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Achieving and Maintaining Deep Space 1 Spacecraft High-Gain Antenna Pointing Control by Data Monitoring and Immediate Corrective Commanding

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The Deep Space 1 (DS1) onboard stellar reference unit failed in November 1999, leaving the spacecraft able to achieve only Sun point, with 8.4 GHz (X-band) communications reduced to the low rates supportable via a low-gain antenna. By January 2000, the DS1 project flight team implemented an interim three-axis pointing concept called the "HGA activity" because it made the high-gain antenna (HGA) usable again. The HGA activity involves the telecommunications analyst as an integral part of a closed-loop ground–spacecraft pointing control system. The HGA activity initiates pointing of the high-gain antenna toward the Earth and subsequently maintains pointing for the duration of one or two passes. The concept requires the tracking station to lock its receiver on the X-band carrier and provide carrier signal-to-noise ratio in monitor data in real time. The project telecommunications analyst uses the data to prepare accurate event timing predictions and to assess performance through rapid and precise comparisons of monitor and prediction data. Use of this labor-intensive and real-time process enabled the project to receive high-rate telemetry data from 14 passes through May 2000. Finally, another 14 HGA activities in June 2000 enabled the project to reload several megabytes of flight software at a high rate. The new software brought to an end the routine use of the HGA activity because it operates the science camera to generate star data for onboard pointing control. With full three-axis pointing capability restored for ion-propulsion subsystem thrusting, DS1 has resumed its science mission with a flyby of the comet Borrelly planned for September 2001.

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[1] Communications Systems and Research Section.

[2] Terrestrial Science Research Element.

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I. Introduction

The prelaunch design of telecommunications analysis for deep-space mission operations emphasizes the standard modeling of Earth–spacecraft links so their performances can be predicted and then compared against the predictions. As with other spacecraft subsystems, the intent is to plan normal operations by means of command sequences stored onboard days or weeks in advance of use. These normal operations become routine in the sense that they are made up of repetitive actions that are perfected through practice and use of standard procedures and data products. In addition to carrying out these routine activities, experienced telecommunications analysts with their adaptive tools can bring another significant value to a project. When a problem occurs, first-of-a-kind or one-of-a-kind analysis sometimes makes it possible to go beyond the existing "state of the practice" of standard sequenced operations by wringing more information out of the in-flight data or modeling capability inherent in the tool. Such improvisation and innovation is stressful and expensive in human effort relative to original plans but can make the difference between mission success and project termination.

This article describes how the Deep Space 1 (DS1) flight team responded to an onboard subsystem failure by replacing its functions with an innovative combination of analysis and control in near-real time from the ground. The functionality to be replaced was the control of the pointing of the body-mounted high-gain antenna (HGA) within an acceptable angle of the Earth. The "HGA activity," as it is called, is labor intensive and exacting in timing requirements. The round-trip light-time (RTLT) delay in the control loop is manageable. Ground-in-the-loop pointing resulted in the DS1 mission being able to continue until a new onboard pointing capability, not making use of the failed subsystem, could be invented. HGA activities started in December 1999 and continued through June 2000, when updated flight software enabled the new onboard method. In the future, HGA activities will be required during the reboot process for flight software updates. At least one more update, to enable comet flyby functions, is planned, in March 2001. This means the project needs to maintain the HGA activity skills described in this article.

This description of the HGA activity is from the perspective of the Telecommunications and Mission Operations Division (TMOD) telecommunications analysis service provided to the DS1 project.

II. Motivation for Ground-in-the-Loop Spacecraft Pointing Control

The DS1 spacecraft has a single Sun sensor assembly (SSA) and a single stellar reference unit (SRU). Together, these hardware and software provided for three-axis control of spacecraft pointing. During the prime mission (October 24, 1998, to July 31, 1999) and until November 11, 1999, the spacecraft pointed the high-gain antenna boresight at the Earth within a dead-band tolerance of 1 deg. The boresight, which is the nominal direction of peak gain for both the uplink and downlink X-band frequencies (nominally 7.1 GHz and 8.4 GHz, respectively), is aligned with the +x-axis of the spacecraft.

The spacecraft was found to be in safe mode after the scheduled tracking station was unable to acquire the expected downlink on November 11, 1999. Subsequent in-flight activities and data analysis indicated the SRU was inoperative with no recovery possible. The SRU was turned off permanently in June 2000 [1].

After November 11, the normal spacecraft orientation was with the +x-axis pointed at the Sun and the spacecraft rotating about that axis at one revolution per hour. In this Sun-standby SSA mode, DS1 communicated via one of its low-gain antennas (LGAs). This antenna is named LGAX because, like the HGA, it is boresighted on the +x-axis. The HGA has a 3-dB beamwidth of slightly greater than ±4 deg as compared with ±34 deg for LGAX. Supportable rates during the first half of 2000 via the Sun-pointed LGAX were 15.625-b/s uplink from a 34-m high-efficiency (HEF) station and 79-b/s downlink to a 70-m station. These contrast with the 2000-b/s uplink and 9480-b/s downlink being used with the Earth-pointed HGA prior to the SRU failure.

To return valuable science data already stored onboard at the time of the failure, as well as to maintain the possibility of a science mission to achieve data collection during a comet flyby in 2001, it was necessary to invent methods to point the spacecraft in the required directions. The ground-in-the-loop method using the ground-interpreted downlink carrier power level adequately achieved the easiest pointing requirement: HGA-to-Earth. This gave the project time to develop the pointing methods, not dependent on the RF signals, that are needed for arbitrary ion thrust and science-instrument pointing directions.

Fundamental to the ground-in-the-loop HGA activity is the idea of moving the spacecraft from its SRU-failed condition (+x-axis to the Sun), but by using only onboard attitude control system (ACS) inputs from the SSA. This initial motion was needed to ensure the x-axis would periodically point near the Earth within a predetermined time. With the HGA selected by onboard sequence for both uplink and downlink communications, the first part of the process was to determine from the downlink the timing (phase reference) of the +x-axis motion relative to the Earth. Next was to transmit a precisely timed uplink carrier to lock the spacecraft receiver, followed by a command to stop the continuous x-axis motion. And last was to maintain the x-axis pointing position for the remaining hours of the station pass.

Using the measured downlink, P_c/N_o (carrier power-to-noise spectral density ratio), from the Block V receiver (BVR), people on the ground determined the pointing condition as a function of time. By plan, once the HGA was stopped near Earth point, the position was fairly stable but still subject to drift of several degrees per hour. The drift could be counteracted by sending corrective turn commands to the spacecraft. The size and timing of the corrective turn were based on the telecommunications analyst's judgment of recent downlink performance. This technique was made more complex by the RTLT delay between sending a command and seeing the first evidence of its effect in the downlink data. DS1 RTLT varied from 29 to 35 minutes during the first half of 2000.

Ground-in-the-loop HGA pointing control, once it became routine, required an hour or so of telecommunications planning and prediction in advance of the pass. Prepass planning was so the analyst could determine uplink times within a few minutes of seeing the periodic downlink. Prediction was so the analyst could determine from observed carrier levels what downlink data rate to command. The planning tool was an Excel spreadsheet (to be described), customized for the particular station pass times and RTLT. The prediction tool was the Telecom Forecaster Predictor (TFP) [2].

Once the 6- to 10-hour pass began, conducting an HGA activity required that a telecommunications analyst watch the data full-time. It also required "additional duty" work by the systems analyst who was the flight director and by the project mission controller (known by the voice-net call sign "ACE") who coordinated tracking-station activities and radiated commands. HGA activities were done approximately once every 2 weeks for data return through May 2000. They were required daily during the flight software upload in June 2000, with uplinking for as long as 16 hours per day.

III. Modeling and Verifying Signal Level During an HGA Activity

Prior to the SRU failure, DS1 telecommunications links during HGA Earth-pointed operation were modeled using standard statistical link design techniques [3,4]. A link budget or design control table at a specified time shows the mean value and the variance of each link parameter and those of the various observable quantities, such as carrier power, P_c, and signal-to-noise ratio (SNR). These quantities also can be tabulated or plotted as a function of time using the DS1 link prediction program called the TFP.

To model the planned DS1 HGA coning, the TFP was augmented with the following attitude-pointing heuristic.[3] This pointing mode is called coning because it makes the +x-axis (and HGA boresight) sweep out the surface of a cone. This heuristic is quick and dirty, but it closely matches what the TFP would

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[3] Provided by R. H. Tung, personal communication, Jet Propulsion Laboratory, Pasadena, California, December 16, 1999.

predict from using the actual geometry because the Sun–spacecraft–Earth (SCE) angle does not vary much over one pass:

(1) Set the unit vector spacecraft-to-Sun aligned with the x-axis [1 0 0] of the spacecraft reference frame.

(2) Set the unit vector spacecraft-to-Earth aligned with $[\cos(SCE)\,\sin(SCE)\,0]$, where SCE is the Sun–spacecraft–Earth angle at the time of the first prediction point, normally the station beginning of track (BOT).

(3) Generate the rotation matrix to rotate about the Sun line (simple rotation about the +x-matrix) at the given rate, and rotate the unit vector spacecraft-to-Earth about this line.

(4) Compute the angle from the HGA boresight to Earth by finding the vector between the rotating vector and the original unit vector spacecraft-to-Earth.

Prior to HGA activities, there were precursor HGA coning tests in late 1999. In the coning tests, the +x-axis and the HGA were put into the same initial motion as for an HGA activity, but the antenna was not stopped. Figure 1 shows the good agreement between the TFP heuristic and the observed downlink level during the second HGA coning test on December 22, 1999. The smooth curve is the predicted P_c/N_o assuming a coning rate of 1/45 minute. The irregular curve is made from the values of P_c/N_o at 1-second intervals produced by the full-spectrum recorder (FSR). The HGA downlink pattern modeled by the TFP and the coning heuristic together produced a very accurate prediction for the dB level of the main HGA beam and accurate predictions of the relative timing of the first nulls relative to the peak gain time. The absolute time of the main beam cannot be predicted; it is observed during the activity. The first null is the angular location in the antenna pattern of the minimum dB level between the main beam and the

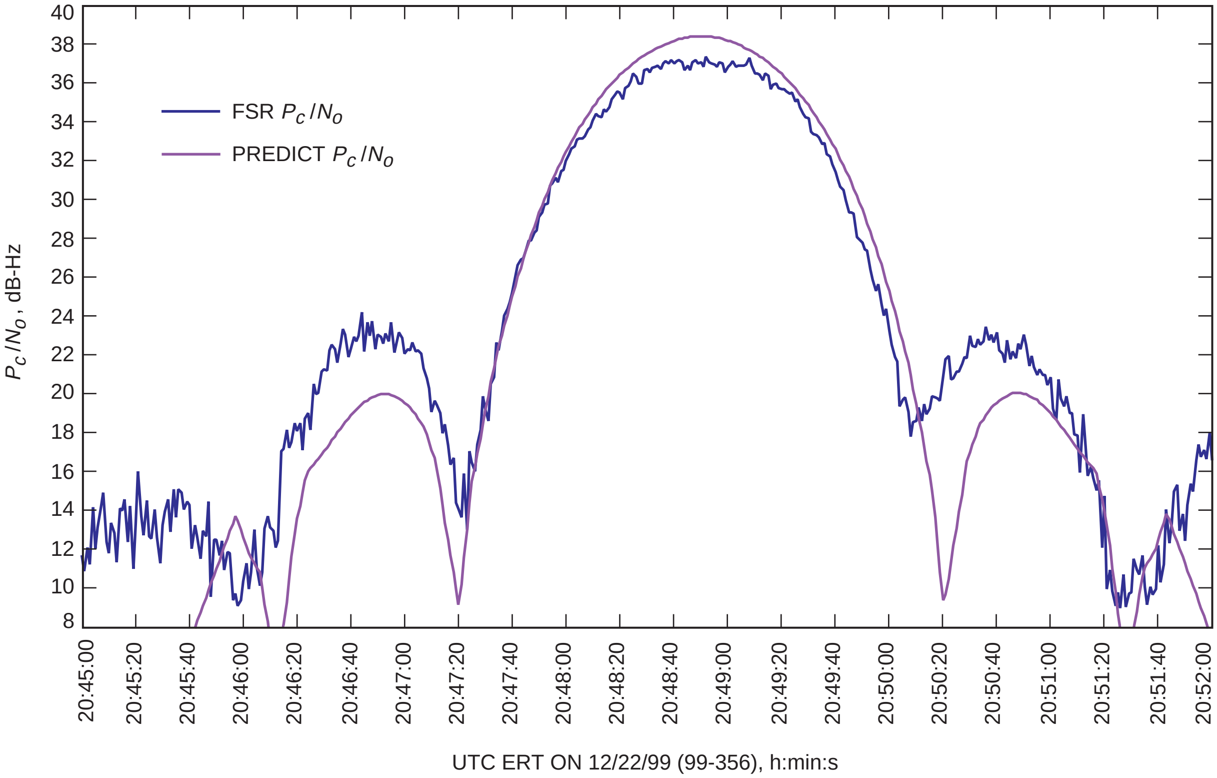


Fig. 1. FSR P_c/N_o versus TFP predicts for the second coning test.

first side lobe. In Fig. 1, first nulls were predicted at 20:47:20 and 20:50:20 assuming the observed main peak at 20:48:50. The first nulls were observed at 20:47:23 and 20:50:08, for a relative accuracy of better than 10 seconds out of 45 minutes. The first side-lobe peak levels were modeled within 2.5 dB of the level observed, and the second null relative times were predicted within 20 seconds of the observed times.

