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Pointing Calibration of the MKIVA DSN Antennas Voyager 2 Uranus Encounter Operations Support

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The MKIVA DSN introduced significant changes to the pointing systems of the 34-meter and 64-meter diameter antennas. To support the Voyager 2 Uranus Encounter, the systems had to be accurately calibrated. Reliable techniques for use of the calibrations during intense mission support activity had to be provided.

This article describes the techniques used to make the antenna pointing calibrations and to demonstrate their operational use. The results of the calibrations are summarized.

I. Introduction

In October 1985, a concentrated effort was undertaken to complete and demonstrate the antenna pointing calibrations needed to support the January 1986 Voyager 2 Uranus Encounter (UE) operations. There were two principal objectives of the effort.

The first objective was to develop calibrations of the systematic pointing errors for all MKIVA DSN antennas as required to support Voyager 2 UE operations. Interim operational techniques for making and using the calibrations were to be developed and promulgated.

The second objective was to demonstrate the technical and operational pointing capabilities of the antennas in a realistic Voyager 2 mission support environment.

Both objectives were accomplished.

This article describes the MKIVA antenna pointing system, and the techniques used to calibrate its major systematic errors. The results obtained from the calibrations are summarized.

II. Need for Antenna Calibrations

The MKIVA antenna pointing system was a new system requiring new calibrations and new procedures for obtaining the calibrations. The inheritance from the MKIII era was generally inapplicable. The equipment and detailed methods for producing the antenna pointing predicts were changed. At the Network Support Subsystem in the JPL Network Operations Center, the old multiuser computers used to support predict generation were replaced by new VAX dedicated computers. The programs in the new computers use new algorithms and new operating procedures.

At the network complexes, all pointing system equipment, with the exception of the 64-m and 34-m Ha-Dec antenna structures and drives, was replaced. New 34-m Az-El high-efficiency antennas were implemented at the Goldstone and Canberra complexes. The old Scientific Data Systems antenna pointing computer was replaced with a ModComp Classic central computer plus a microcomputer located at each antenna. The antenna control systems were completely redesigned. In the MKIVA configuration, microcomputers at each antenna enable monitor and control of the antenna from a remote operating console in the Signal Processing Center.

III. Technical Requirements for Pointing Calibrations: Operational Requirements for Use of Calibrations

Voyager 2 UE support required the capability to point the DSN antenna beams solely by predict control very close to the direction of arrival of the signal from the spacecraft (S/C). "Very close" means that the error in pointing would not significantly degrade the received signal. Predict control implies "blind pointing" – pointing without the benefit of knowledge of the received signal strength or any other indicator for operator guidance.

Accurate blind pointing was specifically required to support the Voyager 2 UE critical radio science data acquisition, because without it the data would be degraded. Also, blind pointing was required for S/C acquisition and reacquisition, and for emergency command.

The pointing accuracy specification adopted for the Voyager 2 UE preparations was 0.16 of the antenna half-power beamwidth. That corresponds to $\leqslant 6$ and $\leqslant 11$ millidegrees (mdeg) total beam pointing error for the 64-m and 34-m antennas respectively at X-band (8.4 GHz). That specification provides $\leqslant 0.3$ dB signal degradation from pointing errors.

The requirements we adopted for operational use of the antenna calibrations were that the process be practical and reliable in the station environment during Voyager 2 UE support activities. During the test and demonstration work we tried to develop and validate a system capability and the operating procedures to meet those requirements. It soon became evident that automatic antenna systematic error correction capability was essential. Manual pointing offset entry at the Link Monitor and Control console during a high activity period was not viable.

The needed automatic capability was planned for the MKIVA, and strongly endorsed by the operational complexes. However, it was not available at the beginning of our work. A determined effort by engineering and operations personnel produced the automatic capability in time to support our real needs.

IV. The MKIVA DSN Antenna Pointing System

The basic block diagram of the end-to-end antenna pointing system is shown in Fig. 1; the glossary of abbreviations used is in Table 1. The process of pointing a MKIVA DSN antenna at a S/C signal is as follows.

At JPL, the Project provides S/C ephemeris data, in the form of position and velocity vectors, to the NSS Navigation team. The data are on magnetic tape. Using VAX computers, these data are converted into topocentric antenna pointing predicts for each station and placed on file in the NSS. The predicts give direction cosines of the S/C at two-minute time intervals. Several days before a scheduled tracking period, the predicts are transmitted over the NASCOM high-speed data lines via the complex SPC ARA to the CMC, where they are filed on disk. Before each tracking pass, the complex CMC operator transfers the antenna predicts to the APA. The APA transforms the direction cosines of the predicts to Az-El coordinates. The LMC operator then downloads the antenna Az-El predict points and a pointing systematic error correction table from the APA computer disk to the antenna mounted ACS microcomputer.

The ACS automatically corrects the pointing predicts for refraction and subreflector position, and adds the proper systematic error correction and any manually entered antenna offsets. Then, the ACS interpolates the predict points into an angular position command for each antenna axis once per second. These ACS position commands are used by the ASC or the 64-m MEC to generate rate commands that are subsequently used to point the antenna. In this mode, the antenna is being pointed automatically in response to the predicts with automatic corrections. It is being "blind pointed."

The antenna can also be pointed in a mode that can sense and correct for all pointing errors including those from the S/C predicts supplied. That mode is Conscan. It can correct for errors as large as the half-power beam width of the antenna. Conscan (for conical scan) works as follows. Again, refer to Fig. 1. The APA generates a circular scan pattern for th antenna and sends it to the ACS. The ACS adds the scan pattern to the corrected pointing angle predicts. Software in the REC computes and then sends received signal levels to the APA via the SPC LAN. The correlation of the scan position of the antenna, as reported by the ACS, with the received signal level variations, allows the APA to compute offset changes to the scan pattern center. The APA sends the offset changes to the ACS. Thus, within the capability of the closed-loop control system, the scan center is pointed precisely to the apparent direction of arrival of the S/C signal.

V. Pointing Error Calibration Concept

The process of calibrating antenna systematic pointing errors involves iteration of three steps. Step 1 is to collect pointing offset data from observations of radio sources of accurately known position. Step 2 is to use the pointing offset data to determine the constant parameters in a model that represents the systematic pointing error behavior of the antenna. Step 3 is to use the model to generate a table of antenna systematic pointing errors vs antenna pointing direction.

The three-step process is iterated until a final table of acceptable accuracy is obtained. The final systematic error table is used to correct the pointing of the predict driven antenna in operational tracking support.

The complete process as used for the Voyager 2 UE antenna calibrations is depicted in Fig. 2. It is described in the following paragraphs. Again, refer to the Glossary of Abbreviations in Table 1. Also, refer to the Appendix for a summary of the software programs used.

A. Step 1: Collection of Pointing Offset Data

1. **Offset Data from Radio Star Observations**. A process developed by the Madrid Deep Space Communication Complex (MDSCC) was used for initial pointing calibration of the MKIVA configured antenna using radio stars. It was used because initially we lacked confidence in the accuracy of the new S/C antenna pointing predict system.

The basic technique is to scan a strong and precisely located radio star and observe the received signal power level as a function of scan position about the star's predicted location. The functional assemblage of the antenna pointing data acquisition and analysis programs used is shown in Fig. 3. The observation on a preplanned set of stars, and the data collection and analysis to determine pointing offsets vs azimuth and elevation can be accomplished essentially automatically. That capability is provided using programs written at MDSCC. Calibrated signal power from a radio star is obtained using an updated DSN MKIII NAR program in the MDA computer. NAR diodes at the antenna front end are modulated by the MDA computer, and the receiver IF output is square-law detected. The detected signal is converted to a varying frequency, processed by the MDA frequency counters, and recorded on disk.

After a series of radio star observations, the data are reduced to pointing angle offsets in azimuth and elevation using the MDSCC AGA program. The resulting offset data are input to the PHO program (see Fig. 2) which produces an updated antenna systematic pointing error model. The systematic pointing error model development and the use of the PHO program are described in Subsection V.B.2.

Antenna pointing error models developed from the radio star observations were fairly accurate in sky areas near the stars observed. Typical accuracies were $\leqslant 4$ mdeg for the 64-m antenna, $\leqslant 6$ mdeg for the 34-m Az-El antenna and $\leqslant 10$ mdeg for the 34-m Ha-Dec antenna.

Radio stars near the 23-deg south declination of the Voyager 2 S/C were not readily available. For that declination, Conscan offset data from Voyager 2 support passes were used to refine the error models derived from radio star tracks. The Conscan process is described in the next section.

2. **Offset Data from Tracking S/C in Conscan Mode**. The principle of obtaining pointing calibrations using Conscan is as follows. When the antenna is operating in Conscan mode, the apparent direction of the S/C radio signal is sensed. The difference between that direction and the direction the corrected pointing predicts define is the Conscan offset. The system resolves the offset into Az and El offset components that are recorded with the corresponding antenna Az and El, or Ha and Dec. To the extent that the Conscan system properly senses the apparent direction of the S/C signal, the Conscan offsets determine the total system pointing errors.

To verify the Conscan performance, beam scans were performed during Voyager 2 tracks at the Goldstone Deep Space Communications Complex (GDSCC); they demonstrated that the Conscan-defined axis and the antenna beam axis were coincident within the experimental error of 1 to 2 mdeg.

Any errors in the pointing predicts are embedded within the total system errors determined by the Conscan data. In the early phase of the calibration work there was a 3 to 5 mdeg error identified in the NSS predict calculations. That was repaired. Later, another predict error of 1 to 4 mdeg, depending on the complex, was found; it resulted from incorrect use of station location coordinates in the calculations. That error was not repaired during our work; however it was stable, and was accounted for in the pointing calibrations. By the end of the work, we concluded that the NSS-supplied Voyager 2 pointing predicts were consistent to our level of visibility, $\leqslant 1$ mdeg.

The computer-based process that was developed and used for collection and analysis of Conscan tracking offset data is depicted in Fig. 4. It is explained in the following paragraphs. We note that at the start of the calibration effort, the software programs to realize Fig. 4 did not exist. For example, Conscan tracking data were initially hand tabulated from the LMC console displays – a very impractical operational process. But in a most timely way, R. Livermore of the Canberra Deep Space Communications Complex (CDSCC) developed an IBM-PC compatible program to automatically log the needed antenna pointing data on a noninterference basis during mission support passes. That program, CAPTURE.BAS, provided an essential capability; it was modified, adapted, and used by all three complexes during the calibration effort.

To use the automatic logging program, an IBM-PC computer is connected to a monitor port on the APA modem patch panel (see Fig. 4). This accesses antenna information being sent to the APA from the ACS. Antenna pointing angles, azimuth and elevation Conscan offsets, and time are logged on diskettes and printed out on a line printer. Figure 5 is a sample of the collected data from CAPTURE.BAS.

The Conscan offset data collected are analyzed using a plotting program, PLOT.BAS, initially developed by R. Murray of the CDSCC (see Fig. 4). The program graphs the azimuth and elevation conscan offsets for the antenna as a function of azimuth (or local hour angle for the 34-m Ha-Dec antennas). Another program, CSN-ANAL.EXE, by R. Riggs of JPL, provides the mean and standard deviation of the offsets, and other summary parameters of the antenna pointing performance.

The plotting and analysis programs were modified, adapted, and used by all complexes, and at JPL. Several samples of the outputs from the programs will be presented near the end of this article, in Section VI.

The Conscan offset data were used via the PHO program to upgrade the parameters in the antenna pointing systematic error model. The development of the model and the use of the PHO program are described in Subsection V.B.2.

Conscan offset data were collected regularly on an essentially noninterference basis from Voyager 2 pre-encounter period support passes. The data provided the basis for establishing accurate systematic pointing error correction to prepare all network antennas for supporting the Voyager 2 UE operations.

B. Step 2: Use of the Antenna Systematic Pointing Error Model

1. Introduction – Description of the Model. The concept of the antenna systematic pointing error model and the rationale of its use are discussed in the next paragraphs. Excepting environmental effects, the major sources of errors in an antenna pointing system are systematic and repetitive, and can therefore be closely modeled. Examples are residual errors in the geometric alignment of the mount axes and shifting of the antenna beam relative to the elevation axis angle readout as the antenna is tipped.

An antenna error model is used in the pointing calibration process. In the process, data from S/C or radio star observations are used to establish the parameters in the model; the model is then used to generate a systematic error correction table for accurately pointing the antenna.

The basic pointing error modeling approach used was originally devised by optical astronomers. Radio astronomers adapted the model for antennas. The model is based on logical expected physical behavior of the antenna. It has been successfully applied at major radio astronomy facilities: for example, the Bonn 100-m Az-El antenna (Stumpff, Ref. 1) and the Haystack 37-m Az-El antenna (Meeks et al., Ref. 2).

A. Rius, MDSCC, adopted the work of Stumpff and Meeks to develop a pointing error model for the DSS 63 64-m Az-El antenna operating in the computer control mode. W. Peters, CDSCC, developed the error model for the DSS 42 34-m polar mount (Ha-Dec) antenna. Engineering personnel from the three complexes and from JPL collaborated in merging the two DSN antenna models to provide a preliminary error model for the 64-m Az-El antenna pointing under Master Equatorial control.

The complete pointing error model for an antenna is a sum of individual error functions. The individual error functions typically have a constant multiplier and depend on variables that are accessible in the system, for example, Az and El. For example, Table 2 shows the individual error sources and the El and Cross-El error models for the DSN 34-m Az-El antennas.

The P constants in the individual error function models of Table 2 can be determined by collecting and analyzing data from instrumented pointing calibrations on radio signals whose sky positions are accurately known. The quality of the functional representations and their constants can be improved by collection and analysis of additional pointing calibration data.

We note that the systematic pointing correction for the Y axis motion of the subreflector is not included in the pointing error model of Table 2. That function is accomplished automatically by the ACS. The ACS receives subreflector position information from the SRC via the ASC. The required elevation-angle correction is computed and summed with other offsets in the generation of position data.

As previously stated, our use of a systematic error model for calibrating an antenna for blind pointing is iteration of a three-step process: (1) measurements of pointing errors on sources of known position, (2) determination of the error model parameters from the measurements, and (3) development of a table of required pointing offsets vs pointing angles from the completed error model. One might ask if such a complex process is necessary, or fundamentally useful.

In principle, the pointing errors derived from the S/C or radio star observations can be used directly to develop a systematic error table. However, the table so developed is accurate only in pointing directions very near the directions (i.e., within 2 to 4 deg) of the observations. Sans model, no legitimate extrapolation or interpolation of the errors is available; cum model, a compact set of properly chosen observations can yield an error table useful for the full sky coverage of the antenna. Also, the model process provides needed filtering of errors in the observational data.

That economy of calibration effort in an operational environment has fueled development, refinement, and use of the model technique at all major radio astronomy facilities. The DSN is developing error models of its operational antennas for the same reason.

Also, the model technique provides a useful, powerful tool to antenna design engineers. That is because the separable individual model error functions are identified with particular physical characteristics of an antenna. Careful analysis of pointing calibration data in relation to specific terms in the model can yield quantitative understanding of the stability and precision of elements of an antenna. That understanding is essential to the process of engineering improvements to the DSN antennas for their current applications, and for future applications (for example, ka-band operations on the 34-m and 64-m/70-m Az-El antennas).

We must observe that the models developed during the calibration effort were based almost entirely on Conscan offsets relative to NSS pointing predicts from Voyager 2 tracking. The quality of the models in the sky regions of the Voyager 2 S/C (23 deg S. Dec) was demonstrated to be good. In other regions of the sky, the quality of the models was not examined; that remains a task for the future.

