GBT MEMO 157

A Status Report on The GBT Laser Demonstration At The 140 Foot Telescope

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Chapter 1

Background

1.1 Introduction

The laser ranging system design has undergone a number of evolutionary changes since the first working instrument was built in 1990. The first unit had no pointing mirror capability and a commercial phase meter was used to measure the phase of the returned signal and output it to a strip chart recorder, i.e., no software was involved.

Since that demonstration of the basic concepts, practically every component—the optics, oscillator, detector, modulator, mechanics, and control system has been refined. With the addition of a dual axis servoed mirror and an embedded computer system operated over a network; mirror pointing, digital signal processing techniques, remote operation, and multiple instrument control has changed the systems architecture to meet the requirements of the GBT surface and pointing functions.

Each of these refinements was individually tested by experimentation. Some of these experiments were hastily constructed to confirm the immediate question at hand, with little constraint placed on them by possible future areas of concern. For example, there was little concern about pointing accuracy for the first mirror systems, as long as they were repeatable. The immediate concern was to get data about the atmospheric changes in the index of refraction, since this was the least understood aspect of the instrument (and a potential show stopper). Of course for a production system on the GBT, pointing accuracy is critical due to the logistics of operating 18 instruments with 2209 retroreflectors on the surface, moving targets on the telescope, and the need for a routine procedure to interchange instruments with minimum field calibration.

Now that all of the subsystems are coming together into final production instruments, and the software is mature enough to support a full scale demonstration; it was felt that a demonstration that incorporates all of the refinements was in order. Since the GBT is behind schedule and we don't have access to the site or the luxury of moving the telescope, the 140 foot telescope was chosen as the test location.

1.2 Objectives

The fundamental philosophy of the 140 foot demonstration is to use this experience to refine the group index of refraction model, test the software, and to expedite the actual start-up on the GBT when it becomes available. With this in mind, we decided to make everything as close as practical to the GBT design and to use actual hardware and software. A good photograph library has been maintained to serve as reminders of how things were done.

When the systems are placed on the GBT, most hardware aspects will be identical to the 140 foot demonstration. Calibrations, measuring, tracking moving retroreflectors, correcting for index of refraction, software design and operation will also be exactly the same. The only unproven aspect will be be software that is specific to the GBT like pointing the telescope and moving the surface.

The major objectives can be outlined as:

1. Laser monument design
   - (a) stability
     - i. short term
     - ii. long term
   - (b) Kelvin mount
   - (c) calibration
     - i. vertical
     - ii. horizontal
     - iii. Kelvin mount
   - (d) shelters
2. Laser rangers
   - (a) mirror calibrations
   - (b) software
   - (c) tracking
   - (d) IRIG sync
   - (e) ethernet
   - (f) optics
   - (g) group index of refraction corrections
   - (h) rubidium clock
   - (i) control panels
   - (j) differential measurements between monuments

   (k) absolute measurements between monuments
   (l) establish traceability to NIST

3. Retroreflectors
   (a) solid glass cube
      i. calibration of offset as a function of angle
      ii. mounting
      iii. environmental protection
   (b) spherical
      i. calibration of offset
      ii. mounting
      iii. environmental protection
4. Safety procedures
5. Model telescope
   (a) establish ground control network
   (b) construct model of telescope
   (c) confirm model
6. Control center
   (a) ZIY program
   (b) status screen
   (c) engineering mode
   (d) data analysis
   (e) interface to 140 foot encoders
   (f) interface to weather station

Chapter 2

Construction

2.1 Monument Construction

Since the ground based lasers will be the only quasi-fixed geometry in the system, and the trilateration calculation is very sensitive to laser locations, the objective is to design a monument that is as stationary as practical. While concrete is not the ideal material, since it cures for years and is sensitive to humidity conditions, it is assumed that with the proper design the movements will be slow and can be corrected. It is an objective of the experiment to confirm this theory.

The most obvious problem to avoid is heaving due to freezing. In order to minimize heaving, the piers go down 5 feet below grade. In order to minimize tilting due to nonuniform side loads, the 36" concrete pier foundations were drilled at a 42" diameter and round sonotube forms were used all the way down to undisturbed soil. The resulting smooth wall finish avoids any rough sides for freezing soil to catch on, and drilling provides a symmetric entry into the undisturbed soil. In order to minimize wicking of ground water, the sonotube forms were split and removed all the way down. The 3" gap between the concrete and undisturbed soil was filled with building sand to form a fluid bed between the concrete and undisturbed soil. To avoid possible differential expansion and internal stresses, no reinforcement steel was used and all stainless steel anchor bolts were set to the same depth.

In order to use the hydrostatic level (which has a small differential elevation range) to very accurately measure the z coordinate of the monuments, the piers were all set at the same elevation. Natural ground contours resulted in about a 6 foot difference between the elevations above grade. The intention was to place modular buildings over the monuments, which would later be moved to the GBT. An earth berm was built, which provides thermal stability for the pier above grade.

Several modular building designs were evaluated, but initial designs for a motor operated door which provided the necessary viewing angles for the GBT proved to be over budget, so the decision was made to manually cover the instruments with commercially available 150 gallon plastic covers, for the 140 foot experiments. Maintenance of the sloped berms was a consideration also. It was decided that at the conclusion of the experiments, the berms would be leveled in order to eliminate the need to cut the grass with a weed eater. For the GBT, we will evaluate the merits of using an outside metal retaining wall, which would avoid mowing.

In order to make the monuments as symmetric as practical, and yet avoid backfilling against the monuments, the monuments were cased with 48" corrugated metal pipe and backfill was built up against the pipe leaving a gap between the pier and backfill. This backfill and casing also prevents lateral forces due to freezing and thawing since the concrete only contacts undisturbed earth below the freeze line. To minimize air circulation and stabalize the pier temperature, a reflective vinyl skirt was placed around the top of the pipe and attached with stainless steel bands. This may later be filled with insulation. This is all shown on drawing D35420C002.

Concrete shrinks as it cures, with the most change taking place the first few years. Since stability measurements were a major part of the experiment, it was decided to build the monuments early in the project. These piers were drilled and poured in July 1994, and the earth berms were built in March 1995.

Due to the design of the Kelvin mount on the laser, and the need to keep the point under the mirror stationary, the fixed point on the monument is in the center of the monument. This takes advantage of first order radial symmetry in changes of the monument due to temperature, moisture, cure, etc.

There was some concern that the total length of each concrete column is not the same. This could cause differential changes in elevation as the concrete cures, moisture level changes, or temperature changes. This was confirmed by recent measurments which will be talked about in a later section. It is now felt that for the GBT monuments it is necessary to keep the lengths constant (15 feet) with the minimum depth being 5 feet. Moreover, the casings may need to be the same length in order for the air pockets to be symmetric.

2.2 Construction Problems

Major problems were experienced pulling the Siecor type DFNR fiber optic cable for the ethernet. The PVC conduit was run before the earth berms were constructed and configured for conventional wire pulls into a pull box under the control panel, with the cable cascaded from monument-to-monument. As it later turned out, the fiber optic cable required a single uncut cable from the telescope control room to each monument, which meant that 4 cables had to be pulled into the first pull box and 3 looped back down to the next monument, etc.

Of course this required measuring each cable length and measuring it off the spool before starting the pull. At the first monument, the copper wires were cut and the spools moved to the next section of the pull. The remaining 3 fibers had to be pulled past the copper cables in the first section of conduit. The slack had to be coiled on the ground, and of course became dirty. Even by using excessive wire lube on the cable we were unable to pull it with less than 50 pounds of force.

This, compounded by the bends in the conduit up into the pull boxes (which are no problem for copper) resulted in 3 of the 4 cables being broken. This resulted in replacing the fiber cables with armored direct burial fiber cables—one of which was promptly cut by a backhoe!

Chapter 3

Calibration

3.1 Hydrostatic Leveling

A number of modifications were made to the H5 level to improve the reliability and accuracy, and schematic diagrams of the electronics and hydraulics systems were generated. We spent some time looking at an improved design to extend the hose length to span between monuments, but it was decided to postpone this project—although it may become necessary for the GBT monument calibration.

A series of hydrostatic level measurements was made on ZY10–ZY13 in the fall of 1995. These measurements were repeated in the summer of 1996 to measure movements of the monuments over an unusually cold and wet winter. Operation of the hydrostatic level over the ground presented several major problems, which were eventually overcome. Since the distance between monuments exceeds the hose length, two temporary turning points were needed between monuments. A modular scaffold style stand was designed to support the weight of the level. The 0.750" tooling ball, measurement point coupling on the level was gently rested on an isolated support post with about 5 pounds of force for a temporary elevation. The turning points were made by driving unistrut several feet into the ground to provide a temporary stable point. Since the range of the hydrostatic level is small, the unistrut was cut to the proper elevation, in place, and tooling ball end fixtures were adjusted using a conventional optical level. The unistrut was insulated with a foam tube of pipe insulation to moderate the impact of sunshine.

The hydrostatic level is sensitive to temperature differences if the hose is allowed to sag like a U tube, i.e., if the density is not the same in the two sides of the U, the elevations in the wells will differ. The density of water changes by 1497 parts per million between 10° and 20°. To a first approximation, the water temperature is uniform due to circulating the fluid prior to a measurement. A secondary correction is to keep the hose level, and of course to do the measurements on an overcast day or in the evening. The maintenance group devised a method to keep the hose level by using temporary wood post stands and C-clamped cross supports to support aluminum extension ladder sections in a cable tray type arrangement that bridges between the ends of the instrument. The bridges were then leapfrogged to the next set of monuments. Note that for the GBT, the circumference of a 120 meter radius will be a half mile!

There were a number of simple logistical problems in coordinating a successful closed loop run between all four monuments. After some experience, we were able to complete a survey with three runs between each set of monuments in about 4 hours. A detailed procedure was developed and refined in this process, and is included in the GBT archive files.

