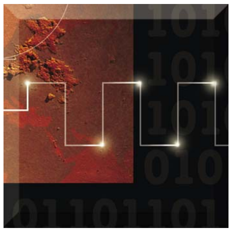

A Decade of Advancements in Spacecraft Communications Technology at APL

Robert S. Bokulic

The past decade has seen a rapid transition of new spacecraft communications technology into flight programs at APL. Key technologies have been transitioned from concept to flight implementation on a timescale as short as 4 years, resulting in considerable benefits to flight missions. The science return of the MESSENGER mission to Mercury has been doubled through the infusion of circularly polarized waveguide antenna technology. The New Horizons mission to Pluto has been enabled through the development of a low-power digital receiver that has reduced power consumption by 70% relative to current command receiver technologies. The distance over which the New Horizons mission can precisely perform Earth-to-spacecraft ranging has been extended by a factor of 10, enabling a medium-gain antenna to be used for routine ranging operations out to Pluto and beyond. These accomplishments and others have been realized in part by the close coupling between communication systems engineering and technology development within the APL Space Department.

INTRODUCTION

Spacecraft communications engineering and RF technology have historically been areas of strong capability for APL, beginning with the inception of the Space Department in 1959. This early era was marked by innovation; the industrial technological base was still evolving so new developments were required in many areas. One example was the APL ultrastable oscillator (USO), known today for its uniquely stable Allan frequency deviation of $\sigma_y = 2 \times 10^{-13}$ over 10-s intervals. The USO was developed to meet the needs of the Navy's Transit satellite navigation system, which depended heavily on the frequency stability of its spacecraft oscillators to derive the VHF and UHF downlink signals required for accurate surface navigation. Another example was the VHF command receiver flown on early APL satellites that consumed just 120 mW of power. It was needed to provide robust command uplink capability on the small, power-limited satellites of the early era. Simplicity was the key to this receiver, as it performed amplification and amplitude demodulation directly at VHF without the need for downconversion. APL also invented new antenna technologies, including the quadrifilar helix antenna in 1968, an early version of the patch antenna in 1972, and a novel matching technique for the bifilar helix antenna in 1986. The helix antennas provided optimized patterns for low-Earth-orbiting satellites and circular polarization for receiving the signals in any spacecraft orientation.

During the mid-1980s through the mid-1990s, APL's capabilities in communication systems engineering focused more on systems than technologies. Off-the-shelf flight RF hardware was purchased for compatibility with the Air Force Satellite Control Network. The ground stations of this network were used to establish S-band (2-GHz) command and telemetry links as well as real-time video downlinks for the "Delta" series of spacecraft for the Strategic Defense Initiative Organization. A notable APL technology development during this period was the X-band transmitter built for the MSX satellite. This transmitter enabled the required 25-Mbits/s wideband downlink for the mission and stimulated APL's in-house capabilities in microwave circuit design.[1]

In the last 10 years, continued developments have been needed to meet the challenge of maximizing science return while minimizing resource impacts for NASA missions. Mission applications have ranged from the low-Earth-orbiting TIMED spacecraft to numerous deep space spacecraft including NEAR-Shoemaker, CONTOUR, MESSENGER, STEREO, and New Horizons. APL's involvement with both the spacecraft design and the NASA Deep Space Network (DSN) has resulted in opportunities for innovation that have significantly improved the performance of NASA missions. This work was accomplished by a large group of dedicated people (see Acknowledgments).

CROSSING THE MID-TECHNOLOGY READINESS LEVEL REGION

The past decade has seen a significant infusion of new communications technologies into NASA flight programs by APL. The technology readiness level (TRL) scale used by NASA runs from 1 (basic research) through 9 (flight proven). The middle region (levels 4–6) is where technologies are advanced from laboratory breadboards into flight-like hardware that can be infused into programs with low risk. Advancing a new technology through this region is difficult because funding sources are focused more on the lower and higher TRLs. Over the past decade, this "mid-TRL" region has been traversed many times at APL with advancements such as a phased array antenna system, circularly polarized slotted waveguide sticks, transceiver-based communication systems, noncoherent Doppler tracking, low-power digital receiver technology, onboard radio science, and regenerative ranging. As a result, spacecraft missions have benefited considerably. For example, the science return of the MESSENGER mission to Mercury has been doubled through the infusion of circularly polarized waveguide antenna technology. The New Horizons mission to Pluto has been enabled through the development of a low-power digital receiver that has reduced power consumption by 70% relative to current command receiver technologies. The distance over which the New Horizons mission can precisely perform Earth-to-spacecraft ranging has been extended by a factor of 10, allowing a medium-gain antenna to be used for routine ranging operations out to Pluto and beyond.

How has this infusion of new technology into flight programs been accomplished? The answer lies in several areas, but a key factor is the close coupling between communication systems engineering for flight programs and new technology developments at APL. Both functions exist within the same organizational group, with the communication systems engineers taken from the ranks of the hardware development engineering staff. Consequently, a flight system need for a given technology is identified early and subsequent development is focused with a clear path into flight. Other positive factors include cooperative management and the dynamics of a small organization.

