A New Blind Pointing Model Improves Large Reflector Antennas Precision Pointing at Ka-Band (32 GHz)

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Abstract—The National Aeronautics and Space Administration (NASA), Jet Propulsion Laboratory (JPL)-Deep Space Network (DSN) subnet of 34-m Beam Waveguide (BWG) Antennas was recently upgraded with Ka-Band (32-GHz) frequency feeds for space research and communication. For normal telemetry tracking a Ka-Band monopulse system is used, which typically yields 1.6-mdeg mean radial error (MRE) pointing accuracy on the 34-m diameter antennas. However, for the monopulse to be able to acquire and lock, for special radio science applications where monopulse cannot be used, or as a back-up for the monopulse, high-precision open-loop blind pointing is required. This paper describes a new 4^{th} order pointing model and calibration technique, which was developed and applied to the DSN 34-m BWG antennas yielding 1.8 to 3.0-mdeg MRE pointing accuracy and amplitude stability of 0.2 dB, at Ka-Band, and successfully used for the CASSINI spacecraft occultation experiment at Saturn and Titan. In addition, the new 4^{th} order pointing model was used during a telemetry experiment at Ka-Band (32 GHz) utilizing the Mars Reconnaissance Orbiter (MRO) spacecraft while at a distance of 0.225 astronomical units (AU) from Earth and communicating with a DSN 34-m BWG antenna at a record high rate of 6-megabits per second (Mb/s). [1 2]

TABLE OF CONTENTS

1. INTRODUCTION

The sources for pointing errors of a large reflector antenna which are related to this work are due to atmospheric refractivity, gravitationally induced structural deformation, antenna geometry (axes and mirror misalignments for a beam waveguide (BWG) antenna), azimuth track level errors, azimuth encoder ring gear errors, elevation encoder coupling hysteresis, thermally induced structural deformation, wind-induced structural deformation & servo errors, ground tilt (seismic and diurnal motion), and pointing measurement errors.

The traditional systematic pointing error correction model, which is mathematically a 1st order model and typically has 6 to 8 mathematical terms (Fig 1.), is a physical model which was originally developed by Peter Stumpff [1]. This paper describes a new pointing model that is mathematically of 4th order (Fig 2.). The new 4th order pointing model was devised as a result of noticing systematic error residuals remaining in the data after applying the conventional 1st order model. the model was derived by expanding the spherical harmonics, which are related to the associated Legendre polynomials (equations 1& 2), to the 4th order and resulting in 59 mathematical terms:

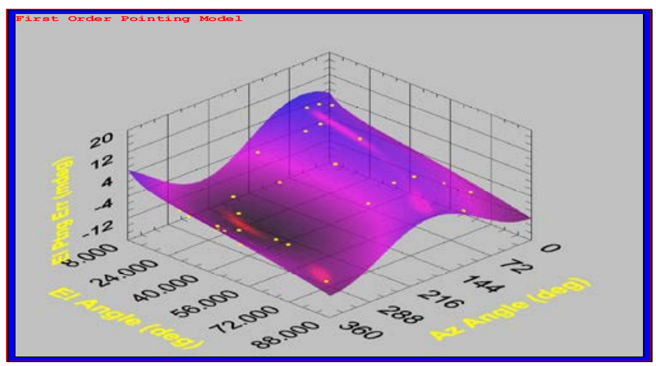

Figure 1. A 1^{st} order model derived for an antenna elevation axis

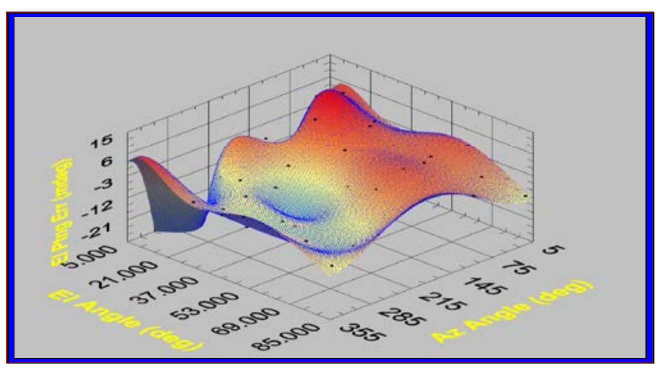

Figure 2. A 4th order model derived for an antenna elevation axis

Figures 1. and 2., show the derivation of a 1^{st} and 4^{th} order pointing model (respectively) from the same set of gathered

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data for a NASA-JPL-DSN 34-m BWG antenna (DSS-25) and resulting in a residual errors of 2.7-mdeg and 1.5-mdeg respectively for the 1st and 4th order models and indicating an approximate 2 to 3 times improvement for the 4th order model. This improvement ratio turns out to be critical especially for tracking the NASA spacecrafts at Ka-Band frequencies (26 to 32 GHz).

