

Change Log

Rev	Issue Date	Affected Paragraphs	Change Summary
Initial	10/7/2004	All	New Module
A	12/15/2009	Many	Removed references and information related to the decommissioned 26-m antennas.
B	6/1/2010	Table 1	Changed Azimuth Motion Limits to Travel Range and Corrected DSS-27 cable wrap center value. Eliminated the Rev. E designation for the document series.

Note to Readers

The 810-005 document series has been structured so that each document module can be independently revised without affecting others in the series. Hence, the Revision E previously designated for 810-005 has become unnecessary. This module is one of the many in the 810-005 series; each may be published or changed, starting as an initial issue that has no revision letter. When a module is updated, a change letter is appended to the module number in the header and a summary of the changes is entered in the module's change log.

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1 Introduction

1.1 Purpose

This module describes the pointing capabilities of the antennas used by the Deep Space Network (DSN) in sufficient detail to enable a telecommunications engineer to design spacecraft missions that are compatible with these capabilities.

1.2 Scope

This discussion in this document is restricted to the mechanical limitations of the antennas, their control algorithms, and the error sources that influence the ability to point the radio frequency (RF) beam in the desired direction. Wind velocity statistics that can be used to estimate the effects of wind on antenna pointing are presented in module 105. Coverage and restrictions to coverage caused by terrain masking are discussed in module 301.

2 General Information

Antenna positioning or pointing is the process of directing the antenna beam towards the desired target. The target may be a spacecraft or radio source that is producing a receivable signal. The target may also be a spacecraft other object at a known or suspected position that is not producing a signal but to which RF energy must be directed. The antenna must keep its RF beam properly aimed for the scheduled duration of the spacecraft or other observation, often referred to as a pass.

There are two types of antenna beam pointing. The first of these is blind pointing, sometimes referred to as open loop pointing, that relies on the ability to model the direction of the antenna beam in the presence of systematic and random processes. The second is closed-loop pointing that derives corrections from the received signal. Blind pointing produces larger errors but is the only method available in the absence of a received signal or during radio science observations when the data quality would be adversely affected by closed loop positioning.

Antenna pointing is not only influenced by random errors due to wind and thermal effects, but also due to imperfect modeling of systematic pointing errors that vary unpredictably throughout the sky or along a particular path in the sky when tracking a spacecraft. Standard first-order systematic error pointing models (used for blind pointing) may not be adequate to describe “high frequency” (e.g., 2 or more cycles per 360 degrees movement in azimuth or elevation) variations in pointing.

2.1 Antenna Characteristics

The DSN employs three general types of antennas. At least one of each type antenna exists at each DSN complex. The antenna types are the 70-m antennas, the 34-m high-efficiency (HEF) antennas, and the 34-m beam waveguide (BWG) antennas. All of these antennas employ an azimuth-elevation (AZ-EL) mount.

The antennas are pointed by variable-rate servo systems that use the antenna pointing commands as input and the axis position encoders (azimuth and elevation) as feedback. The 70-m antennas also have a *precision mode* where the main reflector is slaved to a small hour-angle/declination instrument, referred to as the *Master Equatorial (ME)*, using optical collimation techniques. The ME is mounted at the intersection of the 70-m azimuth and elevation axes in a controlled environment and on a separate foundation to eliminate vibration and other effects. Servo performance is generally a function of antenna size with higher tracking and slew rates being available from the smaller antennas. The high-speed, 34-m BWG (HSB) antenna at the Goldstone Deep Space Communications Complex (DSCC) is an exception and has the fastest tracking and slew rates of any DSN antenna. Table 1 summarizes the primary mechanical characteristics of the various antennas.

2.2 *Coverage Restrictions and Servo Performance Limits*

DSN antennas have restrictions to their coverage from two sources other than terrain masking. The first of these is the antenna *keyholes* – areas where coverage is not possible because the reflector would need to be positioned about the secondary (upper) axis in such a way that it would run into the primary (lower) axis or its supporting structure. The sizes of the keyholes can be inferred from the motion limits given in Table 1 and are illustrated on the horizon mask charts in module 301. The second restriction occurs near the ends of the primary axis where the amount of motion required to correctly position the antenna beam exceeds the capability of the primary axis servo should the orbital path passes near an imaginary extension of the lower axis.

Azimuth-elevation antennas have an area of non-coverage directly above the antenna resulting from the fact that should a spacecraft pass directly overhead, the antenna would have to instantaneously rotate 180 degrees in azimuth to follow it. Clearly, this is not possible but, for spacecraft passing nearly overhead, the azimuth rate is finite and can be calculated from the equation.

$$r_{AZ} = \frac{r_{SC}}{\cos(EL_{Peak})} \quad (1)$$

where

- r_{AZ} = the peak azimuth rate required of the antenna
- r_{SC} = the cross-elevation rate of the spacecraft as seen from the antenna
- EL_{Peak} = the maximum elevation reached by the spacecraft.