ADVANCEMENT IN THREE KEY AREAS

Over the past decade, APL has engineered solutions to problems in three key areas of spacecraft communications: science return, transceiver systems, and emergency-mode communications. The first area relates to the capacity of the science data link to Earth. The data transferred on this link are the reason that a mission exists, yet the capacity of the link is often a bottleneck, especially on deep space missions. This bottleneck has been opened with several technologies, including an electronically steered antenna system, solid-state power amplifiers (SSPAs), and advanced reflector antennas. The second area, transceiver systems, relates to the electronics used for modulation and demodulation within the spacecraft communication system. These electronics have historically been implemented in the form of a coherent transponder with a well-defined, yet limited, set of capabilities. APL has created a new spacecraft communications architecture based on plug-in transceiver cards to enable significant improvements in power consumption and onboard radiometric capabilities. The third area relates to the recovery of a spacecraft from emergency-mode conditions. An RF beacon technique has been developed using a fanbeam antenna on the spacecraft to enable robust emergency-mode communications. The transmitted RF beacon is observed periodically on Earth as the spacecraft rotates, similar in principle to the observation of a lighthouse beacon by a ship.

Science Return

The MESSENGER mission launched in August 2004 and will be the first to orbit Mercury, spending 1 year gathering science data and transmitting it back to Earth through a set of electronically steered phased array antennas.[2] Figure 1 shows the RF communications system block diagram and key hardware elements. The two X-band (8.4-GHz) phased array antennas, located on opposite sides of the spacecraft, are used to provide broad angular coverage for the science downlink. Each antenna is driven by the outputs of two redundant SSPAs. Electronic steering in one dimension over a ±45° range is accomplished by controlling the relative phases of the signals sent to the eight waveguide "sticks" in each phased array. This approach is a departure from the traditional gimbaled dish antenna and was chosen because of the tight packaging requirements of the spacecraft, the high-temperature environment near the Sun (+300°C), and motivation to eliminate moving parts from the design to maximize reliability.

The performance of the MESSENGER mission has been improved by the invention of a technique for producing circular polarization from the slotted waveguide antenna sticks used in each phased array.[3] This technique enables the polarization of the spacecraft radiation to match that of the DSN antennas, thereby avoiding a mismatch loss of 3 dB. The invention has doubled the science return of the mission relative to the original (linearly polarized) implementation and, importantly, has enabled block redundancy to ensure that the

