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Using the Landsat Data Collection System for Field Geophysics : Operations in the British Virgin Islands –

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October 1980

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ABSTRACT

We review the systems engineering considerations necessary to apply the Landsat Data Collection System to field geophysical measurements. This particular application was to vertical geodesy by tide gauge and tiltmeter on a small desert island in the British Virgin Islands. The performance of the Landsat system under potentially marginal circumstances was found to be excellent.

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USING THE LANDSAT DATA COLLECTION SYSTEM FOR FIELD GEOPHYSICS: OPERATIONS IN THE BRITISH VIRGIN ISLANDS

INTRODUCTION

Anegada, British Virgin Islands (see Fig. 1 for location map), is a small island at the northern end of the Lesser Antillian arc where the chain of Caribbean Islands suddently turns westward. The seismicity in this area is less than neighboring areas along the arc, suggesting that this is a locked zone where energy is building up for a major earthquake. Thus, it may prove to be a promising area for collecting earthquake precursor data. (See Appendix II by Bilham and Beavan.) For this reason, the Lamont-Doherty Geological Observatory has installed in this area geophysical monitoring instruments such as tiltmeters, tide gauges, strain gauges, leveling lines and seismometers. Much of these data are collected by resident caretakers and returned to Lamont by mail or courier. This imposes an undesirable delay in analyzing the data, allows instrument breakdowns to exist for some time before being discovered, and does not allow quick reaction responses to sudden changes in geophysical parameters.

In 1976, Goddard entered into a joint project with Roger Bilham of Lamont to demonstrate the feasibility of collecting low data rate (a few kilobits per day) information from Anegada using the Landsat satellite relay system. The instruments for accomplishing this were essentially "off the shelf," but specific Data Collection Platform (DCP)/geophysical instrument interfaces did not exist and satellite reliability from this area had not been proven. Real-time satellite relay is only possible when the satellite is in mutual view of both the transmitting station and the receiving center at Goddard. In order to relay transmissions from Anegada, the satellite is relatively close to the horizon at GSFC. This could have resulted in reliability problems.

The initial installation consisted of one General Electric (G.E.) DCP relaying tide gauge data. The tide gauge/DCP interface was jointly designed and constructed by Lamont and Goddard. The system, which was installed in May of 1976 by Roger Bilham of Lamont and William Webster of Goddard, performed satisfactorily for over a year until the batteries were depleted.

It was then decided that, using more versatile DCPs, data would be relayed back from the Lamont tiltmeters on the island. We will describe the Goddard designed and built interface for this system. The interface was used to tie the six tiltmeters into two LaBarge DCPs in October 1977. This installation was made by Webster and Dee Breger and John Beavan of Lamont.

This paper discusses the systems engineering considerations involved, describes the special-purpose equipment constructed and reviews the performance of the Landsat data collection system in this experiment. The scientific results of the experiment have been reviewed by Bilham and Beavan (1979).

INITIAL ANEGADA EXPERIMENT

The initial experiment was designed to assess the extent of coverage of the Anegada area from the Goddard tracking station. Although Anegada is essentially flat (maximum elevation 20 ft. above sea level), the location of the Goddard Satellite Tracking and Data Acquisition Network Station (GSTDN) is such that the horizon is obscured by trees and hills to the south and east. Since it is network practice to command spacecraft off while it is still possible to assure execution and to hold "on" commands until the main beam of the tracking antenna clears the horizon, it was not possible to guarantee the extent of mutual visibility between GSTDN and Anegada.

The situation is illustrated in Figure 2. On a Mercator projection the intersections of the apparent elevation circles form a series of lunes. In the interest of simplicity only the 0° elevation semicircle is shown for Anegada (NNE-W segment) while the 0°, 5°, and 10° semicircles are shown for GSTDN. A relay is possible anytime Landsat is within the region enclosed by the semicircles. A typical pattern of ascending and descending node orbital tracks is also shown together with an orbit yielding the maximum simultaneous visibility ($10^m\ 30^s$).

In order to investigate the available coverage in practice, a DCP was deployed on the south side of the island (18°33:7N, 64°23:2W). The DCP was connected to a Lamont sea level recorder (Bilham 1977) through a voltage to frequency converter (VCO) and integrating counter interface constructed at Lamont. The Lamont interface provided eight parallel digital words on latch integrated circuits (ICs) corresponding to the tide gauge voltage integrated over a 1½ hour period. Conventional CMOS logic was employed in the integrating counter and a low power VCO/Operational Amplifier IC was used for the voltage to frequency converter.

A GE DCP was used for this initial experiment. A measured output of 12.2 watts into a 50 ohm load was obtained at the rated input DC voltage (24 V). In order to keep the antenna size small enough to transport easily, a printed circuit bifilar helix antenna manufactured by Chu Associates was used. The battery pack consisted of four 7½ Ampere-Hour (AH) gellcells and a bank of 1000 AH carbonaire aircell batteries. The gellcells acted as a buffer to the aircells. This combination was necessary because the 2½ ampere instantaneous current drain during transmissions caused the input voltage to vary by 2+ volts from the unloaded output. When using aircells alone and the gellcells did not provide enough capacity. The gellcells acted as a regulator for the main power bus supplied by the carbonaire batteries.

The DCP proper was enclosed in a weather tight case and it and the VCO/counter assembly were located in a shed at the yacht anchorage at Flamingo Bay on the south side of the island. The tide gauge used was one of two located at the lagoon and was connected to the interface by a buried cable. In Figure 3, we plot the results of six months of coverage on the diagram of Figure 2. The dotted area shows the subsatellite points for which GSTDN received transmission through Landsat from Anegada. As expected, the northeast and southcentral quadrants of the coverage diagram are empty. Figure 4 shows the tide gauge head and the shed where the DCP was located while Figure 5 shows the antenna installation. Although the antenna cleared the surrounding building by a comfortable margin (around 1-2 ft.), it was not practical to put the antenna high enough (an additional 8-10 ft.) to clear the surrounding palm trees. Since these trees were west-northwest of the antenna, the trees are responsible for the gap in coverage in the northwest quadrant.

The DCP system functioned for over a year (58 weeks) before the battery pack was depleted. For the last 48 hours of operation, the successful relays per pass decreased dramatically (cut to ¼ normal) due to drastically reduced transmitter output. It is typical of the depletion characteristics of carbonaire batteries that the end-of-life failure is abrupt. The 48 hour period probably represents the total discharge time of the gellcell buffer pack. The 58 weeks lifetime is about 10% greater than predicted from the nominal battery capacity.

Data returned through the DCS were compared with strip-chart recordings made on-site. The comparison showed no loss of quality in transmission. An example of the diurnal total variation is given in Figure 6. Because the Lamont tide gauges are intended to monitor the mean sea level, hydraulic damping is used to decrease the tidal amplitude (Bilham 1977). Thus, although all of the relative features of the tide at the Anegada yacht basin are apparent, the actual tide is much larger than indicated. Relative changes in amplitude, both long short time scale changes, are preserved, however.

TILTMETER RELAY SYSTEM

The success of the initial experiment encouraged us to proceed with Landsat relay of the tiltmeter array installed by Lamont on Anegada. The tiltmeters used in the Lamont array have two orthogonal outputs and thus require two DCP channels per tiltmeter. In addition to the tiltmeter signals, it is also important to get a regular readout of the DCP battery condition. With the storage characteristics of the DCP used in this experiment, this proved no problem.

The instrumentation used (i.e., the tiltmeters and the DCPs) for the tiltmeter DCP system was "off-the-shelf." The two DCPs were manufactured by LaBarge, Inc. and are adaptable to either Landsat or the Geostationary Operational Environmental Satellites (GOES). The tiltmeters were Kinemetrics, Inc. borehole tiltmeters of the same design as used by the USGS, Menlo Park, CA for their central California array (Mortenson and Johnston, 1975). Although this instrumentation is of a conventional nature, the problem of interfacing the tiltmeters and the DCP did require some sophisticated systems engineering considerations. The level of sophistication is not apparent from the simplicity of the actual interface.

