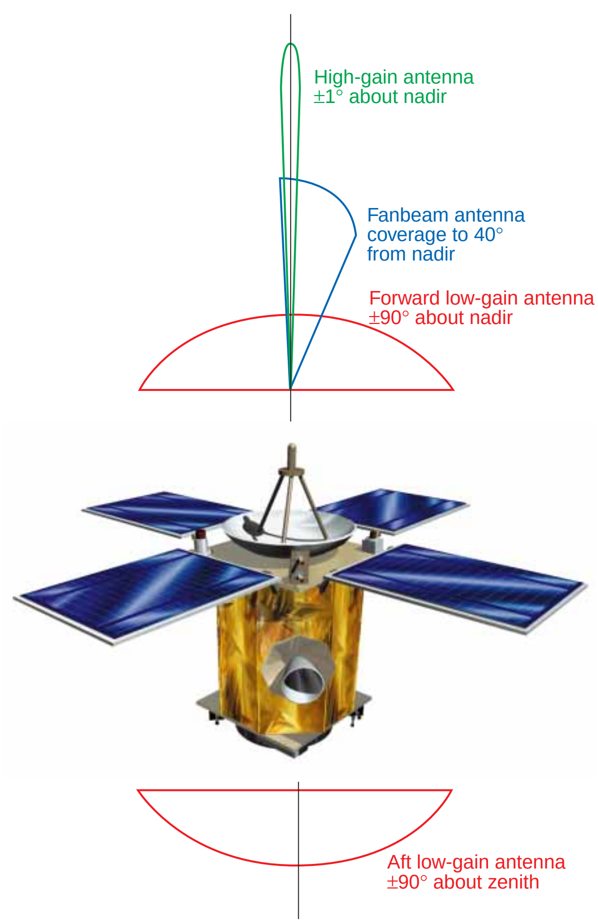

Figure 3. NEAR spacecraft antenna coverage.

17.6 and 26.5 kbps. Two convolutional codes are incorporated into NEAR: a rate 1/2, constraint length 7 code for cruise and emergency operations and a powerful rate 1/6, constraint length 15 code for asteroid operations. In all cases, the symbols are concatenated with a Reed-Solomon 8-bit (255,223) block code. The NEAR telecommunications system takes advantage of the newly deployed Block V digital receivers in the DSN.

TRANSPONDER SYSTEM TECHNOLOGY

As shown in Fig. 2, the Motorola transponders are used for command reception, telemetry transmission, and coherent tracking. These units were developed for the Cassini program (NASA's mission to Saturn) under sponsorship from the Jet Propulsion Laboratory (JPL) and are being flown for the first time on NEAR. To condense the packaging and enhance performance, surface mount technology is used extensively in the transponders, along with technologies such as dielectric resonator oscillators, surface acoustic wave oscillators, and high electron mobility transistors. The transponders are easier to produce than previous designs owing to a significantly reduced number of unique hybrid designs and RF modules.

The RF output of the transponder is amplified to a 5-W level by an APL-developed solid-state power amplifier (SSPA, Fig. 5). The use of solid-state X-band power amplification is a first for a deep space mission, breaking with the traditional traveling-wave-tube amplifier approach. The unit incorporates metal-semiconductor field-effect transistor technology with open-loop gain compensation and is powered by an external power converter unit.

Baseband data conditioning is accomplished by two components: the command detector unit (CDU) and telemetry conditioning unit (TCU). The CDU design was developed by JPL for the Cassini program. Exact

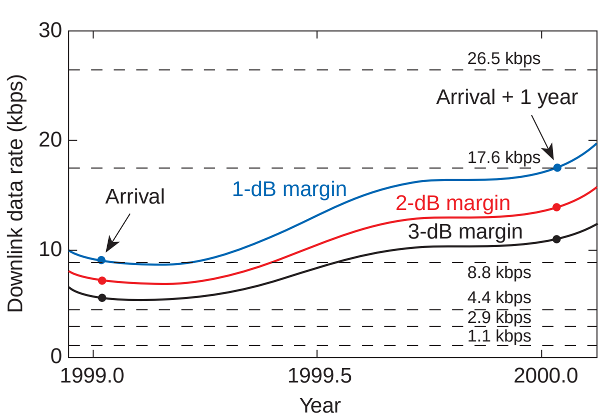

Figure 4. NEAR downlink data rate capability at the asteroid assuming use of the rate 1/6, constraint length 15 convolutional code and a 34-m ground antenna. These data hold for 90% of weather conditions. Ground antenna elevation angle = 20°.