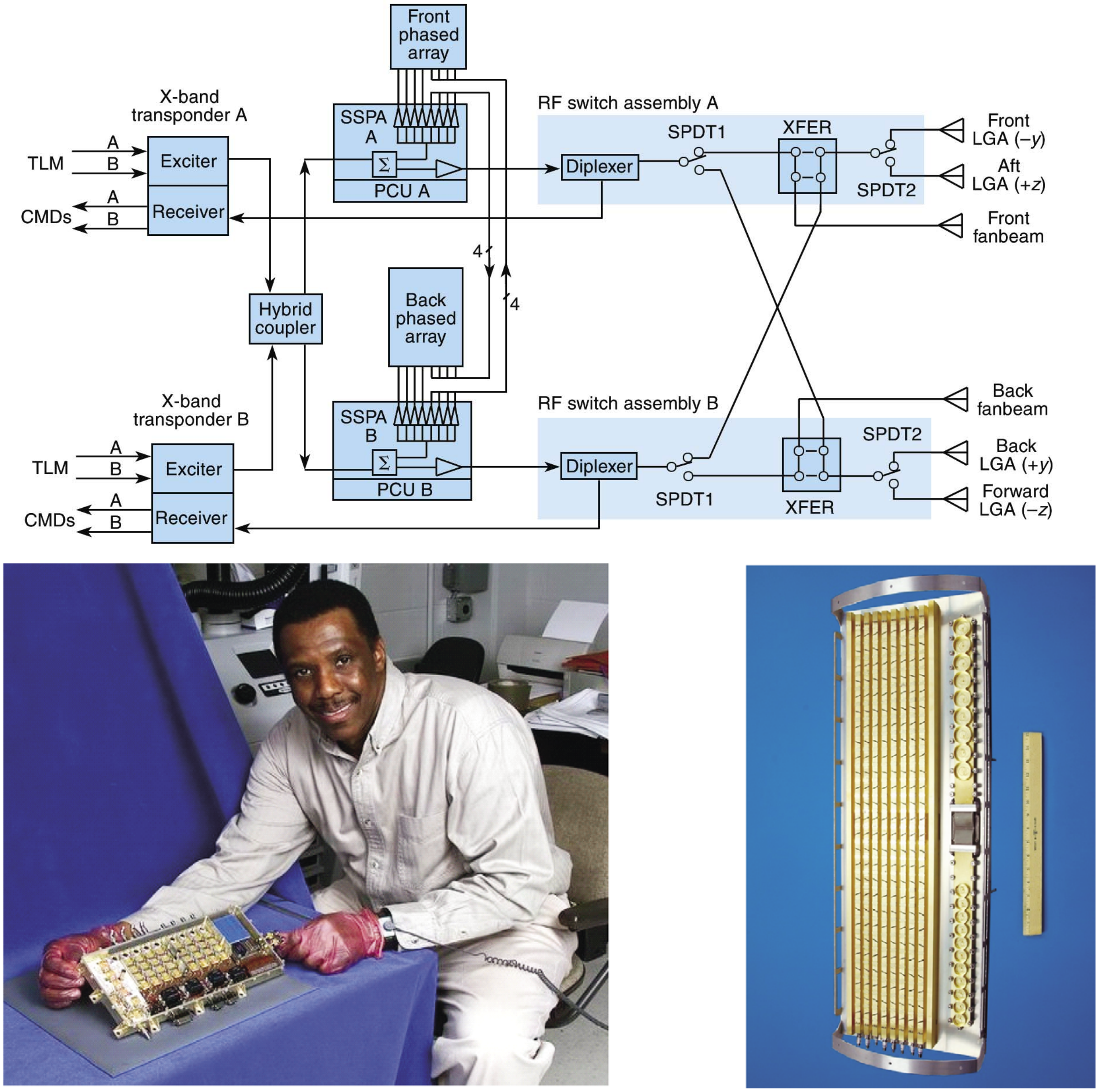

Figure 1. Block diagram of the MESSENGER communication system showing redundant phased array systems (top; all antennas are right-hand circular polarization). Cross-strapping between each SSPA (bottom left) and phased array antenna (bottom right) ensures block redundancy and enables both SSPAs to be powered simultaneously to produce higher science return. (CMDs = commands, LGA = low-gain antenna, PCU = power control unit, SPDT = single pole double throw, SSPA = solid-state power amplifier, TLM = telemetry, XFER = transfer.)

minimum required science return of 16 Gbits is returned by the mission. Cross-strapping between the redundant SSPAs and phased array antennas allows the total science return to be increased to as much as 100 Gbits if both SSPAs are powered simultaneously in Mercury orbit.

SSPA technology has a long history at APL, starting with the VHF and UHF amplifiers flown on the Oscar satellites in the 1960s. These early amplifiers incorporated bipolar junction transistors and were designed for Class-C operation to optimize efficiency. More recently, MSX and NEAR-Shoemaker used X-band SSPAs with an output power of 5 W.[1,4] These SSPAs incorporated high-reliability packaged field-effect transistors and were designed to balance efficiency with high reliability. The overall efficiency of the SSPAs (RF output power divided by input bus power) was 14%.

APL's most state-of-the-art design is the X-band SSPA developed for the MESSENGER spacecraft.[2] It incorporates a combination of monolithic microwave integrated circuit (MMIC) chips and discrete microwave devices. This SSPA includes a "lumped" section with an output power of 10 W for driving the low- and medium-gain antennas on the spacecraft and a "distributed" section for driving and controlling the beam pointing of the phased array antennas. The distributed section contains eight amplifier channels, each with a 4-bit phase shifter, to generate an RF output power of 11 W for each phased array. The MESSENGER SSPA is densely packaged, incorporating an APL-developed RF hybrid package for the MMICs and discrete microwave devices in the design.[2,5] The output amplifiers within the SSPA are designed for Class-A/B operation, again to balance efficiency with high reliability. The overall efficiency of the MESSENGER SSPA is 22–23%. This increase in efficiency relative to the older NEAR-Shoemaker design represents a 60% increase in downlink bit-rate capability for a given amount of input bus power.

The Ka-band (32-GHz) frequency range will enable significant increases in the downlink data rate of future spacecraft relative to X-band operation. For example, deep space probes can achieve a factor of 4 increase (including weather effects) for a given antenna diameter and transmit power. For applications requiring relatively low RF power levels ($\leq$5 W), solid-state technology provides a viable alternative to traveling wave tube technology. APL has been developing solid-state Ka-band SSPAs since 1999 under both NASA and internal technology development funding. Harmonic matching techniques are used to control the voltage and current waveforms at the transistor so that the power dissipation internal to the device is minimized. The goal is to achieve a chip-level power-added efficiency of 60%, a large signal gain of 9 dB, and an RF output power of 1 W. This collaborative effort with Morgan State University is described in more detail in the article by Wallis et al., this issue.

Reflector antennas are the typical choice for deep space missions because of their simplicity and high efficiency. Over the past decade, APL has flown these antennas on the ACE, NEAR-Shoemaker, and CONTOUR spacecraft. Reflector antennas for the STEREO and New Horizons spacecraft are currently under development. Overall efficiencies in the range of 50–65% are typical when using parabolic reflectors. The New Horizons high-gain antenna[6] is being designed with specially shaped main and sub-reflectors to produce a more uniform field across its 2.1-m-dia. aperture, achieving an overall efficiency of 74% in the engineering model implementation. A key tool in the design process is an advanced reflector antenna code from Ohio State University, available to APL as a member of the Ohio State University Satellite Antenna Consortium. This code uses physical optics and Gaussian beam numerical techniques to quickly analyze reflector antenna designs. The increase in efficiency relative to standard Cassegrain designs is substantial, representing a potential 20% increase in science return.

Inflatable antennas are an enabling technology for missions requiring a very large aperture but lacking the mass margin and/or packaging volume needed for a rigid parabolic dish. Historically, progress in this area has been slow because of fear of the "all or nothing" scenario, where an inflation problem could cause loss of the mission. APL has met this challenge through development of a hybrid inflatable antenna, for which a rigid inner reflector provides backup capability in the event of a deployment problem (Fig. 2). Industry partner ILC Dover has developed a 2-m-dia. breadboard antenna with a measured surface accuracy of 1.1 mm rms using a rigid frame.[7] They have applied special construction techniques that eliminate the W-shaped "Hencky" curve, an undesired perturbation to the parabolic shape that is commonly encountered with inflated membranes. Hybrid inflatable antenna technology promises quicker insertion into flight programs because it can be incorporated into a mission at lower risk than an all-inflatable technology. Alternatively, missions that meet their minimum science requirement with the smaller rigid inner reflector can use the inflated annulus for "bonus science" capability.