These results from the HGA coning gave us confidence to begin designing an HGA activity that would build on the coning but that would stop the HGA while it was pointed near the Earth. The coning tests were downlink only. However, the TFP also had a modeled HGA uplink pattern (a lookup table equivalent to Fig. 2). The telecommunications analyst ran a number of test cases in which the uplink received power and command E_b/N_o (energy per bit-to-noise spectral density) were predicted for various coning rates and SCE angles. These runs assumed the use of the 4-kW transmitters at 34-m beam-waveguide (BWG) antennas. From this work, telecommunications recommended the project use a 1/45-minute coning rate, a short uplink acquisition sweep, and a 31.25-b/s command rate to stop the HGA:

(1) Coning (spin) rate: This rate determines how often the HGA peak passes by the Earth as well as the duration that the main beam is on the Earth. Telecommunications specified a coning rate of 1/45 minutes to minimize the time to get the HGA stopped while providing for enough reaction time (from downlink observation to uplink command).

(2) Short sweep: The station transmitter should tune ±10 kHz from the best-lock frequency of the spacecraft receiver for DS1 instead of the standard ±30 kHz. Use the same 300-Hz/s sweep rate as for the low-gain antenna. The efficient, short sweep pattern required less than 2 minutes to complete, in contrast to the standard of nearly 7 minutes.

(3) Command rate: For a fixed command acquisition and data length in bits, the higher the rate is, the quicker the command is completed and the higher the required signal level. The 31.25-b/s rate has a duration of 24 seconds and a threshold compatible with the 34-m BWG stations and the HGA coning rate.

Because we did not know how variable the nominal 1/45-minute coning rate would be, we planned to observe two peaks, establish the interval between them, and then assume the interval to the third peak would be the same.

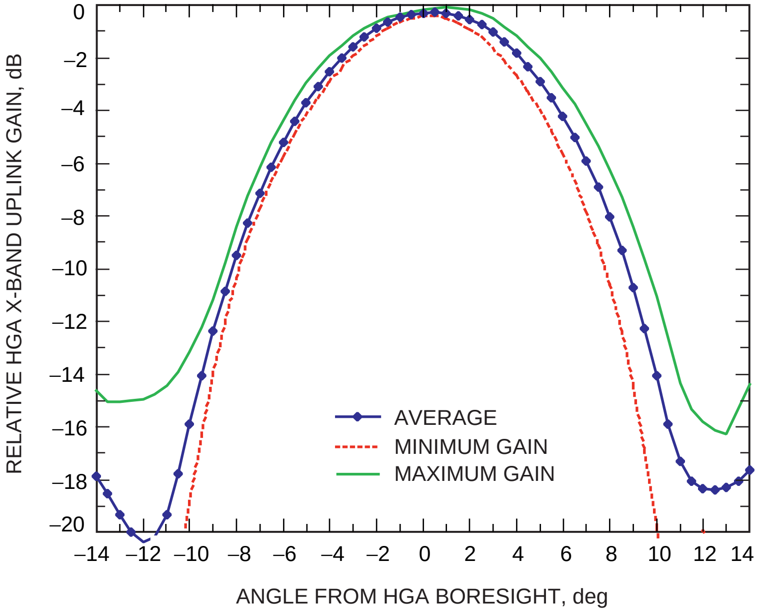


Fig. 2. X-band HGA uplink pattern for DS1 HGA command timing.

The telecommunications analyst is one member of the DS1 flight team. The attitude control system (ACS), mission control, and systems people played integral parts in this planning work. It became apparent that a standardized and therefore repeatable process would be necessary to determine the times the peaks occurred and to perform the consequent station and project actions required to stop the HGA successfully. The DS1 telecommunications lead analyst (Jim Taylor) developed the spreadsheet described below to accomplish these observations and actions.

IV. The Planning Spreadsheet

Figure 3 is a schematic showing as timelines the relationship between activities on the spacecraft and those on the ground from the time the downlink from the HGA is first observed to the time the stop-coning command reaches the spacecraft. The top and bottom horizontal lines represent the flow of time at the spacecraft and the ground, respectively. The diagonal lines suggest the movement of downlink radio signals from the spacecraft or uplink signals to the spacecraft. No absolute times appear on the chart, only a 45-minute coning interval and (as an example) a 32-minute RTLT.

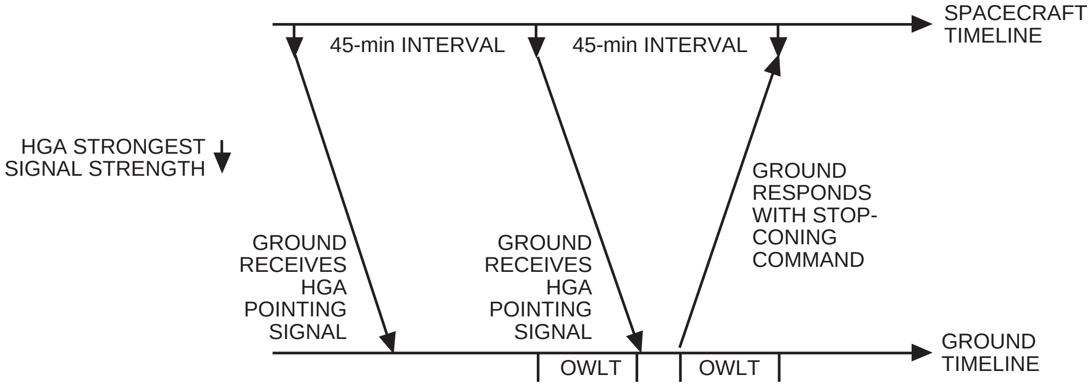
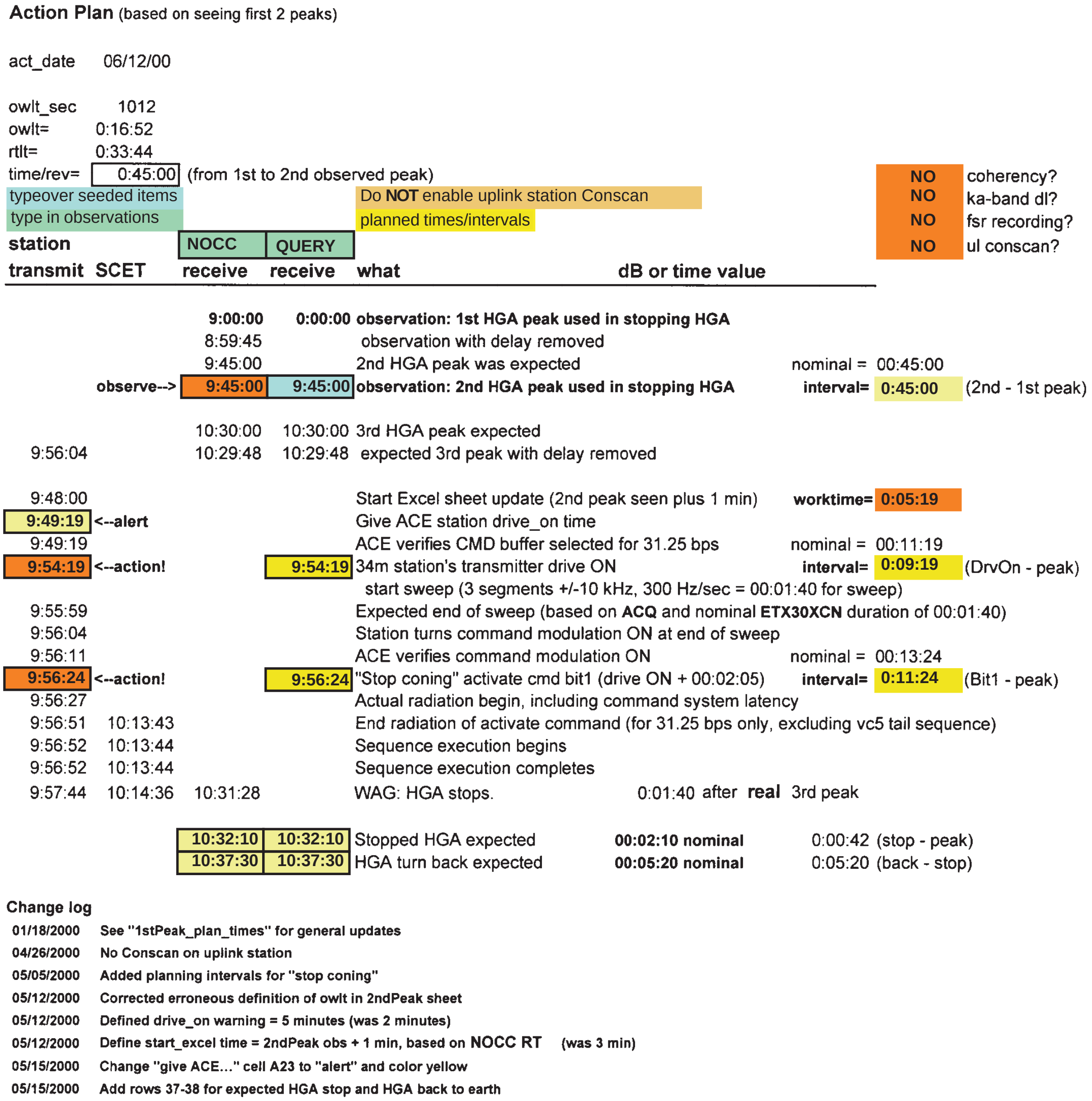


Fig. 3. Timeline at the spacecraft and on the ground for a 45-minute coning interval.

The spacecraft performs one coning every 45 minutes. For the spacecraft to be commanded, the coning HGA must be close enough to Earth while uplink carrier acquisition occurs and command reception/decoding completes. The highest downlink signal strength received by the ground is a one-way light-time (OWLT) (16 minutes in this example) after the HGA on the spacecraft is Earth pointed. The uplink signal from Earth also takes an OWLT to reach the spacecraft. For a coning rate of 45 minutes, an OWLT of 16 minutes, and zero downlink observation, carrier acquisition, and command durations, the ground will have 13 minutes to analyze the signal and send the commands. Because these durations are not zero, and the coning period can vary from ±1 minute, the actual time to react in May 2000 was about 5 minutes.

Since the spacecraft is coning, the window for successfully stopping the HGA spans no more than 2 minutes with a 4-kW BWG transmitter. With an 18-kW HEF transmitter, the window spanned no more than 4 minutes. Figure 3 shows DS1 usually had the telecommunications analyst observe two peaks to a pass to see the actual rate of coning. The rate of coning, assumed constant during a particular activity, is taken as the time of the second observed peak minus the time of the first observed peak. We then applied that as the coning rate to the third peak, based on a constant-rate assumption for the spacecraft environment on that day. The non-zero window durations allowed for this to work.