The Lamont array was deployed along a 2km baseline with each tiltmeter connected by cable to a central recording station. Because of the long cable length, CMOS operational amplifiers were used to build the signal levels up to the requirements of the Lamont recorders. These amplifiers because of their high impedance also acted as impedance matching devices to the relatively low impedance tiltmeter lines. Impedance transformation into the DCPs was required since the analog to digital converter (ADC) used in the DCP requires an input impedance of 100Ω max.

TILTMETER ARRAY SATELLITE DATA COLLECTION SYSTEM DESCRIPTION

The system consists of six tiltmeters with their associated electronics, an interface box, two Data Collection Platforms (DCPs), and their related power sources and cabling. The latter parts of the system will be discussed in this document, with only a brief review of the tiltmeter output characteristics. The six tiltmeters, each having two orthogonal outputs, feed two DCPs. This gives twelve channels of tiltmeter data. The four power sources for the tiltmeters and the DCPs were also monitored. Therefore, there is a total of sixteen channels of data. Each channel was sampled four times a day and the data relayed by satellite twice a day through the Landsat satellite. Data sequence tags were included in the data so that the relative time that each data sample was taken could be determined. It should be noted that the data was instantaneous and was *not averaged* over the time between samples. The data were stored in the DCPs until relayed to the satellite. The timing and sequence setup for the two DCPs is described in a later section dealing with the DCP initialization.

The output impedance of the tiltmeter system that drives the DCP interface circuits must not exceed 100 ohms due to the DCP ADC. The output voltage should not exceed plus and minus seven (7) volts to avoid overdriving the ADC but a sensitivity of 40 milli-volts per microradian or tilt must be preserved since this is the intrinsic accuracy of the tiltmeters.

Interface

All signal outputs to the DCPs are required to be 0-5 volts DC. The output of the tiltmeter is plus and minus seven (7) volts buffered by the op. amp. To interface these two units a circuit was designed to insert a DC bias on the DCP input such that 0 volts from the tiltmeter would result in approximately 2.5 volts into the DCP (mid range). Since maximum sensitivity was desired with a minimum loss in dynamic range the circuit was designed to preserve the sensitivity as much as possible using only passive components. The resultant output signal of the interface circuit represents approximately 34 microradians of tilt per volt of signal with a dynamic range of plus and minus 85 microradians. The DCP has an input sensitivity of approximately 20 millivolts per count (one digit). This gives an overall sensitivity of at least 0.7 microradians.

The tiltmeter power sources were approximately plus and minus 15 volts. Each was a bank of 1000 ampere-hour carbonair cells. The positive supply was interfaced by a simple voltage divider. This gives approximately 3.2 volts into the DCP for 15 volts. The negative supply had a DC bias inserted such that minus 15 volts results in approximately 2.0 volts into the DCP and any less negative voltage increases the input. The input to DCP goes to approximately 5 volts if the negative supply should go to zero. The DCP power sources are both plus 12 volts. These channels are also used for a data sequence tag on the data. This channel (one for each DCP) alternately samples a voltage divider on the DCP power source and then ground. The sampling control was done by a latching relay which is controlled by the switched 12 volts available from the DCP. Details of this circuit are discussed later.

The overall cabling diagram is shown in Figure 7. This shows the cabling harness which brings the tiltmeter signal and tiltmeter power supply voltages from the tiltmeter array junction box to the interface box, and from the interface box to the two DCPs. Also the power for the DCPs was handled by this harness.

The interface electronics was packaged in a box which is approximately 10.5 x 8.0 x 7.0cm. Figure 8 shows the arrangement of the nine cards within the box. The cards are designated TM-1, TM-2, TM-3, KY-1, PS, KY-2, TM-4, TM-5 and TM-6. Card TM-1 has the interface for tiltmeter #1 and so forth. Cards TM-1, TM-2, TM-3 and KY-1 are connected to DCP#1, while cards KY-2, TM-4, TM-5 and TM-6 are connected to DCP#2. The center card (marked PS) is connected to both DCPs, i.e., the positive supply interface is connected to DCP#1, and the negative supply interface is connected to DCP#2. (Caution: if the cards need to be removed from the box, the cable harness must be disconnected first to protect the DCPs, as well as the zener diodes on the TM cards.)

The plug for the interface box was mounted on one of the two covers to the box. The other cover could be removed during setup in the field. This cover had to be tightly replaced after the setup procedure is finished to reform the environmental seal. It should be noted that certain bus wires are run along the back of the cards (the end toward the 50 pin connector). This will prevent removal of the cards from the front of the box. Removal must be done from the rear connector end as a group.

Six of the cards are for the tiltmeter interface circuits (see Fig. 9) and are designated by TM-#. Each card has the circuits for both the "X" and "Y" channels of the tiltmeter. Figure 10 shows the circuit for the tiltmeter interfaces. The reference voltage (switched 12 volts) with its dropping resistor and zener diode is shared between the two interface circuits on the card. The potentiometers for zeroing the circuit (setting the output to 2.5 volts with zero volts in) are separate for each circuit. The result is: an input of approximately plus 3.4 volts, drives the output of the interface to plus five volts; an input of approximately minus 3.4 volts will drive the output to 0 volts. Any voltage beyond these extremes is clamped by a diode to protect the DCP input circuit.

One card has the interface circuits for both the plus and minus power supplies for the tiltmeters (see Fig. 11) and is designated PS. Figure 12 shows the interface circuits. It should be noted that this is the only card which had circuitry driving both DCPs. The positive supply interface circuit drives channel 7 of DCP#1 and the negative supply interface circuit drives channel 7 of DCP#2.

The last two cards contain the DCP power supply monitoring and the data set identification switch for each DCP (see Fig. 13) and are designated by KY-#. The circuit is shown in Figure 14. The relay is a bistable relay and it changes state once each time the switched 12 volts power is applied. The switched 12 V is applied about 80 seconds prior to the actual sampling of data and remains on during the sampling of the data. Therefore, the relay changes state just prior to each sampling period and remains in that state until the next sampling period starts. The relay can be set in either state during setup by applying +12 volts to either TP 1 or TP 2. It should be noted that as the next sample period begins, the relay will change state. Care must be taken to insure that the state of the relay is known at initialization of the DCPs. This can be accomplished by measuring the voltage on TP #3 during the sampling period.

Timing and Sampling Sequence

The Landsat satellite passes within view of the island at least twice a day. That is, at least once before noon and once before midnight. During each pass, all the data collected by the system during the last two sampling periods can be relayed through the satellite. This was accomplished by two consecutive transmissions of the DCPs. Each DCP transmits an average of once every 1.5 minutes whether or not the satellite is above the horizon. Thus the DCP would send at least six consecutive transmissions per visible pass and the data are repeated at least three times during each of these passes. Since the data are sampled every six hours, two sets of data were taken between passes and are transmitted during the next pass. A diagram of this sequence is shown in Figure 15. Each channel sampled results in one word stored in the memory of the DCP.

After the first eight channels are sampled, the first eight words of data are stored in the DCP memory. During the second sampling period another eight words are stored in the DCP memory, i.e., 16 words of data are stored for transmission. On a transmission, eight of the data words are transmitted, and on the next transmission the second eight data words are transmitted. This is repeated over and over again until the next sampling period, when the first eight words are written over, i.e., destroyed and a new set of eight data words are substituted. On the next sampling period the second eight words are updated. The sampling occurs every six hours and, therefore, both sets of data words are updated between passes. Although the DCP is transmitting new and old data in consecutive transmission between sampling, the data is completely updated before the next satellite pass.

Difficulties on the island (Bilham and Beavan 1979; see Appendix II) made it impossible to use the entire tiltmeter array with the DCP system. Because of weather and animal damage, no more than four tiltmeters were operational at any one time. Nonetheless, the system operated well from start up to completion of the experiment in early 1979.

