JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 37, No. 6, November–December 2000

Recovery of a Spacecraft from Sun-Safe Mode Using a Fanbeam Antenna

R. S. Bokulic* and J. R. Jensen†
Johns Hopkins University, Applied Physics Laboratory, Laurel, Maryland 20723

A technique for recovering a spacecraft from a sun-oriented safe mode using a fanbeam antenna is described. This technique is useful for deep space missions where the downlink signal margin does not permit recovery using traditional broadbeam antenna methods. This method uses the position of the sun as a reference and employs a fanbeam antenna to search for the Earth through rotation of the spacecraft about the spacecraft–sun line. Recovery can be either autonomous using an uplink beacon or manual using a downlink beacon. The general design of the technique and its implementation and use on the Near Earth Asteroid Rendezvous spacecraft are described. Experience with this spacecraft, using a downlink beacon, has shown the technique to be very effective. During two sun-safe episodes, the spacecraft rotation was successfully stopped on the first try, and the rotation was halted close to the peak of the downlink pattern. Using telemetry available from one of the sun-safe episodes, we have determined that the spacecraft rotation was stopped 2.7 deg from the targeted angle, representing an error of 0.75% of a rotation period.

Nomenclature

B_L	=	one-sided phaselock loop noise bandwidth, Hz
f_0	=	spacecraft receiver center frequency, Hz
$G_N(\Psi_N)$	=	gain pattern in narrow plane of fanbeam antenna
$G_w(\Psi_w)$	=	gain pattern in wide plane of fanbeam antenna
ΔF	=	sweep range of uplink carrier frequency during acquisition, Hz
θ	=	angle off of spacecraft z axis, rad
ϕ	=	rotation phase of spacecraft, rad
Ψ_N	=	angle in narrow plane of fanbeam antenna, rad
Ψ_w	=	angle in wide plane of fanbeam antenna, rad

Introduction

As part of the system design of typical scientific spacecraft, a method for securing the spacecraft in the event of an emergency is required. This usually involves the location of an easily identifiable object in space so that the attitude of the spacecraft with respect to that object can be fixed. Very often, the spacecraft goes into what is called sun-safe mode, where the solar panels are oriented toward the sun and only the most essential onboard hardware and software controlled functions are powered.

Once the spacecraft has autonomously saved itself by going into sun-safe mode, the task remains to make contact with the Earth so that debugging and eventual recovery can occur. Deep space missions in the past have typically used a low-gain antenna (LGA) to transmit data to the Earth while in sun-safe mode. The technique is effective because the Earth is usually within the broad beamwidth of the LGA. A coning procedure can be used in which the spacecraft wobbles its pointing axis in a conical manner to cover a wider range in the event that Earth is outside the LGA beamwidth. The Mars Global Surveyor is an example of a spacecraft that uses this technique.

The present day emphasis on smaller, less expensive spacecraft has resulted in the use of lower power transmitters on some missions. This limits the ability of using an LGA to recover from sun-safe mode because the downlink signal level is more difficult to detect at interplanetary distances. One way to overcome this problem is to incorporate a medium-gain antenna, such as one with a fanbeam pattern, on the spacecraft. Although this approach leads to the use of an additional antenna that adds complexity and mass to the antenna system, it is often favorable when compared to the overall spacecraft mass increase that might result from using higher transmitter power. The challenge with the medium-gain antenna approach is to maintain a robust recovery capability with a narrower antenna beamwidth. This paper addresses that challenge by describing the design and implementation of a sun-safe recovery method that incorporates a fanbeam antenna on the spacecraft.

Recovery Method Using Fanbeam Antenna

A method has been developed for recovering the spacecraft from sun-safe mode using a medium-gain fanbeam antenna. This has the advantage of providing the extra antenna gain needed to counteract the lower transmitter power on the spacecraft. The peak gain of the typical fanbeam antenna assumed in this paper is in the region of 10–20 dB relative to isotropic circular polarized (dBic), as compared with a peak gain of 6 dBic that is typical of LGAs flown on deep space missions. We assume that the spacecraft z axis is pointed toward the sun in sun-safe mode. The fanbeam antenna is oriented so that its wide plane pattern extends radially (as viewed from the sun) from the spacecraft z axis to a prescribed angle off of that axis. When the spacecraft enters sun-safe mode, it rotates slowly about the z axis so that a conical volume of space is swept out by the fanbeam pattern.