The planning spreadsheet (Fig. 4) is the tool we used to achieve initial HGA pointing, starting from the +x-axis to the Sun condition. Figure 4 is the second of three parts of the planning sheet, and this part is used to direct the most time-critical parts of the HGA activity. Part 1 (not shown), largely prepared before the pass, has one observation time value to enter in real time. Part 3 (not shown) is



Action Plan (based on seeing first 2 peaks)

act_date 06/12/00

owlt_sec 1012
owlt= 0:16:52
rtlt= 0:33:44
time/rev= 0:45:00 (from 1st to 2nd observed peak)

typeover seeded items
type in observations

Do **NOT** enable uplink station Conscan
planned times/intervals

NO	coherency?
NO	ka-band dl?
NO	fsr recording?
NO	ul conscan?

station **transmit**	**SCET**	**NOCC** **receive**	**QUERY** **receive**	**what**	**dB or time value**		
		9:00:00	**0:00:00**	**observation: 1st HGA peak used in stopping HGA**			
		8:59:45		observation with delay removed			
		9:45:00		2nd HGA peak was expected	nominal =	00:45:00	
	observe-->	**9:45:00**	**9:45:00**	**observation: 2nd HGA peak used in stopping HGA**	**interval=**	**0:45:00**	(2nd - 1st peak)
		10:30:00	10:30:00	3rd HGA peak expected			
9:56:04		10:29:48	10:29:48	expected 3rd peak with delay removed			
9:48:00				Start Excel sheet update (2nd peak seen plus 1 min)	**worktime=**	**0:05:19**	
9:49:19	**<--alert**			Give ACE station drive_on time			
9:49:19				ACE verifies CMD buffer selected for 31.25 bps	nominal =	00:11:19	
9:54:19	**<--action!**		**9:54:19**	34m station's transmitter drive ON	**interval=**	**0:09:19**	(DrvOn - peak)
				start sweep (3 segments +/-10 kHz, 300 Hz/sec = 00:01:40 for sweep)			
9:55:59				Expected end of sweep (based on **ACQ** and nominal **ETX30XCN** duration of 00:01:40)			
9:56:04				Station turns command modulation ON at end of sweep			
9:56:11				ACE verifies command modulation ON	nominal =	00:13:24	
9:56:24	**<--action!**		**9:56:24**	"Stop coning" activate cmd bit1 (drive ON + 00:02:05)	**interval=**	**0:11:24**	(Bit1 - peak)
9:56:27				Actual radiation begin, including command system latency			
9:56:51	10:13:43			End radiation of activate command (for 31.25 bps only, excluding vc5 tail sequence)			
9:56:52	10:13:44			Sequence execution begins			
9:56:52	10:13:44			Sequence execution completes			
9:57:44	10:14:36	10:31:28		WAG: HGA stops.	0:01:40 after **real**	3rd peak	
		10:32:10	**10:32:10**	Stopped HGA expected	**00:02:10 nominal**	0:00:42	(stop - peak)
		10:37:30	**10:37:30**	HGA turn back expected	**00:05:20 nominal**	0:05:20	(back - stop)

Change log

01/18/2000	**See "1stPeak_plan_times" for general updates**
04/26/2000	**No Conscan on uplink station**
05/05/2000	**Added planning intervals for "stop coning"**
05/12/2000	**Corrected erroneous definition of owlt in 2ndPeak sheet**
05/12/2000	**Defined drive_on warning = 5 minutes (was 2 minutes)**
05/12/2000	**Define start_excel time = 2ndPeak obs + 1 min, based on NOCC RT (was 3 min)**
05/15/2000	**Change "give ACE..." cell A23 to "alert" and color yellow**
05/15/2000	**Add rows 37-38 for expected HGA stop and HGA back to earth**

Fig. 4. The planning spreadsheet used to observe HGA peaks and to stop the coning.

mainly intended as a log of command transmission times and spacecraft and station configuration change times that occur once the spacecraft x-axis coning-motion stops. All three parts have columns for station transmit time (called TRM), spacecraft event time (SCET), which is an OWLT later, and Earth receive time (ERT), yet another OWLT later.

We continuously improved the spreadsheet design based on experience from each HGA activity. Figure 4 is the one that was used on June 12, 2000. The first part of the spreadsheet is prepared prior to the BOT of the station pass. In this part 2, only a "peak 2" observation time, to be described later, needs to be entered in the "observe→" shaded cells. Except for the "peak 1" observation time entered previously on the first part of the sheet, all other timing in the part 2 sheet is based on the one entered value. With that entry, the sheet updates everything else, including the times in the two dark-shaded "←action" cells, also to be described later. Spreadsheet parts 2 and 3 are filled in with data monitored during the pass. The spreadsheet is on a PC in the DS1 mission support area, within a few steps from the telecommunications displays and the ACE's position. The telecommunications analyst monitors station and spacecraft data and operates the spreadsheet. When time is short, the analyst is able to immediately communicate the ←action times by voice from the PC to the ACE.

Also prior to BOT, an onboard sequence ("start coning") activates at a previously commanded time to put the ACS into a coning mode that ensures the HGA will sweep the direction of maximum gain past the Earth periodically. The same sequence also switches the telecommunications system from LGAX to HGA, removes telemetry modulation from the downlink carrier, and sets the onboard command reception rate to 31.25 b/s. The spacecraft is now in a communications mode that is not supportable unless the tracking station can command to the HGA and can receive downlink from the HGA. Should an HGA activity fail to stop the coning, a "lifeboat" sequence would execute at the end of the pass to automatically return the +x-axis to Sun point, reselect LGAX, and reduce the command rate to 7.8125 b/s. (None of the DS1 planned HGA activities failed, however.)

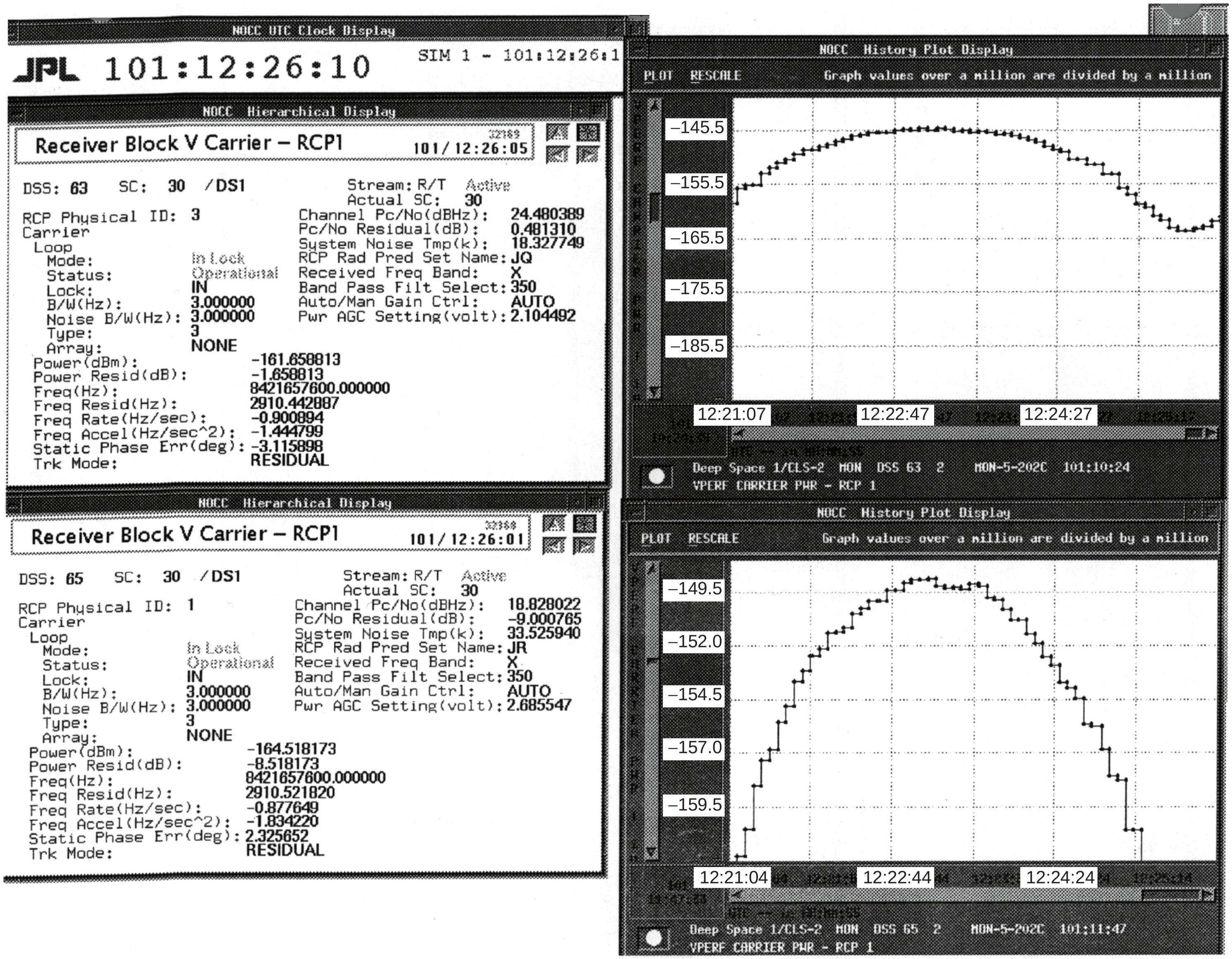
Here's how the spreadsheet is used, in cooperation with the ACE, the project mission director (who authorizes command radiation), and the operating personnel at the tracking station. Using the spreadsheet, the telecommunications analyst observes and times the occurrence of two sweeps of the boresight past Earth. These are referred to the first peak and the second peak. These peak times and the OWLT determine when an uplink has to be sent to reach the spacecraft as the HGA is pointed near the Earth the third time.

The spreadsheet also relies on reasonable stability in the rate of the coning motion. From in-flight coning tests we did in December 1999, we found we could shorten the time for one coning revolution from an hour down to 45 minutes and still have time to do the actions shown in Fig. 4. Although the rotation rate is known with good accuracy, the time calculations in Fig. 4 utilize the actual interval between first-peak and second-peak observation times. Because of drift in the onboard inertial measuring unit (IMU) portion of the ACS, no attempt is made to control when the boresight will first sweep past the Earth after BOT. Thus, observations of the peaks are required because the onboard coning motion starts at an arbitrary time before the first peak sweeps past Earth.

Based on the two spreadsheet ←action cells in Fig. 4, the telecommunications analyst advises the project's mission controller (ACE) of the exact time to have the tracking station initiate an uplink to the spacecraft. The analyst also tells the ACE the exact time to radiate a real-time command (called "stop coning" in this article). Through June 2000, the DS1 project scheduled 28 HGA activities. This spreadsheet process was successful in stopping coning every time. In two cases, the spreadsheet had to be adapted in real time to stop the antenna on a third or fourth observed peak. One case was when ground-station problems prevented the uplink from being initiated or completed in time to radiate the command. The other was when everything seemed to have been done correctly, yet the spacecraft continued to cone. On the other hand, the sheet was adapted in advance for June 10, 2000, to stop the antenna after one observed peak (counting on the coning rate to be close enough to 45 minutes). This single-peak observation coning stop was also successful.

