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FM7:RONobles:rmr

Mission Planning and Analysis Division
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS 77058

REPLY TO
ATTN OF: 71-FM73-36

JAN [illegible]

MEMORANDUM TO: FA/Chairman, Software Control Board

FROM : FM/Chief, Mission Planning and Analysis Division

SUBJECT : Completion of MPAD Action Items from the Apollo 14 Flight Software Readiness Review

The Mission Planning and Analysis Division (MPAD) was assigned three action items at the Apollo Flight Software Readiness Review (FSRR) as a result of anomalous software behavior experienced on the Grumman Aircraft Company (GAC) hybrid simulator. These action items were associated with the LUMINARY program and are as follows:

1. Explain the excessive N49's (ΔR, ΔV) experienced in the rendezvous navigation (P20) during the nominal rendezvous sequence.

2. Explain the higher than expected altitude rate during the automatic rate of descent (P66).

3. Explain the small vehicle yaw angle buildup in the last 10 seconds of the approach phase (P64).

The MPAD was assisted by GAC, MIT, and DELCO in answering these action items. As a result of this combined effort, the anomalous behavior has been explained for all three items. Detailed explanations to these items can be found in the attached memorandums. The following is a brief summary of the explanations:

1. It has been ascertained that the excessive N49's are a result of the simulated rendezvous radar (RR) data input to the LUMINARY program. The Mathematical Physics Branch (MPB) engineering simulation exhibits the same characteristics when given the same input data as the GAC hybrid. The culprit is apparently the angle data from the GAC hybrid model. GAC attributes this to a combination of the "ZONKER"(?) effect and a 0.3° attitude deadband. I will attempt to explain; however, Mr. Zonker should be consulted for conclusive evidence. An instantaneous lag in the RR antenna dish is created with each RCS jet firing. This creates RR angle errors until the dish is damped. If the RR is sampled during this interval it apparently picks up some angle errors. A 0.3° attitude deadband agitates the "ZONKER" effect as there is RCS action

about every 3 seconds. However, when simulating a 1° deadband and the concentric rendezvous geometry (as in Apollo 12) the data is not consistent with the postflight data or Pete Conrad's recollection. It appears that the magnitudes of the disturbances used in Mr. Zonker's model is somewhat conservative and not what should be expected from the flight hardware.

2. The high descent rate in P66 was traced to an error in the erasable load targets for P64. The target was corrected and subsequent test cases exhibited a slower than expected descent rate. This was attributed to a combination of vertical acceleration (twice that of the previous missions), navigation updates due to terrain, and computer delays associated with program switching from P64 to P66.

3. The vehicle yaw at the end of P64 was attributed to a combination of three things (1) Truncation of the landing site vector, (2) a programming error affecting the last computation cycle in P64 (The program picks up an incorrect gain constant which results in an erroneous rotation of the guidance coordinates. The magnitude of the rotation is a function of the out of plane velocity at that time and normally is small) and (3) the guidance will normally yaw the vehicle to null any out of plane velocity.

None of the above anomalous occurances are of a critical nature. The investigation has led to a thorough understanding of the occurances and that in itself adds more confidence in the quality of the Apollo 14 LUMINARY program.

Carl R. Huss
for John P. Mayer

Enclosures (5)

cc: (See attached list)

Mission Planning and Analysis Division
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
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January 26, 1971

REPLY TO
ATTN OF: 71-FM47-21

MEMORANDUM TO: FM7/Chief, Guidance and Performance Branch
Attn: R. O. Nobles

FROM : FM4/Mathematical Physics Branch

SUBJECT : An analysis of the V06 N49 problem at GAC

1. During simulations at the Grumman Aircraft Corporation (GAC) simulator, abnormal V06N49 displays occurred which put the Luminary 178 rendezvous program P-20 for Apollo 14 in question. The analysis of the GAC simulation runs indicates that the problem lies in the generation of the data. In the simulator case analyzed in detail by MPB in which GAC attempts to simulate error-free data the middle gimbal angle had a drift rate of $.01^\circ$/min (which is about 20 times the 1_σ spec value). In addition, there was noise on the data that appeared to be in excess of 3σ. The LGC downlink data was processed in the MPB bench program and results identical to the GAC were obtained which indicated that the software was correct. In addition the N49 problem is occurring on the concentric rendezvous where it had not occurred for previous missions, this also indicated a problem with the GAC data generation program. On January 25, 1971, the GAC notified MPB that the radar model is creating an error which has a sinusoidal distribution with an amplitude of $.15^\circ$ (the spec value for random noise is $1\sigma = .057^\circ$) and a period of one second.

2. The program P-20 is designed to display to the crew any state vector corrections which exceed 2000 ft RSS position and 2 fps RSS velocity. These tolerances are set pre-launch in erasable memory and were established by studies at both MSC and MIT. If a correction occurs larger than these limits the RSS correction in position is displayed in register 1 with RSS velocity in register 2 and a code identifying the type of measurement in register 3 of the DSKY. Normally, these displays occur during the early part of the rendezvous because of state errors but are accepted if less than 12000 ft and 12 fps until they no longer appear which is usually about mark 8.

3. The GAC sims discovered V6N49's as late as mark 12 of 15 mark sequences. It was suggested that a case be run in which no state vector errors were included in the initial conditions. This run resulted in displays at marks 4, 5, 6, 8, 11 and 12 due to both RR shaft and trunnion. A film of the case was transmitted to MSC and the run was duplicated on an 1108 digital simulation program developed under MSC/TRW task A-164. Using the same initial conditions and same raw data the MSC digital run corresponded in every

Enclosure 1

respect including the N49's. At this point two more runs were requested from GAC. The first was a duplicate of the case just discussed except that the RR shaft and trunnion biases were not solved for. The second was a repeat of the Apollo 11 and 12 type concentric rendezvous. (The first two cases had been the direct).

4. In the Kalman filter, the state is corrected as a linear function of the residual and if the filter is working properly excessive corrections can only occur from large residuals. The residual is made up of three parts:

a. the raw observation

b. the LGC estimated observation

c. the last estimate of the observation bias

The residual is computed as [(a-b) - c], and can only be excessively large if (a-b) is large or if c is of the opposite sign of (a-b) or of course if c is very different from (a-b). An analysis of the data of the original run showed that the bias solution always had the same sign but that the sign of (a-b) was random. In addition the N49's occurred when the signs were different. These facts point to a large random error.

5. The purpose of the first additional case (no bias) was to see if the bias solution could be causing the problem. The case was run and no N49's occurred after mark 4. This might lead one to the false conclusion that the bias solution is bad but further study shows that in the absence of a bias estimate the opposite sign problem cannot occur.

6. The purpose of the second case (concentric plan) was to see if the geometry of the rendezvous could be the problem. In addition, many similar cases had been run at GAC on this rendezvous in the past without problem. The run showed N49's on marks 7, 8, 12, 23 and 26 out of a mark schedule of 33 marks. At this point the GAC became convinced that the RR math model used to generate raw observations was in question. At the present time the GAC is investigating the math model model and have discovered abnormal math model behavior when a RCS jet fires.

7. Based on the results presented above the conclusions are:

a. the N49's were caused by large "random" sensor errors

b. the sensor errors are not real but model errors

c. that P-20 can be considered to operate normally during rendezvous.

B. F. Cockrell

APPROVED BY:

James C McPherson

James C. McPherson, Chief
Mathematical Physics Branch

RTS

Distribution: (See attached list)

FM4:BFCockrell:fdb

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/Chief
Deputy Chief
Chief, MPSO (2)
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Mission Planning and Analysis Division
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REPLY TO ATTN OF: 71-FM22-21

JAN 25 1971

MEMORANDUM TO: FM7/Guidance and Performance Branch
Attention: Mr. R. O. Nobles

FROM : FM2/Landing Analysis Branch

SUBJECT : Yaw deviation during P-64

References:

1. Delco Electronics System Engineering Memorandum SE-71-10, "The two degree yaw at the end of P-64," dated January 12, 1971.

2. MIT/DL Luminary Memorandum 194, "Analysis of the deviation at P-64 terminus," dated January 22, 1971.

During the Apollo 14 FSRR, Grumman reported that a small yaw deviation was occurring the last 6 sec of program P-64. After investigation, it was determined that the yaw occurred in the earlier Apollo programs. The yaw deviations were generally 1 to 2 deg in magnitude; however, some runs had slightly larger values, up to 4 deg.

Several organizations have been looking into this phenomenon, including GAC, Delco, MIT, TRW, and MSC. In reference 1, L. Hull of Delco reported that the landing site vector was being truncated by the computer. This truncation causes an out-of-plane trajectory resulting in a yaw to compensate for the truncation. Allan Klump of MIT expanded on this problem in reference 2 and also determined that even for the nominal case, small out-of-plane velocities existed. To correct for this velocity, the vehicle would require more yaw. During Mr. Klump's investigation, he uncovered a program error which increased the yaw angle near the end of P-64.

The conclusion from all the studies indicate that all three contribute to the yaw maneuver; however, the total yaw is small. No change to the Apollo 14 program is recommended and only the program error be corrected for Apollo 15.

James H. Alphin
James H. Alphin

WMB

Enclosure 2

APPROVED BY:

Floyd V Bennett

Floyd V. Bennett
Chief, Landing Analysis Branch

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Mission Planning and Analysis Division
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JAN 20 1971

REPLY TO
ATTN OF: 71-FM22-5

MEMORANDUM TO: FM7/Guidance and Performance Branch
Attention: Mr. R. O. Nobles

FROM : FM2/Landing Analysis Branch

SUBJECT : Altitude rates during vertical descent phase of the Apollo 14 lunar landing

LM simulations have shown a tendency for the automatic guidance system to achieve lower than expected descent rates during the vertical descent phase of the lunar landing maneuver. Because the earlier missions experienced descent rates of approximately -3 fps, these lower rates appeared to be abnormal. Two changes, one program and one targeting, have contributed to the resulting descent rate. The first change was the addition of auto P-66 and deletion of P-65. Auto P-66 does not use a target to control the descent rate (as P-65 did), but maintains the rate existing at the transition from P-64 to P-66. The targeting change increased the vertical acceleration from around 0.1 fps^2 to 0.5 fps^2.

The program switch is initiated when the guidance time-to-go (TGO) is less than 12 seconds with a time delay of 2 seconds. The program is targeted so that a -3 fps descent rate is achieved at 10 seconds (12 seconds minus the 2-second delay). However, because the TGO is only calculated every 2 seconds, the computer timing allows approximately 2 seconds variation in the actual switch TGO. The nominal simulations have been switching at TGO's of less than 10.5 seconds (instead of 12); therefore, the expected rate would be at least 0.75 fps low. In addition to the time delays, terrain perturbations have biased the descent rate profile low (see figure 1) causing the actual rate to be even less.

Figure 1 shows the variation of altitude rate with TGO for several cases. The first case is the analytic (ideal) solution. It would switch at a TGO of 12 seconds and achieve a descent rate of -3 fps at 10 seconds. The second case is an operational trajectory run without terrain switching at 10.7 seconds achieving a rate of -2.2 fps. The third case is the operational trajectory run with terrain. It reached program switch at a TGO of 11.5 with the resulting rate of -2.0 fps.

Enclosure 3

Similar results were obtained from MIT, GAC, and TRW. However, no change to the Apollo 14 trajectory or guidance programs is recommended. If the Apollo 14 crew chooses to enter auto P-66 in this manner, they can alter the descent rate with the rate of descent (ROD) switch to some other desired rate.

Burl G Kirkland
Burl G. Kirkland

James H. Alphin
James H. Alphin

WMB

APPROVED BY:

Floyd Bennett
Floyd V. Bennett
Chief, Landing Analysis Branch

Enclosure

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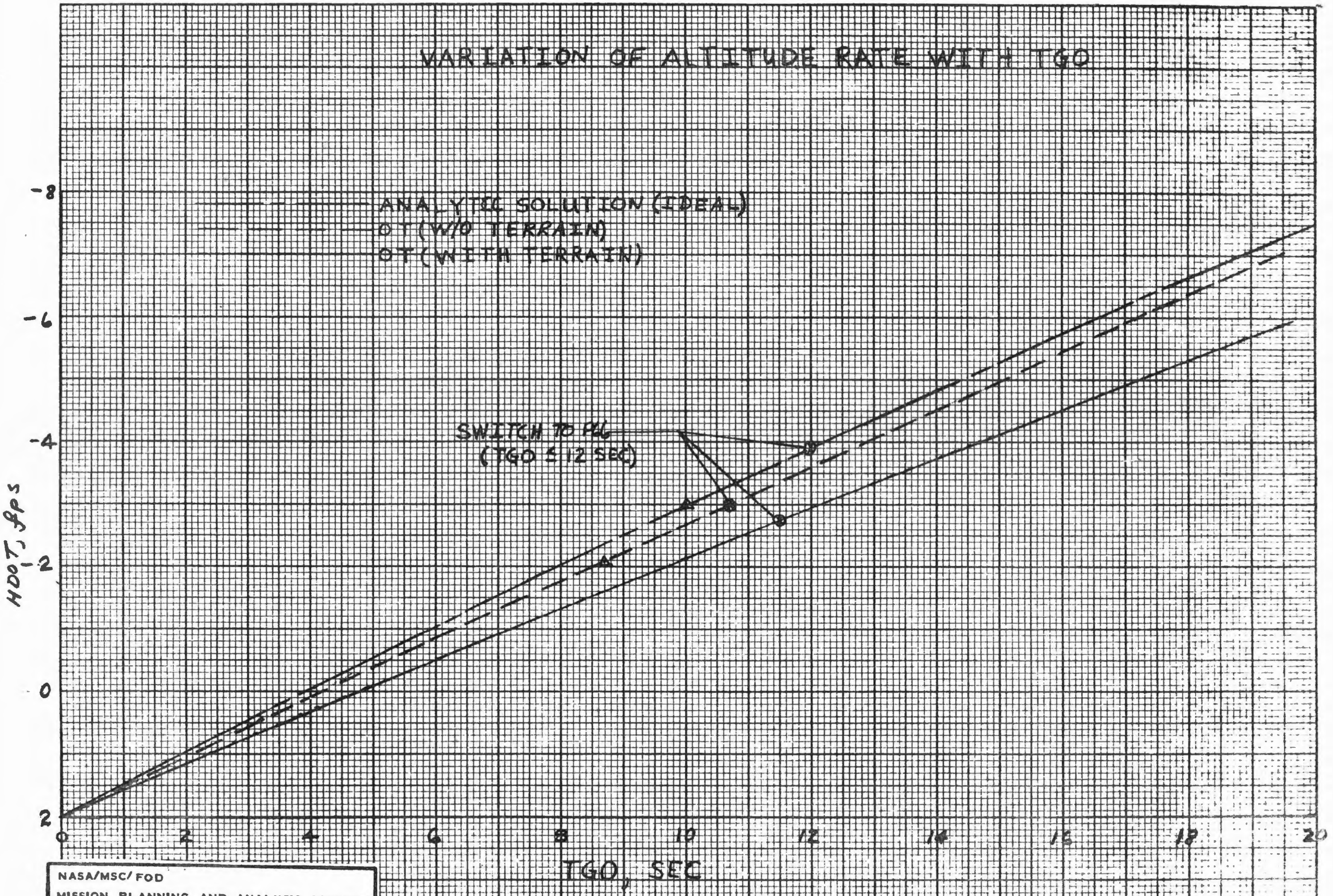
FM7/R. O. Nobles
FM15/Editing
TRW/D. P. Johnson (3)

FM2/BGKirkland:JHAlphin:djr



NASA/MSC/FOD
MISSION PLANNING AND ANALYSIS DIVISION
BRANCH LAB DATE 1/20/71
BY BGK/JHA PLOT NO. 4

Massachusetts Institute of Technology
Charles Stark Draper Laboratory
Cambridge, Massachusetts

Luminary Memo # 194

TO: Russell Larson
FROM: Allan Klumpp
DATE: January 22, 1971
SUBJECT: Analysis of the Yaw Divergence at P64 Terminus

INTRODUCTION

My memo to you on January 12 (Ref. 1) reported on the results of an examination of several anomalies and stated that analyses would be made and the results published shortly. The analysis of the yaw divergence has been completed and is reported here. Analyses of other anomalies about whose causes I was uncertain in the preceding memo will be completed and reported separately.

This analysis is basedon rollbacks of a single descent simulation. The relative importance of the sources of yaw divergence may be different in other simulations.

SHORT DESCRIPTION OF GUIDANCE AND YAW CONTROL INTERACTION

This is intended to provide enough background information on descent guidance and control to understand what follows. During lunar descent the guidance equations are processed in a "guidance coordinate frame" (see Fig. 1) which rotates with the moon and whose origin is, on each guidance pass, brought into coincidence with the current landing site produced by lunar rotation and landing site redesignations, if any. On a nominal descent, the XG, YG, ZG axes of the guidance coordinate frame are parallel to the XP, YP, ZP axes of the platform frame at the instant of touchdown, but this is true only at that instant because the guidance frame rotates with the moon and the platform frame does not. Figure 1, adapted from Ref. 2, shows the erection of the guidance coordinate frame. TTF is the current time relative to reaching the phase targets (the negative of the time to go) and GAINBRAK = 1 or GAINAPPR = 0 is selected according to phase. Thus during the approach phase the guidance coordinate frame is oriented about the vertical XG axis such that the YG axis is normal to the vertical plane defined by the line of sight to the landing site and the XG axis. The ZG axis is therefore horizontal and roughly forward along the direction of motion.