Using the fanbeam recovery method, the spacecraft rotates until the Earth is within the narrow plane of the fanbeam pattern, then the rotation is stopped. Two methods for stopping the rotation have been considered. The first method involves radiating a beacon from the Earth and using signal strength readings from the onboard receiver to autonomously stop the spacecraft rotation. This technique can be tricky because the onboard software must be sophisticated enough to prevent the spacecraft from stopping at an undesirable rotation phase due to false or misleading signal strength readings. Such readings could arise from spacecraft antenna sidelobes or return lobes. The second method involves radiating a beacon from the spacecraft and detecting it on the ground. This technique gives ground controllers information on the rotation phase and permits them to transmit a command to the spacecraft that will stop the rotation at the proper time. This technique has proven to be very effective and will be the focus of this paper.

The rate of spacecraft rotation is a compromise between two competing requirements. The first requirement is for the mission operations team to recover the spacecraft in a reasonable amount of time. This requirement favors a faster rotation rate. The second requirement is for sending a precisely timed stop-rotation command

Received 5 January 2000; revision received 25 May 2000; accepted for publication 29 May 2000.

*Supervisor, Radio Frequency Communications Section, Space Department, 11100 Johns Hopkins Road.

†Principal Professional Staff, Space Department, 11100 Johns Hopkins Road.

to the spacecraft. The onboard receiver must be locked up, and the command must be received in time to stop the rotation near the center portion of the fanbeam pattern. This requirement favors a slower rotation rate. Proper choice of the rotation rate will depend on the mission geometry (which affects the wide plane beamwidth), spacecraft transmitter power (which affects the narrow plane beamwidth), and command sequence duration.

Design Example: Near Earth Asteroid Rendezvous Spacecraft

System Design

In this section, a design example will be reviewed that illustrates the tradeoffs and methodology of the fanbeam technique. Whereas this example is specific to the Near Earth Asteroid Rendezvous (NEAR) spacecraft mission,[1] the methodology can be readily extended to many deep space missions.

The NEAR spacecraft was launched on 17 February 1996 with a mission objective to rendezvous with and orbit the asteroid 433 Eros. With its 5-W solid-state transmitter and a maximum Earth distance of 3.2 astronomical units (AU), a reliable sun-safe downlink could not be established with Earth over much of the mission using the LGA. Inspection of the mission geometry, however, revealed that the sun–probe–Earth (SPE) angle stays within 38.4 deg over most of the mission (Fig. 1). The SPE angle increases above this value only when the Earth–spacecraft distance is small. This scenario is typical of most deep space missions that venture beyond the Earth's orbit around the sun. Consequently, a fanbeam antenna with a 3-dB beamwidth of 40 × 8 deg was incorporated into the spacecraft design. The wide plane beamwidth was chosen to cover the SPE angle variation, while the narrow plane beamwidth was chosen to give adequate gain in the link. The antenna was designed to be dual frequency (7.2-GHz uplink, 8.4-GHz downlink) and constructed using microstrip patch technology.[2]

The fanbeam antenna provides coverage between the z axis and approximately 40 deg off of that axis (Fig. 2). Actually, the antenna is physically tilted by a slight angle so that its −3-dB beam edge extends to the left of the z axis as viewed in Fig. 2. This tilt gives some needed gain improvement in the z axis direction, but creates a return lobe at a spacecraft rotation phase of 180 deg from the phase of the main lobe.

When the NEAR spacecraft enters sun-safe mode, it points its z axis at the sun, turns most of its systems off, and transmits an unmodulated 8.4-GHz beacon through the fanbeam antenna. The signal is unmodulated to maximize the probability of carrier detection on the ground. The spacecraft rotation rate was chosen at 2 deg/min, resulting in a rotation period of 3 h. This period permits recovery of the spacecraft in a reasonable amount of time (typically 6–12 h) with adequate time margin for reception of the stop-rotation command.