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Bilham, R. and J. Beavan, 1979, Tilt measurements on a small tropical island, Final Report, NASA Grant NSG 5072, (See Appendix II).

Mortenson, C. E. and M. J. S. Johnston, 1975, The nature of surface tilt along 85km of the San Andreas Fault–Preliminary results from a 14 instrument array, Pageoph, 113, 237-249.

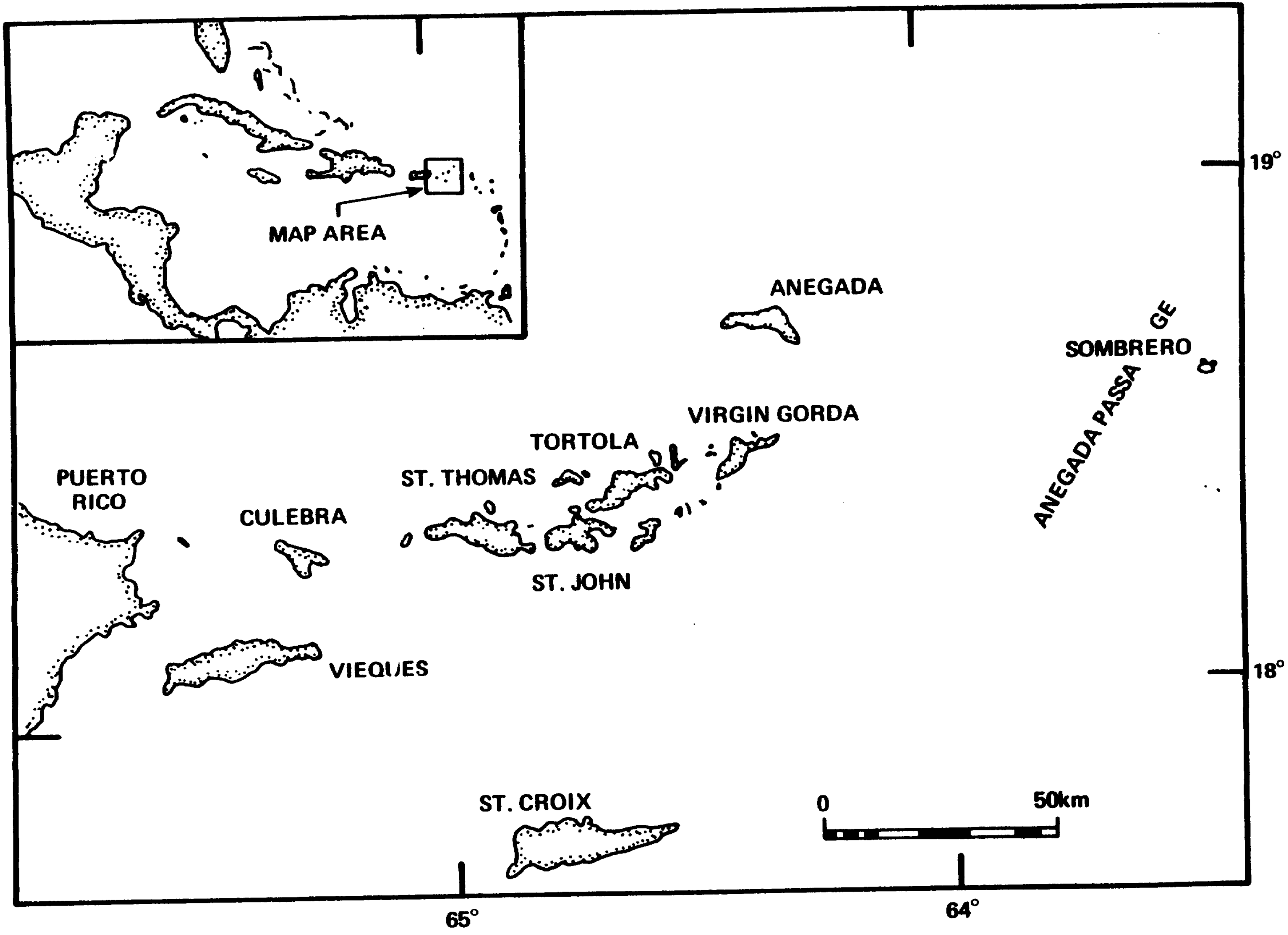