Table 1. DSN Antenna Mechanical Characteristics

Parameter	70-m	34-m HEF	34-m BWG	34-m HSB
Antenna Mount	AZ-EL	AZ-EL	AZ-EL	AZ-EL
Slew Rate, each axis (deg/s)	0.25	0.8	0.8	3.0 (AZ) 2.0 (EL)
Minimum Tracking Rate, each axis (deg/s)	0.0001	0.0001	0.0001	0.0001
Maximum Tracking Rate, each axis (deg/s)	0.25	0.4	0.4	3.0 (AZ) 2.0 (EL)
Acceleration each axis (deg/s ²)	0.2	0.4	0.4	1.0 (AZ) 0.5 (EL)
Deceleration (braking) each axis (deg/s ²)	2.5	5.0	5.0	5.0
Axis Encoder Resolution (mdeg)	0.021	0.021	0.021	0.021
Axis Encoder Accuracy (mdeg)	±0.171	±0.171	±0.171	±0.171
Master Equatorial Axis Encoder Resolution (mdeg)	0.021	–	–	–
Master Equatorial Axis Encoder Accuracy (mdeg)	±0.343	–	–	–
Azimuth Travel Range from Wrap Center (deg)	±265	±225	±225	±292
GDSCC Wrap Center (deg)	45	135	135	0
CDSCC Wrap Center (deg)	135	45	45	–
MDSCC Wrap Center (deg)	45	135	135	–
Elevation Motion Limits (deg)	6 – 89.5	6 – 89.5	6 – 89.5	5 – 89.5

* The 0.0035 deg/s lower limit is defined as smooth motion provided by the antenna mechanical and servo assemblies. “Smooth” means continuous, monotonically increasing or decreasing motion, or motion in a specific direction without stopping or reversal. The antenna controller can emulate a much lower rate through the use of stopping intervals when tracking of slower moving targets is required.

For spacecraft tracked at near-sidereal rates, the areas of non-coverage are not large but must be avoided by appropriate scheduling. The maximum peak spacecraft elevation is limited to 89 degrees for continuous tracking when using the 70-m antennas. For the HEF and BWG antennas, the maximum peak elevation for continuous tracking is limited to 89.4 degrees.

Formula (1) can be used for Earth-orbiter spacecraft; however, the rate of spacecraft as seen from the antenna will be a function of orbit altitude. Figure 1 illustrates the effect of orbit altitude on peak azimuth rate for several circular orbits.

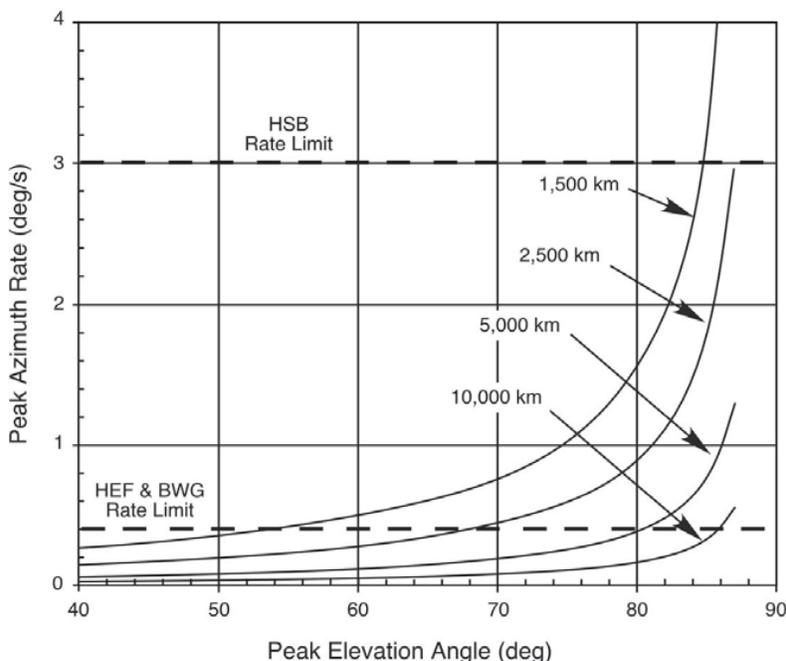


Figure 1. Azimuth Rates for Selected Circular Orbits.

2.3 Pointing Modes

DSN antennas are normally operated by aiming their RF beams in accordance with a pre-determined set of instructions referred to as antenna pointing predictions or *predicts*. The format and contents of the predicts depends on their source, the type of support being provided, and the antenna being used. In addition to predict-driven modes, there are specialized pointing modes available for the antenna type. All pointing is provided in terms of the actual direction to the target. The antenna controller adds whatever corrections are required to compensate for the atmosphere and imperfections in the antenna response, calculates the rate at which each axis must move to reach the next point at the desired time and delivers this information to the antenna servos. Position feedback from the selected axis position encoders is constantly monitored and used to adjust the axis tracking rates.

