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PERKIN-ELMER NO. 8736

THEODOLITE WITH SHAFT ANGLE ENCODER AND DISPLAY (U)

FINAL REPORT

By J. G. Schaberg

THE PERKIN-ELMER CORPORATION

June 1967

U.S. ARMY ENGINEER

GEODESY, INTELLIGENCE AND MAPPING RESEARCH AND DEVELOPMENT AGENCY

FORT BELVOIR, VIRGINIA 22060

CONTRACT DA44-009-AMC-1489(X)

[redacted]

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TASK 1M623501A57601

[redacted]

FOREWORD

This report covers the work performed by Perkin-Elmer Corporation under Contract DA44-009-AMC-1489(X), Task 1M623501A57601 to design, develop, fabricate, test, and deliver a theodolite with Shaft Angle Encoder and Display.

SUMMARY

The Perkin-Elmer Corporation has designed, developed, fabricated, tested, and delivered a portable theodolite with Shaft Angle Encoder and Display capable of proving the feasibility of using a state-of-the-art angle encoder for military surveying. The work was performed in two phases. Phase I was directed toward developing and testing of the encoder system, and Phase II covered fabrication of the remainder of the system including the combining of the encoder with the theodolite in order to test the complete system.

The design of the instrument system was restricted to use of existing components, which when combined with costs and efficiency objectives, resulted in a system that is heavier than desired. It is recommended that modifications be introduced which would result in a lighter, more practical instrument.

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LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

According to the contract requirements, Perkin-Elmer has designed, developed, fabricated, tested and delivered a Theodolite with Shaft Angle Encoder and Display in a physical configuration as shown in figures 1 and 2.

The work to be done should prove the feasibility of using a state of the art shaft angle encoder for military surveying. The angular information has been presented by a direct readout device indicating the full degrees and fractions thereof down to 0.0001 of one degree or 0.36 second of arc.

The accuracy required was specified to ± 2 seconds of arc as deviations from the theodolite reading. These basic requirements have been met in the delivered instrument.

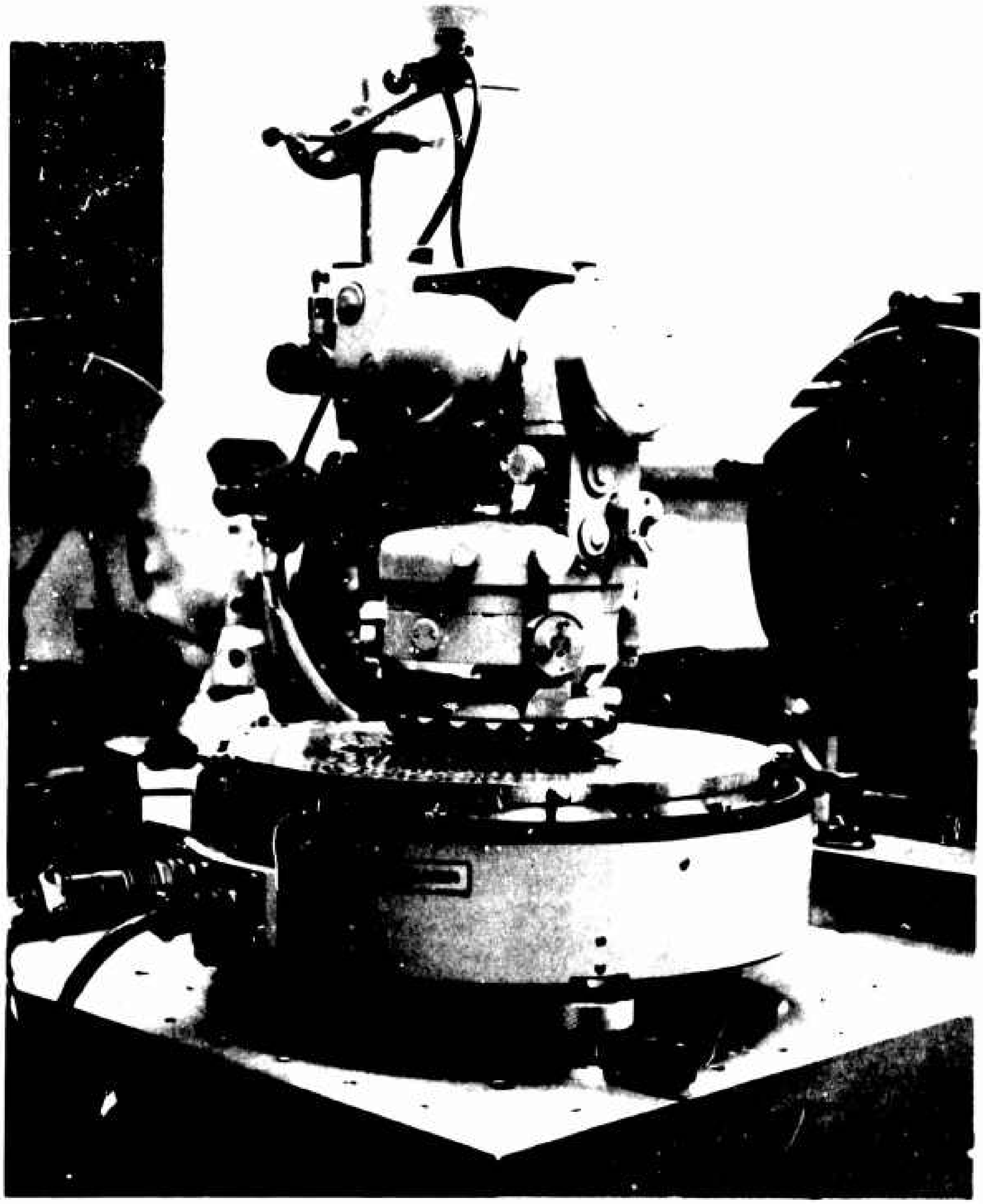

Figure 1. Theodolite With Shaft Angle Encoder on Test

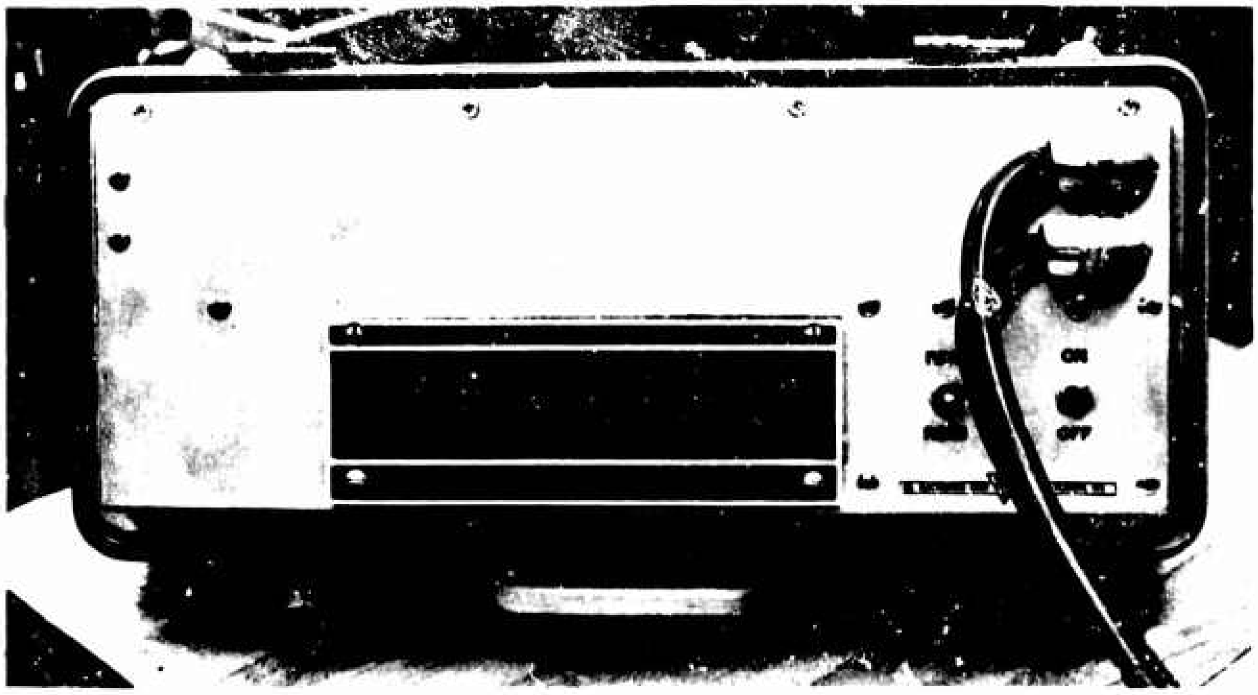

Figure 2. Shaft Angle Encoder Display

2.0 DISCUSSION

2.1 STATEMENT OF PROBLEM

The work to be accomplished under this contract had to be directed towards providing a portable system capable of testing the feasibility of using the state of art in shaft angle encoders in the military field of surveying. It was required to divide the program into two phases. Phase one was directed towards development and testing of the encoder system, and Phase two towards the fabrication of the remaining system and combining the encoder with the theodolite for testing of the complete system. Cost, size and weight of the instrument and the readout device had to be considered. The transportability of the system had to be accomplished by dividing it into man-portable units. Preferred solutions for the readout were indicated as follows: (1) Indication of absolute angle, (2) direct reading, and (3) free of slip-rings or sliding contacts. Alternates to these approaches were given as (1) incremental readout, (2) interpolation of readouts, and (3) use of slip-rings and sliding contracts.

Size instructions were given as follows: The support structure in which the encoder is mounted should be equipped with three equally spaced foot screws on a radius of 6-5/16 inches; the height should not exceed 12 inches, and the diameter should not be over 14 inches. The weight instructions were given to comply with the requirement for man-transportability of this system. Spare parts were required.

2.2 BACKGROUND INFORMATION

The currently available theodolites can only be used in the field under favorable weather conditions. Recent technological advances have changed surveying operations by providing all weather distance measuring capabilities. All weather and other pointing devices as such allow only for the alignment of the sensor to the target. It is, therefore, desirable to supplement these techniques by angular measurements. A device is required to measure included angles between multiple targets. The optical theodolites with glass scales with angular measurement are mainly fabricated in Europe. These instruments have been accepted for decades because of their reliability, accuracy, ease of operation and light weight. It is highly desirable, particularly for military use, to produce the entire instrument in the United States. It was, therefore, decided to initiate a program utilizing American made shaft angle encoders for angular measurements. The obvious disadvantages such as size, weight, and complexity had to be minimized.

The program had to be split into several domains of investigation. We have mentioned already the pointing device as one; a second one is the angular measurement device which is the subject of this contract.

2.3 APPROACH TO PROBLEM

Basically, Perkin-Elmer used the instrument arrangement as described in Perkin-Elmer Technical Report No. 8063A* This report was submitted as the technical part of the proposal.

Perkin-Elmer has investigated the different encoders which could be applied to the design. The resolution and accuracy was indicated by the manufacturer to be acceptable. The Inductosyn as fabricated by Del Electronics, under the trade name of Multisyn(R), was finally chosen for several reasons. The reliability of the measurement plates of the Inductosyn is high. It is an inductive system and hence there is no need for lamps, which usually are short lived and hard to replace. It has no constantly rotating parts such as are used in the encoder of Norden Division of United Aircraft. It meets the accuracy requirements better than any available optical encoder. It is the lowest priced encoder of required resolution and accuracy. It is supplied with a rotary transformer, thus avoiding any slip-rings. The ambiguity of the 720 pole unit, which was chosen, can easily be removed by use of a commercially available small two-pole resolver.

The second major problem is the adaptation of the azimuth axis of the theodolite to the Inductosyn axis. We considered a solution which did not require any modification of the theodolite as superior to any approach whereby the azimuth axis of the highly complex DKM3 Theodolite would have to be modified. The system requires that theodolite and instrument axes be parallel to each other but they need not be precisely concentric with each other. We found it most convenient to build the encoder instrument as a complete unit with an adapter plate to mount the theodolite to it. The parallelism of the two axes in this arrangement can always be readjusted by the user by means of the leveling screws available on the DKM3 Theodolite. If this adjustment need be preserved, it can be done by clamping screws added to the leveling screws of the theodolite. With this arrangement, it is also possible to conveniently use the plate level of the theodolite itself to level the encoder instrument.

We incorporated into the design, at one time, an adjustment of the zero position of the stator of the Inductosyn. We have eliminated this feature because it leads to instability of the azimuth axis around which the Inductosyn rotates.