3.1.1 Leveling Results

Complete elevation surveys were made on the evening of 10/11/95 and repeated in the early mornings of 8/7/96 and 8/8/96. ZY10 was assumed to be the reference point for each survey. The results in mm are shown in the following table.

Date	ZY10		ZY11		ZY12		ZY13	
	elev	σ	elev	σ	elev	σ	elev	σ
10/11/95	0	-	.130	.022	.204	.032	.174	.019
8/8/96	0	-	-.106	.004	-.140	.030	-.671	.019

These results are very interesting! Using the H5 level (and a great deal of care), measurements in the order of 0.030 mm are obtainable over distances of 30–100 meters. This corresponds to 0.1–0.2 arc seconds, which is an order of magnitude better than the best commercial optical instrument. Moreover, since this method measures the differential geoid (sea level) elevation directly, no correction for refraction and earth curvature is required.

Since there is no absolute stable reference elevation bench mark around the monuments to reference from, ZY10 was arbitrarily assigned elevation 0.000 for each set of measurements. Plots of each set of measurements are shown in the Appendix. In each case, the monuments showed a decrease in elevation relative to ZY10 in the 1996 data when compared to the 1995 data. Knowing that the concrete should shrink with age, we did a fit assuming a linear relation with the column length. An excellent fit was obtained yielding a contraction of 745 parts per million for the 10 month period. Using this coefficient, the measurements are plotted on the same graph to show the changes in elevation with respect to ZY10 on 8/8/95. Another plot of the change in elevation vs column height clearly shows the excellent fit.

This would seem to indicate that the monuments shrunk at the same rate, and they did not experience frost heave or settle, even though ZY10 is in a very wet area and ZY13 is well drained. One caution in these results is that 745 parts per million is a high number when compared to published data by the Portland Cement Association which would indicate that we should see numbers in the range of 100 parts per million. This could be explained by the water to cement ratio which affects the coefficient, but we did not know this at the time these monuments were poured and thus did not specify a low ratio.

A monument which was poured for the quadrant detector experiment on 4/29/96 used the mix recommended by the Portland Cement Association. A test cylinder of this mix is being measured to check the shrinkage rate. Experimental results after 106 days are shown in the Appendix.

3.2 Monument Euler Angles

In order to point the laser, the instrument is calibrated in the lab with respect to the Kelvin mount. The monuments must also be calibrated. This is a somewhat more difficult calibration to perform in the field. The monument center fixed points were leveled using a conventional optical level. These points were then locked down and should not ever be disturbed. The flat and "V" were leveled as well as practical with respect to the fixed point using a machinest level. The final calibration of the tilts was done using a flat and parallel granite plate and a precision Clineometer level.

By far the most difficult angle measurement is the angle between the fixed point and "V" to the survey grid. With care, the azimuth on the Topcon survey instrument can be used to measure this angle. A plate with the Kelvin mount and a tribrack centered on the fixed point is placed on the monument. Angles can then be measured to other survey points. The problem is referencing the Topcon azimuth to the tooling ball on the plate. We have done this in the lab where we have a "V" that is 90° to a target within a few arc seconds. The instrument can be moved a short distance without losing the reference, but it must be brought back to check the closure.

Since there is no reference angle in the field, we had to establish one at night. An alignment telescope with an autocollimating eyepiece was centered on monument ZY10. It was aligned on a precision target located on ZY11. The target was then removed and a granite straight edge was then placed against 0.750" balls in the center point and "V" on ZY11. A 21" granite sine bar with a flat Croblox mirror attached was sighted on by the autocollimator and adjusted using gage blocks between the sine bar and straight edge. This angle was then used to bootstrap the Topcon to measure the angles on the other three monuments. We now have a calibration 12 sided optical polygon which may be faster to use for the GBT monuments.

3.3 Telescope Tracking Model

In order for the lasers to track moving targets on the 140 foot telescope, it is first necessary to construct a model of the motions as a function of hour angle and declination. These angles are provided by high accuracy encoders, through a hardware interface designed and built by Dwayne Schiebel. This hardware interface is read by a PC and interfaced to the laser instrumentation over the ethernet.

The hardware model was constructed from a number of previous measurements, design drawings, and surveys of the 140 foot telescope. All data was translated from NAD 27 to NAD 83 using a NGS PC program called CORPSCON, which translates coordinates and calculates convergence angles. Elevations were converted from NGVD 29 to NAVD 88 datum using the NGS data sheet for the first order elevation in Cass. The data was adjusted using a PC program called STAR*NET.

The earliest data was taken from a technical report generated by Geonautics, Inc., dated July, 1960, titled "Precise Control Survey Network for Radiotelescope Construction; Greenbank, West Virginia". They established an extensive network of bench marks around the 140 foot telescope. Unfortunately, only 4 of these points remain for our use. The primary marks are brass plugs in the north and south end of the deck of the telescope identified as Geonautics 2 and Geonautics 1. The original marks are punch points in the brass plugs. Later, as-built correction marks were punched and marked with a letter "C". Unfortunately, no one here knows the origin of the "C" corrections or how they were determined. In addition, Geonautics 3 is located across the road to the northeast, and Geonautics 12 is located due south of the telescope in the woods and protected by a fence.

The Air Force did a survey of the 140 foot location in 1970 and established a monument named Site, located up on the hill east of the telescope. They established the center of the telescope with respect to Site, Geonautics 1, 2, and 3. In addition, they surveyed the elevation of Site with respect to a first order monument in Cass. Sid Smith generated drawing 31D00501, "Relations of the 140's Axes to U.S.A.F. Survey Point, 9/9/70". Site was later tied to a new monument T-007 established by the Corps of Engineers in 1971.

In 1982, the National Geodetic Survey established monuments Scorpio and Taurus, located west and southwest of the telescope. Note that the NGS data sheets on Site, Scorpio, Taurus, and Geonautics 3, show them to be First Order elevations. This is in error and will be corrected on future data sheets. We are also finding problems with the NGS coordinates on Taurus, and Bank and the Air Force coordinates on Site, with respect to T007, which we took as fixed. It should be noted that T007 has been used by the NGS for GPS crustal motion studies and will be published as Order A horizontal accuracy in the 1997 CD ROM. This corresponds to an accuracy of 5 mm + 0.1 parts per million with respect to other NGS monuments across the United States.

In the summer and fall of 1995, the laser group completed rough (± 3 mm) surveys of the 4 new laser monuments, ZY10–ZY14, with respect to these bench marks. The azimuth between Site and Geonautics 3 from the published Air Force report was used to establish astronomical north and grid north. In addition, high precision (± 100 μm) differential hydrostatic leveling was done between the laser monuments, and optical leveling was done between ZY11 and all ground level bench marks. The elevations of Geonautics 1 and Geonautics 2 were not checked.

The Kelvin mounts on the monuments have been calibrated for direction and tilts to an accuracy of about 5 seconds. This level of accuracy should be more than required to track points on the telescope, but much higher accuracy of the baseline is required to perform trilateration calculations with 100 μm accurcy.

With this information and the additional design dimensions given on drawing 36D00022, one can construct a mathematical model of the telescope with respect to these bench marks. In principle, any systematic errors in the pointing of the telescope could be used to refine the model, e.g., if the polar shaft is not pointed true north or the encoders have an offset, it should show up as a pointing correction. Inquiries failed to find anyone that knows of any such physical terms that have been measured, so we assumed a perfect telescope.

One way to derive the equations is to imagine the telescope pointing along the polar axis, as shown on 36D00022, except where the polar axis is horizontal to the earth, pointing to the survey grid north, and the spherical bearing is at sea level. Define a coordinate system (u, v, w) in the reflector with an origin at the center of the declination shaft. The u axis points out of the drawing along the declination shaft. The v axis points toward the focus, and w points up in a right-handed coordinate system.

Rotation about the declination shaft (u axis) will be defined as θ with a positive direction defined by the right hand rule, i.e., rotations to the south are positive. This is handled by a rotation matrix. The (u, v, w) coordinates are then translated to the center of the spherical bearing via a translation matrix. Rotations of the polar shaft are defined as α with positive rotation to the east, i.e., using the right hand rule. The telescope is then rotated about the spherical bearing by an angle ϕ with respect to the horizontal in order to tip the telescope polar axis parallel to the earth axis. The telescope is rotated an angle γ around the grid coordinate z axis to point it to astronomical north, i.e., astronomical north is 43' 11" to the left of grid north (if we ignore the LaPlace correction). Finally, it is translated to 841.2163 meters above sea level. This is all expressed as:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix}$$
$$\left[\begin{pmatrix} 0 \\ 5.3308 \\ 14.9272 \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} \right] + \begin{pmatrix} 0 \\ 0 \\ 841.2163 \end{pmatrix} \quad (3.1)$$

where

$$\begin{aligned} (x, y, z) &= \text{ground coordinates} \\ \gamma &= \text{convergence angle} \end{aligned}$$

$$
\begin{aligned}
&= 00-43-11\\
\phi &= \text{latitude}\\
&= 38-26-16\\
\alpha &= -2\pi/24 \text{ hour angle}\\
\theta &= \pi/2 - \text{declination}\\
(u,v,w) &= \text{reflector coordinates.}
\end{aligned}
$$

Note that hour angle is positive west of zenith, and declination is positive north of a right angle to the polar shaft.

Putting in the latitude and convergence angle, this reduces to

$$
\begin{pmatrix} x\\ y\\ z \end{pmatrix} = \begin{pmatrix} .999921 & -.009839 & .007809\\ .012561 & .783222 & -.621616\\ 0 & .621665 & .783283 \end{pmatrix} \begin{pmatrix} \cos\alpha & 0 & \sin\alpha\\ 0 & 1 & 0\\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix}
\left[\begin{pmatrix} 0\\ 5.3308\\ 14.9272 \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0\\ 0 & \cos\theta & -\sin\theta\\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} u\\ v\\ w \end{pmatrix} \right] + \begin{pmatrix} 0\\ 0\\ 841.2163 \end{pmatrix} \quad (3.2)
$$

Thus, one can transform from a (u, v, w) coordinate on the reflector to the (x, y, z) coordinate on the ground, with the (x, y) origin in the center of the spherical bearing and the (z) origin at sea level in the North American Vertical Datum 88 (NAVD 88), and the direction vectors are in the West Virginia State Plane Coordinate System, North American Datum, 1983 (NAD83).