Transceiver Systems

By changing the architecture of communications electronics, APL has significantly reduced the power consumption of deep space receivers while incorporating new onboard radiometric functions. These performance improvements have been achieved without increasing the mass relative to previous systems and in an environment where the technology had previously been viewed as mature.

In 1995, APL adopted a new, highly integrated architecture for its spacecraft called the Integrated

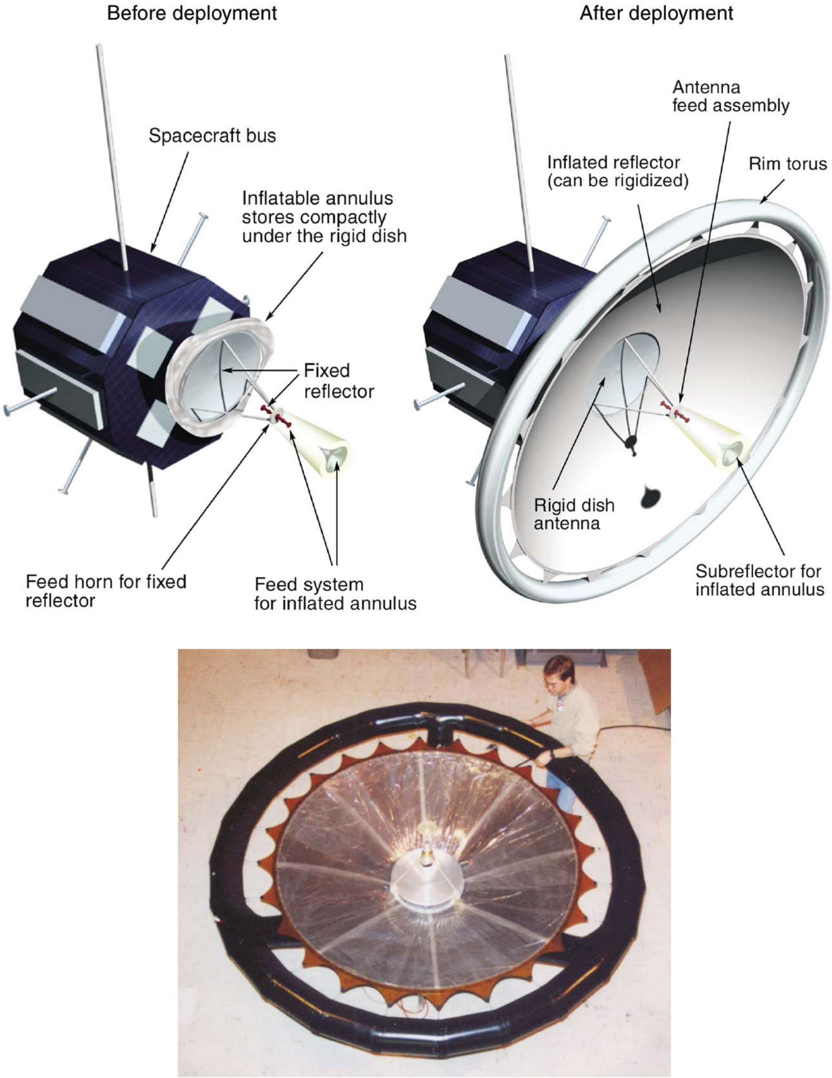

Figure 2. Hybrid inflatable antenna concept (top) and 2-m-dia. breadboard antenna (bottom, shown with an inflated rim torus).

Electronics Module (IEM). The IEM contains most of the major spacecraft subsystems, including command and data handling, guidance and control, RF communications, and, when applicable, GPS navigation. It is implemented in a single chassis with a set of 15 × 23 cm plug-in cards. A transceiver system, consisting of uplink and downlink cards, is used for RF communications instead of a coherent transponder. In a transponder, phase coherency between the downlink and uplink signals removes the effect of onboard oscillator drift from the downlink frequency, enabling precise ground-based Doppler tracking. However, phase-coherent turnaround complicates the spacecraft hardware by tying the receiver and transmitter designs together. In a transceiver system, a free-running oscillator is used to generate the downlink signal instead of deriving it from the uplink signal. The transceiver architecture enables the uplink and downlink designs to be developed and tested independently. Its main limitation is that ground-based Doppler tracking measurements (made by measuring the frequency of the received downlink signal over time) are affected by the stability of the onboard oscillator, thereby limiting orbit determination accuracy. A transceiver system can be made to operate like a transponder, however, through the use of a specialized noncoherent Doppler tracking technique for removing onboard oscillator drift.