We tried to correct the instability by introducing an additional pair of preloaded ball bearings to center the axis more precisely. The results were negative. We, therefore, concluded that it would be best to follow the specifications by having an arbitrary zero position of the readout.

We found excessive noise in the readout device which had to be eliminated by changing some of the components.

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* Perkin-Elmer Report No. 8063A, Theodolite with Shaft Angle Encoder and Display, November 22, 1965.

We also found that the system had a zero shift depending upon voltage changes. Some of the components had to be eliminated and replaced by new components and improved filtering introduced to eliminate supply voltage dependency and lower the noise level.

The detailed approach to the problems is given in paragraph 2.4.

2.4 DESCRIPTION OF DESIGN

2.4.1 General Description (See figure 3.)

The table, which has a diameter of approximately 12 inches, can be freely rotated by hand. It can also be clamped and moved through small angles by a spring restrained tangential screw. The table top has provisions to mount a Kern DKM3 Theodolite by means of an adapter. (Since the theodolite is a standard product, it is not described.) The instrument has basically a cylindrical form of approximately 14 inches in diameter and average height of 6-1/2 inches.

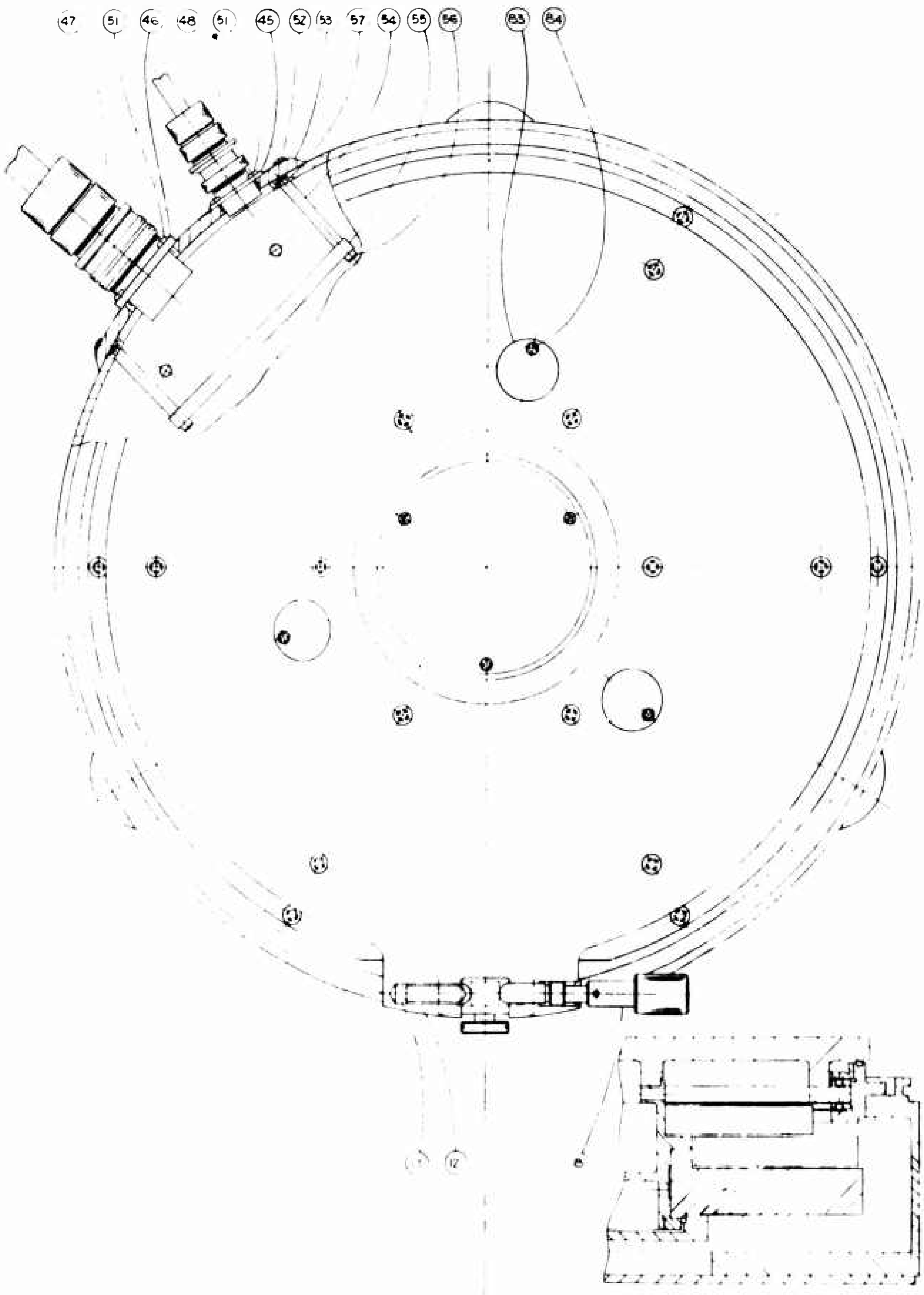
The encoder and all the other electrical and mechanical sensitive elements are mounted inside the main housing. The main housing is sealed by a rotary seal in order to protect the inside from dust or water. A rotary transformer is used instead of slip-rings. The ambiguity of the 720 pole Main Encoder is eliminated by using a two-pole resolver for coarse angular information. The design is made such that all wiring can be inspected and troubleshooting can be accomplished on the outer diameter of the housing. A harness, which has two female plugs on one end, connects the unit with the display box.

The display box shows seven digits; degrees and decimal fraction of degrees. It is built into an aluminum box, and has slightly less than one cubic foot volume. If the cover is removed, the display is visible. Two cables, one as mentioned above connecting to the instrument, and one to the prime power battery of ±12 volts, are then free to be connected. The cables are permanently connected to the display unit in form of pig-tails. The display unit is equipped with an interrogation switch and a power switch. The interrogation switch has three positions. One is the store position for the display numbers. Position two is the manual interrogation position. Position three is the automatic interrogation position. Automatic interrogation is updated 300 times per seconds. The power consumption is in the order of 30 watts.

2.4.2 Detail Design Description

2.4.2.1 Encoder Instrument (See figure 3.)

The encoder instrument can be leveled by three foot screws while on a horizontal surface in the laboratory or field. The foot screws (37) are



A.

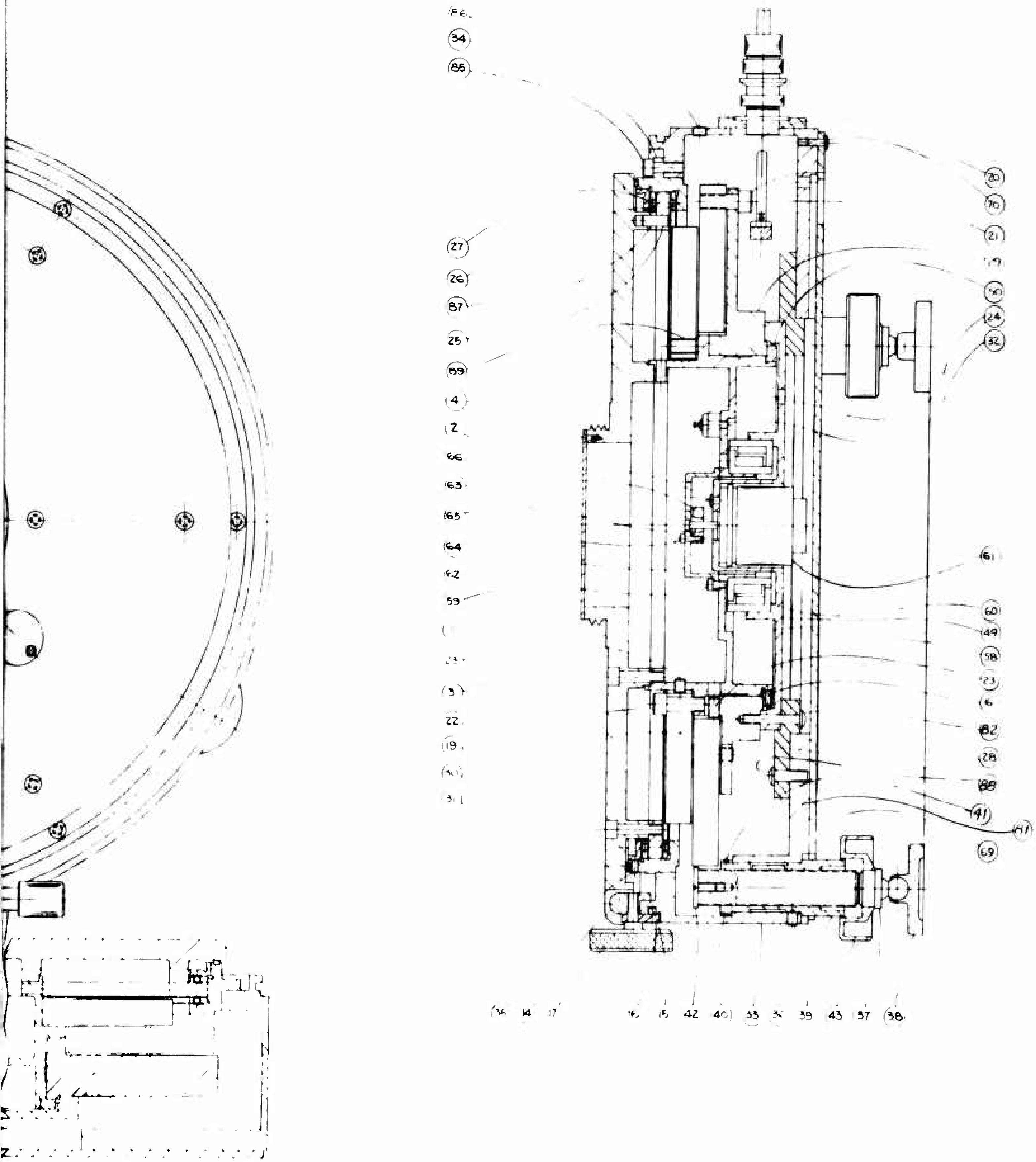


Figure 3. Encoder Readout Unit

B.

Key to Figure 3.

1. Table
2. Center Cover Plate
3. Holding Screws
4. Holding Screws
5. Deleted
6. Setscrew
7. Theodolite Adapter
8. Tangential Screw
9. Deleted
10. Deleted
11. Deleted
12. Spring Housing
13. Coil Spring
14. Azimuth Clamp, Main
15. Short Pin
16. Azimuth Clamp
17. Clamp (Screw)
18. Deleted
19. Inductosyn Rotor
20. Inductosyn Stator
21. Capscrew
22. Capscrew
23. Capscrew
24. Electrical Distributor
25. Bearing Ring
26. Ball Separator
27. Precision Balls
28. Setscrew
29. Stator Holder
30. Ring Nut
31. Seal
32. Screw
33. Main Housing
34. Bearing Support
35. Setscrew
36. Setscrew
37. Footscrews
38. Footplate
39. Bushing
40. Cap
41. Setscrew
42. Screw
43. Knob
44. Deleted
45. Socket
46. Socket
47. Plug Receptacle
48. Plug Receptacle
49. Support Plate
50. Ring Nut
51. Solid Rivet
52. Screw
53. Housing Cover
54. Standoff
55. Large Distributor Terminal Board
56. Capscrew
57. Screw
58. Axis
59. Capscrew
60. Rotary Transformer
61. Resolver
62. Aluminum Cap
63. Clamping Ring
64. Clamping Capscrew (Parts)
65. Clamping
66. Screw
67. Deleted
68. Deleted
69. Plate
70. Screw
71. Deleted
72. Deleted
73. Washer
74. Deleted
75. Deleted
76. Deleted
77. Deleted
78. Deleted
79. Deleted
80. Deleted
81. Deleted
82. Screw
83. Plate, Cover
84. Screw
85. Capscrew
86. Setscrew
87. Dowel
88. Screws
89. Setscrew
90. Deleted

equipped with foot plates to provide a solid stand for the instrument. The theodolite foot screws have the purpose of leveling the theodolite to the encoder instrument.

The foot screws of the theodolite can be clamped at a fixed position. It is therefore possible to use the theodolite level vial in conjunction with the foot screws (37) to level the instrument. For the purpose of leveling, the table top is rotated into such a position that the theodolite level is approximately parallel to the connecting line between two of the leveling screws. The leveling is done by adjustment of these two screws. After the bubble is centered, the table top is rotated through 90 degrees and the third foot screw used to level the instrument in this position.