Beacon View Period

At first look, one may be tempted to calculate the beacon view period on the ground as the ratio of the narrow plane beamwidth divided by the rotation rate, or 8 deg/(2 deg/min) = 4 min (240 s). However, consideration of the effect of the SPE angle reveals that the view period is typically much longer than that. The downlink gain in the Earth direction, with the spacecraft z axis pointed toward the sun, can be expressed as

$$G = G_w(\Psi_w)G_N(\Psi_N) \tag{1}$$

The measured gain pattern of the NEAR fanbeam antenna in the wide plane is given in Table 1. The gain in the narrow plane is modeled as

$$G_N(\Psi_N) = \frac{\sin^2(\Psi_N/A)}{(\Psi_N/A)^2} \tag{2}$$

where $A = 0.0502$ for a full-width, half-power beamwidth of 8 deg. The angles Ψ_w and Ψ_N can be related to angles in the spacecraft coordinate system by

$$\Psi_w = \sin^{-1}(\sin\theta\cos\phi) \tag{3}$$

$$\Psi_N = \sin^{-1}(\sin\theta\sin\phi) \tag{4}$$

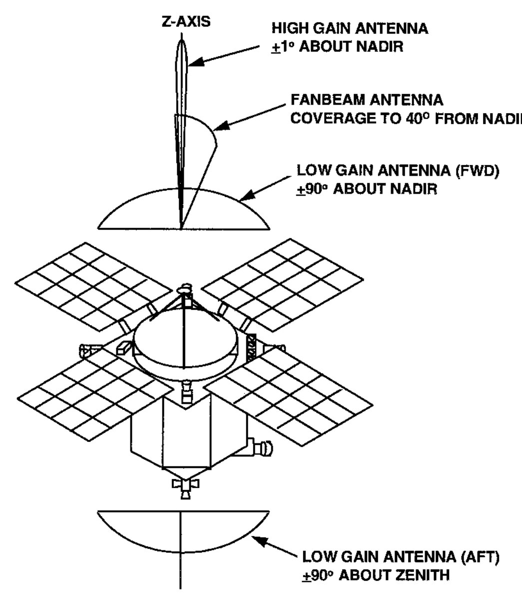


Fig. 2 NEAR spacecraft antenna orientation diagram.

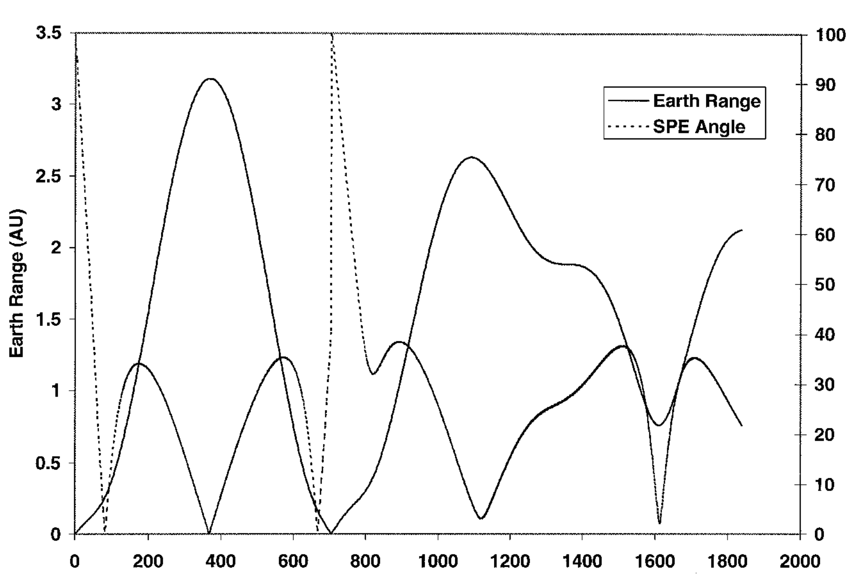


Fig. 1 NEAR spacecraft mission geometry.

In sun-safe mode, the angle θ is equal to the SPE angle. The angle $\phi = 0$ corresponds to the plane in which the wide plane pattern of the antenna falls.

Equation (1) is plotted in Fig. 3 for the downlink case for rotation phases between 0 and 90 deg. The pattern is symmetrical about a rotation angle of $\phi = 0$ deg. It can be seen that at small SPE angles, the effective 3-dB beamwidth of the downlink gain pattern approaches 360 deg, whereas at larger SPE angles, the effective 3-dB beamwidth becomes progressively smaller. Fortunately, for typical deep space missions beyond Earth's orbit, the maximum Earth range occurs at lower SPE angles, resulting in greater fanbeam antenna gain over a longer period of time at those ranges.