V. Initially Pointing the HGA

At BOT, the tracking station has its antenna pointed in the predicted direction of DS1. However, it was unlikely that the BVR would be in lock since the HGA pointing at BOT would probably not be toward the Earth. Using a specific DS1 configuration table for the station's BVR that admits a wide range of received downlink levels, the station was required to acquire lock on the downlink X-band carrier when it came above threshold. At a 45-minute spacecraft rotation rate, the carrier at a 34-m station rises from threshold to maximum level and back to threshold in about 6 minutes. In the DS1 mission support area (MSA), the telecommunications analyst monitored the BVR P_c/N_o data that were displayed graphically on the network operations control center real-time (NOCC RT) workstation. Figure 5 is an



```
NOCC UTC Clock Display
JPL 101:12:26:10          SIM 1 - 101:12:26:1

NOCC Hierarchical Display
Receiver Block V Carrier – RCP1                 32189
                                            101/ 12:26:05
DSS: 63    SC:   30   /DS1           Stream: R/T   Active
                                     Actual SC:   30
RCP Physical ID:  3                Channel Pc/No(dBHz):     24.480389
Carrier                            Pc/No Residual(dB):      0.481310
  Loop                             System Noise Tmp(k):     18.327749
   Mode:              In Lock      RCP Rad Pred Set Name:   JQ
   Status:            Operational  Received Freq Band:      X
   Lock:              IN           Band Pass Filt Select:   350
   B/W(Hz):           3.000000     Auto/Man Gain Ctrl:      AUTO
   Noise B/W(Hz):     3.000000     Pwr AGC Setting(volt):   2.104492
   Type:              3
   Array:             NONE
 Power(dBm):                -161.658813
 Power Resid(dB):           -1.658813
 Freq(Hz):                  8421657600.000000
 Freq Resid(Hz):            2910.442887
 Freq Rate(Hz/sec):         -0.900894
 Freq Accel(Hz/sec^2):      -1.444799
 Static Phase Err(deg):     -3.115898
 Trk Mode:                  RESIDUAL

NOCC Hierarchical Display
Receiver Block V Carrier – RCP1                 32368
                                            101/ 12:26:01
DSS: 65    SC:   30   /DS1           Stream: R/T   Active
                                     Actual SC:   30
RCP Physical ID:  1                Channel Pc/No(dBHz):     18.828022
Carrier                            Pc/No Residual(dB):      -9.000765
  Loop                             System Noise Tmp(k):     33.525940
   Mode:              In Lock      RCP Rad Pred Set Name:   JR
   Status:            Operational  Received Freq Band:      X
   Lock:              IN           Band Pass Filt Select:   350
   B/W(Hz):           3.000000     Auto/Man Gain Ctrl:      AUTO
   Noise B/W(Hz):     3.000000     Pwr AGC Setting(volt):   2.685547
   Type:              3
   Array:             NONE
 Power(dBm):                -164.518173
 Power Resid(dB):           -8.518173
 Freq(Hz):                  8421657600.000000
 Freq Resid(Hz):            2910.521820
 Freq Rate(Hz/sec):         -0.877649
 Freq Accel(Hz/sec^2):      -1.834220
 Static Phase Err(deg):     2.325652
 Trk Mode:                  RESIDUAL

NOCC History Plot Display
Deep Space 1/CLS-2  MON  DSS 63  2    MON-5-202C  101:10:24
VPERF CARRIER PWR - RCP 1

NOCC History Plot Display
Deep Space 1/CLS-2  MON  DSS 65  2    MON-5-202C  101:11:47
VPERF CARRIER PWR - RCP 1
```

Fig. 5. Real-time display of station monitor data during observation of HGA peak.

example of the NOCC RT display set up for an HGA activity. This one includes a P_c/N_o plot from each of two stations and was made about 3 minutes after the second peak that occurred on the April 10, 2000, HGA activity, indicated in universal time as day of year 101. This example shows the downlink was being received simultaneously at the 70-m station (DSS 63) and a 34-m station (DSS 65) at Madrid.

With the time of the first-peak observed P_c/N_o entered, part 1 of the spreadsheet calculates corresponding "heads-up" drive-on and stop-coning command times for the ACE to verify the uplink configuration. The ACE made sure the station entered the correct tuning parameters (lacking only an exact start time, which will come from part 2) for the "short sweep" uplink acquisition. The ACE and DS1 telecommunications discovered an effective, practical way to verify station sweep parameters and frequency predicts. The station was asked to enter the nominal transmitter drive-on time, read the resulting end-tune time, and then delete the entry. Correct predicts and parameters resulted in tunes that are 1 to 2 minutes long. As an additional heads up, the ACE advised the station when they should be able to lock the BVR to the downlink on the second peak. About 45 minutes later, the telecommunications analyst repeated the process of observing and timing the (second) peak and entering the time into the planning spreadsheet. The spreadsheet calculated the time difference from 45 minutes of the actual interval between observed first and second peaks. The spreadsheet calculated a revised transmitter drive-on time and stop-coning command radiation time accordingly. The telecommunications analyst provided the flight director with these times as recommendations. Using an independent spreadsheet, the flight director verified the times and gave the ACE direction to act. After the first half dozen HGA activities, it was clear that DS1 telecommunications and the ACE could perform the stop-coning activity and the subsequent maintain-pointing activity on their own.

For more precision, the analyst also used the multimission ground data system (MGDS) to query and plot the channelized data with standardized vertical and horizontal scales of 20 dB and 5 minutes, respectively (Fig. 6). Moving a carefully sized plastic overlay of the HGA downlink pattern (Fig. 7) over the printed MGDS plot, the analyst could determine the first peak time within ±2 seconds. Figure 6 shows such a scaled MGDS plot for the second peak on April 12, 2000 (the time axis labeled as 00-101). The peak was determined at 12:23:10 as compared with the 12:23:07 "eyeballed" from the smaller and less well-scaled NOCC RT (Fig. 5). The analyst enters the "2nd peak observed" time in the "observe→" spreadsheet cell. Two cells are available, one for the NOCC RT time and the other for the MGDS plot time. The agreement between the two plots was usually within 10 seconds, more than sufficient.

The first HGA activities gave the analyst about 10 minutes of work time, starting from the observation of the second peak, to calculate and give the drive-on time to the ACE. This work time came from the magnitude of the RTLT as well as from the willingness of many station crews to enter and confirm the drive-on setup parameters in less than the standard 5 minutes. With the increasing RTLTs of the later activities, as well as the need to allow all crews the standard drive-on setup time, the telecommunications analyst work time shrank. Figure 4 shows the work time was little more than 5 minutes on June 12, 2000. Obviously there was no time for recovery, except to wait for another 45 minutes, if any computer or system was down or any human miscue occurred. From experience, the following expedients resulted in very few miscues:

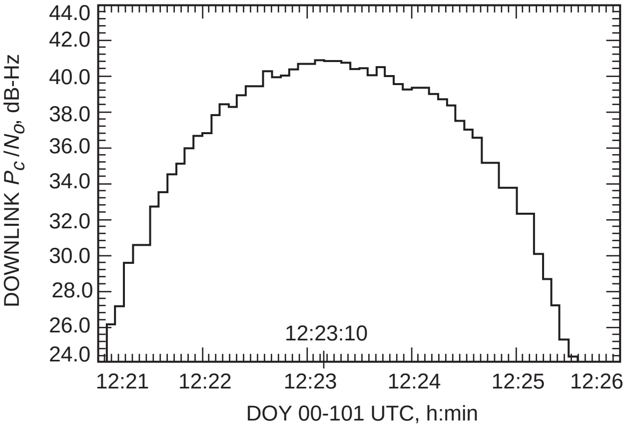


Fig. 6. P_c/N_o monitored during HGA peak, from non-real-time query of station data.

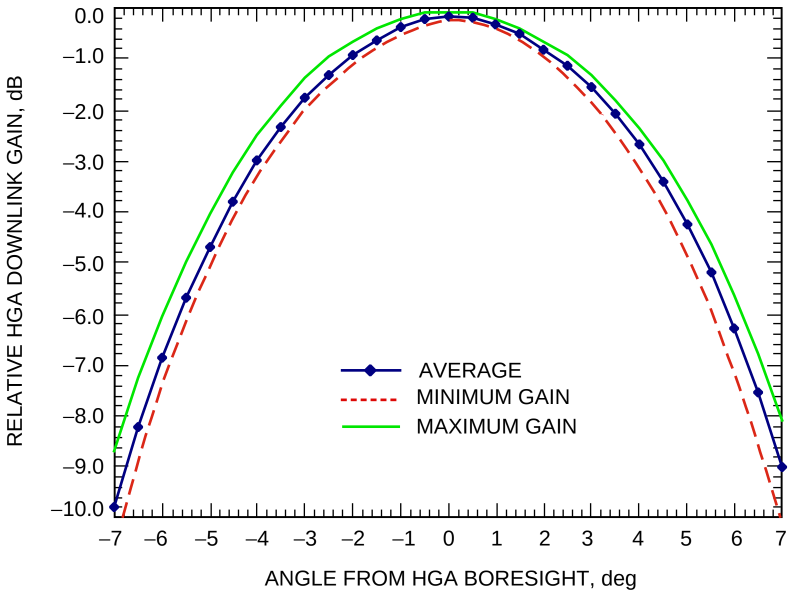


Fig. 7. X-band downlink pattern for DS1 HGA activity peak timing.

(1) Verification of correct station tune parameters and predicts based on nominal drive-on from first-peak time

(2) Operation of the planning spreadsheet in the MSA (formerly, it was done in the telecommunications analyst's nearby office)

(3) All HGA activities done by a single well-trained ACE and either of two well-trained telecommunications analysts

(4) Reliance on the NOCC RT display only, eliminating time for query, rescaling, printing, and analysis of the MGDS plot

(5) Adding to the planning spreadsheet the expected time from the third-peak observation to the stopped-antenna observation

This last expedient provided the telecommunications analyst a stop/no stop time criterion, after which the analyst could immediately redefine the third peak as the ←action peak. This saved one 45-minute rotation time, because the analyst could give the ACE a new drive-on time to get the antenna stopped on the fourth peak.

Besides what could be put on the planning spreadsheet and be seen in the NOCC RT displays, the station and DS1 personnel had no immediate feedback that their actions were correct. Because of RTLT, the station had no downlink carrier in lock at the time the uplink sweep started. Even so, the 45-minute rotation rate proved to allow sufficient time to accomplish the steps while minimizing the time lost at the beginning of the track getting the HGA pointed to Earth and telemetry started. For the HGA activities in March and April 2000, the time from BOT to when high rate (normally 4424 kb/s for a 70-m station) telemetry began to flow varied from 2-1/2 to 2-3/4 hours. The project used a time of 3 hours when planning the number and duration of station passes for the flight software upload in June.

The uplink ←action times account for the time delay of 12 seconds from the time the BVR received the peak carrier power to when the measurement of P_c/N_o was time tagged in the channelized monitor data. We determined this delay by comparison of time tags in the monitor data, the BVR log file (which includes P_c/N_o, but is not normally available to operations), and an independent open-loop system, the

FSR. Both the BVR log file and the FSR P_c/N_o log file provide data at 1-second intervals, as compared with the 5-second intervals of the channelized monitor data. Figures 8 and 9 (expanded time scale) show the BVR log file and the FSR log file 1/s P_c/N_o outputs in contrast with the 1/5-s monitor data for the January 14, 2000, HGA activity in which the 12-second delay was first pinned down. The plots also show the excellent time agreement between P_c/N_o from the BVR and that from the FSR, as well as showing less than 0.3-dB average difference in level between the two systems.

As Fig. 4 shows, the station is assumed to take about 1-1/2 minutes to perform the short uplink acquisition sweep that allows for ±10 kHz at X-band at a rate of 300 Hz/s. This sweep reached the spacecraft when the Earth was sufficiently close to HGA boresight, coming up on the main lobe of

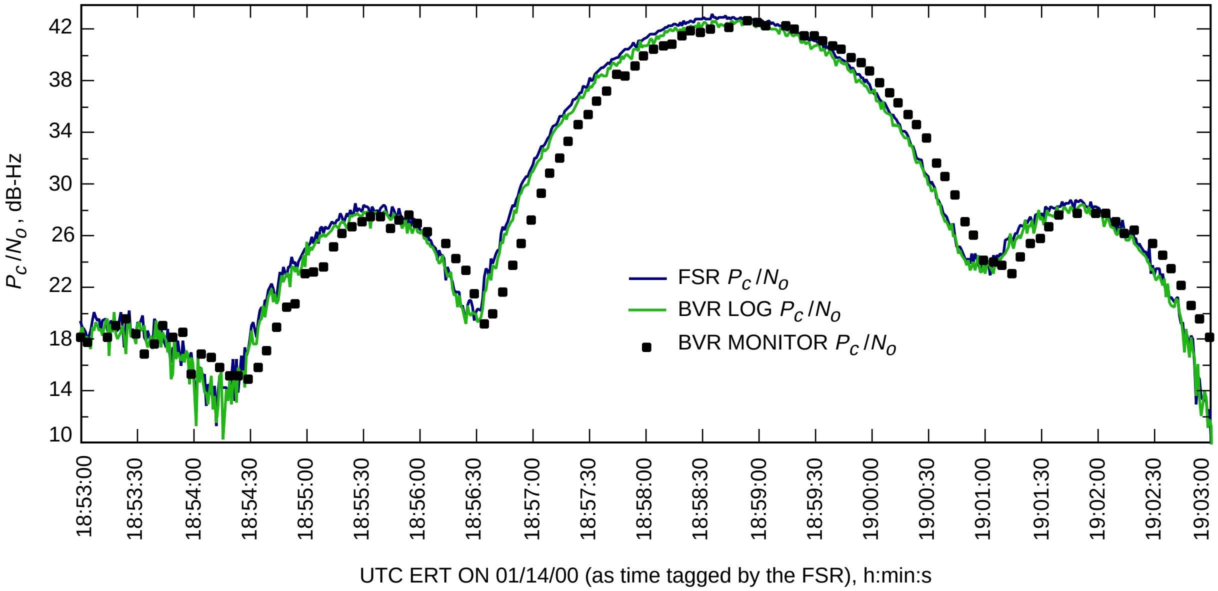


Fig. 8. Comparison of P_c/N_o from the FSR, the BVR log file, and the station monitor data from the BVR.

