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A Stretched-Wire, Remote, Position-Sensing Device for EPICS

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ABSTRACT

This report describes design considerations, physical layout, electronics, and PDP-11 computer programming for the Energetic Pion Channel and Spectrometer (EPICS) taut-wire system. EPICS is a high-resolution pion channel and spectrometer facility at Los Alamos Meson Physics Facility (LAMPF). The taut-wires are remote, position-sensing devices attached to the relatively inaccessible channel magnets for monitoring their relative positions.

I. INTRODUCTION

The high resolution ($\Delta p/p = 2 \times 10^{-4}$) of the EPICS channel and spectrometer requires that the magnets be aligned to an accuracy of 0.25 mm. The channel magnets must not move from their aligned position, or we must know how they do move, during and after their enclosure in the shielding wall, and the spectrometer magnet alignment must not be lost owing to twisting of the spectrometer frame as it is being moved. Any effects that might cause magnet motion during data-taking should also be monitored, because random 0.2-mm displacements could shift the channel beam spot as much as 2 mm, equivalent to one resolution width.

The EPICS alignment can be monitored continously by means of the taut-wire system described here. The system is based on, and is conceptually similar to, one in use at Stanford Linear Accelerator Center (SLAC),[1] although it has been completely redesigned here.

Figure 1 illustrates the basic principles of a position-sensitive, taut-wire system. An alternating current $i(\omega)$ is applied to a tightly strung wire (0.25- to 0.35-mm-diam stainless steel in this case). The voltage induced in the opposed pickup coils is $V = i\omega M$ where M is the mutual inductance between the two coils and the wire. This mutual inductance is proportional to the displacement of the wire toward either coil, and is inversely proportional to the gap between the coils. If the two transformers are wired to oppose each other, as shown, the induced signals cancel when the wire is centered. As the wire is displaced, an output signal appears whose phase depends on the direction of displacement, and whose amplitude depends on the magnitude of displacement. An input amplifier adds this signal to one called the reference phase to produce an output signal whose phase is a function of displacement. The readout circuit converts this signal to a dc voltage whose sign indicates the direction of displacement, and whose amplitude is proportional to the amount of displacement. The EPICS PDP-11 computer reads this voltage by means of an analog-to-digital converter.

The transformers in Fig. 1 react to displacements in one dimension only. In practice, we mount two pairs of transformers at right angles to each other about the same wire on a single aluminum disk to form a sensor unit. Such a sensor (Fig. 2) can measure the two directions of wire displacement perpendicular to the wire axis.

II. EPICS CHANNEL AND TAUT-WIRE

The design layout of the taut wires and sensors on the EPICS channel is shown in Fig. 3. Taut wires 1, 3, and 5 are on the north side of the channel, with the others on the south side. Wires 2 and 4 are about 67° from the horizontal. The configuration is sensitive to all possible translations and rotations of the magnets and the separator box. Wherever possible, three sensors are attached to each magnet for each taut wire passing it, providing a substantial degree of redundancy.

Conceptually, a taut wire is a tightly strung, fixed, signal wire surrounded by sensors attached to slightly wandering magnets. But we lack an obvious, rigidly fixed surface on which to mount the wire ends so that we can measure magnet motions with respect to this surface. One reference point could be either the pion production target or the beam profile monitor just upstream from it. The other could be the scattering target at the end of the channel. However, it is not possible to run wires in a straight line between the two points. Because it is more important to monitor the relative magnet positions than to know the exact object and image positions of the whole channel, we chose the central pedestal that supports channel magnets BM02 and BM03 as the reference surface. To this large, rigid mass of steel are attached all of the endpoints of taut

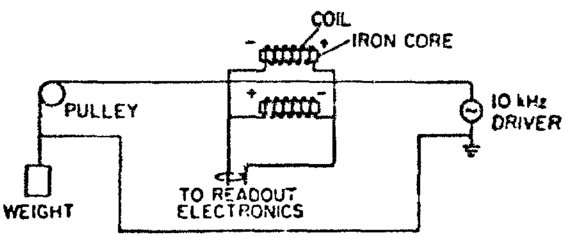

Fig. 1.
Conceptual diagram of a taut-wire unit.

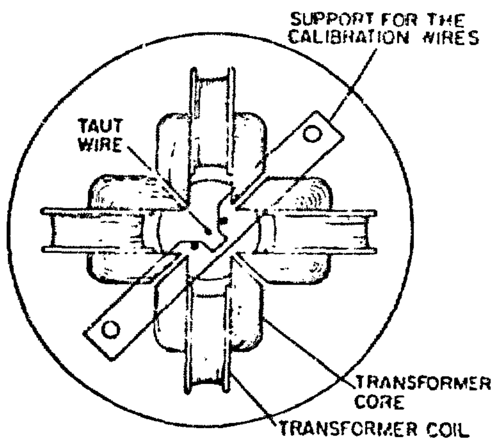

Fig. 2.
Taut-wire sensor configuration.

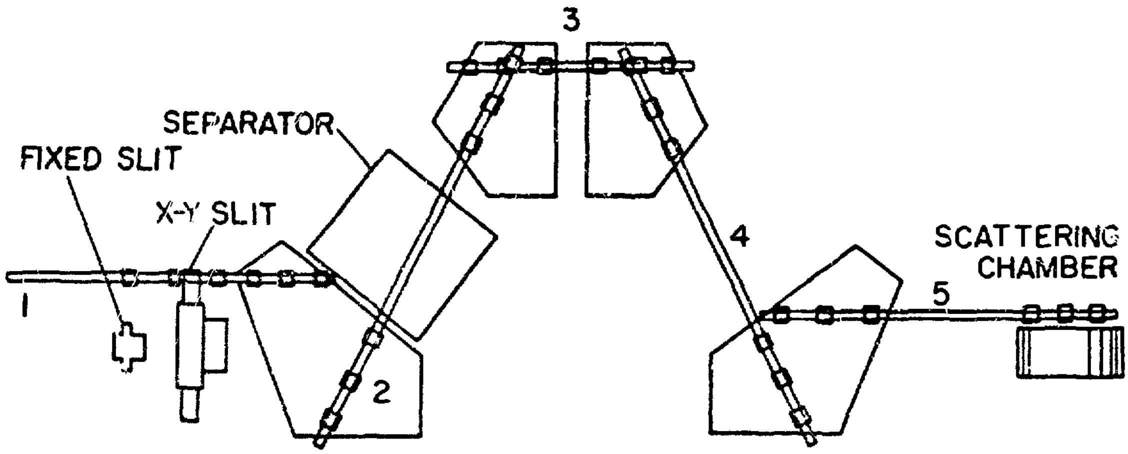

Fig. 3.
Planned taut-wire configuration on EPICS channel.

wires 1, 2, 3, 4, and 5, except for those that could be attached to the profile monitor or to the scattering chamber.

Given this taut-wire layout, channel motions might be analyzed as follows. Any bending magnet may be represented as in Fig. 4. A least-squares-fit program like TWFIT (described later) may be used to calculate the translations and rotations required for transformation from any old to any new taut-wire reading. If the calculated transformations are larger than the errors, there has been a statistically significant magnet displacement.

However, measurement errors make it difficult to detect such motion. Figures 5 and 6 illustrate the expected error. If each sensor has a measurement error of e mils, a translation of the magnet in Fig. 5 can be measured to about $e/\sqrt{3}$ mils. As in Fig. 6, however, where a translation or rotation is determined by the difference between two taut wires, the error is 2-3 e. For typical EPICS channel dimensions the error e appears to be ~0.1 mm--the system's long-term stability. The final accuracy of the system is yet to be determined, but will depend on whether the translations and rotations calculated by the least-squares-fit analyses are larger than the associated errors.

III. ELECTRONIC READOUT CIRCUITRY

The EPICS taut-wire system readout electronics are contained in one NIM bin near the channel. The bin contains one "master" module and eight "16-channel" modules. The latter each contain 16 amplifier circuits, a multiplexer, and a circuit to convert taut-wire readings to dc voltages (Fig. 7). The master module provides the reference phases and multiplexer addresses to each 16-channel module, and routes their output voltages to the analog-to-digital converter (ADC, Fig. 8).

Figure 9 diagrams the input amplifier circuits. The differential amplifier is an LM301AN with a gain of $Ro/Ri \approx 200$. One input to this amplifier is the 10-kHz signal from a pair of transformers wired in parallel and in parallel with a 953-Ω resistor. This configuration was chosen empirically to minimize oscillations in the sensitivity vs wire displacement curve. We believe the oscillations are caused by unequal capacitances between the sensor coils and ground when

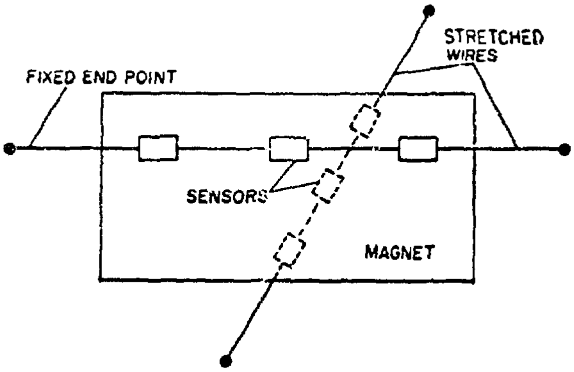

Fig. 4.
Bending magnet with two taut wires, each with three sensors.

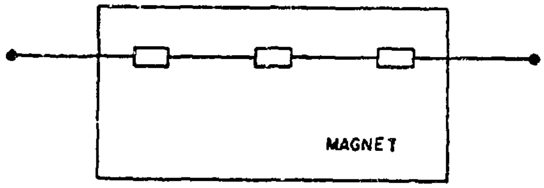

Fig. 5.
Bending magnet with taut wire.