The 34-m BWG and HSB antennas have two predict-driven modes, direction cosine and Improved Inter-Range Vector (IIRV). The 34-m HEF and 70-m antennas have the direction cosine predict-driven mode. In addition, the 70-m antennas also have the precision tracking mode. Common to all antennas are the planetary and sidereal tracking modes. These pointing modes are further described below.

2.3.1 *Direction Cosine Mode*

Target positions are delivered to the station as a binary file of predict points, where each point contains time, target range, and topographic direction cosines (X, Y, and Z) with their 2nd and 4th differences for use in an Everett Interpolation algorithm within the antenna controller. The points may represent the location of a single spacecraft from which data is to be acquired for an entire pass, a collection of radio sources that are to be observed on a pre-determined schedule, or in the case of delta-differential one-way ranging (Δ DOR), a series of observations alternating between a spacecraft and one or more radio sources. The direction cosine predict-driven mode is commonly available for all DSN antennas.

2.3.2 *Improved Inter-Range Vector (IIRV) Mode*

The IIRV (“I-squared RV”) mode is most normally used for tracking Earth orbiter spacecraft or deep space spacecraft during their launch and acquisition phase. Target position is expressed as a text file of state vectors in the geocentric Greenwich rotating coordinate frame. Each vector contains time and the three components of target position and velocity. The antenna controller converts the predicts to pointing commands by interpolation or integration and translates them to the coordinate system of the antenna. The time increment between predicts is normally 4 hours; however, predictions can be interpolated over intervals as small as 30 seconds and extrapolated up to 24 hours. The IIRV mode is only available for the BWG and HSB 34-m antennas (i.e., DSS-24, DSS-25, DSS-26, DSS-34, DSS-54, DSS-55, and DSS-27).

2.3.3 *Planetary Mode*

Planetary mode is used to track an object with slowly varying right ascension and declination. Pointing commands are interpolated from three planetary predict points entered from the control position or read from a locally-created file of at least four predict points. The points may be geocentric or topocentric and should include precession and nutation corrections. Each point contains time, right ascension, declination, and range. Parallax correction is available for use with geocentric points when a non-sidereal object (such as a planet) is to be tracked.

2.3.4 *Sidereal Mode*

This mode, also called Star Track Mode, is used to track a celestial object at a fixed position described by geocentric right ascension (RA) and declination (DEC) coordinates including precession and nutation. The points may be entered from the local control position or may be read from a locally-created file containing time, RA, and DEC. A capability to boresight the antenna after arriving on point is included. The boresight algorithm performs a small cross-elevation (XEL) scan centered on the expected target location followed by a small elevation (EL) scan. Pointing corrections are estimated from signal strength measurements. This mode is mainly

used for evaluating antenna performance and collecting very-long baseline interferometry (VLBI) data.

2.3.5 *70-m Precision Tracking Mode*

The 70-m antennas have a precision tracking mode that makes use of an instrument called the *master equatorial* (ME). The master equatorial is a 7-inch (17.8 cm) mirror on an hour-angle/declination mount. The mount is attached to the top of a concrete and steel tower on a separate foundation in an environmentally controlled area within the antenna pedestal and alidade structure. The mirror can be positioned to better than 1 mdeg in each axis and the 70-m reflector is optically slaved to it. The precision tracking mode is available with any of the above modes but should only be used when needed because of its extra complexity.

2.4 *Statistics of Pointing Errors*

If an antenna has EL and XEL random pointing errors due to any number of causes that are normally (Gaussian) distributed, it can be shown that for equal EL and XEL standard deviations, σ , the radial pointing error (two dimensional) becomes Rayleigh distributed. The characteristics of the Rayleigh distribution are that the probability density function (PDF) is zero at zero pointing error, rises to a maximum value at the EL and XEL σ , and decreases with a long tail out to large values of radial pointing error. The cumulative distribution (CD) of the pointing error at a particular value is the integral of the PDF from zero to that value. The mean radial error (MRE) for the Rayleigh distribution of radial pointing errors is related to the standard deviation of the axial (XEL and EL) distributions as:

$$\text{MRE} = \sqrt{\pi/2} \cdot \sigma = 1.2533\sigma \quad (2)$$

and the cumulative distribution at the MRE is 0.545. This means that 54.5% of the pointing errors are less than or equal to the MRE. Conversely, 45.5% of the pointing errors are larger than the MRE. Once the MRE is known, the radial error associated with any CD can be calculated from the properties of the Rayleigh distribution. Table 2 provides the factors by which the MRE must be multiplied to obtain the radial error at the selected CD.

Table 2. Mean Radial Error Multipliers for a Rayleigh Distribution.