APL's transceiver-based communication systems have been developed through a combination of internal and (mainly) spacecraft program funding. Figure 3 shows the development progression and the vision for the future. This progression has advanced the technology from initial concept development through flight hardware implementation in 4 years and through launch in 6 years. The transceiver architecture for the New Horizons mission is highly capable, including a low-power digital receiver (Fig. 4), regenerative ranging capability, and onboard uplink radio science capability.[8] The conditioned power consumption of the digital receiver is only 2.3 W, including the command detector unit and critical command decoder,[9] compared to 8 W consumed by commercially available deep space receivers. This savings in power, magnified by the need for redundancy, is a key enabler for the mission, which is power-limited by its radioisotope thermoelectric generator power source. The New Horizons regenerative ranging capability uses a pseudorandom code that is locked to and regenerated in the spacecraft to reduce turnaround noise compared to tone-based ranging.[10] The result is an improvement in ranging performance that extends the distance at which the New Horizons Earth-to-spacecraft range can be accurately determined from 5 to 50 AU using the medium-gain antenna on the spacecraft. This capability improves mission robustness by enabling routine communications and navigation out to Pluto distance (32 AU) and beyond using a medium-gain (broader-beam) antenna on the spacecraft instead of a high-gain (narrower-beam) antenna. The onboard radio science capability provides a means for measuring the atmospheric composition of Pluto using a stable

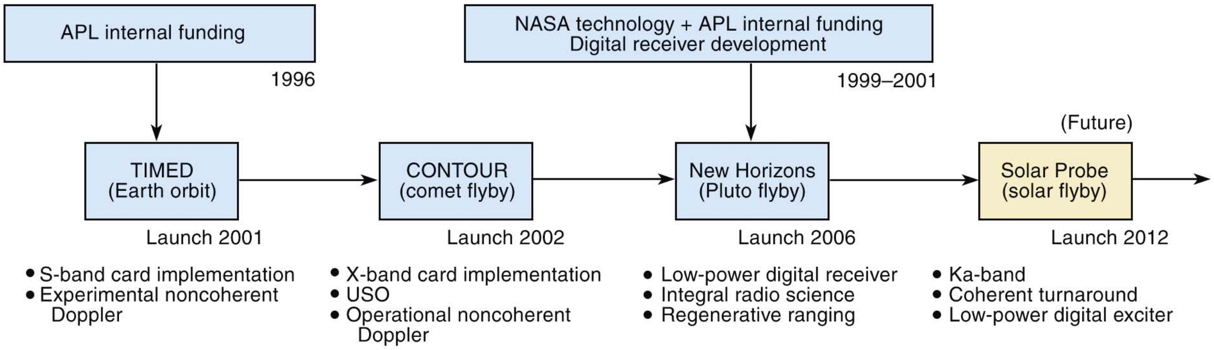

Figure 3. Progression of spacecraft transceiver development activities at APL (bullets under each block indicate new capabilities).

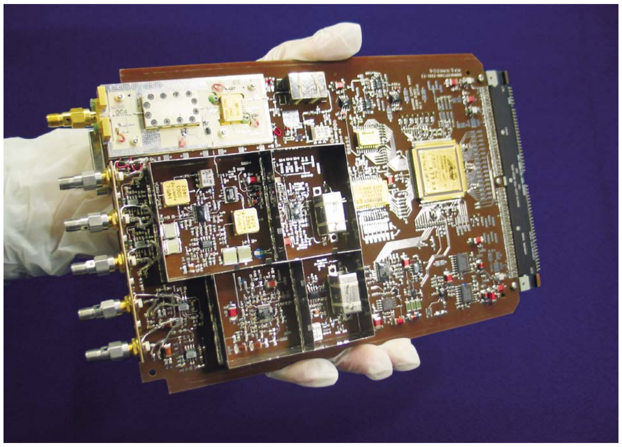

Figure 4. The New Horizons X-band uplink card.

uplink signal transmitted from the DSN. This capability is enabled with a USO that provides an Allan frequency deviation of $\sigma_y = 2 \times 10^{-13}$ over 10-s intervals. Future plans for the APL transceiver system include a low-power downlink card and a factor of 2 reduction in the transceiver card size.

USOs are an important tool in APL transceiver systems. They enable onboard radiometric capabilities such as radio science and autonomous radio navigation. Their low phase noise is ideally suited for generating Ka-band downlink signals. USOs also enable ultralow-bit-rate telemetry and commanding using beacon tone techniques.[11,12] APL has built over 400 USOs for flight programs to date.

APL's invention of a method for performing two-way noncoherent Doppler tracking has enabled the transceiver-based architecture to be used in deep space.[13] The 1-σ velocity precision needed for deep space Doppler tracking is 0.1 mm/s, corresponding to a 1-σ frequency precision of 3.3×10^{-13} over 60 s. Initially, the question was posed as to whether APL's USO technology could be used to provide the required Doppler tracking precision in lieu of coherent transponding. The Allan frequency deviation of an APL USO ($\sigma_y = 2 \times 10^{-13}$ over 10 s) is comparable to the required frequency precision, but the USOs lack the long-term stability of the atomic standards used by the DSN for coherent transponding. Ultimately, the solution was to make two Doppler frequency measurements (uplink and downlink) and combine them on the ground to produce corrected downlink Doppler measurements equivalent to those that would have been obtained using a coherent transponder. The uplink measurement is made by comparing the frequency of the received signal to that of the free-running oscillator on the spacecraft using simple counters. The counter measurements are placed into the downlink telemetry for post-processing on the ground. The downlink measurement is made by the DSN using existing procedures. The counter values are extracted from the telemetry and used to correct the downlink Doppler frequency measurements in a post-pass processing step (Fig. 5). Performance at the 0.1-mm/s level is readily achieved without relying on a USO on the spacecraft.[14]

