35-Meter Deep Space Antenna Pointing Calibration System

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Abstract

SED Systems is developing an antenna pointing calibration system (PCS) suitable for use with large X-band and Ka-band Deep Space Telemetry, Tracking and Command (TT&C) antennas (DSAs) to improve the pointing accuracy of such antennas. The PCS integrates with existing cryogenic LNA and downconverters used by ESA, without degrading downlink RF performance. The system automates measurement of pointing errors and parameterization of systematic pointing errors.

The PCS integrates with the antenna servo system to provide compensation for pointing errors due to thermal distortion of the reflector and subreflector struts, and systematic errors caused by tower tilt, encoder offsets, feed and beam waveguide mirror alignment errors, Az/el axis orthogonality errors, collimation error, and gravity flexure. It also compensates for frequency and polarization dependent beam squint caused by curved beam waveguide reflectors or phase shifts in the antenna's optical/RF system.

The PCS also provides tools for quickly and routinely measuring pointing accuracy and system noise temperature of the antenna. These include the ability to quickly measure pointing error, with different components of the error model applied. Accurate downlink noise temperature measurements can also be made using the radiometer integrated into the PCS. As a result, the long-term operational health of the servo and downlink RF systems can be routinely monitored.

The system is being developed for installation in ESA's new 35 m deep space antenna to be located in Cebreros, Spain (DSA2). When installed and commissioned by June 2005, the PCS will ensure that the antenna achieves a Ka-band pointing error of less than 6 mdeg.

This paper describes the main elements of the PCS, including the radiometer developed by SED to measure noise temperature. Operational characteristics of the PCS and its measurement accuracy are also presented.

Background

In February 2003, SED Systems of Saskatoon, Canada was awarded a contract by ESA's Space Operations Centre (ESOC) to supply a 35-meter X/Ka-band Telemetry, Tracking and Command (TT&C) antenna system for installation at Cebreros, Spain in 2005. This antenna will be remotely operated from Darmstadt, Germany. The pointing error requirement of 6 mdeg (3-sigma) under worst-case environmental conditions (50 km/h average wing speed, gusting to 70 km/h, and over a -20°C to 50°C temperature range) is based on the maximum permissible gain loss to support X and Ka-missions. At Ka-band, the loss due to 6 mdeg pointing error (PE) is 1.3 dB. X-band pointing losses are typically less than 0.1 dB.

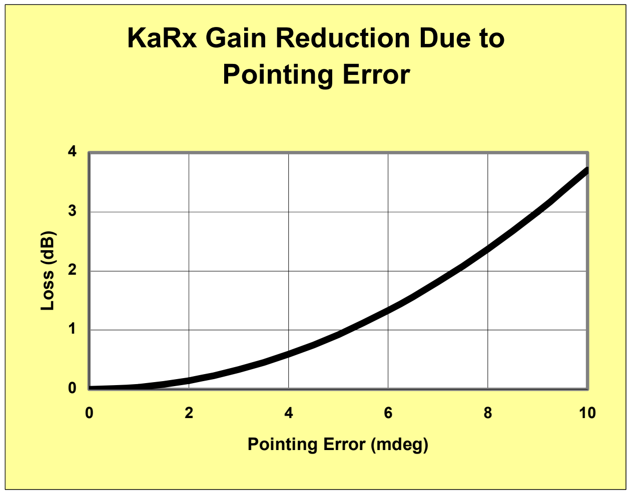

Figure 1 Ka-band (32 GHz) Pointing Loss

As part of the project, SED is designing and supplying a pointing calibration system (PCS) and integrating it with the servo subsystem to ensure the pointing accuracy requirements are met. The system is designed to measure the antenna's systematic pointing errors, and together with other parts of the servo system, compensate for them. Systematic pointing error sources include:

- Az and El encoder offsets
- Gravity deformation of the main and subreflector as elevation angle changes.
- Thermal gradients in the antenna building and reflector back-structure
- Az/El Axis non-orthogonality
- RF collimation
- Beam waveguide mirror and feed alignment errors
- RF beam squint (polarization and frequency band dependent)
- Atmospheric refraction
- The servo system also contains sensitive tiltmeters to compensate for steady state (i.e., > 30 sec) deflection of the antenna and tower due to steady wind pressure and non-symmetric thermal loads on the tower and antenna structure.