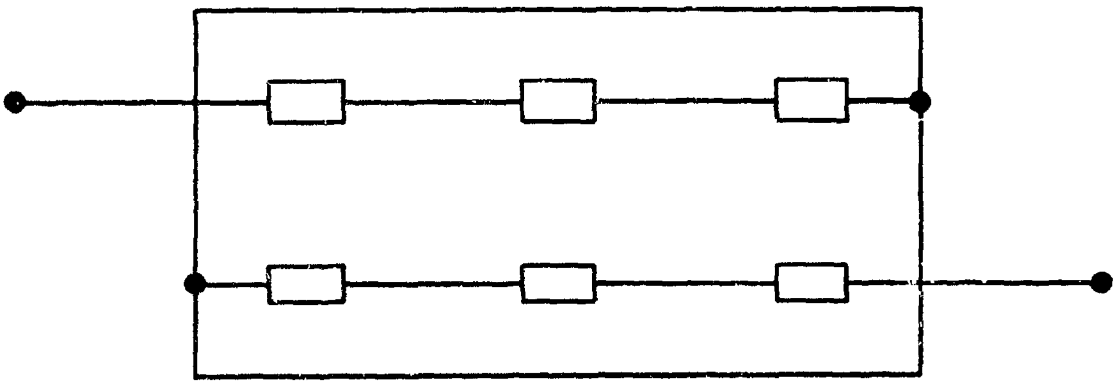

Fig. 6.
Bending magnet with two taut wires.

the coils are wired in series. When the coils are wired in parallel, the capacitances to ground are more nearly symmetric. The 953-Ω resistor creates an LR circuit that also helps dampen the oscillations. This resistor is wired directly across the coils at the sensor to prevent voltage drops across the finite impedance of the signal cable from the sensor to the amplifier modules.

Figure 10 illustrates the integral and differential sensitivities of one transformer pair. Some small fluctuations are apparent in the latter curve, but they are 10 times lower than the oscillations that occur when the transformers are wired in series.

Individual transformer inductance is about 30 mH; for a pair, series inductance is 12 mH and parallel inductance is 4 mH. Signal cable capacitance must be held to no more than 4000 pF to avoid excessive phase shift. The wire-driver circuits (Fig. 8) are constant-current drivers that supply 100 mA peak at 10 kHz to the taut wire, for up to 100-Ω load resistance. Under these conditions

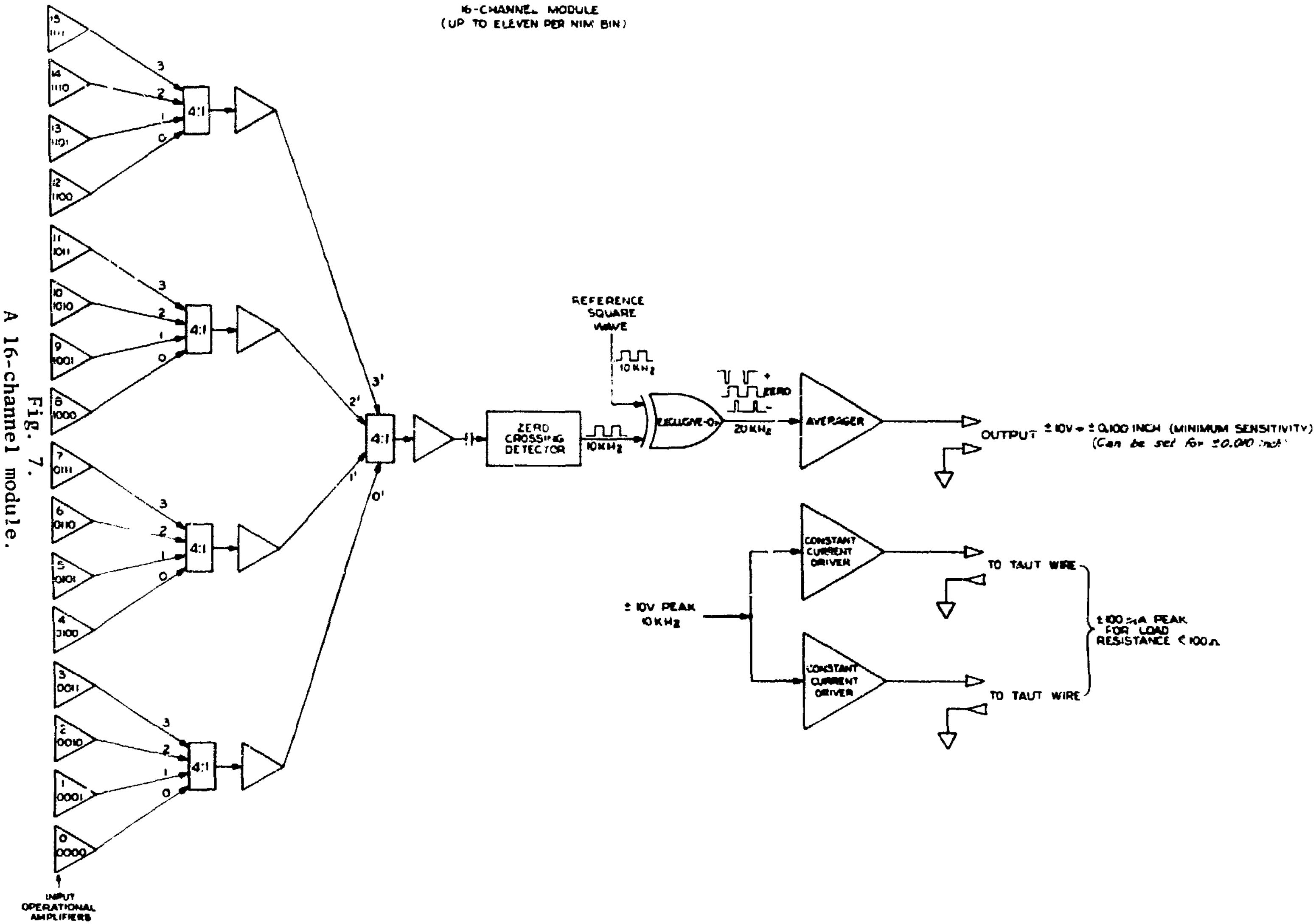

Fig. 7.
A 16-channel module.

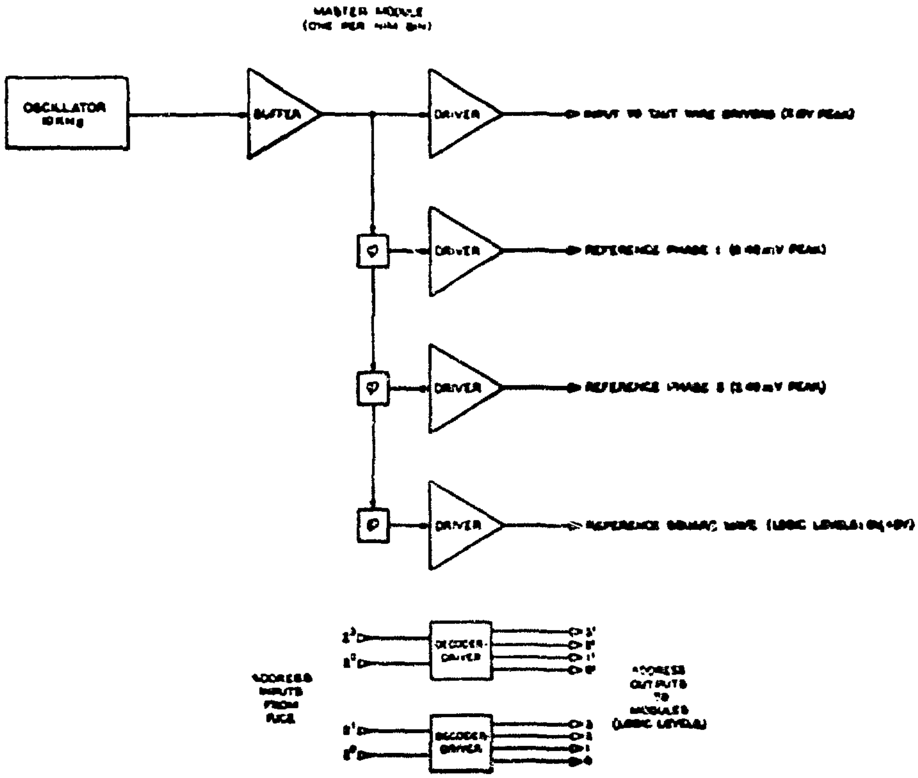

Fig. 8.
A master module.

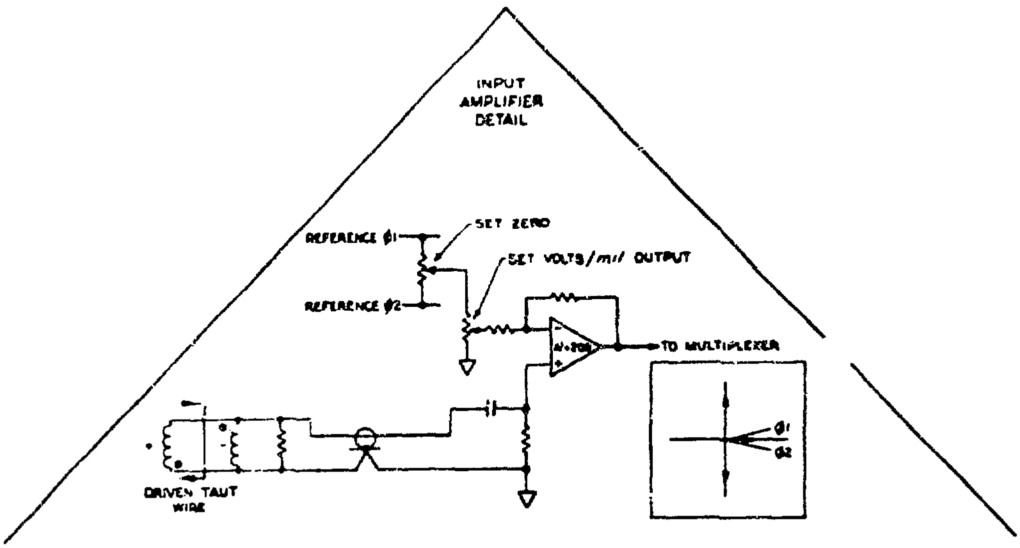

Fig. 9.
A sensor amplifier.