Table 1 NEAR fanbeam antenna gain data

Angle off of z axis Ψ_w, deg	Downlink gain at center of narrow plane pattern, dBic	Uplink gain at center of narrow plane pattern, dBic
0	16.1	16.5
5	17.8	17.5
10	18.1	18.0
15	17.3	18.1
20	16.0	17.5
25	15.9	17.2
30	15.2	16.2
35	13.8	15.0
40	11.6	12.5

With a rotation rate of 2 deg/min, if we combine the SPE angle profile (Fig. 1) with Eq. (1), then we can generate a plot of the downlink signal viewing period as a function of mission time (Fig. 4). The viewing period is defined as the time between the −3-dB points of the downlink signal strength as viewed from the ground. The minimum viewing period for NEAR is 394 s, occurring on mission day 892. This viewing period coincides with a SPE angle of 38.4 deg. Gaps in the data at days 0–50 and 704–790 occur because the SPE angle is greater than 40 deg and the LGA is used for recovery.

Stop-Rotation Command Timing

A challenge with using a fanbeam antenna for spacecraft recovery is the timing of the stop-rotation command sent from the ground. This command must be sent so that the spacecraft stops rotating with the fanbeam pattern directed at the Earth. If the spacecraft is stopped at the wrong time, then communications may be lost, requiring an autonomous restart of the spacecraft rotation. The following parameters must be taken into account when transmitting the

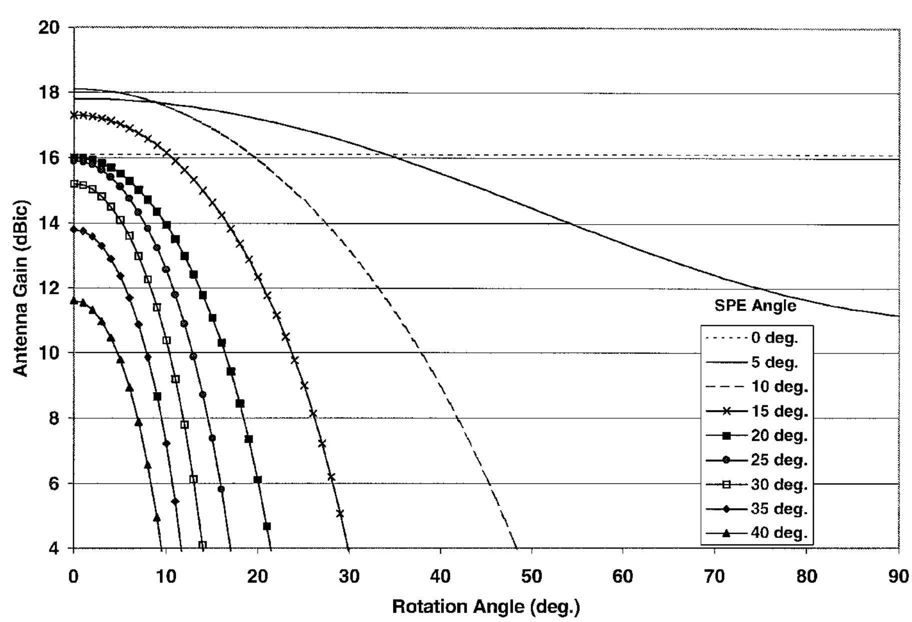


Fig. 3 Fanbeam antenna effective gain as a function of SPE angle and rotation phase; antenna gain as viewed from the ground while the spacecraft rotates in sun-safe mode.