The noncoherent Doppler tracking technique has allowed APL to build simplified transceiver systems for deep space missions, resulting in a more integrated approach and lower receiver power consumption relative to existing transponder systems. The first APL spacecraft to carry two-way noncoherent Doppler capability was the TIMED low-Earth orbiter, which carried it as an experiment.[15] The capability was successfully tested in flight with the help of the DSN through a series of passes over the Goldstone complex between March and May 2002.[16] The CONTOUR mission, which launched in July 2002, used two-way noncoherent Doppler tracking as the operational spacecraft navigation system.[17] This spacecraft was tracked successfully while in a highly elliptical Earth orbit for 43 days, until the mission abruptly ended with a failed solid rocket motor burn. The radiometric tracking results during the mission were very good, with 98% of all Doppler measurements and 74% of all ranging measurements successfully accomplished. In using two-way noncoherent Doppler techniques, it became apparent that onboard oscillator stability is more important for spacecraft ranging than it is for Doppler

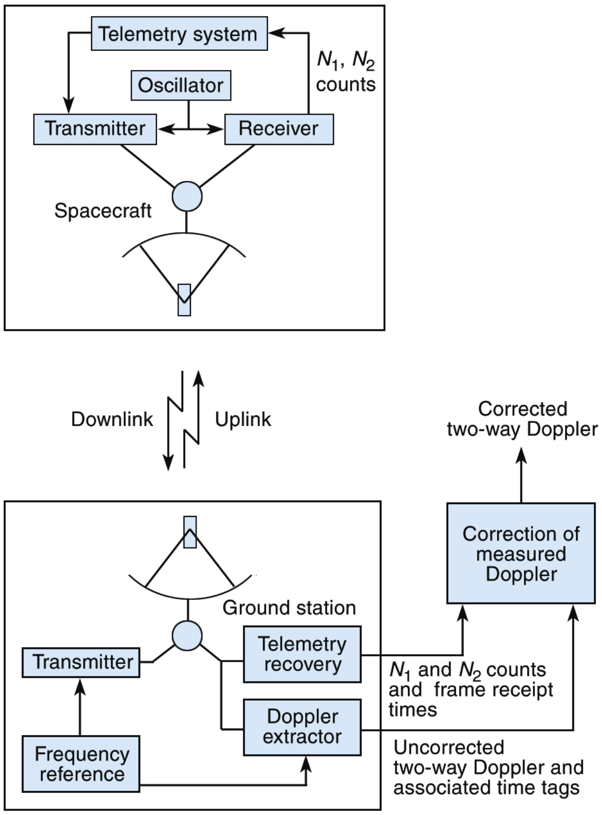

Figure 5. Operation of two-way noncoherent Doppler tracking. The uplink Doppler counts are input to the spacecraft telemetry data. On the ground, the telemetry is used to correct the downlink Doppler frequency measurements, making them equivalent to those of a coherent transponder.

tracking, an unanticipated side effect that was minimized by using USOs in the CONTOUR design.[17,18]

Emergency-Mode Communications

A method has been devised for establishing robust emergency-mode communications on deep space missions where the spacecraft transmit power is limited.[19] The method enlists a fanbeam antenna to broadcast a beacon signal as the spacecraft rotates and relies on a precisely timed "stop rotation" command from the ground to regain communications. It was first implemented on the NEAR-Shoemaker mission and used to recover that spacecraft on several occasions. The method has also been incorporated into the MESSENGER spacecraft design.

Historically, the approach for emergency-mode communications in deep space has been to use a broad-beam antenna pattern on the spacecraft to establish low-bit-rate communications with the DSN. This approach, while often robust for missions using a traveling wave tube amplifier (TWTA) with an output power of 15 W or more, is less robust for missions with lower transmit power or missions that travel to extreme distances (say, beyond Jupiter). The NEAR-Shoemaker asteroid orbiter mission, as noted earlier, incorporated a 5-W SSPA to minimize mass and cost relative to the traditional TWTA approach. However, its relatively low RF transmit power created a challenge in achieving robust emergency-mode communications at the maximum mission distance of 3.2 AU.

Coincidentally, APL had incorporated a medium-gain antenna with a fanbeam pattern into the NEAR-Shoemaker design for other purposes. This antenna provided the gain required to establish an emergency-mode link, but with a broad-beam pattern in only one dimension. Consequently, the antenna was mounted on the spacecraft to give coverage between 0° and 40° from the spacecraft z-axis in one dimension (Fig. 6). In emergency mode, the three-axis controlled spacecraft pointed its z-axis at the Sun and rotated slowly about the spacecraft–Sun line, causing the antenna pattern to sweep out a conical section of space. Because of the mission geometry, this conical section contained the Earth direction during all portions of the mission when the moderate gain of the fanbeam pattern (12–18 dBic) was needed. An unmodulated X-band signal was transmitted from the fanbeam antenna and observed every rotation interval (3 h) by the DSN using their 34- or 70-m-dia. ground antennas. With knowledge of the rotation rate and phase, a "stop rotation" command was transmitted by the DSN at precisely