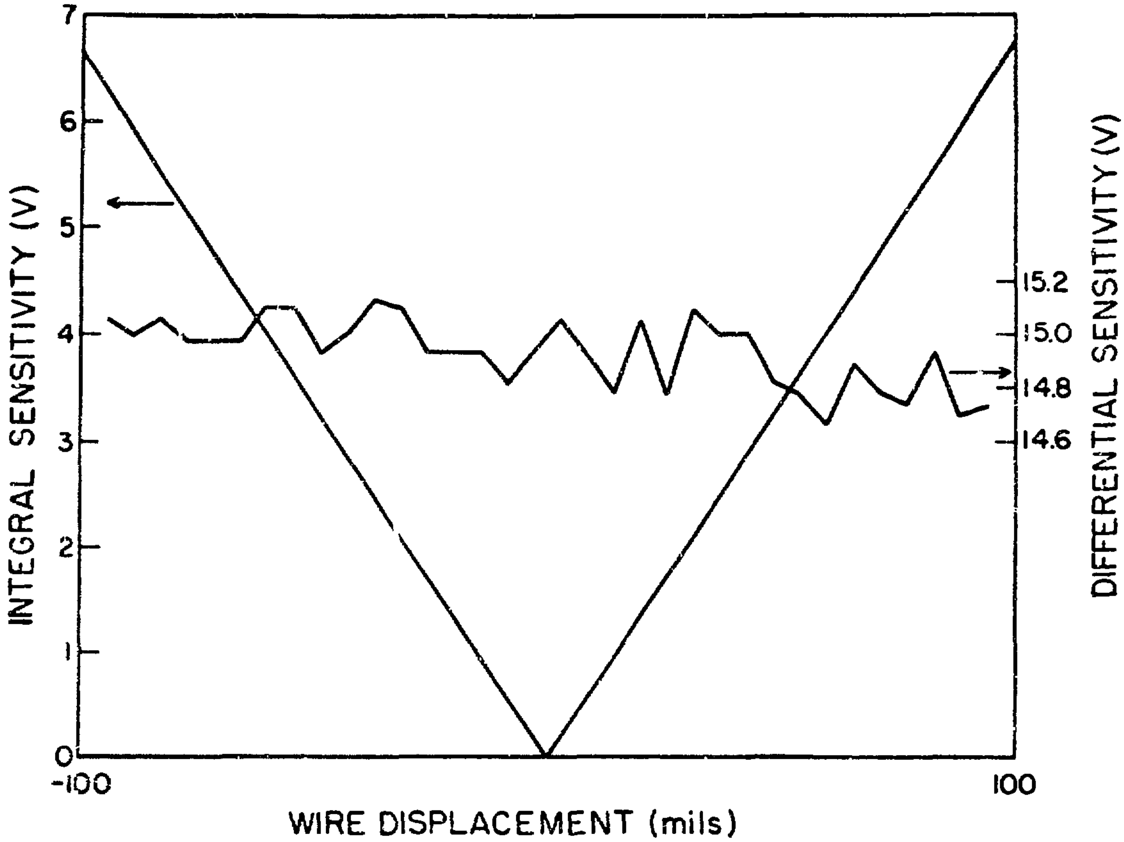

Fig. 10.
Sensitivities vs displacement of a typical sensor.

the input signal to the differential amplifier from the sensors is typically 13 mV peak-to-peak for 2.54-mm displacements.

The second input to the differential amplifier is derived from two ±90-mV reference phases, ϕ_1 and ϕ_2, from the master module. These two phases are about 10° apart and are at about 90° to each of the sensor coil outputs. The reference phases permit setting the zero and the sensitivity of the amplifier output (see inset Fig. 9). The zero adjustment range is ±2 V. One of its important uses is to produce a null output reading when the taut wire is off center, allowing a nonzero reading if the wire breaks — an important diagnostic technique.

Typical wire-displacement and output-voltage sensitivities of 0.25-0.4 mm/V should make it possible to detect 0.01-mm displacements. The maximum dc output voltage from the electronic circuits is 13 V, but the ADC system cannot accommodate >10-V signals. Therefore, it is important to adjust the sensitivity so that wire displacements of up to 4 mm do not exceed the ADC limit. If the sensitivity adjustment range is exhausted, the output voltage can be decreased by decreasing the gain of the averaging amplifier in the 16-channel module.

The multiplexer addresses may be set manually at the master module (LOCAL mode) or remotely by CAMAC (REMOTE mode). In the REMOTE mode, the computer confirms that the addresses are correctly set. Four channels of a KS 3086 output register are used as B-lines (binary command). A binary 1 from the computer closes the appropriate relay in the KS 3086 register. This relay drops the corresponding line of the master module to zero volts, thereby setting the address bit to zero. For example, in the absence of any command from CAMAC, the master module will be at address 15 (1111 binary). The return response to CAMAC is in TTL logic. For a particular master-module address "1" bit, the +5-V line to a KS 3420 binary-data register (L-line) drop to zero volts, which appears as a "1" bit when the computer interrogates CAMAC.

From the multiplexers the signal feeds to a zero-crossing detector that changes the 10-V peak-to-peak sinusoidal output to a +5-V, 10-kHz square wave, preserving the signal phase. A capacitor removes from the input to the zero-crossing detector the various dc offsets of the individual channels.

Both the output from the zero-crossing detector and a +5-V, 10-kHz reference square wave from the master module are fed into an exclusive-or gate. The 20-kHz output of this circuit varies from 3.1 to 1.9 V dc, depending on the relative phases of the sensor input amplifier and on the reference phase (Fig. 7).

The signal then feeds a signal-averaging circuit, another LM 301 differential amplifier in the 16-channel module. The reference voltage for this amplifier is about 2.5 V, and the gain for input voltages other than 2.5 V is given by Ro/Ri = 17. Under these conditions, the voltages described in the preceding paragraph are amplified to ±10 V.

The integration-time constant of this circuit is τ = RC = 72 ms, a compromise between speed of readout and the resultant error due to ripple. After an input signal change, this circuit is ready to be read by the ADC in 100 ms. Ripple error is 15 mV, which corresponds to 0.005 mm for a typical sensitivity.

The output voltage from each signal-processing circuit is hard-wired through the master module to one channel of an Analog Data Systems (ADS) ADC, which in turn is hard-wired to a KS 3420 input register in CAMAC. When the computer is used to select a particular address in a 16-channel module, the output voltage from that address is simultaneously presented to the ADC system for every 16-channel module in the NIM bin. Thus, it is unnecessary to select a module address by other means.

Each ADS unit contains 64 input channels and 4 amplifiers, with 4 sets of multiplexing units for choosing which of 16 channels is to be read by an amplifier. The taut-wire system has been assigned 11 channels for the HPICS channel and 11 channels for the spectrometer. For the taut-wire channels the corresponding input amplifiers must be set to a gain of ±10 V. These amplifier outputs then drive a sample-and-hold circuit which provides a "clean" input to the ADC. The analog signal is converted to an 11-bit (0-2047)-plus-sign parallel output (2's complement) to the KS 3420 register. The readout precision of this ADC is then 1 part in 2000, a further error of about 5 mV (0.002 mm) in taut-wire position. The multiplexer input address is from a six-bit address word in the KS 3420 register.

The total time required for "enable conversion" and "end of conversion" signals is not more than 135 ms per channel. By means of the "end of conversion" signal, the ADS system manages its time requirements. Taut-wire readout electronics that precede the ADS require at least 100 ms for addressing and signal averaging. This time is allowed for by inserting a 2-s time delay between address changes in the readout program (App. B).

IV. EQUIPMENT DETAILS

Most aspects of the taut-wire system are well described by blueprints of sensor units and mounting hardware, cable layout prints, electronic schematics, and the CAMAC channel list. Some of the construction and assembly details not so covered are discussed here.

A. Transformers

Figure 11 illustrates one of four transformers used in a sensor assembly. Each transformer has an inductance of approximately 30 mH, a Q of 7-8 at 1 kHz, and a resistance of 4 Ω. The ferrite core is built up of laminations of 0.05-mm Selectron tape, an unoriented silicon steel. The coils consist of 300 turns of No. 30 copper wire with a radiation-hardened coating of ceramic powder covered with teflon. The coils are supported by radiation-hard Mycalex board. It was necessary to lap the faces of the ferrite cores to make them flat enough to permit mounting four tightly together. Other irregularities in transformer construction made it necessary to glue them in place, so that reasonably good alignment could be obtained by skewing or tilting them with respect to the mounting disk as they were glued. Sauereisen cement, a ceramic powder with a potassium silicate binder, was used for this purpose. This cement is highly radiation-resistant, but is susceptible to moisture or mechanical shocks. A Glyptal coating was used to protect the cement from moisture.

B. Other Radiation-Hard Materials

The high-radiation fields near the pion-production target require some additional precautions. The calibration wires inside each sensor unit are mounted inside ceramic tubes, and the electrical feedthroughs to the sensors are made of ceramic material. The stretched wire itself is insulated from ground by ceramic and glass. The signal return cable is Fiberglas-insulated, shielded, twisted-pair or RG-180-U coaxial cable with polyethylene dielectric.

C. Stretched Wire

The stretched wire with its assiciated sensors, housings. and cable is known as a taut-wire assembly. The wire itself is 0.254-mm-diam stainless steel. For a 3.66- to 4.57-m length, the wire provides a 50- to 70-Ω load on the driver circuit. The resistance of the RG-180 cable, 1 Ω/m, raises the load close to the 100-Ω limit.

The wire is clamped at one end and is passed over a glass rod to a 2.7 kg steel weight represents about a quarter of the wire's yield strength. At this tension, the wire is stretched by 3 mm/m. Early attempts to eliminate the hanging weight by stretching the wire and then clamping it at both ends were unsuccessful. The weight passing over

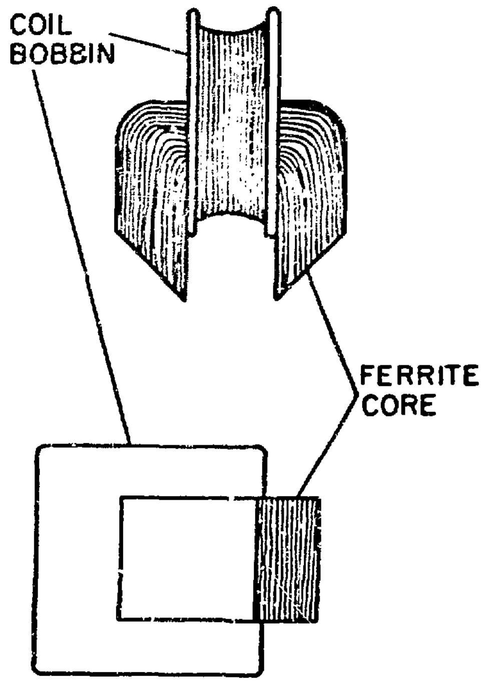

Fig. 11.
The sensor transformer element.

the glass pulley is necessary to maintain constant tension in the wire regardless of temperature variations. The wire hangs in the form of a catenary curve. A 4-m-long wire would have a center sag of 0.15 mm with a tension of 5.5 kg, 0.30 mm with 2.7 kg, 0.9 mm with 1 kg, and so forth. Thus any release of tension due to slippage or thermal expansion, among others, could appreciably effect the taut-wire readings.