3.3.1 Retroreflector Angles

Due to the finite acceptance angle of retroreflectors, retroreflectors mounted on the moving structure will only retroreflect for particular ZY locations as a function of retroreflector type, mounting location, orientation, hour angle, and declination. Modifying the coordinate transformation equation for the telescope model, to a vector transformation equation and assuming a unit vector (r_u, r_v, r_w) in the telescope coordinate system and a unit vector (r_x, r_y, r_z) in the ground coordinate system, the equation can be written as:

$$
\begin{pmatrix} r_x\\ r_y\\ r_z \end{pmatrix} = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0\\ \sin\gamma & \cos\gamma & 0\\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \cos\alpha & 0 & \sin\alpha\\ 0 & 1 & 0\\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix}
\begin{pmatrix} 1 & 0 & 0\\ 0 & \cos\theta & -\sin\theta\\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} r_u\\ r_v\\ r_w \end{pmatrix}. \quad (3.3)
$$

Putting in the latitude and convergence angle,

$$\begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix} = \begin{pmatrix} .999921 & -.009839 & .007809 \\ .012561 & .783222 & -.621616 \\ 0 & .621665 & .783283 \end{pmatrix} \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix}$$
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} r_u \\ r_v \\ r_w \end{pmatrix}. \tag{3.4}$$

Recall that the ZY instrument computes the vector from instrument i to target j in the ground coordinate system as

$$\vec{R}_{ij} = \vec{R}_j - \vec{R}_i. \tag{3.5}$$

If the retroreflector unit vector is defined such that it points along the axis of symmetry in the direction of beam entrance, and the acceptance angle α_a defines the maximum cone around this vector, then the criteria for using a retroreflector is

$$\frac{\vec{R}_{ij} \bullet (r_x, r_y, r_z)}{|\vec{R}_{ij}|} > \cos(\alpha_a). \tag{3.6}$$

3.3.2 Confirmation of Model

In order to confirm the model, 3 retroreflectors were mounted near the top of the prime focus. Two of these were surveyed at a number of hour angle and declination positions from monuments, Scorpio, and Geonautics 3. This survey data was adjusted using Star*Net and the (x, y, z) coordinates were then converted to (u, v, w) coordinates as a function of hour angle and declination. Of course, if everything is correct the (u, v, w) coordinates should remain constant for all telescope positions. If not, errors must be corrected and adjustments in the model may be required.

The inverse equation to convert from (x, y, z) to (u, v, w) coordinates is

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}^{-1}$$
$$\left\{ \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix}^{-1} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{pmatrix}^{-1} \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix}^{-1} \right.$$
$$\left. \left[\begin{pmatrix} x \\ y \\ z \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ 841.2163 \end{pmatrix} \right] - \begin{pmatrix} 0 \\ 5.3308 \\ 14.9272 \end{pmatrix} \right\}. \tag{3.7}$$

This reduces to

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sin\theta & \cos\theta \\ 0 & -\cos\theta & \sin\theta \end{pmatrix} \left\{ \begin{pmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} .999921 & .012561 & 0 \\ -.009839 & .783222 & .621665 \\ .007809 & -.621616 & .783283 \end{pmatrix} \right.$$

$$\left[\begin{pmatrix} x \\ y \\ z \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ 841.2163 \end{pmatrix}\right] - \begin{pmatrix} 0 \\ 5.3308 \\ 14.9272 \end{pmatrix}\Bigg\}. \tag{3.8}$$

3.3.3 Telescope Model Results

The coordinates of each measured position of the retroreflectors is tabulated in Figure A. This data was transformed back into the (u, v, w) coordinates using the Mathematica program in Figure A. The output data is tabulated in Figure A. Notice that the coordinates of the two retroreflectors are not constants for each measurement. This is most likely due to errors in the model, i.e., the spherical bearing location or the declination shaft relation to the spherical bearing. When we get the lasers running, we will go back and refine the model to make it conform to a higher precision, but for initial work this model is probably good enough to acquire the targets.

Chapter 4

Results

4.1 Operations

The ZIY program is running from a control desk at the laser lab. The operator has a dedicated computer and display running the instruments and a dedicated status panel display (see example format in the Appendix). A storyboard showing the organization of the available screens is available on drawing D35420K011. These screens are reproduced in the Appendix.

A trailer and telephone were added in the field to support the experimental work. Each control panel also has a telephone jack. A spare ethernet cable was pulled into the trailer for a local computer which can be used to interface a local weather station and video frame grabber to provide the operator with video capability both for the general grounds as well as an optional "through the instrument" capability. A ZIY computer may be added in the trailer if field experiments require operator attention.

All previous experimental work has been conducted in remote fields. The 140 foot telescope location requires additional eye safety precautions due to the greater likelihood of sightseers and untrained personnel wandering around the lasers. This is compounded by the use of higher power, tighter beam lasers being used on the production instruments. Of course, this will also be the operating environment at the GBT.

An amber warning beacon is switched on when the covers are removed. Large signs have been located around the perimeter of the Nominal Hazard Zone (NHZ). The telescope operators and grounds people have been notified that they must wear safety glasses if they enter the NHZ when the beacon is on. In addition, an attenuator is placed in the beams to reduce the power—except when long ranges are being measured.

4.2 Start-Up

After some initial gross blunders in the pointing calculations were rectified, an instrument was tested in the field in December, 1995. Pointing errors of several arc minutes were traced to errors in the encoders. After extensive investigations in the lab, the decision was made to replace these encoders. This required a major mechanical revision to the mirror design, as well as a significant modification to the encoders to reduce the size and fit in the space envelope. These modifications have now been made on the production units and checked using an optical polygon and autocollimator with excellent results.

Early operation was plagued with hardware and software problems. We experienced long unexplainable delays with the ethernet, the IRIG signal would not lock, and software bugs made operation cumbersome. Most troublesome were frequent hardware resets on the ZY control panels. These problems were resolved by July 1996, and field testing began. A prototype and three production instruments are now in place at the 140 foot telescope.

4.3 Instrument Pointing

The first experimental objectives were to confirm the pointing calibration of the instruments and monuments and to build refractometer baselines in order to measure the group index of refraction. An acid test of the pointing calibrations was designed by mounting a 3" retroreflector on an existing rigid structure located on a mountain nearly 1000 meters away at an elevation of 906 meters (the GBT track elevation is about 807 meters, and the 140 foot telescope lasers are at about 818 meters). The pointing calibration capability has now been demonstrated with ZY10 and ZY13 (the only 2 instruments that have a clear path to the 1000 meter target) hitting the target with sufficient accuracy to get a return signal based only on the calibration data.

This path will later be used as a refractometer over a long distance in order to measure the correlation between the local group refractive index and a calculated group refractive index at the GBT weather tower about 1000 meters away.

4.4 Tracking Software

Another objective is to track a moving retroreflector mounted to the telescope. The prototype spherical retroreflector was mounted on the south underside of the telescope. Survey measurements were made at a number of hour angles and declinations and the (u, v, w) coordinates were determined using the same procedure that was used to confirm the telescope model. It is interesting to note that the spherical retroreflector can easily be seen with a flashligh (at night) from the laser lab which is 1400 meters away. It is also interesting to see the dispersion as one moves his eye off axis from the line between the flashlight and retroreflector. The color will change from white to blue. This does not happen with a cube retroreflector.

The ZIY program can now read the 140 foot encoders and calculate the ground coordinates of the retroreflector, using the model. These coordinates are then updated in the ZY control panels and all lasers can scan the retroreflector. This demonstration software is designed only to check the algorithms on a point basis instead of the more difficult smooth tracking requirements that will be needed for the GBT.

Appendix A

Telescope Model Data

140W_1	160211.7068	701634.6576	878.4726	.000306	.670987
140W_2	160211.7049	701634.6543	878.4766	.000306	.670987
140W_3	160211.7501	701633.2436	878.3948	.166972	.670987
140W_4	160212.1167	701629.0585	877.8656	.666972	.670987
140W_5	160214.7162	701618.6626	874.4350	2.00000	.670987
140W_6	160218.0456	701612.1825	870.1352	3.00000	.670987
140W_7	160211.7034	701634.6524	878.4760	.000306	.670987
140W_8	160215.5663	701634.6003	878.1316	.000306	.845520
140W_9	160222.8196	701634.5044	875.4730	.000306	1.194586
140W_10	160225.9945	701634.4618	873.2394	.000306	1.369119
140W_11	160190.1401	701634.9324	861.8644	.000306	-.645971
140W_12	160211.7049	701634.6533	878.4758	.000306	.670987
140NE_1	160212.6241	701637.5666	878.5042	.000306	.670987
140NE_2	160213.6205	701645.7444	877.3720	-1.0003	.670987
140NE_3	160217.1920	701656.0557	873.0378	-2.4169	.670987
140NE_4	160212.6222	701637.5699	878.4950	.000306	.670987
140NE_5	160216.4772	701637.5180	877.9942	.000306	.845520
140NE_6	160219.3190	701637.4785	877.1720	.000306	.978257
140NE_7	160226.5948	701637.3764	872.7846	.000306	1.361556
140NE_8	160212.6228	701637.5707	878.5002	.000306	.670987
140NE_9	160204.5774	701637.6806	877.3708	.000306	.304444
140NE_10	160212.6261	701637.5708	878.5040	.000306	.670987