Figure 1. Location Map for British Virgin Islands

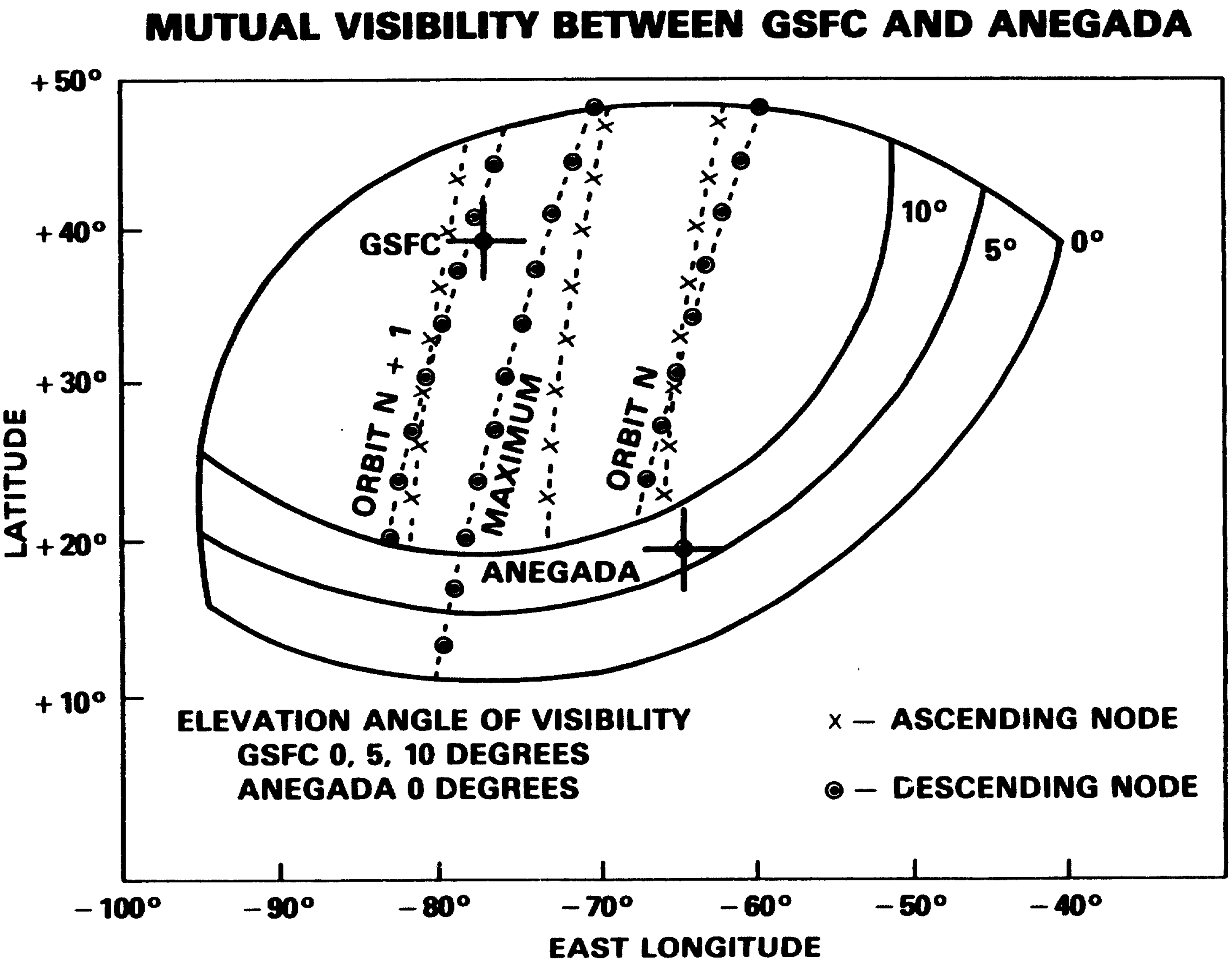
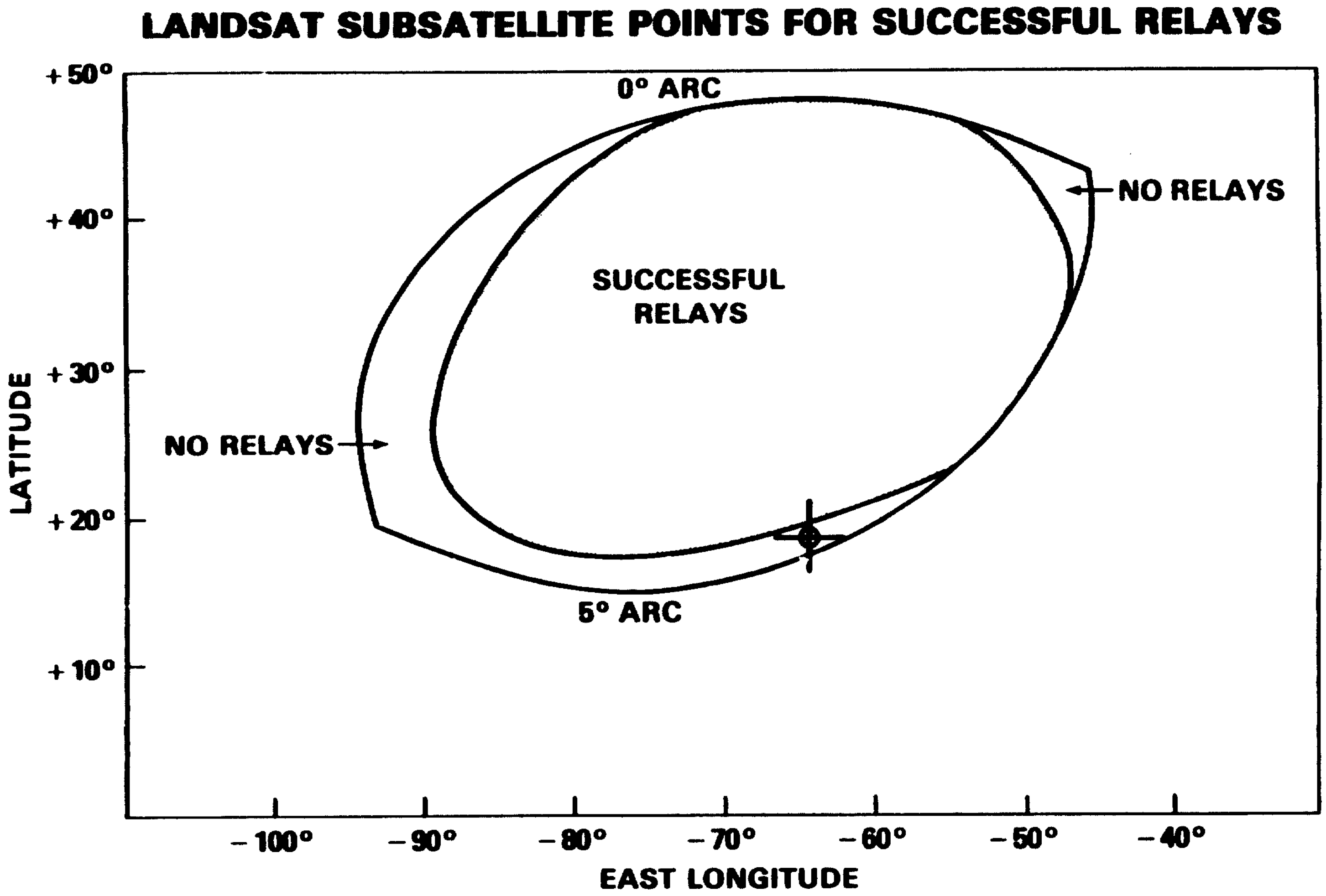


Figure 2. Predicted Coverage Diagram for Anegada Through GSTDN
Landsat 3 Orbit



LANDSAT SUBSATELLITE POINTS FOR SUCCESSFUL RELAYS

Figure 3. Observed Coverage Diagram
The filled-in area shows the subsatellite points where successful relays occurred.