CD	Mean Radial Error Multiplier	CD	Mean Radial Error Multiplier
0.0	0.000	0.6	1.080
0.1	0.366	0.7	1.238
0.2	0.533	0.8	1.431
0.3	0.673	0.9	1.712
0.4	0.806	0.95	1.953
0.5	0.939	0.98	2.232
0.545	1.000 (MRE)	0.99	2.421

Figure 3 shows a graph of the PDF and cumulative distribution function (CDF) for a Rayleigh distribution with axial (XEL and EL) σ of 3.19 mdeg, chosen to yield a mean radial error of 4.00 mdeg. Pointing performance such as this would be acceptable for a 34-m DSN antenna operating at X-band where the pointing loss (see module 104) would be less than 0.13 dB 90% of the time. It would not be acceptable pointing for the same antenna operating at Ka-band antenna where the beamwidth is substantially smaller. The resulting Ka-band pointing loss (see module 104) would be greater than 0.7 dB, 45.5% percent of the time and greater than 2 dB 10% of the time.

Figure 4 shows cumulative distributions of pointing error for values of mean radial error ranging from 2 to 20 mdeg and includes the pointing loss curves from modules 101 (70-m Telecommunications Interfaces) and 104 (34-m BWG Telecommunications Interfaces). As an example of the use of this figure, consider the inverse of the preceding example. Assuming it has been determined that a 90% probability of having no more than 2 dB of pointing loss for a Ka-band experiment is acceptable, the chart is entered from the right along the 2-dB line until it intersects the Ka-band Pointing Loss curve. The line is extended vertically to the CD = 0.9 line where it intersects the MRE = 4 curve. Thus, to accomplish the experiment with the desired probability of success will require an antenna with an MRE capability of 4 mdeg.

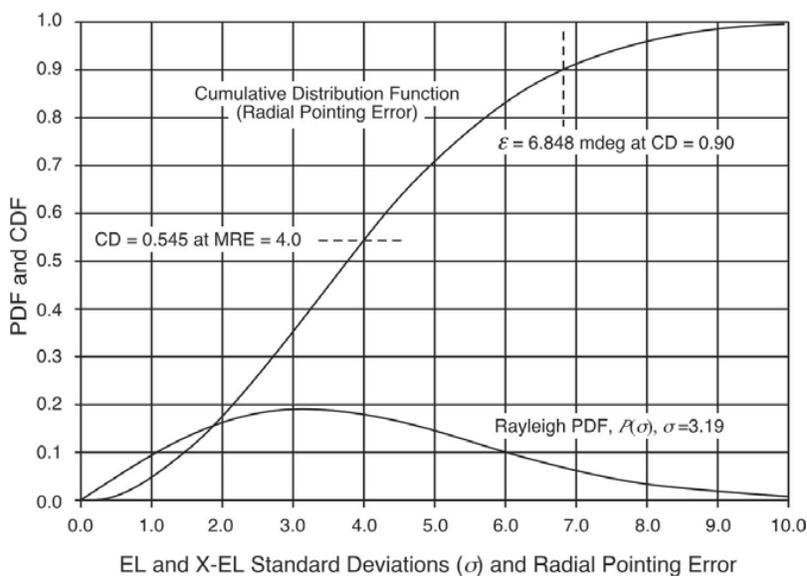


Figure 2. Rayleigh PDF and CDF for a Mean Radial Pointing Error = 4.0 mdeg.