Figure A.1: Coordinates of retroreflectors (name, north, east, elevation, hour angle, declination).

```
(* xfm140.eq
   transformation to convert coordinates in 140 foot telescope dish
   coordinate system into WVSP grid coordinates centered at the
   spherical bearing and sea level *)
lat := 0.6708664 (* 38-26-16 *)
conv := 0.0125615   (* 00-43-11 *)
polar := {701636.1825, 160216.7894, 841.2163}
(* coordinates of polar bearing *)
(* Declination is positive for north, negative for south, zero at a
right angle
to the polar shaft. *)
theta := Pi/2 - dec
(* Hour angle is positive for west, negative for east, zero at
zenith *)
alpha := -hour 2 Pi/24
a := {{1,0,0}, {0, Cos[theta], -Sin[theta]}, {0, Sin[theta],
Cos[theta]}}
b := {0, 5.3308, 14.9272}
c := {{Cos[alpha], 0, Sin[alpha]}, {0,1,0}, {-Sin[alpha], 0,
Cos[alpha]}}
d := {{1,0,0}, {0, Cos[lat], -Sin[lat]}, {0, Sin[lat], Cos[lat]}}
e := {{Cos[conv], -Sin[conv], 0}, {Sin[conv], Cos[conv], 0}, {0, 0,
1}}
r := N[e.d.c.(b+(a.{u, v, w})) + polar]
g := N[ Inverse[a].(( Inverse[c].Inverse[d].Inverse[e].
({x,y,z}-polar) )-b)]
coordinates = ReadList["b:xfm140.pts",
{Word,Number,Number,Number,Number,
Number}]
(* Coordinates output by StarNet are {north (y), east (x), elevation
(z)} *)
Do[{ x := coordinates[[i,3]], y := coordinates[[i,2]], z :=
coordinates[[i,4]],
hour := coordinates[[i,5]], dec := coordinates[[i,6]],
OutputForm[ PaddedForm[ g, {10,4} ] ] >>>b:xfm140.out}, {i,22} ]
```

Figure A.2: Mathematica program.

```
{     -1.5860,      22.2502,      -0.0384}
{     -1.5894,      22.2542,      -0.0365}
{     -1.5906,      22.2509,      -0.0371}
{     -1.5908,      22.2446,      -0.0413}
{     -1.6082,      22.2323,      -0.0582}
{     -1.6256,      22.2211,      -0.0650}
{     -1.5913,      22.2536,      -0.0350}
{     -1.5951,      22.2538,      -0.0345}
{     -1.6004,      22.2490,      -0.0324}
{     -1.6034,      22.2470,      -0.0365}
{     -1.5821,      22.2544,      -0.0525}
{     -1.5904,      22.2534,      -0.0365}
{      1.3342,      22.2817,      -0.9192}
{      1.3354,      22.2695,      -0.9239}
{      1.3446,      22.2572,      -0.9355}
{      1.3375,      22.2725,      -0.9173}
{      1.3338,      22.2702,      -0.9195}
{      1.3298,      22.2723,      -0.9216}
{      1.3185,      22.2545,      -0.9292}
{      1.3383,      22.2777,      -0.9179}
{      1.3475,      22.2972,      -0.9244}
{      1.3384,      22.2815,      -0.9212}
```

Figure A.3: Output of Mathematica program (u, v, w)

Appendix B

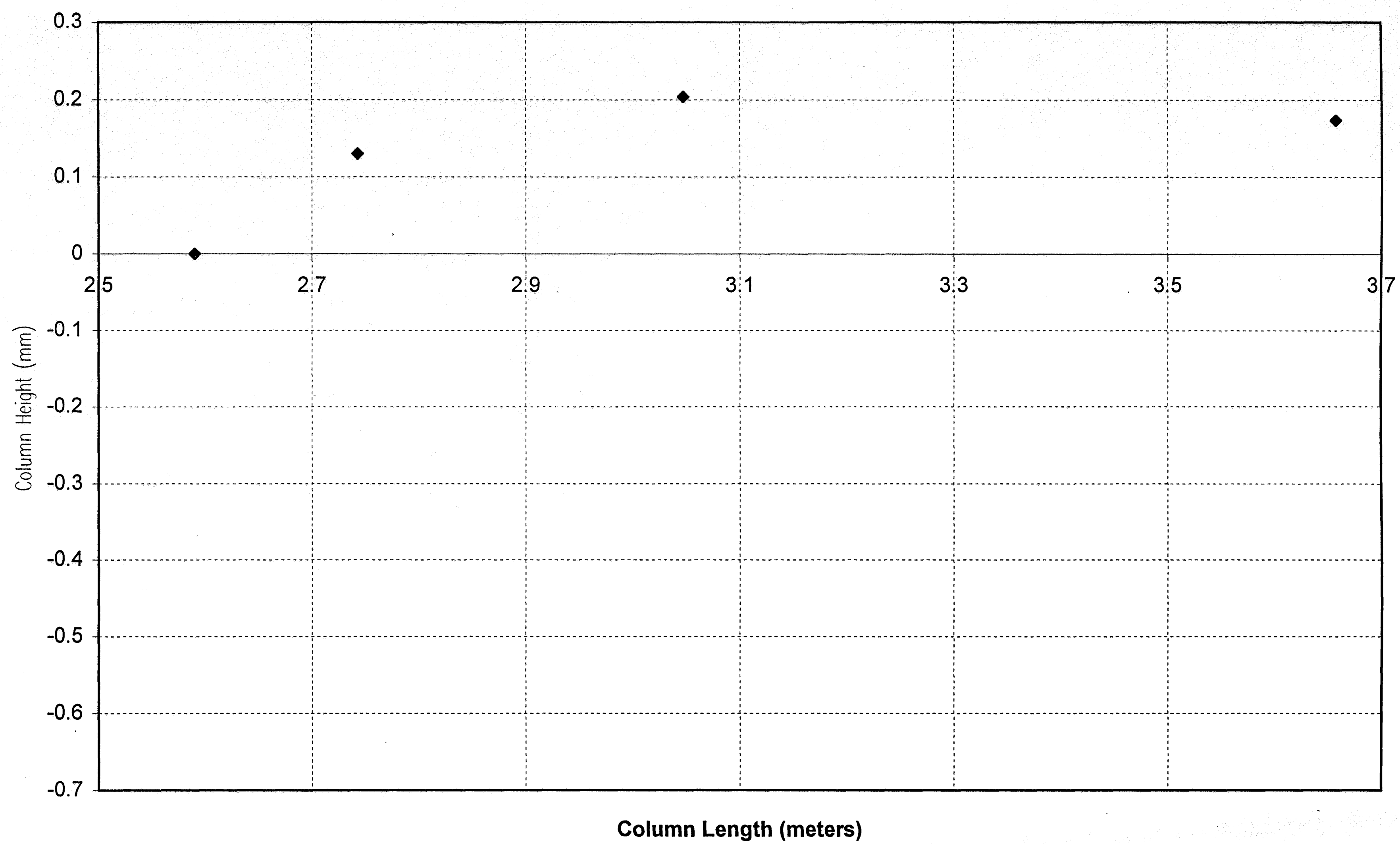
Hydrostatic Level Data

Monument Stability Data
8/12/96

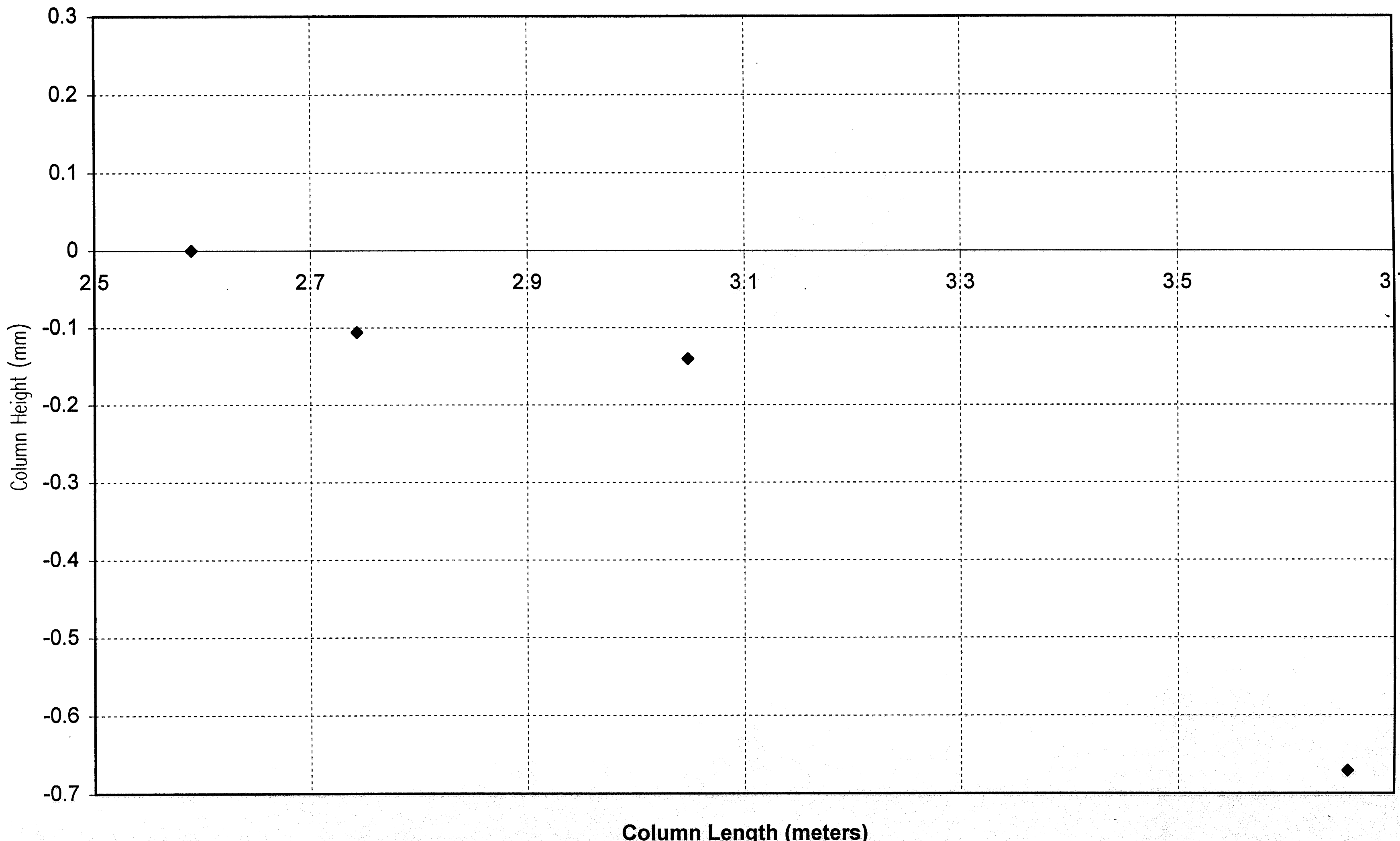
Const A	1.886
Const B	-0.745

ZY #	Column Length (metres)	10/11/95	8/8/96	8/8/96 + offset	Best Fit	Residual	
ZY10	2.59	0	0	-1.886	-0.04355	0.04355	-1.886
ZY11	2.743	0.13	-0.106	-1.992	-0.02753	-0.07847	-2.122
ZY12	3.048	0.204	-0.14	-2.026	-0.18076	0.04076	-2.23
ZY13	3.657	0.174	-0.671	-2.557	-0.66447	-0.00654	-2.731