2. Updating the Antenna Systematic Pointing Error Models from the Observational Data. The observational data are used by the PHO error model program to generate or refine the antenna systematic pointing error model. For radio star observations, refer to the diagram of Fig. 3. The observational data are available from the MDA disk via the AGA program. The AGA output data must be translated to the proper format for input to the PHO error model program. That translation involves extensive hand editing and manipulation of the data.

For S/C Conscan offset observations, refer to the diagram of Fig. 4. Conscan offset data logged in the IBM-PC are hand edited to remove obvious bad data points and abnormalities. That file is then converted to a format directly usable by the PHO program. The conversion is done using CON2DAT, a utility program written by R. Livermore of CDSCC.

Refer back to Fig. 2, the diagram of the complete three-step calibration process. PHO reads the converted Conscan or radio star observations offset data file. PHO then sums the offsets from the "original" error model and the offsets from the new observations (the "original" model is the model used to generate the offsets used during the new observations). Finally, PHO uses a linear least-square error fitting routine to generate an updated systematic error model for the summed offsets.

C. Step 3: Generation of the Systematic Error Correction Table from the Antenna Error Model

The antenna systematic error model is used to generate a new or updated table of antenna pointing offsets. The process is as follows.

Again, refer to Fig. 2. The model is processed by the IBM-PC program APACRCTB to generate an APA protocol compatible systematic error table. Basically, the table is a matrix of azimuth and elevation errors vs azimuth and elevation at 5-deg increments. The table includes a cyclic redundancy code (CRC) check number to verify its integrity.

The IBM-PC is then loaded with the PCPLOT VT-100 terminal emulator program, which allows direct communication with the APA through its maintenance terminal port. Then, using the Batch Operating System software, the APA is configured to receive the systematic error correction table.

After successful transfer to the APA high-capacity disk, the table is available for downloading to the ACS for S/C tracking support. During the support, the ACS automatically interpolates the systematic error table entries, combines the resulting errors with the pointing predicts, and provides corrected pointing commands for use by the ASC or MEC.

VI. Samples of MKIVA DSN Antenna Pointing Performance Data

The plots in Figs. 6(a) through 6(h) display the pointing accuracy of the antennas of the three complexes as prepared for Voyager 2 UE support using the techniques described. They depict Conscan El and Cross-El components of the pointing errors relative to the predicts, and the total beam error calculated as the square root of the sum of the squares of the components.

The plots were obtained directly from our data capture and data plotting and analysis programs during Voyager 2 operational support passes. The data were obtained at X-band (8.4 GHz). During the early phases of the work, we demonstrated that Conscan offset results authentically indicate blind pointing capability. For illustration, Fig. 7 shows a plot of received signal level during a Voyager 2 pass at DSS 14 in which blind pointing was alternated with Conscan tracking. The received signal level is not significantly affected by the pointing mode changes. At CDSCC, long periods of accurate blind pointing were required for Voyager 2 UE Radio Science support. Therefore, the CDSCC performed extensive demonstrations of this type prior to the encounter.

VII. Secondary Results From the Work

In the course of the work, we conducted some tests, and collected and superficially analyzed some experimental data, that looked interesting – potentially important. But we lacked the time to explore any of them in depth. Those items are discussed in the following paragraphs.

A. Pointing Errors from the Sun's Atmosphere

X-band Conscan offset data were obtained from DSS 14 immediately before and after the Voyager 2 solar conjunction in December 1985. Also, some data were obtained from DSS 15 following the conjunction. The data in Fig. 8 show the approximate total pointing jitter vs Sun-Earth-Probe angle for DSS 14. The available data from DSS 15 are also shown. These data help characterize antenna system performance when tracking near the sun.

B. Refraction Correction Quality

The ACS is operated with a fixed "default" refraction correction for each antenna. The correction is based on mean annual barometric pressure, temperature, and humidity of the particular complex.

The ACS software is designed to accept in situ observed meteorological parameters from the station Meteorological Monitoring Assembly (MMA) via the APA. At the time of our work, the MMA could not provide the needed data; also, the APA software could not handle it. As a result, the ACS was not able to react to locally observed temperature, atmospheric pressure, or humidity parameters that deviate from the default values. Figure 9(a) displays plots of pass-average elevation angle Conscan offsets versus day of year from Voyager 2 tracks on DSS 14 and DSS 15. The antennas are colocated at GDSCC. The plots show significant errors that are highly correlated. Similar plots of azimuth angle offsets, Fig. 9(b), show small errors without evident correlation. The results point strongly to refraction correction error as the cause of the elevation errors.

To probe the matter, crude local weather observations were obtained during acquisition of a small set of the antenna Conscan offset data. Predicted angle-of-arrival deviations based on the observed atmospheric refraction effects were compared with the measured Conscan elevation offsets. The comparisons showed reasonable agreement.

We conclude that for X-band (8.4 GHz) pointing of the 64-m antennas, the refraction correction needs to incorporate some level of local and timely assessment of atmospheric conditions. There are planned implementation upgrades of the APA software and the MMA. They will allow the APA to accept needed data from the local MMA. That will enable automatic updating of the ACS refraction correction. Our results support the importance of the MMA and APA upgrades.

The refraction correction upgrade should significantly improve the operational accuracy of the antenna pointing by predicts. Concurrently, elimination of refraction error will aid engineering studies that use tracking error data to identify intrinsic capability, and hence growth capability, of the 64-m antennas.

C. Wind Effects on Pointing Accuracy

Several times during testing and demonstration of antenna pointing at GDSCC, unusual azimuth offsets were observed during strong winds. The errors were variable, usually positive in sign, and were observed at both DSS 14 and DSS 15. The tracks were from east to west, with a maximum elevation of 32 deg. The winds were generally from the southwest.

Conscan errors caused by wind are expected to appear as offsets into the prevailing wind. Thus, wind from the southwest would cause positive offsets.

The results noted suggest that useful data on the effects of wind on beam pointing accuracy can be obtained as a by-product of X-band Conscan S/C support tracking. In concept, merely be prepared to collect wind conditions and Conscan offsets when very windy days occur.

D. Sidereal Mode Tests

The primary ACS operating mode for the Voyager 2 UE was the predict mode. A secondary ACS mode, sidereal, was tested with systematic error tables to demonstrate it as a backup capability in case of a failure in the predicts mode system.

The planetary mode, a preferred backup, could not be used. That was because the ACS software then available could not support the use of systematic error tables in the planetary mode.

To operate in the sidereal mode, the conventional planetary predicts routinely supplied to the complexes by the NSS are used. The predict points, spaced a day apart, are manually interpolated to provide right ascension and declination coordinates and rates. At the time of track start, the coordinates, rates, and time are entered into the ACS.

The sidereal mode demonstrations yielded the same antenna performance as the prime predicts mode provided. Figure 10(a) shows antenna Conscan offsets during a DSS 14 Voyager 2 track when the sidereal and predict modes were alternately used. Figure 10(b) shows the received signal level during that track. For the period 2030 to 2200 GMT, the antenna was blind-pointed in the sidereal mode.

Interim operating procedures were developed and promulgated so that all stations could invoke sidereal as a backup tracking mode during the Voyager encounter operations. With the system capability at the time, LMC Console operations in the sidereal mode were complicated – errors were easy to make.

D. Girdner, GDSCC, planned and conducted the tests of the sidereal mode. He also developed the interim procedures.

E. Conscan Snap-on Tests

Dynamic response tests were run for demonstration and to evaluate the transient behavior of the DSS 15 antenna pointing system in the Conscan mode as used during Voyager 2 tracks.

The tests involved turning Conscan off and then offsetting the antenna by 30 percent of its beamwidth. The received signal level was observed on a strip-chart recorder and the Conscan offsets were logged when Conscan was turned back on. The signal level and Conscan offset signatures allowed dynamic characteristics to be analyzed for response time, damping factor, and amount of cross coupling between the azimuth and elevation axes.

Analysis of the signal-level recording from single-axis offset snap-on tests of DSS 15 is summarized in Table 3. The signatures of the Conscan offsets from the test are shown in Figs. 11(a) and (b). The Conscan single-axis offset behavior and the signal-level results of Table 3 are consistent.

The Conscan snap-on tests indicated that the operating parameters of the antenna were approximately correct and that the Conscan system was performing acceptably for Voyager 2 support.

D. Girdner, GDSCC, planned and conducted the snap-on tests.

F. Observations on Pointing Predicts

We noted in Subsection V.A.2 that errors in the S/C pointing predicts are embedded in observations of Conscan offsets. Two errors of significance to 64-m X-band (8.4-GHz) pointing were identified. The first was repaired; the second, which is related to use of station location coordinates, is currently being investigated. When the second error is corrected, its effect on the antenna pointing calibrations must be accommodated. The pointing predicts need to be an impeccable standard for antenna pointing in S/C mission support.

Also, we have observed that during S/C Conscan support passes, valuable pointing offset data can be obtained concurrently, on a noninterference basis. High-precision predicts are a prerequisite to the analysis of such data for the purpose of identifying and quantifying the intrinsic performance capabilities of the DSN antennas.

VIII. Concluding Observations, Acknowledgements

The process of automatic collection and machine analyses of Conscan offset data provided a very effective means of calibrating and monitoring antenna system pointing. Usually the data were of excellent quality. Almost all of the Conscan data were collected during committed Voyager 2 mission support passes – had we not been able to do that, we could not have achieved our objectives in the time available.

We express our appreciation to the Voyager Project, and especially D. G. Griffith, the Flight Operations Office Manager, for cooperation and support of our tests, demonstrations, and collection of calibration data.

The JPL engineering and operations organizations provided exemplary support throughout the calibration activity. We cite

especially personnel of the Ground Antennas and Facilities Engineering Section, the Radio Frequency and Microwave Subsystems Section, the DSN Control Center Operations Section, and the DSN Operations and Engineering Support Section.

Generally, the calibration and demonstration techniques used were applied first at the GDSCC, a special burden on the staff during the busy period of preparations for the Voyager 2 UE. All of the complex personnel involved were patient, resourceful, and professional.

All of the DSN complexes made critical contributions to the techniques for performing the calibrations and the demonstrations. The cooperation and support from the Management and Staff of the CDSCC, MDSCC, and GDSCC were splendid. Also, and most importantly, they calibrated their antennas in a timely manner.

References

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2. Meeks, M. L., Ball, H. A., and Hull, A. B., "The Pointing Calibration of the Haystack Antenna," *IEEE Transactions on Antennas and Propagation*, Vol. AP-16, No. 6, pp. 746–751, November 1968.

Table 1. Glossary of abbreviations for text and Figs. 1, 2, 3, and 4

ACM:	Antenna Control and Monitor
ACS:	Antenna Control Subassembly
APA:	Antenna Pointing Assembly
ARA:	Area Routing Assembly
ASC:	Antenna Servo Controller
CMC:	Central Monitor and Control (console)
FEA:	front end area
IRS:	intermediate reference structure
LAN:	Local Area Network
LMC:	Link Monitor and Control (console)
MEA:	Master Equatorial Assembly
MEC:	Master Equatorial Controller
MDA:	Metric Data Assembly
MMA:	Meteorological Monitoring Assembly
NAR:	noise adding radiometer
NASCOM:	NASA Communications
ND:	noise diode
NSS:	Network Support Subsystem
PC:	personal computer (IBM compatible)
REC:	Receiver-Exciter Controller
SETBL:	systematic error table
SPC:	Signal Processing Center
TWM:	traveling-wave maser

Table 2. Systematic pointing error model for 34-m Az–El antennas

Error source	Model function for Cross–El error	Model function for El error
Az collimation	*P*1	(n/a)
Az encoder bias	*P*2 × cos (El)	(n/a)
Az/El nonorthog	*P*3 × sin (El)	(n/a)
Az axis tilt	*P*4 × sin (El) × cos (El)	–*P*4 × sin (Az)
	*P*5 × sin (El) × sin (Az)	*P*5 × cos (Az)
Source Dec	*P*6 × sin (Az)	*P*6 × sin (El) × cos (Az)
El encoder bias	(n/a)	*P*7
Grav flex, source Dec	(n/a)	*P*8 × cos (El)
Refraction	(n/a)	*P*9 × cot (El)

Table 3. Summary of results from DSS 15 Voyager 2 X-band single-axis offset Conscan snap-on tests

Offset change, deg	90% settling time, min	First-scan undershoot, %	Fourth-scan overshoot, %	Cross coupling, %
El +0.020	7	40	0	18
El –0.020	8	50	0	21
Az +0.020	4	25	5	7
Az –0.020	3	45	6	10