The largest remaining source of pointing error is due to wind gusts. Errors caused by this source, together with other dynamic or random (repeatability) errors such are not corrected by the PCS. Rather, the rigidity of the antenna structure, bearings, gearboxes, and drive motors, and the design of servo algorithms are used to control the PE caused by such sources.

Typically, pointing calibration systems have been engineering intensive and require expert personnel to operate and use. Such systems are not well suited to a remotely operated, high usage TT&C antenna. The new system developed by SED will introduce a high degree of automation to the planning, PE measurement, calibration, and compensation capabilities of the PCS, to provide a more practical solution for such antennas.

System Design

A block diagram of the PCS for the X/Ka-band DSA2 antenna is shown in Figure 2. All of this equipment is designed for unattended operation and contains extensive monitor and control capability.

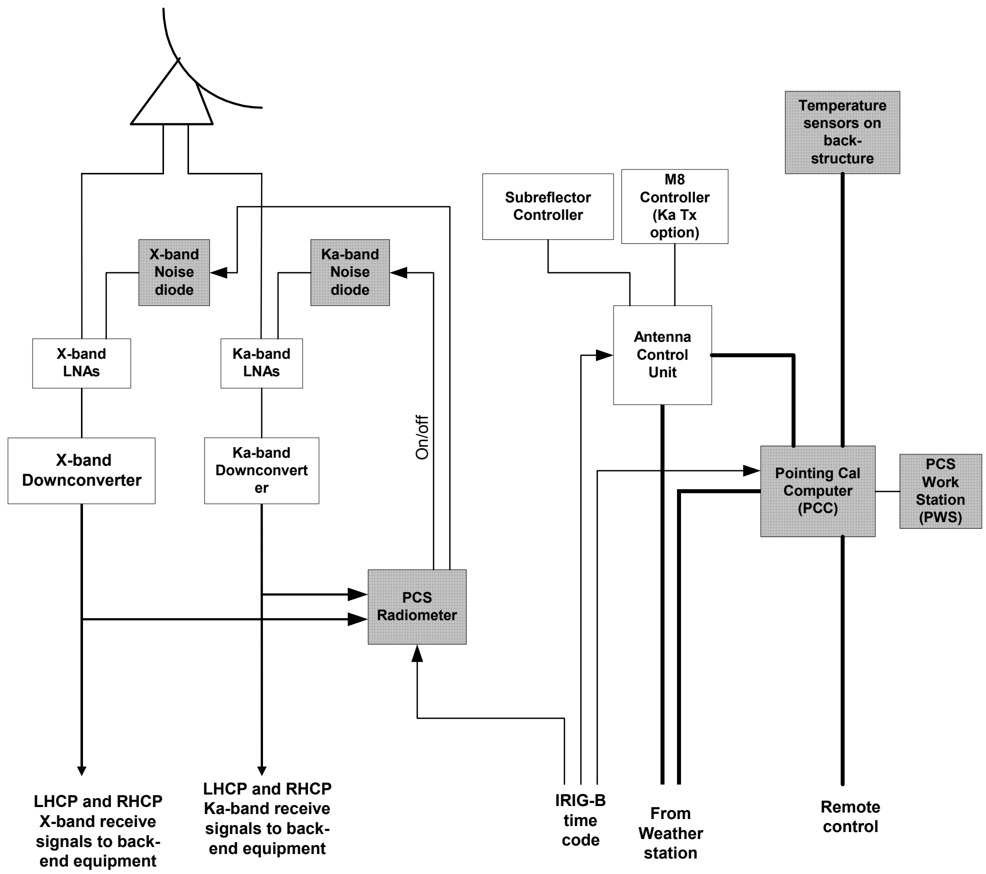

Figure 2 PCS Block Diagram

The main elements of the PCS are:

- Pointing Calibration Computer (PCC), and its associated software. This computer runs the PCS application software that controls the pointing calibration process. It is connected via an Ethernet LAN to ESA’s mission center, for remote control, and to the site’s weather station. It is connected via a separate LAN to the antenna control unit (ACU), the radiometer, and antenna physical temperature measurement system (TMS).
- Pointing Calibration Workstation (PWS), and its associated software. This computer provides the local user interface used to control and monitor the operation of the PCS. A remote access capability is also provided to allow the same user interface from a remote workstation.
- Radiometer, and its associated RF noise diodes. This equipment is used to measure downlink system noise temperature.