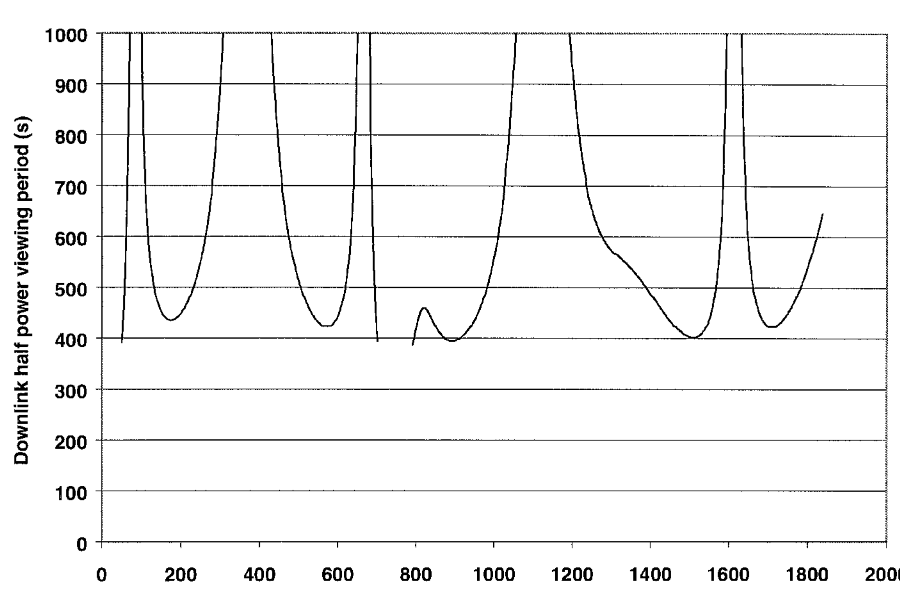


Fig. 4 Downlink beacon half-power viewing period as observed from the ground.

uplink stop-rotation command sequence: 1) two-way light time to the spacecraft, 2) uplink carrier acquisition sweep time, 3) length of the command sequence, including synchronization and other overhead bits, 4) time for ground operator delays, and 5) spacecraft deceleration time.

Figure 5 shows a typical uplink command scenario used for the NEAR spacecraft sun-safe recovery. The first element of the sequence is a sweep of the uplink carrier frequency to lock up the spacecraft receiver. The frequency range and sweep rate determine the time required to lock up the receiver. These parameters in turn depend on the predicted uplink signal strength, knowledge of the spacecraft receiver center frequency, and the characteristics of the spacecraft receiver carrier tracking loop. The sweep is followed by a delay of 15–30 s for ground station personnel to turn on the command subcarrier manually. A value of 30 s is assumed in the scenario. Following subcarrier turn on, the subcarrier is modulated with command data. The total number of bits per command is 464, including synchronization and other overhead bits. For the NEAR design two commands are sent, one for each of the redundant command processors onboard, at a bit rate of 7.8125 bps. Finally, a spacecraft deceleration time is accounted for.

The uplink stop-rotation sequence should be timed to stop the spacecraft rotation when the fanbeam antenna pattern is at its peak. This requires that adequate uplink signal margin exist for the entire sequence before the peak of the pattern. Typically, the uplink signal margin is strong enough to provide a wide enough window for the sequence to execute. If required, the sequence can be shortened by minimizing the sweep width ΔF through accurate knowledge of the receiver center frequency. Also, the stop-rotation sequence might be transmitted into a spacecraft LGA instead of the fanbeam antenna. Because the signal strength readings of the downlink beacon are recorded as a function of ground time, the two-way light time to the spacecraft must be accounted for in transmitting the stop-rotation sequence.

Flight Experience

The NEAR spacecraft went into sun-safe mode on two occasions during the 1996–1998 time frame. On both occasions, recovery was accomplished using the fanbeam antenna technique. The first episode occurred 17–19 August 1996 due to an improper ground control operation. This corresponded to mission days 182–184, with the spacecraft at an Earth distance of 1.3 AU and a SPE angle of