This ratio of improvement was substantiated by field demonstration tracking the NASA spacecrafts.

2. DSN Ka-Band Pointing Requirements

The pointing accuracy of an antenna, often referred to as its blind-pointing performance, is the difference between the calculated (or commanded) beam direction and the actual beam direction. The error has random and systematic components. The systematic component is that which is assumed repetitive and therefore can be modeled. This paper concentrates on this systematic component of the antenna pointing. The first of these errors includes the computational errors and uncertainties associated with the radio sources used to calibrate the antenna, and the location of the spacecraft provided by its navigation team. The second has many components associated with converting a calculated beam direction to the physical positioning of a large mechanical structure. Included are such things as atmospheric wind and refraction effects, servo and encoder errors, thermally and gravitationally induced structural deformation, azimuth track leveling (for an azimuth-elevation antenna), and both seismic and diurnal ground tilt.

Blind pointing is modeled by assuming equal pointing performance in the elevation (EL) and cross-elevation (X-EL) directions. That is, the random pointing errors in each direction have uncorrelated Gaussian distributions with the same standard deviation. This results in a Rayleigh distribution for pointing error where the mean radial error is 1.2533 times the standard deviation of the EL and X-EL components. For a Rayleigh distribution, the probability that the pointing error will be less than the mean radial error (MRE) is 54.4%, which is equivalent to a cumulative distribution (CD) = 54.4%. A CD of 90% implies that 90% of the time, the pointing error or pointing loss will be less than the value specified. For simplicity, we will specify all pointing performances in this paper in terms of MRE.

One can gain a better appreciation of the implications of these pointing errors reduction by considering the corresponding antenna gain loss associated at Ka-Band (32 GHz). These values are presented in Table 1, which covers the current technology capability of the DSN antennas.

The DSN pointing requirements at Ka-Band depend on the application of the ground segment support. For Radio Science observations to achieve its desired amplitude stability of 0.2-dB [2], a 2-millidegree (mdeg) mean radial error (MRE) pointing accuracy is required (see Table 1.) to ensure reliable Ka-band optical depth measurements over tenuous ring regions. A 2.5 mdeg all-sky pointing accuracy would be needed for the detectability of quasars for navigation delta-differential one-way ranging (delta-DOR) [3], Earth rotation, and clock synchronization. For spacecraft tracking which can utilize the monopulse, a 10-mdeg pointing accuracy is required to enable the monopulse capture range to lock on the spacecraft radio frequency (RF) signal carrier.

Ka-Band monopulse-aided pointing uses a monopulse tracking coupler within the cryogenic feed package to establish a feed pattern with a theoretical null on axis. The magnitude of the pointing error is proportional to the magnitude of the signal received by this pattern, and the azimuthal error is proportional to the phase difference between the sum and difference outputs of the coupler. Thus, by measuring the complex ratio of the sum and difference signals, pointing corrections can be generated to command the antenna servo system to drive the pointing error to zero. The system achieves its specified performance when the ratio of the signal in the sum channel (that is, the signal from which tracking and telemetry information will be derived) to the noise level in the difference channel is 26 dB-Hz. The monopulse pointing performance on the 34-m BWG antennas at Ka-Band (32 GHz) is 1.6-mdeg when the signal-to-noise ratio (SNR) is greater than 26 dB-Hz. This performance level (which is also the requirement) is based on 3% (0.11 dB) power loss for telemetry. A 3 mdeg pointing error produces 10% (0.4-dB) power loss and can cause complete loss of telemetry signal. Based on the limits set by the 34-m BWG structural design, wind, thermal effects, servo performance, and as a backup for the monopulse, a committed capability for an all-sky 4–mdeg MRE performance was set.