D. Wire-Supporting "Pulley"

It was difficult to find a suitably rigid, insulated, radiation-hard, frictionless surface over which to pass the wire at the weighted end. Our choice of a rigidly clamped, nonrotating glass rod with a circumferential V-groove (impressed by a hot, pointed tool on a lathe) to confine the wire worked well in bench tests. But the rod is not entirely frictionless in use. This may be due to deformation of the glass in the V-groove under the pressure of the loaded wire. Our solution was to coat the glass rod and groove with molybdenum disulfide. A better solution may be to use an insulated ball-bearing assembly. This was not done with EPICS because of very tight space restrictions, but it is being done in the taut-wire system for the LAMPF high resolution spectrometer. In this case it is important to use precision-machined, "preloaded," double ball-bearing assemblies. Because the wire passes over the ball-bearing shaft, any transverse motion in the bearings affects the taut-wire readings.

E. Magnetic Field Effects

The original design called for steel tubing to surround the length of the stretched wire, to eliminate the small interaction between sensors and channel-magnet fields observed in a prototype taut wire. In tests of an advanced prototype of the final design, wire deflections of up to 0.1 mm were recorded during a 60- to 90-s period after switching on or off the EPICS channel magnet to which the wire was attached.

The sign of the deflection was independent of whether the field was raised or lowered, suggesting an effect due to eddy currents in the sensor assembly or in the magnet side plate on which it was mounted. Such transient effects should not be troublesome.

V. TUNEUP AND CALIBRATION

Mounted in each sensor unit are two rigid wires that, like the stretched wire, pass through the hole between the transformers (Fig. 2). These are the "upper" and "lower" calibration wires. By switching the driver signal from the stretched wire to the fixed calibration wires, it is possible to correct for any electronically caused shifts in the output readings, because these wires will cause a constant reference output. Bench testing and calibration procedures for the sensors and electronics are as follow:

1. Set up a 16-channel module in a NIM bin provided with the proper inputs as shown in App. A. For any unused driver circuit, remove the appropriate IC, either A21 or A22, to prevent noise in the circuit.

2. Remove IC A23, thus disconnecting the zero-crossing detector from the exclusive-or gate. In the absence of all signals except the reference square wave, the signal-averaging circuit should now have zero output after warming up.

The adjacent potentiometer (200-Ω resistor in reference-voltage input to the LM301 amplifier) may need adjusting to give this zero at the digital voltmeter (DVM) output from the master module. Replace IC A23.

3. Suspend a stretched wire through one sensor unit. Because the position of the driver return wire can create electrical offsets in the sensor, route this wire in the orientation it will have on the finished assembly. All possible offset sources should be similarly localized or stabilized. Attach this sensor's output to the 16-channel inputs with which it is to be installed. Examine the outputs of the amplifiers at TP1 (see App. A) and of the signal-averaging circuit at the DVM "out" on the master module. For each of the 16 channels on the circuit board, the upper potentiometer is the sensitivity adjustment, and the lower is a zero adjustment.

4. Set the sensitivity potentiometer to 0 mil/V. This sets the reference phase signals ϕ_1 and ϕ_2 to zero. The amplifier circuit output is now determined solely by the input from the sensor.

5. Move the stretched wire laterally in the sensor until the amplifier output (TP1) is at its minimum. This point is the "electrical zero" of the sensor. Readjust the sensitivity potentiometer until the amplifier output is 10 or 11 V peak-to-peak. This output should correspond to a sensitivity of about 13 mils/V. If the sensitivity cannot be set to the desired range, alter the signal averager gain by changing the 154-kΩ output resistor.

6. Now adjust the zero potentiometer to obtain zero output at the DVM. This zero is to a small extent a function of the sensitivity.

7. After completing the above steps for both horizontal and vertical sensor channels, move the stretched wire by known distances and record

HSENS - horizontal sensitivity, and
VSENS - vertical sensitivity.

8. Switch the driver signal to one calibration wire and then the other and record

HVL - horizontal voltage, lower wire,
VVL - vertical voltage, lower wire,
HVU - horizontal voltage, upper wire,
VVU - vertical voltage, upper wire.

Add a resistor in series with the calibration wires to provide the same driver load as the stretched wire.

Appendix B shows HSENS, VSENS, HVL, HVU, VVL, and VVU from the bench tests for each sensor. Sometimes it was impossible to calibrate a sensor at the electrical zero because the stretched wire was not well centered in the sensor aperture at that reading, an effect largely due to difficulty of manufacture. Zero potentiometer settings were used to offset this difficulty and were recorded in the taut-wire calibration charts.

The above measurements will not be exactly repeatable when the sensors are installed in their final positions. Unless the same amplifier is used, the zero offset and sensitivity will not be preserved. Unless the same driver circuits are used, there may be up to 20-mV offsets. Removal of the modules from the test extender on which they were adjusted may cause 100-mV offsets. If the master module or 16-channel module is changed, or if the driver return wire is displaced substantially from its calibration position, there may be 1- or 2-V offsets.

These effects can be corrected for by again switching the driver to the calibration wires and remeasuring the induced sensor voltages. The results, HVLNEW, HVUNEW, VVLNEW, and VVUNEW, may be used to compute new voltage offsets and sensitivities HZNEW, VZNEW, and HSNEW, VSNEW.

Suppose that the horizontal position of the wire during bench calibration is

x = HSENS * voltage. (1)

After installation or any electronic change or drift,

x = HSNEW * (voltage + HZNEW). (2)

If the relative sensitivities at the center of the sensor and at the calibration wire positions are unchanged,

HSNEW = HSENS * (HVU-HVL)/(HVUNEW-HVLNEW), (3)

and if the sensitivity at the sensor center equals that at the calibration wires,

HSNEW = (HVL * HVUNEW-HVU * HVLNEW)/(HVU-HVL). (4)

A computer code TWCAL is used to measure and generate the "NEW" offsets and sensitivities, Eqs. 3 and 4, and their counterparts in the vertical orientation. The taut-wire readout code TAUT uses Eq. 2 and the latest offsets and sensitivities from TWCAL, to automatically renormalize taut-wire displacements to the latest calibration. Present results indicate that this procedure eliminates 80-90% of spurious wire-displacement readings produced by module exchanges and electronic drifts.

Note that during the bench calibrations of the sensors it was occasionally necessary to introduce zero offsets or large sensitivities in order to satisfy two constraints: (1) the stretched wire must be centered in the sensor aperture; and (2) calibration wire voltages must be less than 10 V. To aid in meeting the second constraint, a mu-metal shield was placed in the front aperture of the coils to shield them from effects induced by bending the signal wires to feed-throughs near the coils.

If the sensors are wired to different amplifiers during installation, these offsets may be corrected for by the above recalibration and renormalization procedure. This procedure could, however, leave the stretched wire substantially off-center, even though the voltage readings are near zero. This situation can be prevented by first ensuring that the calibration wires read close to their bench readings.

VI. USE OF THE COMPUTER PROGRAMS

The following programs have been written for taut-wire readout, calibration, and analysis:

Program :	TAUT	TWCAL	TWFIT
Subroutines :	TWREAD	TWREAD	TWLSQF MATINV
Files Read :	TWDATA TWCALI	TWDATA	TWDATA TWPOS
Files Written:	TWPOS	TWCALI	

Program TAUT reads the taut wire by means of CAMAC as described earlier. Sensor identities and bench calibrations are taken from TWDATA. The latest voltage offsets and sensitivities are taken from TWCALI. Wire displacements are calculated using Eq. (2). Wire displacements are then stored in TWPOS for use by the analysis program TWFIT. A listing of TAUT appears in App. B.

TWCAL reads the sensors by using CAMAC, with the driver signals connected to the calibration wires. Before calling the UPPR or LOWR commands, one must manually switch the driver to either the upper or lower calibration wires. The UPPR and LOWR commands will then read the appropriate sensors and compare their values to the last calibration results stored in TWCALI. After both wires have been read, the command SAVE is used to calculate the new offsets and sensitivities using Eqs. (3) and (4), and to store them with the voltage readings in TWCALI. A listing of TWCALI appears in App. B.

The TWFIT is used to compare the original taut-wire positions (from TWDATA) with the latest positions (from TWPOS). A three-dimensional, simultaneous, linear, least-squares fit to the first-order transformation equations

$$X_f = \phi Y_o + \psi Z_o + a,$$

$$Y_f = \phi X_o + Y_o - \theta Z_o + b, \text{ and}$$

$$Z_f = \psi X_o + \theta Y_o + Z_o \;\; c \tag{5}$$

can then be made for each magnet. TWPOS also requires the positions and angles of the sensors with respect to the magnets. The input and output parts of this program still require some work. The least-squares-fit part has been written and tested.

VII. OPERATION RESULTS

Configuration changes about the EPICS channel (shielding, plumbing, etc.) precluded installation of wires 1, 5, 6, and 7. The functions of 1 and 5 will be replaced by visual alignment procedures. Wires 6 and 7 were redundant to the functions of 2, 3, and 4, so no information was lost by their elimination.

The system is now fully operational with wires 2, 3, and 4. Primary emphasis is on monitoring the relative magnet and separator positions while emplacing the shielding in the Line A-EPICS area. Daily, sometimes twice-daily, readings are made and are correlated to the shifting of massive objects in the immediate channel vicinity.

The channel has good, long-term stability of about ±0.05 mm. Occasional fluctuations occur when shielding is moved. Figure 12 is a graphic analysis of the motions of taut wire 3 for about one month. The sharpest spike reflects a movement of the shield doors over the A1 target area of the main beam line. Sensors 2EAST horizontal and 3EAST vertical are high sensitivities, so they exaggerate every motion. But the magnitudes of the shifts are fairly uniform in most sensors.

Through use of the taut-wire system we were able to keep track of the relative magnet positions, indicate where mechanical couplings between magnets could be strained, and check the stability of the EPICS channel with respect to changes in shielding configurations.