The main housing of the encoder instrument consists of an aluminum part which houses the encoder and other electronic elements. The housing (33) is closed on the bottom by plate (69), which can easily be taken off to reach the interior parts for inspection and cleaning. The top of the housing is closed by a stainless steel table (1), which supports the theodolite adapter. This adapter is fixed to the table and should not be removed during normal use of the instrument.

Between table (1) and the main housing (33), a clamp screw (17) and tangential screw (8) are provided. The tangential screw is used to rotate the table and is spring loaded by spring (13) in spring housing (12).

The table top has three holes covered by plates (83), which can be taken off for the purpose of adjustment of the Inductosyn Rotor plate. The table can be removed by removing the clamping mechanism by opening clamp screw (17) completely and unscrewing the table holding screw (3). If it is desired to reach the Inductosyn rotor and stator centering screws, this can be done by removing the center cover plate (2), by unscrewing holding screws (4). The Inductosyn plates are made from 440 stainless steel in order to obtain similar temperature expansion properties throughout the instrument.

The bearing part (34) supports the seal (31). The two Inductosyn rotor leads are magnetically shielded and are connected to the electrical distributor (24), and from there to the larger distributor (55), which is arranged directly behind plugs (47 and 48).

The plugs can be removed by removing the plug cover plate (53). The opening in the housing, after plate (53) is removed, is large enough to reach the electrical distributor (55).

The axis (58) is made of stainless steel. It supports the Inductosyns stator (20) as well as the stator holder (29).

Axis (58) supports the rotor of the rotary transformer (60). The resolver (61) and the stator of the rotary transformer (60) are supported by support plate (49). The axis of resolver (61) is connected to the axis (58) by an aluminum cap (62) and a clamping mechanism consisting of parts

(63, 64 and 65). The support plate (49) is screwed to the stator holder (29) by screws (82). The electrical wires from resolver (61) are connected to the distributor (55), passing through grooves and holes in the appropriate parts.

The theodolite DKM3 is mounted in its normal transportation case. Certain accessories are included in this case.

The Encoder Instrument transportation case has, in its upper compartment, the spare parts consisting of one NIXIE type display lamp, one each of the different types of electrical circuit boards for the display unit and any other spare parts required.

The whole instrumentation is therefore divided into three boxes, all with water-tight, rubber seals. The boxes are made of aluminum and have handles for easy transportation.

2.4.2.2 Display Unit

The display unit is housed in an aluminum box that can be closed watertight. There is no special transportation case for the display unit.

Figure 4 (sheets 1 through 3) shows the assembly arrangement of the electronic angle readout system. The numbers in the circles refer to the parts list which is also provided.

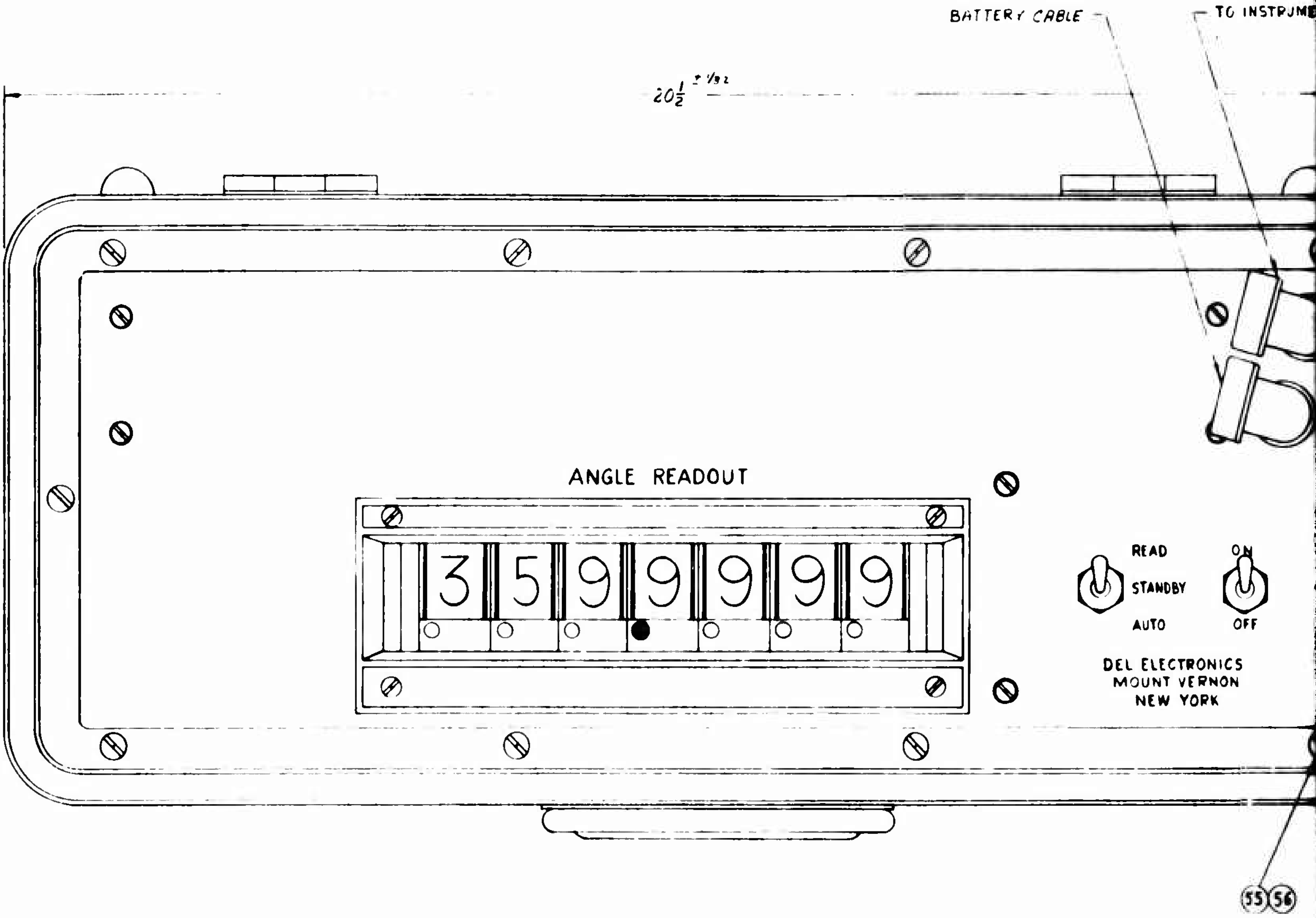
Figure 5 shows the wiring and logic of this system. The same callout numbers are used on this diagram as on figure 4, so that the components can be located easily.

2.4.2.2.1 Mechanical Arrangement - The electronic system is mounted in a waterproof drawn aluminum instrument case of about one cubic foot volume, as shown on sheet 1 of figure 4. Space has been provided in the upper part of the lid for the two cables when the instrument is being transported.

The electronic system is removable as a complete assembly from the waterproof case, as shown on sheet 2 of figure 4. Portions of the assembly are mounted on hinges for easy access to the plug-in circuit cards, and to make test work easier.

Sheet 3 of figure 4 provides a backview of the electronic assembly so that the locations of components in the rear can be indicated.

The completed system will be essentially waterproof even when open for normal operation.



FRONT VIEW
(COVER REMOVED)

A.

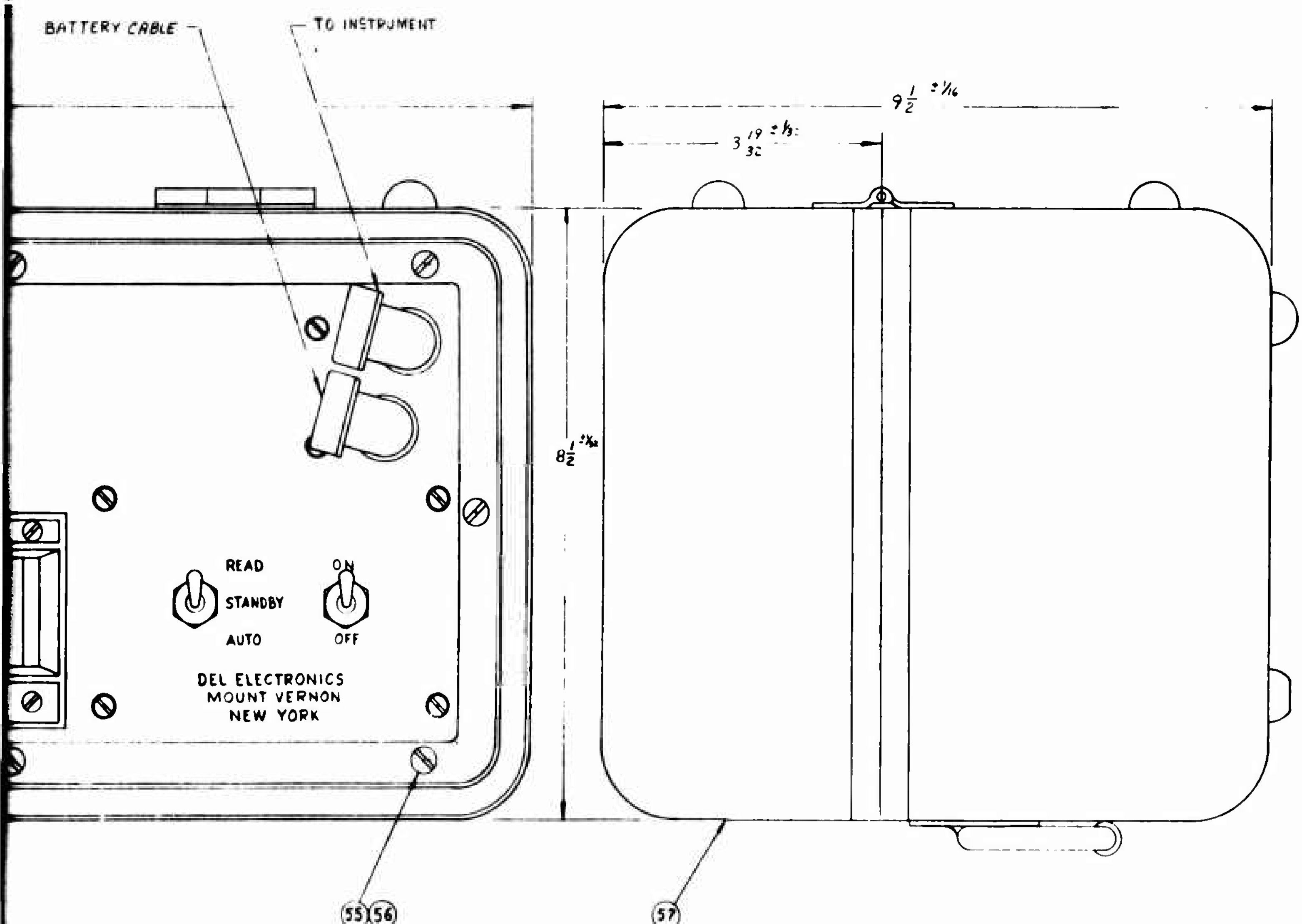


Figure 4. Angle Readout Chassis Assembly
Sheet 1 of 3

B.