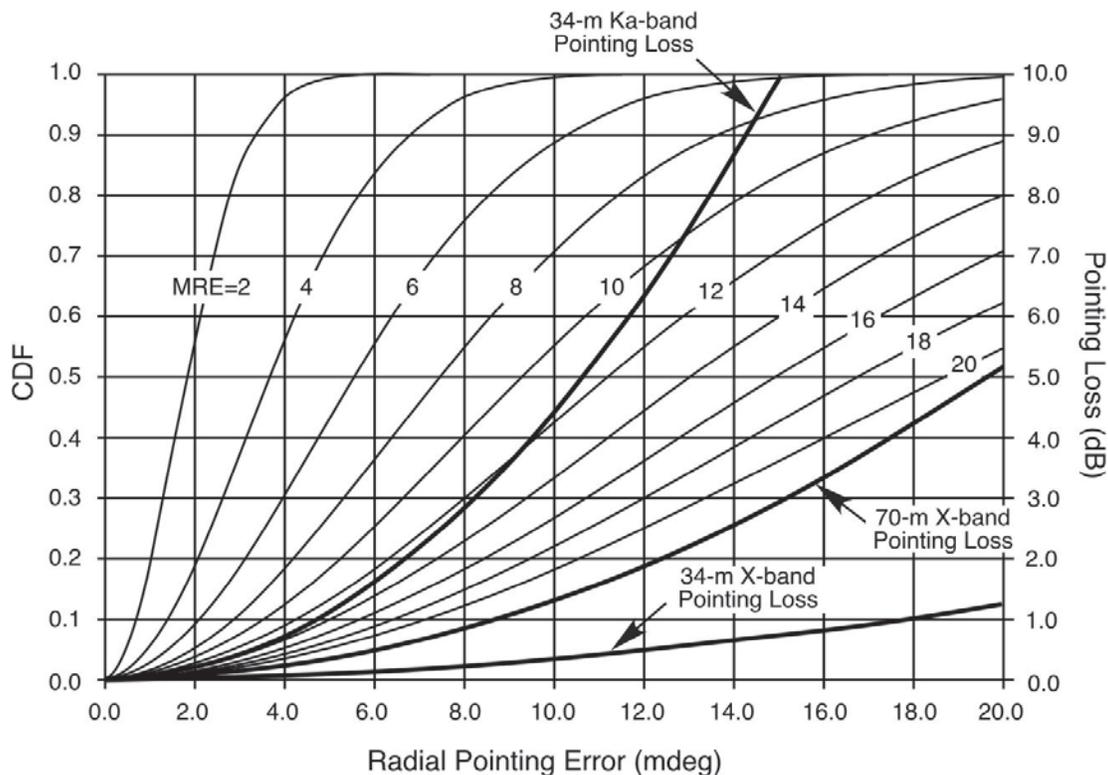


Figure 3. Cumulative Distributions of Pointing Errors for Selected MREs

2.5 *Blind Pointing*

Blind pointing relies on calibration and computer modeling to compensate for errors between the antenna beam direction and the direction as reported by the antenna axis position encoders. Blind pointing errors result in a pointing loss that is most severe on the BWG antennas when operating at Ka-band because of the extremely narrow beamwidth. The 70-m antennas have a relatively narrow X-band beamwidth but this is mitigated by use of the precision tracking mode. The BWG antennas' beam waveguide tube at the center of the antenna prevents use of a master equatorial, and there are additional error sources. The BWG error sources, their magnitude, and the degree to which they can be reduced by modeling are tabulated in Table 3 and discussed in the following paragraphs.

Table 3. 34-m BWG Antenna Pointing Error Sources

Error Source	Estimated Size (mdeg)	Correction Method	Residual Error (mdeg)
Atmospheric refractivity	83 at EL = 10°	Surface weather model	0.8, 1 σ at EL=10°
Gravity deformation of dish and quadripod	100, EL (max)	Subreflector lookup table	5 – 10 P-P (\cong 6 σ)
Systematic errors	100, EL (max)	12 term, first order trigonometric model	1 – 8 (range)
Azimuth track level	8 P-P (\cong 6 σ)	Lookup table	0.3 XEL, 0.1 EL
Azimuth encoder gear noise	0.44, 1 σ	Uncorrected	0.44, 1 σ
Elevation encoder	0.2	Uncorrected	0.2, 1 σ
Thermal deformation	8 P-P (\cong 6 σ , EL & XEL)	Uncorrected	8 P-P (\cong 6 σ)
Wind displacement of foundation	1.1 (30 mph wind)	Uncorrected	1.1 (30 mph wind)
Wind distortion of structure	6 – 9 (30 mph wind)	Uncorrected	6 – 9 (30 mph wind)
Calibration measurements	1, 1 σ	Uncorrected	1, 1 σ
Mean pointing error (without wind)			2.3 – 8.4 (range)
Mean pointing error (with 30 mph wind)			6.5 – 12.4 (range)

2.5.1 *Pointing Corrections*

2.5.1.1 *Atmospheric Refraction Correction*

The antenna controller uses local surface weather measurements to calculate and apply a pointing correction in elevation to compensate for atmospheric refraction. The weather data normally is provided from a local weather station but may be manually entered, if necessary.

2.5.1.2 *Gravity Deformation Correction*

The main reflector and the quadripod structure that supports the subreflector change shape slightly when the antenna moves in elevation. Because of this, the subreflector must be moved continuously during a pass in both the up and down as well as the in and out directions to optimize the gain. The up-down component of the motion causes a shift in antenna pointing referred to as *squint*. This is compensated for by a squint correction algorithm that

adjusts the elevation pointing depending on how far the subreflector has been moved. The 34-m HSB S-band antenna has a fixed subreflector because of its relatively wide beamwidth and squint correction is not necessary.

2.5.1.3 *Systematic Error Correction*

All antennas, no matter how well they are designed and how carefully they are built, have certain repeatable pointing errors that can be measured by referencing well-known radio sources. Among the causes for these errors are imperfections such as angle-encoder offsets, azimuth axis tilt, gravitational flexure, axis skew, structure aging, etc. The DSN models these using constants and spherical harmonic functions of the antenna pointing angle in what is called a first-order pointing model. This model works reasonably well over the entire sky at S-band and X-band. However, experiments requiring extremely accurate pointing can benefit by special calibrations and adjusting the model for optimum performance in the portion of the sky where the experiment will occur. Antenna calibrations are performed periodically and the best model for the planned activity is always used.