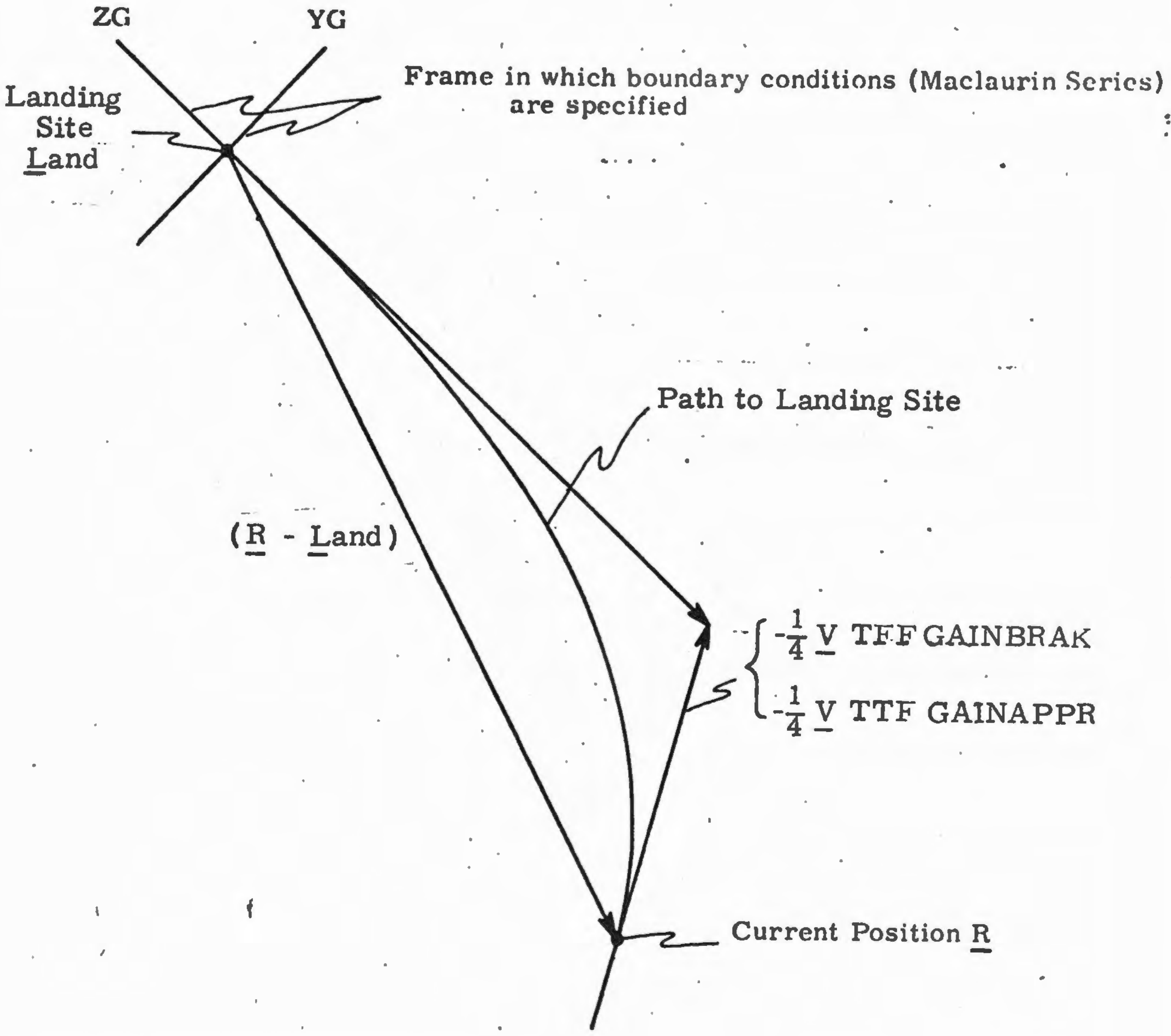


Fig. 1 : Plan View Showing Orientation of the Guidance Coordinate Frame.

The guidance equations produce a window pointing command vector $\underline{U}$NWC for the powered flight attitude maneuver routine FINDCDUW. For most of the approach phase, $\underline{U}$NWC is merely the line of sight vector to the landing site. The intention is to yaw the LM such that its plane of symmetry— defined by the ZB, XB LM body axes - contains the vector $\underline{U}$NWC. With $\underline{U}$NWC being the line of sight vector, the landing site will be superimposed upon the LPD reticle. Line-of-sight yaw control works well provided the line of sight is separated from the XB axis by a sufficient angle. Figure 2, adapted from Ref. 2, shows why line-of-sight yaw control cannot be used all the way to the landing site. As the line of sight approaches the XB axis, yaw control becomes indeterminate, and an alternate window pointing command vector must be used. The alternate used is the guidance coordinate frame ZG axis. The criterion for switching between the line-of-sight vector and the ZG axis need not be explained in detail here (see Ref. 2), but for a landing which is approximately planar, the line of sight vector is used exclusively until the LPD angle reaches 65°, the ZG axis is used exclusively beyond 75°, and between 65° and 75° the two vectors are mixed as a linear function of the cosine of the LPD angle.

In a nominal automatic landing, the transition between window pointing command vectors starts about 5 seconds before the end of P64, and will just about be complete on the final P64 pass. Thus the landing site will be kept on the LPD reticle until it disappears out the bottom of the window, and then the LM will yaw slightly to aline the reticle in the direction of the ZG axis. The yaw motion produced by the final P64 command will normally persist into the second pass of P66.

Guidance commands to the powered flight attitude maneuver routine FINDCDUW consist of a thrust pointing command vector $\underline{U}$NFC and the window pointing command vector $\underline{U}$NWC. Using these two vectors FINDCDUW erects a commanded body axis coordinate frame twice, as shown in Fig. 3, adapted from Ref. 3. The first iteration satisfies the geometry constraints exactly but fails to account for the angular displacement between the thrust vector and the true X body axis. The second iteration corrects for this thrust offset and introduces a small error in window pointing. This window pointing error, defined as the angle between the ZCB XCB plane and the line of sight vector, is the product of the sine of the LPD angle and the thrust offset angle about the ZCB axis. Consequently the window pointing error ranges from zero when the LPD angle is zero, to the thrust offset about Z (whose maximum is under 1°) when the LPD angle is 90°. FINDCDUW does not correct this error.

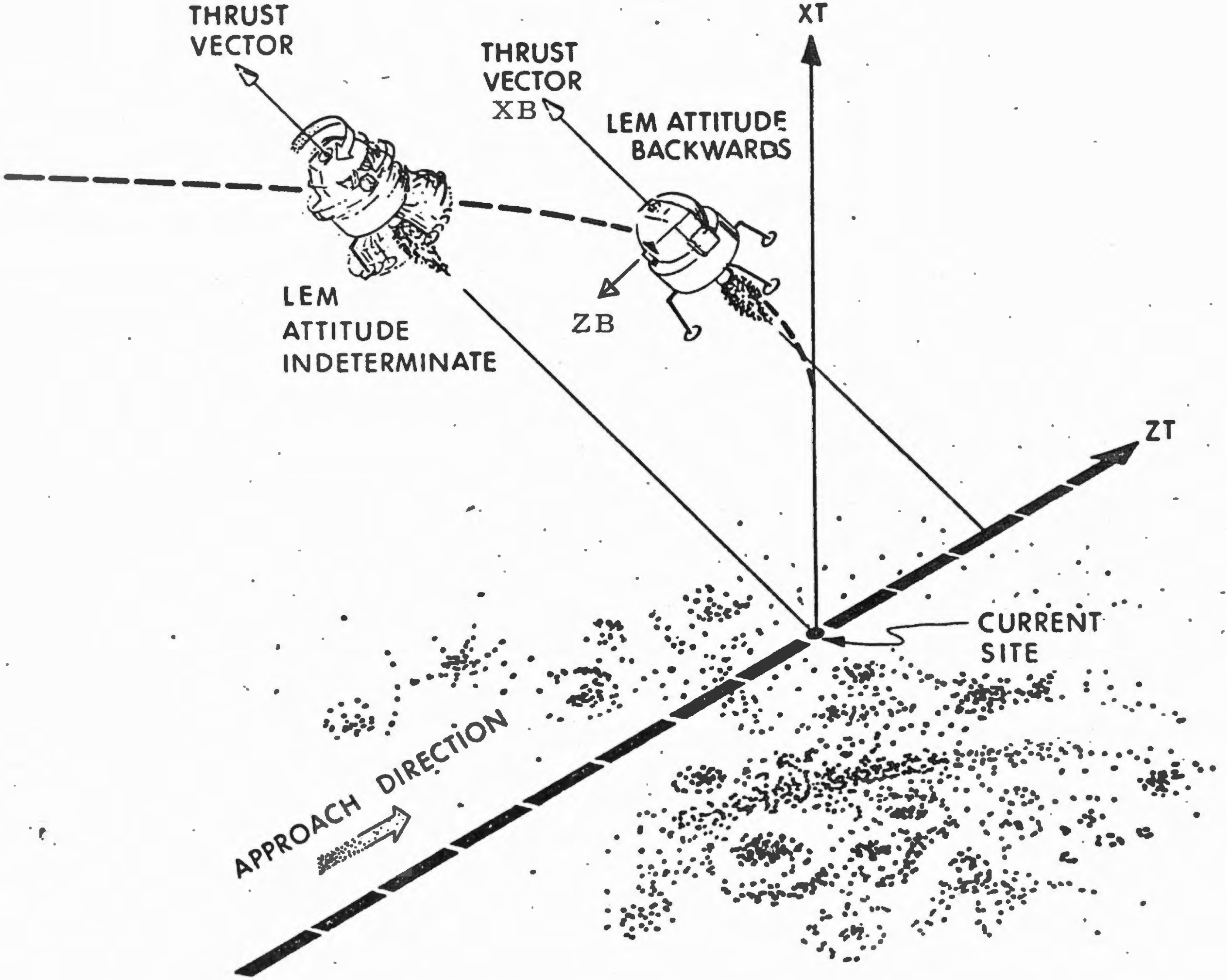
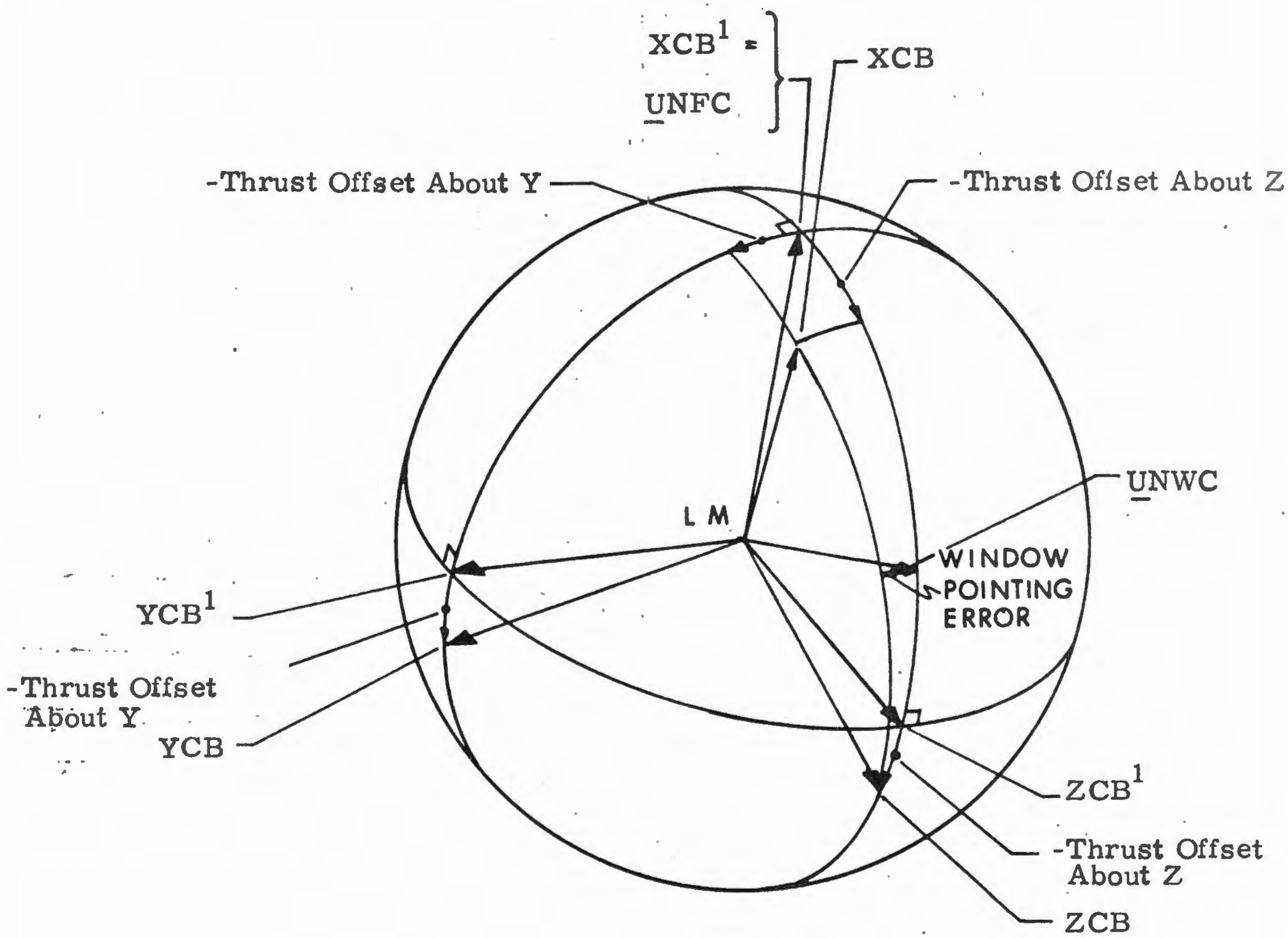


Fig. 2 Why Keeping the Landing Site in the Center of Vision cannot be the Sole Criterion for Controlling Attitude about the Thrust Axis.



NOTE: Commanded body axes are computed in two steps. Vectors computed the first step are identified by the superscript 1. Final values have no superscripts.

Fig. 3 Geometry of Erection of Commanded Body Axes Viewed on a LM Centered Unit Sphere.

Using the commanded body axis coordinate frame of Fig. 3, FINDCDUW computes corresponding commanded gimbal angles to bring the actual body coordinate frame into coincidence with commanded frame. FINDCDUW issues to the digital autopilot gimbal-angle-increment commands that the autopilot uses to increment the desired gimbal angles every tenth of a second during the succeeding two seconds. At the end of the two second period the autopilot's desired gimbal angles coincide with FINDCDUW's commanded gimbal angles of the beginning of the two second period, and FINDCDUW updates the gimbal-angle-increment commands from new information. The digital autopilot closes the attitude control loop driving the actual gimbal angles into close proximity with its desired gimbal angles.

One statement of the preceding memo (Ref. 1) was not correct. The sudden increase in the yaw rate a few seconds prior to P64 was not caused by switching from line-of-sight window pointing to ZG-axis window pointing. The simultaneity of the break point in the yaw profile with the 65° LPD angle was coincidental not causal. The roll angle in the simulation described was caused by thrust offset rather than by an out-of-plane thrust pointing command vector. Because FINDCDUW does not correct yaw for thrust offset, the yaw attitude was not being suppressed by the roll attitude prior to attaining 65° LPD angle as erroneously reported in Ref. 1.

SOURCES OF YAW DIVERGENCE

Four sources of yaw divergence have been found:

1. Out-of-plane velocity due to initial condition dispersions and accelerometer bias eventually detected by the landing radar, or due to azimuth landing site redesignation. This produces a non-planar approach phase trajectory as illustrated in Fig. 1, and the yaw angle acquired is not erroneous but is a normal and desirable feature of a non-planar approach. In the run analyzed, the Y velocity in guidance coordinates at the start of the approach phase was .31 m/s to the right and the guidance frame was rotated 4 mr about the vertical.

2. Truncation of the landing site update by the descent guidance equations. (This source was discovered by Lowell Hull, Ref. 4.) Every guidance pass the landing site is updated in platform coordinates by the equation

$$\underline{\text{LAND}} = \underline{\text{LAND}}\ \text{UNIT}\,(\underline{\text{LAND}} + \underline{\text{W}}\text{M} \times \underline{\text{LAND}}\ \Delta t)$$

where $\underline{\text{W}}\text{M}$ is the lunar angular rate vector and Δt is the guidance period. With an approach azimuth north of west, the landing site is updated to the right each guidance pass. The updating is truncated to an integer 1/8 m, consequently on every guidance pass there is an apparent landing site redesignation to the left of up to 1/8 m. For a given latitude, the magnitude of this truncation error is a sawtooth function of the cosine of the approach azimuth (defined to the east of north) as illustrated in Fig. 4. The approach azimuth of the Apollo 14 trajectory is 283.7° and produces a truncation error every two seconds of -.059 m, about half of the maximum. With these repeated apparent landing site redesignations to the left, the LM will yaw increasingly to the left, and, regardless of how small the redesignation is, the yaw increment will increase each guidance pass and become unbounded as the LM flies over the site. Of course, P66 begins automatically before this can happen.

3. The digital autopilot is incapable of attaining zero roll error. Consequently any roll error (about the ZB axis) will produce an out-of-plane acceleration error, rotation of the guidance coordinate frame about the vertical, and rotation of the LM in yaw. In simulations, this error has been found small compared to the previous two.