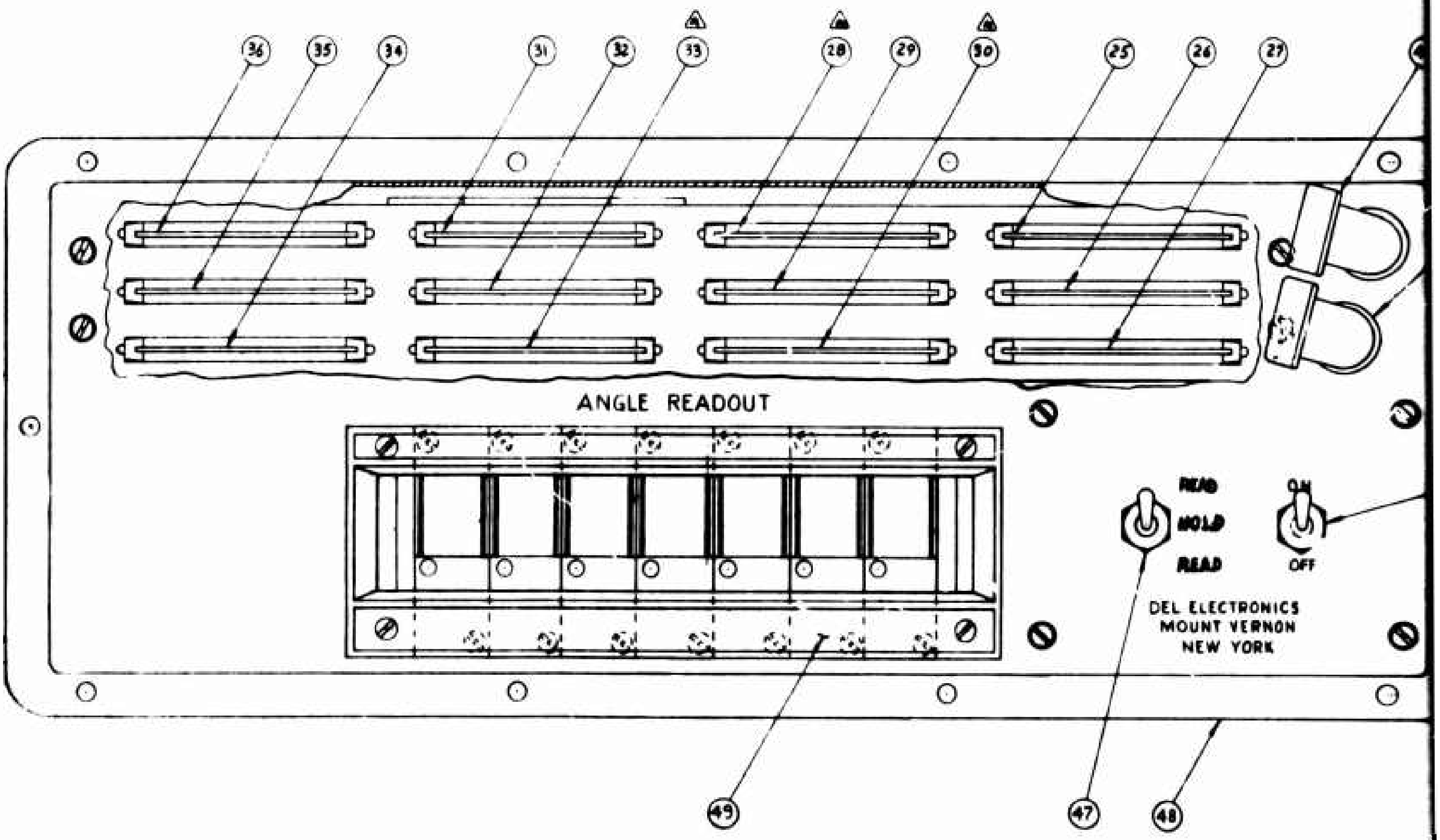
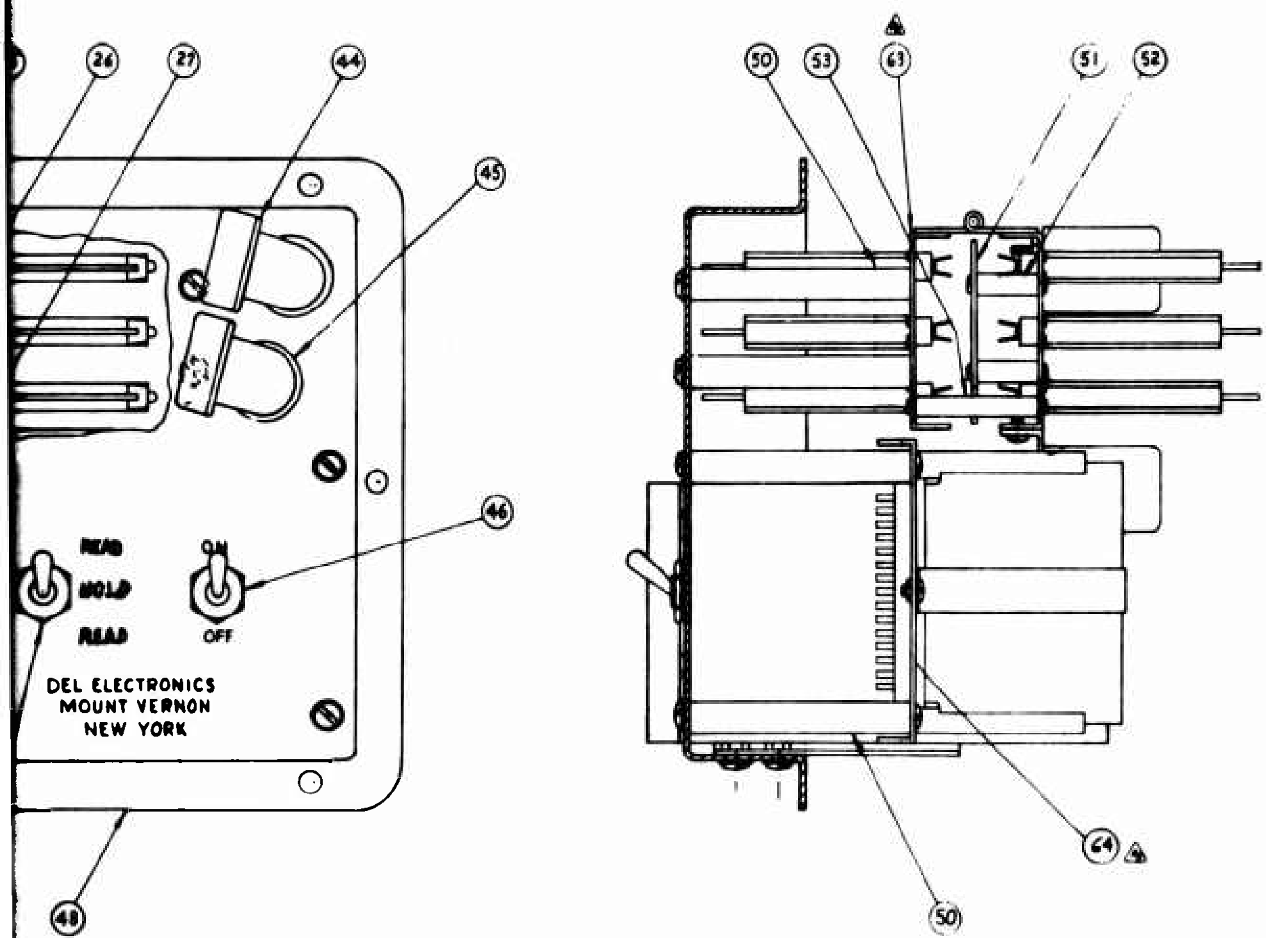
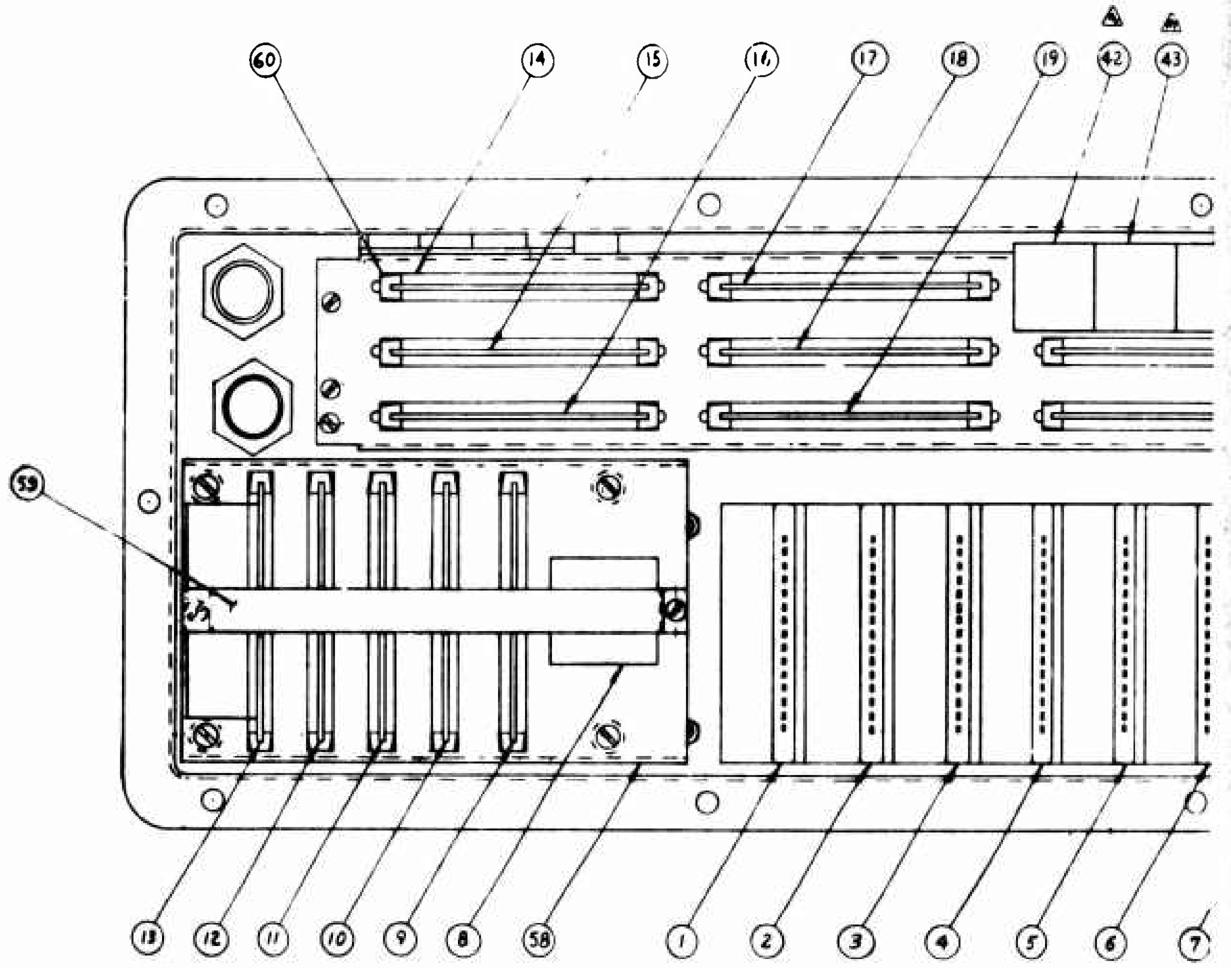


Figure 4. Angle Readout Chassis Assembly
Sheet 2 of 3

A.


26
27
44
45
46
48
ON
OFF
DEL ELECTRONICS
MOUNT VERNON
NEW YORK
50
53
63
51
52
64
50

B.



REAR VIEW

A.

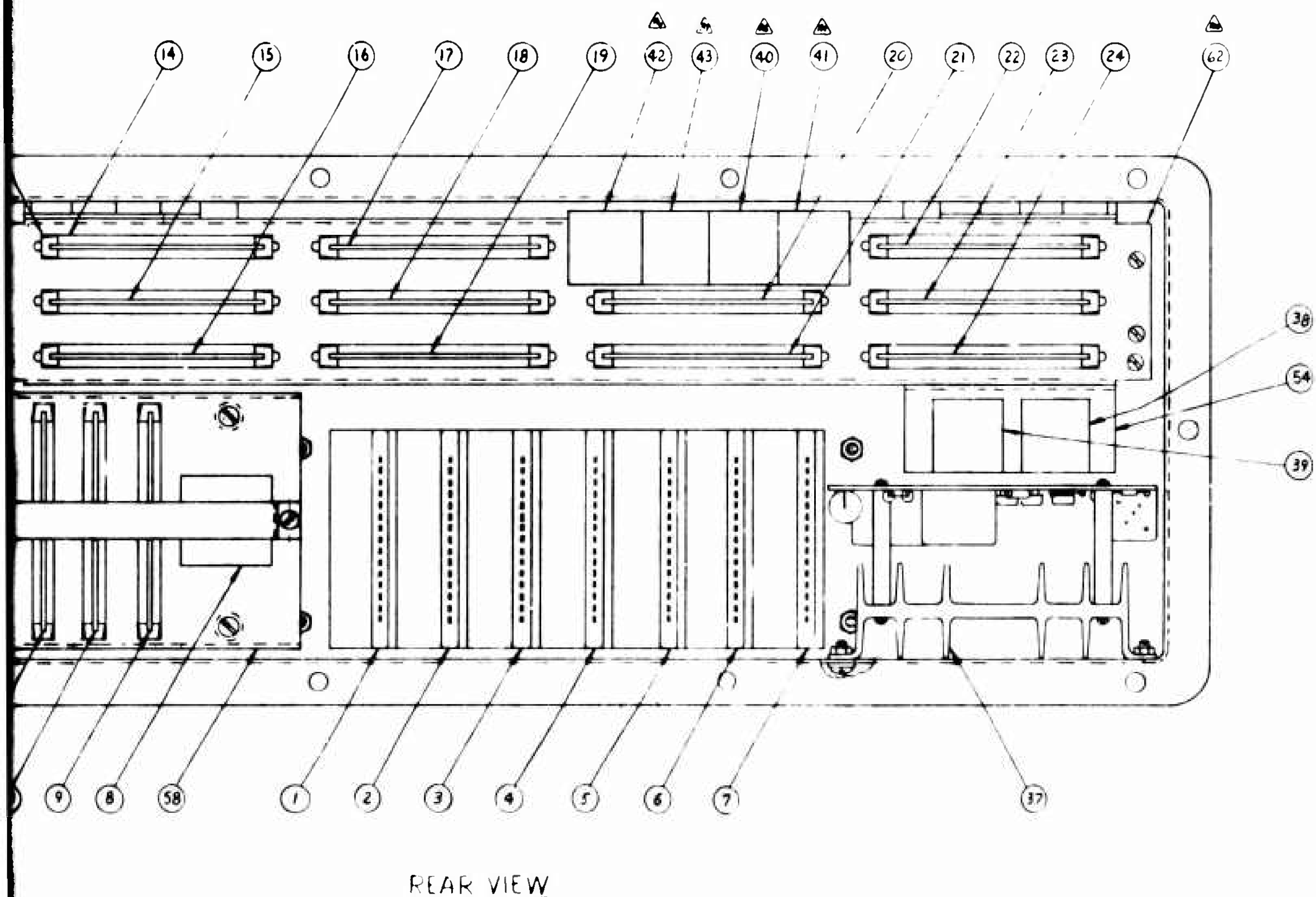


Figure 4. Angle Readout Chassis Assembly
Sheet 3 of 3

B.