ACKNOWLEDGMENTS

We would like to acknowledge the work of Kenneth Chellis, LASL Group MP-10, on the original prototype taut wire and on the very difficult installation of the present system. We most especially acknowledge the work of James H. Richardson, Group MP-1, on the circuitry designs and the extra time he spent in correcting and maintaining those circuits through various design changes.

We also thank Carl Larson and Kelly Kanizay, of the University of Colorado, who did much of the assembly and testing.

REFERENCE

1. W. K. Panofsky, "The use of a Magnetic Pickup as an Alignment Indicator with a Stretched-Wire Technique," and W. F. Marshall, "Proposed Systems and Circuits for Magnetic Alignment Pickups," SLAC-TN-65-74 (1965).

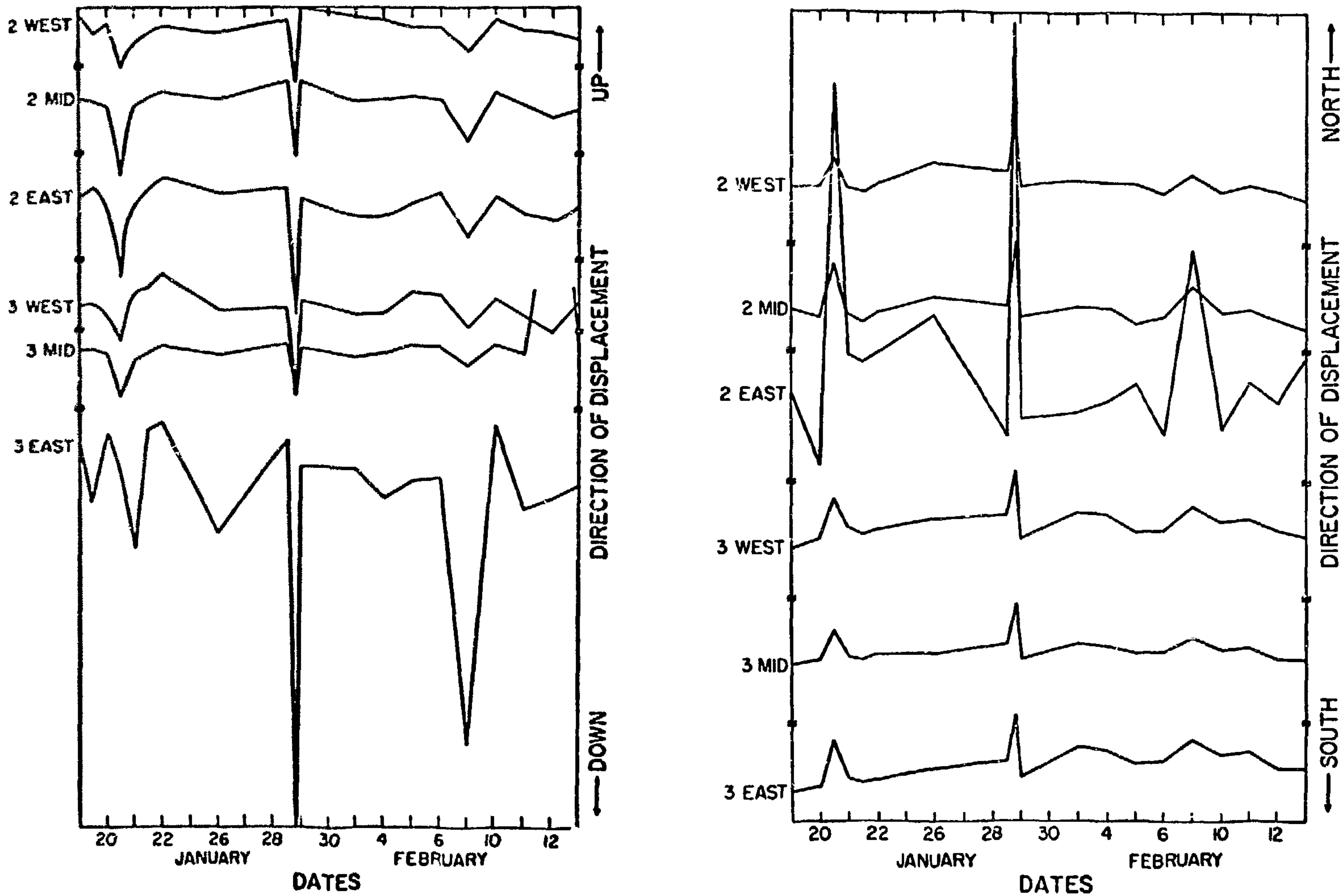

Fig. 12.
Horizontal (left) and vertical (right) fluctuations of taut wire 3. Traces of all sensors, labelled by magnet number and relative position, are compared. Average fluctuations ≈ 0.1 mm.

APPENDIX A

READOUT ELECTRONICS

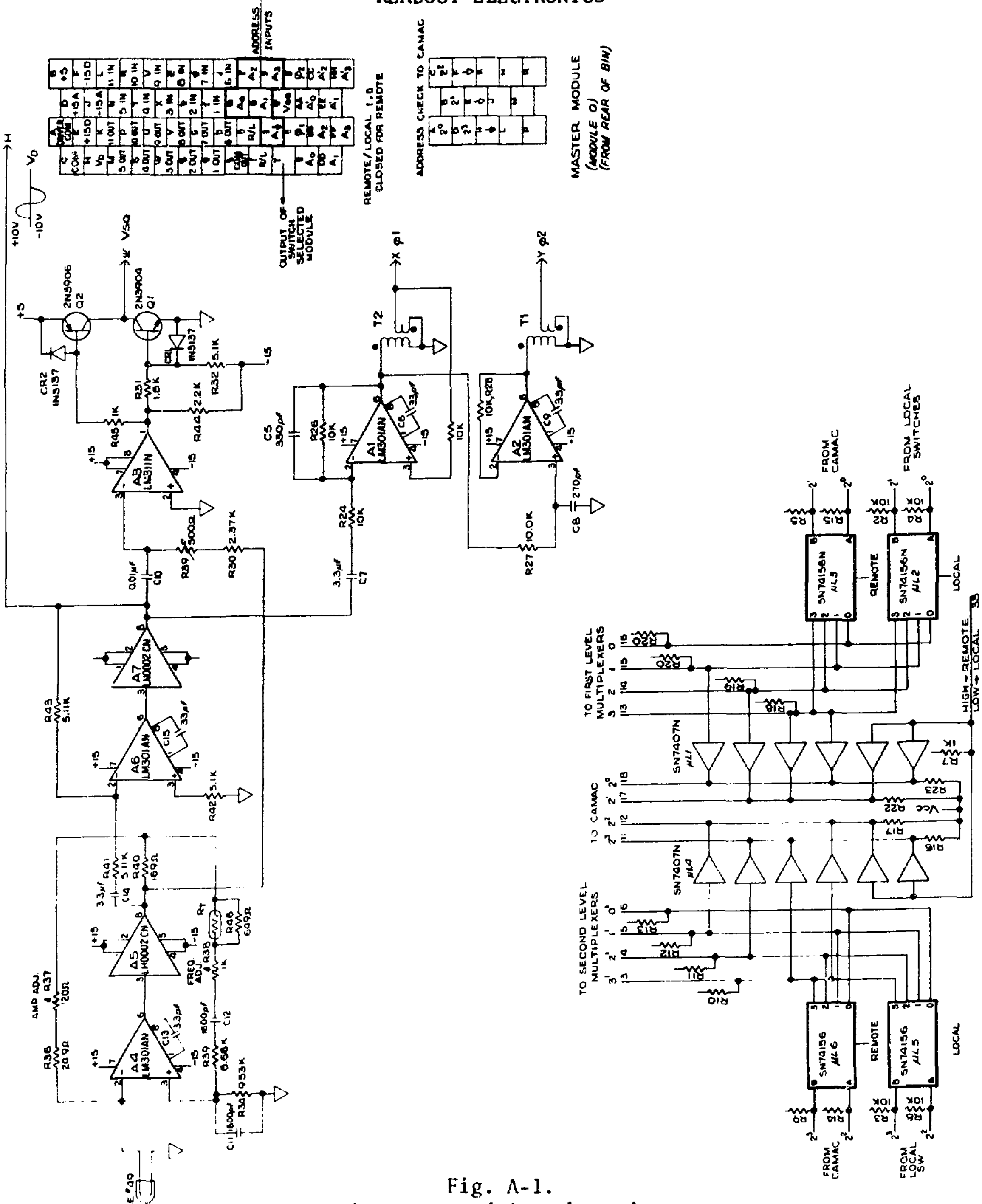

Fig. A-1.
A master module schematic.