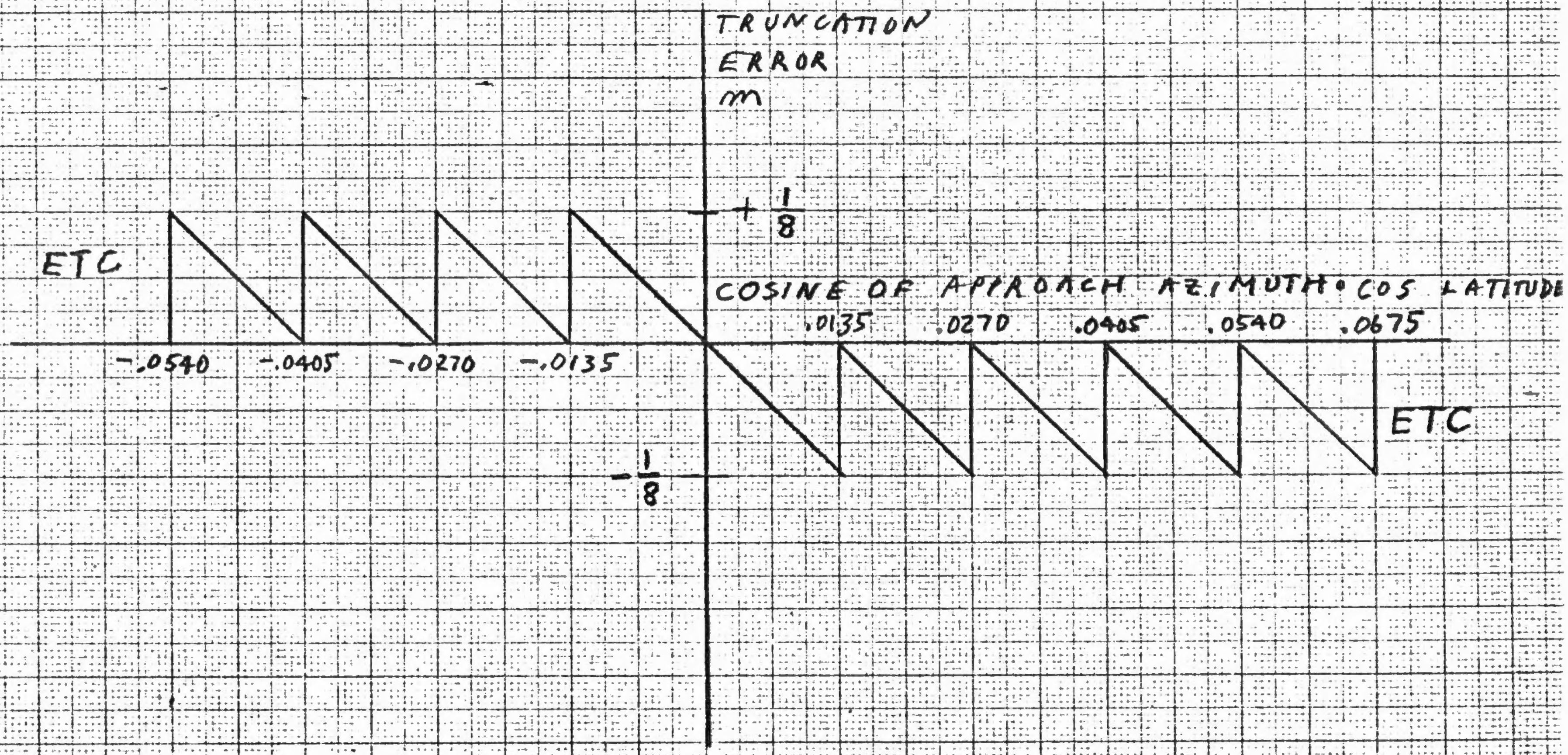
4. A mistake was made twice in the LGC program computations erecting the guidance coordinate frame. (See Ref. 5.) The net result of these mistakes is that, with Apollo 14 erasables, on the final pass of P64 the LGC uses .246155 for GAINAPPR instead of 0. This means that the orientation of the guidance coordinate frame is based on the out-of-plane velocity on the final P64 pass, a violation of the intended procedure. We are favored by chance that this gain constant is small compared to unity.

SIMULATION RESULTS

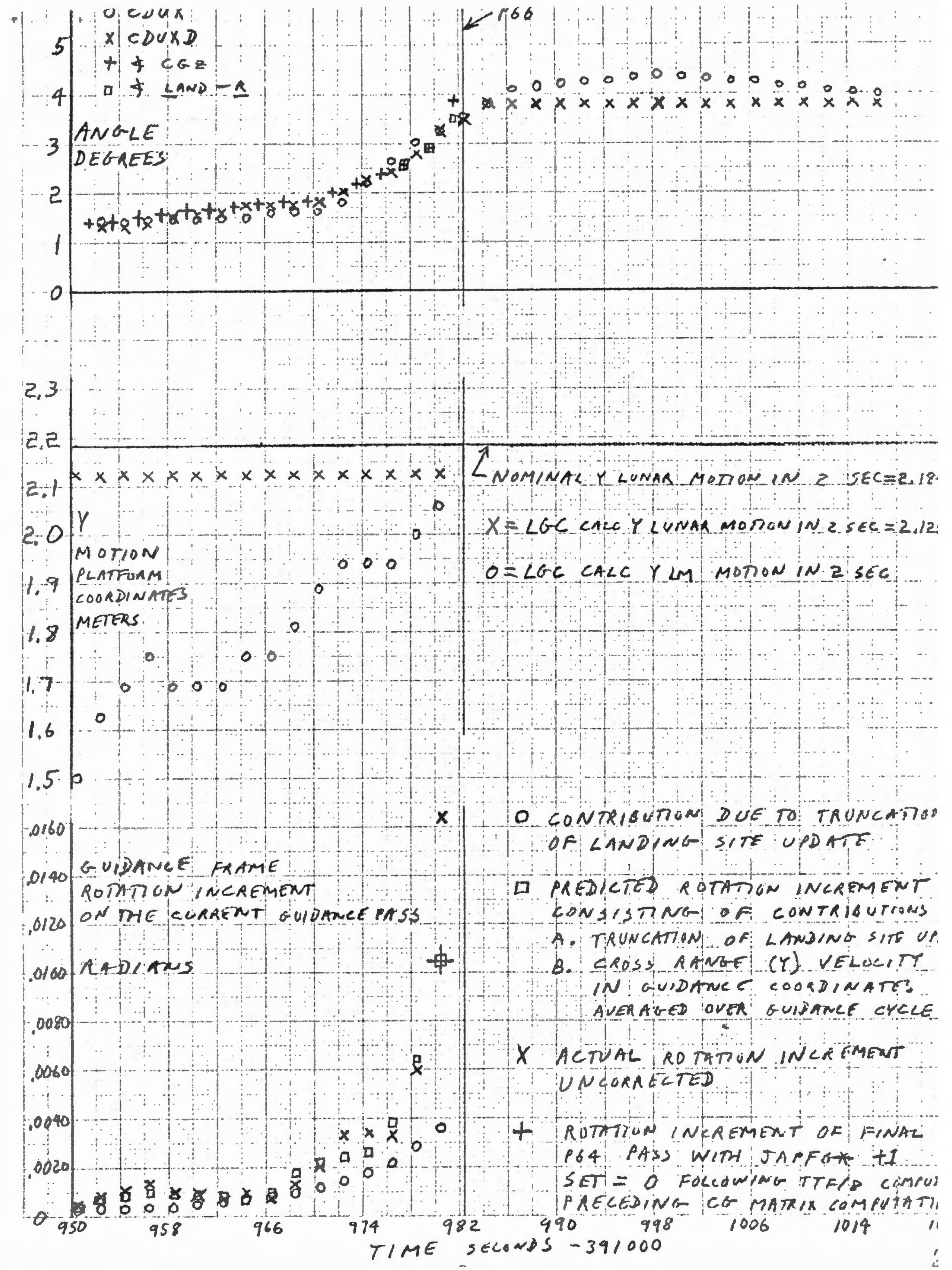
Simulation results have been analyzed to determine whether or not the sources cited explain all of the yaw observed, and we believe they do. Figure 5, illustrating these results, contains three parts. The upper part shows that the yaw angle and the azimuth angle of the guidance coordinate frame follow very closely, as to be expected. The second part of Fig. 5 shows that the landing site does move precisely 2.125 m each 2 seconds, as predicted. The LM motion is also plotted, and it converges on the landing site motion, as expected.

CLEARPRINT CHARTS

FOR LANDING SITE RADIUS = 1 738 090



LANDING SITE TRUNCATION ERROR IN THE Y PLATFORM DIRECTION PER GUIDANCE CYCLE



NOMINAL Y LUNAR MOTION IN 2 SEC=2.18

X=LGC CALC Y LUNAR MOTION IN 2 SEC=2.12

O=LGC CALC Y LM MOTION IN 2 SEC

O CONTRIBUTION DUE TO TRUNCATIO
OF LANDING SITE UPDATE

□ PREDICTED ROTATION INCREMENT
CONSISTING OF CONTRIBUTIONS
A. TRUNCATION OF LANDING SITE UP
B. CROSS RANGE (Y) VELOCITY
IN GUIDANCE COORDINATES
AVERAGED OVER GUIDANCE CYCLE

X ACTUAL ROTATION INCREMENT
UNCORRECTED

+ ROTATION INCREMENT OF FINAL
P64 PASS WITH JAPF~~G*~~ +1
SET = 0 FOLLOWING TTF/8 COMPU
PRECEDING CG MATRIX COMPUTATI

The most interesting revelation of Fig. 5 is the bottom plot which shows the rotation increment of the guidance coordinate frame on each guidance cycle (X) as compared to a predicted rotation increment (□). The rotation increment is within 1 mr of the prediction every pass except the last P64 pass when the discrepancy is about 6 mr. The discrepancy on this final pass is due entirely to the mistakes in the LGC coding; when the LGC coding is patched to correct the effect of the mistakes, the discrepancy becomes zero, i. e. the prediction (□) coincides with the rotation increment (+).

This lower section of Fig. 5 also separates the individual contributions to guidance coordinate frame rotation. The circles display the rotation increment contributions due to landing site truncation, and the squares represent the combined effects of landing site truncation and cross-range velocity. In this simulation, the contributions are about equal except the cross-range velocity becomes dominant near the close of P64. The truncation contributions were computed by dividing the truncation error by the current range. The cross-range velocity contributions were computed by averaging the Y components of velocity in guidance coordinates at the start and finish of the current guidance cycle, multiplying by the 2 second guidance period, and dividing by the current range. The maximum prediction error, (X) - (□), is under 1 mr and corresponds to under 1 bit error in position.

The final Figs, 6A thru 12C, display the yaw response to seven redesignation situations for each of three program configurations. The redesignation situations are defined on the figures and the three program configurations are as follows:

A. The LGC is patched to cause the apparent GAINAPPR to be close to unity on the final P64 pass. This aggravates the program mistake to the maximum extent. This was done in such a way as to avoid any other effect on the run. For those who are familiar with LGC coding, this effect was achieved by replacing JAPFG* +1 by POSMAX <u>after its final use in computing TTF/8.</u>

B. Displays unmodified Apollo 14 behavior.

C. The LGC erasables are modified to prevent guidance coordinate frame erection the final two passes of P64. This is done by loading TCGFBRAK with 77776 and TCGFAPPR with 1D 14 E+02 B-17 = 1O 00257.

The dots of Figures 6A thru 12C represent the autopilot's desired yaw gimbal angle CDUXD at two second intervals. These figures show that the maximum spurious yaw produced by the mistakes in the program using either the Apollo 14 erasables or unity apparent GAINAPPR was about 5°. However, the behavior under the three configurations was markedly different in every case, and the behavior was generally worst with unity apparent GAINAPPR.

HALVING THE MAXIMUM LANDING SITE TRUNCATION ERROR

It appears that the maximum truncation error could be cut in half by doubling the magnitude of the landing site radius (LAND) before multiplying by the semi unit vector in the direction of the updated landing site. This would have to be done two places; in the computations following TTFINCR and in those following REDES1. In addition it would have to be demonstrated that the redesignation equations could never contribute to the truncation error when no redesignation was made, or else, if this could not be demonstrated, the redesignation equations could be skipped in cases of zero redesignation.

Considering that the yaw bias seems to work out at about 2° for Apollo 14 with a .059 m truncation error per pass, the maximum truncation error of .125 m would probably produce about 4° yaw bias. Is fixing the program worth the effort?

CONCLUSIONS

The mistakes found in the program should certainly be corrected for Apollo 15 as there is no guarantee we will be as lucky with erasables as we are on Apollo 14. Guidance frame erection on the final pass of P64 could be avoided on Apollo 14 or 15 by reloading TCGFBRAK with 77776, and there would be no other consequence. However, with the Apollo 14 erasables, the consequences of doing nothing are benign and that is our recommendation. The maximum landing site truncation error could be halved by the minor program change suggested herein, but it is doubtful that even this would be worth the effort. All other known sources of yaw rotation are normal.

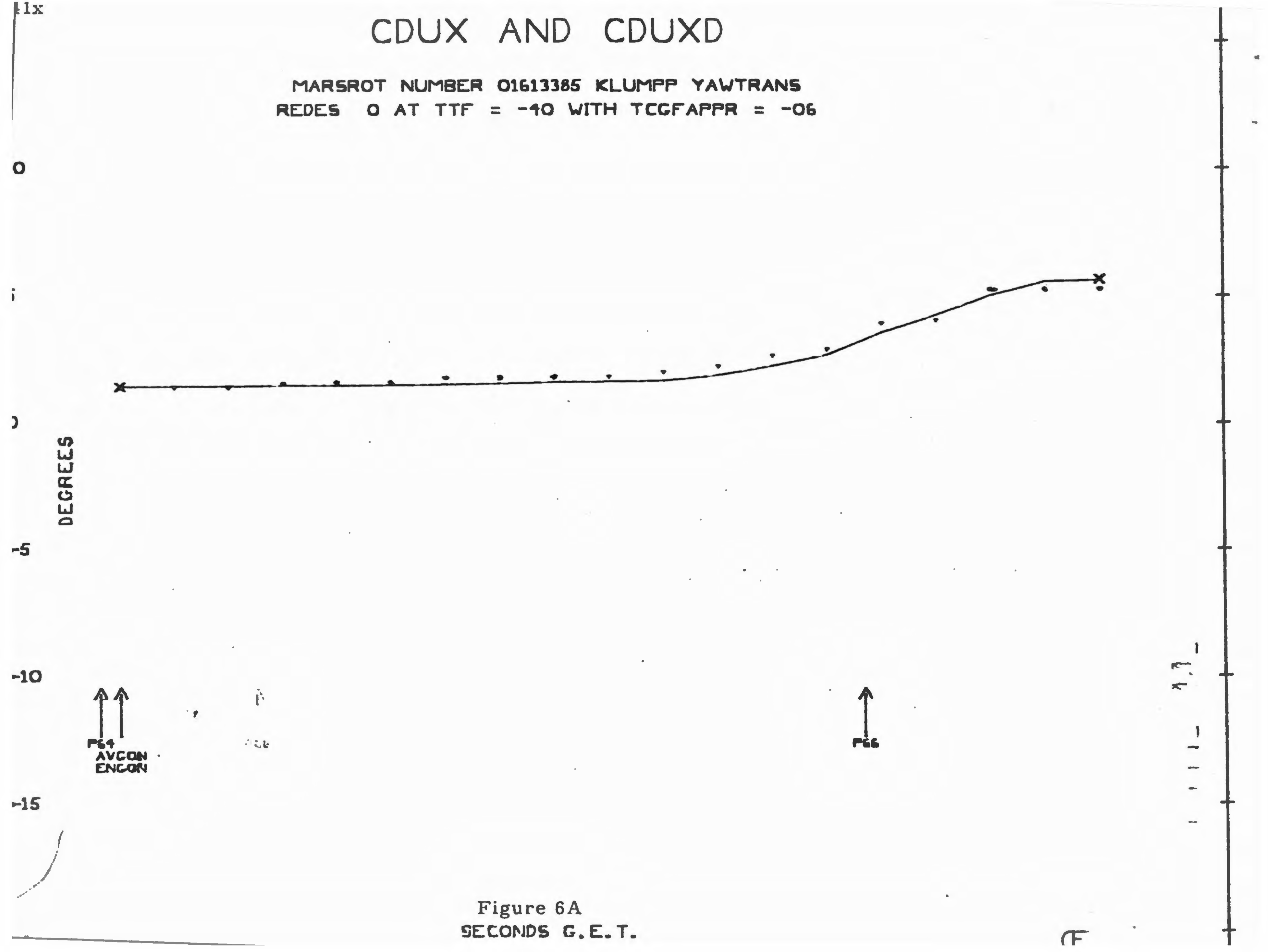

1x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES 0 AT TTF = -40 WITH TCGFAPPR = -06
0
0
-5
-10
-15
DEGREES
P64
AVCON
ENGON
P66
SECONDS G.E.T.