- Antenna Physical Temperature Measurement System (TMS). This consists of an array of 250 temperature sensors located on the main reflector back-structure and the subreflector quadrapod struts. Temperature data collected by this subsystem is used by the PCS to calculate the pointing error due to thermal distortion of the mechanical structure.

The PCC, ACU, and radiometer are synchronized to a common IRIG-B time source to ensure their actions are coordinated to an accuracy of ≤ 1 msec.

The antenna's downlink RF systems use cryogenic HEMT LNAs and low phase noise downconverters. Technical characteristics of the downlink chains are:

Parameter	X-band	Ka-band
RF frequency range	8400 – 8500 MHz	31.8 GHz – 32.3 GHz
LNA Noise temperature (K)	≤ 17K max	≤ 30K max
DC IF frequency (MHz)	640 – 540 MHz	420 – 620 MHz
Overall G/T @ 10 deg El	50.8 dB/K	55.8 dB/K
Overall G/T @ 40 deg El	51.7 dB/K	57.2 dB/K
Overall G/T @ 90 deg El	51.8 dB/K	57.4 dB/K

Radiometer

The radiometer is a specialized noise temperature measurement system designed by SED to provide accurate noise temperature readings during PE measurements, and pass these measurements to the PCC. The radiometer is operated in a Noise Adding Radiometer (NAR) mode, in which a noise diode is turned ON and OFF in sequence to inject a known level into the downlink during the measurement. The Y-factor derived from the ON and OFF states is used to calculate Tsys using:

$$Tsys = \frac{TND}{\left(\frac{VON}{VOFF} - 1\right)}$$

where VOFF and VON are the voltages after integration by the radiometer for the noise diode ON and noise diode OFF portions of the measurement cycle, and TND is the effective noise temperature of the noise diode referenced to the input of the LNA. TND depends on the excess noise ratio (ENR) of the noise diode, and the insertion and coupling loss between the diode and LNA RF path. For DSA2, values are: X-band: ENR = 26 dB, Loss = 28.7 dB, TND = 156.96K

Ka-band: ENR = 23.2 dB, Loss = 28.5 dB, TND = 86.06K

The ON and OFF cycling periods are 10 msec to eliminate degrading effects of short term (i.e., AM flicker noise) and long-term LNA/DC gain drifts.