The addition of Ka-band to the network has made the first order model inadequate as an all-sky model. As a result, a 4th order systematic error model has been developed to handle pointing variations that are not directly traceable to physical imperfections in the antenna. More frequent calibration and possible use of different models for day and night operation are also being investigated to improve Ka-band pointing.

2.5.1.4 *Azimuth Track Level Compensation*

The BWG antenna azimuth tracks are composed of eight, precision-machined segments. Extremely small irregularities in the track, coupled with the four-wheeled rectangular support structure for the antenna, result in a 32-node signature that is more complex than can be modeled by the 1st order or 4th order systematic error correction model. The antenna controller employs a lookup table and applies appropriate corrections to both elevation and azimuth axes.

2.5.2 *Measured Performance of DSN Antennas*

Pointing performance can be observed by monitoring the corrections applied to pointing predicts during closed-loop tracking. Assuming the predicts are perfect and the antenna controller is applying corrections properly, the closed-loop residuals represent the difference between the desired beam pointing and the actual pointing – in other words, the pointing error. Figure 5 shows the X-band pointing corrections (the negative running sum of the pointing errors) as determined by conical scan (CONSCAN, see paragraph 2.6.1) measurements made by the Goldstone DSS-26 BWG antenna while tracking the Voyager I spacecraft on July 11, 2004. CONSCAN corrected the antenna pointing during the track, but there are still residual pointing errors relative to the existing systematic pointing error model (the blind-pointing model). These are presented in the figure. This represents about 5 hours of data, from an azimuth nearly southeast to shortly before setting in the west.

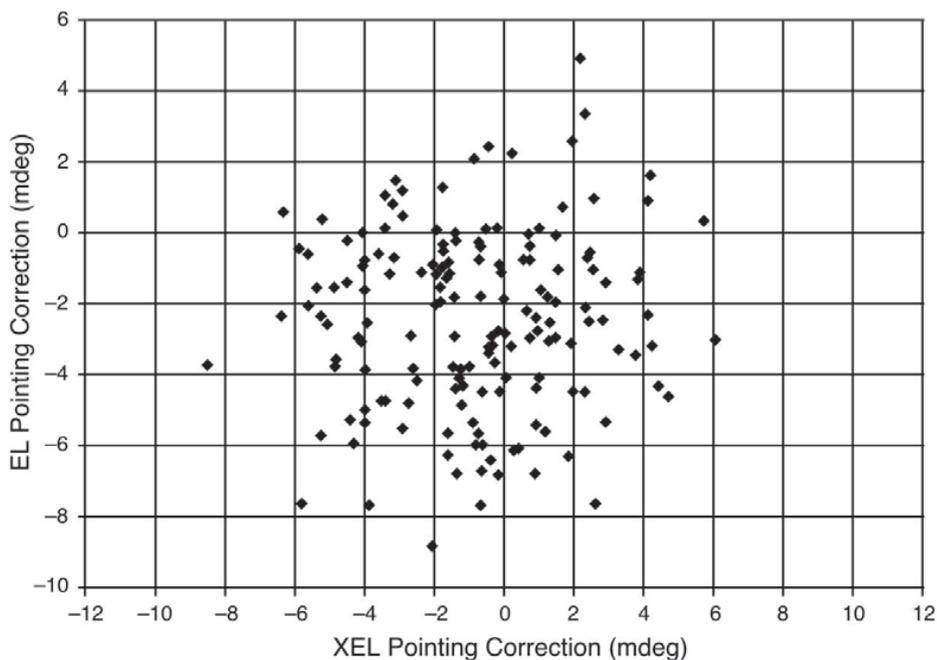


Figure 4. DSS-26 X-band Pointing Performance, July 11, 2004

From this figure it is seen that the points seem to cluster around $(0, -2)$. The actual average XEL correction is -0.9 mdeg and the EL correction is -2.5 mdeg. The mean radial error (relative to $0, 0$) for these points is 4.1 mdeg. When additional data from tracking the Cassini and Odyssey spacecraft are added to the set, the mean radial error for the total data set becomes 4.9 mdeg. This pointing performance is considered to be fairly typical of BWG antennas.

Figure 6 shows DSS-26 X-band radial pointing errors determined by open-loop CONSCAN tracks at various wind speeds while tracking the Cassini and Deep Space 1 spacecraft in December, 2001. It is been suggested that the pointing errors are a quadratic function of wind speed, although insufficient data have been collected to thoroughly investigate the relationship. The large pointing errors (above 8 mdeg) at low wind speeds (below 5 mph) are believed to be due to thermal effects on the antenna alidade and main reflector structure as the morning sun shone on the back of the antenna. Excluding those points and the high wind speed points, it is seen that the mean radial error for this data set is below 4 mdeg.