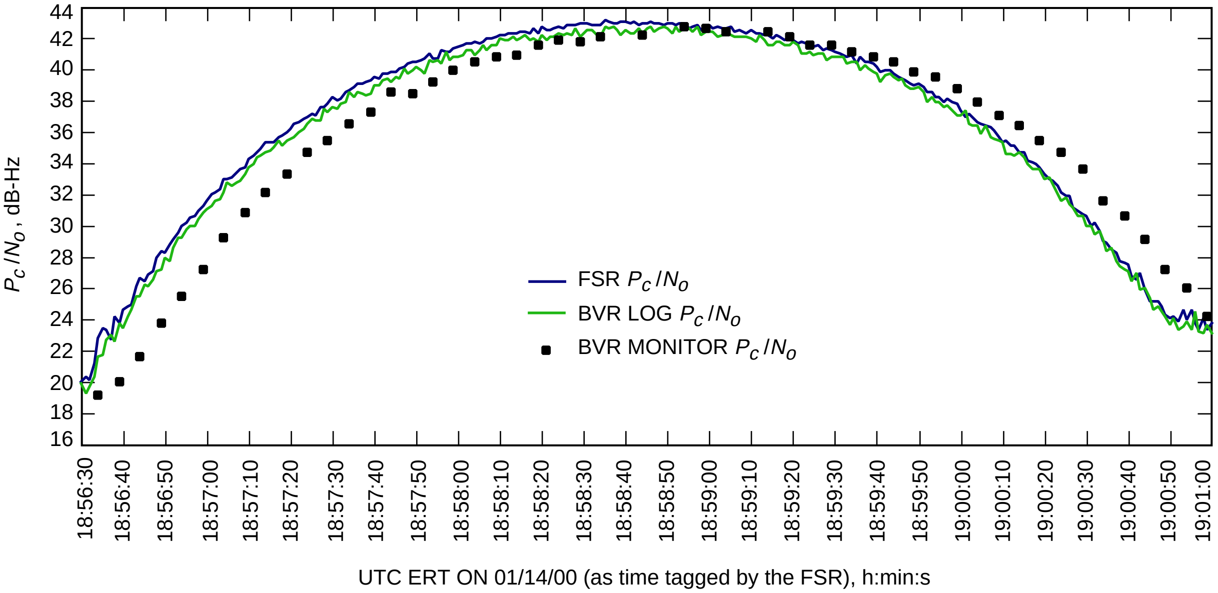


Fig. 9. Expansion of Fig. 8 P_c/N_0 values showing main-beam timing and amplitude differences.

the antenna pattern. The station would be instructed in advance to turn command modulation on immediately at the completion of the sweep, without waiting for direction from the ACE. The ACE had the stop-coning command on disk ("staged") at the station, and then made the command go active at the time determined by the spreadsheet. There were delays inherent in the systems as well as non-zero durations of the uplink sweep and the command radiation. Figure 4 shows a planned 2-1/2-minute span from transmitter drive on to end of command radiation.

At the spacecraft, the station's uplink frequency sweep was timed to arrive when the HGA boresight was still about 6 deg from Earth line. The sweep would complete and the command modulation would be put on the uplink to arrive when the boresight was near Earth line. HGA activities used a command rate of 31.25 b/s for the stop-coning command. This rate was high enough for the command to complete before the boresight reached 6 deg from Earth line on the other side of the pattern, and low enough that a 34-m beam waveguide station with a 4-kW transmitter would remain above command threshold at the 6-deg angle. The ±6 deg limits correspond to about the -6 dB points of the HGA X-band uplink pattern. For a 4-kW 34-m BWG transmitter, we had estimated this entire process to have a tolerance of about 30 seconds, after which command decoding might go below threshold before it could complete. The third-peak downlink P_c/N_o data from the April 27, 2000, HGA activity, not included here, indicated the stop-coning command nearly did not get in. The uplink sweep was on time, but command system problems delayed transmission of the stop-coning command from the 34-m BWG station by about 1-1/2 minutes.

The stop-coning sequence that is activated includes a turn to move the HGA boresight back to Earth line after the 1/45-minute coning motion stops. The turn size is about 13 deg in the negative y-direction, and it is included in the stored sequence and is the same for every HGA activity. Therefore, the full success of the stop-coning sequence depends on the sequence being activated within a few seconds of the time dictated by the planning spreadsheet. Figure 10, for the January 14, 2000, activity, shows the 1/s BVR log and 1/s FSR log P_c/N_o values through the third peak (~20:29 UTC), the HGA stop (~20:33 UTC), and the sequenced turn back to Earth (completed at ~20:39 UTC). For well-timed HGA

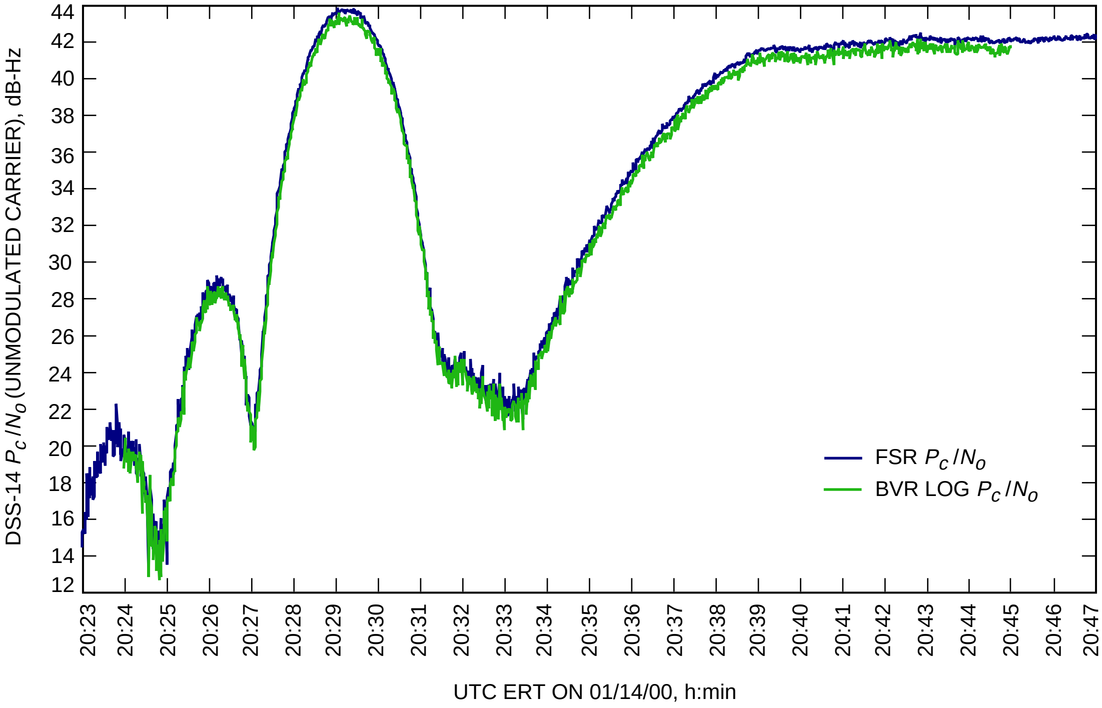


Fig. 10. Comparison of FSR and BVR log data during HGA stop: third peak and turn back.

activities, the stop occurs less than 2-1/2 minutes after the third peak, at a level of about 8 dB below the peak. Figure 10, with its 3-minute and 22-dB stop, shows our stop-coning skills still needed honing.

For one HGA activity in June 2000, the DS1 project requested that telecommunications plan to stop the coning after observing one peak—that is, stop it on the second peak. The need arose just after the flight software update. DS1 had scheduled several 34-m passes to check out performance of the new software. To maximize the amount of time for data observation, it was necessary to shorten the 3-hour stop-coning and data-initialization time at BOT. Telecommunications modified the planning spreadsheet to give ←action times based on the time of the first observed peak and an assumed exact 45-minute coning period. The spreadsheet, telecommunications analyst, ACE, and station all worked properly, providing the project data 45 minutes earlier than otherwise possible. As it turned out, the actual coning period was about 46 minutes, so the antenna was stopped on the "early" side of the boresight. The antenna-pointing maintenance phase of this activity (described in general later) was complicated by lack of certain knowledge about which side of the boresight the Earth was on.

VI. Uplink and Downlink Data for Real-Time Control

During the stop-coning part of the HGA activity, the only observable real-time datum was the P_c/N_o from the BVR. Unlike carrier power, P_c, in dBm, this quantity did not require the station to have the system noise temperature (SNT) enabled, although its value is affected by the actual SNT. For DS1 tracking, the station operates two BVRs. They attempted to get both in lock as each HGA peak occurred, to provide time signal level correlation.

After the ACE had radiated the stop-coning command, the telecommunications analyst used the RTLT interval before seeing the antenna stop to evaluate the P_c/N_o for each of the first two peaks from each of the two receivers. The analyst also compared these values against the predicted mean value that assumes the HGA boresight is Earth-pointed and all of the other components of the telecommunications link are operating at their expected values. The purpose of this evaluation was to estimate the maximum downlink rate that the link could support that day, taking into account the station's performance as well as the HGA pointing control demonstrated during previous HGA activities. The first HGA activity, on January 14, 2000, provided no experience to draw on, so commands were prepared in advance to activate any of three downlink bit rates: 6636 b/s, 4424 b/s, or 3150 b/s. The yet higher 9480-b/s rate would be supportable at a 70-m station if pointing could be maintained at no more than 2 deg from boresight, including spacecraft dead banding. Each successively lower data rate in this series requires about 1.5 dB less capability than the preceding one.

For each HGA activity from January through April, the analyst authorized an initial rate of 6636 b/s, with a "heads up" that the 4424-b/s rate would have to be commanded toward the end of the pass as elevation angle and, therefore, link performance decreased. The specific criterion for 6636 b/s is that the P_c/N_o average no worse than 41 dB-Hz at the second peak, and that this level be confirmed when the HGA is stopped and returned to nominal Earth point after the third peak. HGA activities conducted over only 34-m stations in May and June typically started at the 1050-b/s rate.

Activating a downlink rate starts a short sequence of commands to the onboard telecommunications systems. Within 15 seconds, these set a packet data priority table (DPT) for real-time engineering data only, select the appropriate subcarrier frequency and the modulation index, and start the specific downlink rate with (15,1/6) convolutional coding. Ten minutes later, to allow time for the station to lock to and begin output of valid data, the sequence resets the DPT to play back the particular stored data in order of priority.

VII. Controlling the Nominally Earth-Pointed Antenna

With telemetry in lock and the BVR producing a symbol signal-to-noise ratio (SSNR), the maintenance phase of the HGA activity can begin. The purpose of this phase is to monitor downlink and uplink performance and to send commands that activate an onboard sequence to correct the HGA pointing when necessary. By monitoring performance and directing command transmission from the ground, the analyst, rather than onboard software, becomes part of the feedback control loop that maintains spacecraft pointing. The analyst's act-observe-respond process was made more difficult because of RTLT. The 30- to 35-minute delay from command radiation to performance observation sometimes resulted in loss of downlink data. It never resulted in the loss of commandability because the command rate was made more conservative than the telemetry rate.