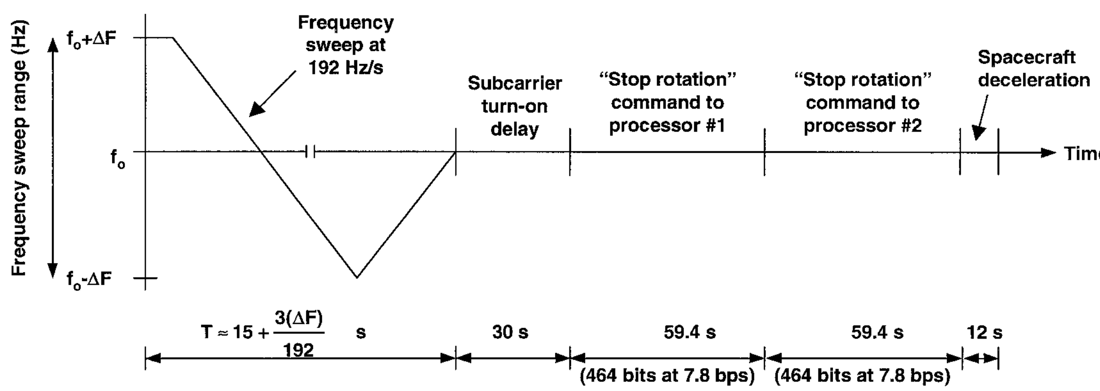
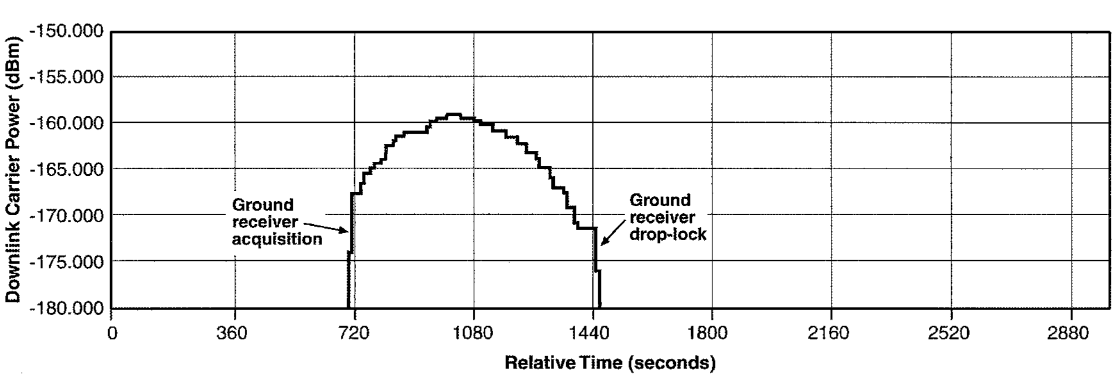
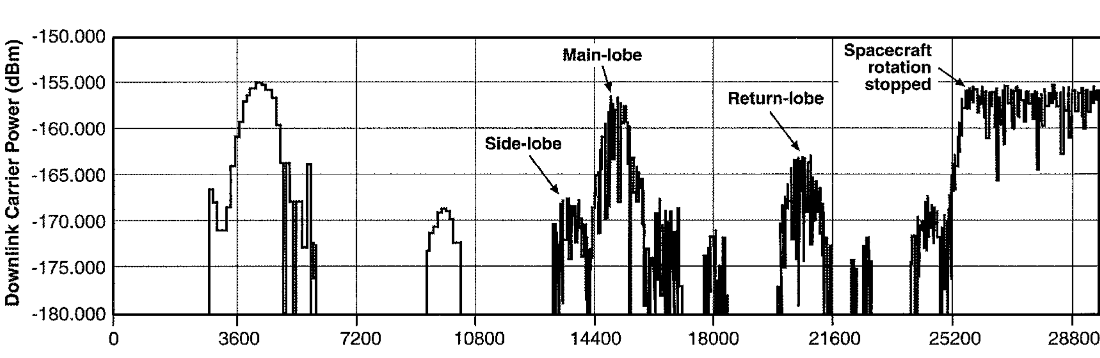


Fig. 5 NEAR uplink receiver acquisition and command timeline.



a) Record on 17 August 1996



b) Record on 22 December 1998

Fig. 6 Downlink signal strength records for the two NEAR sun-safe recovery episodes; note the difference in timescale between the two records.

33.9 deg. A link analysis predicted that the peak downlink signal strength would be −160 dBm using the Deep Space Network (DSN) 34-m-diam, high-efficiency dishes for recovery. With a system noise temperature of 30 K and a receiver phaselock loop bandwidth of $B_L = 3$ Hz, the lock threshold of the 34-m receiving system was about −172 dBm.

Figure 6a shows a record of the downlink signal strength during the August 1996 recovery. From Fig. 4, the predicted viewing period (−3 dB width) of the downlink signal is 436 s on mission day 182. This viewing period correlates reasonably well with the record in Fig. 6a. During this recovery effort, the spacecraft stayed in sun-safe rotation mode for 3 days before it was stopped with a ground command. The reason for the delay was that the command subcarrier frequency and bit rate, which were 16 kHz and 7.8125 bps, respectively, had not been compensated for Doppler shift. Once they were compensated, the stop-rotation command was received successfully on the first try. When this occurred on 19 August 1996, the spacecraft rotation was stopped 2.7 deg, or 81 s, later than the targeted phase. This error was likely due to the difficulty in determining the center of a relatively broad signal strength record. The error is 0.75% of a spacecraft rotation period.