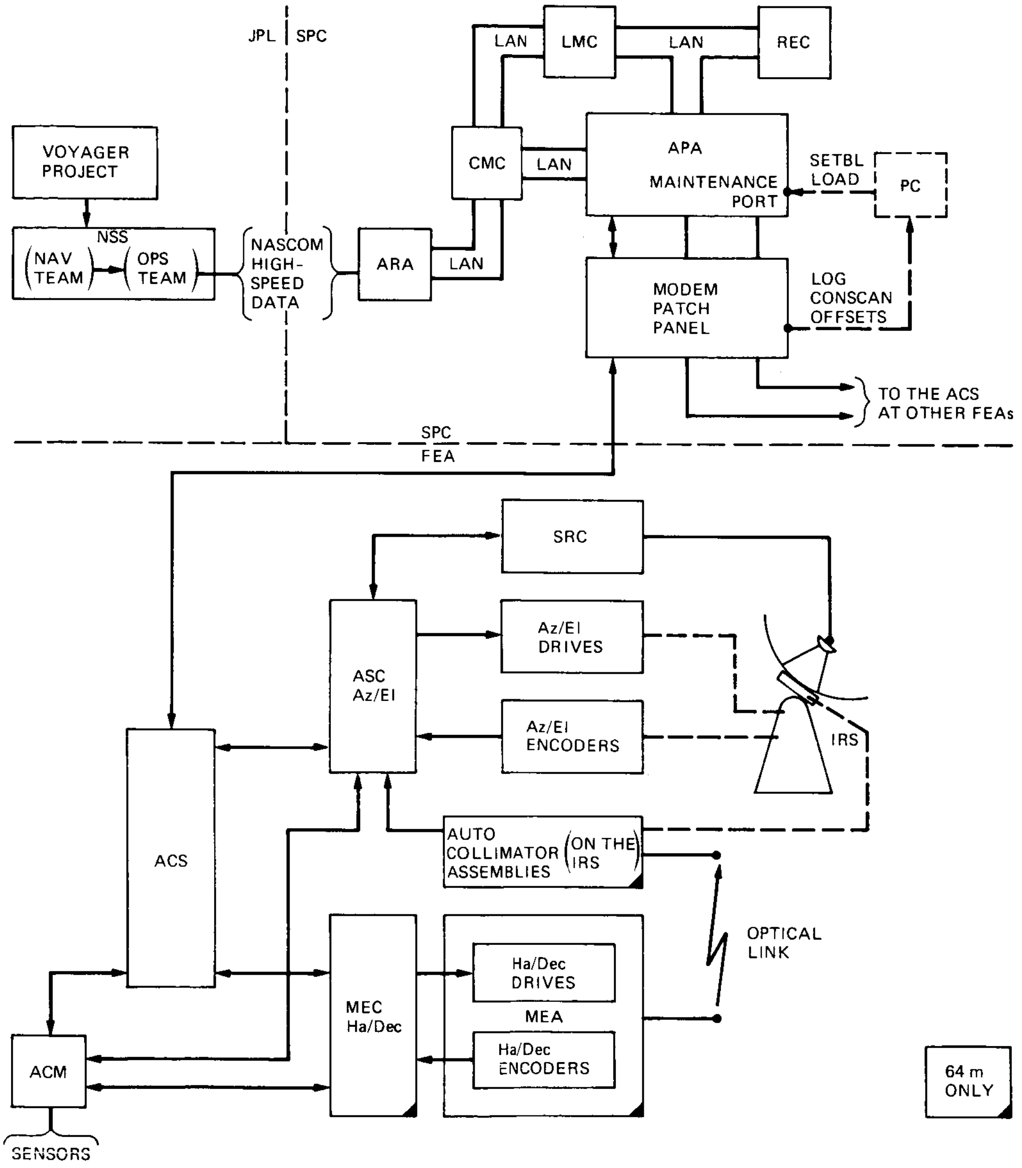

Fig. 1. MKIVA end-to-end antenna pointing system

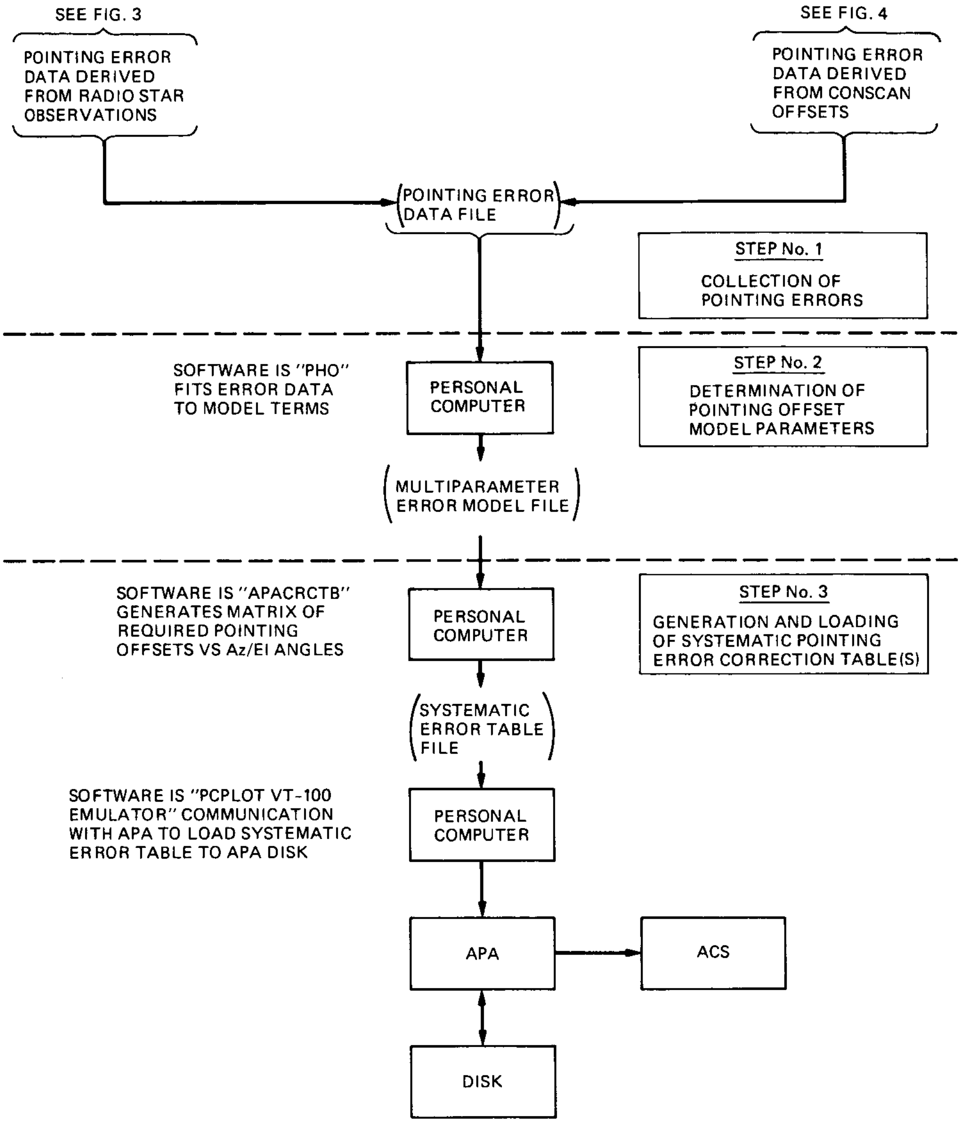

Fig. 2. Process for calibration of antenna systematic pointing errors

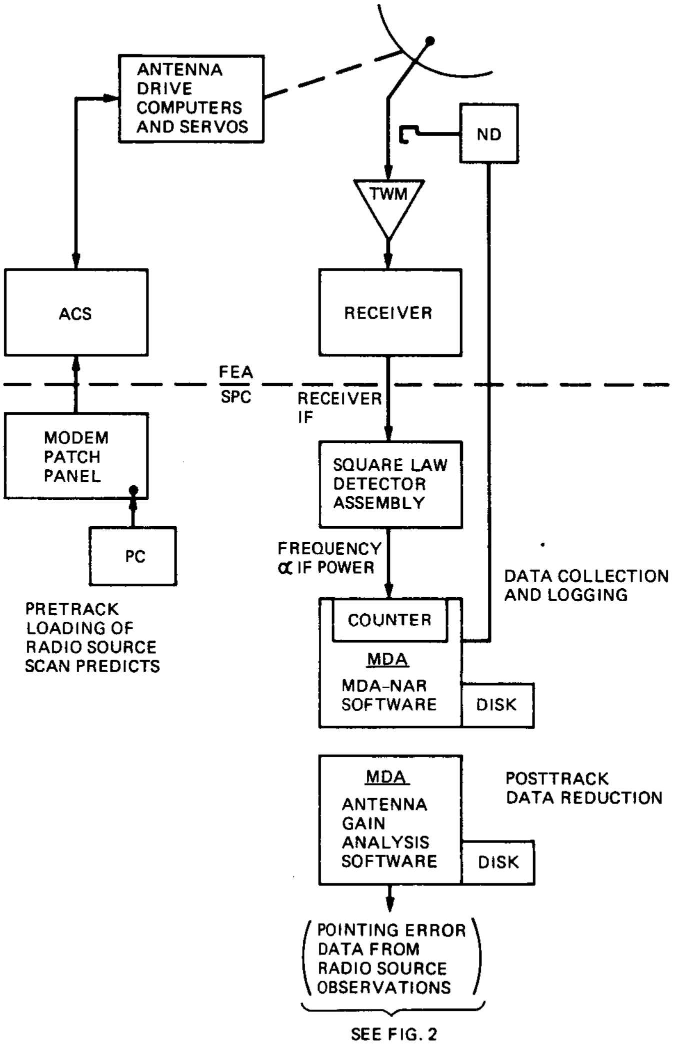

Fig. 3. Block diagram of A. Rius/MDSCC radio star antenna pointing data acquisition and analysis process

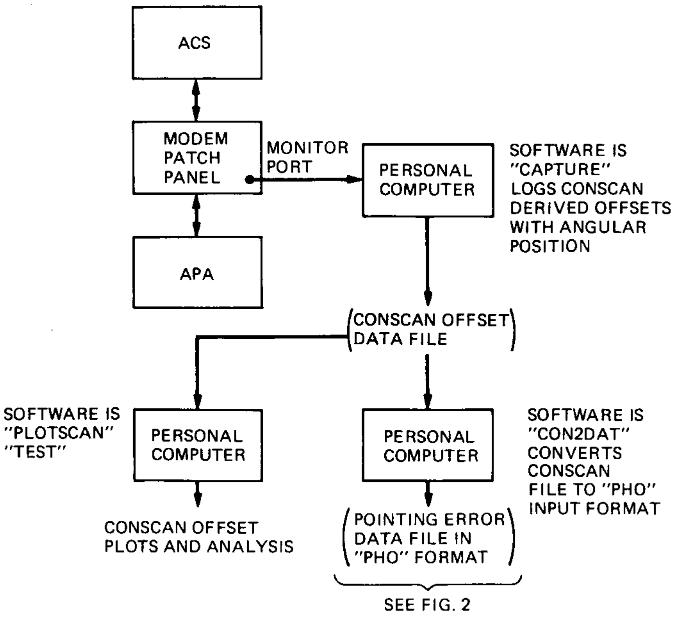

Fig. 4. Block diagram of S/C tracking Conscan offset data acquisition and analysis process

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DSS-14 VGR-2 DOY 026 SETBL=14EX1 Light overcast, mild, calm
    Az        El        ΔAz         ΔEl        GMT        DATE       SETBL
" 126.320  008.479  +000.0007  -00.0011  12:45:51  01-26-1986  14EX1"
" 126.649  008.806  +000.0008  -00.0012  12:48:02  01-26-1986  14EX1"
" 126.978  009.131  +000.0011  -00.0012  12:49:51  01-26-1986  14EX1"
" 127.313  009.453  +000.0015  -00.0012  12:51:51  01-26-1986  14EX1"
      :        :         :          :          :          :          :
      :        :         :          :          :          :          :
" 206.930  026.401  +000.0036  -00.0006  18:30:19  01-26-1986  14EX1"
" 207.401  026.216  +000.0031  -00.0003  18:32:30  01-26-1986  14EX1"
" 207.869  026.025  +000.0031  -00.0006  18:34:19  01-26-1986  14EX1"
" 208.334  025.832  +000.0030  -00.0006  18:36:19  01-26-1986  14EX1"
" 208.797  025.636  +000.0027  -00.0006  18:38:20  01-26-1986  14EX1"
```

Az, El, ΔAz, ΔEl in degrees

SETBL≡Identification of Systematic Error Correction Table in ACS

Fig. 5. Sample of output from R. Livermore/CDSCC Conscan offset data acquisition program

Fig. 6. Plots and summary analyses of Conscan offset data from Voyager 2 tracking by calibrated MKIVA DSN antennas

Discussion: The plots and analysis summaries are reproductions of outputs from PLOT.BAS and CSN-ANAL.EXE programs using data from CAPTURE.BAS (see text, Subsection V.A.2, and the Appendix). These products can be made at the complexes right after a tracking pass, and the data for making them can be sent immediately to JPL by electronic mail.

The headings of the plots and analysis summaries record support parameters such as V214D021 (meaning Voyager 2; DSS 14; Day of Year 21).

The plots are Conscan offsets vs Az (or Ha for Ha-Dec antennas). Az and El angles for each offset point are in the right columns. Also, the dB losses (–dB) calculated to result from each offset point are in the rightmost column. On the plots, elevation offsets are "e," the cross-elevation offsets are "x," and the space (or total beam) offsets are "S." The "S" are calculated as the square root of the sum of the squares of "e" and "x;" the positive value is presented. The "S" are always plotted; for overlaps of "e" and "x," the "e" survives.

The analysis summaries are statistical calculations on the file data. They provide a succinct view of the antenna pointing performance: in particular, mean space offset and mean beam pointing loss that would be incurred under blind pointing. Other analysis results are available from the program, but are not shown here, e.g., specific occurrences of offsets where the pointing loss would exceed the specified maximum.

The data represented in the plots and analysis summaries are from the antennas in their prime operating modes for Voyager 2 UE support: all predict driven and with precision (Master Equatorial) control on the 64-m antennas. There is one exception. Figure 6(a2) shows results from an unusual DSS 14 pass during which the first part of the pass was in the prime precision mode and the second part was in the backup computer control mode. The periods of use of the two modes are indicated on the plot; a separate analysis summary for each mode is shown. The difference in tracking quality of the two modes is illustrated.

For reference in reviewing the plots and analyses, the pointing specification adopted was: $\leqslant 6$ mdeg total beam pointing error ($\leqslant 4$ mdeg each for equal El and cross-El errors) for the 64-m antennas; $\leqslant 11$ mdeg total beam pointing error ($\leqslant 8$ mdeg each for equal El and cross-El errors) for the 34-m antennas. That specification limits the allowable pointing loss to 0.3 dB, maximum.

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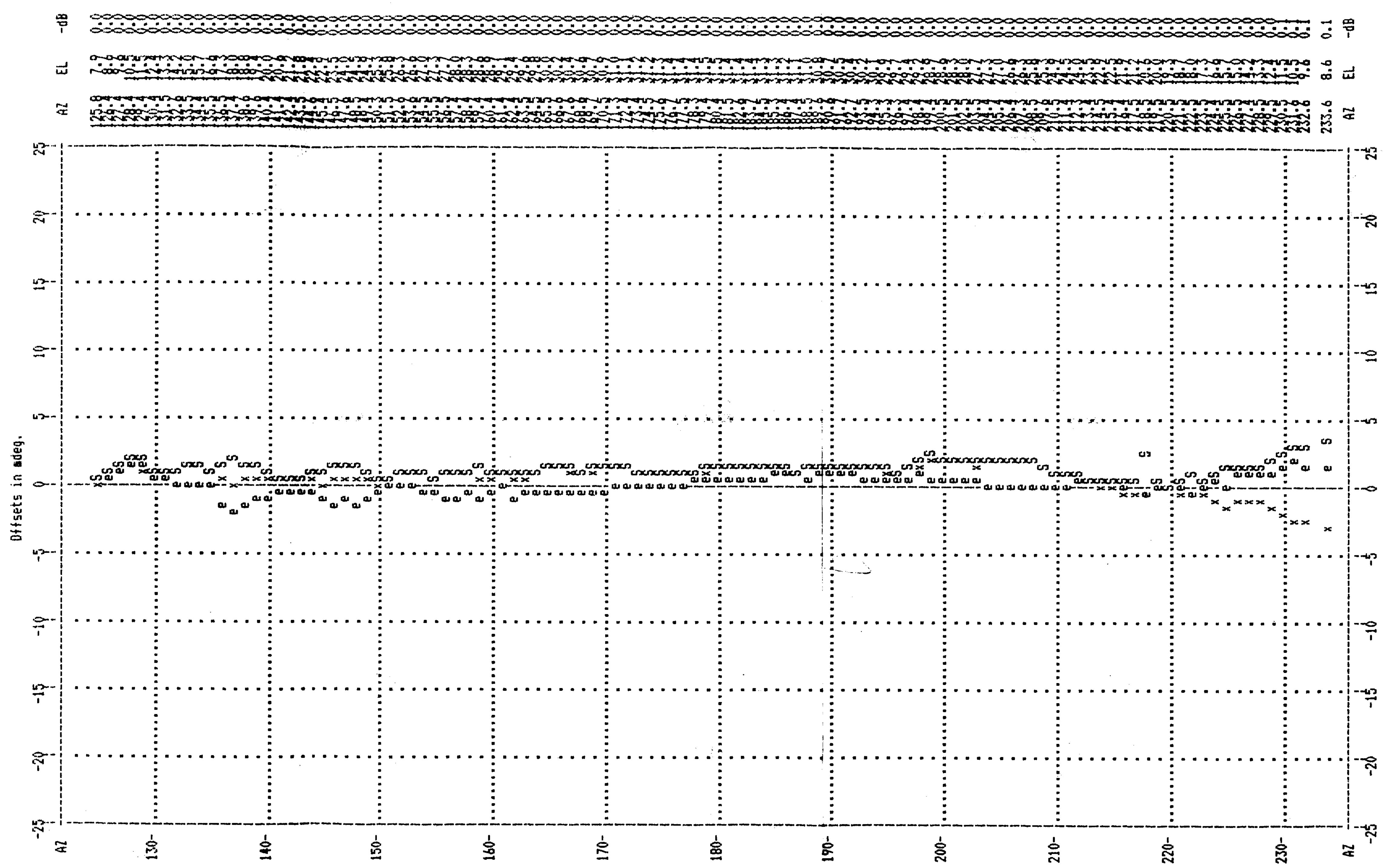
```
Data plot from file: V214D021  from DSS - 14
Data captured starting at 13:00:43 01-21-1986
AZ bias =  0  mdeg.   EL bias =  0  mdeg.
```



```
ANALYSIS of CONSCAN DATA FILE: V214D021 from DSS- 14
   Data captured starting at: 13:00:43 01-21-1986
   File contains  243  lines

MEAN AZ  offset=  +0.7 mdeg.      SDEV AZ  offset=   1.2 mdeg.
MEAN EL  offset=  +0.1 mdeg.      SDEV EL  offset=   0.8 mdeg.
MEAN XEL offset=  +0.6 mdeg.      SDEV XEL offset=   1.1 mdeg.