Table 1. 34-m Diameter Antenna Gain Loss at 32-GHz Due to Pointing Errors

MRE* (mdeg)	**Pointing Loss** (dB)**	**SNR reduction*** (dB)**
1.5	0.085	0.1
2.0	0.16	0.21
3.0	0.33	0.42
4.0	0.65	0.85
6.0	1.5	2.0
8.0	2.6	4.0

* *MRE: Mean Radial Error*

** *Pointing Loss: based on the Bessel function*

*** *SNR reduction: takes into account statistical variation*

Table 2. 1st Order Pointing Model Parameters

Term No	XEL Term	EL Term	Description
1	1	0	AZ collimation (a.k.a. Xel)
2	cos(el)	0	AZ encoder fixed offset
3	sin(el)	0	AZ/EL skew
4	sin(el)cos(az)	–sin(az)	AZ axis tilt (E-W component)
5	sin(el)sin(az)	cos(az)	AZ axis tilt (N-S component)
6	sin(az)	sin(el)cos(az)	Source Dec error
7	0	1	EL encoder fixed offset
8	0	cos(el)	Gravitational flexure
9	0	cot(el)	Residual refraction
10	(AZ/360)cos(el)	0	AZ encoder scale error
11	cos(az)cos(el)	sin(az)cos(el)	Residual de-rotation (E-W component)
12	sin(az)cos(el)	cos(az)cos(el)+ sin(az)sin(el)	Residual de-rotation (N-S component)

The extremely narrow beamwidth of the antenna main beam at Ka-band (16 mdeg) for its half power beamwidth (HPBW) requires that a Ka-band uplink signal be aimed at where the spacecraft will be when the signal arrives (look ahead), while simultaneously receiving a signal that left the spacecraft one light-time previously. This is accomplished at the DSN DSS-25 34-m BWG antenna, by mounting the Ka-band transmit feed on a movable X-Y platform that can displace the transmitted beam by as much as 30 mdeg from the received beam. DSS 25 is the only antenna with a Ka-band transmit capability. The fact that the transmit feed is displaced from its optimum focus causes it to have a gain reduction relative to the optimized receive feed.

3. Pointing Models

The 1st order systematic pointing model [1], is a physical model where the mathematical terms in the model have physical significance and are related to a physical performance parameter of the antenna. Table 2 shows a typical set of the 1st order model and the significance of each term for a DSN 34-m BWG antenna. In Table 2 the original model which was developed by Peter Stumpff [1] was augmented by Bob Riggs and Leon Alvarez of JPL during 1970–1995 with additional terms [4]. The parameters of the systematic models are derived via a least squares fit solution [5].

The new 4th order pointing model was derived by expanding the spherical harmonics, which are related to the associated Legendre polynomials by the equations 1 and 2 below, to the 4th order resulting initially in 25 mathematical terms for each axis. Parameters from the physical 1st order model, which did not appear in the expansion, were added to the model For the cross-elevation axis (Xel) the four parameters which were added are: **cos(el), sin(el)cos(el, sin(el)sin(az), sin(az)**. For the elevation (El) axis model, the five parameters which were added are: **cos(el), sin(el)cos(az), sin(az), cos(az), cot(el).** This resulted in 59 mathematical parameters for the model.

$$Y_{lm}(\theta,\phi)=\sqrt{\frac{2l+1(l-m)!}{4\pi(l+m)!}}P_l^m\cos(\theta)e^{im\phi} \tag{1}$$

where,

$$P_l^m(x)=(-1)^m(1-x^2)^{m/2}\frac{d^m}{dx^m}P_l(x) \tag{2}$$

and to convert from the spherical coordinate system to the physical antenna coordinate system, the following coordinate transformation were selected:

$$\theta=\pi/2-el \tag{3}$$

and

$$\phi=-az \tag{4}$$

and therefore the complex exponential term, which corresponds to two real terms, becomes:

$$e^{i\phi}=e^{-iaz}=\cos(az)-j\sin(az) \tag{5}$$

The application of the 4th order pointing models improve the DSN blind pointing performance by approximately a factor of 2 [6], [7], [8].

4. APPLICATIONS

To facilitate an efficient all-sky survey for the observation of radio sources, a scheduling program was written and integrated within the antenna pointing and calibration tool. At each radio source observation point, residual pointing error offsets are computed, and these represent the systematic pointing error of the antenna at that coordinate.

Each yellow dot in Figure 3, represents a radio source to be observed, and data are recorded utilizing a 2-D cross-scan as illustrated in Figure 4 .

The gathered data are then processed by the 4th order pointing model software that computes a new pointing model for the antenna.

Prior to the application of the new 4th order pointing model, a typical blind pointing performance level of 7–10-mdeg was achieved for the 34-m BWG antennas subnet. When the new 4th order model was applied for the first time at the DSS-26 BWG antenna at Goldstone, California, and subsequently used in operational activity to track Voyager I, a new record of performance level of 3.5-mdeg mean radial error (MRE) was achieved (Figure 5).