The second sun-safe episode occurred as a result of an attitude anomaly that followed an aborted engine burn on 20 December 1998. The signal from the spacecraft was lost on 20 December 1998 due to a low voltage alarm that triggered an autonomous 24-h power down of the transmitter. When the signal was observed again on 21 December 1998, the spacecraft was in sun-safe mode. Recovery occurred on 22 December 1998. This corresponded to mission day 1039, with the spacecraft at an Earth distance of 2.5 AU and a SPE angle of 17.7 deg. A link analysis predicted that the peak downlink signal strength would be −157 dBm using the DSN 70-m-diam dishes for recovery. With a system noise temperature of 25 K and a receiver phaselock loop bandwidth of $B_L = 3$ Hz, the lock threshold of the 70-m receiving system was about −173 dBm.

Figure 6b shows a record of the downlink signal strength during the 22 December 1998 recovery. From Fig. 4, the predicted viewing period (−3 dB width) of the downlink signal is 809 s on mission day 1039. This viewing period correlates reasonably well with the record in Fig. 6b. The mission operations team observed one complete rotation to establish the rotation period, then sent the stop-rotation command. It was received successfully on the first try. Because of insufficient telemetry data, we were unable to determine the precise rotation angle at which the spacecraft stopped; however, it is apparent in Fig. 6b that the rotation was stopped close to the peak of the downlink pattern. A return lobe in the antenna pattern can be observed in Fig. 6b. This lobe is caused by the physical tilt of the antenna mount, as discussed earlier, which causes the wide plane radiation pattern to extend to the opposite side of the z axis. There is some variation in signal strength between main lobe events, possibly due to differences between ground stations or wobbling of the spacecraft z axis during recovery.

Conclusions

We have described an effective, robust, sun-safe recovery technique using a medium-gain fanbeam antenna. The technique is useful when insufficient signal margin exists for recovery of a deep space probe using traditional LGA techniques. The critical issues with this technique are the selection of rotation rate and the need for precise timing of the uplink stop-rotation command. Selection of the rotation rate is a compromise between the desire to recover the spacecraft quickly and the need for adequate time margin in the stop-rotation command sequence.

We have shown from experience on NEAR that the fanbeam recovery technique is robust. For both of the sun-safe episodes described (and all episodes to date), the spacecraft rotation was stopped on the first try. For the recovery event in August 1996, available telemetry shows that the rotation was stopped 2.7 deg from the targeted rotation phase. This corresponds to a timing error of 81 s, or 0.75% of a spacecraft rotation period. We believe that this timing error was due mainly to the difficulty in determining the rotation phase from the downlink signal strength record. For the recovery event in December 1998, precise stop-rotation phase data is not available, but the ground station signal strength record indicates that the rotation was stopped near the peak of the downlink signal pattern.

The fanbeam recovery technique is potentially useful for any deep space mission that has the freedom to rotate the spacecraft about the spacecraft–sun line during emergency mode. For outer planet trajectories, a single fanbeam antenna is adequate because the Earth typically falls within a limited angle of the sun as viewed from the spacecraft. For inner planet trajectories, two fanbeam antennas, each of 90-deg wide plane beamwidth and diametrically opposed, are likely to be required to cover the mission.

Acknowledgment

The Near Earth Asteroid Rendezvous program is sponsored by the NASA Office of Space Science.

References

[1] Bokulic, R. S., Flaherty, M. K., Jensen, J. R., and McKnight, T. R., "The NEAR Spacecraft RF Telecommunications System," *Johns Hopkins APL Technical Digest*, Vol. 19, No. 2, 1998, pp. 213–219.

[2] Bokulic, R. S., Flaherty, M. K., Jensen, J. R., and McKnight, T. R., "The NEAR Spacecraft RF Telecommunications System," *Johns Hopkins APL Technical Digest*, Vol. 19, No. 2, 1998, pp. 216, 217.

A. C. Tribble
Associate Editor