MEAN of AZ  absolute offsets=   1.2 mdeg.
MEAN of EL  absolute offsets=   0.6 mdeg.
MEAN of XEL absolute offsets=   1.1 mdeg.

** MEAN SPACE offset=  1.4 mdeg.      SDEV SPACE offset=  0.6 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.0 dB
```

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Fig. 6(a1). DSS 14 64-m precision mode (GDSCC)

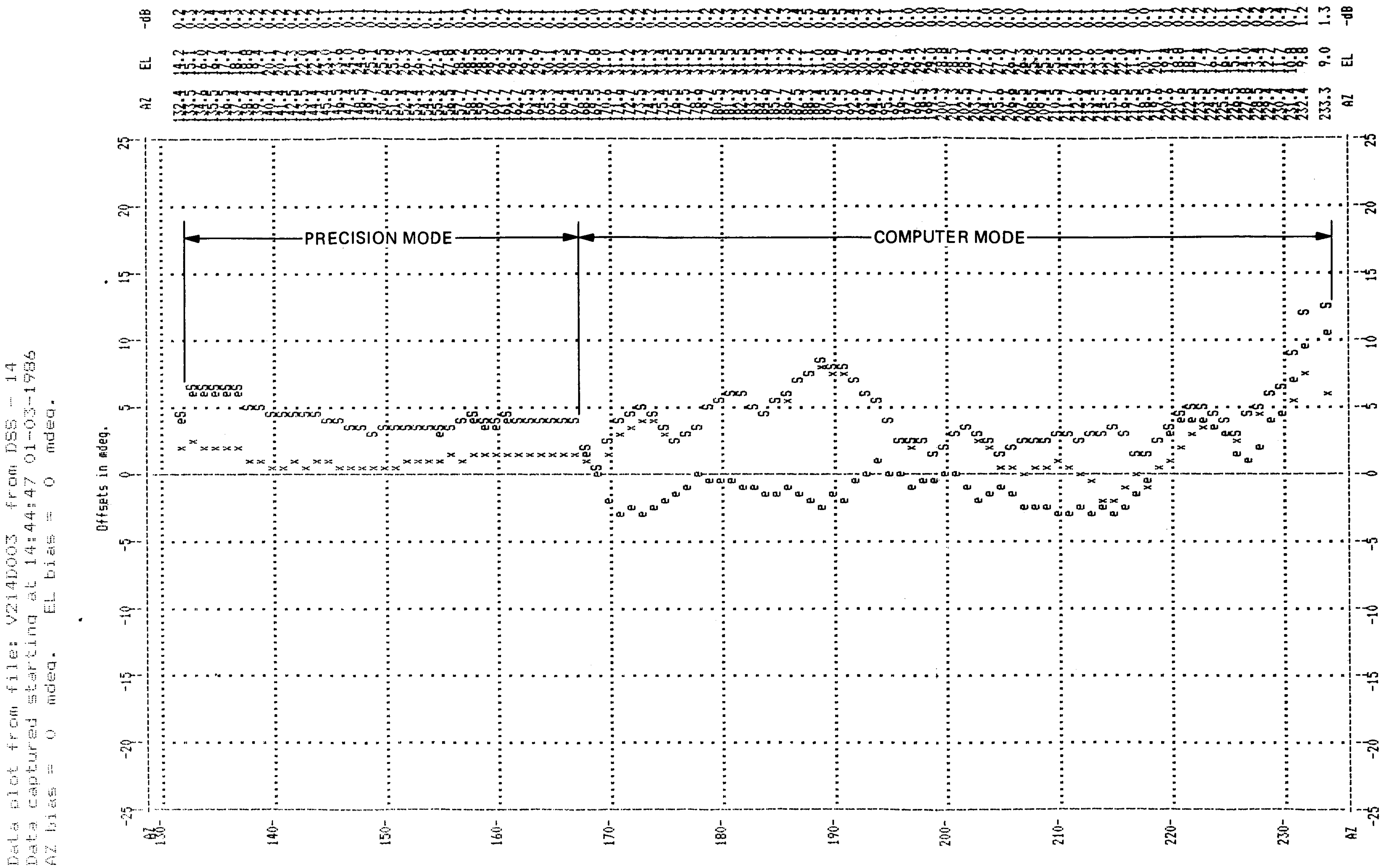

Fig. 6(a2). DSS 14 64-m precision mode and computer control mode (GDSCC)

```
ANALYSIS of CONSCAN DATA FILE: V214D003.P1 from DSS- 14
   Data captured starting at: 14:44:47 01-03-1986
   File contains  77  lines

MEAN AZ  offset=  +1.4 mdeg.     SDEV AZ  offset=   0.6 mdeg.
MEAN EL  offset=  +4.3 mdeg.     SDEV EL  offset=   1.0 mdeg.
MEAN XEL offset=  +1.3 mdeg.     SDEV XEL offset=   0.6 mdeg.

MEAN of AZ  absolute offsets=   1.4 mdeg.
MEAN of EL  absolute offsets=   4.3 mdeg.
MEAN of XEL absolute offsets=   1.3 mdeg.

** MEAN SPACE offset=  4.5 mdeg.     SDEV SPACE offset=  1.0 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.2 dB

ANALYSIS of CONSCAN DATA FILE: V214D003.CC from DSS- 14
   Data captured starting at: 17:16:44 01-03-1986
   File contains  146  lines

MEAN AZ  offset=  +3.3 mdeg.     SDEV AZ  offset=   2.8 mdeg.
MEAN EL  offset=  +0.3 mdeg.     SDEV EL  offset=   3.1 mdeg.
MEAN XEL offset=  +3.0 mdeg.     SDEV XEL offset=   2.5 mdeg.

MEAN of AZ  absolute offsets=   3.6 mdeg.
MEAN of EL  absolute offsets=   2.4 mdeg.
MEAN of XEL absolute offsets=   3.2 mdeg.

** MEAN SPACE offset=  4.4 mdeg.     SDEV SPACE offset=  2.4 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.2 dB
```

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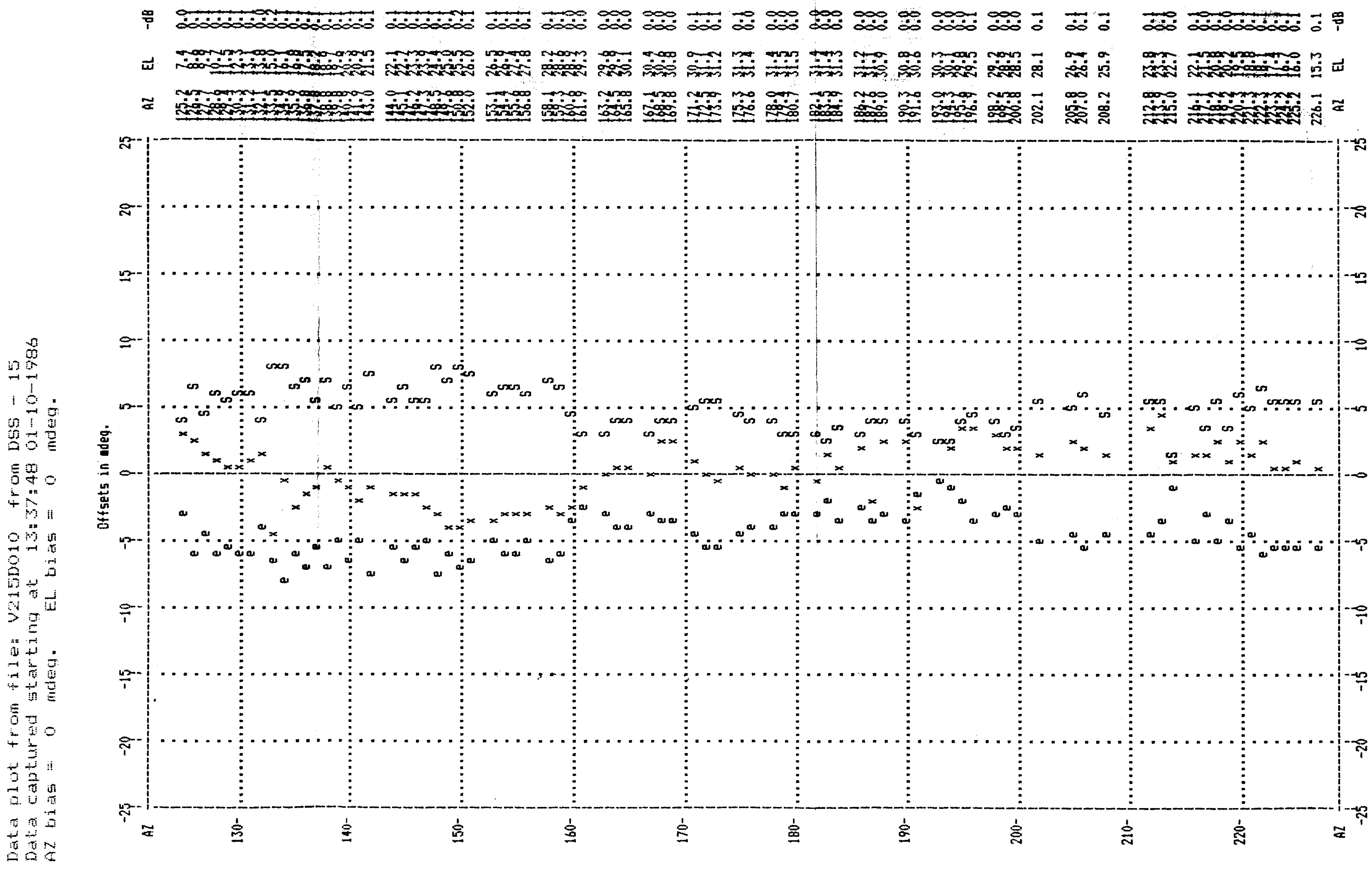

Data plot from file: V215D010 from DSS - 15
Data captured starting at 13:37:48 01-10-1986
AZ bias = 0 mdeg. EL bias = 0 mdeg.

```
ANALYSIS of CONSCAN DATA FILE: V215D010 from DSS- 15
   Data captured starting at:  13:37:48 01-10-1986
   File contains  83  lines

MEAN AZ  offset=  +0.2 mdeg.     SDEV AZ  offset=   2.5 mdeg.
MEAN EL  offset=  -4.6 mdeg.     SDEV EL  offset=   1.6 mdeg.
MEAN XEL offset=  +0.2 mdeg.     SDEV XEL offset=   2.2 mdeg.

MEAN of AZ  absolute offsets=   2.0 mdeg.
MEAN of EL  absolute offsets=   4.6 mdeg.
MEAN of XEL absolute offsets=   1.8 mdeg.

** MEAN SPACE offset=  5.1 mdeg.     SDEV SPACE offset=  1.6 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.1 dB
```

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Fig. 6(b). DSS 15 34-m Az–El (GDSCC)

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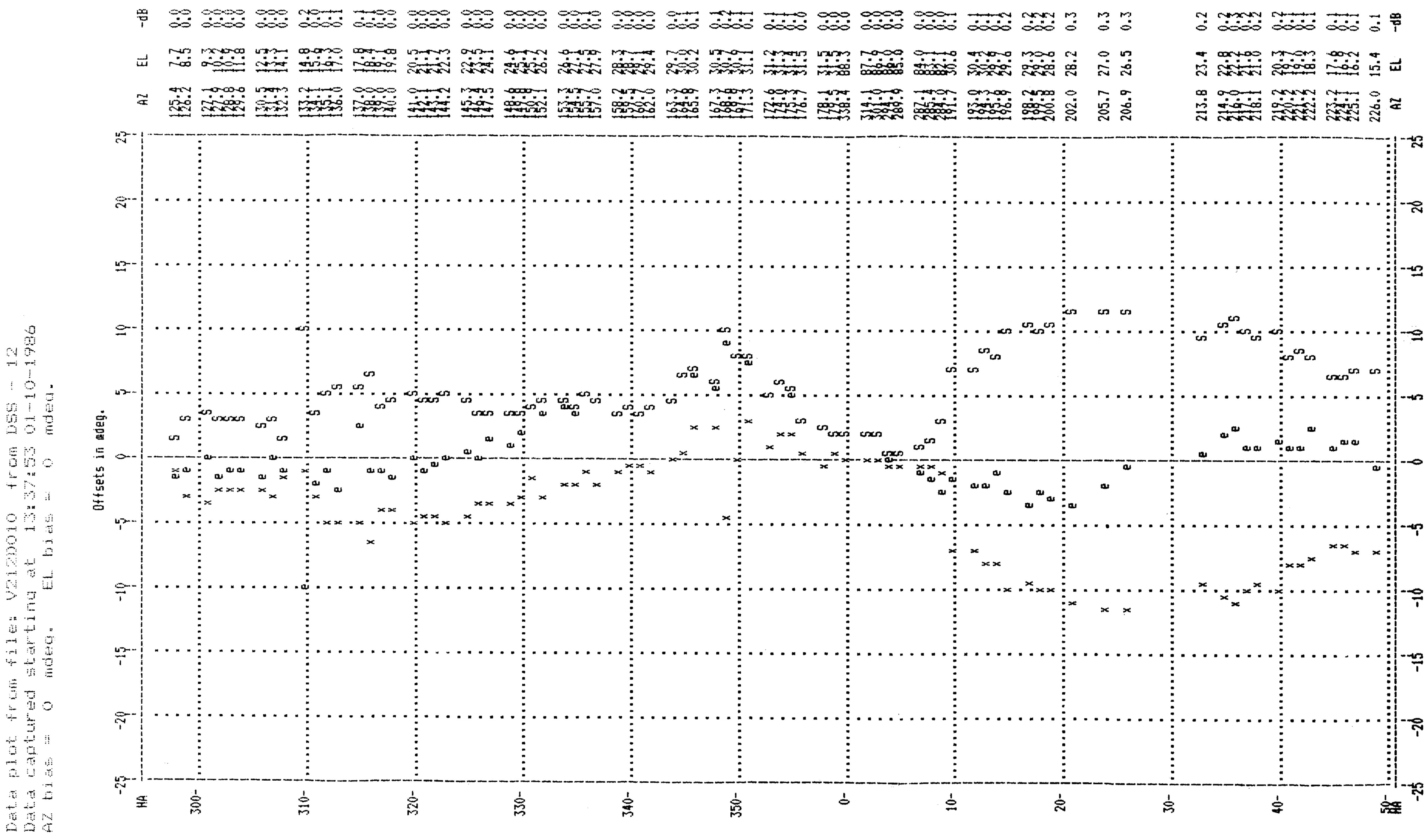

Fig. 6(c). DSS 12 34-m Ha–Dec (GDSCC)

```
ANALYSIS of CONSCAN DATA FILE: V212D010 from DSS- 12
   Data captured starting at:  13:37:53 01-10-1986
   File contains   81  lines

MEAN AZ   offset=  -4.5 mdeg.     SDEV AZ   offset=   4.2 mdeg.
MEAN EL   offset=  +1.0 mdeg.     SDEV EL   offset=   3.1 mdeg.
MEAN XEL offset=  -3.8 mdeg.      SDEV XEL  offset=   3.9 mdeg.