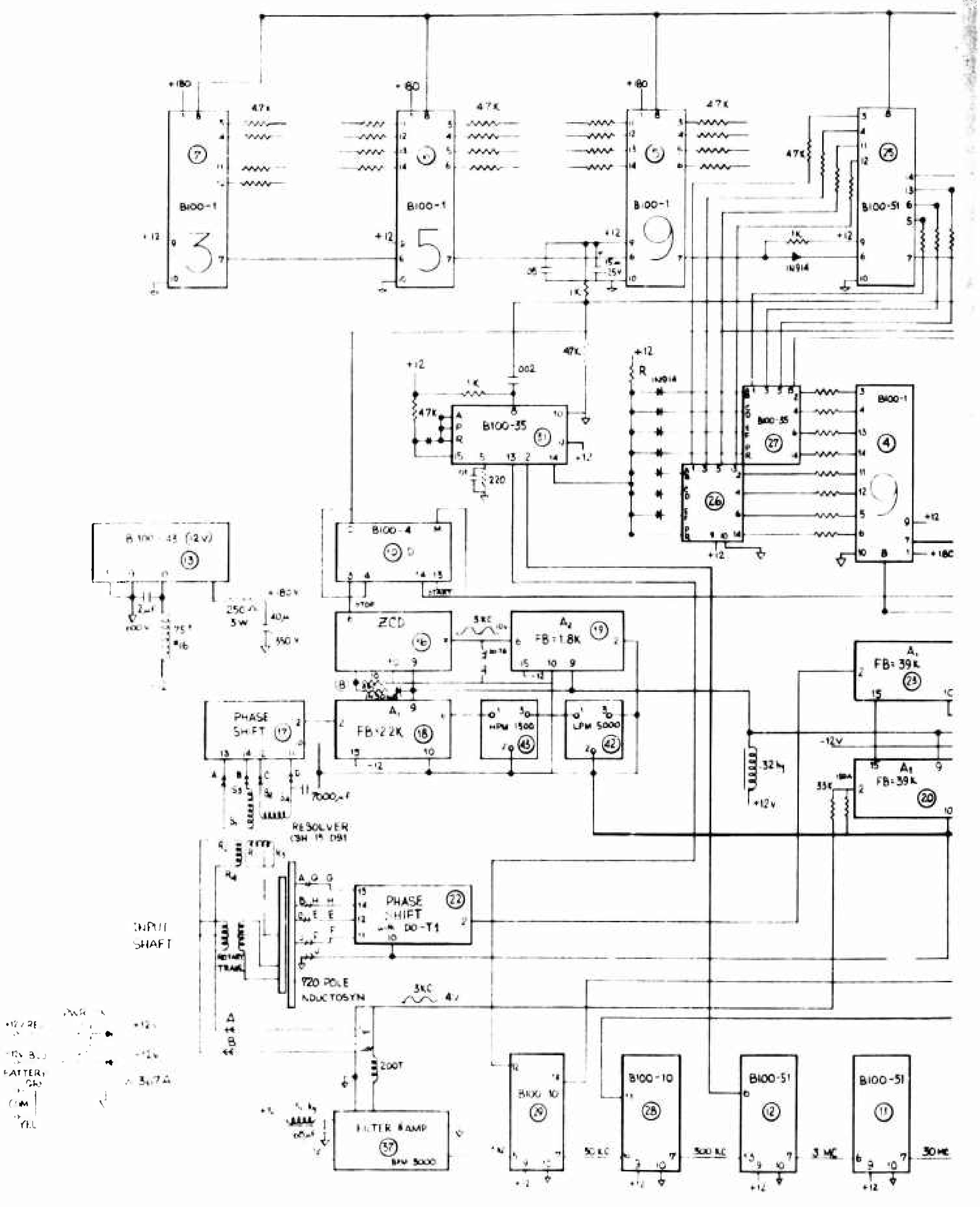
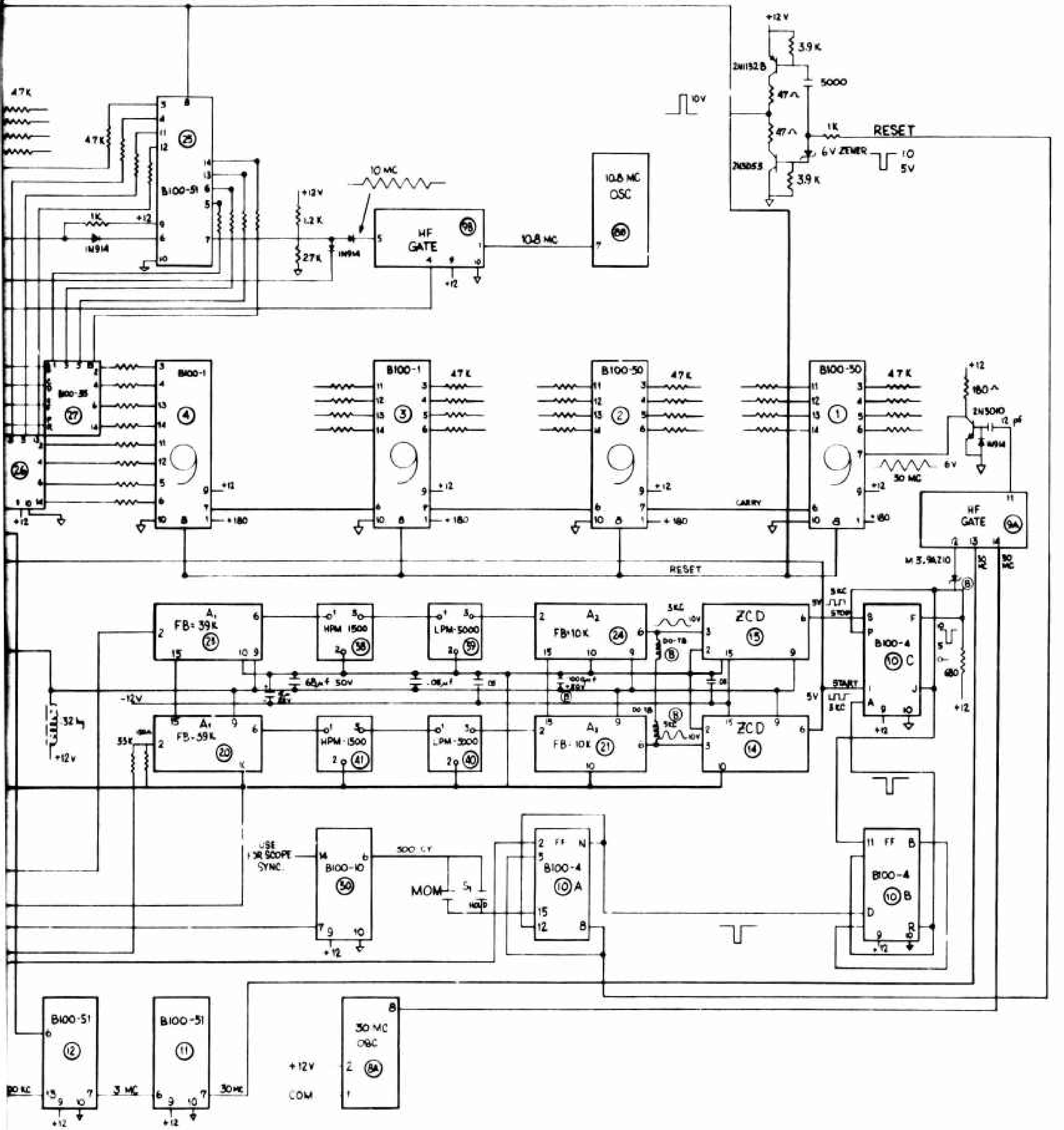


Figure 5   Angle Readout Block Diagram

A



+12 V
3.9 K
2N1132 B
5000
47 Ω
10V
1K
RESET
6 V ZENER
10
5V
2N3053
3.9 K
47 K
47 K
25
B100-51
1K
+12
1N914
+12 V
1.2 K
27 K
1N914
10 MC
HF GATE
9B
10.8 MC
10.8 MC OSC
8B
+12
B100-35
27
B100-1
4
B100-1
3
B100-50
2
B100-50
1
26
+180
CARRY
+12
180 Ω
2N5010
12 pf
1N914
6V
30 MC
HF GATE
9A
M 3.9AZ10
RESET
A1
FB=39K
23
HPM 1500
38
LPM-5000
39
A2
FB=10K
24
3KC
ZCD
15
B100-4
10 C
68 μf 50V
.08 μf
-12V
.32 h
+12V
55K
A1
FB-39K
20
HPM-1500
41
LPM-5000
40
A3
FB-10K
21
ZCD
14
START
3KC
STOP
680
+12
USE FOR SCOPE SYNC.
B100-10
50
500 CY
MOM
S1
HOLD
FF
B100-4
10 A
FF
B100-4
10 B
B100-51
12
B100-51
11
30 MC OSC
8A
+12V
COM
3 MC
30 MC

B.

KEY TO FIGURES 4 AND 5

NO.	DESCRIPTION		MANUFACTURER	DWG. NO.
1	Decade Counter - Display	50mc	Janus B100-50	DY2697
2	Decade Counter - Display	50mc	Janus B100-50	DY2697
3	Decade Counter - Display	2mc	Janus B100-1	CY2584
4	Decade Counter - Display	2mc	Janus B100-1	CY2584
5	Decade Counter - Display	2mc	Janus B100-1	CY2584
6	Decade Counter - Display	2mc	Janus B100-1	CY2584
7	Decade Counter - Display	2mc	Janus B100-1	CY2584
8	30mc - 10.8mc Oscillator		Accutronics	JJ-25-262
9	High Frequency Gate		Del	AY2725
10	4 Flip-Flops		Janus B100-4	CY2586
11	Decade Counter	50mc	Janus B100-51	DY2699
12	Decade Counter	50mc	Janus B100-51	DY2699
13	12V - 180V Converter		Janus B100-43	12 volt
14	Zero Crossing Detector		Del	BY2594
15	Zero Crossing Detector		Del	BY2594
16	Zero Crossing Detector		Del	BY2594
17	Phase Shifter Coarse		Del	AY2846
18	Amplifier #1 Coarse		Del	BY2612
19	Amplifier #2 Coarse		Del	BY2613
20	Amplifier #1 Reference		Del	BY2612
21	Amplifier #2 Reference		Del	BY2613
22	Phase Shift Fine		Del	AY2599
23	Amplifier #1 Fine		Del	BY2612
24	Amplifier #2 Fine		Del	BY2613
25	Decade Counter		Janus B100-51	DY2699
26	Gates		Janus B100-35	CY2585
27	Gates		Janus B100-35	CY2585
28	Decade Counter		Janus B100-10	CY2583
29	Decade Counter		Janus B100-10	CY2583
30	Decade Counter		Janus B100-10	CY2583
31	Gate		Janus B100-35	CY2585

KEY TO FIGURES 4 AND 5 (CONT).