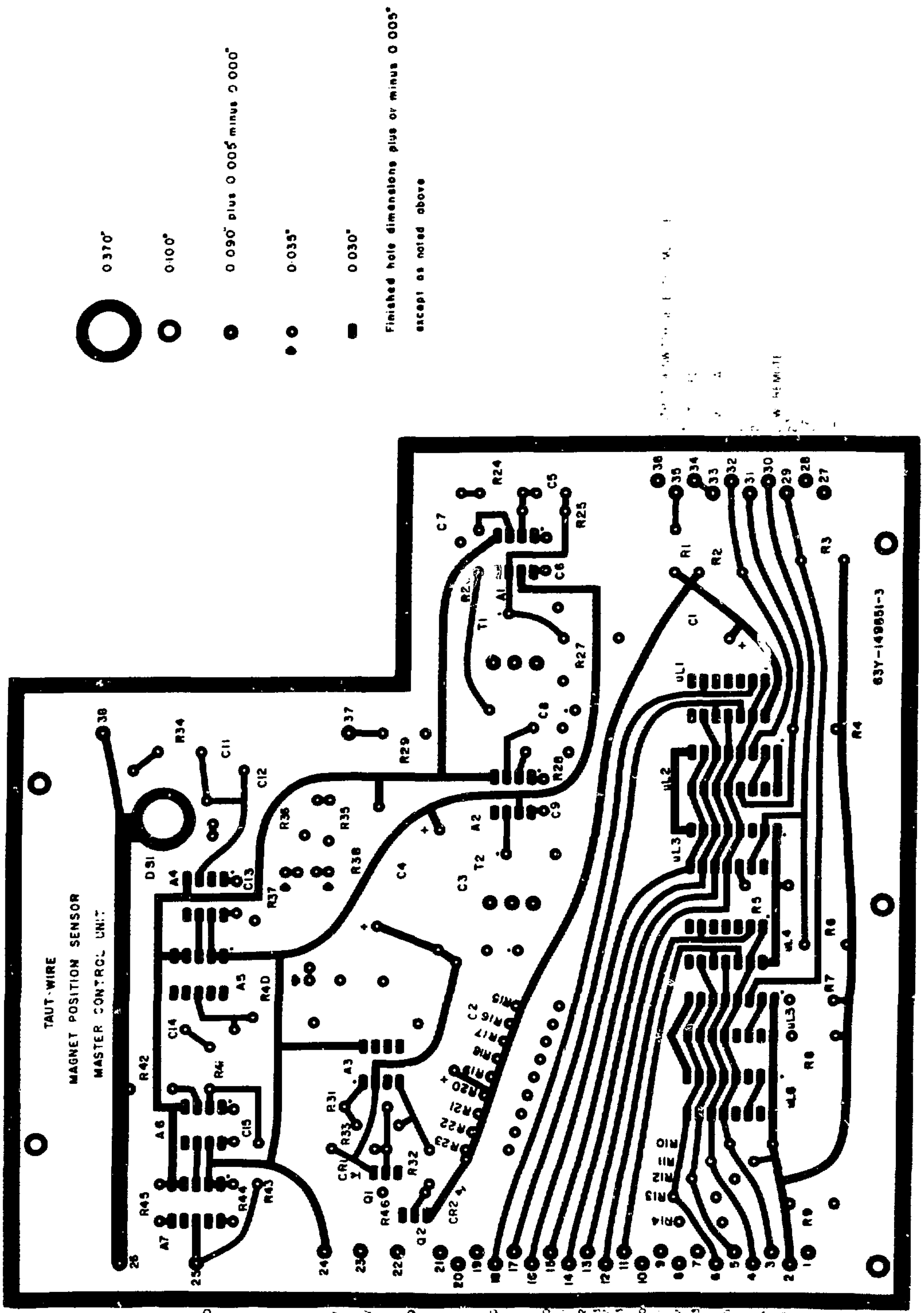

Fig. A-2.
Master module pc board.

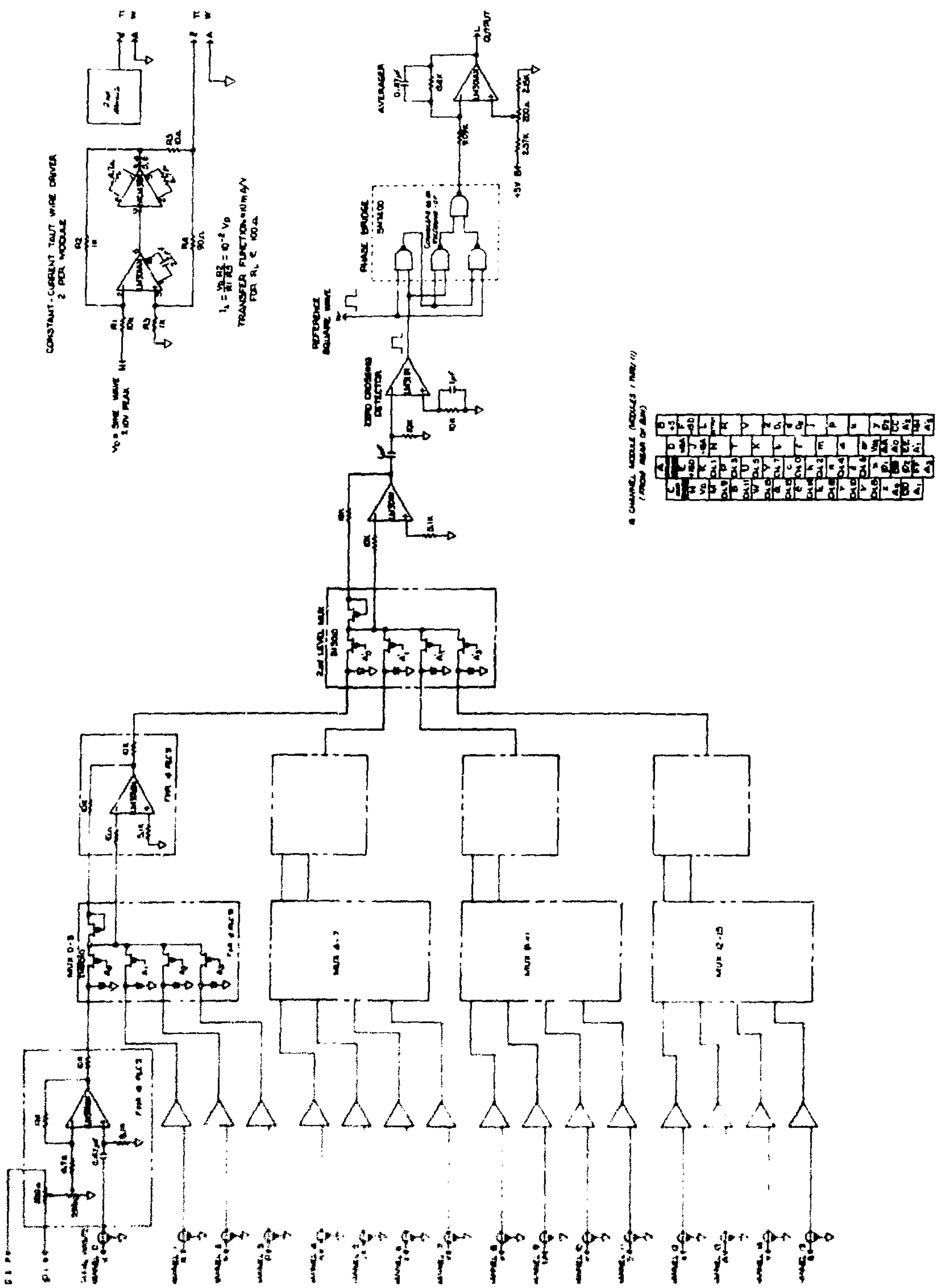

Fig. A-3.
A 16-channel module schematic.

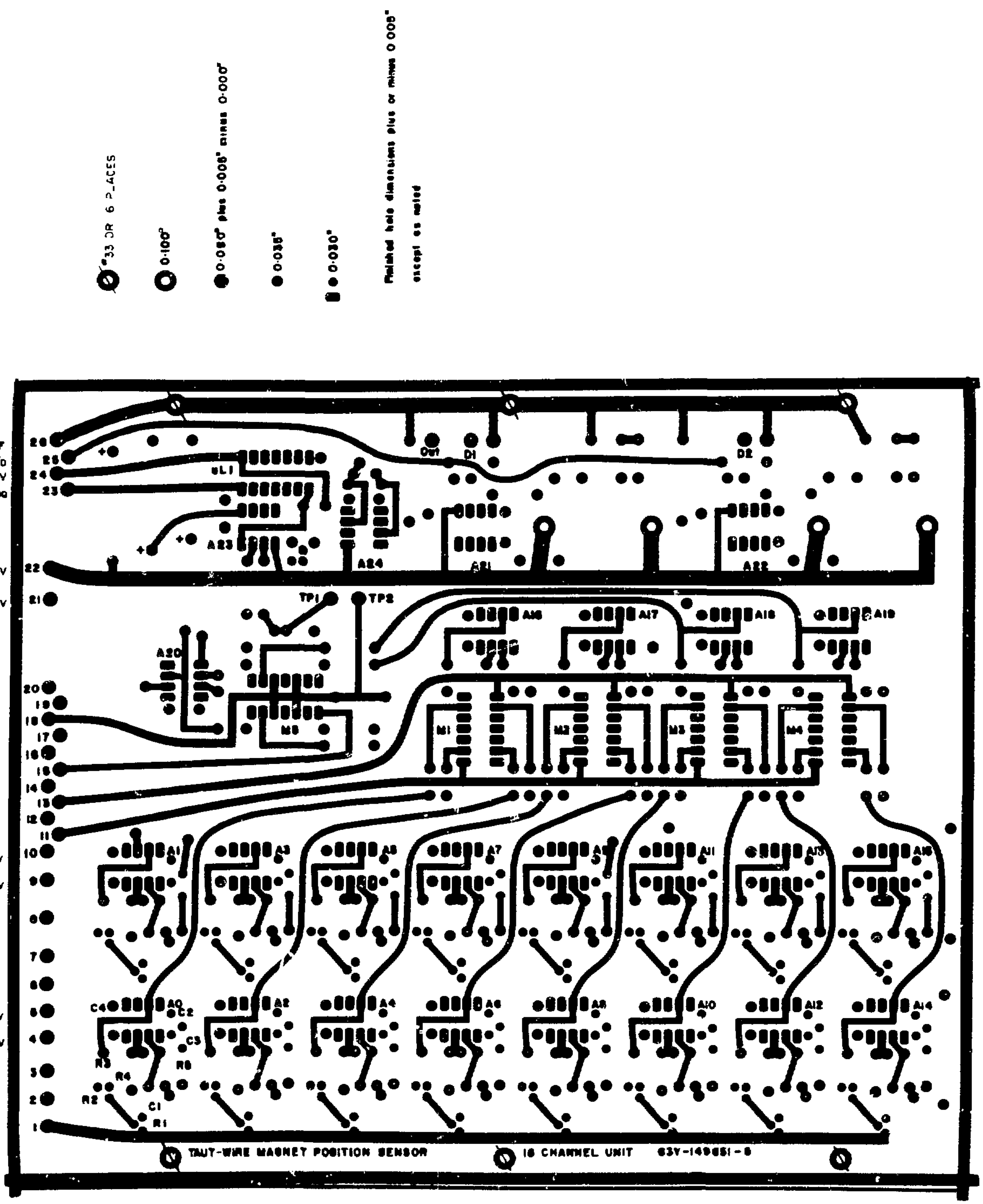

Fig. A-4
16-channel module pc board.