MEAN of, AZ  absolute offsets=  4.9 mdeg.
MEAN of EL   absolute offsets=  2.5 mdeg.
MEAN of XEL  absolute offsets=  4.2 mdeg.

** MEAN SPACE offset=  5.6 mdeg.     SDEV SPACE offset=  3.0 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.1 dB
```

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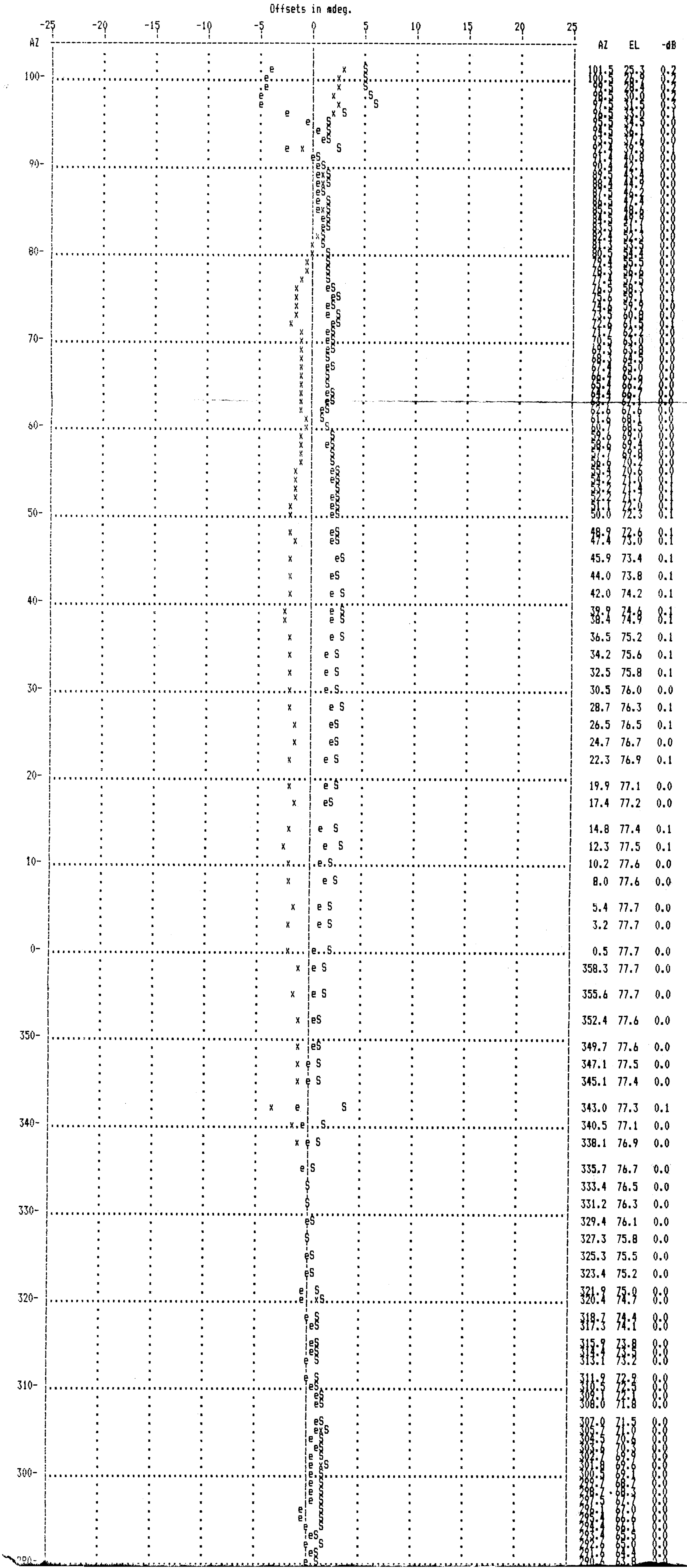
```
Data plot from file: V243D018.P1F  from DSS - 43
Data captured starting at  18:28:43 01-18-1986
AZ bias =  0  mdeg.    EL bias =  0  mdeg.
```



AZ	EL	-dB
101.5	25.3	0.2
100.5	26.9	0.2
99.5	28.4	0.2
98.5	30.0	0.2
97.5	31.5	0.3
96.5	33.0	0.1
95.5	34.5	0.0
[illegible]	[illegible]	[illegible]
62.6	67.6	0.0
61.9	68.1	0.0
60.7	68.5	0.0
59.6	69.0	0.0
58.9	69.4	0.0
57.7	69.8	0.0
56.9	70.2	0.0
55.4	70.6	0.0
54.2	71.0	0.1
53.5	71.4	0.1
52.5	71.7	0.1
51.1	72.0	0.1
50.0	72.3	0.1
48.9	72.6	0.1
47.4	73.0	0.1
45.9	73.4	0.1
44.0	73.8	0.1
42.0	74.2	0.1
39.9	74.6	0.1
38.4	74.9	0.1
36.5	75.2	0.1
34.2	75.6	0.1
32.5	75.8	0.1
30.5	76.0	0.0
28.7	76.3	0.1
26.5	76.5	0.1
24.7	76.7	0.0
22.3	76.9	0.1
19.9	77.1	0.0
17.4	77.2	0.0
14.8	77.4	0.1
12.3	77.5	0.1
10.2	77.6	0.0
8.0	77.6	0.0
5.4	77.7	0.0
3.2	77.7	0.0
0.5	77.7	0.0
358.3	77.7	0.0
355.6	77.7	0.0
352.4	77.6	0.0
349.7	77.6	0.0
347.1	77.5	0.0
345.1	77.4	0.0
343.0	77.3	0.1
340.5	77.1	0.0
338.1	76.9	0.0
335.7	76.7	0.0
333.4	76.5	0.0
331.2	76.3	0.0
329.4	76.1	0.0
327.3	75.8	0.0
325.3	75.5	0.0
323.4	75.2	0.0
321.9	75.0	0.0
320.4	74.7	0.0
318.7	74.4	0.0
317.3	74.1	0.0
315.9	73.8	0.0
314.4	73.5	0.0
313.1	73.2	0.0
311.9	72.9	0.0
310.5	72.5	0.0
309.1	72.1	0.0
308.0	71.8	0.0
307.0	71.5	0.0
305.7	71.0	0.0
304.5	70.6	0.0
303.6	70.3	0.0
302.7	69.9	0.0
301.8	69.6	0.0
300.5	69.1	0.0
299.7	68.7	0.0
298.7	68.3	0.0
297.5	67.7	0.0
296.1	67.0	0.0
295.4	66.6	0.0
294.4	66.1	0.0
293.4	65.5	0.0
292.6	65.0	0.0
291.6	64.4	0.0
290.6	63.8	0.0

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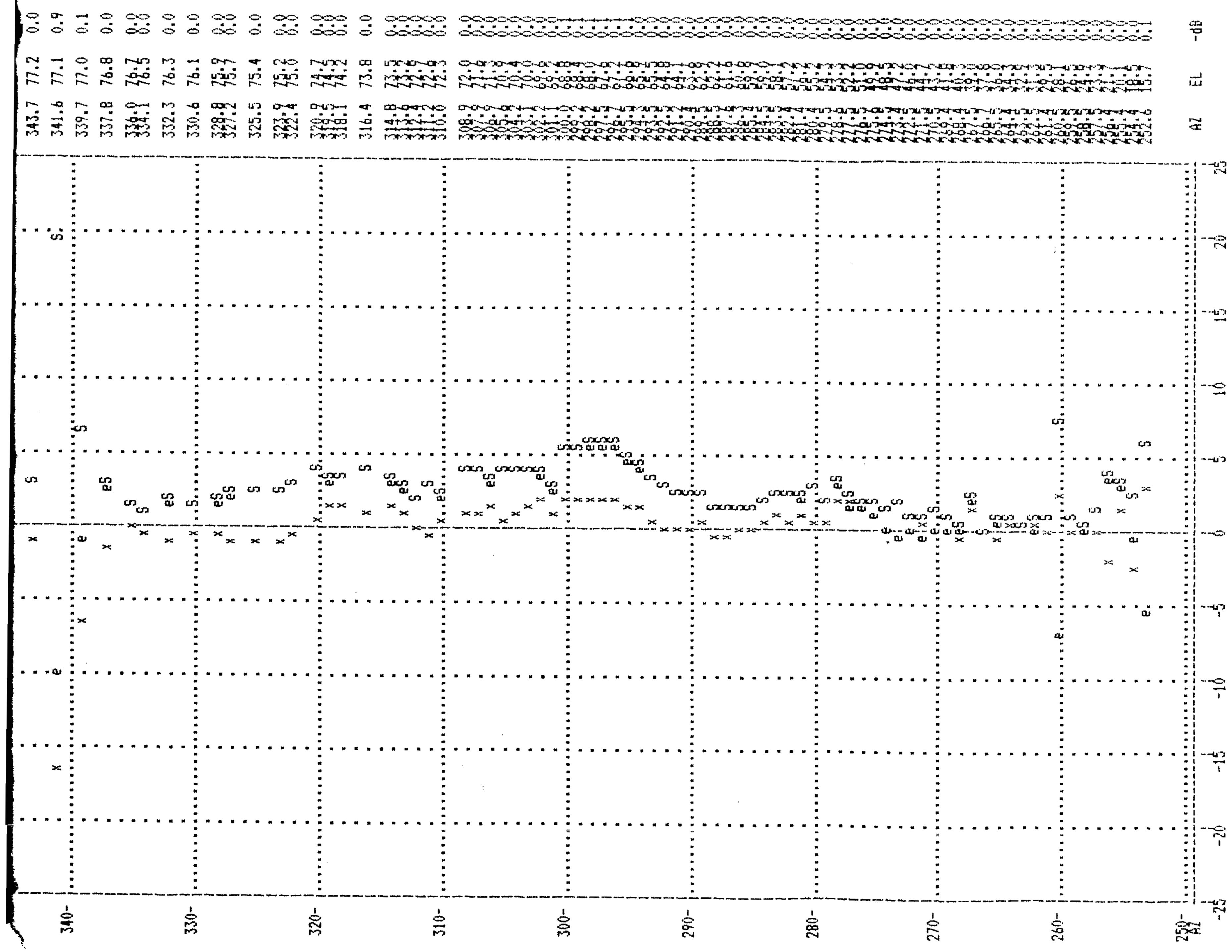

```
ANALYSIS of CONSCAN DATA FILE: V245D018.F from DSS- 45
   Data captured starting at:  19:18:49 01-18-1986
   File contains  276  lines

MEAN AZ  offset=  -0.0 mdeg.     SDEV AZ  offset=   6.3 mdeg.
MEAN EL  offset=  +0.6 mdeg.     SDEV EL  offset=   3.2 mdeg.
MEAN XEL offset=  +0.3 mdeg.     SDEV XEL offset=   3.1 mdeg.

MEAN of AZ  absolute offsets=   3.0 mdeg.
MEAN of EL  absolute offsets=   2.0 mdeg.
MEAN of XEL absolute offsets=   1.6 mdeg.

** MEAN SPACE offset=  2.8 mdeg.     SDEV SPACE offset=  3.5 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.0 dB
```

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```
Data plot from file: V245D018.F  from DSS - 45
Data captured starting at  19:18:49 01-18-1986
AZ bias =  0  mdeq.   EL bias =  0  mdeq.
```

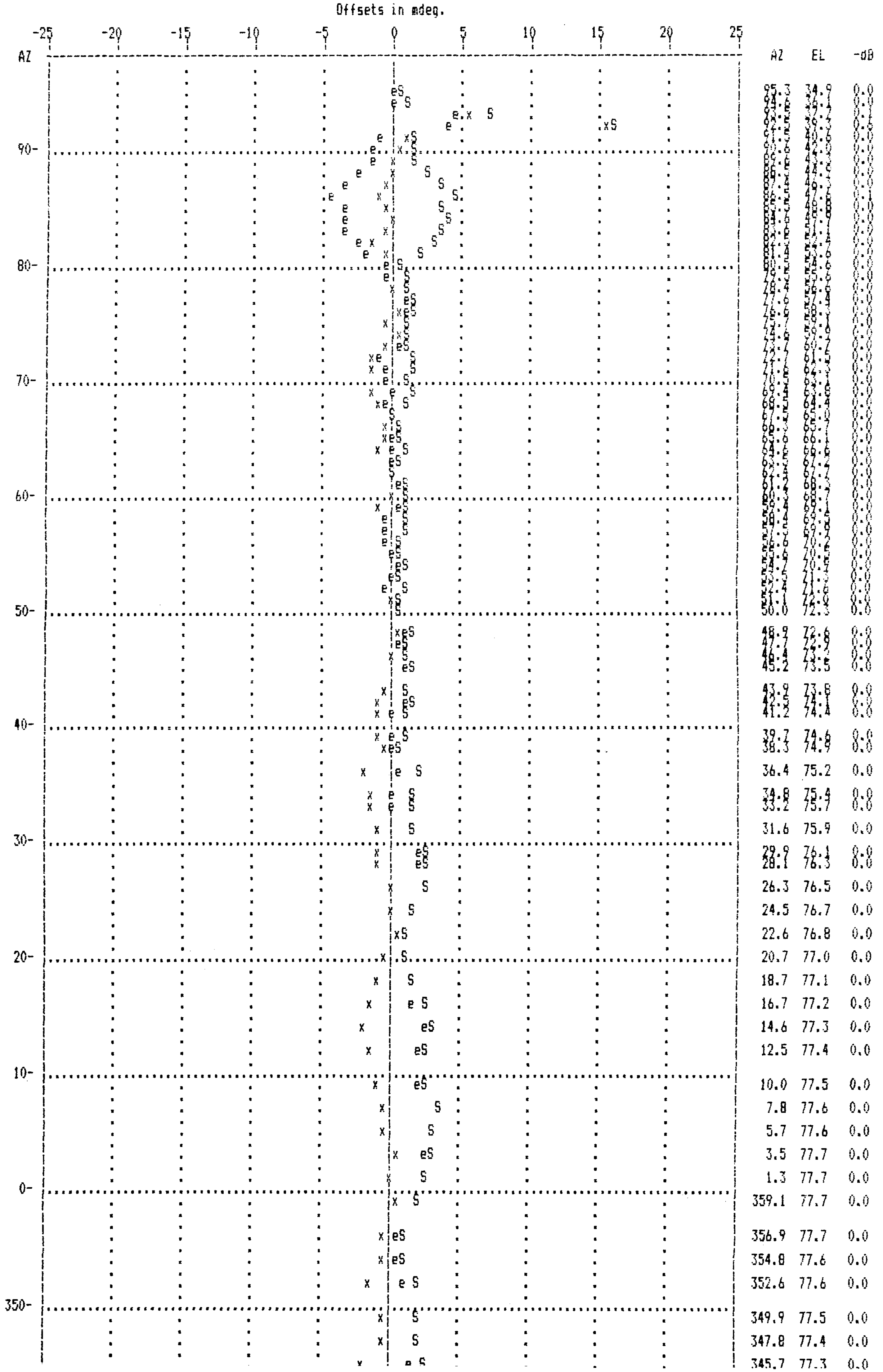

Fig. 6(e). DSS 45 34-m Az–El (CDSCC)