Figure 6A

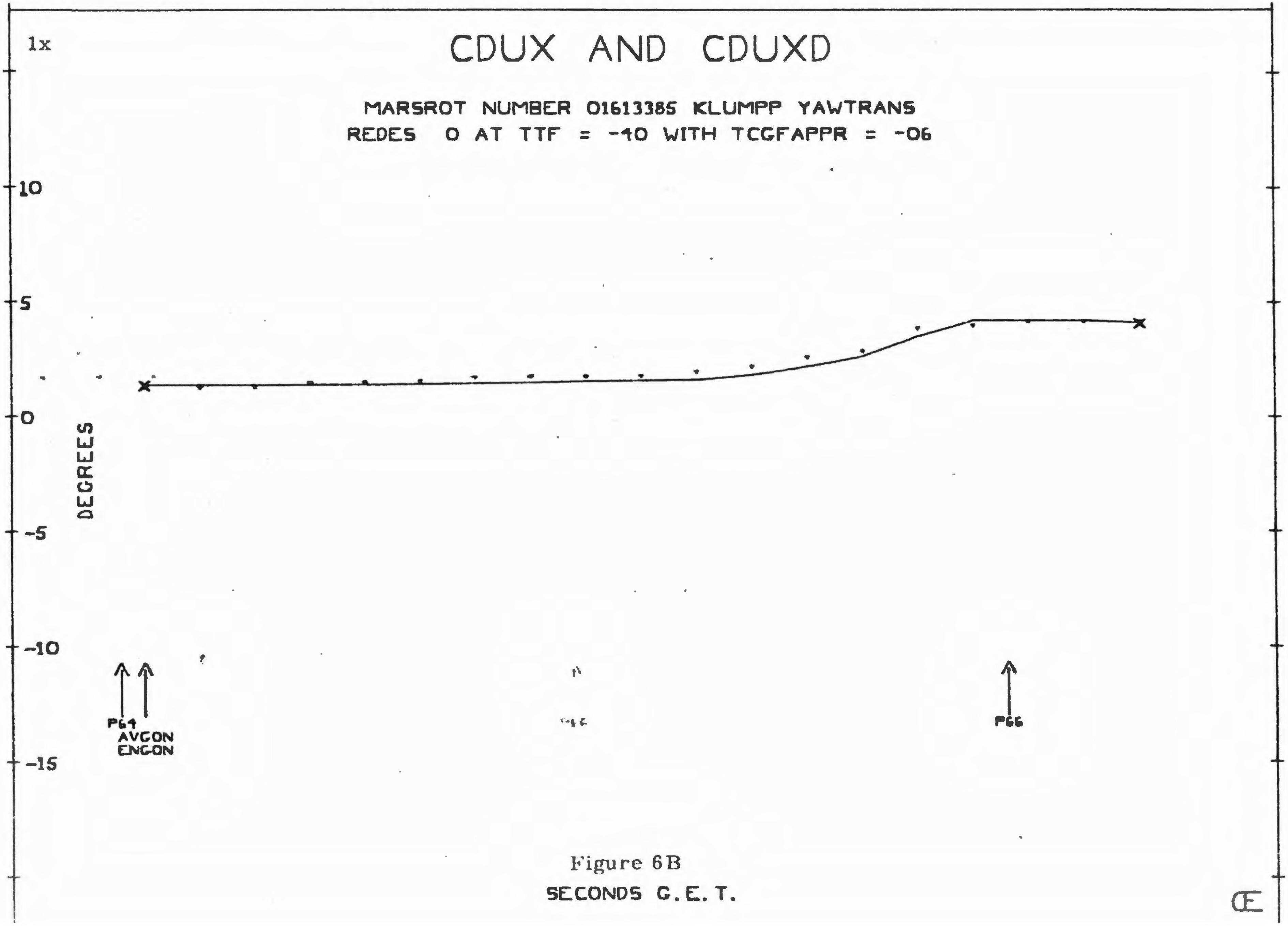

1x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES 0 AT TTF = -40 WITH TCGFAPPR = -06
10
5
0
-5
-10
-15
DEGREES
P64
AVCON
ENGON
P66
SECONDS G.E.T.

Figure 6B

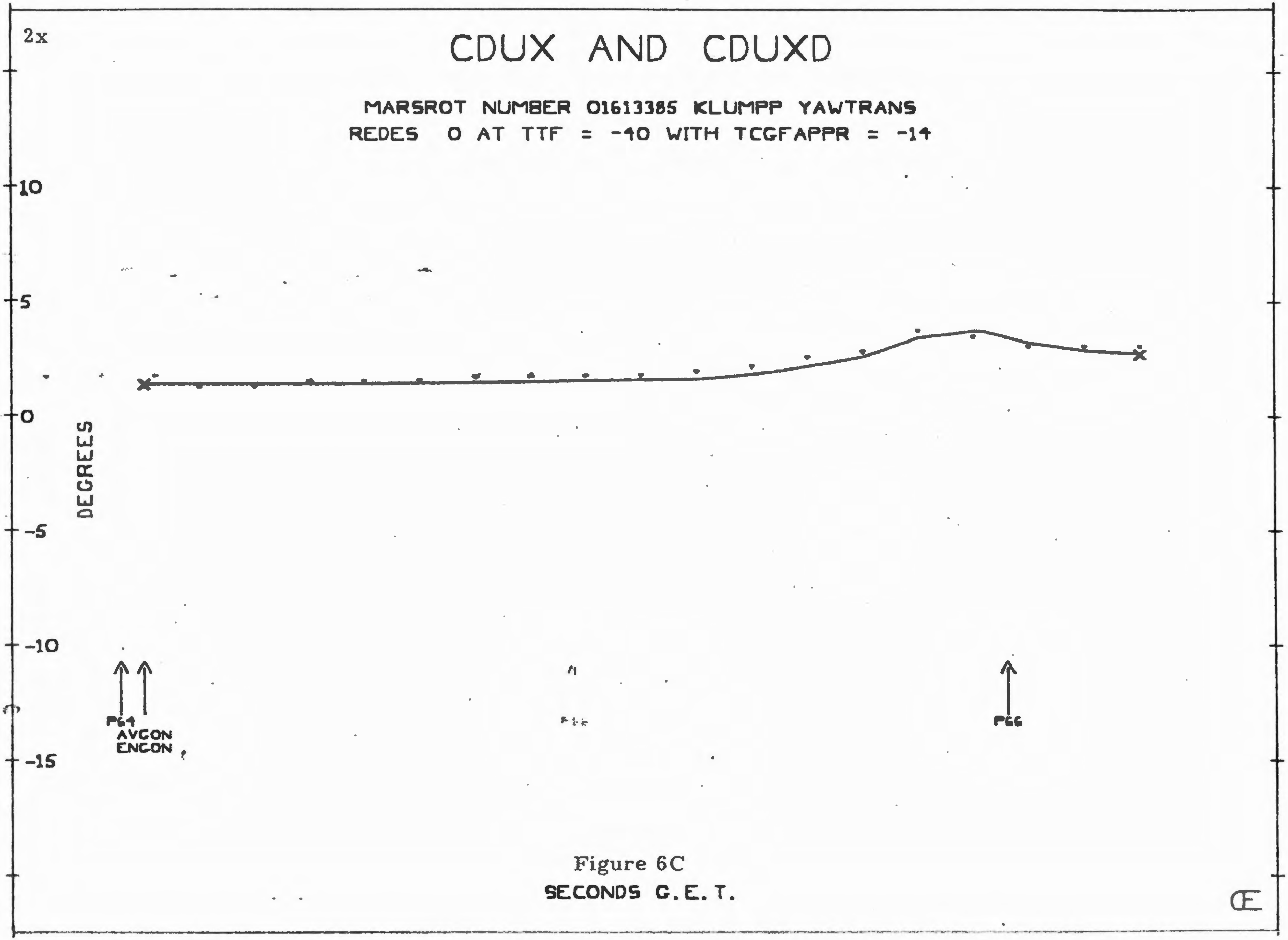
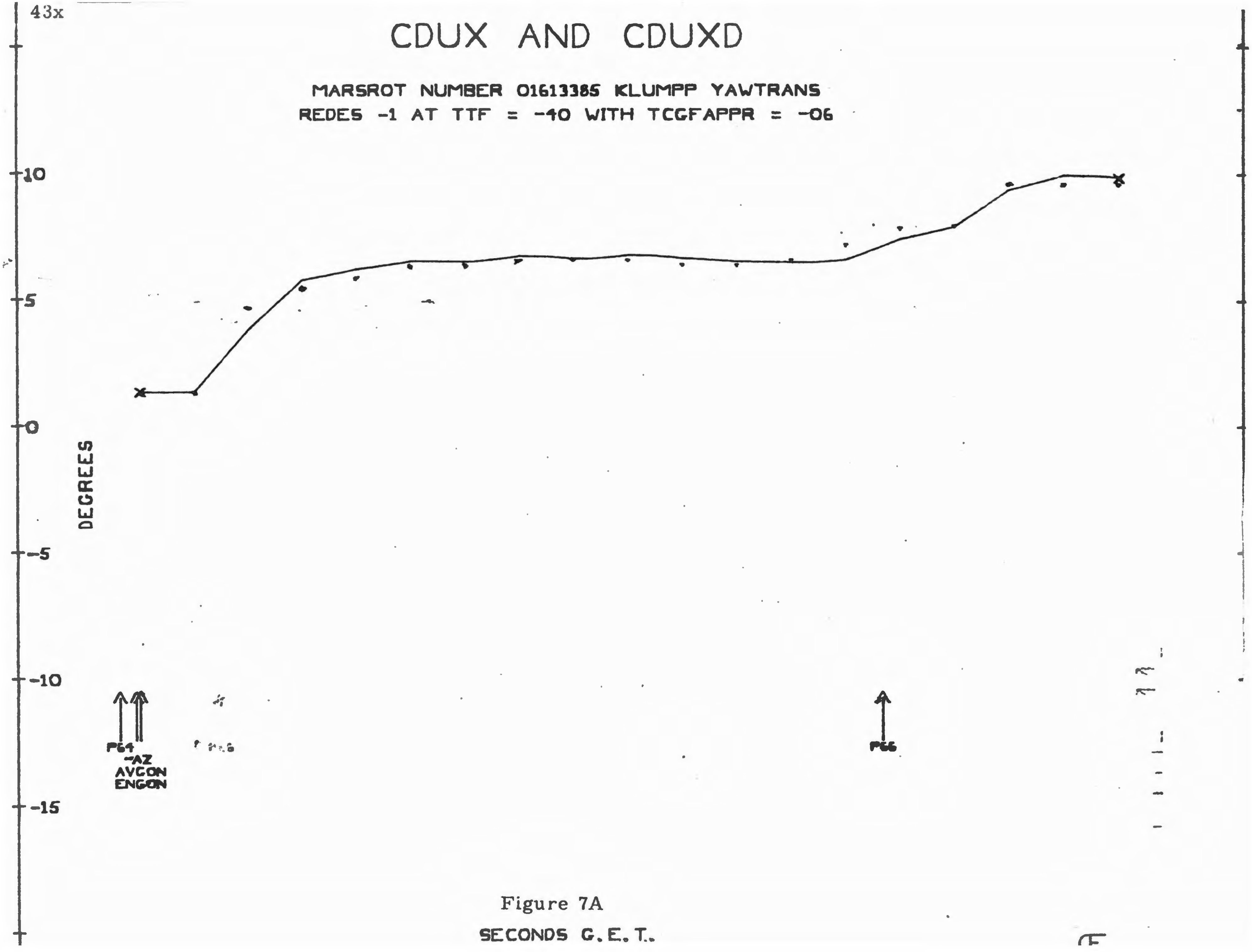

2x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES 0 AT TTF = -40 WITH TCGFAPPR = -14
10
5
0
-5
-10
-15
DEGREES
P64
AVCON
ENCON
P66
SECONDS G.E.T.

Figure 6C


CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -1 AT TTF = -40 WITH TCGFAPPR = -06
10
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0
-5
-10
-15
DEGREES
P64
-AZ
AVCON
ENGON
P66
SECONDS G.E.T.

Figure 7A

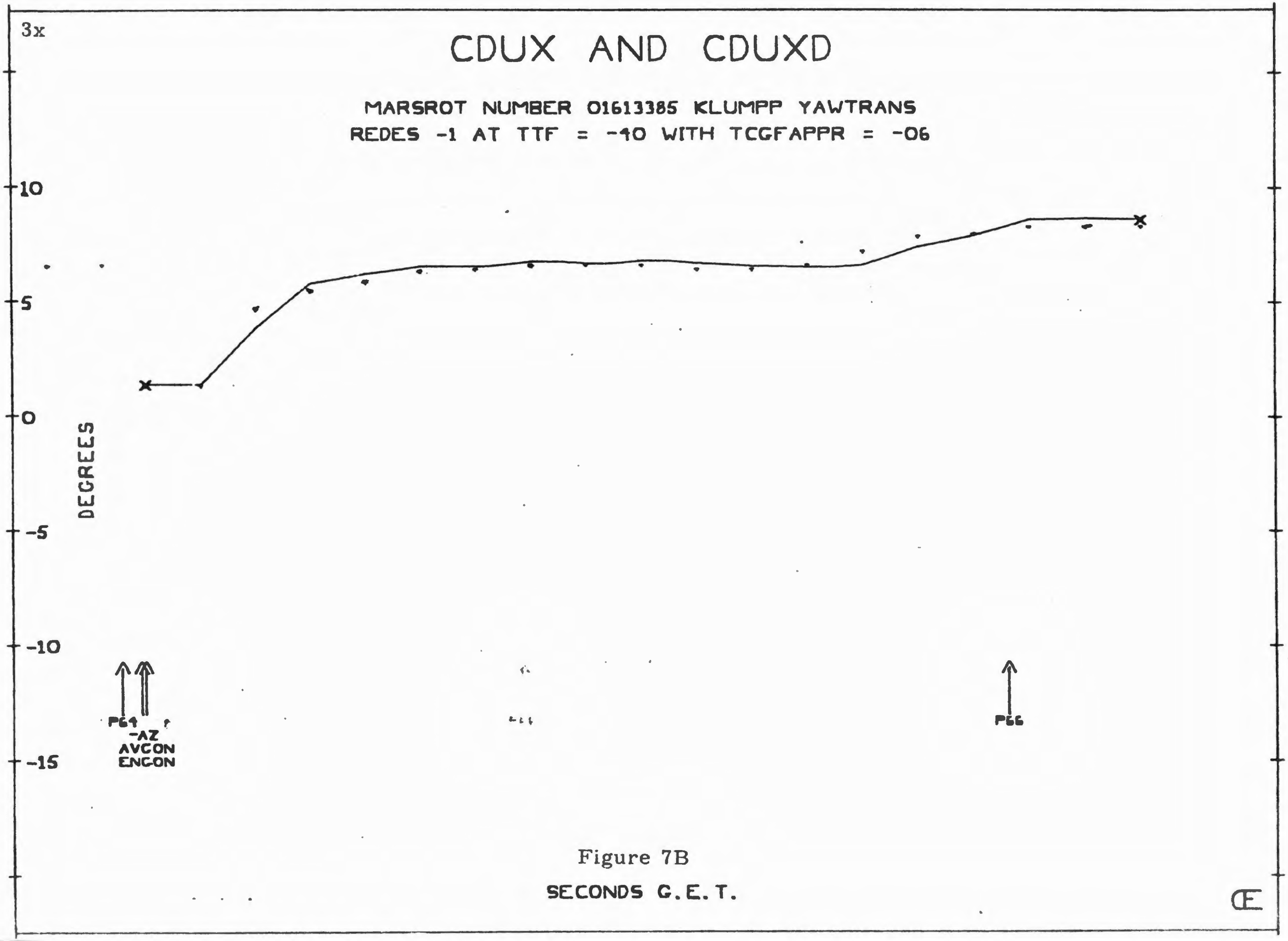
3x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -1 AT TTF = -40 WITH TCGFAPPR = -06
10
5
0
-5
-10
-15
DEGREES
P64
-AZ
AVCON
ENCON
P66
SECONDS G.E.T.