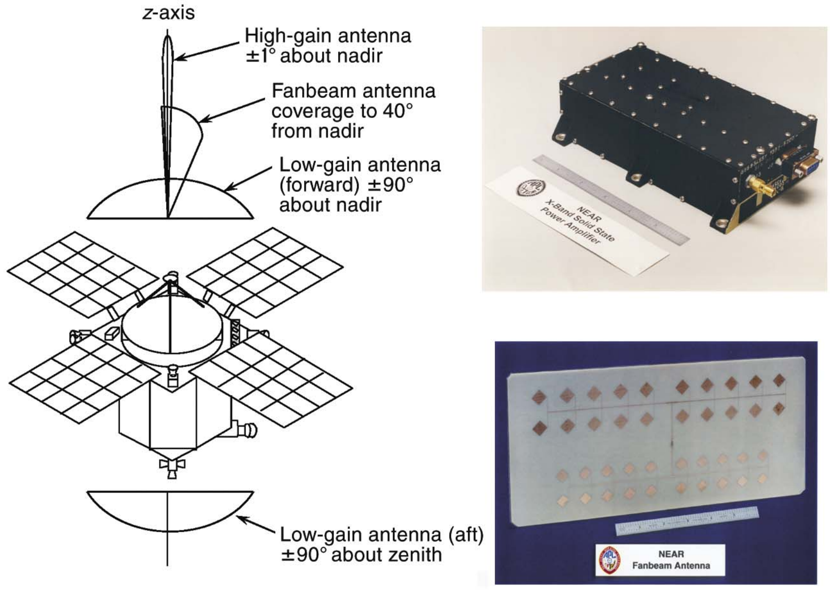

Figure 6. Antenna coverage on the NEAR-Shoemaker spacecraft (left) and the hardware used to implement emergency-mode communications: a 5-W SSPA (top right) and a dual-frequency (uplink and downlink) fanbeam antenna (bottom right).

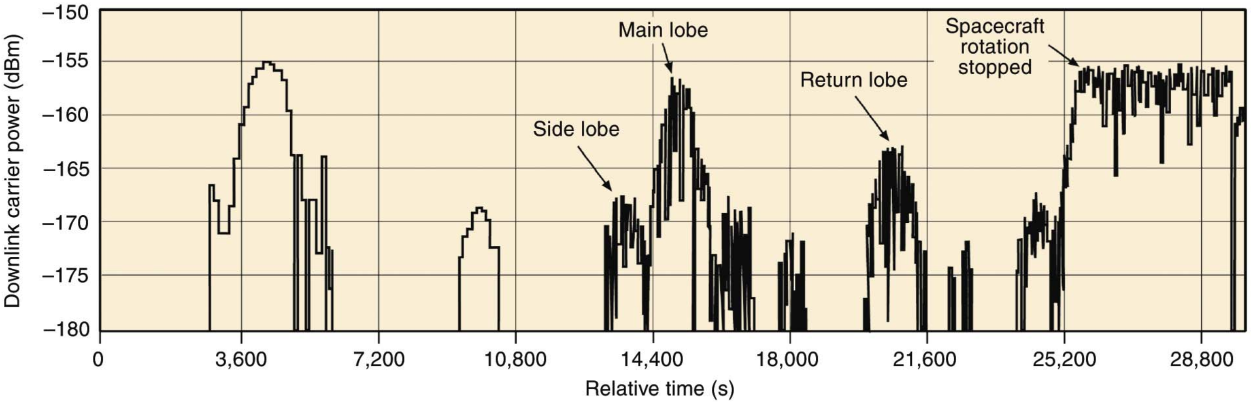

Figure 7. Downlink signal strength received from the NEAR-Shoemaker spacecraft as it rotated in Sun-safe mode on 22 December 1998 at an Earth distance of 2.5 AU. The spacecraft rotation was halted after two rotations by ground command at T = 25,200 s, with its fanbeam antenna oriented toward Earth. Differences in appearance in the plot are due to averaging effects on the reported signal strength from different DSN sites.

the right time to stop the spacecraft rotation with its fanbeam pattern oriented toward Earth, thereafter providing reliable communications. Figure 7 is a downlink signal strength plot that shows the fanbeam pattern sweeping through the Earth direction twice before being halted in that direction by ground command. This technique proved very robust in all of the emergency-mode recovery events of the mission.

CONCLUSION

The coming decade will present challenges for future scientific and exploration missions. Certainly, high-bit-rate capacity (>1 Mbps) from deep space will be a critical issue, especially if manned exploration of the Moon and Mars is to be accomplished. This challenge will be met through operation at Ka-band using efficient power amplifiers and antennas and, eventually, through operation at optical wavelengths. Another challenge will be low-power operation, particularly for deep space missions to the outer planets and beyond. This challenge will be met through development of low-power integrated circuits (both digital and analog), highly efficient SSPAs operating at X- and Ka-band, and bus power conversion technology that is optimized for low-power operation.

The key to success in transferring new technologies to flight programs is having strong technical skills in both the systems design and technology development areas, with a tight coupling between the two. This coupling, and an innovative environment fostered by challenging flight programs and cooperative management, has led to significant improvements in spacecraft communications design at APL. These improvements have played an important role in enabling new discoveries from missions spanning the entire solar system, from Mercury to Pluto.

REFERENCES

[1] Sloan, R. F., Bokulic, R. S., and Sinsky, J. H., "An X-Band Telecommunications Transmitter for the Mid-Course Space Experiment," *Johns Hopkins APL Tech. Dig.* **14**(4), 317–323 (1993).