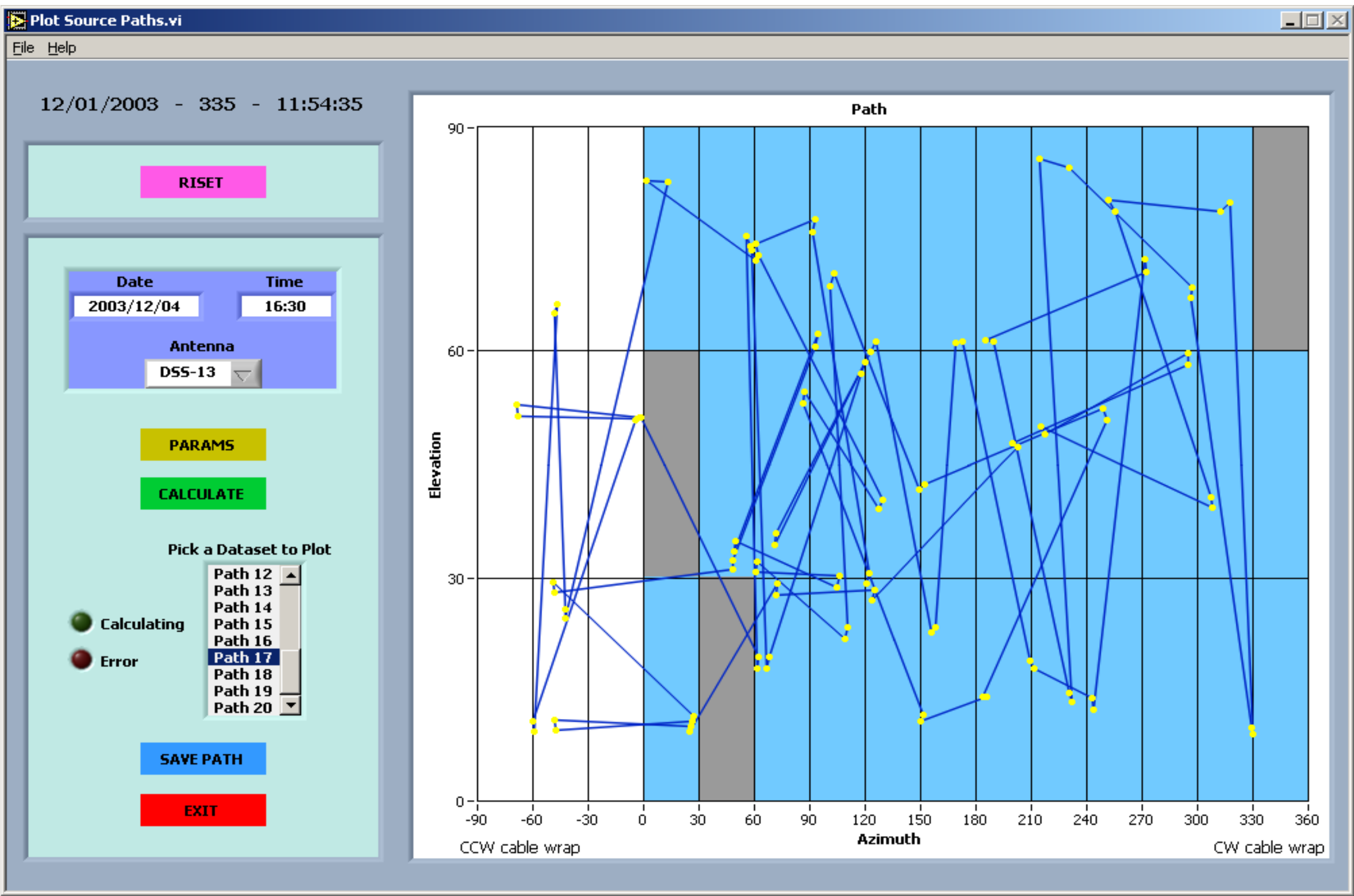

Figure 3. A pointing scheduling program drives the antenna from one radio source to the next to achieve full sky coverage