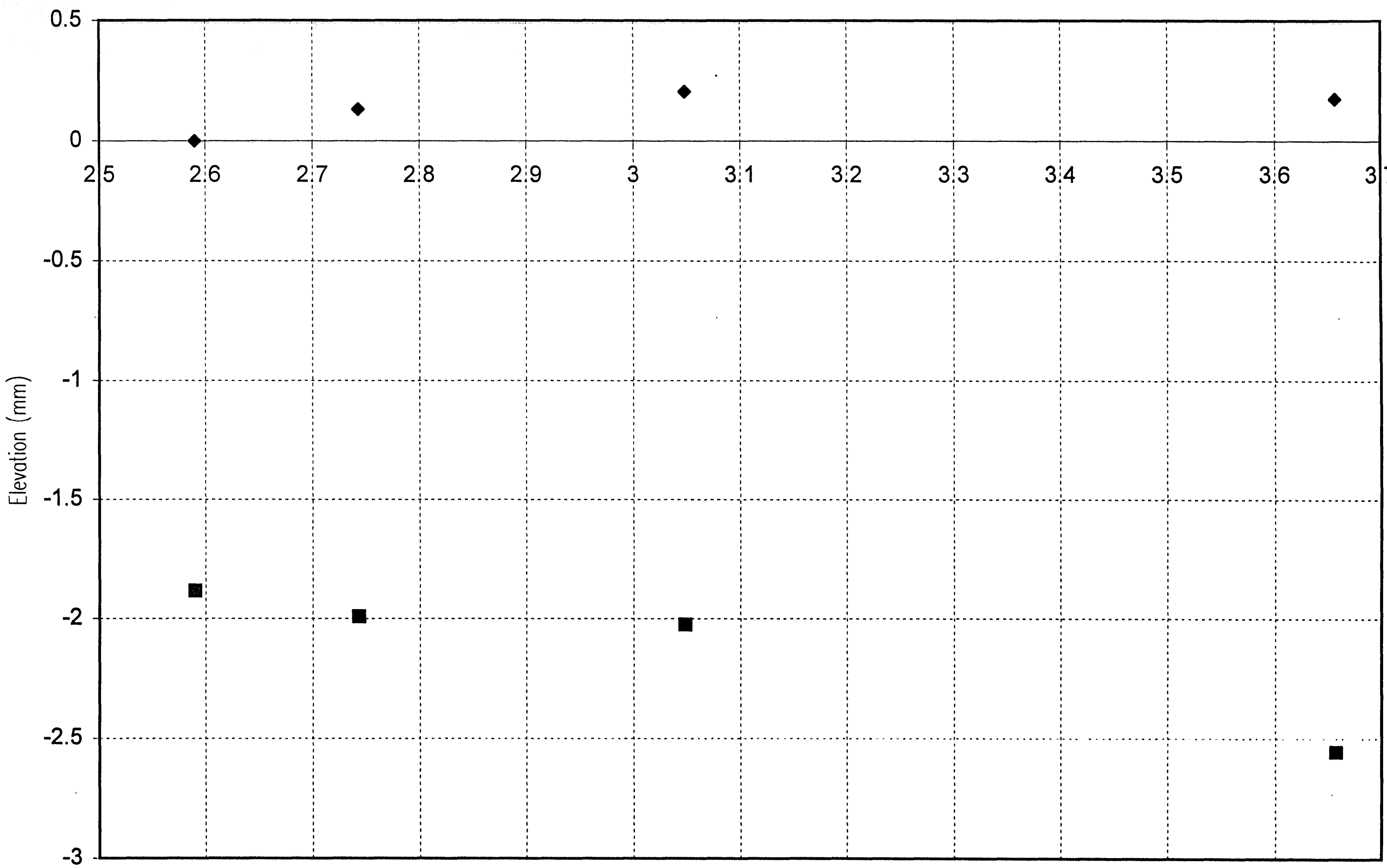
140' Monument Elevation (10/11/95)



140' Monument Elevation (08/08/96)

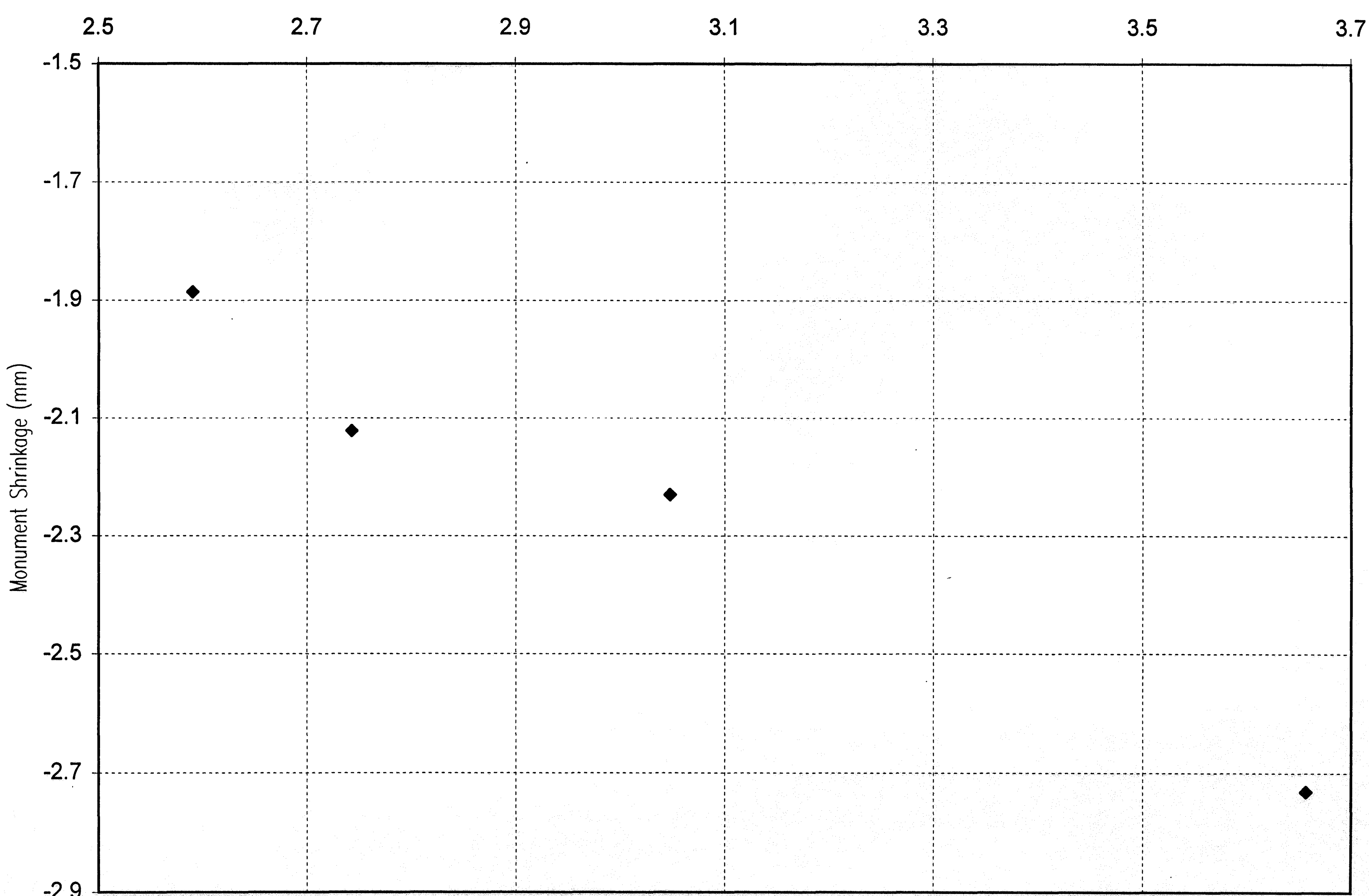


140' Monuments (08/12/96)



Monument Height (meters)