Figure 7B

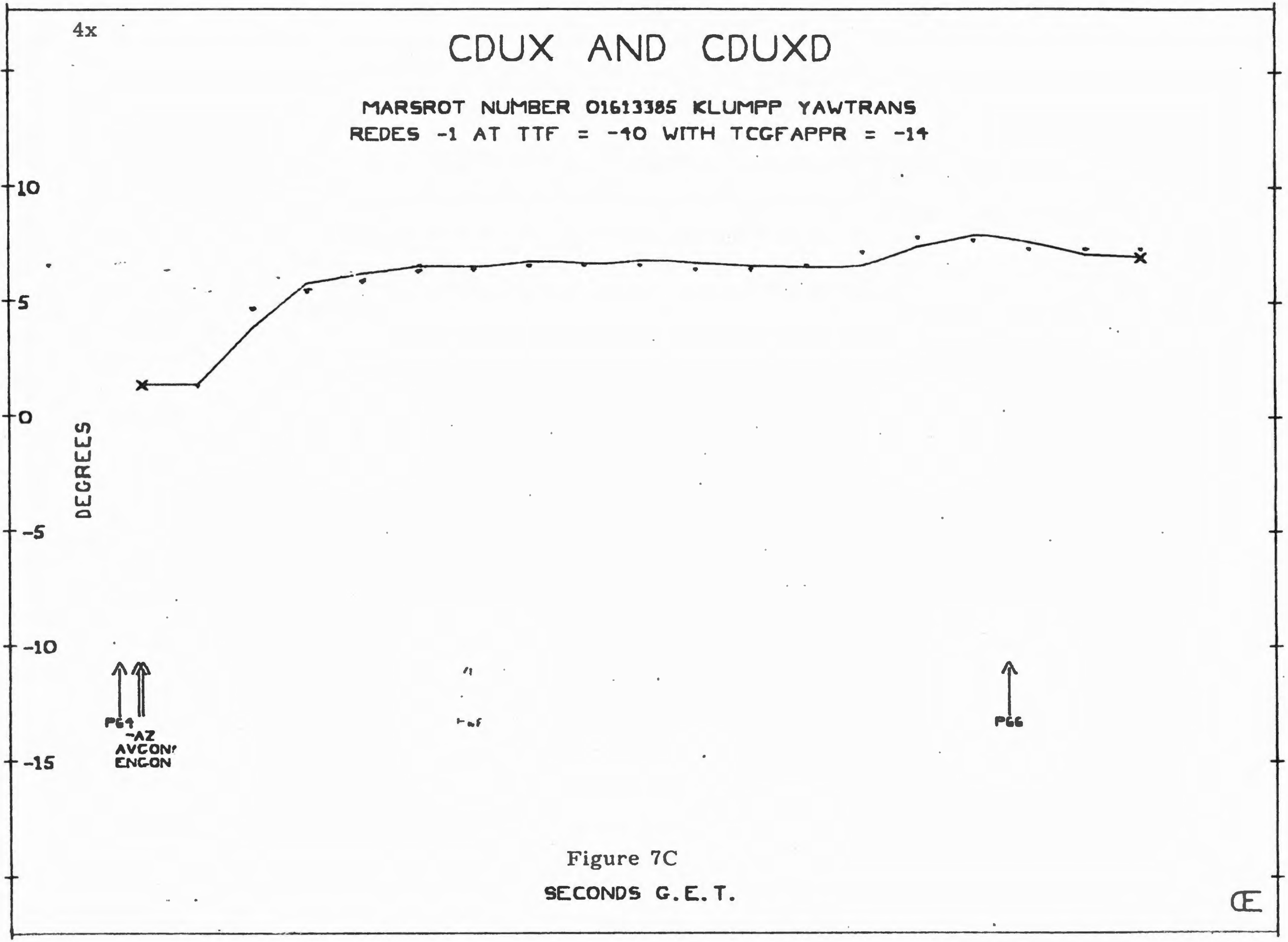
4x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -1 AT TTF = -40 WITH TCGFAPPR = -14
10
5
0
-5
-10
-15
DEGREES
P64
-AZ
AVCON
ENGON
P66
SECONDS G.E.T.
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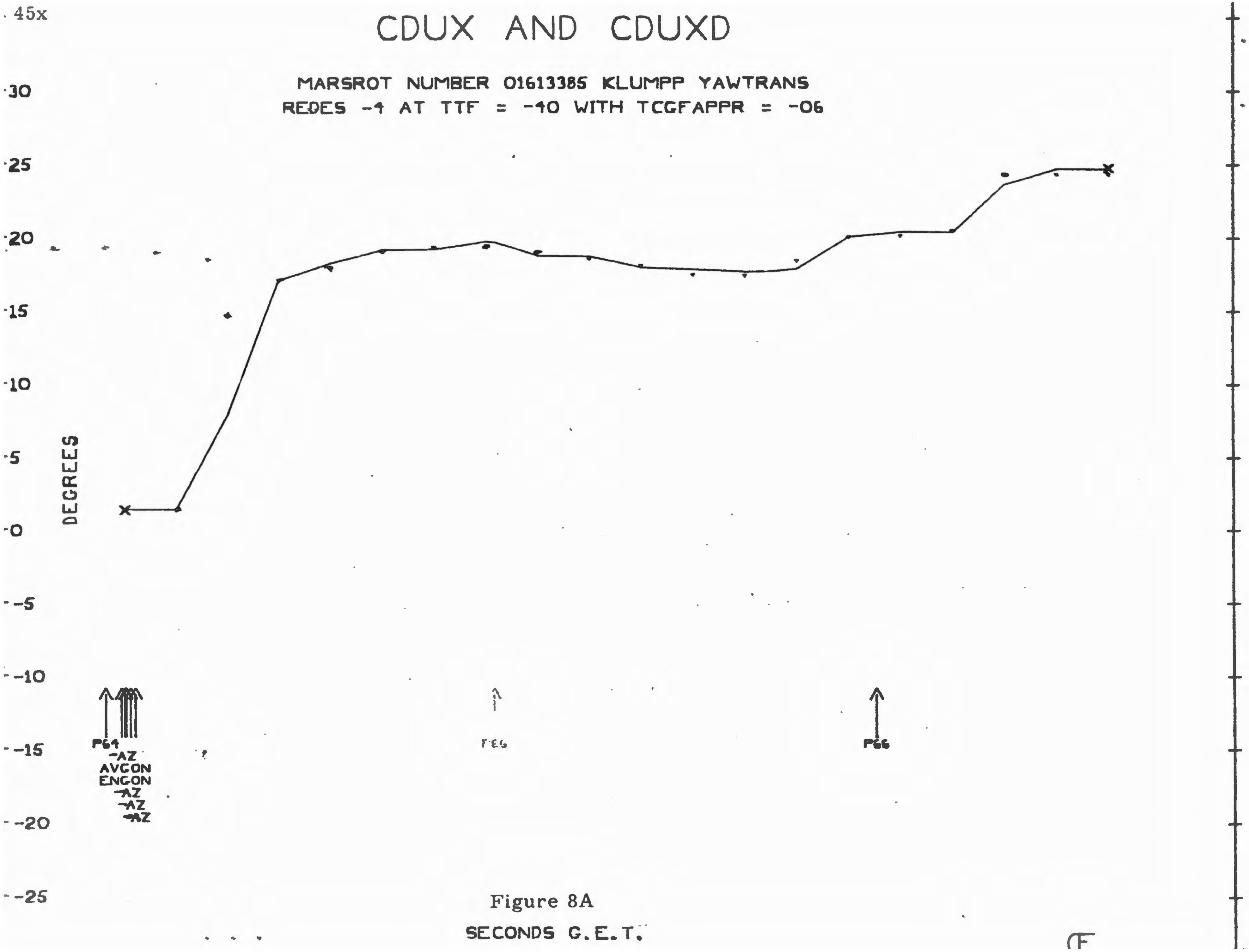
Figure 7C



CDUX AND CDUXD

MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -4 AT TTF = -40 WITH TCGFAPPR = -06

Figure 8A

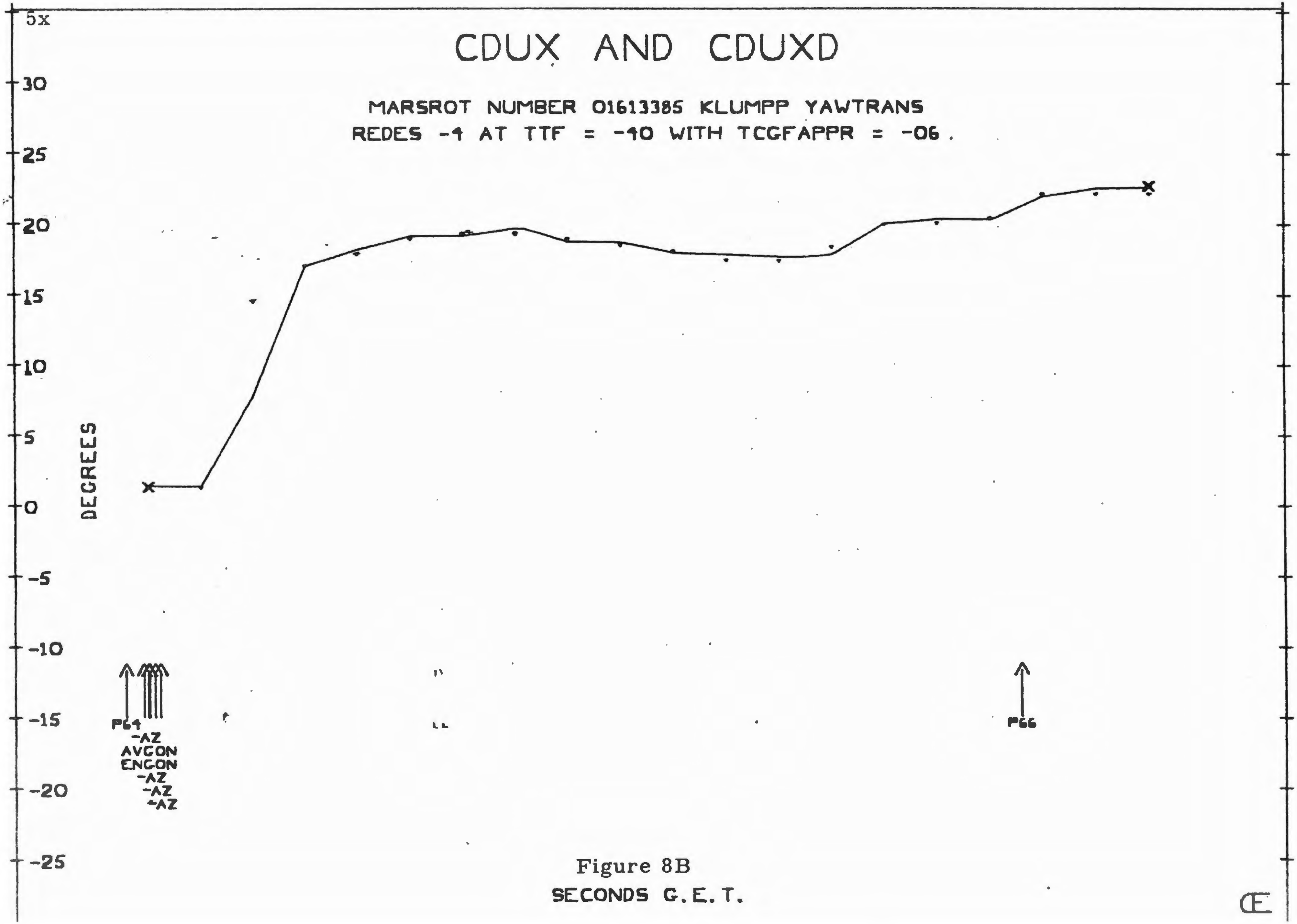
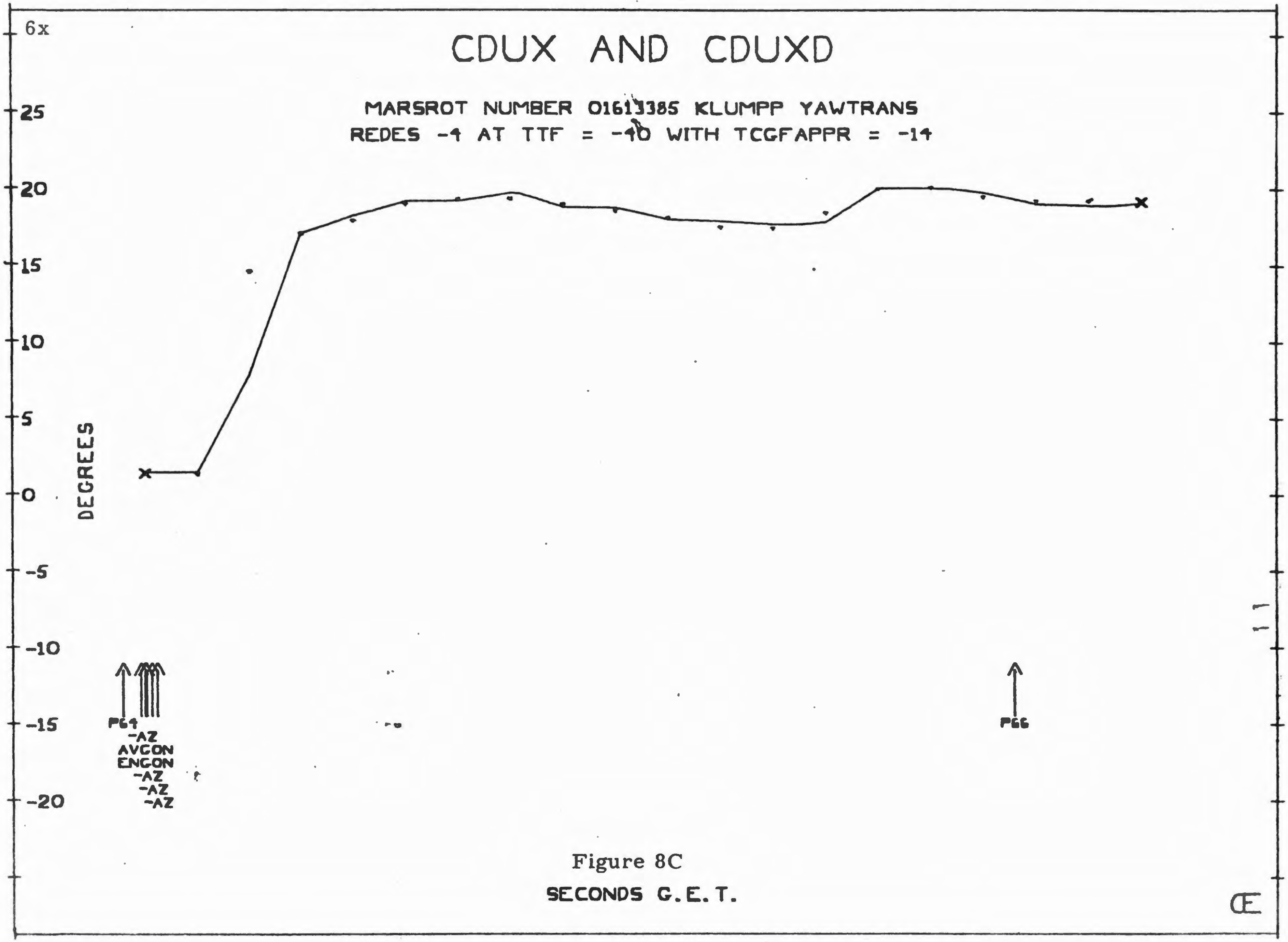
5x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -4 AT TTF = -40 WITH TCGFAPPR = -06.
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
DEGREES
P64
-AZ
AVGON
ENGON
-AZ
-AZ
-AZ
P66
SECONDS G.E.T.

Figure 8B


6x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -4 AT TTF = -10 WITH TCGFAPPR = -14
25
20
15
10
5
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-5
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DEGREES
P64
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SECONDS G.E.T.
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Figure 8C