APPENDIX B

THE TWCALI FILE

I. THE TWCALI FILE - WIRE NUMBER, SENSOR NAME, SENSOR NUMBER, HSENS, VSENS, HVL, HVU, VVL, VVU

1	BM01	EAST	1	12.22	12.20	6.65	-7.88	-4.40	7.20
1	BM01	MIDD	2	12.18	11.73	6.73	-8.25	-7.48	5.71
1	BM01	WEST	3	11.70	11.70	7.48	-7.59	-6.51	6.56
1	FM01		7	11.80	12.40	5.55	-8.96	-8.07	3.46
1	XSLT		5	10.50	10.00	7.74	-5.33	-6.33	6.24
1	FIXD	COLL	6	12.30	11.70	8.49	-5.27	-8.37	5.10
2	BM01	BOTT	4	10.77	12.17	-9.66	7.39	-1.90	9.31
2	BM01	CENT	8	10.58	7.58	-7.36	7.17	-9.03	8.05
2	BM01	TOP	9	11.51	11.85	-9.18	6.37	-3.59	7.43
2	SEP	BOTT	11	10.91	7.66	-9.09	7.25	-9.08	7.26
2	SEP	CENT	12	11.07	10.53	-8.69	5.57	-3.35	9.49
2	SEP	TOP	13	11.36	11.59	-8.76	5.41	-5.14	8.01
2	BM02	BOTT	14	11.98	11.53	-6.20	6.91	-5.60	6.63
2	BM02	CENT	15	12.87	12.33				
2	BM02	TOP	16	11.78	11.45	-6.05	5.50	-7.70	5.64
8	XXXX	XXXX	00						
3	BM02	WEST	40	11.70	10.80	-6.65	8.38	-6.38	5.80
3	BM02	MIDD	41	12.94	12.00	-8.49	4.38	-1.93	8.62
3	BM02	EAST	42	10.80	10.13	-7.50	8.09	-6.61	6.09
3	BM03	WEST	43	10.22	10.90	-8.04	9.32	-9.33	3.28
3	BM03	MIDD	44	10.73	11.15	-7.00	8.21	-5.85	5.28
3	BM03	EAST	45	11.73	10.11	-6.97	8.22	-8.59	4.56
9	XXXX	XXXX	00						
8	XXXX	XXXX	00						
4	BM03	TOP	46	10.52	10.99	-7.25	8.79	-7.41	4.13
4	BM03	CENT	47	11.71	10.32	-8.22	6.16	-6.13	5.90
4	BM03	BOTT	48	11.48	10.75	-7.37	7.60	-6.50	5.95
4	BM04	TOP	49	10.40	10.65	-8.13	8.27	-6.47	6.10
4	BM04	CENT	50	10.34	10.10	-8.00	7.76	-8.10	4.55
4	BM04	BOTT	51	11.87	10.38	-7.27	6.71	-6.83	5.97
8	XXXX	XXXX	00						
8	XXXX	XXXX	00						
5	BM04	WEST	00						
5	BM04	MIDD	00						
5	BM04	EAST	00						
5	FM03	WEST	00						
5	FM03	EAST	00						
5	SCAT	CHAM	00						
6	FILL	TWST	30	11.39	11.55	-8.07	6.45	-6.89	5.41
6	CRAD	TWST	31	12.10	10.71	-7.48	5.53	-5.67	5.44
6	BM02	TWST	32	12.10	11.30	-7.86	6.07	-6.00	6.[illegible]
6	BM02	TEST	33	13.56	13.40	-5.29	6.88	-5.40	4.4[illegible]
6	CRAD	TMID	34	11.13	10.16	-9.19	5.71	-5.01	6.86
6	BM03	TWST	35	11.08	10.74	-7.47	7.28	-8.28	4.42
6	BM03	TEST	36	11.13	10.13	-7.82	5.47	-7.51	5.26
6	CRAD	TEST	37	12.66	10.70	-7.57	6.22	-3.92	7.82
6	FILL	TMID	38	11.30	10.75	-7.45	6.46	-5.15	7.07
6	FILL	TEST	39	12.15	10.79	-6.71	7.21	-6.93	4.48
7	FILL	BWST	10	11.95	10.26	-7.26	6.65	-6.96	6.74
7	SEPR	WEST	17	11.49	11.14	-8.01	7.94	-6.82	4.70
7	SEPR	MIDD	18	10.17	10.51	-8.70	6.49	-7.91	5.63
7	SEPR	EAST	19	11.16	11.43	-8.96	5.88	-5.18	5.85
7	CRAD	BWST	20	10.91	10.81	8.[illegible]3	-6.58	5.37	-6.56
7	BM02	BWST	21	11.94	11.14	-7.27	6.56	-4.78	5.89
7	BM02	BEST	22	12.86	12.50	-7.23	6.04	-5.33	5.51
7	CRAD	BMID	23	11.90	12.18	-7.51	6.74	-4.93	5.22
7	BM03	BWST	24	10.66	10.93	-8.08	7.38	-6.66	4.83

7	BMO3	BEST	25	11.27	10.38	-8.12	7.20	-7.50	4.87
7	CPAD	BEST	26	11.31	10.56	-7.88	6.62	-5.52	7.20
7	PILL	BMID	28	10.75	10.37	-6.13	8.61	-8.68	2.88
7	PILL	BEST	29	11.43	10.72	-7.42	7.35	-6.63	5.52

8	XXXX	XXXX	00
8	XXXX	XXXX	00
8	XXXX	XXXX	00

II. TAUT, THE TAUT-WIRE READOUT PROGRAM ON EPICS PDP-11 COMPUTER

```
C       TAUT WIRE READOUT PROGRAM
        DIMENSION NWIRE(64),TITLE1(64),TITLE2(64),IPOD(64),
        1  HSENS(64),VSENS(64),HVL(64),HVU(64),VVL(64),VVU(64),
        2  X0(64),Y0(64),Z0(64),ANGLE(64),HSNEW(64),
        3  VSNEW(64),HZNEW(64),VZNEW(64),HVLNEW(64),HVUNEW(64),
        4  VVLNEW(64),VVUNEW(64),HZERO(64),VZERO(64),HDISP(64),
        5  VDISP(64),A(4)
        COMMON/BLKA/VOLTS(128),ERROR(128)
        DOUBLE PRECISION A
        DATA A/'UP       ','DOWN     ','NORTH    ','SOUTH    '/
        DATA F1,F2,F3,F4/'ONLY','ALL ','SOME','COPY'/
        DEFINE FILE 2(1,1408,U,LK)
        DEFINE FILE 3(1,896,U,LM)
        CALL ASSIGN(1,'DK1:[44,11]TWDATA.FTN',0)
        CALL ASSIGN(2,'DK1:[44,11]TWCALI.DAT',0)
        CALL ASSIGN(3,'DK1:[44,11]TWPOS.DAT',0)
        IOUT=5
        READ(1,1)(NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),HSENS(J),
        1  VSENS(J),HVL(J),HVU(J),VVL(J),VVU(J),J=1,24)
        WRITE(IOUT,1)(NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),HSENS(J),
        1  VSENS(J),HVL(J),HVU(J),VVL(J),VVU(J),J=1,24)
1       FORMAT(1X,I4,1X,A4,1X,A4,I5,6F6.2)
        LK=1
        READ(2'LK)(NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),HSNEW(J),VSNEW(J)
        1  ,HZNEW(J),VZNEW(J),HVLNEW(J),HVUNEW(J),VVLNEW(J),VVUNEW(J),
        2  J=1,24)
        WRITE(IOUT,100)(NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),HSNEW(J),
        1  VSNEW(J),HZNEW(J),VZNEW(J),HVLNEW(J),HVUNEW(J),J=1,24)
100     FORMAT(1X,I4,1X,A4,1X,A4,I5,6F6.2)
        LM=1
        WRITE(IOUT,101)(NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),
        1  HZERO(J),VZERO(J),HDISP(J),VDISP(J),J=1,24)
101     FORMAT(1X,I4,1X,A4,1X,A4,I5,4F6.2)
30      IOUT=5
        WRITE(IOUT,3)
3       FORMAT(/1X,'ENTER MODE,FIRST,LAST WIRES(A4,2I3)'/)
        READ(IOUT,4) FLAG,I1,I2
4       FORMAT(A4,2I3)
        IF(FLAG.EQ.F4) GO TO 20
        IF(FLAG.EQ.F1) I2=I1
        IF(FLAG.EQ.F2) I1=1
        IF(FLAG.EQ.F2) I2=7
        IF(I1.EQ.0) GO TO 40
        M1=I1
        M2=I2
        IF(I1.EQ.2) M1=1
        IF(I1.EQ.6) M1=5
        IF(I2.EQ.7) M2=8
        NIM=1
        CALL TWREAD(NIM,M1,M2)
C       CALCULATE HORIZ AND VERT DISPLACEMENTS
        J1=(M1-1)*8 + 1
        J2=M2*8
        DO 5  J=J1,J2
        HDISP(J)=VOLTS(2*J-1)*HSNEW(J)+HZNEW(J)
        VDISP(J)=VOLTS(2*J)*VSNEW(J)+VZNEW(J)
        ERROR(2*J-1)=ERROR(2*J-1)*HSNEW(J)+HZNEW(J)
5       ERROR(2*J)=ERROR(2*J)*VSNEW(J)+VZNEW(J)
C       STORE NEW DISP IN TWPOS.DAT FILE
        LM=1
        WRITE(3'LM)(NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J)
```

```
     1  ,HZERO(J),VZERO(J),HDISP(J),VDISP(J),J=1,24)
C       PRINT SELECTED WIRES
22      DO 10 IWIRE=I1,I2
        WRITE(IOUT,11) IWIRE
11      FORMAT(/5X'WIRE',I3/)
        DO 10 J=J1,J2
        IF(NWIRE(J).NE.IWIRE) GO TO 13
        JH=3
        JV=1
        IF(HDISP(J).LT.0.0) JH=4
        IF(VDISP(J).LT.0.0) JV=2
        HABS=ABS(HDISP(J))
        VABS=ABS(VDISP(J))
        WRITE(IOUT,12) TITLE1(J),TITLE2(J),HABS,ERROR(2*J-1),
     1  A(JH),VABS,ERROR(2*J),A(JV)
12      FORMAT(5X,2(1X,A4),2(F10.1,4H +- ,F3.1,2X,A5))
13      CONTINUE
10      CONTINUE
        GO TO 30
20      IOUT=6
        GO TO 22
40      REWIND 2
        REWIND 3
        END
```