Figure 5. The NEAR X-band power amplifier. This unit represents the first use of solid-state power amplification at X-band on a deep space mission. (Photograph courtesy of designers Roy Sloan and John Penn.)

copies of that design, which incorporates uplink subcarrier demodulation, bit detection, and synchronization functions onto a single application-specific integrated circuit chip, are being flown on NEAR. The TCU was built for NEAR by APL and is used to set both the downlink mode (direct or subcarrier) and the modulation index in each mode. In the direct mode, symbols are sent directly to the transponder for modulation onto the carrier at a phase modulation index of 1.2 rad. In the subcarrier mode, low-rate symbols are modulated onto a 23.4375-kHz square-wave subcarrier before being sent to the transponder for modulation onto the carrier at a phase modulation index of 0.9 rad. This index was selected to optimize performance at the 9.9-bps downlink bit rate. Most digital functions of the TCU are incorporated onto a field-programmable gate array. (Table 1 gives a power and weight breakdown for the NEAR telecommunications system.)

ANTENNA TECHNOLOGIES

To minimize weight, the 1.5-m HGA reflector is constructed with a graphite-resin material on a Nomex honeycomb core. The feed is a choke ring horn with a septum polarizer to provide dual-frequency, dual-polarization capability. The overall efficiency (effective area/physical area) of the antenna is 63% at 7.2 GHz and 58% at 8.4 GHz. Co-located on the feed assembly are the forward LGA and a magnetometer. The presence of the magnetometer required careful selection of materials for the feed assembly and coaxial cables, including nonmagnetic RF connectors made with beryllium copper.

The LGAs provide hemispherical coverage along the forward and aft spacecraft directions and are extremely lightweight at 90 g each. The antennas are constructed as dual-frequency stacked microstrip patches on Rogers thermoset microwave material (TMM). This substrate material is highly stable over temperature and provides a relatively hard, yet machinable, surface. Dual polarization is made possible through separate stacked patches on the same substrate (Fig. 6). Each LGA yields a peak gain (+6 dBic) and beamwidth comparable to a horn antenna at a fraction of the weight. The forward LGA is located on the HGA feed to minimize reflections from the spacecraft. Interestingly, a null in its pattern occurs at about 15° off boresight owing to backlobe radiation that is reflected and focused by the HGA reflector.

The fanbeam antenna has proven useful for many scenarios, especially recovery from emergency situations. It incorporates two microstrip patch arrays on a single substrate to give dual-frequency, right-hand circular polarization capability (Fig. 7) and provides wide-plane coverage out to 40° from the spacecraft's *z* axis, with a narrow-plane 3-dB beamwidth of about 8°. The peak uplink and downlink gains are 18.1 and 18.8 dBic, respectively. This antenna is also built on Rogers TMM substrate material. A slip-pin arrangement was designed to prevent thermal working of the RF connector/microstrip interface. The fanbeam antenna's development schedule was accelerated considerably using a tabletop circuit milling machine instead of chemical etching for iterating the design; each design iteration took only 4 to 8 h to perform. The fanbeam antenna weighs 465 g, including an aluminum backing for the substrate material. It has been a workhorse for the mission, providing low bit-rate downlink communications without having to slew the HGA toward Earth.

Table 1. Power and weight breakdown for the NEAR telecommunications system.

Component	Nominal bus power (W)	Weight (kg)	Notes
X-band transponder	9.1[a]	4.0	
CDU	1.0	0.4	Power number includes 79% efficient power converter in transponder
TCU	3.0	0.8	
SSPA	34.0	0.8	Power number includes 80% efficient external power converter unit
External power converter unit for SSPA	0	1.3	
Diplexer	0	0.1	
Coaxial switch assembly	0	0.6	Includes all five switches
HGA	0	6.3	Excludes magnetometer and LGA
Fanbeam antenna	0	0.5	
LGA	0	0.1	

Note: Values are per unit unless otherwise noted.

[a] Combined exciter and receiver power of 2.5 and 6.6 W, respectively.

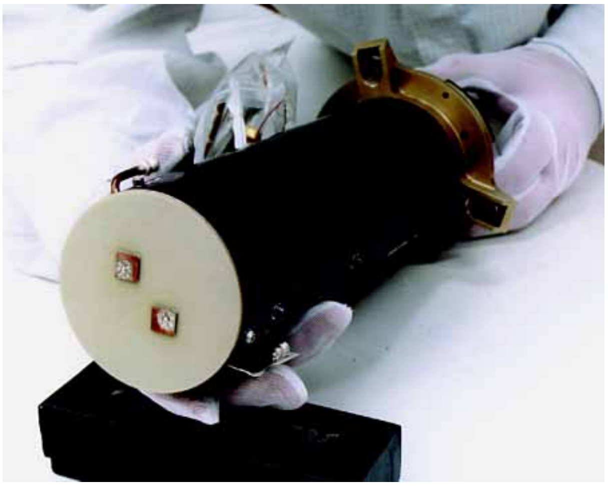

Figure 6. The NEAR LGA mounted at the end of the HGA feed. The antenna incorporates two dual-frequency stacked patches, one for each polarization. (Photograph courtesy of designer Allan Jablon.)