47x

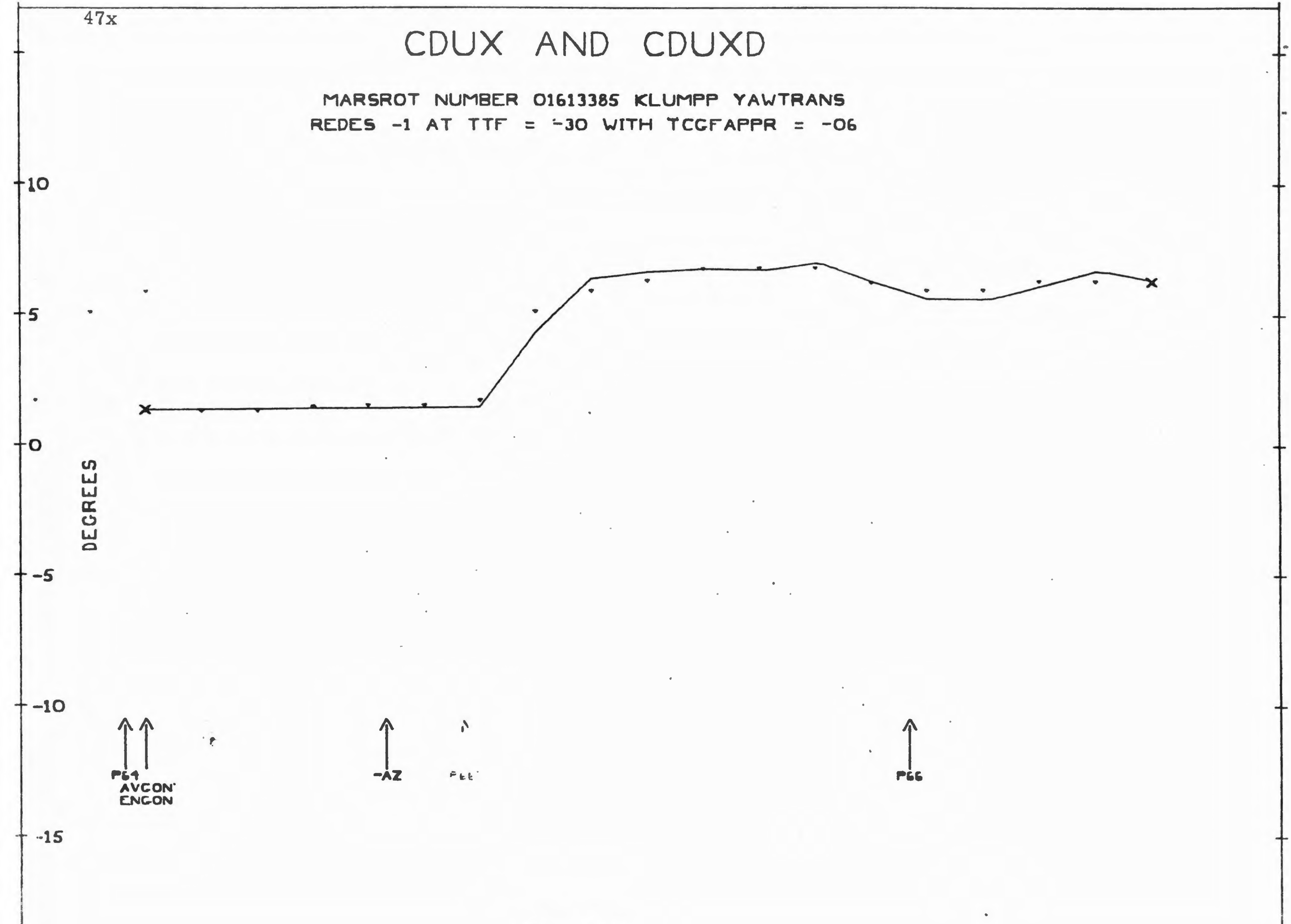
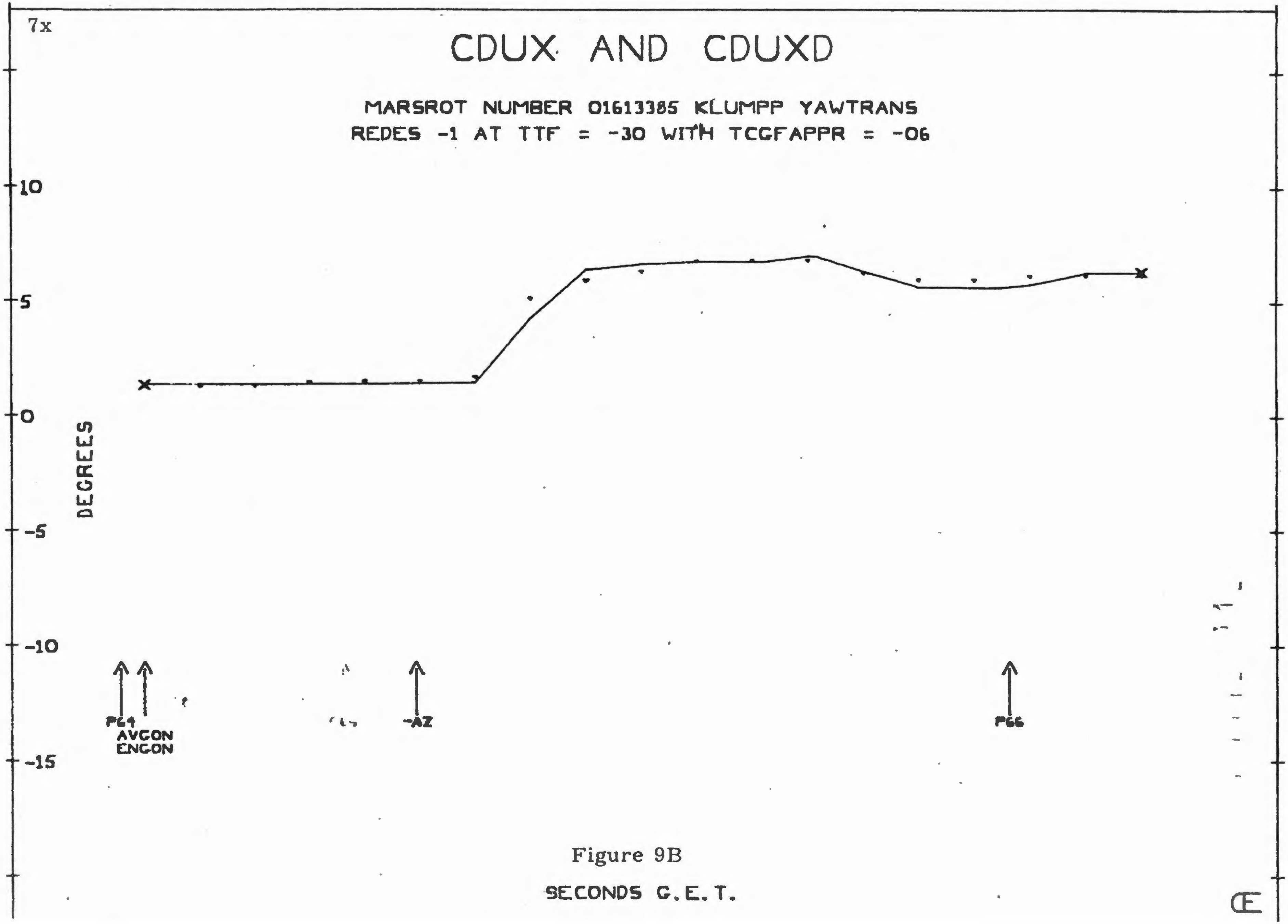


Figure 9A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CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
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-15
DEGREES
P64
AVCON
ENGON
-AZ
P66
SECONDS G.E.T.
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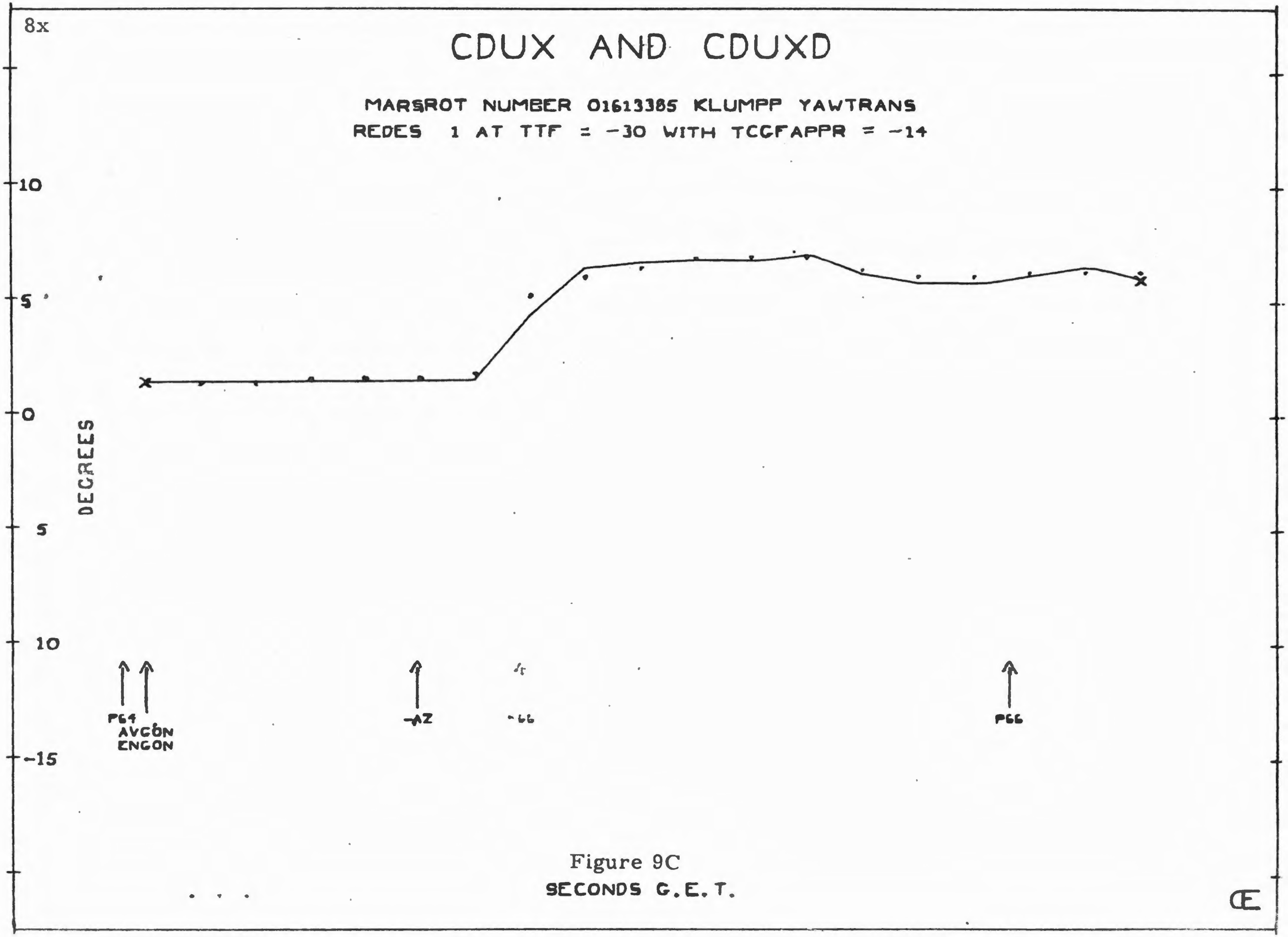
Figure 9B


8x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES 1 AT TTF = -30 WITH TCGFAPPR = -14
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P64
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-AZ
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P66
SECONDS G.E.T.
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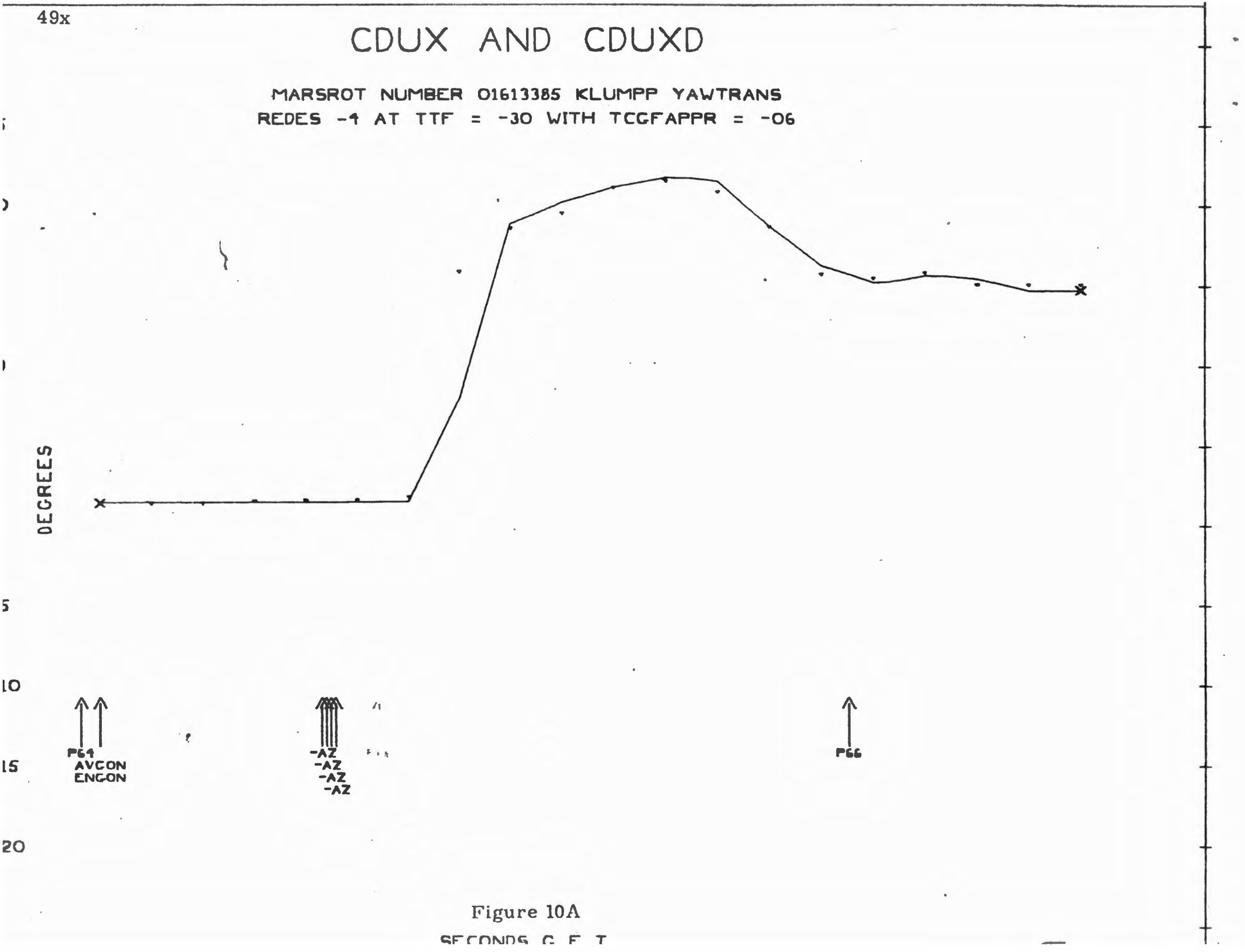
Figure 9C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REDES -4 AT TTF = -30 WITH TCGFAPPR = -06
DEGREES
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P64
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ENGON
-AZ
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P66
SECONDS G.E.T.