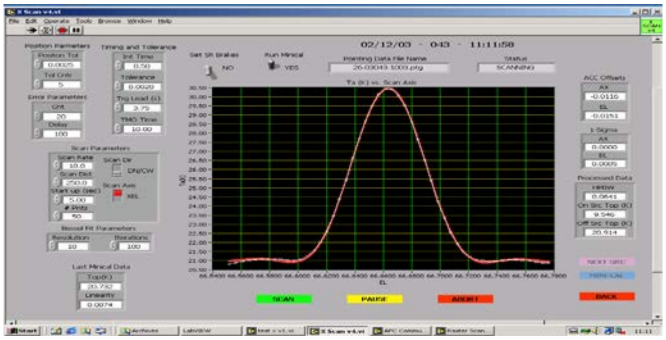

Figure 4. A 2-D cross scan

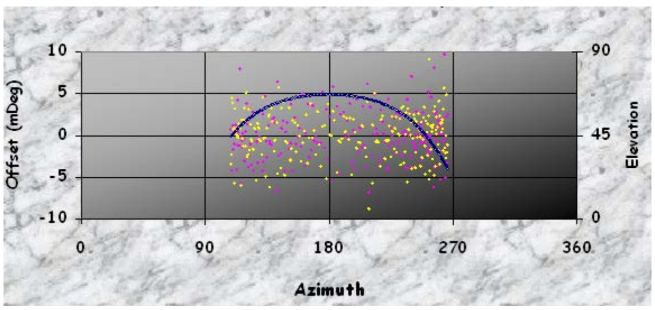

Figure 5. DSS-26 Performance: 4th order pointing model achieved blind pointing performance on the NASA-JPL-DSN 34-m BWG antennas Subnet of 1–3-mdeg MRE for spacecraft tracking. In the figure, the yellow and purple dots are the residual pointing errors in the elevation and cross-elevation axes, respectively.

5. SUMMARY AND CONCLUSION

The new 4th order pointing model was successfully applied in the DSN for over three years supporting the Cassini Radio Science Occultation Experiment with Saturn and supporting Bistatic Radar at Titan. Many scientific results were published, including "Evidence for Likely Liquid Hydrocarbons on Titan's Surface from Cassini Radio Science Bistatic Scattering Observations" [9]. The new pointing model also successfully supported Mars Reconnaissance Orbiter (MRO) with similar performance level at Ka-Band providing 6-mbps telemetry data rate when the monopulse was down. The performance of the 34-m BWG subnet was improved by a factor of approximately 2 relative to the 1st order model. Track-level compensation was applied to specific antennas as needed. Our next goal is to achieve 4-mdeg MRE blind pointing performance over the "all-sky" deploying on-the-fly (OTF) mapping instrumentation across the network.

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BIOGRAPHY

David Rochblatt is the Antenna Calibration Expert at JPL. Mr. Rochblatt has been a design engineer and the manager for R&D ground antennas systems at JPL since 1981. In the early 80's he designed dual cassegrain reflector antennas, low noise amplifiers, and front ends for mobile very long baseline interferometry (VLBI) stations hardware (ARIES and ORION) which were part of NASA's Crustal Dynamics Project managed by Goddard Space Flight Center (GSFC). In the mid to late 80's he was a member of the design team that upgraded the NASA-JPL-DSN 64-m antennas, to 70-m dual shaped cassegrain reflector antennas. In 1992 he proposed to the JPL director, Dr. Lew Allen, the utilization of Phase Retrieval Holography for the characterization of the Hubble Space Telescope mirror spherical aberration problem which then became the method of choice for the repair of the Hubble Space Telescope via the conjugate compensation within the Wide Field Planetary Camera. In 1995 he received the NASA Exceptional Achievement Medal for developing the Microwave Antenna Holography System. Mr. Rochblatt applied the holographic technique to set the panels of the DSN antennas (starting in 1987), improving their performances and the performance of the entire DSN ground network by more than 3 dB. In the late 90's he led the development and demonstration of open-loop technologies for the DSN 70-m antennas (and the 34-m R&D antenna, DSS-13) for compensating their main reflector deformation due to their gravitational distortion utilizing a–Deformable Flat Plate (DFP) and Array Feed Compensation System (AFCS). Also in the late 90's to early 2000, he developed antenna calibration techniques utilizing the raster-scan method and first applied the new technique to calibrate the Cassini Radar as a radiometer at 13.8-GHz, using Jupiter as a calibration reference. He then proceeded and further led the development of the technique as the standardized calibration method for the DSN. Mr. Rochblatt consulted at the Russian Space Agency, the U.S. Naval Research Laboratory (Pomonkey, Maryland), the University of Naples (Italy), the University of Massachusetts at Amherst, and Cedars Sinai Medical Center (Los Angeles, California). Also, he has been an invited speaker at a number of IEEE workshops. Mr. Rochblatt holds a BSEE and an MSEE from the University of California at Los Angeles (UCLA) (received in 1978 and 1980, respectively) and is a senior member of the IEEE. He has published 70 journal and conference papers and received more than a dozen NASA Achievement Awards. His other interests include deep-space telecommunication, inverse scattering problems, and phase retrieval applications for microwaves and optical communications.

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