IN-FLIGHT PERFORMANCE

The in-flight performance of NEAR's telecommunications system has closely matched prelaunch predictions. The special nature of a deep space probe requires careful monitoring of RF signal strengths and spacecraft oscillator frequencies. Uplink and downlink signal strengths are tracked weekly, and the transponder receiver and auxiliary oscillator frequencies are tracked monthly.

Figures 8 and 9 show a portion of the signal strength history when the spacecraft was receiving and transmitting through the HGA and fanbeam antenna, respectively. Experience has shown that the measured signal levels are usually within 1 dB of predicted values. The most noteworthy exception occurred during mission days 22 through 38 when the geometry of the mission resulted in the Earth direction falling near a null in the fanbeam antenna pattern. In this case, the predictions were less accurate because prelaunch measurements of the antenna pattern (made on a mockup of the spacecraft) were less representative of the actual in-flight pattern near the pattern null.

SUN-SAFE MODE RECOVERY

One of the more challenging aspects of the telecommunications system design was the recovery procedure for the spacecraft under emergency conditions. In the event of a serious anomaly (e.g., low bus voltage), the spacecraft is autonomously pointed at the Sun and begins a 2°/min rotation about the spacecraft–Sun axis (the z axis) until contact with the Earth is made. Because of the large distances involved (up to 3.2 AU) and the relatively low transmitter power, a medium-gain antenna must be used to establish Earth communications. The fanbeam antenna provides a radiation pattern that extends from the z axis to approximately 40° off the z axis. As the spacecraft rotates, a beacon signal emitted by the fanbeam will eventually sweep through the Earth direction and be detected on the ground. With knowledge of the rotation rate, ground controllers can then send a "stop rotation" command one revolution later. When the spacecraft roll is stopped, the downlink is modulated with low-rate data (39.4 or 9.9 bps), and troubleshooting can commence. For portions of the mission when the SPE angle is greater than 40°, the Earth range is sufficiently low that commanding can be done through the forward LGA, regardless of rotation phase.

During the weekend of 17 and 18 August 1996, the scenario just described was tested when the spacecraft went into Sun-safe mode. This occurred at an SPE angle of 34° and an Earth range of 1.3 AU. The downlink beacon was observed for about 12 min every 3 h as it emerged from the receiver noise floor (−170 dBm), peaked at −159 dBm, then disappeared back into the noise floor. A stop rotation command was sent successfully, with the peak of the fanbeam pattern oriented closely toward Earth.

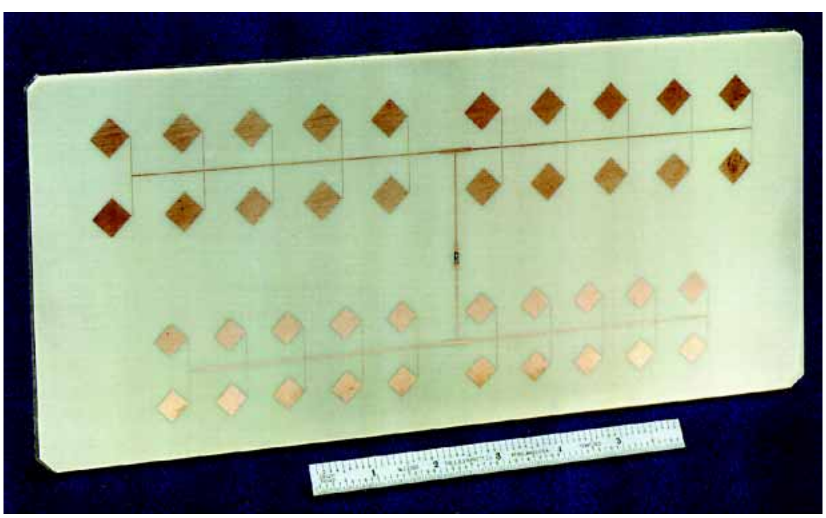

Figure 7. The NEAR fanbeam antenna. The series-fed elements provide improved efficiency over corporate-fed elements. The uplink and downlink arrays are combined with a microstrip diplexer. (Photograph courtesy of designer Jeffrey Sinsky.)