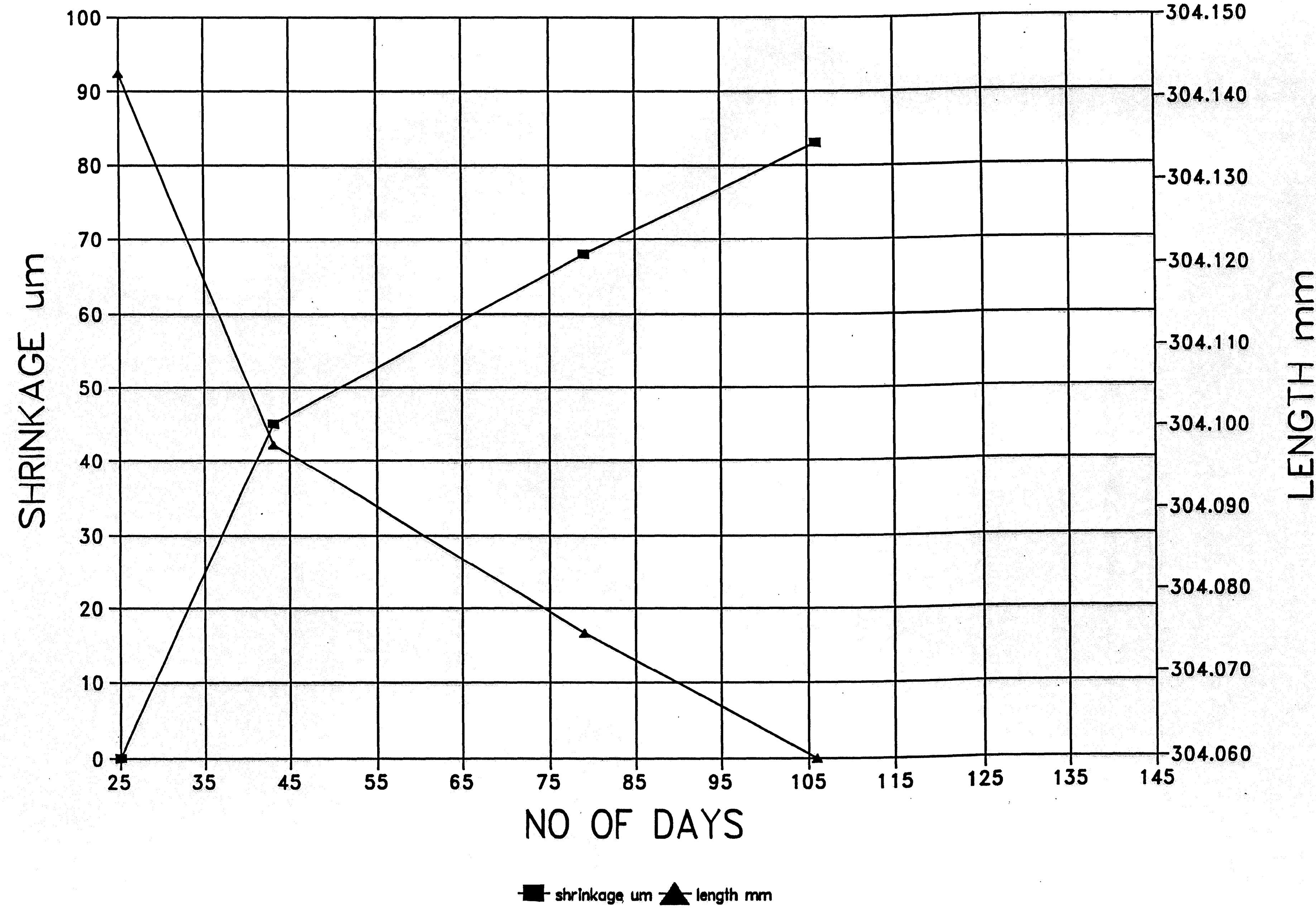
140' Monuments (08/12/96)



Appendix C

Concrete Data

CONCRETE TEST CYLINDER 4-29-96



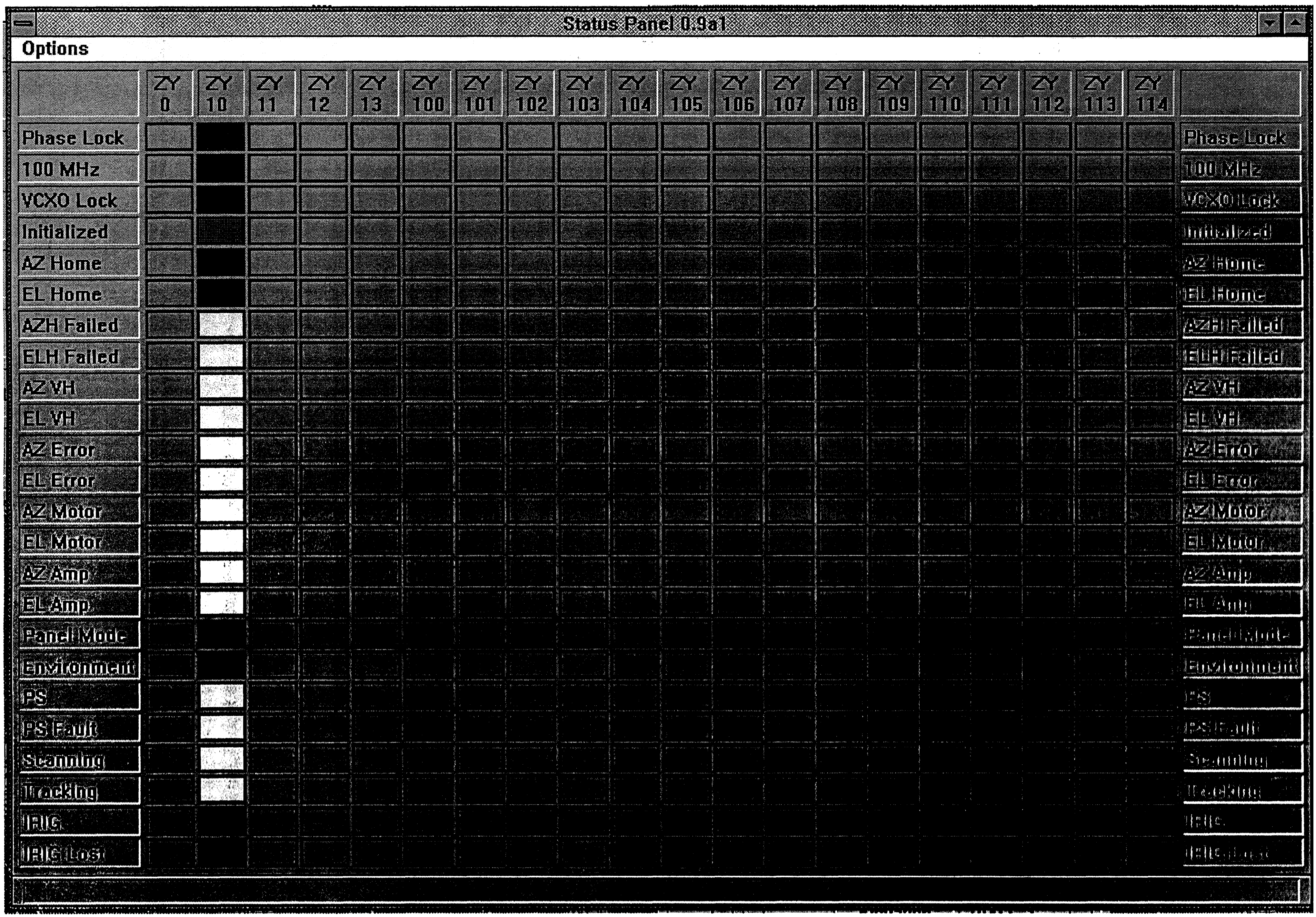
CONCRETE TEST CYLINDER 4-29-96

TEMP., PRESS. & V.O.L. READ FROM HP5508A
HUMID. READ FROM ABBCON - AB62 INDICATOR

DATE	TEMP	HUMID	PRESS	V.O.L.	LENGTHm	REMARKS
4-29-96					304.XXXX	NO MEAS.
5-23-96	18.7C	48%	692.9	751.7	304.1431	25 days
6-11-96	19.4C	63%	692.2	752.6	304.0980	43 days
7-17-96	21.3C	66%	698.0	752.2	304.0750	79 days
8-13-96	19.6C	68%	692.6	752.9	304.0600	106 days