Figure 4. Tide Gauge Used on Anegada

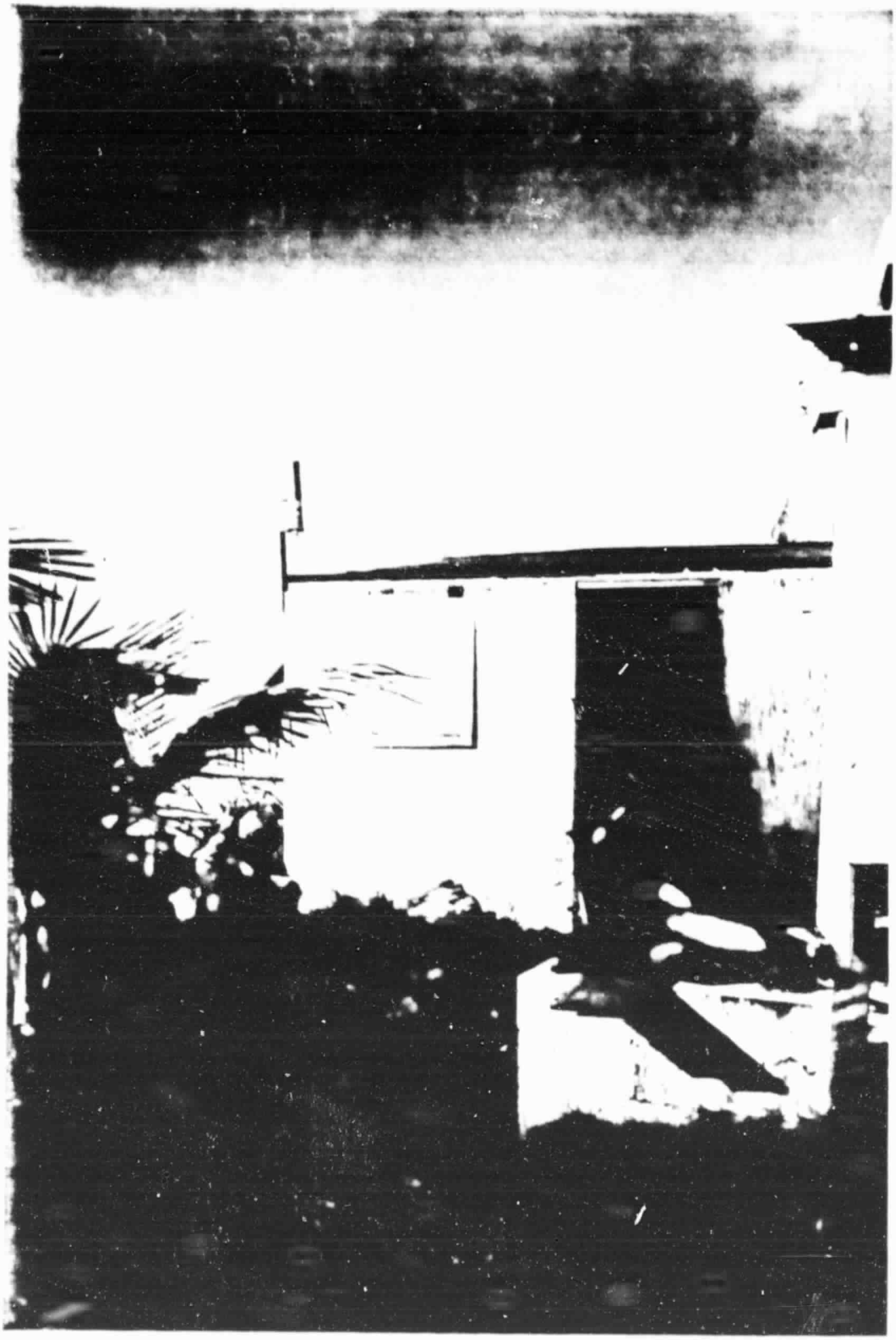


Figure 5. Landsat Antenna Installation

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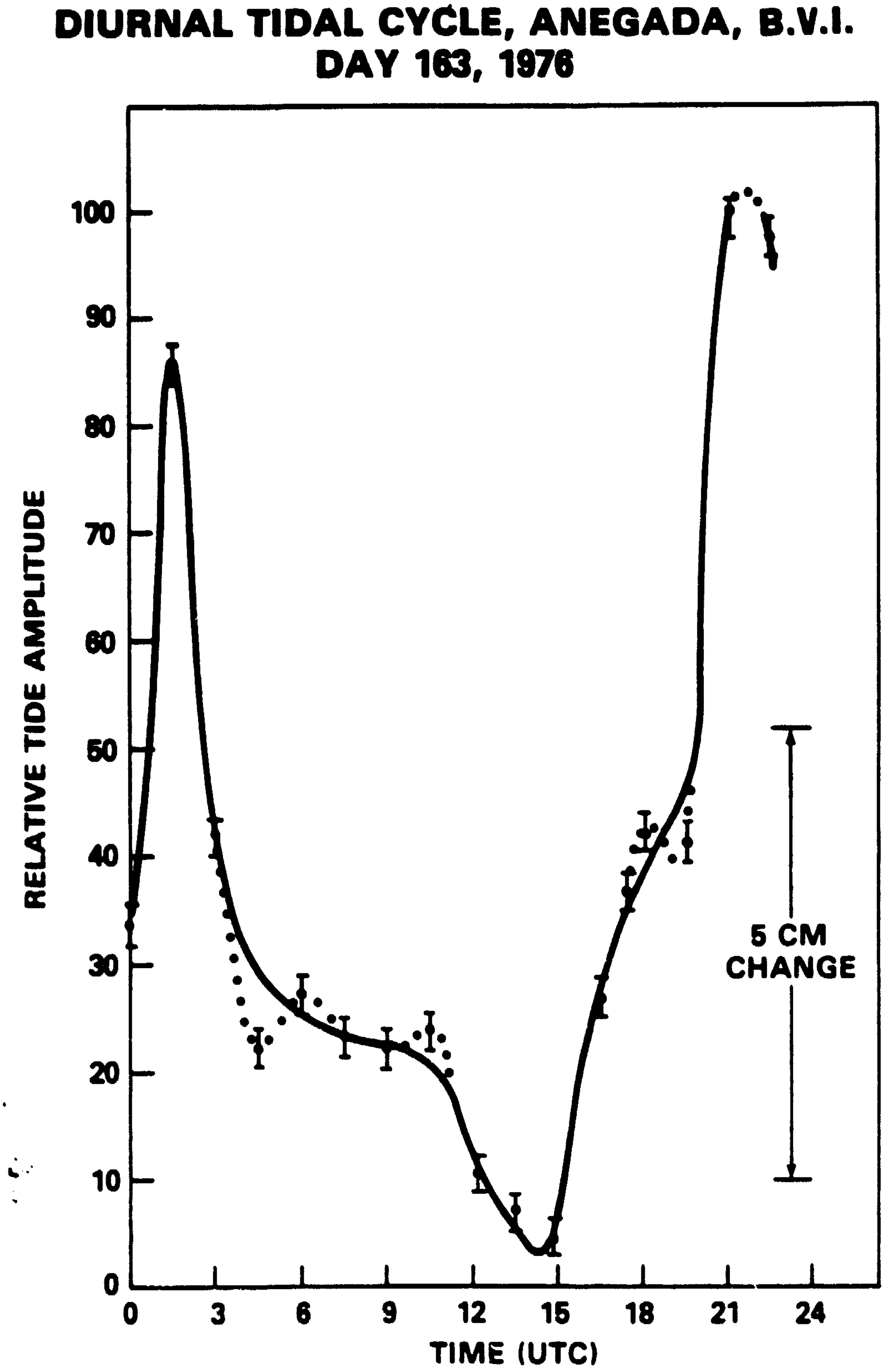


Figure 6. Observed Diurnal Tide Variation Reported by DCP
Dots are individual measurements. Solid line is the predicted variation.
The error bars are the expected variability over the averaging interval.