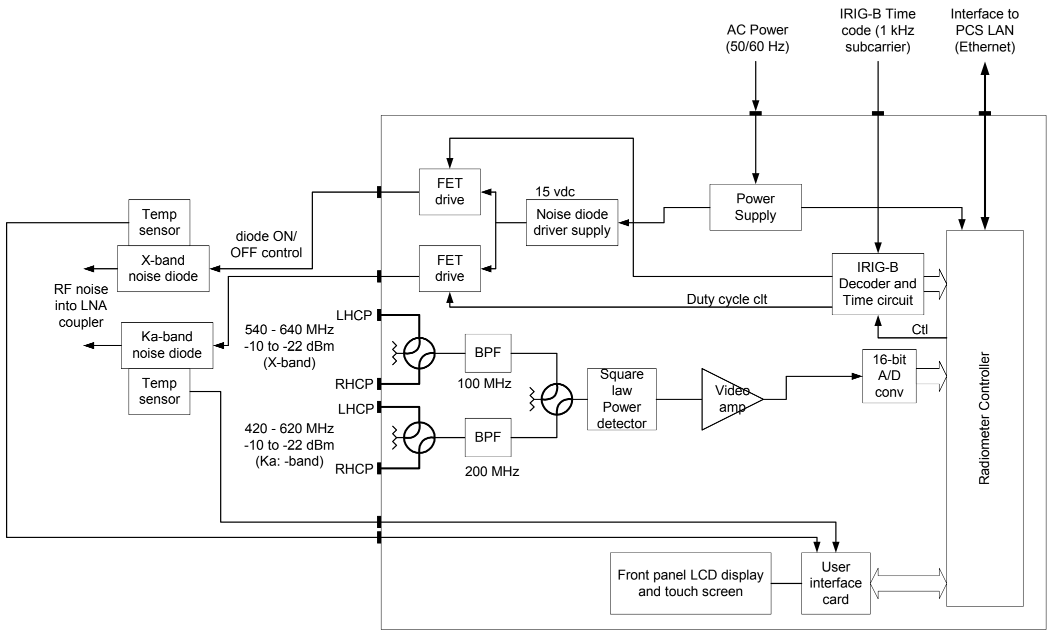

Figure 3 Radiometer Block Diagram

The radiometer operates over the entire downlink passband. Its integration time can be adjusted over a wide range to permit control of its noise temperature resolution. During PE measurements, the integration time is typically 5 seconds.

The radiometer is synchronized to the station's IRIG-B time and can be commanded to take multiple Tsys measurements at specific times. This allows the PCC to command the set of Tsys measurements required for a PE measurement, and ensure they are synchronized to msec accuracy with the current position of the antenna.

Key performance parameters of the radiometer system are:

Description	Comment
IF input frequency band	X-band downlink: 540 - 640 MHz Ka-band downlink: 420 - 620 MHz
Number of IF inputs	Four consisting of IF inputs for: XRx Pol 1 XRx Pol 2 KaRx Pol 1 KaRx Pol 2
Absolute calibration accuracy of noise diode	±0.18 dB
ON/OFF Integration Time	NAR mode: Total integration time, selectable in 10 msec increments up to approx 120 sec.
Noise temperature measurement range	20K to 300K
Absolute accuracy of Tsys	≤ ± 5%
Repeatability of Tsys measurements or between channels	≤ ± 1.4%

Antenna Physical Temperature Measurement System (TMS)

The TMS consist of a set of approximately 250 temperature sensors distributed on the antenna main reflector back structure and subreflector quadrapod struts, and a data logger system to collect the temperature measurements and pass them to the PCC.

The PCC contains an algorithm that uses the temperature measurements to calculate the pointing error due to thermal distortion of the mechanical structure. The algorithm is based on finite element analysis (FEA) modeling of the antenna structure as different thermal loads are applied to different locations on the structure. These are sent to the ACU as pointing corrections every 60 seconds. For DSA2, the corrections are calculated to be ≤ 2 mdeg over all expected environmental and solar load conditions.

Pointing Calibration System Operation

The PCS is designed with the following operating modes:

- Calibration
- SPEM calculation
- Compensation
- PE measurement
- Noise Temperature measurement.

Calibration Mode. A typical calibration for one frequency band, one polarization is expected to take approximately 8 hours. In this time, the PCS can take approximately 80 PE measurements over a wide elevation and azimuth range. It can then determine the coefficients of the systematic pointing error model (SPEM) model, which minimizes the error between the PE measurements and the SPEM model. The coefficients are then passed to the ACU for use in ongoing pointing compensation. The key elements of the calibration algorithm are the scheduler, the PE measurement algorithm, and the SPEM curve fit.

Scheduler: This is an automated planning tool used to provide an optimum measurement schedule for a calibration session. The operator first specifies a start time and duration for the session. The scheduler then selects from a library of over 60 calibration sources. These are typically quasars, whose position is accurately known. The sources have been selected from the Very Large Array (VLA) database of deep space radio sources used by the radio astronomy community to calibrate the pointing of long baseline radio telescopes. The selected sources have a very small angular extent (≤ 1 mdeg) relative to the beamwidth of the antenna, are separated by at least two beamwidths from near by sources, and have flux densities ranging from 1.5 Jy to 20 Jy in both X- and Ka-band. Figure 4 shows the distribution of the sources visible from Cebreros, Spain (latitude of 40 deg N).