SUBSYSTEM TEST AND CHARACTERIZATION

The design goals for the RF ground support equipment (GSE) were to provide (1) a capable and cost-effective way to test the RF telecommunications system during subsystem integration and (2) RF

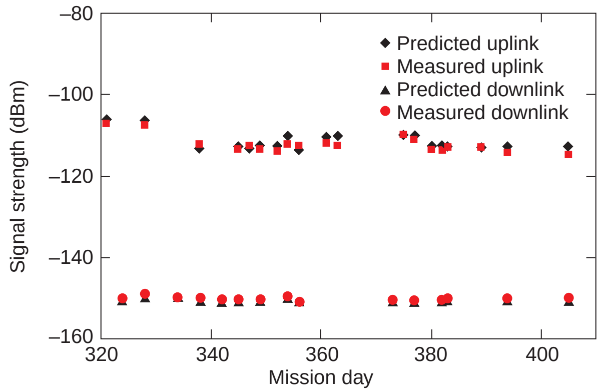

Figure 8. Uplink and downlink signal strengths for the NEAR spacecraft while transmitting and receiving through the HGA. Predicted and measured values are shown as a function of mission time.

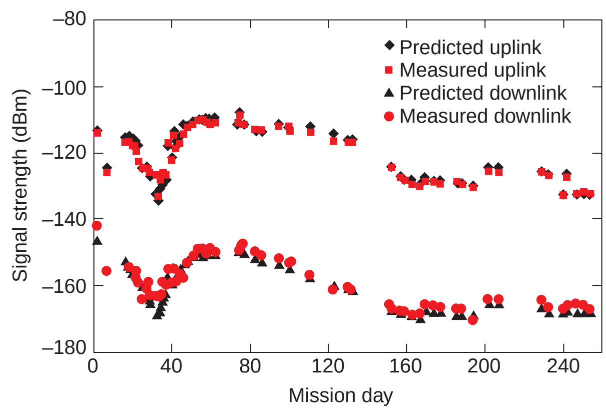

Figure 9. Uplink and downlink signal strengths for the NEAR spacecraft while transmitting and receiving through the fanbeam antenna. Predicted and measured values are shown as a function of mission time.

communications to the spacecraft during spacecraft integration and test activities. A significant challenge of the design was to ensure that the equipment could receive deep space signaling formats without incurring prohibitive costs. The resulting design is a combination of off-the-shelf and special-purpose equipment with technical innovations in several key areas.

The RF GSE provides uplink and downlink RF interfaces to the flight subsystem. A split-channel receiver system, developed by Microdyne, supplies carrier threshold performance that is superior to traditional telemetry receiver designs. In addition, the RF GSE can decode the rate 1/6, constraint length 15 convolutional coding employed by NEAR. The decoder design, which was realized on a single VME 6U card, performs code inversion at high signal levels. This is made possible by synchronizing a local encoder with the received encoded frame sync word and performing hypothesis testing on correlations between the local encoder output and the input symbols (developed by Mark Simpson and Ed Mengel of APL). This innovation permits testing at the spacecraft level without requiring a complicated decoder. The GSE also allows for Reed-Solomon decoding, thus yielding bit error rate (BER) measurements of the concatenated-coded downlink data. Uplink BER testing is accomplished with a software BER tester (developed by Dan Minarik of APL and Orbital Sciences Corp.). This tester counts and updates errors on a frame-by-frame basis, giving the user continuous insight into the performance at low data rates.

FUTURE TECHNOLOGY DEVELOPMENT

Development of the NEAR telecommunications system has led to the identification of several key areas where technology improvements can enhance the performance of deep space missions. For example, room exists for substantial integration and simplification of the transponder. APL is pursuing an approach to break the unit into simpler transmit and receive functions that can be integrated onto cards in an integrated electronics module. This approach is being used for the RF system for NASA's TIMED (Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics) spacecraft currently being designed at APL. Portions of the command and data handling system are integrated onto the cards along with the RF circuitry (e.g., the command receiver card also contains a real-time command decoder). For applications that require Doppler tracking, the cards use a highly accurate noncoherent navigation technique recently developed at APL. This innovation provides accuracy suitable for deep space missions (< 0.1 mm/s) and is compatible with existing ground station assets.

Room also exists for substantial improvements in SSPA efficiency. The overall efficiency (RF output power divided by 28-V bus input power) of X-band SSPAs using today's GaAs field-effect transistor (FET) technology is typically 15 to 25%. The goal over the next 5 years is to double this range, thus potentially doubling the science return of future missions. These efficiency values can be improved through the use of heterostructure FET, heterojunction bipolar, and pseudomorphic high electron mobility transistors.

Finally, NEAR has shown that microstrip antenna technology provides a lightweight, low-cost alternative to conventional antennas for deep space missions. Further technological advances, such as aperture feeding of the elements, will make large arrays more efficient and easier to fabricate. Such advances will open the door to the use of this technology for electronically steered HGAs.

ACKNOWLEDGMENTS: The NEAR program is sponsored by the NASA Office of Space Science. The authors thank all the members of the RF Engineering Group (formerly the Microwave and RF Systems Group) at APL who worked so hard on this challenging project. This work was supported under contract N00039-95-C-0002 with the U.S. Navy.

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