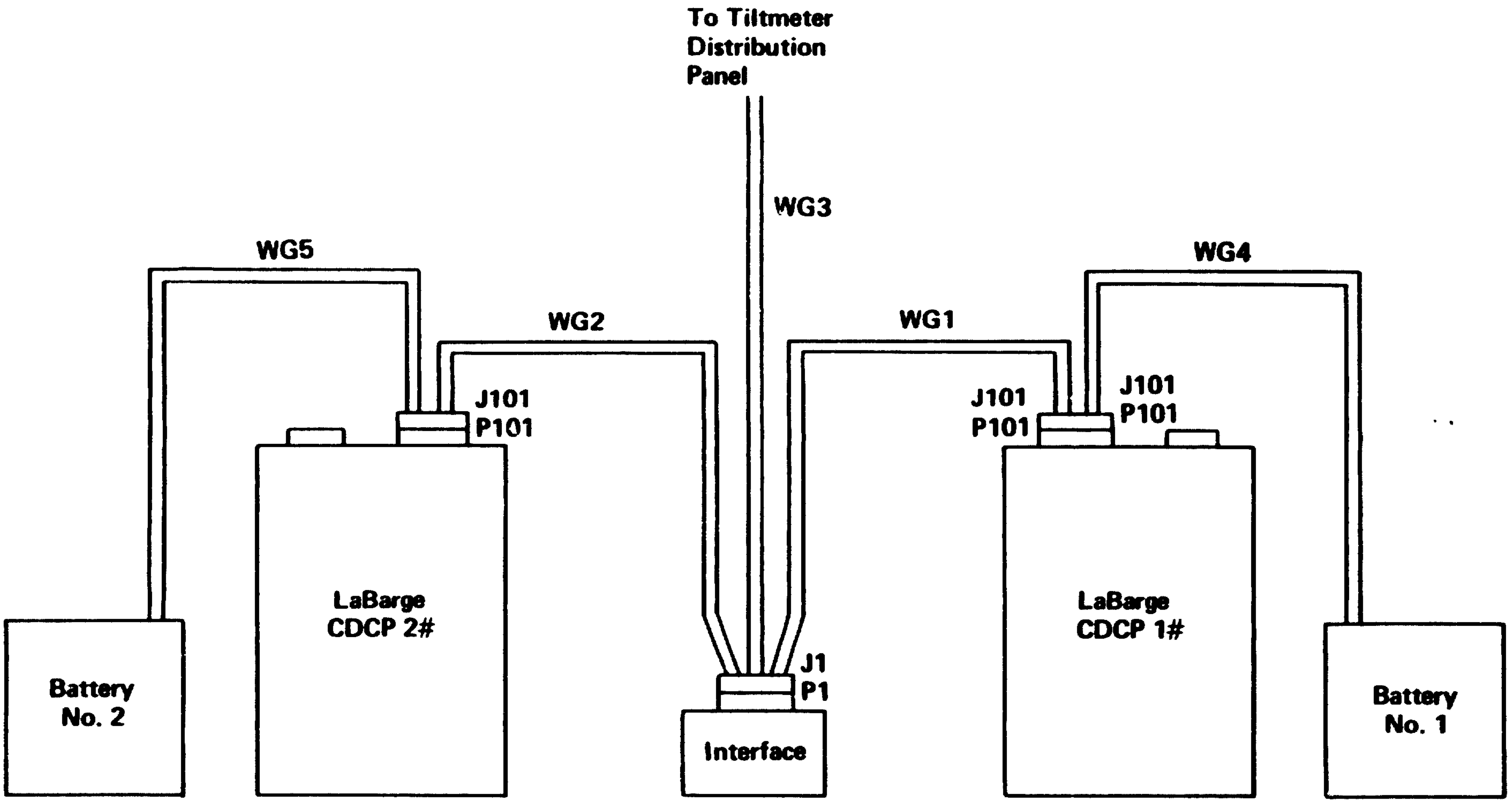


Figure 7. Wiring Harness for Tiltmeter System

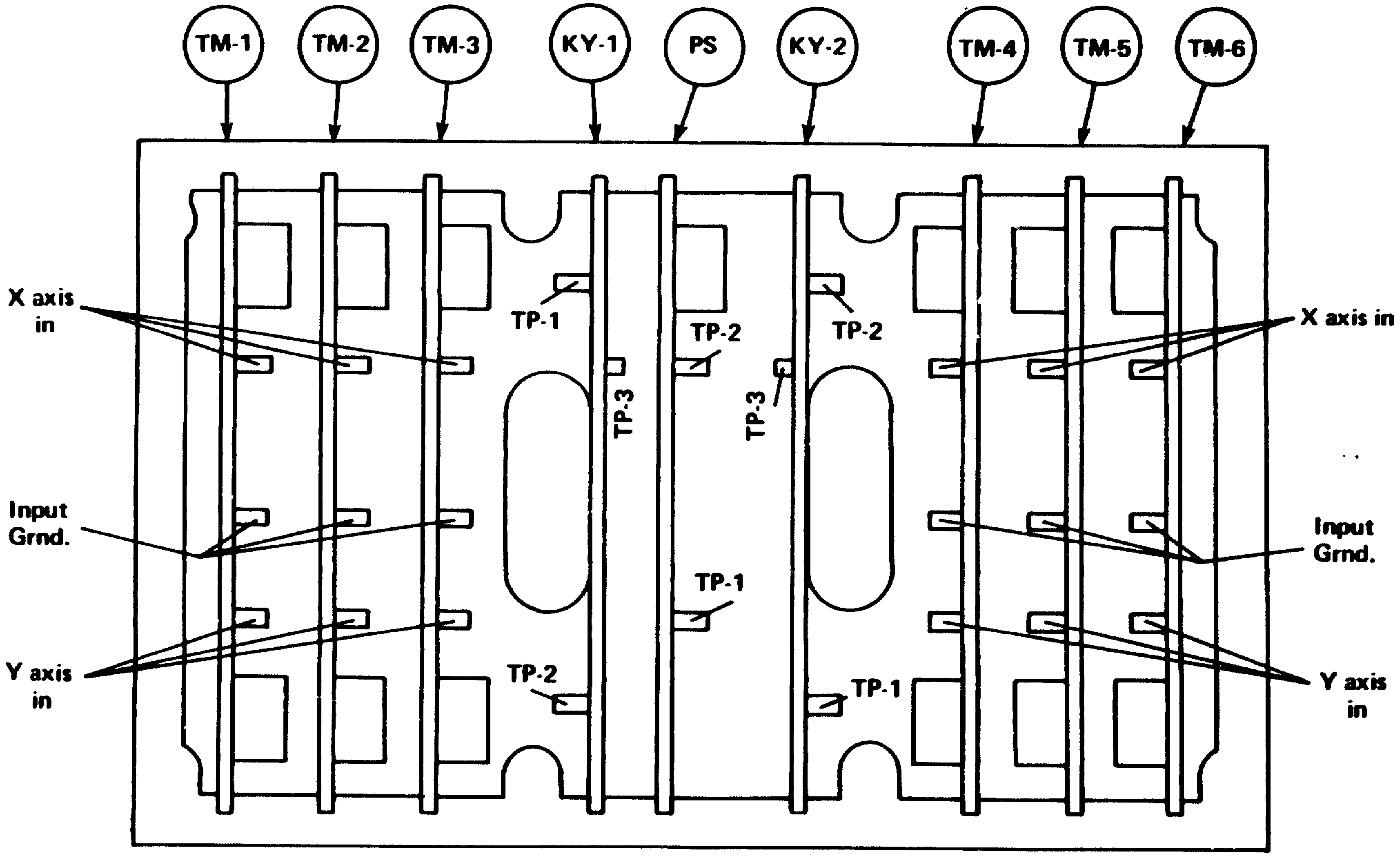


Figure 8. Interface Box Card Locations

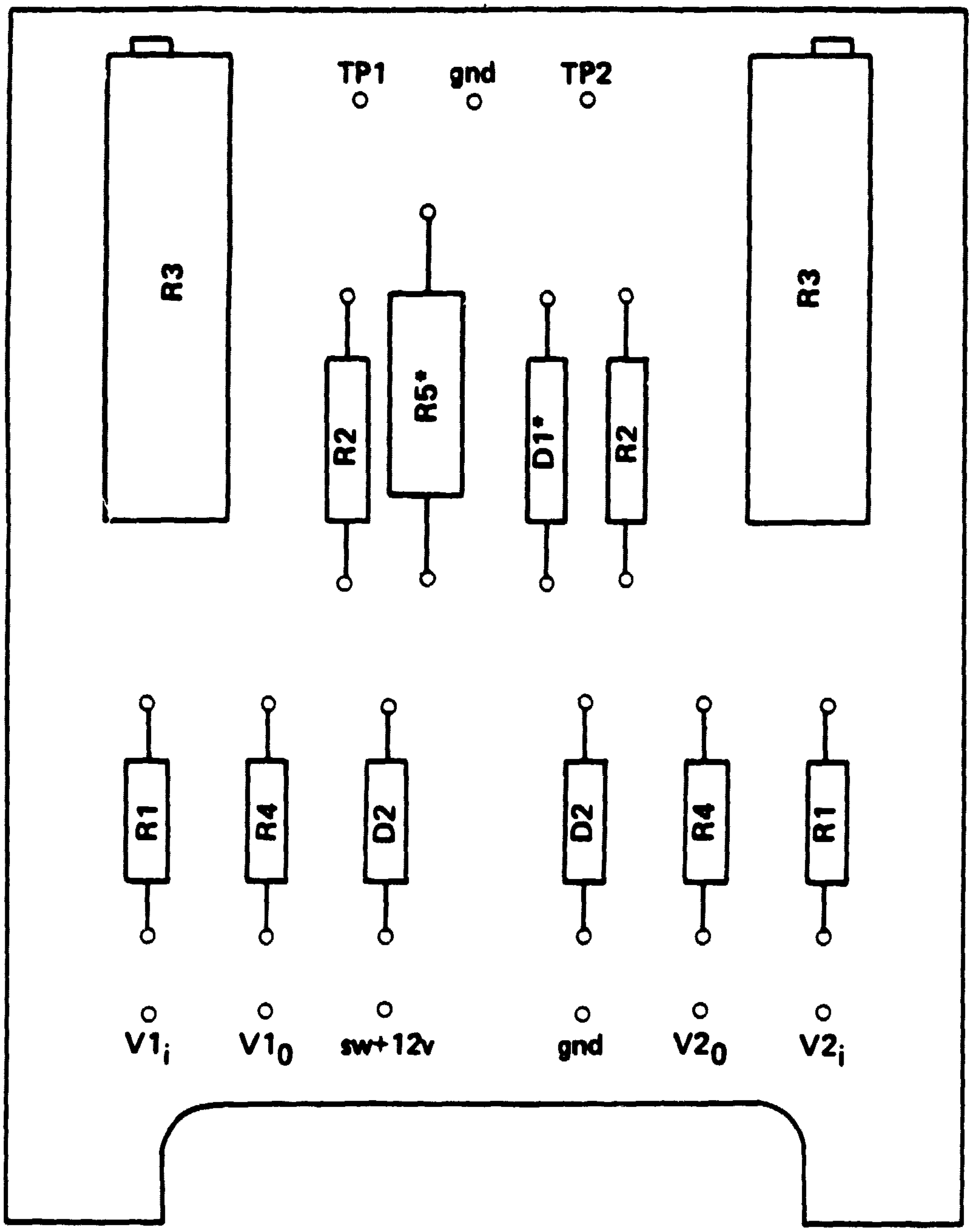


Figure 9. Two Channel Tiltmeter Interface Board
Starred components are selected for a particular tiltmeter.