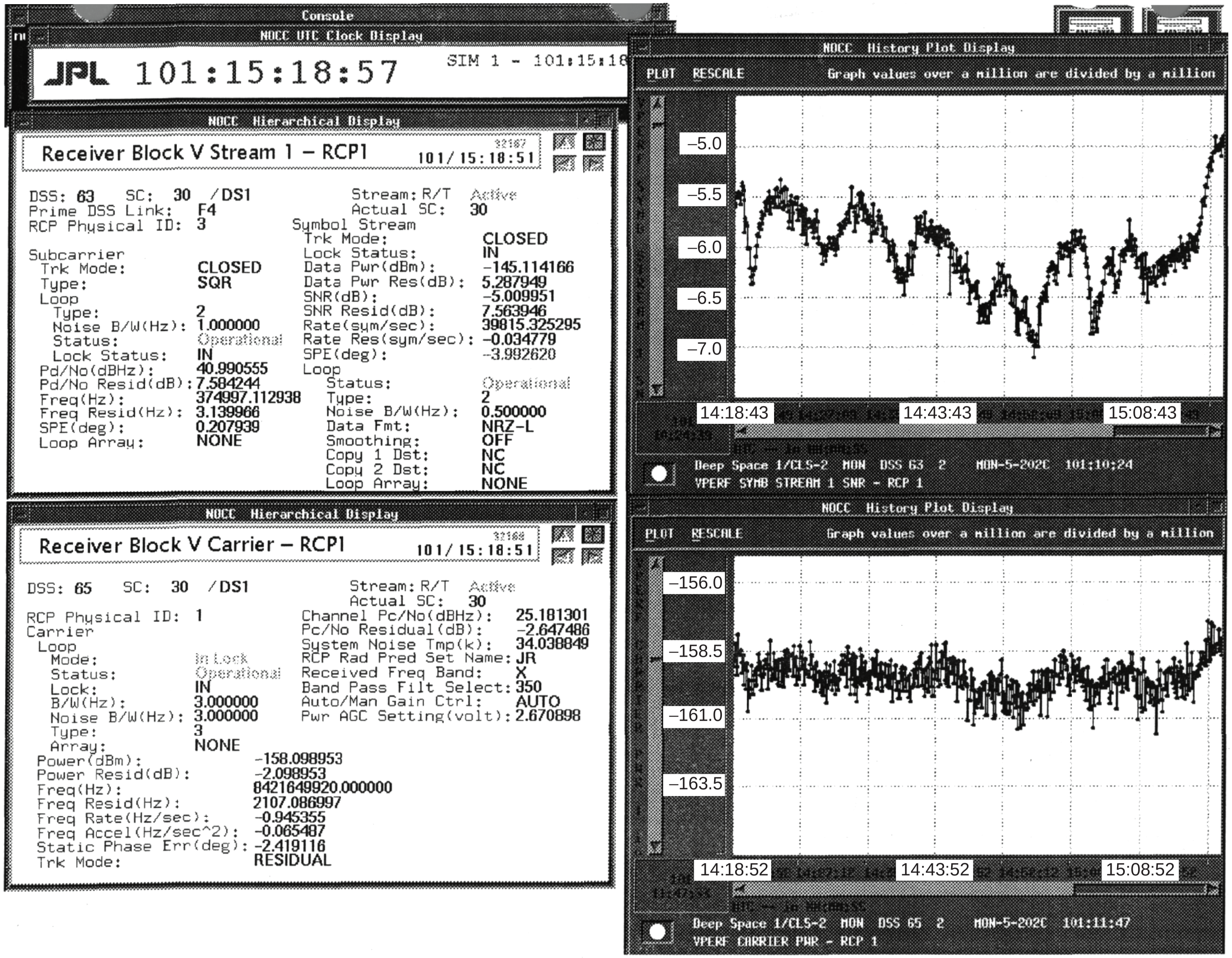
In the months leading up to the flight software reload, the main purpose of each HGA activity was to provide high-rate downlink data. The SSNR, as a direct measure of telemetry performance, was used as the indicator for when to correct HGA pointing. Through the maintenance phase, the target SSNR value is in the -4 to -5 dB range, as compared with a threshold of -7.5 dB for (15,1/6) coding. To monitor the performance, the analyst set a time scale of 30 to 60 minutes on the NOCC RT and a vertical scale of -4 to -8 dB, as in the example in Fig. 11. The criterion for corrective-turn activation was established as when the SSNR first fell to -6 dB fairly rapidly or fell to -6 dB two times less rapidly. The -6 dB criterion provided a reasonable 1.5-dB margin against further mispointing during the RTLT delay. Establishing the criterion at -6 dB was based on the experience gained with the HGA activities in January 2000. In Fig. 11, the 70-m SSNR in the top plot had fallen through the -6 dB value, causing the analyst to recommend a corrective turn. The effect of the turn appears in the upswing of SSNR at the right side of the plot.

Because the 70-m stations did not have X-band transmitters for uplink to DS1, most HGA activities scheduled 34-m and 70-m stations with simultaneous or overlapping coverage. The telemetry rate, set for the 70-m station, would be below threshold for the 34-m station. However, the smaller station could lock the carrier and produce P_c/N_o or P_c for display to the telecommunications analyst, as in Fig. 11. A plot with quantities from two stations on the same time scale immediately eliminates the effects of problems present at only one station. When the SSNR at one station and the P_c/N_o at a second exhibit similar behavior at the same time, this confirms the spacecraft HGA pointing as the cause of the variations.

Originally the process for the maintenance phase included the telecommunications analyst recommending to the flight director the timing and size for each corrective turn activation. In the same way that sequences for several downlink rates are stored onboard, sequences for turns (rolls) of -4 deg, -8 deg, $+4$ deg, $+8$ deg, etc., were available for activation. These magnitudes are about the spacecraft–Sun axis. This axis and the +x-axis (HGA) form the Sun–spacecraft–Earth (SCE) angle. After the flight director reviewed and discussed the SSNR signature with the telecommunications analyst, he authorized the ACE to radiate a particular command.

In the January to April period, the SCE decreased from slightly greater than 32 deg to slightly less than 28 deg. At these SCE angles, a spacecraft turn of a given size causes the antenna boresight to move about half that amount. Further, experience in January and February showed us that the angular drift rate about the controlled axis was always in the same direction. As a result of this geometry and the drift direction, we have used -8 deg and -4 deg corrective turns. These would move the HGA boresight relative to the Earth by about -4 deg and -2 deg, respectively. Depending upon how far off the Earth the boresight was, we would expect improvements in performance of between 2 and 5 dB.

To the telecommunications analyst, the ACS seemed to have a mind of its own in responding to corrective turns. Without an operative SRU, the spacecraft was unable to provide any telemetered information on the actual motion about the x-, y-, and z-spacecraft axes. The best explanation the attitude control analysts could offer regarding the poor results of some corrective turns is this: with residual motion around any of the axes, an intended corrective turn about the x-axis could also couple undesired motion about one or both of the other axes. The extent of the undesired (and uncontrollable) motion was believed to depend on the turn magnitudes and rates about each axis present when the corrective turn command reached the spacecraft. These differed from the values assumed a round-trip



```
JPL 101:15:18:57          SIM 1 - 101:15:18
```

```
Receiver Block V Stream 1 – RCP1                32167
                                         101/15:18:51

DSS: 63    SC:  30   /DS1            Stream: R/T   Active
Prime DSS Link:    F4                Actual SC:    30
RCP Physical ID:   3            Symbol Stream
                                  Trk Mode:             CLOSED
Subcarrier                        Lock Status:          IN
 Trk Mode:            CLOSED      Data Pwr(dBm):        -145.114166
 Type:                SQR         Data Pwr Res(dB):     5.287949
 Loop                             SNR(dB):              -5.009951
  Type:               2           SNR Resid(dB):        7.563946
  Noise B/W(Hz):      1.000000    Rate(sym/sec):        39815.325295
  Status:             Operational Rate Res(sym/sec):    -0.034779
  Lock Status:        IN          SPE(deg):             -3.992620
 Pd/No(dBHz):         40.990555   Loop
 Pd/No Resid(dB):     7.584244     Status:              Operational
 Freq(Hz):            374997.112938 Type:               2
 Freq Resid(Hz):      3.139966     Noise B/W(Hz):       0.500000
 SPE(deg):            0.207939     Data Fmt:            NRZ-L
 Loop Array:          NONE         Smoothing:           OFF
                                   Copy 1 Dst:          NC
                                   Copy 2 Dst:          NC
                                   Loop Array:          NONE
```

```
Receiver Block V Carrier – RCP1                 32168
                                         101/15:18:51

DSS: 65    SC:  30   /DS1            Stream: R/T   Active
                                     Actual SC:    30
RCP Physical ID:  1            Channel Pc/No(dBHz):      25.181301
Carrier                        Pc/No Residual(dB):       -2.647486
 Loop                          System Noise Tmp(k):      34.038849
  Mode:            In Lock     RCP Rad Pred Set Name:    JR
  Status:          Operational Received Freq Band:       X
  Lock:            IN          Band Pass Filt Select:    350
  B/W(Hz):         3.000000    Auto/Man Gain Ctrl:       AUTO
  Noise B/W(Hz):   3.000000    Pwr AGC Setting(volt):    2.670898
  Type:            3
  Array:           NONE
 Power(dBm):                 -158.098953
 Power Resid(dB):            -2.098953
 Freq(Hz):                   8421649920.000000
 Freq Resid(Hz):             2107.086997
 Freq Rate(Hz/sec):          -0.945355
 Freq Accel(Hz/sec^2):       -0.065487
 Static Phase Err(deg):      -2.419116
 Trk Mode:                   RESIDUAL
```

```
Deep Space 1/CLS-2  MON  DSS 63  2      MON-5-202C   101:10:24
VPERF SYMB STREAM 1 SNR - RCP 1
```

```
Deep Space 1/CLS-2  MON  DSS 65  2      MON-5-202C   101:11:47
VPERF CARRIER PWR - RCP 1
```

Fig. 11. Real-time display of station monitor data during the HGA activity maintenance phase.

light-time earlier when the corrective turn decision was made. Because the spacecraft continues its deadbanding motions about the other axes, it is sometimes difficult to confirm from the SSNR or P_c/N_o exactly how a given size corrective turn about the x-axis would actually move the HGA boresight relative to the Earth line. Complicating the assessment of HGA pointing, transient link effects from other causes can also masquerade as HGA motions. Over the months, we accumulated a database of characteristic P_c/N_o

and SSNR signatures from both the real-time monitoring and non-real-time data analysis (next section). We used these signatures to try to improve our command timing in each successive HGA activity, so as to reduce the amount of telemetry data lost.

Despite our best efforts to reduce them, fluctuations in SSNR during the maintenance phase might be so large that corrective turns alone would be insufficient to maintain telemetry. There were several HGA activities when the drift rate towards the -7.5 dB threshold was much faster than anticipated. The drift seemed to get worse late in an HGA activity, almost as if the spacecraft were getting tired. During one activity, the drift was so severe that -12 deg rolls were sent about every 80 minutes, as compared with normal -8 deg turns sent about every 2 to 3 hours. The team did not have an understanding of what may have caused the unusual drift. On another occasion, the 70-m tracking station's subreflector got stuck, causing a continuing degradation. The station provides no direct monitor output of subreflector position, and the effect was indistinguishable from a continued uncorrectable HGA off point. In these two situations, telecommunications recommended more (successive) downlink rate reductions to be activated in the same way as the initial downlink rate. In both the high-drift-rate activity and the stuck-subreflector activity, the commands could not prevent loss of some data.

From the experience gained with the first half dozen HGA activities, the project subsequently entrusted the telecommunications analyst to work with the ACE directly for commanding corrective turns and downlink rate changes.

VIII. Non-Real-Time Performance Assessment

After the real-time act-observe-respond activities were complete, the telecommunications analyst processed both the station monitor data (primarily P_c/N_o, SSNR, decoded telemetry bit SNR, and SNT) and the spacecraft telemetry (primarily uplink carrier power measurements, called "SDST carrier_lock_accumulator" and "narrowband_AGC") to make a best estimate of the achieved HGA pointing. In non-real time, it was possible to evaluate additional aspects of the data to help the analyst improve the real-time portion of the next HGA activity as well as create information for subsequent use by other parts of the DS1 and DSN teams. Telecommunications data preparation involved the standard "Ez-query" capability of the MGDS, with subsequent text tabular file transfer to the PC. For comparison with the data values, the analyst also prepared predictions of these same quantities using the TFP. These predictions would be made with the same data-point spacing (normally 1/5 seconds for monitor data and 1/20 seconds for uplink carrier power). For detailed analyses, FSR P_c/N_o values and corresponding 1/1-second data and predicts were put into a spreadsheet.

In the simplest form of performance analysis, a spreadsheet scatter plot, such as Fig. 12, was made with the data time tags determining the x-axis locations of the points and the dB data values determining the y-axis locations. Usually, a plot includes one data set of residuals (actual values minus predicted values) and a second data set of HGA off points corresponding to the residuals. The off point is created using a table-lookup function based on the HGA uplink pattern, Fig. 2, or downlink pattern, Fig. 7.

One example of the result of a detailed non-real-time analysis appears in Fig. 12. This non-real-time performance assessment plot shows the P_c/N_o residual as dB below the 0 level and the corresponding modeled HGA off point as degrees above the 0 level. The analysis revealed the effect of a large but short-lived increase in ground station SNT during the April 10, 2000, HGA activity, masquerading as an HGA pointing variation. The modeled SNT assumes normal weather and has a value around 20 K for higher elevation angles. On this occasion, around 17:55 UTC, the SNT increased to more than 40 K for 7 minutes, then returned to normal. The average performance, which was running -1 to -3 dB below perfect Earth point, sagged to as low as -5 dB. This made it appear in Fig. 12 that the HGA moved from a position of 3 to 4 deg from Earth line to as much as 6 deg. When the excess SNT was accounted for, however, the true degradation due to pointing did not change character through the 17:55 UTC period.