The scheduler automatically builds a measurement schedule which:

- maximizes the number of PE measurements in a the allocated calibration period
- minimizes time lost to antenna motion between measurements
- provides near-uniform distribution of measurements over the hemisphere

- avoids successive measurements in a small region of the sky to minimize impact of thermal effects if a set of measurements is clustered in a small region
- gives preference to higher flux density sources.

Figure 5 shows a typical schedule, showing the tracks of the chosen radio stars during the calibration session, and the measurement sequence. Zenith is at the center of the circle in this figure.

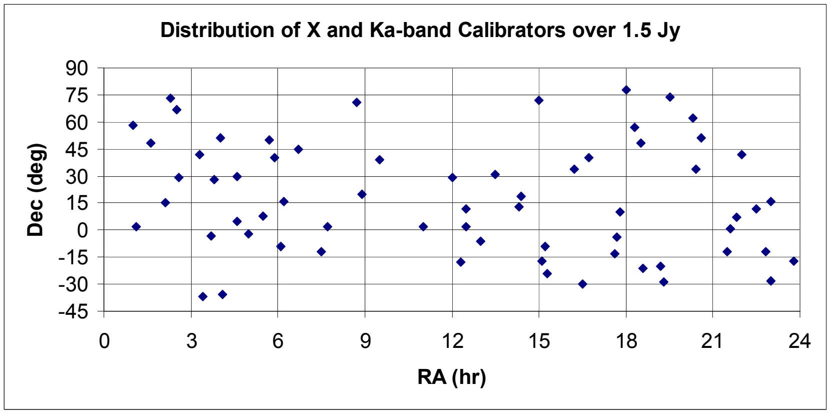

Figure 4 Radio Calibrators Visible from Cebreros, Spain

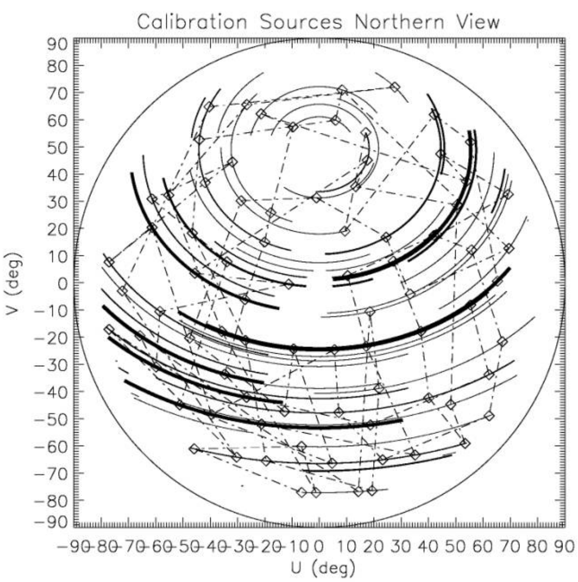

Figure 5 Typical Scheduler Output (80 measurements in 8 hours)

PE measurement. PE measurements are made by measuring system noise temperature with the radiometer, while tracking a radio star. The measurement algorithm uses a grid of azimuth and elevation offsets relative to the nominal position of the star. The grid is ± one 3-dB beamwidth around the nominal position of the star. For the 35 m antenna, the beamwidth is 64 mdeg at X-band, and 17 mdeg at Ka-band. Figure 6 shows a 5 x 5 grid. It is expected that a 7 x 7 grid will be used typically although the PCS can accommodate grids up to 11 x 11.

While the PCS commands the ACU antenna to follow a trajectory through the grid points, it commands the radiometer to measure the system noise temperature at each grid point. The radiometer integration time and the scan rate are carefully synchronized for these measurements. A simulated Tsys profile over a 7 x 7 grid is shown in Figure 7. The downward slope of Tsys over elevation is due to the noise temperature of the atmosphere decreasing as the radio star rises during the PE measurement. The peak at the center of the profile is the radio star. The amount the peak is offset from the center of the grid is a direct measure of PE. Typical time for one PE measurement scan is 5 minutes. After the grid scan is completed, a mathematical model is fit to the measured Tsys data on a least squares basis to determine the location of the RF beam relative to the commanded position. The Tsys model used in the curve fit also provides other parameters about the antenna, including beamwidth and noise temperature.