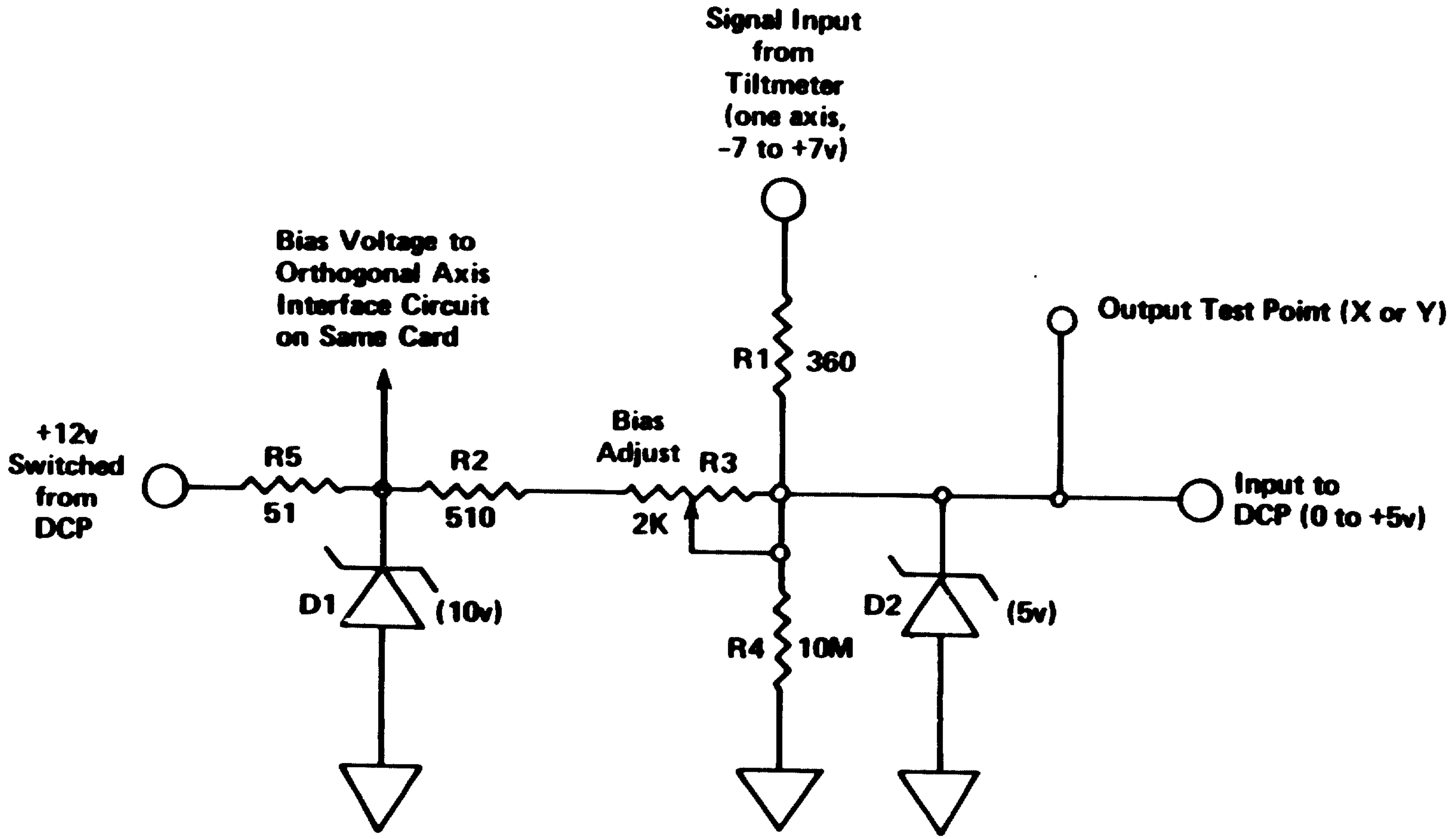


Figure 10. Tiltmeter Interface Circuit

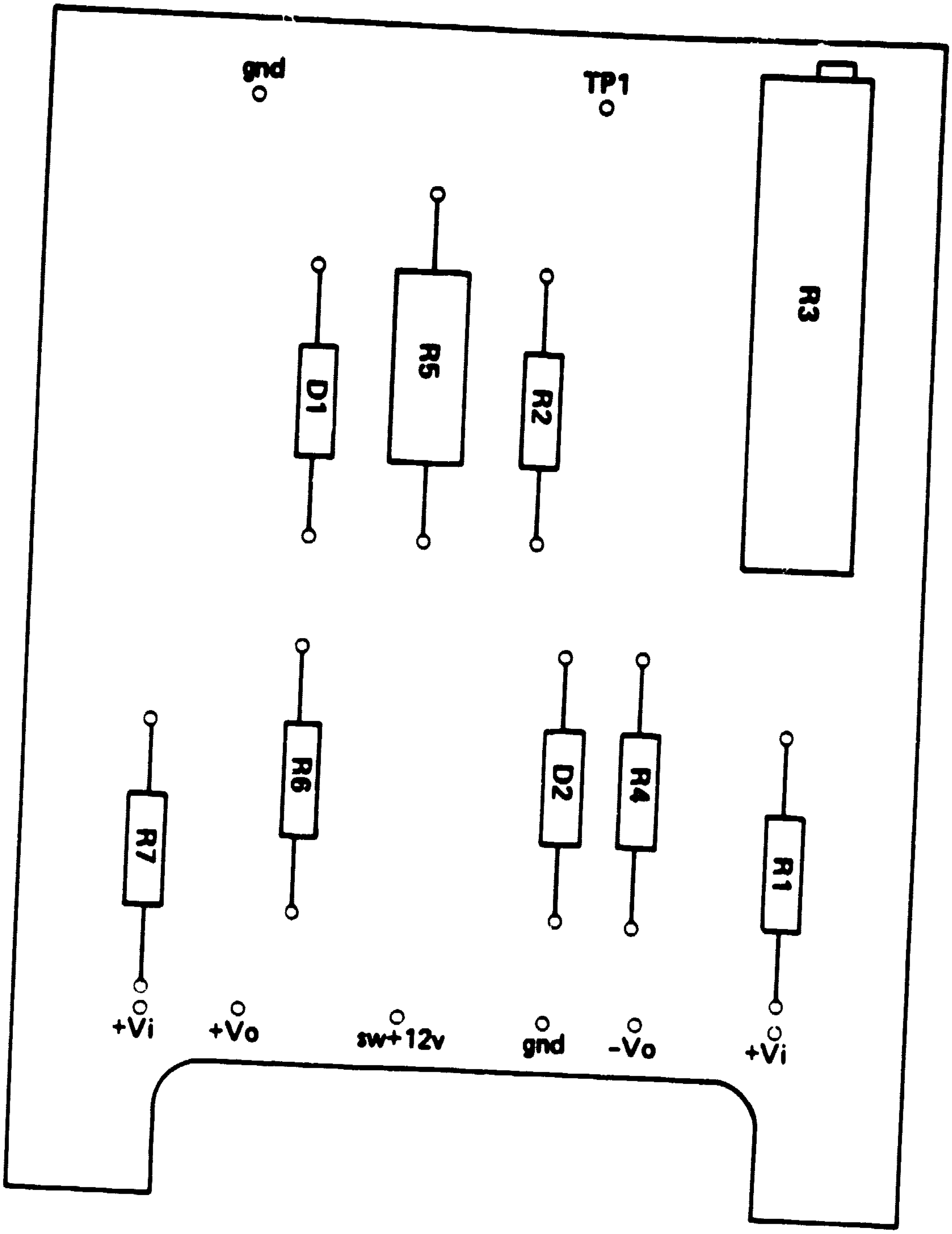


Figure 11. Tiltmeter Power Supply Interface Board