[2] Bokulic, R. S., Fielhauer, K. B., Wallis, R. E., Cheng, S., Edwards, M. L., et al., "MESSENGER Mission: First Electronically Steered Antenna for Deep Space Communications," in *Proc. 2004 IEEE Aerospace Conf.*, Big Sky, MT (Mar 2004).

[3] Stilwell, R. K., Wallis, R. E., and Edwards, M. L., "A Circularly Polarized, Electrically Scanned Slotted Waveguide Array Suitable for High Temperature Environments," in *Proc. IEEE Antennas and Propagation Soc. Int. Symp.*, Vol. 3, pp. 1030–1033 (Jun 2003).

[4] Bokulic, R. S., Flaherty, M. K., Jensen, J. R., and McKnight, T. R., "The NEAR Spacecraft RF Telecommunications System," *Johns Hopkins APL Tech. Dig.* **19**(2), 213–219 (1998).

[5] Nhan, E., Cheng, S., Jose, M. J., Fortney, S. O., and Penn, J. E., "Recent Test Results of a Flight X-Band Solid-State Power Amplifier Utilizing GaAs MESFET, HFET, and pHEMT Technologies," in *Proc. 2002 GaAs Reliability Workshop*, IEEE Catalog No. 02TH 8658, Monterey, CA (Oct 2002).

[6] Schulze, R. E., and Hill, S. W., "The New Horizons High-gain Antenna: Reflector Design for a Spin-Stabilized Bus at Cryogenic Temperatures," in *Proc. 2004 IEEE Aerospace Conf.*, Big Sky, MT (Mar 2004).

[7] Willey, C. E., Schulze, R. C., Bokulic, R. S., and Skullney, W. E., "A Hybrid Inflatable Dish Antenna System for Spacecraft," AIAA paper 2001-1258, in *Proc. 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conf. & Exhibit, AIAA Gossamer Spacecraft Forum*, Seattle, WA (Apr 2001).

[8] DeBoy, C. C., Haskins, C. B., Brown, T. A., Schulze, R. C., Bernacik, M. A., et al., "The RF Telecommunications System for the New Horizons Mission to Pluto," in *Proc. 2004 IEEE Aerospace Conf.*, Big Sky, MT (Mar 2004).

[9] Haskins, C. B., and Millard, W. P., "X-Band Digital Receiver for the New Horizons Spacecraft," in *Proc. 2004 IEEE Aerospace Conf.*, Big Sky, MT (Mar 2004).

[10] Berner, J. B., Layland, J. M., Kinman, P. W., and Smith, J. R., "Regenerative Pseudo-Noise Ranging for Deep-Space Applications," in *Telecommunications and Mission Operations (TMO) Progress Report 42-137* (January–March 1999), Jet Propulsion Laboratory, Pasadena, CA (15 May 1999).

[11] Sue, M. K., Peng, T., and Wyatt, E. J., "A New Approach in Spacecraft Monitoring for Efficient Use of the Deep Space Network," in *Telecommunications and Data Acquisition (TDA) Progress Report 42-130 (April–June 1997)*, Jet Propulsion Laboratory, Pasadena, CA (15 Aug 1997).

[12] Bokulic, R. S., and Jensen, J. R., "Tone-Based Commanding of Deep Space Probes Using Small Aperture Ground Antennas," in *Proc. 5th*

Int. Symp. on Reducing the Cost of Spacecraft Ground Systems and Operations, Pasadena, CA (Jul 2003).

[13] Jensen, J. R., and Bokulic, R. S., "Highly Accurate, Noncoherent Technique for Spacecraft Doppler Tracking," *IEEE Trans. AES* **35**(3), 963–973 (1999).

[14] Jensen, J. R., and Bokulic, R. S., "Experimental Verification of Noncoherent Doppler Tracking at the Deep Space Network," *IEEE Trans. AES* **36**(4), 1401–1406 (2000).

[15] Bokulic, R. S., DeBoy, C. C., Minarik, D. B., Daniels, J., Cheng, S., and Sinsky, J. H., "A Highly Integrated S-Band Transceiver System with Two-Way Doppler Tracking Capability," in *Proc. 11th Annu. AIAA/USU Conf. on Small Satellites*, Utah State University, Logan, UT (Sep 1997).

[16] DeBoy, C. C., Jensen, J. R., and Asher, M. A., "Noncoherent Doppler Tracking: First Flight Results," in *Proc. 3rd IAA Symp. on Small Satellites for Earth Observation*, Berlin, Germany (Apr 2003).

[17] Jensen, J. R., Fielhauer, K. B., Reinhart, M. R., and Srinivasan, D. K., "In-Flight CONTOUR Radiometric Performance," in *Proc. 2003 IEEE Aerospace Conf.*, Big Sky, MT (Mar 2003).

[18] Reynolds, M. K., Reinhart, M. J., and Bokulic, R. S., "A Two-Way Noncoherent Ranging Technique for Deep Space Missions," in *Proc. 2002 IEEE Aerospace Conf.*, Big Sky, MT (Mar 2002).

[19] Bokulic, R. S., and Jensen, J. R., "Recovery of a Spacecraft from Sun-Safe Mode Using a Fan-beam Antenna," *J. Spacecraft Rockets* **37**(6), 822–826 (2000).

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