NO.	DESCRIPTION	MANUFACTURER	DWG. NO.
32	Not Used		
33	Not Used		
34	Not Used		
35	Not Used		
36	Not Used		
37	Filter and Power Amp	Del	BY2593
38	Filter	UTC	HPM1500
39	Filter	UTC	LPM5000
40	Filter	UTC	LPM5000
41	Filter	UTC	HPM1500
42	Filter	UTC	LPM5000
43	Filter	UTC	HPM1500
44	Cable to Theodolite	Del	BY2852
45	Battery Cable	Del	BY2853
46	ON-OFF Switch	Cutler Hammer	8823
47	Read Switch	Cutler Hammer	8815
48	Chassis	Del	DY2624
49	Bezel	Del	BY2619
50	Post	Del	AY2616
51	Shield	Del	CY2623
52	Post	Del	AY2615-2
53	Post	Del	AY2615-1
54	Filter Bracket	Del	AY2614
55	Screw 10-32 X 5/8 Pan Hd.		
56	Seal Washers	Durham Aircraft	600-015-10
57	Instrument Cabinet	Zero	HD1CA22A16
58	Bracket, Card Mtg.	Del	BY2618
59	Clamp	Del	BY2617
60	Guide, Socket	Victor	2VK15S/1-2
61	Guide, Socket	Victor	2VK30S/1-2
62	Bracket Card Mtg.	Del	CY2622
63	Bracket Card Mtg.	Del	CY2621
64	Bracket Card Mtg.	Del	CY2618

2.4.2.2.2 Electronic System - The description of the operation of the electronic system can best be started at the lower part of the block diagram (figure 5) at the 30 Mc oscillator (Item 8A). This frequency is successively divided by 10 in the blocks 11, 12, 28, and 29. At this point the output is a 3KC square wave which serves as the input to the filter and amplifier (37), where it is converted into a sine wave and amplified to provide the excitation for the 720 pole Inductosyn and the one speed resolver. This amplifier delivers about one watt of power.

At this point the system splits into two parts. Separate measurements are made by an electronic system using the signals from the Inductosyn, and another electronic system using the signals from the resolver, and then these two signals are compared and corrected as necessary to prevent ambiguities. The fine system using the signals from the Inductosyn will be described first.

The two signals from the Inductosyn are combined by the phase shift circuit (22), to produce a constant amplitude signal which shifts in phase proportional to the angle of rotation. This phase shift goes through 360 degrees of shift in 1 degree of motion of the Inductosyn.

This signal is amplified and filtered in blocks 23, 38, 39, and 24.

Similarly a reference signal is obtained from the transformer T1 and amplified and filtered in exactly the same manner in blocks 20, 41, 40, and 21. The same transformer, T1, and an exact duplicate of the amplifier and filter chain is used to avoid any relative phase shift between the two signals caused by slight frequency variations, temperature variations, and the like.

The output of the two amplifiers (21 and 24) will be sine wave signals at 3Kc with an amplitude of about 10 volts, peak-to-peak. These two signals are converted into precision square waves by the zero crossing detectors (14 and 15). The zero crossing detectors are high gain, differential amplifiers driving high speed Schmidt trigger circuits.

The output of the zero crossing detector (14) is used as a START command to the flip-flop (10C), and the output of the zero crossing detector (15) is used as the STOP command. The flip-flop (10C) controls the gate (9A), which in turn allows the 30Mc pulses from the oscillator (8A) to pass to the counter indicator units (1, 2, 3, and 4). The total count in the counter indicator units will be a measure of the phase difference between the two signals obtained from the Inductosyn channel and the reference channel. Thus, this count is proportional to the fraction of a cycle of the Inductosyn that the shaft has been rotated, and will read in decimal fractions of a degree.

The coarse angle encoding is accomplished by circuitry similar to that described above for the fine angle encoding system, but it uses a resolver whose output signals are combined in phase shifter (17). One rotation of the table corresponds to one cycle of phase shift of the resolver output signal. This signal is processed by amplifiers and filters similar to those for the fine system (Items 18, 43, 42, 19, and 16). The high frequency flip-flop (10D) uses the start of the fine system as signaled by the flip-flop (10C). The stop is obtained from the amplifiers and zero crossing detector (16).

The gate for the coarse system (9B) controls pulses from a separate oscillator at 10.8Mc. This frequency is necessary because a count of 3600 corresponds to one cycle of phase shift, while a count of 10,000 is obtained for one cycle of phase shift in the fine system.

2.4.2.2.3 Ambiguity Detection and Elimination - It will be noted that there is an overlap of one digit at the tenths of a degree. The counter indicator for the fine system, Item (4), and the counter (25) for the coarse system are both nominally 0.1 degree digits. The coarse system is zeroed by means of the coarse resolver so that on the average the digital output obtained without correction is about 1/2 degree less than that obtained with the fine system. The comparison gates (26 and 27) compare the respective counters of the two systems, and allow extra pulses to be applied to the coarse counter after both systems have completed their cycle and with the aid of gate 31, until the two 0.1-degree digits are the same. This correction will take care of any necessary "carries" into the degree digits and prevent ambiguous readings due to errors of the coarse system.

2.4.2.2.4 System Sequencing - Two modes of system sequencing are provided. The switch S1 controls the mode obtained. When S_1 is closed, a 300 cycle signal is obtained from the output of the decade divider (30) which is used to set the flip-flop (section A of Item 10). This section is reset a short time (about 30 microseconds) later by the output from Item 28. During this time the gate (31) is inhibited, preventing any correction pulses.

During the time that this section A is set, the output is fed to the reset driver circuit in the upper right of the diagram. This pulse is amplified and used to reset all of the counters to zero.

The reset of section A of the Item 10 causes the section B to be set. Section B being in the set condition applies a bias to the High Frequency Flip-flop (10C) so that the next start pulse can cause Item 10C to be set and the fine counting sequence will proceed as described above.

When the high frequency flip-flop, 10C, is set by a start pulse, section B of Item 10 is reset, returning all of the Sections of Item 10 to the normal state, and allowing only one cycle of the phase counting to be counted.

It will be noted that there are several inputs to the gate (31), which prevents any correction pulses until such time as the various counting sequences have been completed.

Manual reading on command from an operator is obtained by closing the contact S_1 momentarily. This causes the sequence just described above, except that the sequence cannot continue repeatedly because contact S_1 is open. Repeated readings can be taken as often as desired by merely closing S_1 again for each desired reading. The last reading will remain on the indicator tubes as long as the power is on and the read switch is not operated.

2.4.2.2.5 Electrical Outputs - Output information in the form of a binary coded-decimal code can be obtained from the outer end of the resistors connected to pins 3, 4, 5, and 6 of the counter indicator units Items 1, 2, 3, 4, 5, 6, and 7. When the connecting wires are to be more than a few inches in length, a series resistor of at least 5K ohms shall be used in lieu of direct connection to either pins 3, 4, 5, and 6 or pins 11, 12, 13, and 14. Use of the series resistor prevents the distributed capacitance from affecting counter operation.

2.5 OPERATION (See figure 3.)

To describe the operation it is assumed that the instrument is set up on a stand in the field and the theodolite is mounted to the theodolite adapter (7). On top of the adaptor is a bayonette lock, which is activated by a lever. One of the foot screws of the theodolite is marked by a red dot. The theodolite should always be set on the adapter in such a way that the red dot on the theodolite foot screw and the red dot on the adaptor are next to each other. This is necessary to be able to use the theodolite level for leveling, since the foot screw on the theodolite itself may be clamped in the proper position to assure parallelism between the encoder axis and the theodolite vertical axis after mounting and dismounting of the theodolite.

Before any measurements are made, the theodolite level should be used to level the encoder instrument with the theodolite on it as an assembly. It is first necessary to rotate table (1) to such a position that the theodolite level is parallel with the connecting line of two foot screws. The foot screws of the theodolite can be clamped at a fixed position, therefore it is possible to use the theodolite level vial, in conjunction with the foot screws, to level the instrument. The leveling is accomplished by centering the spirit level through rotation of the two foot screws. After the bubble is centered, the table top is rotated 90 degrees. The third foot screw is then used to level the instrument in this position. This process should be repeated two or three times to achieve an accurate leveling.

After this is accomplished, a target can be acquired by setting up the theodolite telescope and bringing the target into the field-of-view by rotating table (1) by hand and if necessary, tilting the theodolite telescope in elevation by means of the provisions provided on the telescope horizontal axis. Table (1) should then be clamped by screw (17) and tangential screw (8) adjusted until the target is centered in the reticle.

A reading can then be taken on the display for which the interrogation selector switch has to be switched into the automatic mode.

A second target can then be acquired by repeating the process as described just above.

2.6 MAINTENANCE (See figure 3.)

The foot screws as well as tangential screw (8) should be oiled with fine machine oil from time to time. After a year of field use it is desirable to remove any dust or foreign particles inside the housing by careful use of a vacuum cleaner. To do this it is recommended that plate (69) and table (1) be removed.

Any further disassembly will require readjustment of the encoder and other internal parts and therefore should be done at the factory.

The maintenance of the electronic display box is accomplished as follows:

In general, servicing can be accomplished by observing what portions of the equipment are operating (observing pulses, voltage levels and the like) and then replacing the item where the signal ceases to exist in proper form. Each of the counter and counter-indicators has output pins or test points that make it quite easy to observe the state of the flip-flops, or the pulses generated when these units are counting. The logic voltages are about 10 volts for a logic 1 and 5 volts for a logic zero.

The maintenance of the DKM3 theodolite is not described in this paper since it is a standard unit and experience is available. If the theodolite needs overhauling, it is suggested to employ the manufacturer of the theodolite (Kern) for such work.

If it should be necessary to readjust the Inductosyn plates, procedure No. 123, Revised Sept. 29, 1964, of Del Electronics* should be followed.

2.7 ACCEPTANCE TEST PLAN

2.7.1 Introduction

The instrument to be tested employs an Inductosyn to measure the angle about a vertical axis to a specified accuracy of ±2 seconds of arc and a resolution of 0.36 second of arc. Described in the following is a setup of test equipment which has an accuracy comparable to the resolution of the test object.

2.7.2 The Test Setup (See figure 6.)

The test setup described is considered favorable to find most efficiently the errors in the encoder readout device. The theodolite mounted on top of the instrument with its azimuth axis adjusted parallel to the instrument axis is used as reference. According to the attached horizontal circle test results of the DKM3 PD-2 S-N 75916, the theodolite errors are less than 1/4 of the required tolerance for the electrical readout and can, therefore, be used as a reference.

The equipment, as schematically shown in figure 6, should be mounted on a granite or steel plate in an air conditioned or temperature controlled room. There will be three mirrors mounted in the following angles from the readout axis.

From mirror I to mirror II, 36°10', from mirror II to mirror III, 45°30', therefore, mirror I to mirror III will have an included angle of 81°40'. Measuring clockwise from mirror III to mirror I the included angle is 178°20'.

2.7.3 Test Equipment

The mirrors should be set up in approximately these angles: inside ±1 minute of the nominal value. This kind of arrangement is chosen to allow the observer to make the observation without difficult physical interference by the mirrors.