Figure 10A

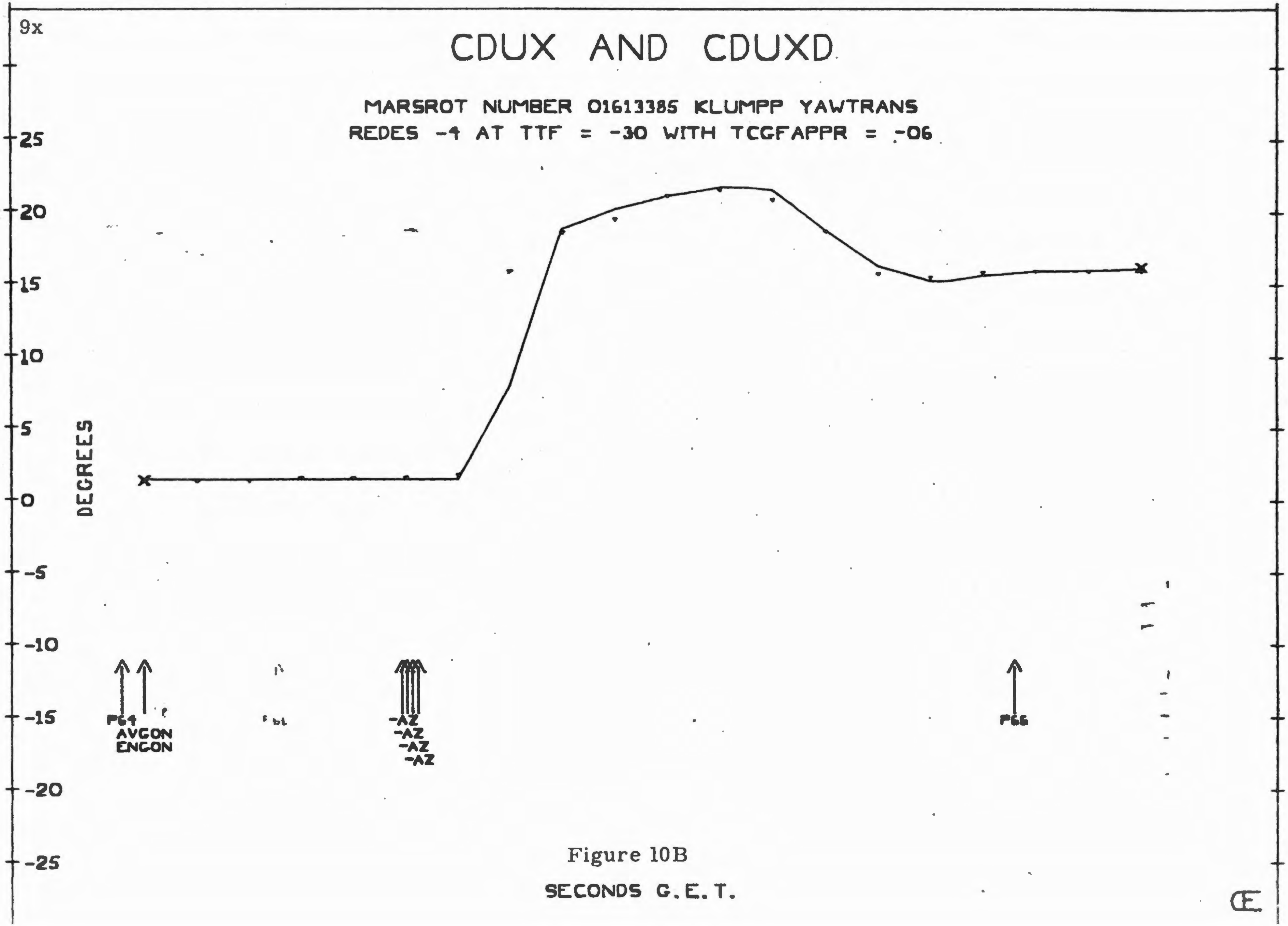
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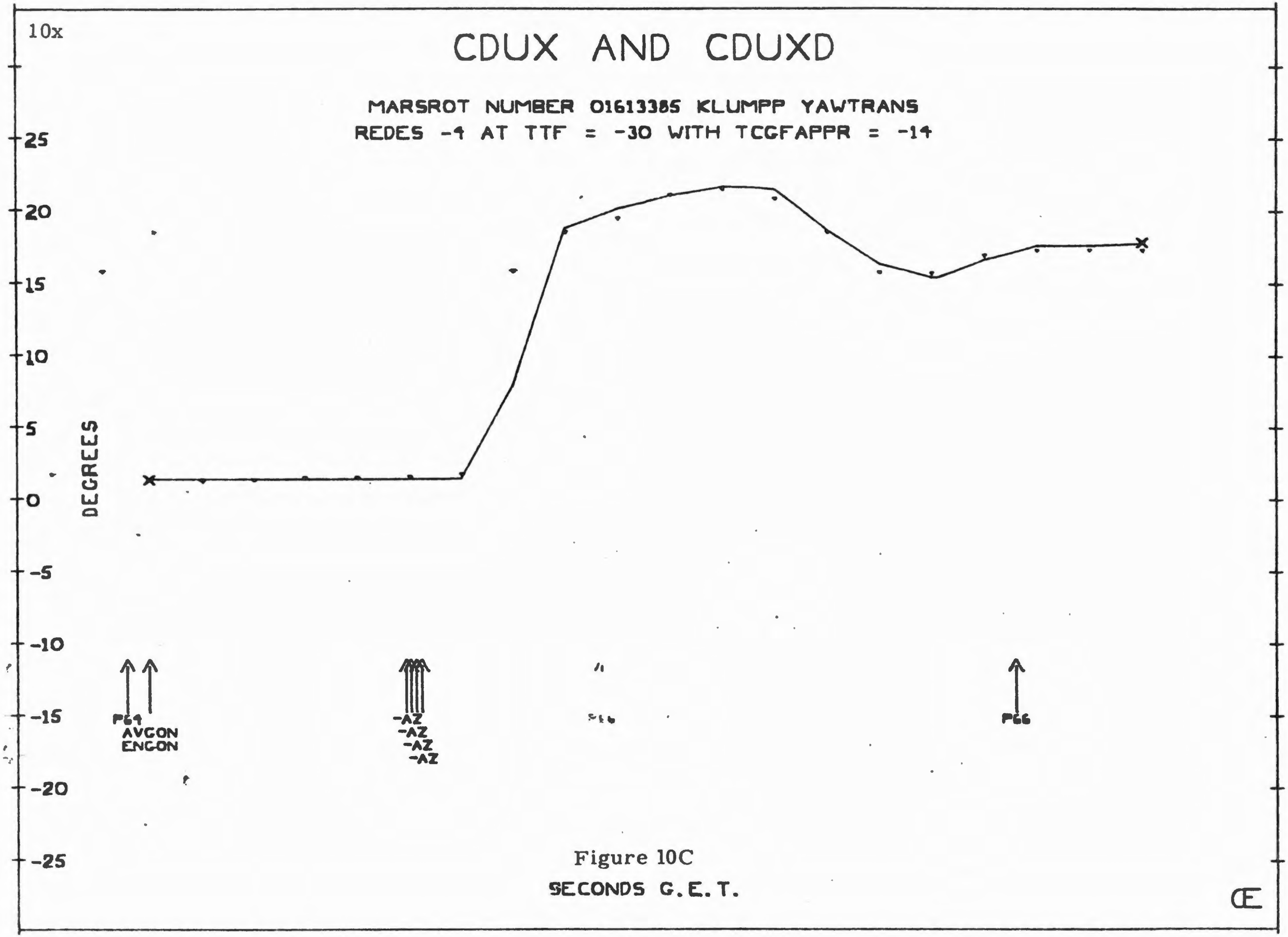
Figure 10B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CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
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P66
SECONDS G.E.T.
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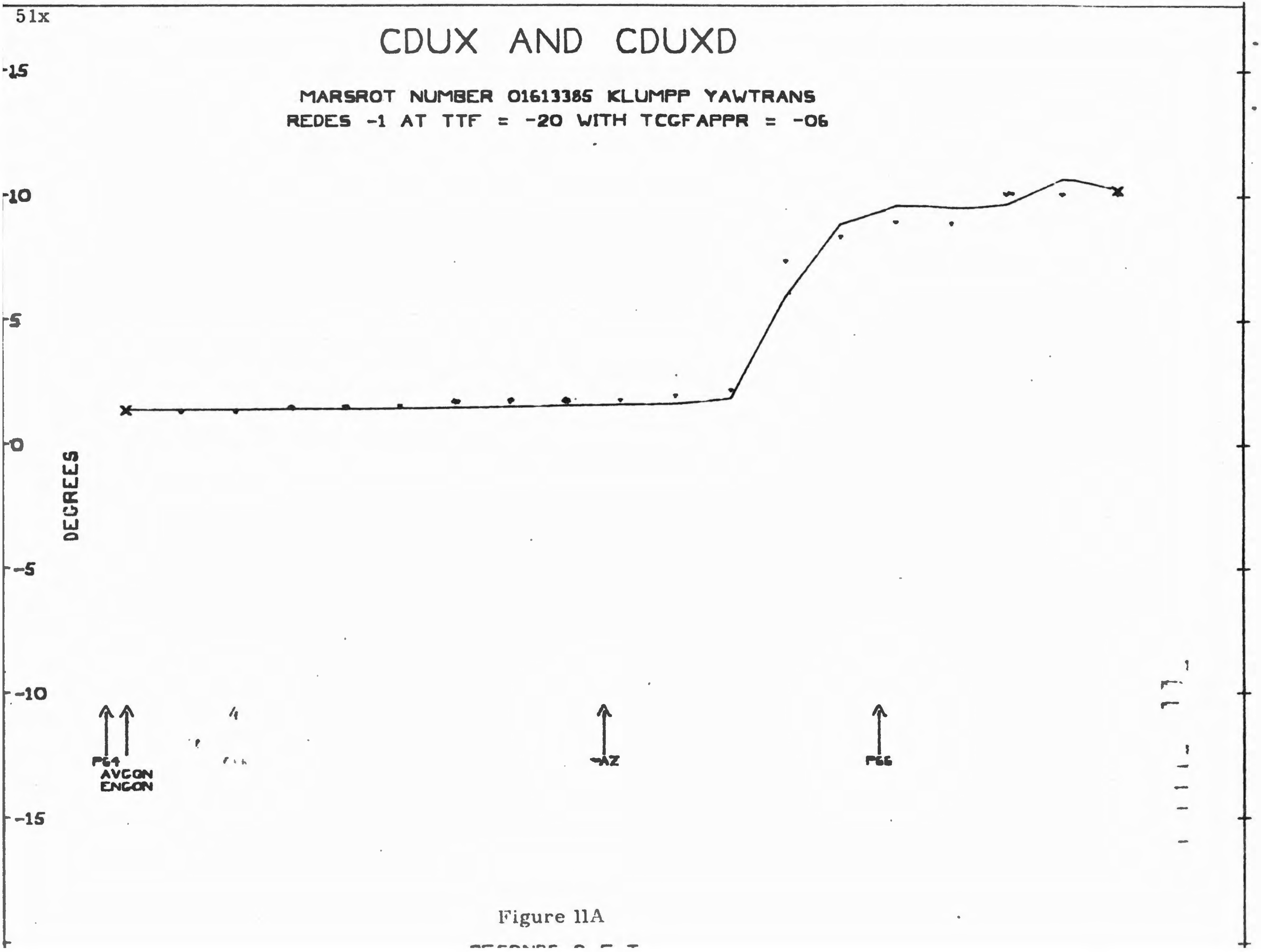
Figure 10C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DEGREES
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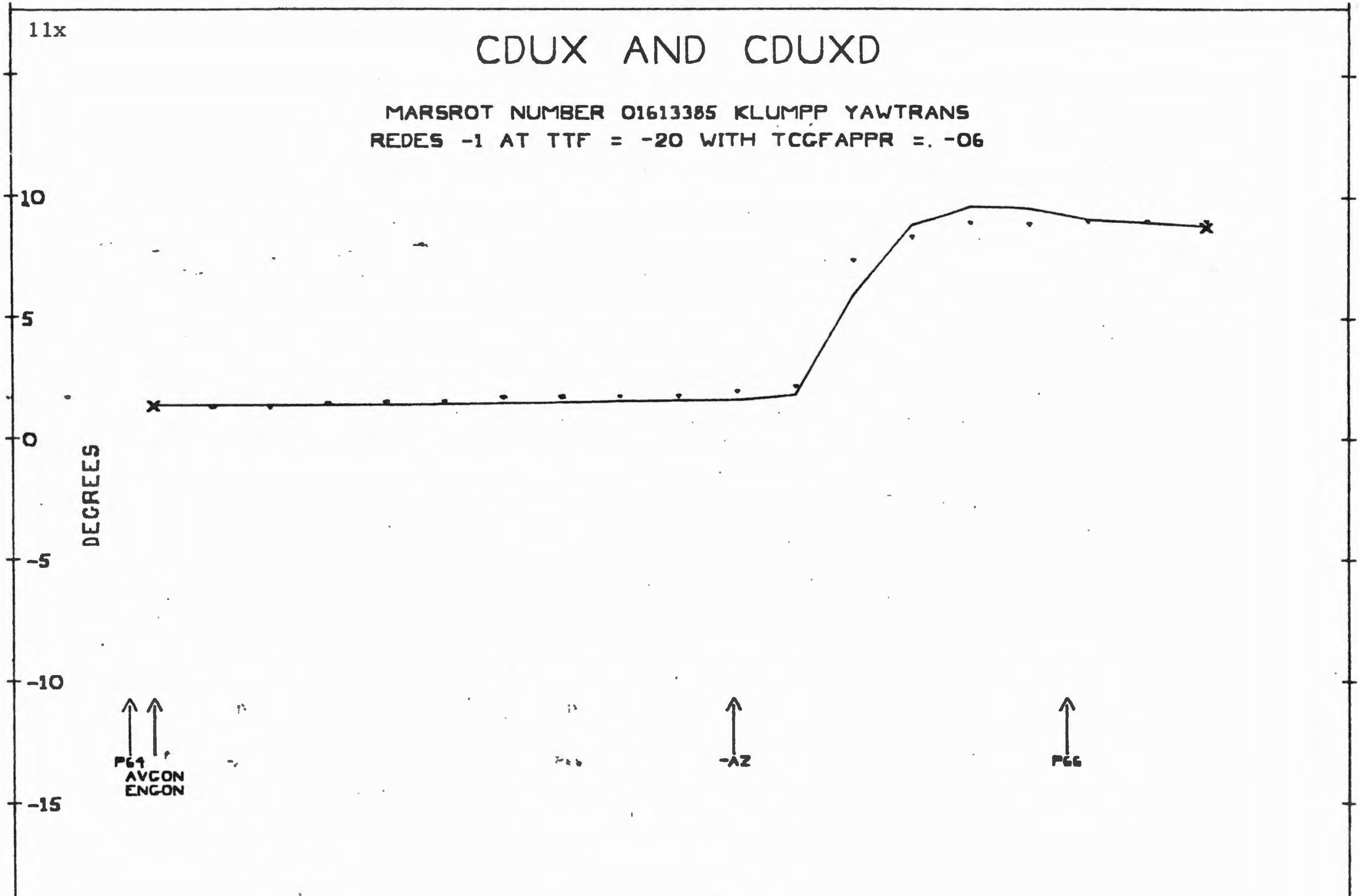
Figure 11A


CDUX AND CDUXD
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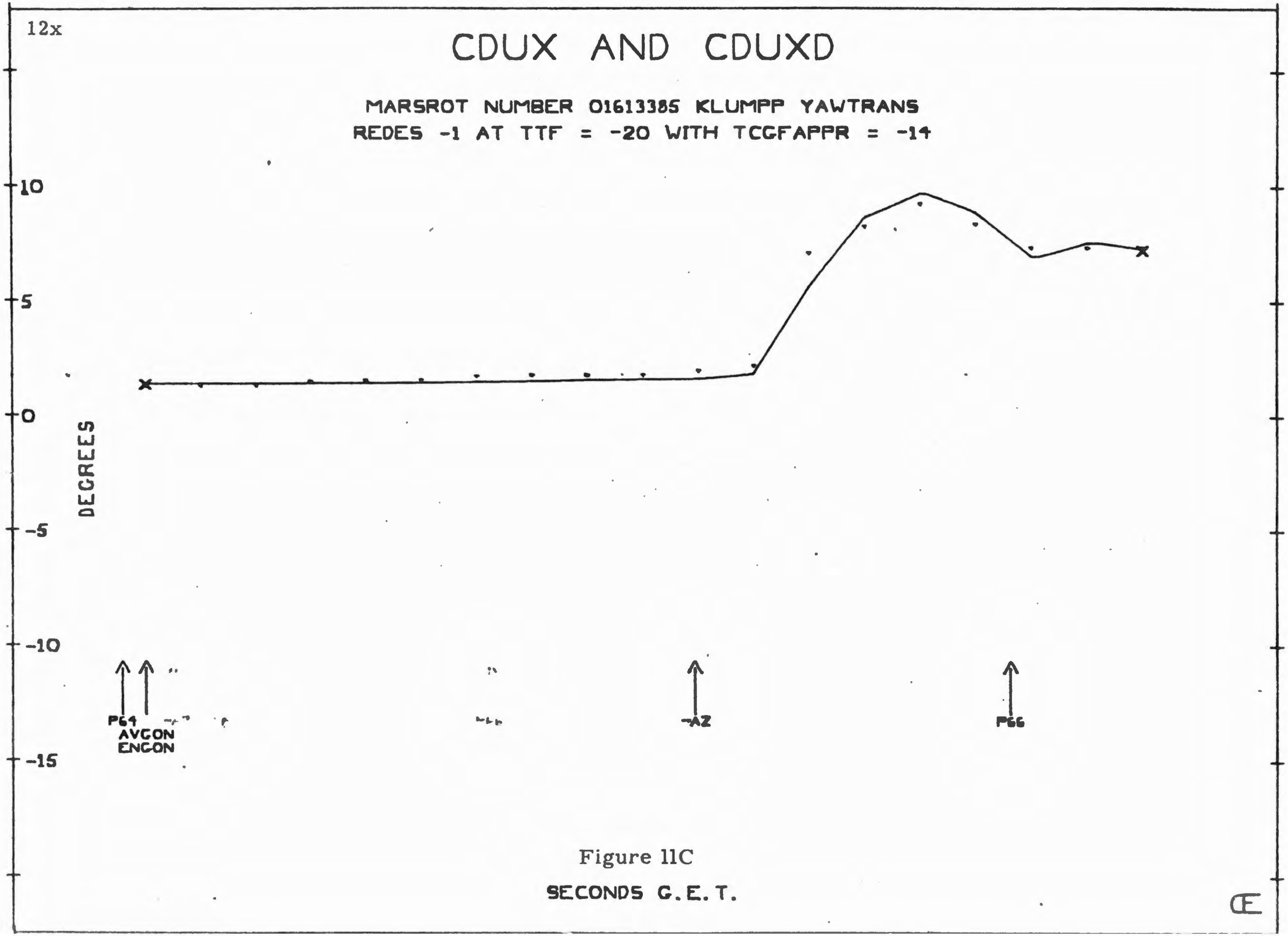
P66
SECONDS G.E.T.

Figure 11B


12x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -1 AT TTF = -20 WITH TCGFAPPR = -14
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DEGREES
P64
AVGON
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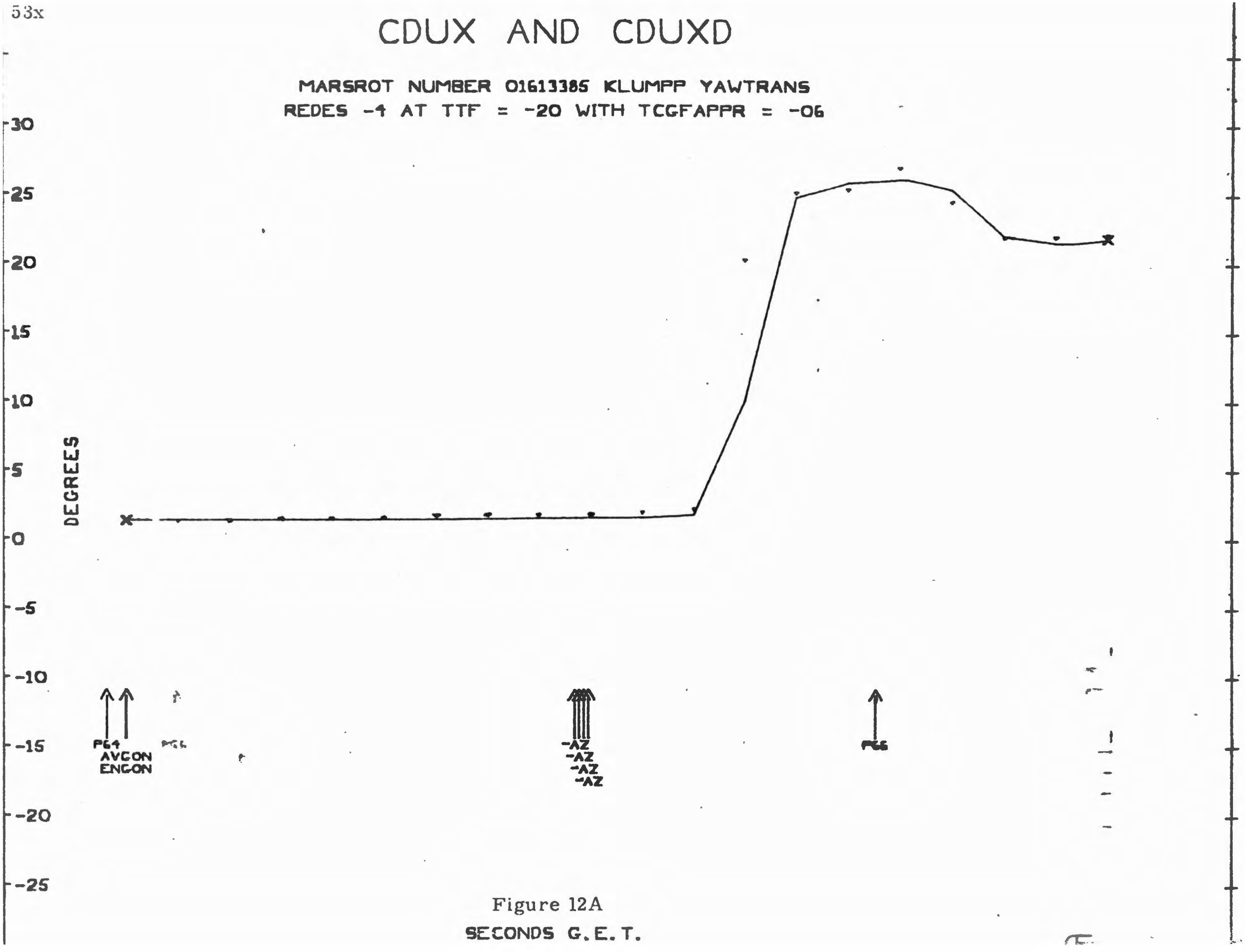
P66
SECONDS G.E.T.