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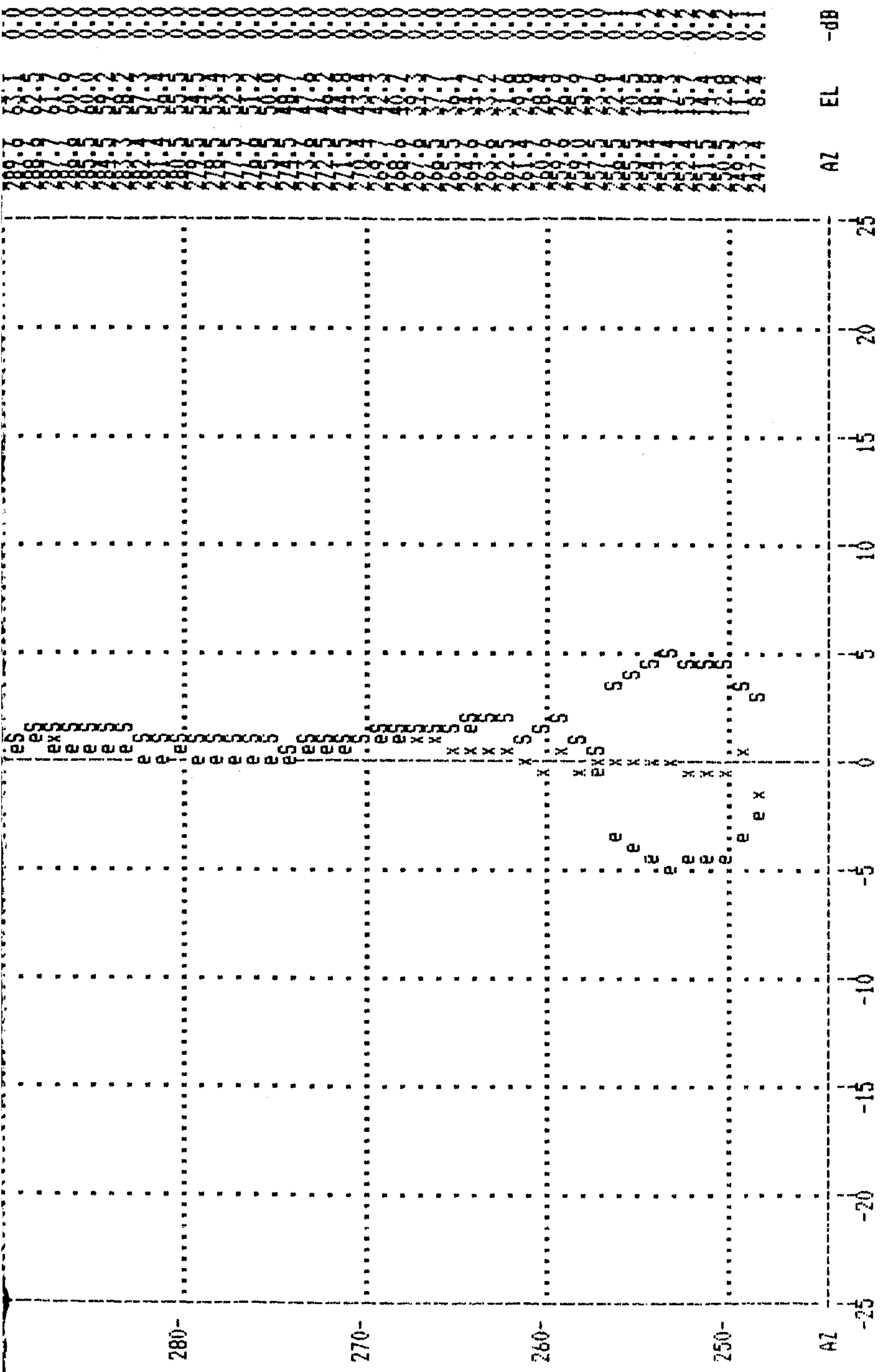

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```
ANALYSIS of CONSCAN DATA FILE: V243D018.P1F from DSS- 43
   Data captured starting at:  18:28:43 01-18-1986
   File contains  300  lines

MEAN AZ  offset=  -0.1 mdeg.      SDEV AZ  offset=   3.3 mdeg.
MEAN EL  offset=  -0.0 mdeg.      SDEV EL  offset=   2.1 mdeg.
MEAN XEL offset=  +0.3 mdeg.      SDEV XEL offset=   1.3 mdeg.

MEAN of AZ  absolute offsets=   2.5 mdeg.
MEAN of EL  absolute offsets=   1.5 mdeg.
MEAN of XEL absolute offsets=   1.1 mdeg.

** MEAN SPACE offset=  2.1 mdeg.     SDEV SPACE offset=  1.3 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.0 dB
```

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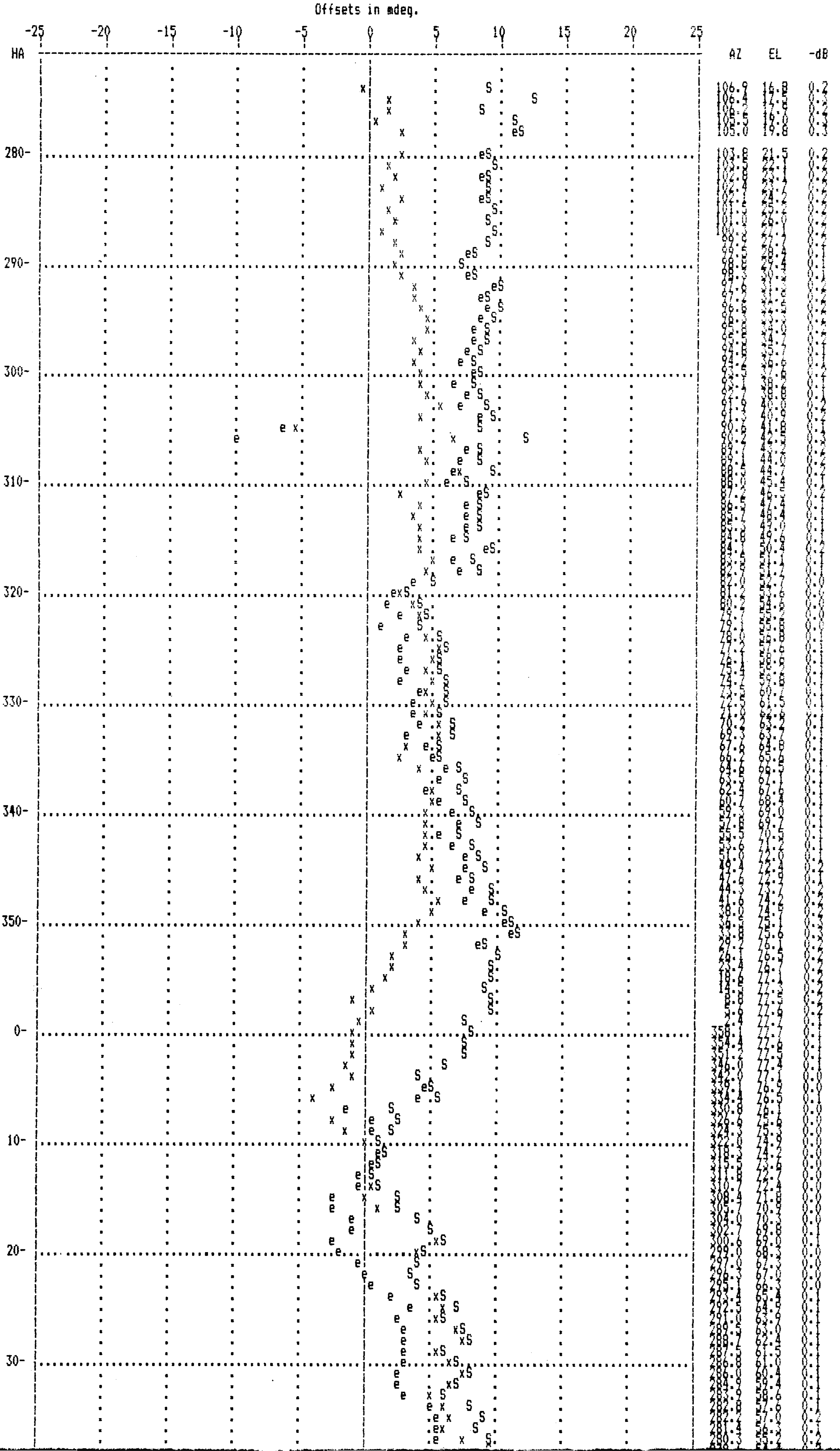
Fig. 6(d). DSS 43 64-m precision mode (CDSCC)

Data plot from file: V242D020.A from DSS - 42
Data captured starting at 17:40:20 01-20-1986
AZ bias = 0 mdeg.   EL bias = 0 mdeg.



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ANALYSIS of CONSCAN DATA FILE: V263D021 from DSS- 63
   Data captured starting at: 06:49:17 01-21-1986
   File contains  220  lines

MEAN AZ  offset=  -1.2 mdeg.      SDEV AZ  offset=   1.1 mdeg.
MEAN EL  offset=  +0.1 mdeg.      SDEV EL  offset=   2.0 mdeg.
MEAN XEL offset=  -1.1 mdeg.      SDEV XEL offset=   1.1 mdeg.

MEAN of AZ  absolute offsets=   1.3 mdeg.
MEAN of EL  absolute offsets=   1.4 mdeg.
MEAN of XEL absolute offsets=   1.2 mdeg.

** MEAN SPACE offset=  2.0 mdeg.     SDEV SPACE offset=  1.4 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.0 dB
```

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Data plot from file: V263D021 from DSS - 63
Data captured starting at 06:49:17 01-21-1986
AZ bias = 0 mdeg. EL bias = 0 mdeg.

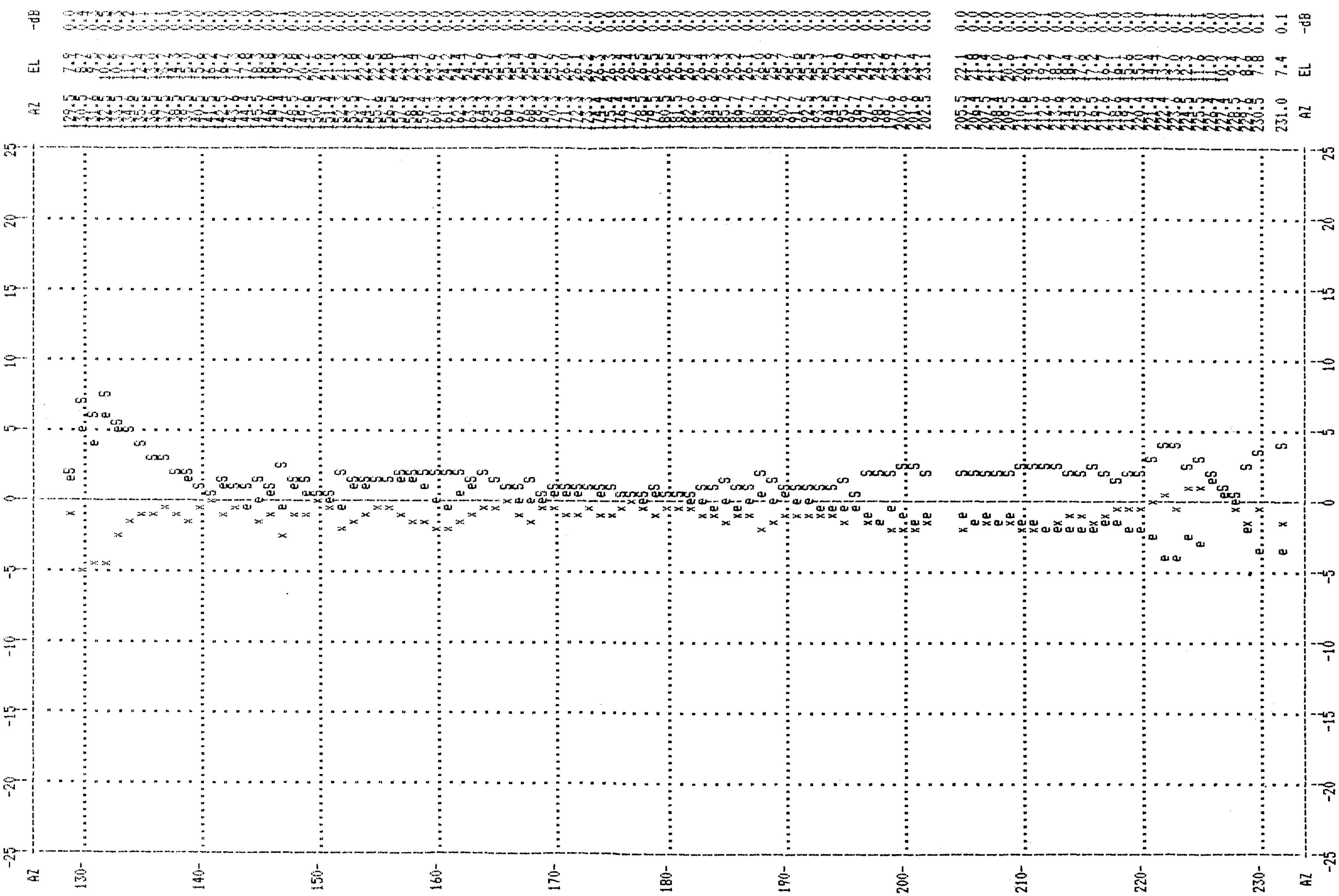
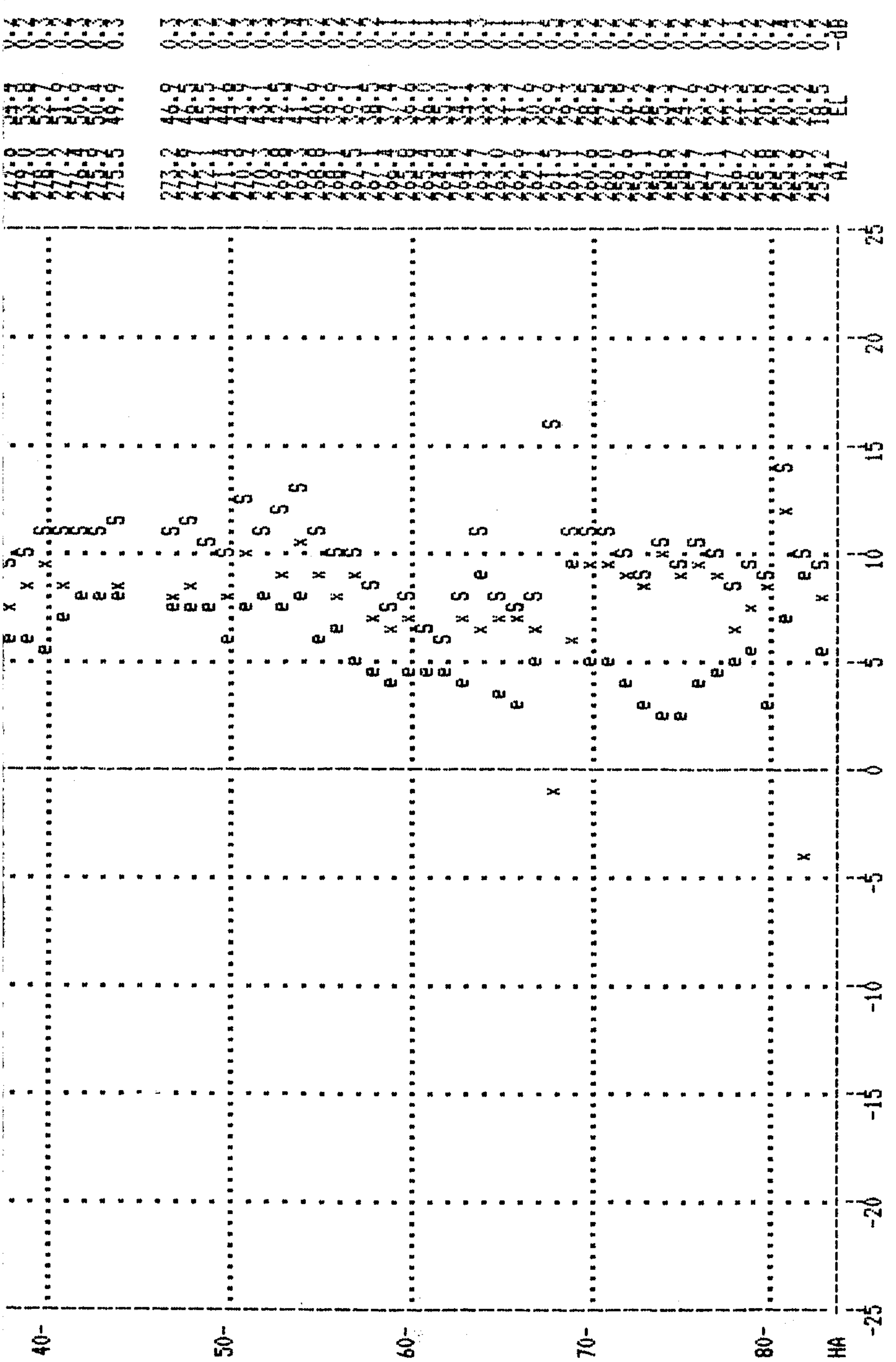