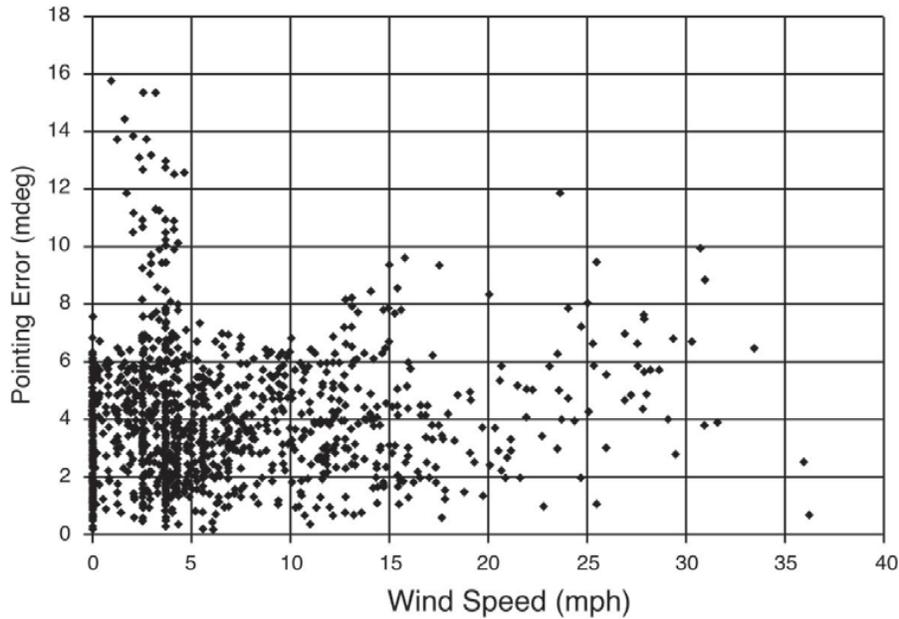


Figure 5. DSS-26 X-band Pointing at Various Wind Speeds

Table 4 presents measured X-band blind-pointing pointing performance of DSN antennas. Insufficient data have been acquired to give a proper assessment of pointing at Ka-band. S-band pointing is not provided as X-band pointing models are good enough to be used for S-band, due to the much large S-band beamwidth.

2.6 *Closed-loop Pointing*

Closed-loop pointing relies on the signal being received to provide corrections for antenna pointing. The DSN employs two methods of closed-loop pointing, CONSCAN and monopulse.

Table 4. Measured Blind Pointing Performance of DSN Antennas

Antennas	Mean Radial Error, mdeg	Remarks
70-Meter		
DSS-14, Goldstone	1.67, precision mode (ME)	limited data set, 4/2004
DSS-43, Canberra	3.04, precision mode (ME) 6.19, normal mode	10/2002-12/2003
DSS-63, Madrid	1.37, precision mode (ME)	limited data set, 3/2004
34-Meter HEF		
DSS-15, Goldstone	TBD	data not available
DSS-45, Canberra	6.69	1/2003-12/2003
DSS-65, Madrid	3.66	limited data set, 3/2004
34-Meter BWG		
DSS-24, Goldstone	TBD	data not available
DSS-25, Goldstone	7.50	9/2003-10/2003
DSS-26, Goldstone	4.91	7/2004
DSS-34, Canberra	6.53	9/2003-12/2003
DSS-54, Madrid	4.81	limited data set, 2/2004
DSS-55, Madrid	4.34	limited data set, 3/2004
34-Meter HSB		
DSS-27, Goldstone	TBD	data not available

2.6.1 CONSCAN

CONSCAN is available on the 70-m antennas and all 34-m antennas except the 34-m HSB antenna. It consists of performing a circular scan (as seen from the target) with the center at the predicted source position and a radius that reduces the received signal level by a small amount, typically 0.1 dB. If the target is at the expected location and antenna pointing is perfect, no variation in the received signal level will be detected. If the initial pointing is imperfect or the target is not at the predicted location, each CONSCAN cycle will see a variation in amplitude from which the radial error and clock angle of the mis-pointing can be calculated. The typical time for a CONSCAN cycle is 120 seconds and the pointing is corrected after each cycle. The process is repeated continuously during the pass. Various amounts of CONSCAN “gain” can be applied for making the pointing correction, ranging from 0 (no correction applied) to 1 (full detected correction applied). A gain of less than 1 is usually applied to reduce the effect

of noise during the CONSCAN cycle. This results in some time delay (perhaps 20 minutes) before fully corrected pointing is obtained.

CONSCAN is available at all frequency bands but is usually not necessary at S-band and is not recommended for Ka-band. The relatively long CONSCAN cycle coupled with the much more severe Ka-band atmospheric effects can provide misleading information to the pointing correction algorithm resulting in the antenna being driven off-point.

The mean pointing error (used for estimating pointing loss) using CONSCAN should be considered as the 0.1 dB point on the antenna pattern for the antenna and frequency in question. For a 34-meter antenna at X-band, this value is 6 mdeg and for a 70-meter antenna at X-band it is 3 mdeg. Considering CONSCAN pointing to be Rayleigh distributed, the pointing error for various CDs can be calculated or extracted from Figure 4. Antenna beam patterns for the various DSN antennas are given in modules 101 through 104.