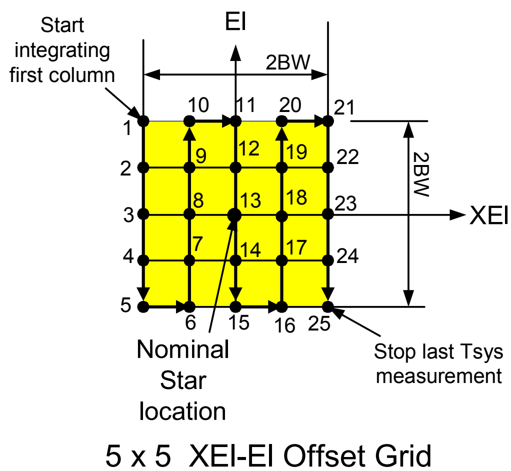

Figure 6 PE Scan Grid

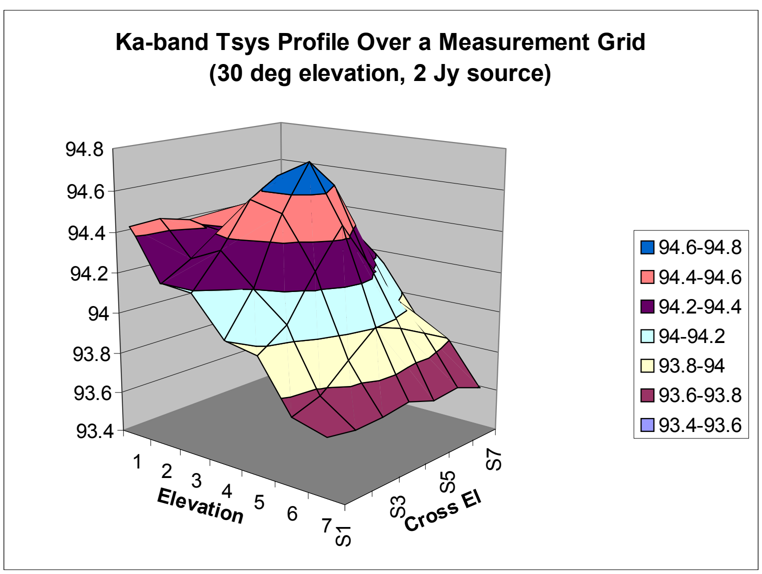

Figure 7 Simulated Noise Temperature Over a Typical Measurement Grid

Monte Carlo simulations have been used to determine optimum values for grid size, integration time, and other parameters affecting measurement accuracy. Figure 8 shows measurement accuracy as a function of radio star flux density. Accuracies better than 1 mdeg are expected for sources with flux density ≥ 1.5 Jy. The measurement accuracy for X- and Ka-bands are comparable for a given grid size, integration time, and flux density.