Fig. 6(g). DSS 63 64-m precision mode (MDSCC)



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ANALYSIS of CONSCAN DATA FILE: V242D020.A from DSS- 12
   Data captured starting at:  17:40:20 01-20-1986
   File contains  283  lines

MEAN AZ  offset=  +7.7 mdeg.      SDEV AZ  offset=   6.1 mdeg.
MEAN EL  offset=  +5.6 mdeg.      SDEV EL  offset=   3.6 mdeg.
MEAN XEL offset=  +7.3 mdeg.      SDEV XEL offset=   5.6 mdeg.

MEAN of AZ  absolute offsets=   8.7 mdeg.
MEAN of EL  absolute offsets=   5.9 mdeg.
MEAN of XEL absolute offsets=   8.1 mdeg.

** MEAN SPACE offset= 10.8 mdeg.     SDEV SPACE offset=  3.5 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.2 dB
```

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Fig. 6(f). DSS 42 34-m Ha–Dec (CDSCC)

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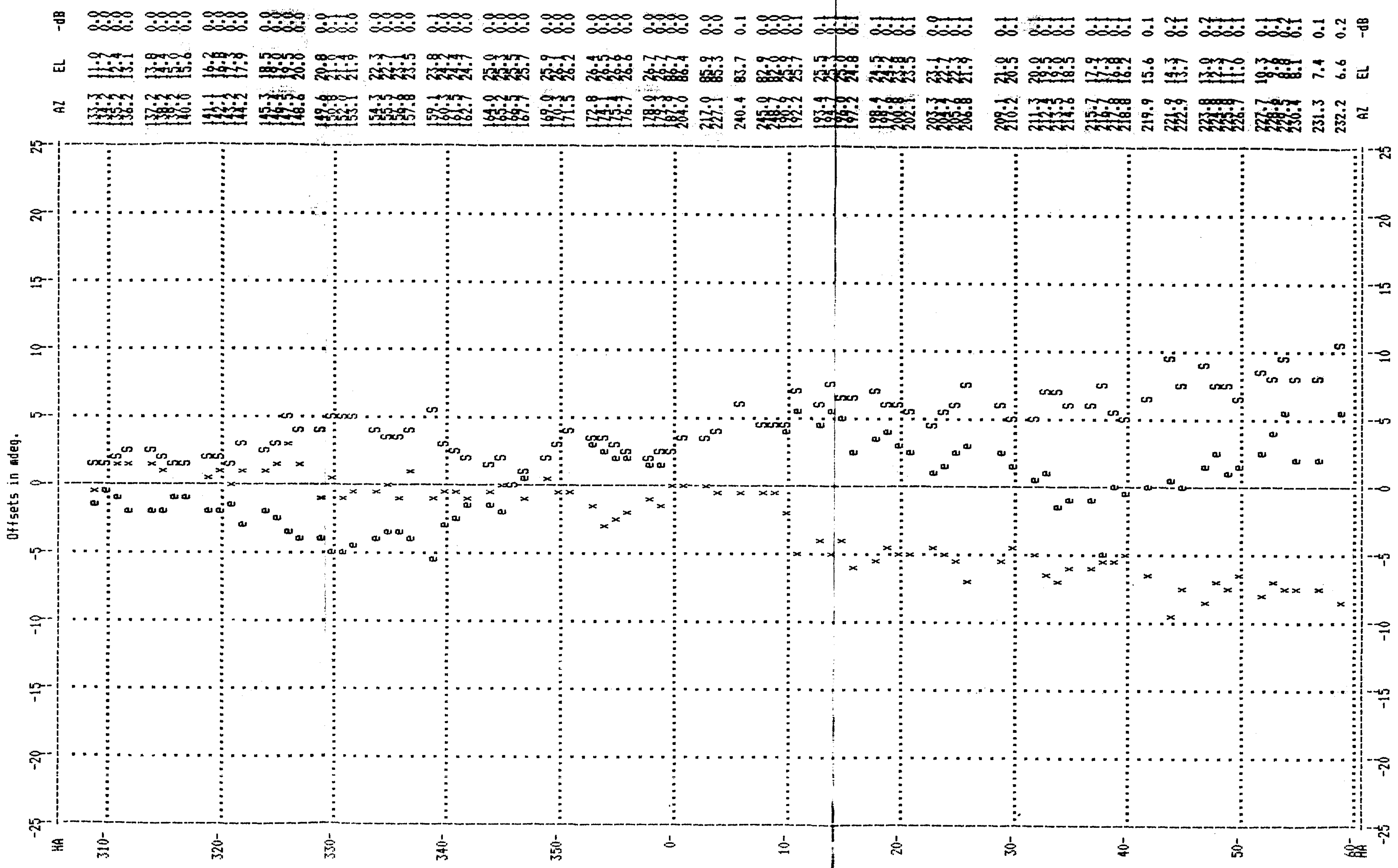
Data plot from file: V261D338 from DSS - 61
Data captured starting at 08:45:00 12-04-1985
AZ bias = 0 mdeg. EL bias = 0 mdeg.



ANALYSIS of CONSCAN DATA FILE: V261D338 from DSS- 61
Data captured starting at: 08:45:00 12-04-1985
File contains 85 lines

```
MEAN AZ  offset=  -3.1 mdeg.     SDEV AZ  offset=   3.4 mdeg.
MEAN EL  offset=  +0.5 mdeg.     SDEV EL  offset=   3.0 mdeg.
MEAN XEL offset=  -2.7 mdeg.     SDEV XEL offset=   3.3 mdeg.

MEAN of AZ  absolute offsets=   3.6 mdeg.
MEAN of EL  absolute offsets=   2.6 mdeg.
MEAN of XEL absolute offsets=   3.2 mdeg.