For making pointing measurements using radio sources, a CONSCAN radius yielding a 3-dB pointing loss is often used as this gives greater sensitivity to small pointing errors than the smaller radii used for spacecraft tracking. Analysis shows that, with the exception of extremely strong radio sources, the optimum tracking of radio sources will occur when the ratio of scan radius to half-power beamwidth equals 0.425. This causes a reduction in effective antenna gain of 2.17 dB and a mean pointing error of 28 mdeg for a 34-m antenna at X-band. The mean pointing error for an X-band 34-m antenna at the 3-dB point is at 0.033 deg. The equivalent mean pointing errors for the 70-m antennas are 0.016 deg at the 3-dB point and 0.14 deg for optimum tracking.

2.6.2 Monopulse

Monopulse is a technique for extracting pointing information from the phase of the received signal while maintaining the source at the peak of the antenna pattern. This technique relies on the presence of a carrier signal to provide a reference for the error channel(s). As a result, it is not suitable for suppressed carrier signals or radio sources.

The monopulse capability is available to support deep space Ka-band (32-GHz) at DSS-25, DSS-26, DSS-34, DSS-54, and DSS-55. It is also planned for the implementation of DSS-35 in Canberra. The Ka-band feeds of these 34-m BWG antennas include a cryogenically cooled TE₂₁ mode coupler that extracts a signal whose phase, with respect to the main beam signal, indicates the direction of the target with respect to the center of the beam and whose amplitude indicates the angular displacement from the beam center. The advantage of such a system over a conventional amplitude monopulse system is that only a single receiver channel is required for the error signal as opposed to two. The monopulse receiver measures the phase and amplitude of the signal in the error channel, calculates elevation and cross-elevation corrections, and forwards this information to the antenna controller 25 times a second. The antenna controller translates the errors into the local antenna coordinate system, integrates them, and applies the corrections to the predicted azimuth and elevation positions. Initial tests on the Cassini spacecraft during cruise indicate Ka-band monopulse tracking performs to an accuracy of better than 2 mdeg.

For initial acquisition using blind pointing, monopulse seems to “pull-in” when the pointing is within about 10 mdeg. For larger pointing errors and/or low signal to noise ratios (SNRs), CONSCAN is used to get on target.

For extremely high signal-to-noise ratios ($SNR > 40$ dB-Hz), the monopulse system is capable of pointing the antenna within 1 mdeg of a stationary target. As SNR decreases, this performance is degraded by servo jitter resulting from noise in the selected servo bandwidth. A study has shown that the mean radial error using monopulse varies with SNR approximately as

$$MRE = 0.2 + 12e^{-0.13SNR}, \text{ mdeg} \quad (3)$$

where SNR is the monopulse signal-to-noise ratio, dB-Hz (signal in the main channel divided by noise in the error channel). For example, for $SNR = 20$ dB-Hz, $MRE = 1.1$ mdeg. SNRs below 10 dB-Hz will probably yield unacceptably poor pointing performance.

2.7 *Beam Alignment*

Most DSN antennas that support more than one frequency accomplish this by having multiple feedhorns. The exceptions to this are the 34-m HEF antennas that have a single S- and X-band coaxial feedhorn and the BWG antennas (with the exception of DSS-25) where there is a coaxial X- and Ka-band feedcone. When multiple feedcones are used, it is likely that there will be a small misalignment between the peak of the two antenna beams. However, if good pointing is achieved at the higher frequency, it virtually guarantees nearly perfect performance at the lower frequency due to the larger beamwidth. For example on the DSS-43, 70-m antenna (Canberra), the S- and X-band beams have a pointing difference of about 4 mdeg in the EL direction. Because the S-band beam has a half-power beamwidth of about 118 mdeg, perfect pointing at X-band would give an S-band pointing loss of less than 0.02 dB.

2.8 *X-band Beam Shift on 70-m Antennas*

The 70-meter antennas have an S/X dichroic plate that is retractable to provide an X-band only low-noise mode. There is an 8.5 mdeg (approximately) beam movement in the negative XEL direction (to the left, when looking outward from the antenna) when it is retracted. Separate systematic error models are maintained for each position of the dichroic plate and are selected automatically by the antenna controller.

2.9 *DSS-25 Ka-band Transmit Aberration Correction*

The extremely narrow beamwidth at Ka-band requires that the DSS-25 Ka-band uplink signal be aimed at the RA and DEC where the spacecraft will be when the signal arrives, while simultaneously receiving a signal that left the spacecraft one light-time previously. This is accommodated by mounting the Ka-band transmit feed on a movable X-Y platform that can displace the transmitted beam as much as 30 mdeg from the received beam. The reduction in gain caused by the feed not being located at the optimum focus of the antenna is discussed in module 104.