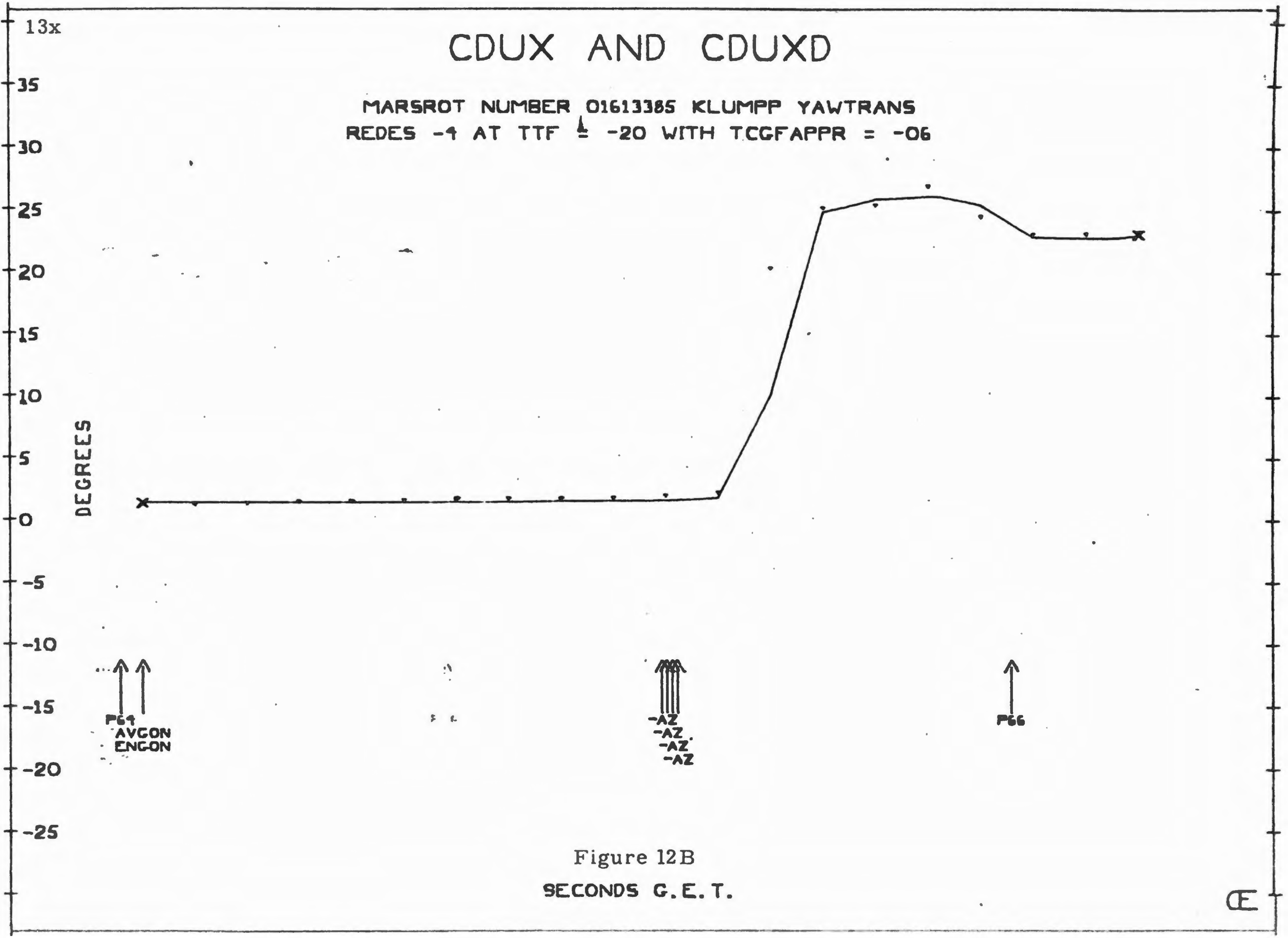
Figure 11C



CDUX AND CDUXD

MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -4 AT TTF = -20 WITH TCGFAPPR = -06

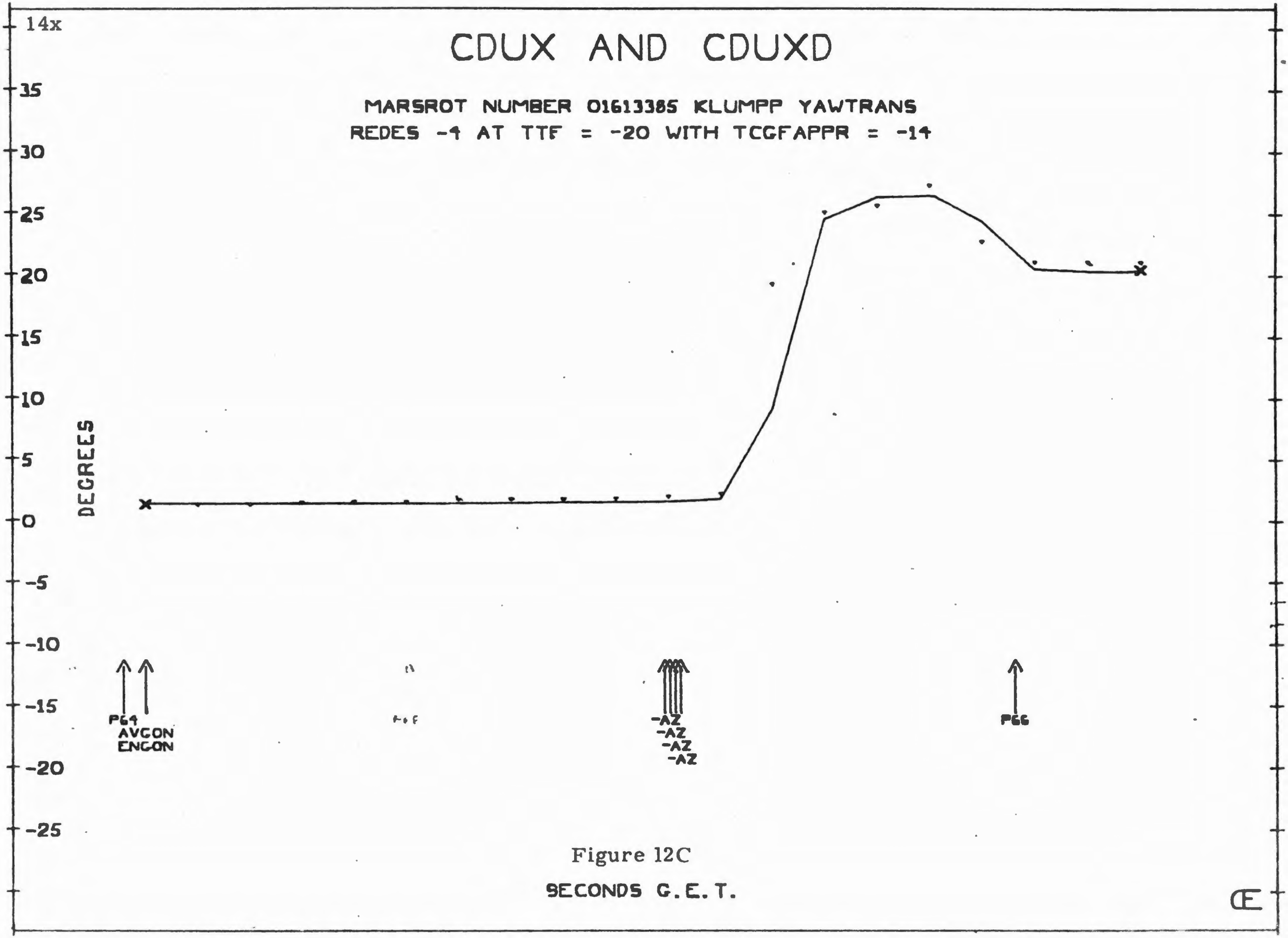
Figure 12A



CDUX AND CDUXD

MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -4 AT TTF ≟ -20 WITH TCGFAPPR = -06

Figure 12B


14x
CDUX AND CDUXD
MARSROT NUMBER 01613385 KLUMPP YAWTRANS
REDES -4 AT TTF = -20 WITH TCGFAPPR = -14
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P66
SECONDS G.E.T.
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Figure 12C

REFERENCES

1. Klumpp, Allan Memo to R. Larson, "Anomalies in Appllo 14 Descent", January 12, 1971.
2. Klumpp, A. R., "A Manually Retargeted Automatic Landing System for LM", MIT Instrumentation Laboratory, R-539 Rev. 1, August, 1967.
3. Klumpp, A., "FINDCDUW-Guidance Autopilot Interface Routine", Luminary Memo #27, Rev. 1, September 26, 1968.
4. Hull, L., "The Two Degree Yaw at the end of P64", Systems Engineering Memorandum SE-71-10, Delco Electronics Division of General Motors, Milwaukee, Wisconsin, 12, January 1971.
5. Klumpp, A., MIT/IL Software Anomaly Report, L-1D-23, Luminary, Rev. 178, 71-01-19.

AC ELECTRONICS
DIVISION OF GENERAL MOTORS CORPORATION ■ MILWAUKEE, WISCONSIN 53201 ■ (414) 762-7000

January 15, 1971
AP71-00038-N0017

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas - 77058

Attention: Mr. R. Albon - Project Officer

Subject: NAS9-10356 - The Two Degree Yaw at the End of P64

Gentlemen:

Attached are copies of Delco Memorandum SE-71-10 which provides an explanation of the positive yaw at the end of LGC Program P64.

The memorandum explains how a truncation error in the integration of the landing site position is sufficient to cause the positive two degree yaw. While this may not be the only error contributing to the yaw, we feel it clearly indicates the diminutive magnitude of cross-range error needed to generate a two degree yaw as P64 approaches the landing site.

Although we do not consider that this two degree yaw will present any mission problems, consideration should be given to correcting these truncation errors for future programs.

This information is of particular interest to Mr. R. Nobles, NASA/MSC.

Very truly yours,

DELCO ELECTRONICS DIVISION
General Motors Corporation

J. L. Stridde - Head
Program Office
APOLLO

JLS:dw
Attachment

CC:w/attach: Messrs. H. Hodges, M. Holley, R. Nobles (2), C. Tilman (GAC),
A. Klumpp (MIT/SDL), R. Larson (MIT/SDL), O. Cerbins (TRW/Houston)

Enclosure 5

SYSTEMS ENGINEERING MEMORANDUM SE-71-10

12 January 1971

To: D. Ziemer

cc: T. Hanley, S. Macy, P. Seligsohn, C. Clark, H. Neuville, J. Stridde, J. Landwehr (10), File

From: L. Hull

SUBJECT: THE TWO DEGREE YAW AT THE END OF P64

An intermittent one degree to three degree positive yaw of the LM during the last six to ten seconds of LGC Approach Phase Program of P64 was discovered by Grumman, Bethpage. Although this problem was not noticed in simulations of missions before Apollo 14, it could have gone unnoticed because it is so small in magnitude.

Conclusions

Program P64 computes a desired yaw angle to point the windows toward the landing site. Changes in this commanded yaw angle (THETAD) are caused by the cross-range motion of the LM. Uncertainties in LM autopilot control appear to generate random cross-range motion. Therefore, the observed variations of $+1^\circ$ to $+3^\circ$ from run to run are logically attributable to the autopilot. However, the autopilot is not generating the positive yaw bias.

This positive yaw bias is a result of truncation errors in the LGC landing guidance equations. The most obvious error is the integration of the landing site position. There is a 1/16 meter per two second servicer cycle error in the Y component of the landing site integration.

Discussion of the Positive Yaw Bias Effect

The pad loaded landing site ($\overline{RLS}$) is operated upon in Program P63 to compute the location of the landing site ($\overline{LAND}$) at throttle-up time in stable member coordinates. From throttle-up time, $\overline{LAND}$ is integrated to present time each two second servicer cycle.

$$\overline{LAND}_{NEW} = /LAND/\ UNIT\ (\overline{LAND}_{OLD} - \Delta t\ \overline{LAND}_{OLD} \times \overline{\omega M})$$

/LAND/ is the magnitude of $\overline{RLS}$

Δt is the difference between PIPTIMES, approximately two seconds

$\overline{\omega M}$ is the moon's rotational rate.

This computation has an intermediate scaling of 2^{25} meters or 1/8 meter quantization. With the platform in the preferred orientation, Y_{SM} is in the cross-range direction. The cross-range velocity of the landing site is approximately 1-3/32 M/sec or 2-3/16 M per servicer cycle. The $\overline{LAND}$ integration truncates this to 2-1/8 meters. Downlink data from the hybrid simulation verified that the LGC indeed updates $LAND_Y$ by 2-1/8 meter every two seconds.

Landing guidance is done in a "moon-fixed" coordinate system. The transformation ($\overset{*}{CG}$) from stable member coordinates to guidance coordinates is done by the following vector equations.

$$\overline{RGU} = \overset{*}{CG}\ (\overline{R} - \overline{LAND})$$

$$\overline{VGU} = \overset{*}{CG}\ (\overline{V} - \overline{\omega M} \times \overline{R})$$

where $\overline{R}$ and $\overline{V}$ are the stable member components of the LM state vector.

During P64 landing guidance can only do velocity nulling in cross-range because $\overset{*}{CG}$ is erected every two seconds. When the cross-range velocity (VGU_Y) is nulled, the LM has 1/32 meter/second cross-range velocity with respect to $\overline{LAND}$. Therefore, the commanded yaw angle will tend to turn at

$$\frac{\text{1/32 M/sec}}{\text{range}} \qquad \text{(approx. .2 deg/sec at end of P64)}$$

where range is computed in vehicle coordinates.

In an effort to verify that the truncation error in the computation of $\overline{LAND}$ was responsible for the yaw bias, the LGC was patched to add 1/8 meter to the Y component of $\overline{LAND}$ each servicer cycle. This is equivalent to "rounding up" in the integration of $\overline{LAND}$, which changes the sign of the cross-range integration error. This "minimum" change was sufficient to change the yaw direction. Therefore, it is concluded that the truncation error of the $\overline{LAND}$ integration is responsible for the positive yaw bias during P64.

Similar results were obtained by a scientific simulation of the landing guidance equations when a 1/16 meter integration error was introduced into the computation of $\overline{LAND}$.

Other Causes Considered

Before finding that $\overline{\text{LAND}}$ has a truncation error in its integration, a number of other things were considered and ruled out as causes for the positive yaw bias.

1. Window Geometry

   Since the thrust vector is not along the X axis of the vehicle, the X axis of the LM will be slightly out of the X-Z guidance plane. This misalignment coupled with the pitch attitude would necessitate a slight yaw angle to point the windows toward the landing sight.

   This was ruled out as a cause when the yaw was still positive when the thrust vector alignment was changed.

2. Loss of Visability

   When the look angle of the landing site exceeds approximately 65°, the LGC points the window in the direction of +Z axis of the guidance coordinate system rather than the landing site. This is done in an attempt to prevent a 180° yaw if the landing site were to be beneath the LM X axis at the end of a nominal auto P64; the look angle is in the neighborhood of 65°.

   This was ruled out as a cause for the yaw because the yaw command seemed continuous. Also, +Z guidance is in the same plane as $\overline{\text{LAND}}$ and the look vector (and the X axis of the LM, almost).

3. Moon Rotation

The guidance frame is rotating about $\overline{\omega M}$, in addition to $\overline{\text{LAND}}$ due to cross-range velocity. Even if there were no cross-range velocity, this would be a changing yaw command due to moon rate.

This was ruled out when it was shown to be a rotation of $-9.5x10^{-6}$ radians/second.

4. Autopilot Bias Error

The LM DAP has a 0.3° deadband during P64. In addition to the deadband, there are truncation errors in the interface between guidance and the DAP, FINDCDUW, which amounts to 0.22° deadband between guidance's desired attitude and the desired attitude of the DAP ($\overline{\text{CDUXD}}$). Even worse, FINDCDUW does not use the same truncation when computing a desired rate ($\overline{\text{OMEGAPD}}$) for the autopilot. Hence, there can be a .11 deg/sec greater rate desired than the rate of change of the desired attitude ($\overline{\text{CDUXD}}$).

Although the inputs to the DAP are inconsistent, no evidence of a significant bias error was found. This was confirmed by the symmetry of the yaw response to quantization of the $\overline{\text{LAND}}$ integration.

Recommendations

The $\overline{\text{LAND}}$ truncation error does not present any mission problem for Apollo 14. Consideration should be given to correcting the obvious truncation errors in the integration of $\overline{\text{LAND}}$ and in FINDCDUW for future programs.