Appendix D

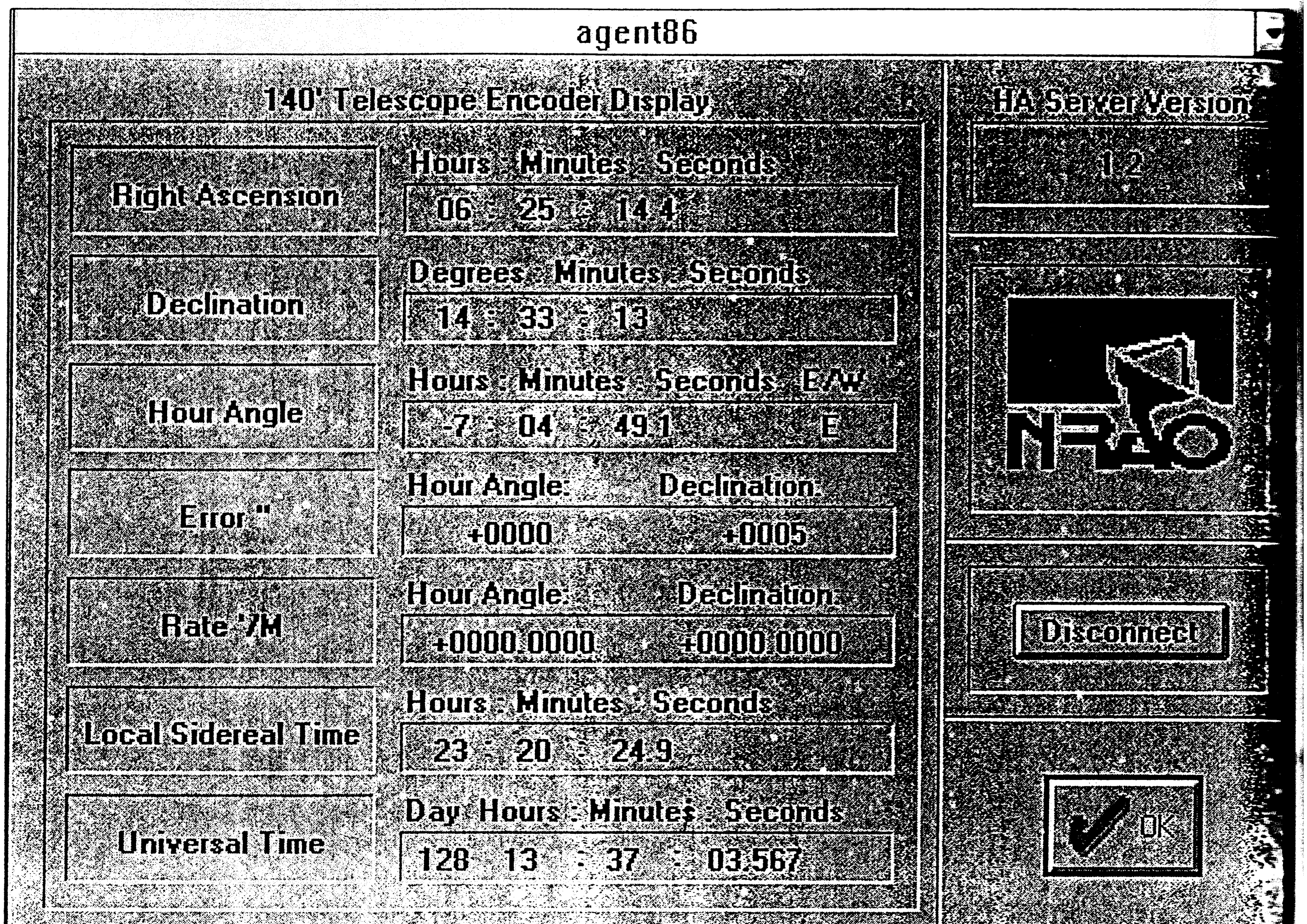
Status Screen


Status Panel 0.9a1
Options
ZY 0
ZY 10
ZY 11
ZY 12
ZY 13
ZY 100
ZY 101
ZY 102
ZY 103
ZY 104
ZY 105
ZY 106
ZY 107
ZY 108
ZY 109
ZY 110
ZY 111
ZY 112
ZY 113
ZY 114
Phase Lock
100 MHz
VCXO Lock
Initialized
AZ Home
EL Home
AZH Failed
ELH Failed
AZ VH
EL VH
AZ Error
EL Error
AZ Motor
EL Motor
AZ Amp
EL Amp
Panel Mode
Environment
PS
PS Fault
Scanning
Tracking
IRIG
IRIG Lost