* Prepared by Del Electronics Corp., Inductosyn Dept., 521 Homestead Ave., Mount Vernon, New York

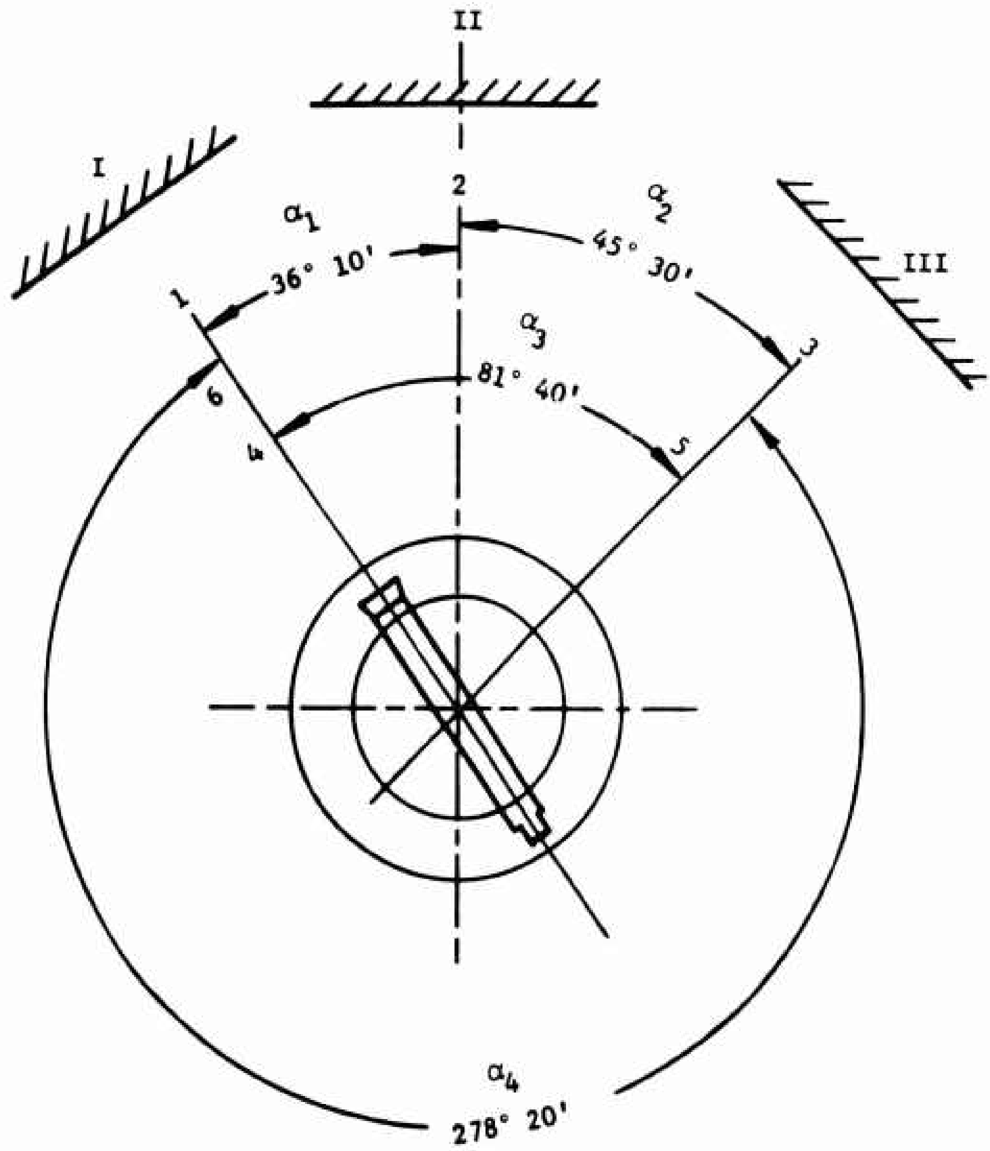


Figure 6. Test Setup

HORIZONTAL CIRCLE TEST ON THEODOLITE (KERN)
PD-2 S-N 75916

Date	Position:	1	2	$\frac{1+2}{2}$	Δ	Δ x Δ
6/6/1966	0-36	19.5	19.0	19.2	+0.3	0.09
	36-72	19.1	18.8	19.0	+0.1	0.01
	72-108	18.6	18.1	18.4	-0.5	0.25
	108-144	18.9	18.3	18.6	-0.3	0.09
	144-180	18.7	18.8	18.8	-0.1	0.01
	180-216	18.2	20.1	19.2	+0.3	0.09
	216-252	18.7	19.8	19.3	+0.4	0.16
	252-288	17.7	18.3	18.0	-0.9	0.81
	288-324	18.8	19.3	19.0	+0.1	0.01
	324-0	19.1	19.5	19.3	+0.4	0.16
				18.9		
	18-54	18.9	19.0	19.0		
	54-90	18.9	18.9	18.9	-0.1	0.01
	90-126	18.2	20.2	19.2	+0.2	0.04
	126-162	18.1	18.3	18.2	-0.8	0.64
	162-198	19.2	19.8	19.5	+0.5	0.25
	198-234	18.3	19.2	18.8	-0.2	0.04
	234-270	18.4	19.7	19.0	-	-
	270-306	19.8	18.8	19.3	+0.3	0.09
	306-342	17.0	19.7	18.4	-0.6	0.36
	342-18	18.9	19.4	19.2	+0.2	0.04
				19.0	±0.7"	3.15

$$m = \pm \sqrt{\frac{\Sigma\ \Delta x \Delta}{n - 1}} = \pm \sqrt{\frac{3.15}{19}} = \pm \underline{\underline{0.41''}}$$

2.7.4 Micrometer Run Error On The Theodolite

The micrometer run error on the theodolite should be determined and, if necessary, corrections for this error applied. It may also be necessary to determine the micrometer indication by averaging several micrometer readings.

2.7.5 Auto-Collimation Error

At least ten observations should be made to determine the auto-collimation error. The instrument would be auto-collimated against one fixed mirror and these settings made in succession by one observer to determine the uncertainty of measurement without the influence of the Inductosyn or circle error on the theodolite. The deviation from the mean value and the number of occurrences of the same error can be graphically plotted in a Gaussian error distribution curve. The graph will show what probable errors exist regarding this particular observation step in the test process. If this test shows an acceptable small error spread it is safe to go over to the main test operation, described below.

2.7.6 Test Operation

It is proposed to make a maximum of 12 runs. Each run will consist of measuring four enclosed angles. After each run the theodolite would be rotated clockwise by 30°. This would give 72 test points. If a second run is desired, it is proposed to use another observer. The readings 1, 2, 3, 4, 5, and 6 would be tabulated in six vertical columns. There will be 13 horizontal columns which are different by theodolite settings. These settings will be 0°, 30°, 60°, and so on until 360° which corresponds to the first setting of 0°. We will, therefore, have 78 readings tabulated. The difference between point 1 and 2 will give the $\alpha 1$ reading (figure 6). Between points 2 and 3 the angle will be called $\alpha 2$; between 4 and 5, $\alpha 3$; and between 5 and 6, $\alpha 4$. These measurements should be done by one observer and may or may not have corrections for the micrometer run error. It will then be necessary to tabulate the values for $\alpha 1$, 2, 3, and 4. A mean value for each of these four angles has to be determined and the deviation of these mean values tabulated. If we add $\alpha 1$, 2, and $\alpha 4$ or $\alpha 3$ and $\alpha 4$ the result should be 360°. The deviation from 360° can either be collimating errors or errors in the test instrument. If we tabulate $\alpha 1$, 2, 3, and 4 for all settings separately and establish a mean and a deviation from that mean, we will arrive at a list of errors that are influenced by the Electrical Readout Instrument and by the theodolite at which settings in 30° intervals were made. It is recommended to draw the Gaussian distribution of $\alpha 1$, 2, 3, and $\alpha 4$. The result will show the percentage probability of what accuracy can be measured with the instrument. As mentioned in Paragraph 2.7.4, it may be necessary to determine the micrometer indication for each line of sight by averaging several micrometer readings. If this should be necessary for all measurements, it can only be determined by practical experience with the test setup.

3.0 CONCLUSIONS

It should be concluded that the instrument as built is very useful as a feasibility model for the purpose intended. It is, however, heavy. The electrical readout box, which uses commercially available components, is large and heavy. The disadvantages listed above can, however, be overcome by the design and development of pre-production models using microcircuits.

As discussed in paragraph 2.3, we reluctantly chose an arbitrary zero position of the stator, however if at any later date, an arbitrary zero should be objected to, it is possible to incorporate the zero adjustment in the design, allowing stator zero orientation to any point. This would be equivalent to a circle setting in a conventional theodolite.

Regarding the weight of the encoder instrument, we have chosen to use stainless steel for many large parts and also for the Inductosyn-plates and make only the housing out of aluminum. Other materials are, however, available which could be employed without sacrificing accuracy. Also, sections of the parts could be reduced in thickness or lightened by holes. If the requirement to have 6-5/16" radii on the foot bolt circle screw can be changed and the travel of the foot screws reduced from 1" to 1/2", a considerable amount of weight can be saved. Figure 7 shows a two-axis theodolite system with digital readout which incorporates many of the suggestions indicated above.

The readout device can be designed to use microcircuitry and could, therefore, be much smaller and lighter, probably a part of the encoder instrument. (Details of the approach chosen in regard to the readout are described in paragraph 2.4.) By selecting the Inductosyn as the encoder, the Readout Design is dictated to be in the present form.

3.1 TEST RESULTS

The attached tables 1, 2, 3, and 4 show results of tests made before and after some improvements on the system were made.

Results tabulated in Table 1 and Table 2 were taken before a re-centering of the Inductosyn plates was performed. The results of Table 3 and Table 4 are final measurements which show smaller errors to prove the system can operate well within the tolerance limits of the specification.

The specification quotes that the deviation from the azimuth readings of the theodolite should not be more than 2 seconds of arc. Following paragraph 2.7.6, a test sheet is presented showing the maximum errors and also the RMS error of the azimuth circle of the theodolite. The maximum error for measurements in steps of 36 degrees twice around the circle shows ±0.7 seconds and the RMS error is indicated to be ±0.41 seconds. These errors would have to be taken in account in calibration and in a decision made to accept or reject the equipment, since the specification states the tolerance as dependent on the theodolite errors.

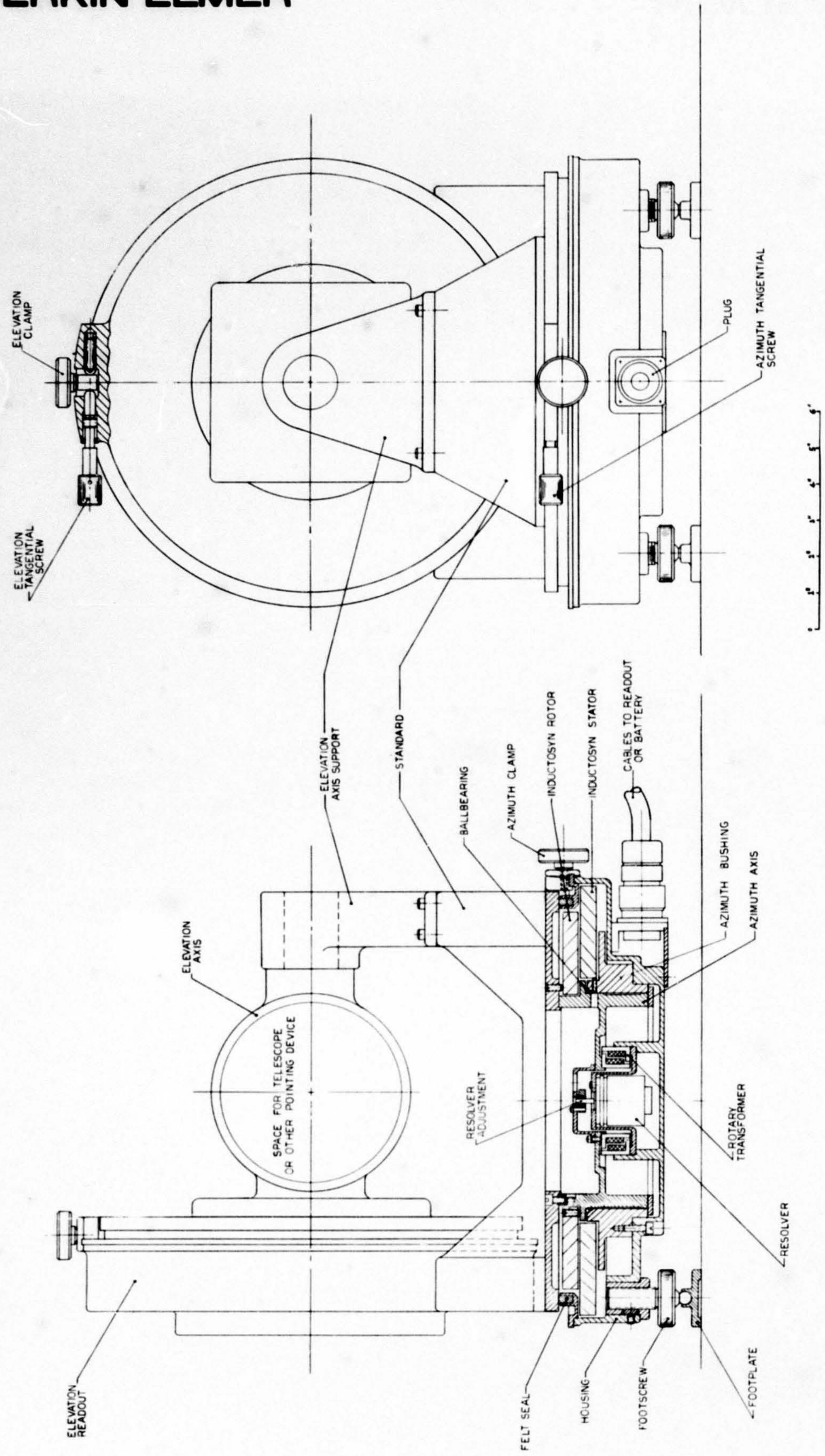


Figure 7. Theodolite System With Digital Readout

We have, therefore, concluded that the theodolite should not be used as referenced, but absolute angular measurements should be made. These measurements were made by using the theodolite as an autocollimator only. The process is similar to that described in acceptance test plan Paragraph 2.7. However, we did choose slightly different angles between the fixed mirrors and determined each line of sight by autocollimating against each mirror. We then noted each line of sight reading and calculated the angle between mirrors by subtracting one line of sight reading from the line of sight reading of the next mirror, etc.