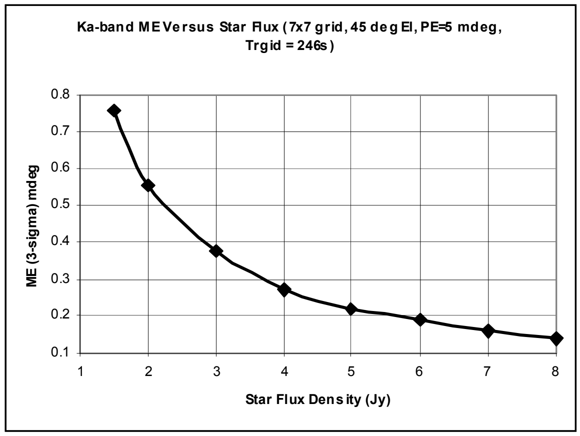

Figure 8 Predicted PE Measurement Accuracy Versus Star Flux Density

SPEM Curve Fit. The systematic pointing error mode (SPEM) used by the Antenna Control Unit (ACU) in the servo system uses 14 coefficients to model the systematic error of the antenna. Once sufficient (approximately 50 to 100) pointing error measurements are made over the whole sky, the PCS fits a multi-variable model to the data to determine the coefficients. The quality of the resulting curve fit is displayed for an operator as shown in Figure 9. This display shows the residual error between the measured data and the “best fit” curve fit model. Any remaining systematic error is immediately visible as patterns in the magnitude and direction of vector residuals. The coefficients of this model are used subsequently by the servo system to compensate for the systematic PE.

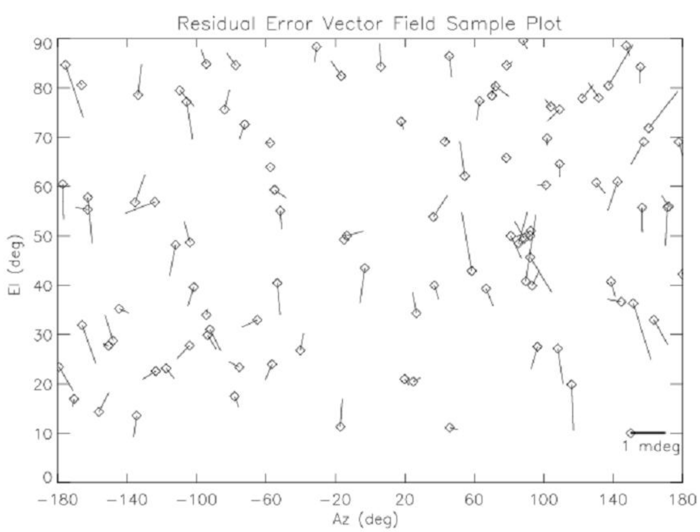

Figure 9 Residual Pointing Error

Compensation Mode: This is the normal operating mode of the PCS. In this case the ACU applies the SPEM, thermal distortion, and refraction corrections to commanded positions. Separate sets of SPEM coefficients are used for each frequency band and polarization. The system is designed such that if the PCS computer goes down, the ACU will continue to apply all corrections, except for the small thermal distortion correction. To determine refraction corrections, the ACU reads real-time atmospheric temperature, barometric pressure and relative humidity from the site's weather station and uses this data to calculate the current refraction correction.

Other PCS Capabilities

The PCS also includes measurement modes used by engineering staff to quickly check the pointing accuracy and downlink noise temperature of the antenna. These include:

- Single PE measurement. For this mode, the operator selects a single radio source from the calibrator database and commands a PE measurement. This measurement provides pointing error, beamwidth, atmospheric and equipment noise temperatures, and the noise temperature contribution from the radio source. This data can then be used to determine the G/T and efficiency of the antenna. The operator can also turn different pointing compensation models on and off, to assess their relative contribution to the PE.
- "Mini-Cal". This provides a quick check of pointing accuracy before critical mission events. In this case PE measurements are made at widely separated elevations and azimuths over a short time period (typically 30 minutes).
- Noise Temperature Measurement mode. This allows engineering staff to use the radiometer via the PCS workstation to perform noise temperature measurements at specific elevation and azimuth angles.

Conclusion

The PCS, and its integration into the ESA 35m X/Ka-band antenna at Cebreros (DSA2), will allow the systematic pointing errors inherent in such large antennas to be accurately determined, and most importantly, removed by the servo system to significantly improve Ka-band performance. The system is designed for use in such a remotely operated, high usage TT&C antenna systems. It provides for automated planning and conduct of pointing calibration sessions, in addition to tools used to routinely check pointing accuracy and system noise temperature between calibrations.

The development of the PCS is well advanced with full testing of the radiometer and PCS software scheduled for completion in September 2004 at SED. Installation and commissioning with DSA2 at Cebreros, Spain, is scheduled for June 2005. Based on measurement, simulation, and analysis results to date, the PCS is expected to meet all of its operational and performance objectives.