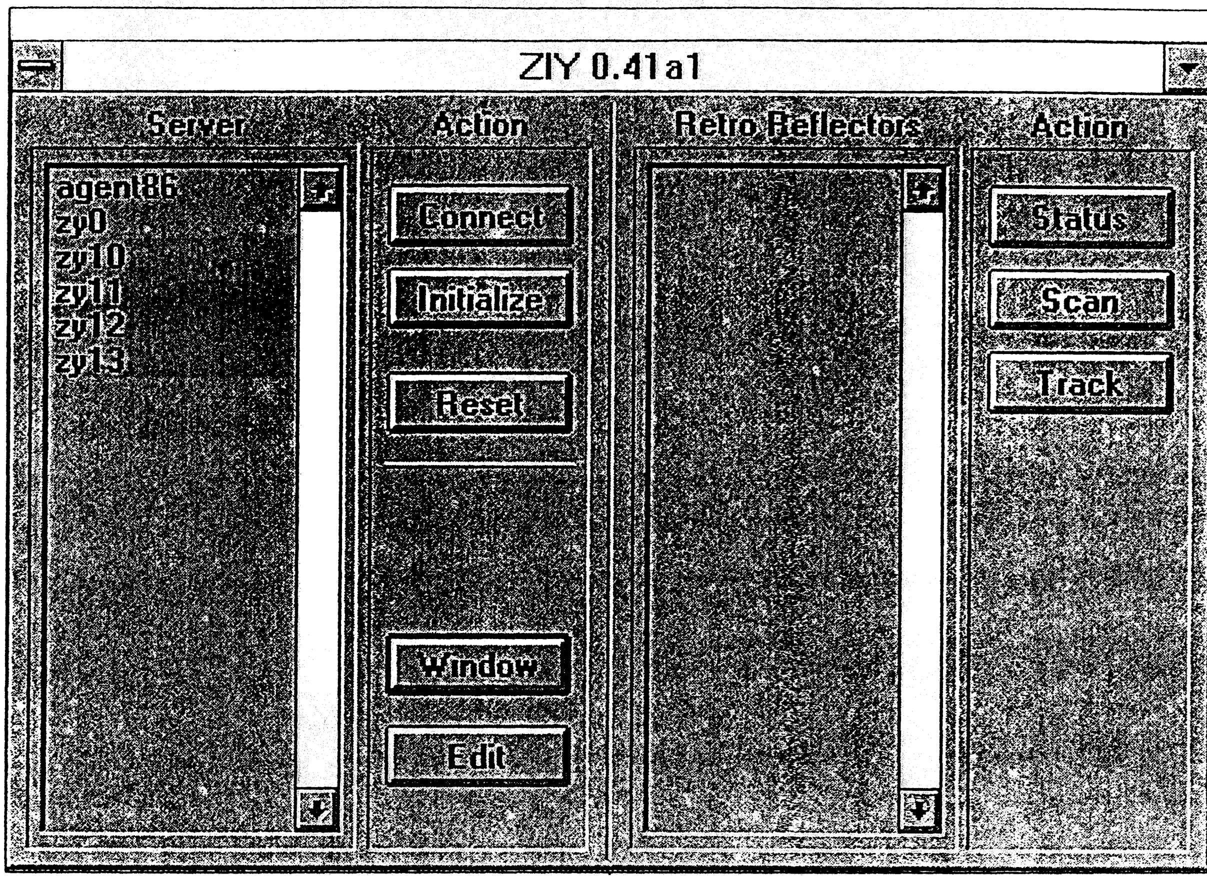
Appendix E

ZIY Screens

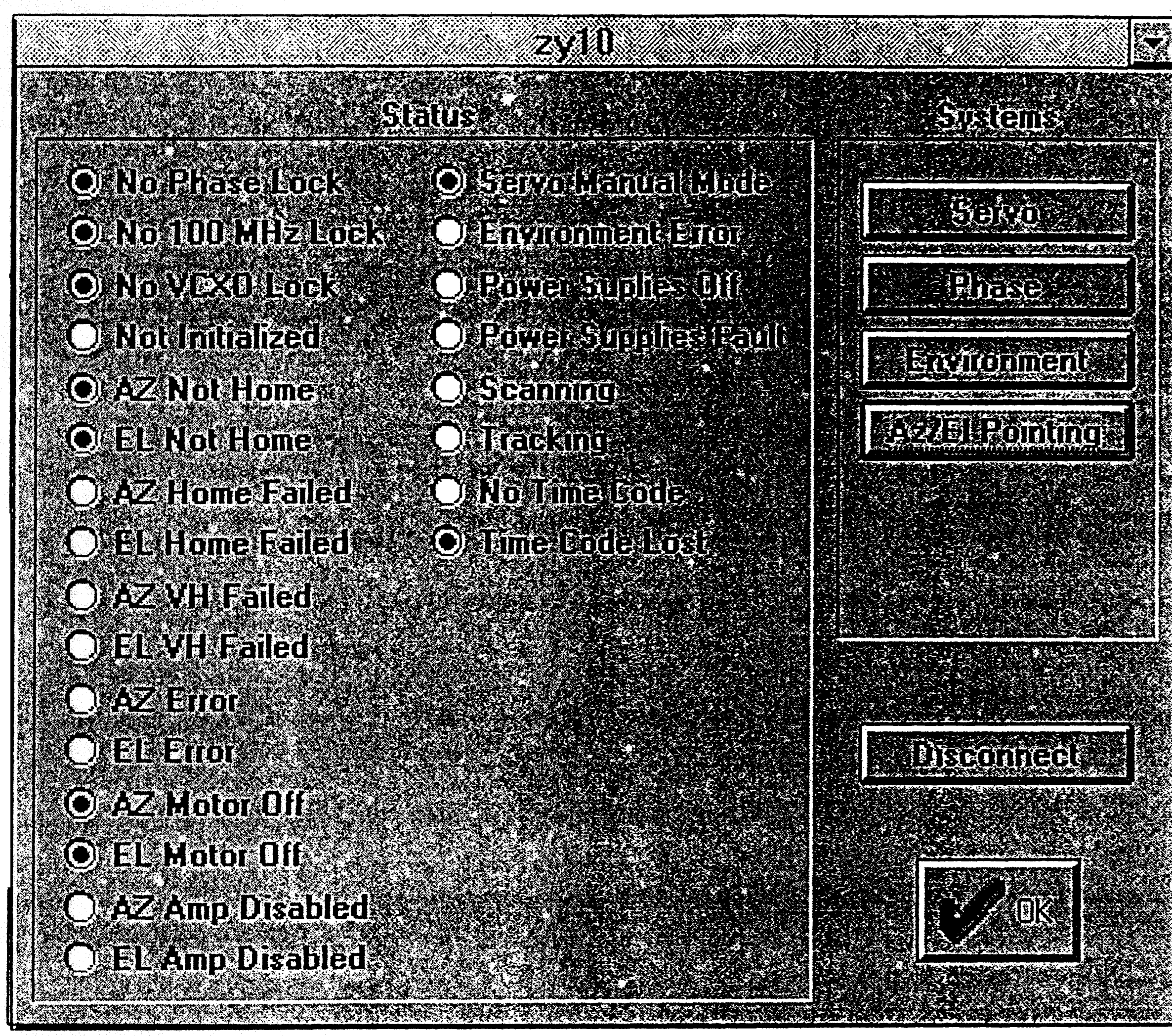
TELESCOPE STATUS WINDOW



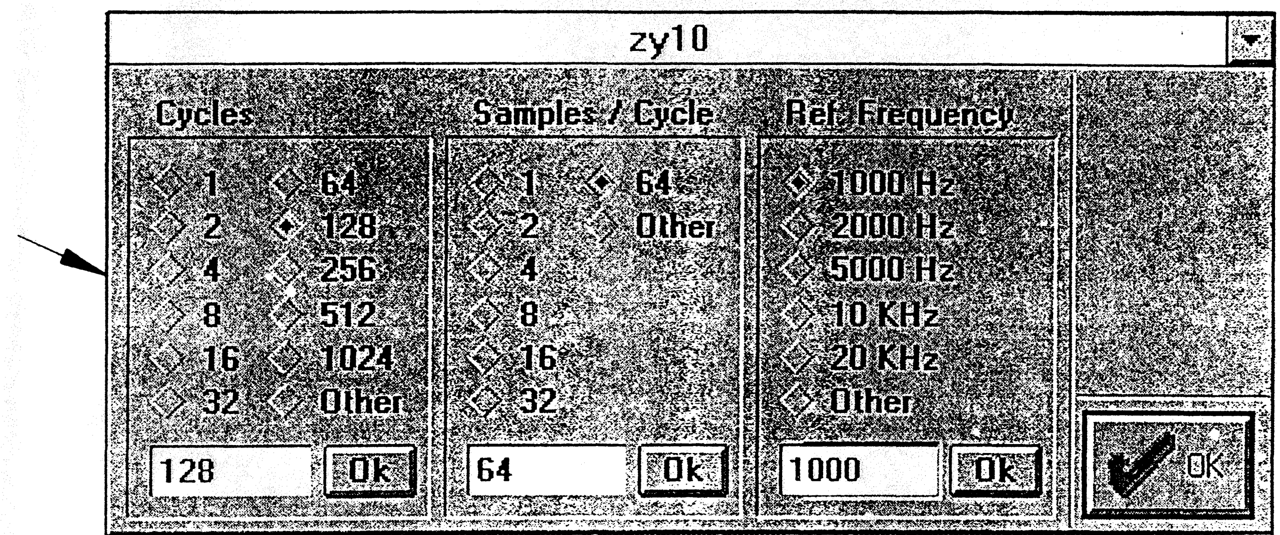
ZIY SERVER SELECT WINDOW



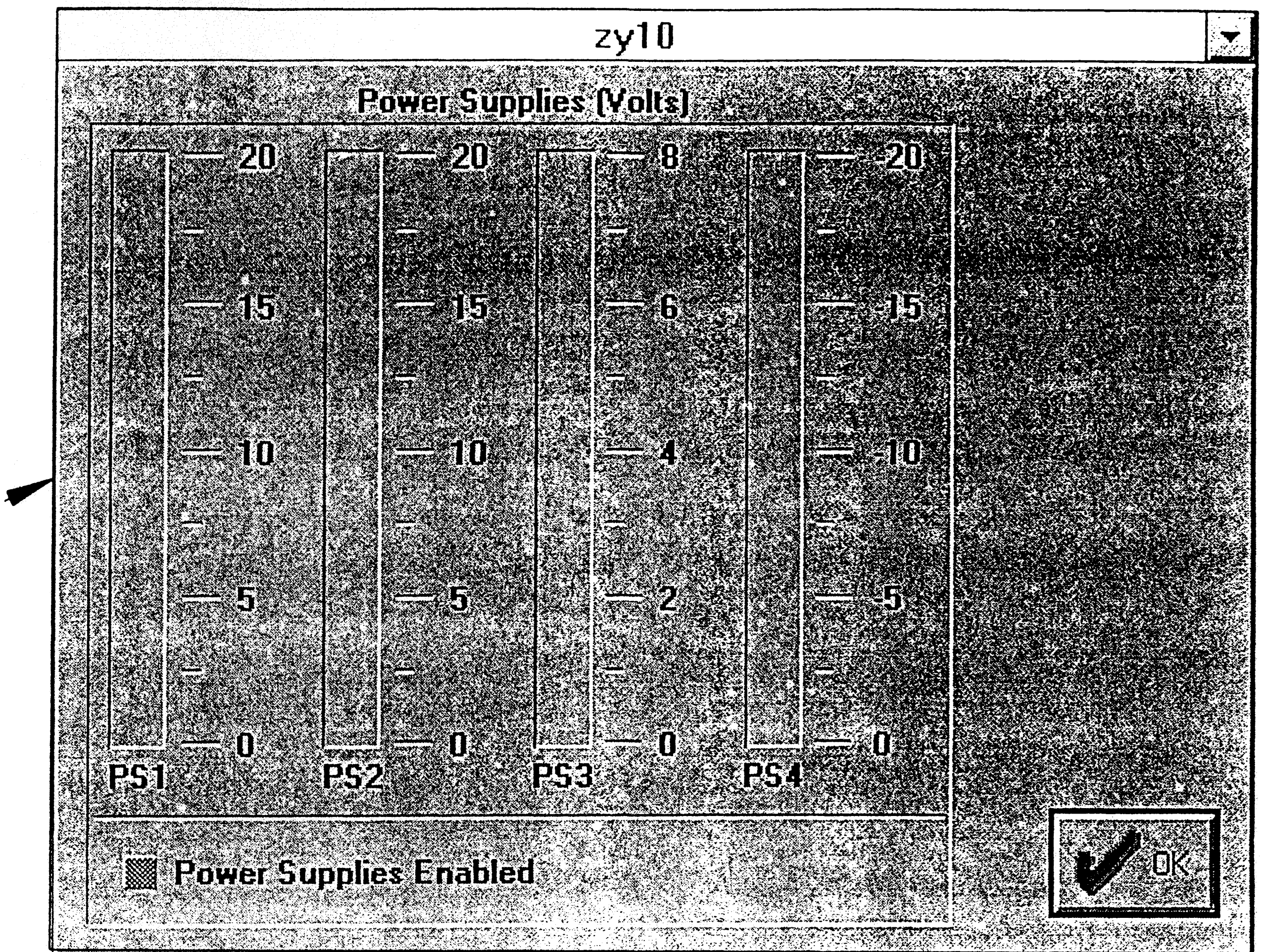
ZY'n' STATUS WINDOW



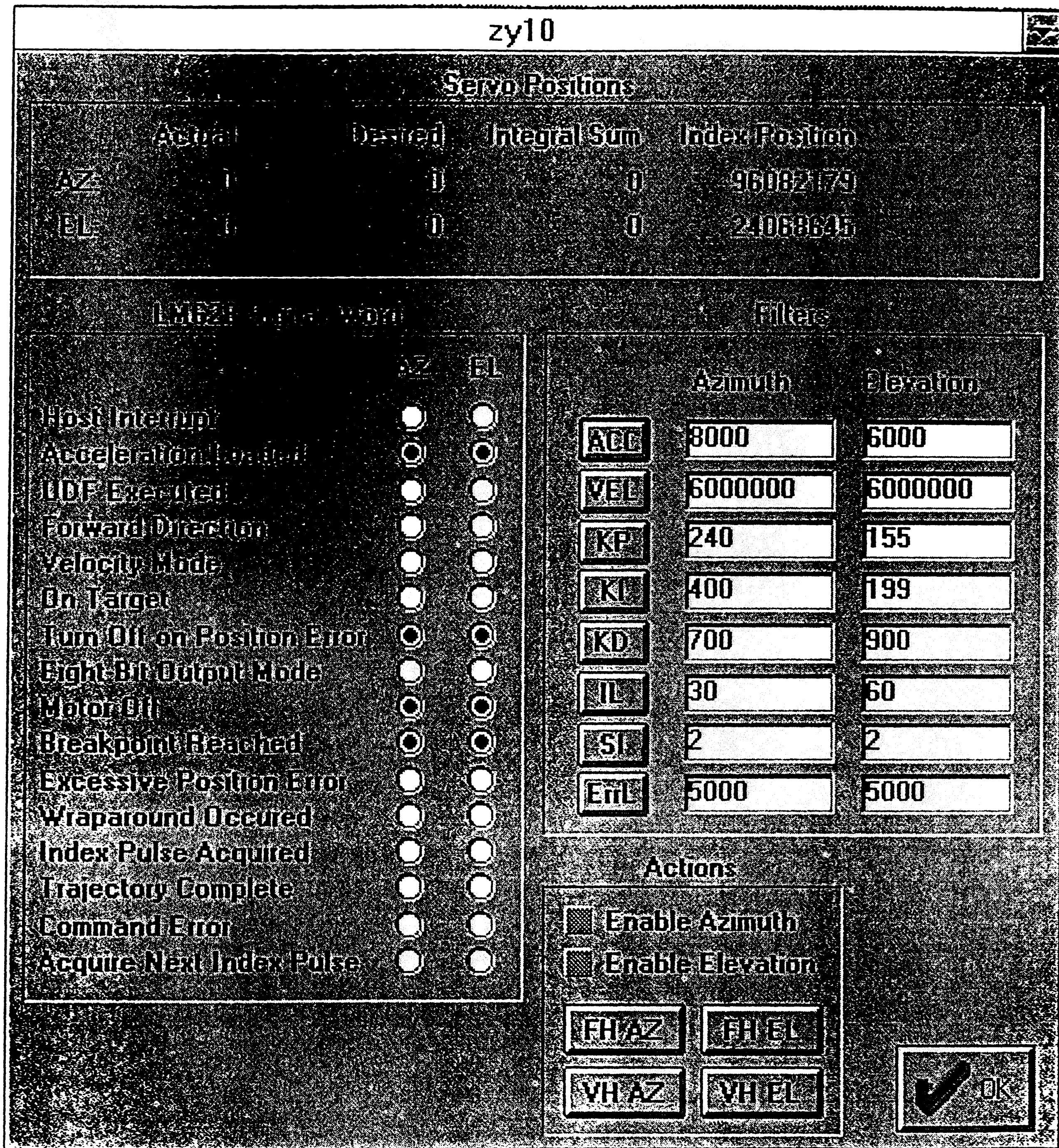
ZY'n' PHASE STATUS WINDOW



ZY'n' ENVIRONMENT STATUS WINDOW



ZY'n' SERVO STATUS WINDOW



ZY'n' AZ/EL POINTING STATUS WINDOW