III. TWCAL, THE CALIBRATION PROGRAM

```
C       TAUT WIRE CALIBRATION PROGRAM
        DIMENSION NWIRE(64).TITLE1(64).TITLE2(64).IPOD(64).
        1  HSNEW(64).VSNEW(64).HZNEW(64).VZNEW(64).HVLNEW(64).
        2  HVUNEW(64).VVLNEW(64).VVUNEW(64).UVOLTS(64).WVOLTS(64).
        3  HSENS(64).VSENS(64).HVL(64).HVU(64).VVL(64).VVU(64)
        COMMON/BLKA/VOLTS(128).ERROR(128)
        DATA G1.G2.G3.G4.G5/'EDIT'.'UPPR'.'LOWR'.'SAVE'.'COPY'/
        DEFINE FILE 2(1.1408.U.LK)
        CALL ASSIGN(1.'DK1:[44.1]TWDATA.FTN',0)
        CALL ASSIGN(2.'DK1:[44.1]TWCALI.DAT',0)
        READ(1.1)(NWIRE(J).TITLE1(J).TITLE2(J).IPOD(J).HSENS(J).
        1  VSENS(J).HVL(J).HVU(J).VVL(J).VVU(J).J=1.24)
        IOUT=5
        WRITE(IOUT.1)(NWIRE(J).TITLE1(J).TITLE2(J).IPOD(J).HSENS(J).
        1  VSENS(J).HVL(J).HVU(J).VVL(J).VVU(J).J=1.24)
1       FORMAT(1X.I4.1X.A4.1X.A4.I5.6F6.2)
        LK=1
        READ(2'LK)(NWIRE(J).TITLE1(J).TITLE2(J).IPOD(J).HSNEW(J).
        1  VSNEW(J).HZNEW(J).VZNEW(J).HVLNEW(J).HVUNEW(J).
        2  VVLNEW(J).VVUNEW(J).J=1.24)
        WRITE(IOUT.5)(NWIRE(J).TITLE1(J).TITLE2(J).IPOD(J).HSNEW(J).
        1  VSNEW(J).HZNEW(J).VZNEW(J).HVLNEW(J).HVUNEW(J).
        2  VVLNEW(J).VVUNEW(J).J=1.24)
5       FORMAT(1X.I4.1X.A4.1X.A4.I5.8F6.2)
100     IOUT=5
        WRITE(IOUT.3)
3       FORMAT(/1X.'ENTER MODE.WIRE(A4.I3)'/)
        READ(IOUT.4) FLAG.I
4       FORMAT(A4.I3)
        IF(FLAG.EQ.G1) GO TO 10
        IF(FLAG.EQ.G2) GO TO 20
        IF(FLAG.EQ.G3) GO TO 30
        IF(FLAG.EQ.G4) GO TO 40
        IF(FLAG.EQ.G5) GO TO 50
        GO TO 200
C       EDIT DATA FILE
10      READ(IOUT.11) J.NWIRE(J).TITLE1(J).TITLE2(J).IPOD(J)
        WRITE(IOUT.11) J.NWIRE(J).TITLE1(J).TITLE2(J).IPOD(J)
11      FORMAT(1X.I4.I5.1X.A4.1X.A4.I5)
        IF(J.EQ.64) GO TO 100
        IF(J.EQ.63) GO TO 13
        READ(IOUT.12) HSNEW(J).VSNEW(J).HZNEW(J).VZNEW(J).
        1  HVLNEW(J).HVUNEW(J).VVLNEW(J).VVUNEW(J)
        WRITE(IOUT.12) HSNEW(J).VSNEW(J).HZNEW(J).VZNEW(J).
        1  HVLNEW(J).HVUNEW(J).VVLNEW(J).VVUNEW(J)
12      FORMAT(1X.F5.2.7F6.2)
        GO TO 10
13      LK=1
        WRITE(2'LK)(NWIRE(J).TITLE1(J).TITLE2(J).IPOD(J).HSNEW(J).
        1  VSNEW(J).HZNEW(J).VZNEW(J).HVLNEW(J).HVUNEW(J).
        2  VVLNEW(J).VVUNEW(J).J=1.24)
        GO TO 100
C       READ UPPER CALIBRATION WIRES
20      M1=I
        M2=I
        IF(I.EQ.2) M1=1
        IF(I.EQ.6) M1=5
        IF(I.EQ.7) M2=8
        CALL TWREAD(1.M1.M2)
        J1=(M1-1)*8+1
        J2=M2*8
```

```
      WRITE(IOUT,22)
 22   FORMAT(1X,'WIRE      NAME  POD VOLTS ERROR',
     1  'HVUNEW VOLTS ERRORVVUNEW'/)
      DO 21  J=J1,J2
      IF(NWIRE(J).NE.I) GO TO 21
      WRITE(IOUT,1)NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),VOLTS(2*J-1),
     1  ERROR(2*J-1),HVUNEW(J),VOLTS(2*J),ERROR(2*J),VVUNEW(J)
      UVOLTS(2*J-1)=VOLTS(2*J-1)
      UVOLTS(2*J)=VOLTS(2*J)
 21   CONTINUE
      IUPPER=I
      GO TO 100
C     READ LOWER CALIBRATION WIRES
 30   M1=I
      M2=I
      IF(I.EQ.2) M1=1
      IF(I.EQ.6) M1=5
      IF(I.EQ.7) M2=8
      CALL TWREAD(1,M1,M2)
      J1=(M1-1)*8+1
      J2=M2*8
      WRITE(IOUT,32)
 32   FORMAT(1X,'WIRE      NAME  POD VOLTS ERROR',
     1  'HVLNEW VOLTS ERRORVVLNEW'/)
      DO 31  J=J1,J2
      IF(NWIRE(J).NE.I) GO TO 21
      WRITE(IOUT,1)NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),VOLTS(2*J-1),
     1  ERROR(2*J-1),HVLNEW(J),VOLTS(2*J),ERROR(2*J),VVLNEW(J)
      WVOLTS(2*J-1)=VOLTS(2*J-1)
      WVOLTS(2*J)=VOLTS(2*J)
 31   CONTINUE
      ILOWER=I
      GO TO 100
C     STORE NEW CALIBRATION VOLTAGES
 40   IF(IUPPER.EQ.ILOWER) GO TO 42
      WRITE(IOUT,41)
 41   FORMAT(1X,'LAST TWO READINGS NOT ON SAME WIRE'//)
      GO TO 100
 42   WRITE(IOUT,43)
 43   FORMAT(1X,'WIRE   NAME     POD HSNEW VSNEW HZNEW VZNEW',
     1  'HVLNEWHVUNEWVVLNEWVVUNEW'/)
      DO 45  J=J1,J2
      IF(NWIRE(J).NE.ILOWER) GO TO 45
      HVLNEW(J)=WVOLTS(2*J-1)
      HVUNEW(J)=UVOLTS(2*J-1)
      VVLNEW(J)=WVOLTS(2*J)
      VVUNEW(J)=UVOLTS(2*J)
      HSNEW(J)=HSENS(J)*(HVU(J)-HVL(J))/(HVUNEW(J)-HVLNEW(J))
      VSNEW(J)=VSENS(J)*(VVU(J)-VVL(J))/(VVUNEW(J)-VVLNEW(J))
      HZNEW(J)=(HVL(J)*HVUNEW(J)-HVLNEW(J)*HVU(J))/(HVU(J)-HVL(J))
      VZNEW(J)=(VVL(J)*VVUNEW(J)-VVLNEW(J)*VVU(J))/(VVU(J)-VVL(J))
      WRITE(IOUT,44) NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),HSNEW(J),
     1  VSNEW(J),HZNEW(J),VZNEW(J),HVLNEW(J),HVUNEW(J),
     2  VVLNEW(J),VVUNEW(J)
 44   FORMAT(1X,I4,1X,A4,1X,A4,I5,8F6.2)
 45   CONTINUE
      LK=1
      WRITE(2'LK)(NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),HSNEW(J),
     1  VSNEW(J),HZNEW(J),VZNEW(J),HVLNEW(J),HVUNEW(J),
     2  VVLNEW(J),VVUNEW(J),J=1,24)
      GO TO 100
C     MAKE HARD COPY OF NEW CALIBRATION

 50   IOUT=6
      WRITE(IOUT,43)
      WRITE(IOUT,44)(NWIRE(J),TITLE1(J),TITLE2(J),IPOD(J),HSNEW(J),
     1  VSNEW(J),HZNEW(J),VZNEW(J),HVLNEW(J),HVUNEW(J),
     2  VVLNEW(J),VVUNEW(J),J=1,24)
      GO TO 100
 200  REWIND 2
      REWIND 3
      END
```

IV. TWREAD

```
        SUBROUTINE TWREAD(NIM,M1,M2)
        DIMENSION V(3)
        COMMON/BLKA/VOLTS(128),ERROR(128)
          IOUT=5
        IF(NIM.GT.1) GO TO 10
C       LOOP THRU NIMBIN ONE CHANNEL ADDRESSES
        DO 1  NCHAN=1,16
        NC=16-NCHAN
        IBIT=NC/8
        CALL BCMD(2,10,3,IBIT,IE)
          NC=NC-8*IBIT
          IBIT=NC/4
          CALL BCMD(2,10,2,IBIT,IE)
          NC=NC-4*IBIT
          IBIT=NC/2
          CALL BCMD(2,10,1,IBIT,IE)
          IBIT=NC-2*IBIT
          CALL BCMD(2,10,0,IBIT,IE)
          CALL DELAY(2000)
          CALL BDAT(1,19,20,IBIT1,IE)
          CALL BDAT(1,19,21,IBIT2,IE)
          CALL BDAT(1,19,22,IBIT3,IE)
          CALL BDAT(1,19,23,IBIT4,IE)
          NCHECK=8*IBIT1+4*IBIT2+2*IBIT3+IBIT4
          IF(NCHECK.EQ.NCHAN) GO TO 3
          WRITE(IOUT,2) NCHAN,NCHECK
2         FORMAT(1X,'CHANNEL ADDRESS ERROR',2I5)
C         READ SELECTED MODULES
3         DO 1  MODULE=M1,M2
          NADS=35+MODULE
          N=(MODULE-1)*16+NCHAN
          DO 4  K=1,3
          CALL RADS(1,22,NADS,IDATA,IE)
4         V(K)=FLOAT(IDATA)/204.8
          VOLTS(N)=(V(1)+V(2)+V(3))/3.
          ERROR(N)=SQRT((VOLTS(N)-V(1))**2+(VOLTS(N)-V(2))**2+
          1  (VOLTS(N)-V(3))**2)/1.414
1         CONTINUE
C         LOOP THRU NIMBIN TWO CHANNEL ADDRESSES
10        CONTINUE
          RETURN
          END
```