** MEAN SPACE offset=  4.7 mdeg.     SDEV SPACE offset=  2.3 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.0 dB
```

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Fig. 6(h). DSS 61 34-m Ha-Dec (MDSCC)

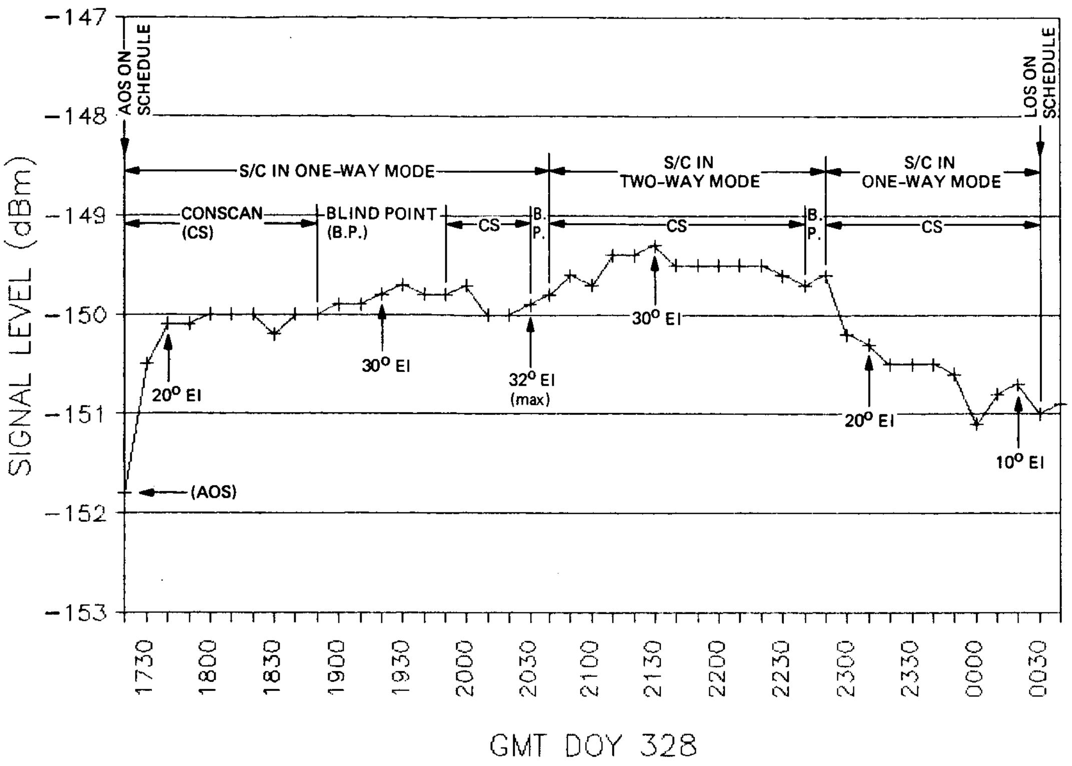

Fig. 7. Received signal level during Voyager 2 tracking in Conscan and blind pointing modes at DSS 14

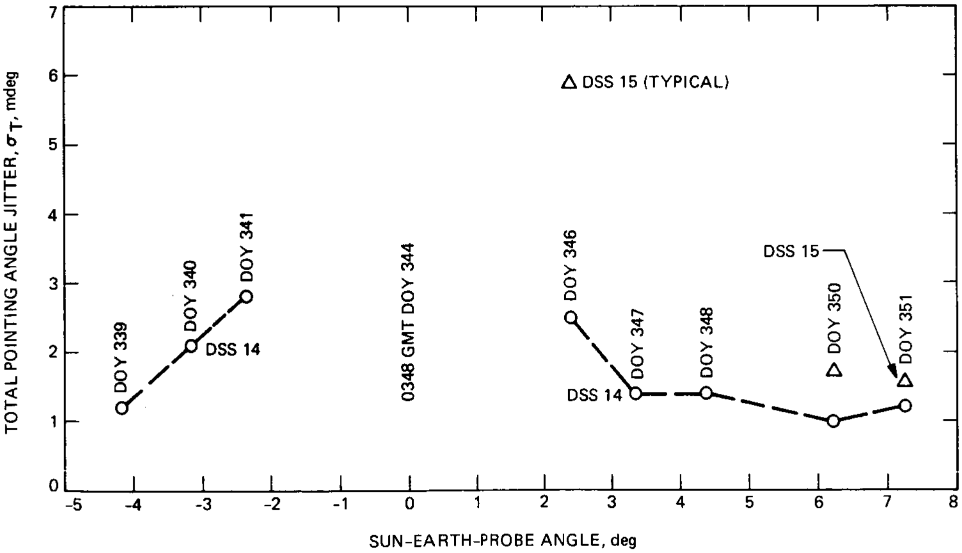

Fig. 8. Pointing angle jitter during Voyager 2 X-band tracking near solar conjunction, DSS 14 and DSS 15

Discussion: The total pointing angle jitter, σ_T, is calculated as the square root of the sum of the squares of the elevation axis and the cross-elevation axes jitters. The jitter of each axis was estimated from examination of the Conscan offset plots for elevation angles above 20 degrees.

Fig. 9. Comparison of pass average Conscan offsets from Voyager 2 X-band tracking at DSS 14 and DSS 15

Discussion: On most days of the period covered, the Voyager 2 S/C was tracked by DSS 14 and DSS 15 simultaneously – the antennas were being arrayed for the near-encounter support. Uranus closest approach was on DOY 23.

Each point represents the arithmetic average of the offsets during the pass, sampled at 1-deg azimuth increments. A full-length Voyager 2 pass at GDSCC covered 125 to 235 deg azimuth and 8 to 32 deg elevation.

Generally, the elevation offsets at the two antennas show high correlation; the azimuth offsets show low correlation (see text). There are inconsistent elevation offsets on DOY 38 (Fig. 9(a)). The pointing predicts for that day were examined carefully, and exonerated. The inconsistency was not resolved.

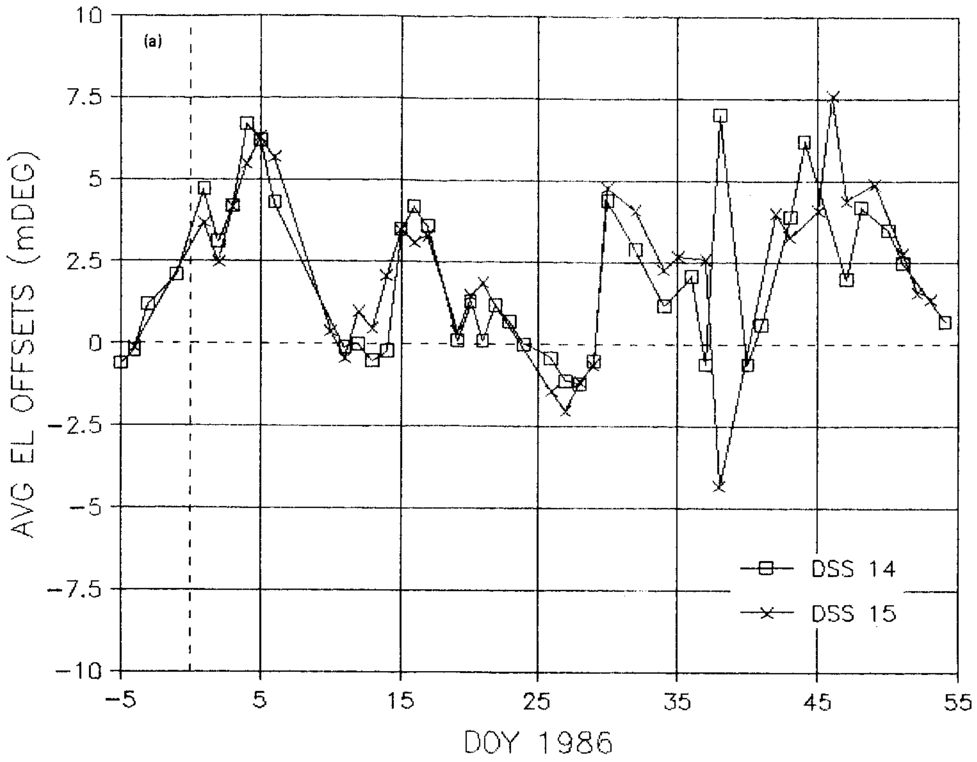

Fig. 9(a). Average elevation offsets

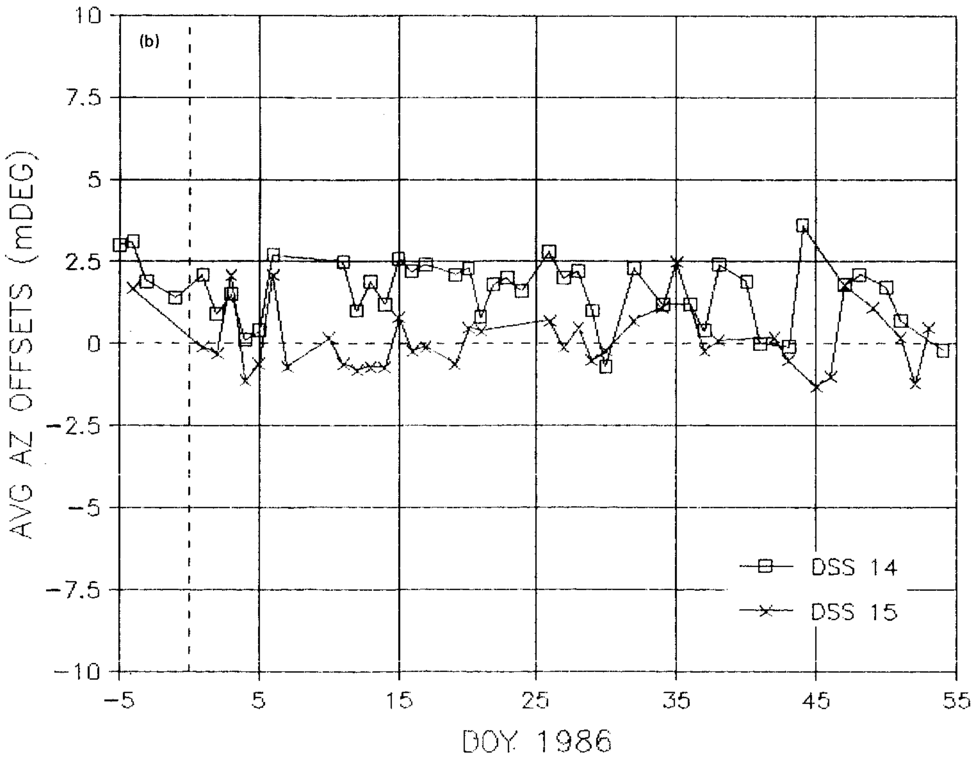

Fig. 9(b). Average azimuth offsets

Fig. 10. Conscan offsets and received signal level during Voyager 2 tracking in sidereal and predict modes at DSS 14

Discussion: The format of the Conscan offset plots and the summary analysis of Fig. 10(a) are the same as for Fig. 6, and the discussion presented there applies. The periods of operation in predict and sidereal Conscan, and sidereal blind-point modes are shown.

The received signal-level plot of Fig. 10(b) shows the periods of use of the different modes, and the antenna elevation angle at intervals during the track.

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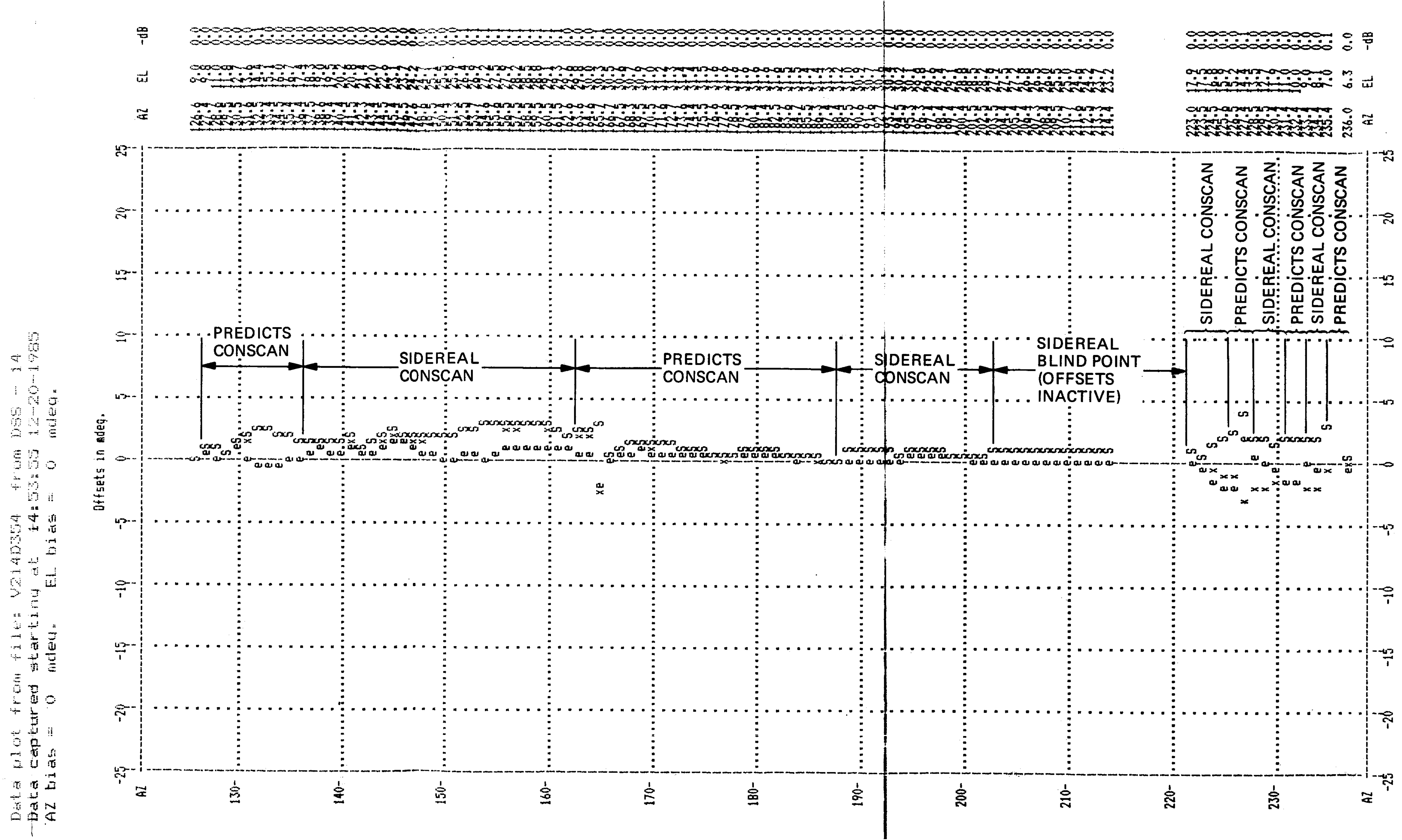

```
ANALYSIS of CONSCAN DATA FILE: V214D354 from DSS- 14
   Data captured starting at:  14:53:55 12-20-1985
   File contains  229  lines

MEAN AZ  offset=  +0.9 mdeg.      SDEV AZ  offset=   1.4 mdeg.
MEAN EL  offset=  +0.2 mdeg.      SDEV EL  offset=   0.8 mdeg.
MEAN XEL offset=  +0.8 mdeg.      SDEV XEL offset=   1.3 mdeg.

MEAN of AZ  absolute offsets=   1.4 mdeg.
MEAN of EL  absolute offsets=   0.6 mdeg.
MEAN of XEL absolute offsets=   1.3 mdeg.

** MEAN SPACE offset=  1.5 mdeg.     SDEV SPACE offset=  0.9 mdeg.

Blind pointing loss would be:

***** MEAN loss=  -0.0 dB
```

Fig. 10(a). Conscan offsets and analysis summary

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2 FOLDOUT FRAME

3 FOLDOUT FRAME

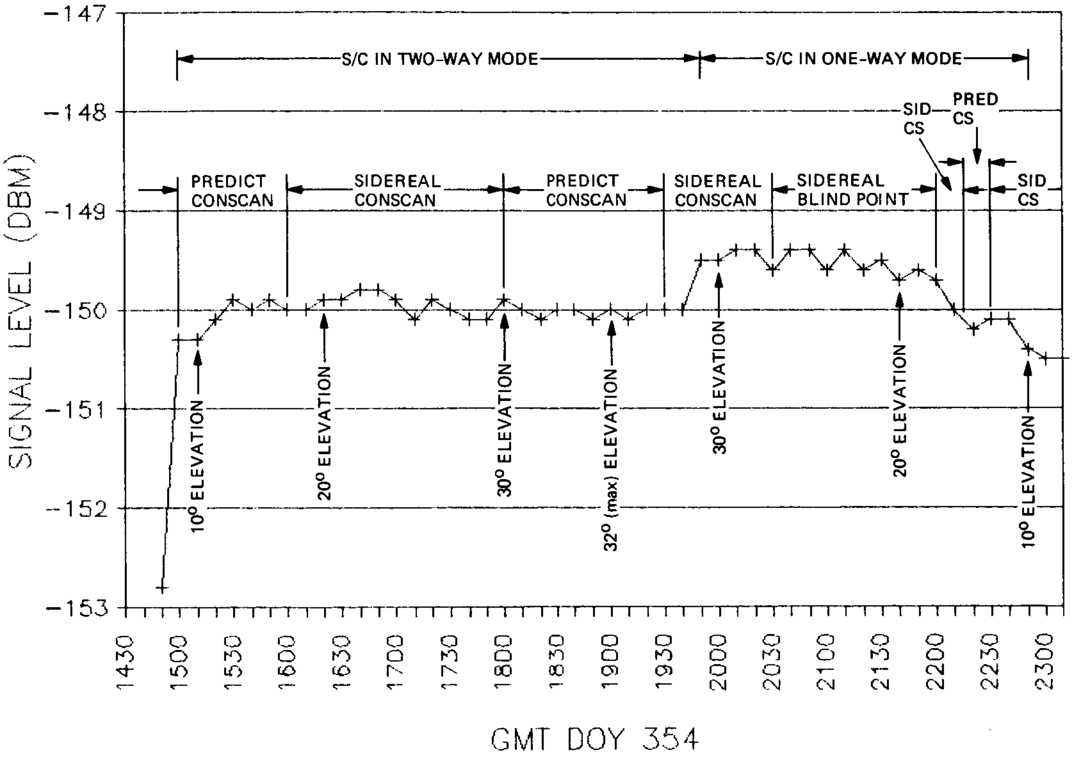

Fig. 10(b). Received signal level at DSS 14 during Voyager 2 X-band tracking

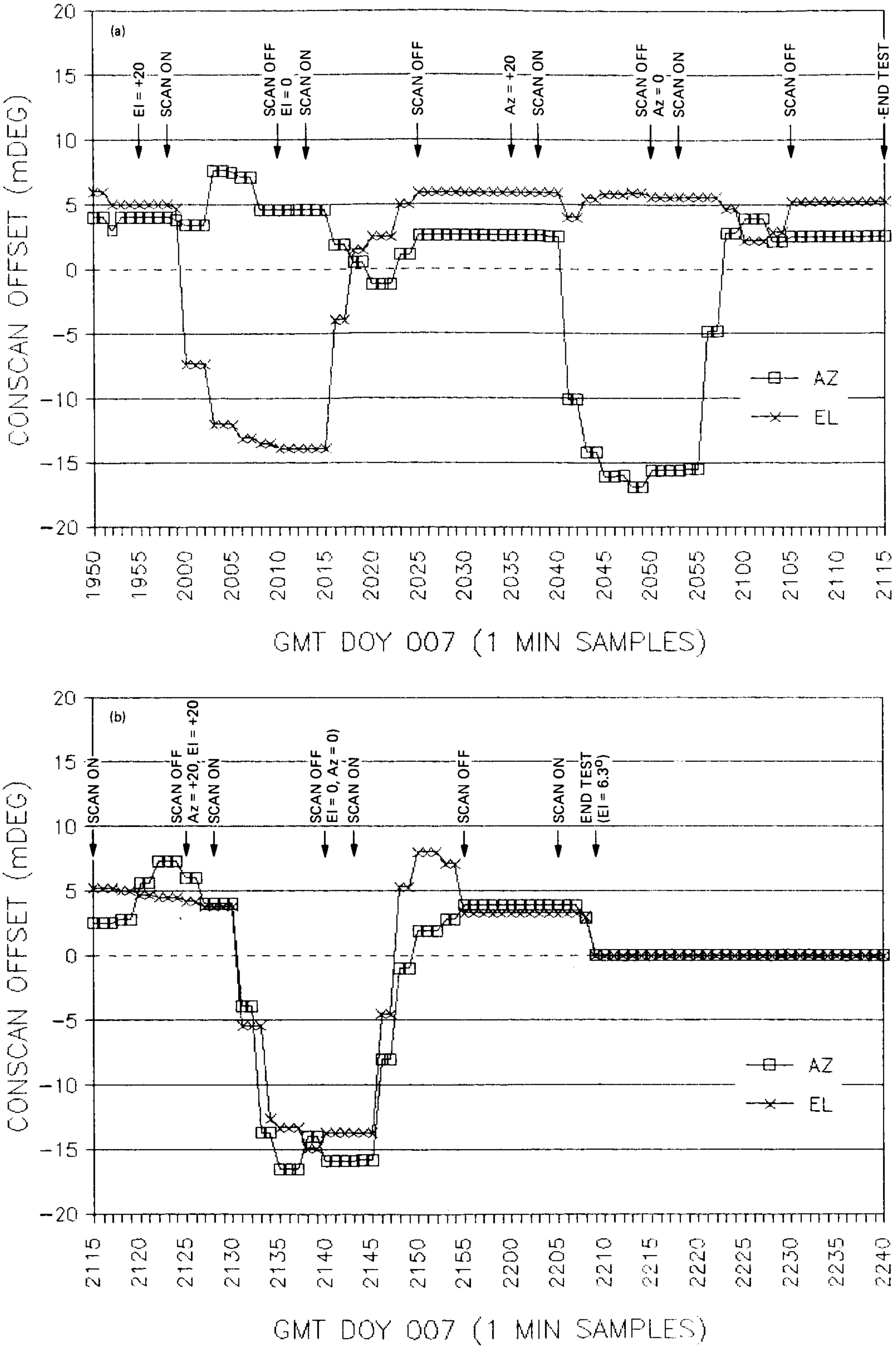

Fig. 11. Conscan offset signatures from DSS 15 Voyager 2 X-band Conscan snap-on tests: (a) snap-ons, one axis offset at a time; (b) snap-ons, both axes offset simultaneously