Discussion of Table 1

We made three tests, each angle was measured on consecutive angular sectors of the Inductosyn plates. The first line of the table lists 2-1, 3-1, 3-2, which indicates that an angle of 45.3472° was measured between mirror 2 and mirror 1 and 90.5041° between mirror 3 and mirror 1, and 45.1569° between mirror 3 and mirror 2. The data processing was done as follows:

We have established the averages of ten angles measured and have established combined averages for tests 1, 2, and 3. The combined average of the measurements 2-1 were 45.34764°. For measurements between mirror 3 and 1, the combined average was established to be 90.50448° and for measurements between 3 and 2, 45.15685°. We then established the deviations of the average compared with the combined average of tests 1, 2, and 3 for each of the 3 angles measured; we found the following list of deviations: -2.1, -0.6, +2.8, -0.8, +0.8, 0, +1.2, +1.3, -2.5 in thousandths of a degree. The maximum deviation, therefore, was 5.3 least significant intervals or ±1.0 seconds of arc.

Discussion of Table 2

As we have seen on Table 1, we averaged over ten readings which in some way could minimize the error unduly. We established, in Table 2, average deviation over three readings of each angle only. We indicated in Table 2 the deviation for each single reading. Havi read the explanation we have given to Table 1, Table 2 should be self-ex natory. We found, considering deviations for each single angular reading, the following error spreads: Mirror 2-1, 11 intervals or ±1.98"; Mirror 3-2, 13 intervals or ±2.34"; Mirror 3-2, 11 intervals or ±1.98". If we consider the average of three readings, we found for angles between mirror 2 and 1, 8.3 intervals or ±1.5"; for angles between mirrors 3 and 2, 11 intervals or ±1.98"; for angles between mirrors 3 and 1, 9.3 intervals or ±1.7". We can conclude that the average of at least three readings gives a better result. After these test results, we decided that an improvement can be made by recentering the Inductosyn plate. This was subsequently done, and new test results are shown on Tables 3 and 4.

Discussion of Table 3

Here again we measured angles of 84.5° approximately, over the full circumference of the Inductosyn, in fact, many times around. The

TABLE 1 - TEST RESULTS

* The Angles Tabulated Were Measured In Steps of 36° Around The Encoder

TEST #1

*	2-1	*	3-1	*	3-2
	45.3472		90.5041		45.1569
	45.3470		90.5043		45.1573
	45.3472		90.5041		45.1569
	45.3473		90.5042		45.1569
	45.3477		90.5041		45.1564
	45.3473		90.5040		45.1567
	45.3474		90.5045		45.1571
	45.3478		90.5052		45.1574
	45.3476		90.5048		45.1572
	45.3478		90.5047		45.1569
Average	45.34743		90.50440		45.15697

TEST #2

*	45.3479	*	90.5047	*	45.1568
	45.3475		90.5046		45.1571
	45.3474		90.5048		45.1574
	45.3478		90.5042		45.1564
	45.3476		90.5039		45.1563
	45.3473		90.5038		45.1565
	45.3468		90.5045		45.1577
	45.3474		90.5050		45.1576
	45.3480		90.5051		45.1571
	45.3481		90.5050		45.1569
Average	45.34758		90.50456		45.15698

TEST #3

*	45.3481	*	90.5048	*	45.1567
	45.3481		90.5048		45.1567
	45.3480		90.5047		45.1567
	45.3479		90.5040		45.1565
	45.3475		90.5039		45.1564
	45.3476		90.5038		45.1562
	45.3478		90.5043		45.1565
	45.3480		90.5045		45.1565
	45.3481		90.5049		45.1568
	45.3481		90.5051		45.1570
Average	45.34792		90.50448		45.15660

TABLE 2 - TEST RESULTS

*The Angles Tabulated Were Measured In 36-Degree Steps Around The Encoder. Three Measurements Were Made For Each Line Of Sight.

* ANGLE 2-1	DEV.	DEV. OF 3	* ANGLE 3-2	DEV.	DEV. OF 3	* ANGLE 3-1	DEV.	DEV. OF 3
040.9968	+2.8		049.5070	-6.8		090.5038	-4.0	
040.9968	+2.8	+3.1	049.5071	-5.8	-6.5	090.5039	-3.0	-3.3
040.9969	+3.8		049.5070	-6.8		090.5039	-3.0	
040.9968	+2.8		049.5070	-6.8		090.5038	-4.0	
040.9970	+4.8	+3.8	049.5071	-5.8	-6.8	090.5041	-1.0	-3.0
040.9969	+3.8		049.5069	-7.8		090.5038	-4.0	
040.9970	+4.8		049.5076	-0.8		090.5046	+4.0	
040.9968	+2.8	+3.5	049.5075	-1.8	-1.9	090.5043	+1.0	+1.7
040.9968	+2.8		049.5074	-2.8		090.5042	0.0	
040.9968	+2.8		049.5079	+2.2		090.5047	+5.0	
040.9971	+5.8	+3.8	049.5078	+1.2	+1.9	090.5049	+7.0	+5.7
040.9968	+2.8		049.5079	+2.2		090.5047	+5.0	
040.9968	+2.8		049.5081	+4.2		090.5049	+7.0	
040.9969	+3.8	+2.5	049.5079	+2.2	+3.5	090.5048	+6.0	+6.0
040.9966	+0.8		049.5081	+4.2		090.5047	+5.0	
040.9964	-1.2		049.5079	+2.2		090.5043	+1.0	
040.9964	-1.2	-1.9	049.5082	+5.2	+4.2	090.5046	+4.0	+2.3
040.9962	-3.2		049.5082	+5.2		090.5044	+2.0	
040.9960	-5.2		049.5080	+3.2		090.5040	-2.0	
040.9962	-3.2	-3.9	049.5078	+1.2	+2.2	090.5040	-2.0	-1.7
040.9962	-3.2		049.5079	+2.2		090.5041	-1.0	

TABLE 2 (CONT)

*	ANGLE 2-1	DEV.	DEV. OF 3	*	ANGLE 3-2	DEV.	DEV. OF 3	*	ANGLE 3-1	DEV.	DEV. OF 3
	040.9963	-2.2			049.5079	+2.2			090.5042	0.0	
	040.9961	-4.2	-3.0		049.5077	+0.2	+0.9		090.5038	-2.0	-2.0
	040.9961	-4.2			049.5077	+0.2			090.5038	-4.0	
	040.9960	-5.2			049.5079	+2.2			090.5039	-3.0	
	040.9962	-3.2	-4.5		049.5078	+1.2	+1.2		090.5040	-2.0	-3.3
	040.9960	-5.2			049.5077	+0.2			090.5037	-5.0	
	040.9963	-2.2			049.5077	+0.2			090.5040	-2.0	
	040.9962	-3.2	-2.9		049.5078	+1.2	+1.5		090.5040	-2.0	-1.3
	040.9962	-3.2			049.5080	+3.2			090.5042	0.0	

TABLE 3 - TEST RESULTS

*The Angles Tabulated Were Measured At 30° Intervals Around The Encoder, Starting at 0°

* ANGLE	DEVIATION: Δ INTERVALS	Δ^2
84.5003	+0.5	0.25
84.5001	-1.5	2.25
84.5001	-1.5	2.25
84.5001	-1.5	2.25
84.5002	-0.5	0.25
84.5000	-2.5	6.25
84.5002	-0.5	0.25
84.5002	-0.5	0.25
84.5002	-0.5	0.25
84.5006	+3.5	12.25
84.5006	+3.5	12.25
84.5006	+3.5	12.25
84.4999	-3.5	12.25
84.5002	-0.5	0.25
84.5000	-2.5	6.25
84.5002	-0.5	0.25
84.5005	+2.5	6.25
84.4999	-3.5	12.25
84.5004	+1.5	2.25
84.5006	+3.5	12.25
84.5005	+2.5	6.25
Average:	**Max. ±3.5 Int.**	$\Sigma\Delta^2 = 109.5$
84.50025°	or ±1.26"	RMS error $= \sqrt{\frac{\Sigma\Delta^2}{n-1}}$
		$= \pm 0.82''$

deviations are listed and also the squares of the deviations in order to find the RMS error. The average turned out to be 84.50025°. The maximum spread of all the readings is ±3.5 intervals or ±1.26". The sum of all delta squares is 109.5, and the RMS error calculated by the listed equation turns out to be ±0.82" of arc. We can see the recentering of the Inductosyn, rendered the errors well below the allowed tolerance.

Discussion of Table 4

Here again, an angle of approximately 84.5° was set between two mirrors and the angles established by repeated measurements going several times around the Inductosyn. The average turned out to be 84.50045° the maximum deviation we found to be ±2.5 interval or ±0.90". The RMS error was calculated and found to be ±0.61". The angle of 84.5° was chosen because it would show the maximum errors which could occur in the Inductosyn. This angle is found in order to show the maximum errors for the particular design of this encoder. Further explanation of the 84.5° as critical angle can be derived by studying the design of the Inductosyn, which is not considered a part of this report.

TABLE 4 - TEST RESULTS

*The Angles Tabulated Were Measured At 30-Degree Intervals Around The Encoder. The 0-Degree Angle Was Measured Twice.

* ANGLE	DEVIATION: Δ	Δ^2
84.5004	-0.5	0.25
84.5004	-0.5	0.25
84.5004	-0.5	0.25
84.5002	-2.5	6.25
84.5004	-0.5	0.25
84.5006	+1.5	2.25
84.5002	-2.5	6.25
84.5004	-0.5	0.25
84.5003	-1.5	2.25
84.5007	+2.5	6.25
84.5007	+2.5	6.25
84.5007	+2.5	6.25
84.5004	-0.5	0.25
Average:	MAX. DEV.	$\Sigma\Delta^2 = 37.25$
84.50045°	±2.5 Int. or ± 0.90"	RMS $= \sqrt{\frac{\Sigma\Delta^2}{n - 1}}$ $= \pm 0.63''$

4.0 RECOMMENDATIONS

Some of the recommendations are mentioned in other chapters of this report, but let us recapitulate.

The encoder instrument itself, and its components, could be designed lighter, smaller in size, and the electrical connector more conveniently arranged between the foot screws. Refer to figure 7, Theodolite System With Digital Readout. This drawing is self-explanatory. It shows a two-axis theodolite without showing the telescope or any other pointing device. It should be noted that the elevation readout would be the same as the azimuth readout and arranged in a housing of the same overall dimensions.

If an Inductosyn should become available which would be slightly smaller in diameter, the instrument overall dimensions could be reduced even more.

If the accuracy should be pushed toward smaller errors, it is desirable to increase the number of poles in the Inductosyn plate over the present number of 720. The drawing we have referenced here represents a general arrangement of a theodolite using encoder readouts in both axes which could be modified without changing the general arrangements to accommodate for any pointing device of reasonable size. If the elevation axis' freedom can be restricted to slightly over 180°, it will be possible to make a design which could accommodate a pointing device having four short wave dishes of about 10 inches in diameter.

Regarding the readout device, we have mentioned before that by use of microcircuits, the size of the box could be reduced to probably 1/10 of the present volume. In such a case, it may be practical to combine the readout with the encoder theodolite itself. The successfully constructed and tested instrument demonstrates the feasibility of the use of the instrument we have built. We are recommending the initiation of further development of a two-axis device to minimize size and weight as described above in both the encoder instrument and the readout.

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13. ABSTRACT

The Perkin-Elmer Corporation reports on the Design, Development, Fabrication and Test of DKM3 Theodolite with Shaft Angle Encoder and Decimal Angular Display. The angular information is presented in instantaneously updated numbers to a resolution of 0.36 second of arc. The absolute accuracy is better than ±2 seconds of arc. Recommendations to improve the design are presented. (U)

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14. KEY WORDS	LINK A		LINK B		LINK C	
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