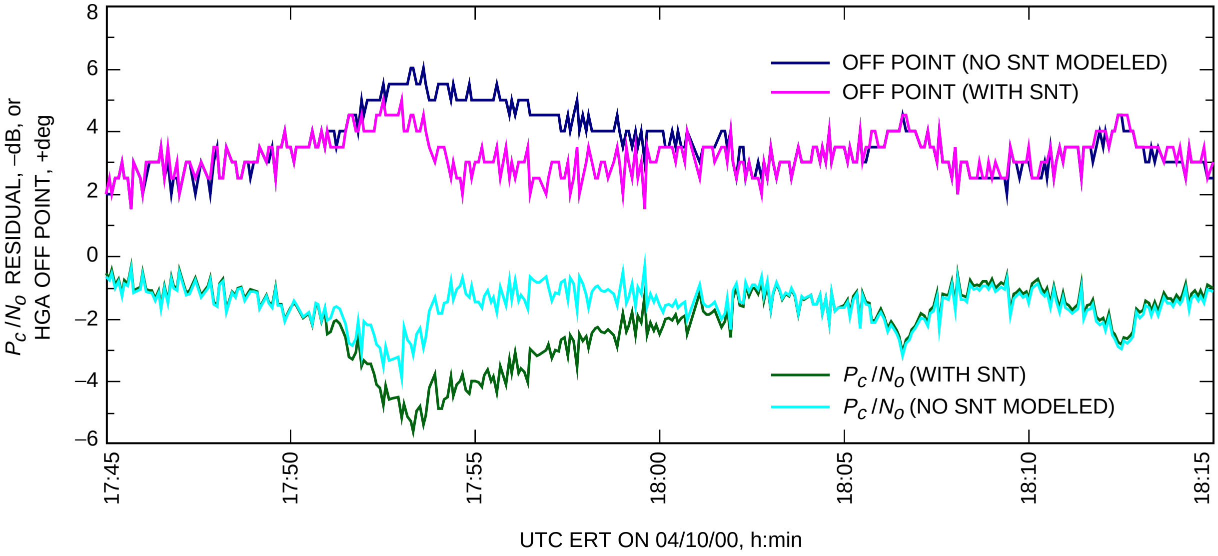


Fig. 12. Effect of SNT modeling on P_c/N_0 residual for a portion of the 2000-101 HGA activity.

Because link modeling is not perfect, several adjustment factors may need to be applied uniformly to all points in a residual data set. On downlink plots, an arbitrary adjustment may move all values of P_c/N_o residuals up or down until the average of the most positive short period of them is equal to zero. Doing this corresponds to an expectation that the HGA boresight was aligned with Earth at some time during the HGA activity. A second adjustment may be made to all P_c/N_o values when telemetry modulation was on, so that pointing before and after modulation can be compared.

If the downlink pointing errors are to be compared for corresponding times on the uplink, an OWLT adjustment may be made to convert all of the Earth received time (ERT) values into spacecraft event time (SCET) values. Figure 13 has both an arbitrary P_c/N_o level adjustment of -0.2 dB and an OWLT time adjustment of 00:14:22, as indicated in the caption. The time adjustment allowed for direct comparison of the downlink P_c/N_o with the behavior of the uplink carrier power in Fig. 14. The February 29, 2000, HGA activity detailed in Figs. 13 and 14 was notable because of the large amplitude variations between 17:10 and 17:40 UTC (SCET reference) observed in real time. Part 3 of the planning spreadsheet (not shown) includes activation of a -8 deg corrective turn that started at 17:37 and was complete by 17:41. The two figures show the effectiveness of the corrective turn in halting the large HGA motions. What ACS activity caused these motions to start a half hour earlier is not known.

On the uplink, an adjustment may be used to remove the decrease in uplink carrier power caused by carrier suppression when command radiation is active. Figure 15, with the same time and value scales as Fig. 14, is of the telemetered “SDST carrier_lock_accumulator” measurement. The short downward spikes, near 14:46, 16:02 UTC SCET, etc., are the result of the power in the received uplink carrier being decreased by command modulation. Figure 14 includes no command-suppression adjustment. As a result, command modulation at 14:46, 16:02, etc., misleadingly suggests HGA pointing errors in excess of 6 deg at these times. Figure 15 adds an empirical value 3.2 dB to each measurement that was affected by command modulation. The 3.2 dB was chosen by trial and error to minimize fluctuations in the plot at known times of commanding. As expected, the 3.2 dB is close to the standard planned value of suppression, 3.1 dB. After this adjustment, the HGA off point appears to be in the 3-deg range, the same as the downlink P_c/N_o in Fig. 13 at the same time.

Telecommunications HGA-activity non-real-time analysis helped the rest of the team also. For example, in Figs. 13 and 15 a pointing disturbance between 17:10 and 17:40 UTC SCET affecting both the

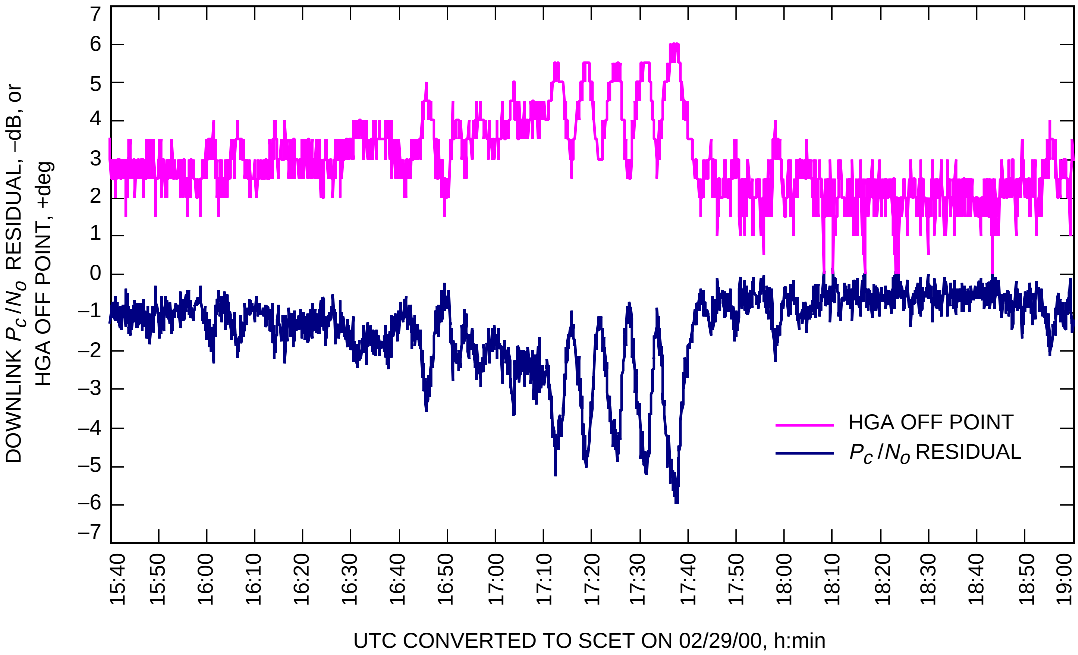


Fig. 13. Downlink P_c/N_0 residual, dB, and HGA off point, deg, on 00-060 (P_c/N_0 adjustment = −0.2 dB, OWLT = 00:14:22).

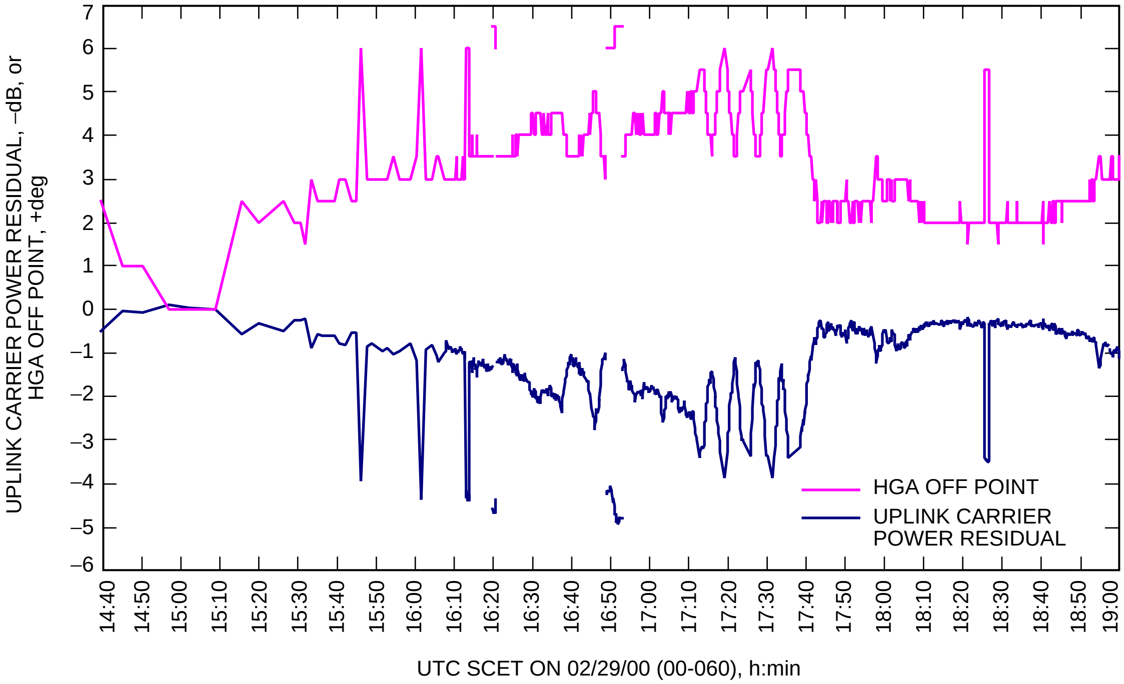


Fig. 14. Uplink carrier power residual and resulting assumed HGA off point.

downlink and the uplink is obvious. Because of the 6-minute periodicity of the disturbance, the ACS thought it was induced by an onboard maintenance pointing dither sequence (named UTILity 100) that made very small turns of opposite polarities on 3-minute centers. Starting on April 27, 2000, a revised UTIL100 with zero-size turns was put into use to decrease the likelihood of such disturbances building up.

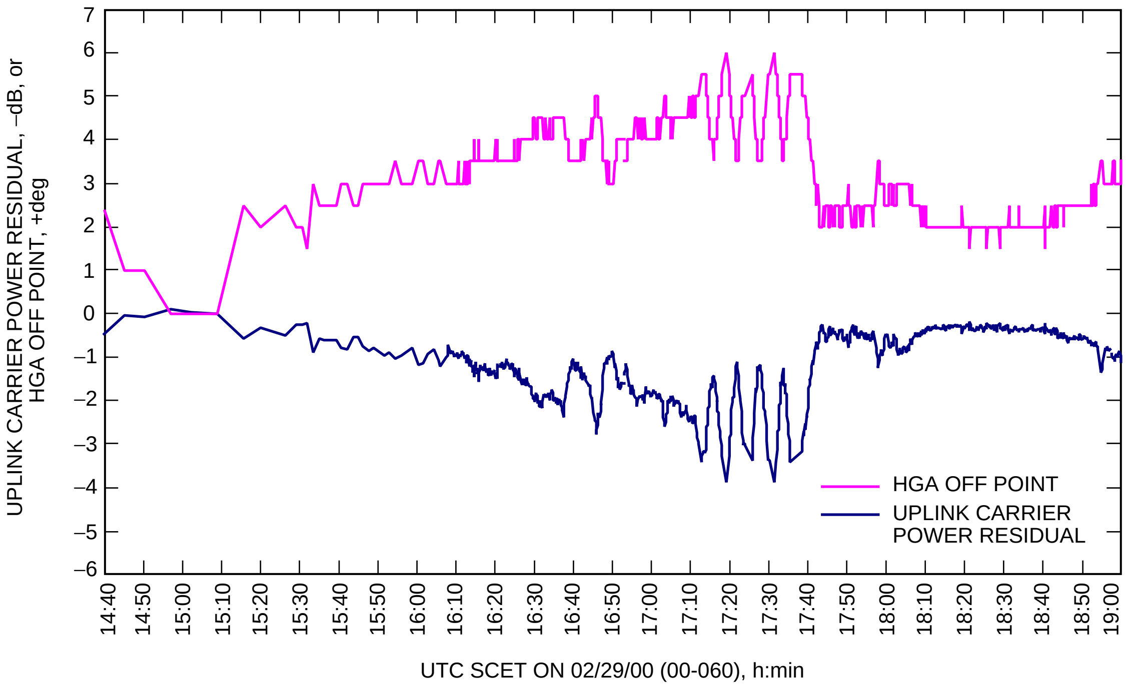


Fig. 15. Uplink carrier power residual with command modulation effect removed, and the resulting assumed HGA off point.

As part of their own non-real-time analysis, the ACS team used the uplink carrier power data to develop and check out the flight software for the autonomous spacecraft pointing capability. As part of the development process, the ACS analyst input the uplink carrier power telemetered in real time to software (named "T-ball") in his workstation in the MSA. This software, using the HGA uplink pattern (Fig. 2) first converted the carrier power into a series of equivalent angles from Earth. It then fit the series to several models of potential three-axis stabilization behavior. For each HGA activity, telecommunications gave the ACS a reference ("zero HGA offpoint") calibration signal level for input to T-ball. With further development, T-ball might have resulted in better choices of corrective-turn command timing and size.

Non-real-time telecommunications analysis of other HGA activities, not included here, show persistent systematic differences between the two link directions. These differences are small (<0.3 dB) over time scales of hours. Their cause remains unexplained. Although the same HGA antenna serves both link directions, there may be errors in the uplink and downlink patterns, based on prelaunch measurements, that are used in the table lookups. Or there may be differences (<0.5 deg) in boresight directions between uplink and downlink frequencies. Or there may be differences in station performance during portions of the pass with increasing elevation angles and later portions with decreasing elevation angles. The DS1 project originally planned to perform an in-flight uplink and downlink HGA calibration as part of technology validation during the prime mission. The HGA calibration would have identified changes from the prelaunch patterns and any difference between uplink and downlink boresight directions. The calibration was deferred due to higher priority workloads. Because an HGA calibration requires accurate knowledge of actual spacecraft pointing, it can no longer be done without a functioning SRU.

IX. Comparison with Post-SRU Onboard Pointing Control

The onboard three-axis pointing control that has been in use since June 2000 uses the miniature integrated camera and spectrometer (MICAS) instead of the SRU to provide the ACS with star data. The pointing algorithm commonly goes by the name "murky" (origin of term uncertain). The MICAS/ACS/murky algorithm provides near-Earth pointing for communications and pointing relative to a thrust star for periods when the ion propulsion subsystem (IPS) is thrusting [5]. “Near Earth” generally means communicating via the HGA within 3.5 deg of boresight. Thrust star attitude requires the use of LGAX, since the +x-axis is 10 to 50 deg from Earth, depending on the date.

Figures 16 through 18 show an example of the capability of the onboard pointing, the familiar link performance quantities (P_c/N_o, SSNR, and uplink carrier power) during the Earth-pointed communications track on July 31, 2000. The estimated planned off-point angle between the HGA boresight and the Earth was 2 deg. The onboard pointing was considerably more constant than we could achieve with the HGA activity on February 29, 2000 (Figs. 13 through 15). Onboard pointing control is considerably easier on the telecommunications analyst than is the HGA activity. There are two sources of signal variation in these figures. For the first hour of the pass, the downlink performance is affected by the increasing elevation angle. Throughout the pass, the short-term (approximately minutes) variations are due to use of conical scanning (Conscan) antenna pointing control at the tracking station.

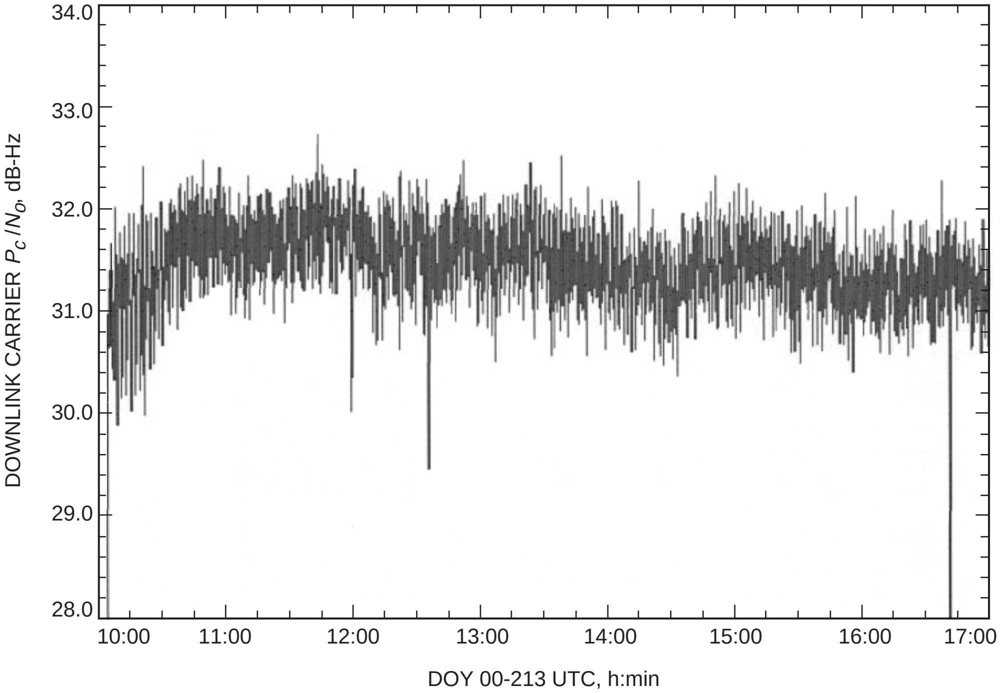


Fig. 16. Downlink P_c/N_0 with onboard attitude control, post-HGA activity.

X. Conclusion

Failure of a non-redundant and apparently essential spacecraft subsystem does not necessarily mean the end of the mission. An innovative and resourceful flight team can sometimes develop a work around wherein human skill adequately substitutes for the failed onboard function. Because remaining spacecraft hardware and software may be used in ways not originally planned for or tested, it is essential to plan out the command sequence changes and to test every one on a test bed before executing them on the spacecraft. When the real-time operations are interactive and complex, it is also necessary to plan them out in advance, reduce the real-time actions to a minimum, adhere to predefined command decision criteria, and follow a time-defined procedure precisely. Performing a real-time work around like “telecom analyst in the loop spacecraft pointing control” successfully is a first step. Subsequent analysis of the resulting data suggests what can be done to automate the work around, extend its capabilities, and move the function back onboard, all to achieve DS1 mission objectives that at first seemed to fall out of reach.

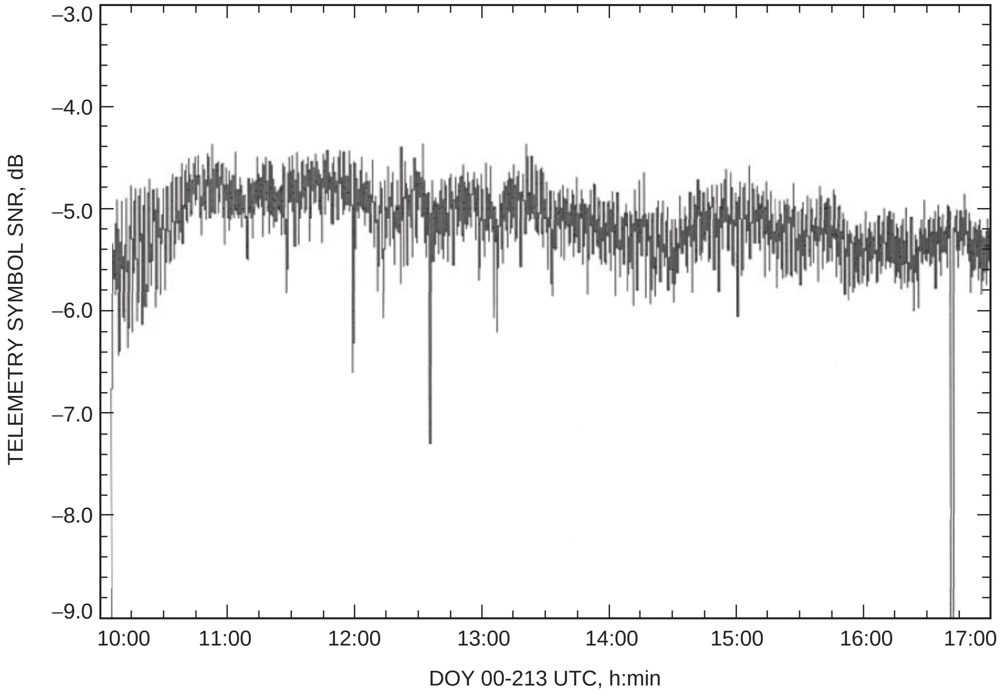


Fig. 17. Telemetry symbol SNR with onboard attitude control, post-HGA activity.

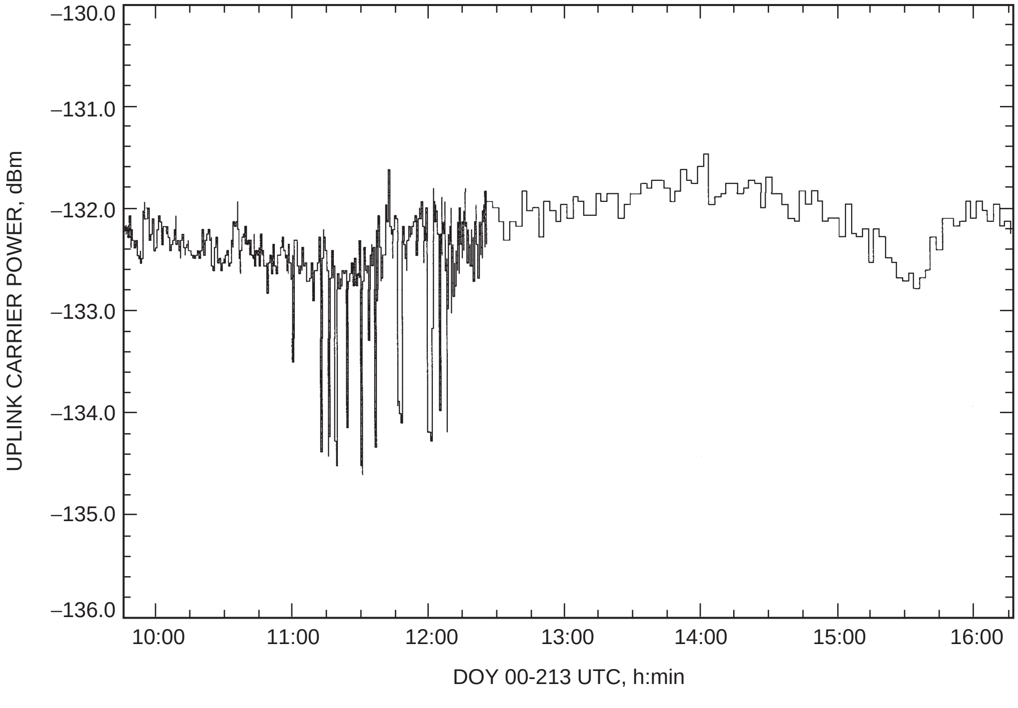


Fig. 18. Uplink carrier power with onboard attitude control, post-HGA activity.

In the broadest sense, the success of telecommunications planning ultimately depends on the knowledge and skill of the engineers doing the job. Good prelaunch planning includes the development or adaptation of the prediction and link performance comparison tools that will be used by the flight operations analysts for routine operations. When safeguarded against erroneous input or unrealistic assumptions, the tools can also be made available to less specialized system engineers for their own assessment of routine performance.

A long-term TMOD goal has been to develop an integral system of prediction and analysis tools that are reliable and easy to use. The tools used for DS1 flight operations represent a good step in that process. Additionally, as the DS1 SRU failure and functional recovery demonstrate, telecommunications capability afforded by experience, ingenuity, and intimate familiarity with the telecommunications discipline and the tools' full capabilities can be of great value. As suggested by the data presented in this article, the successful analyst needs to be able to get the most out of the tools and data then available. In cases like this, experience and familiarity allow the analyst to make the consistency checks to stay out of trouble in developing such first-of-a-kind techniques as described in this article.

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