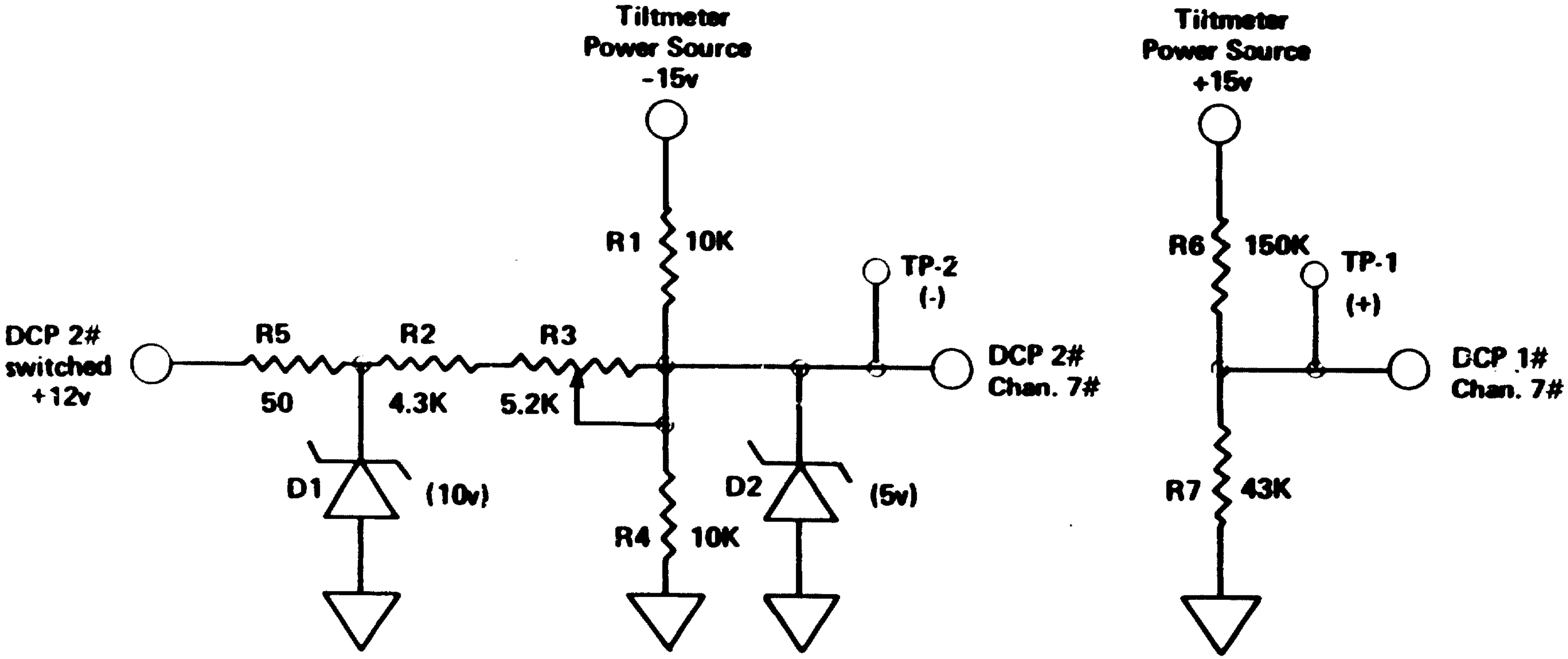


Figure 12. Tiltmeter Power Source Interface Circuit

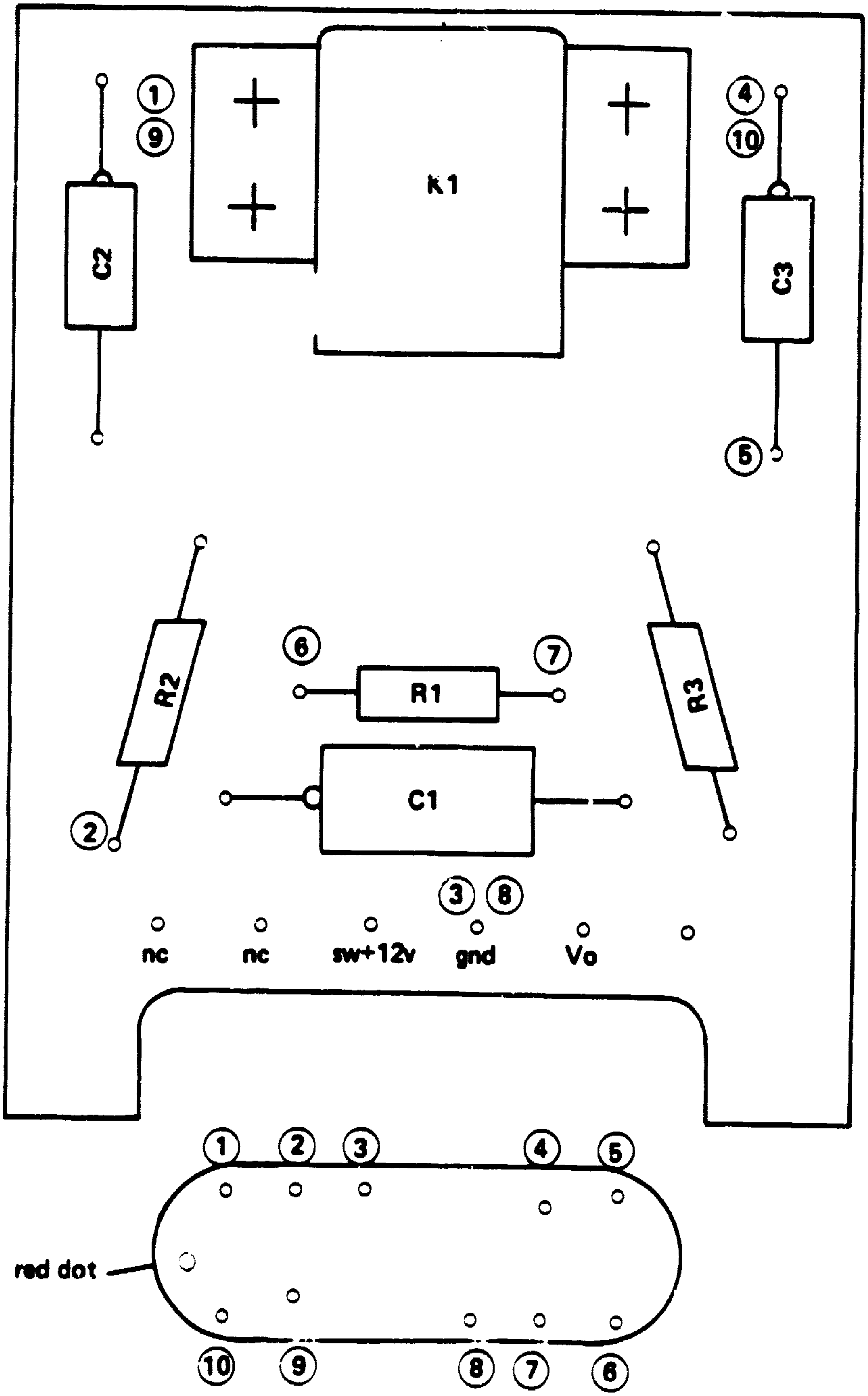
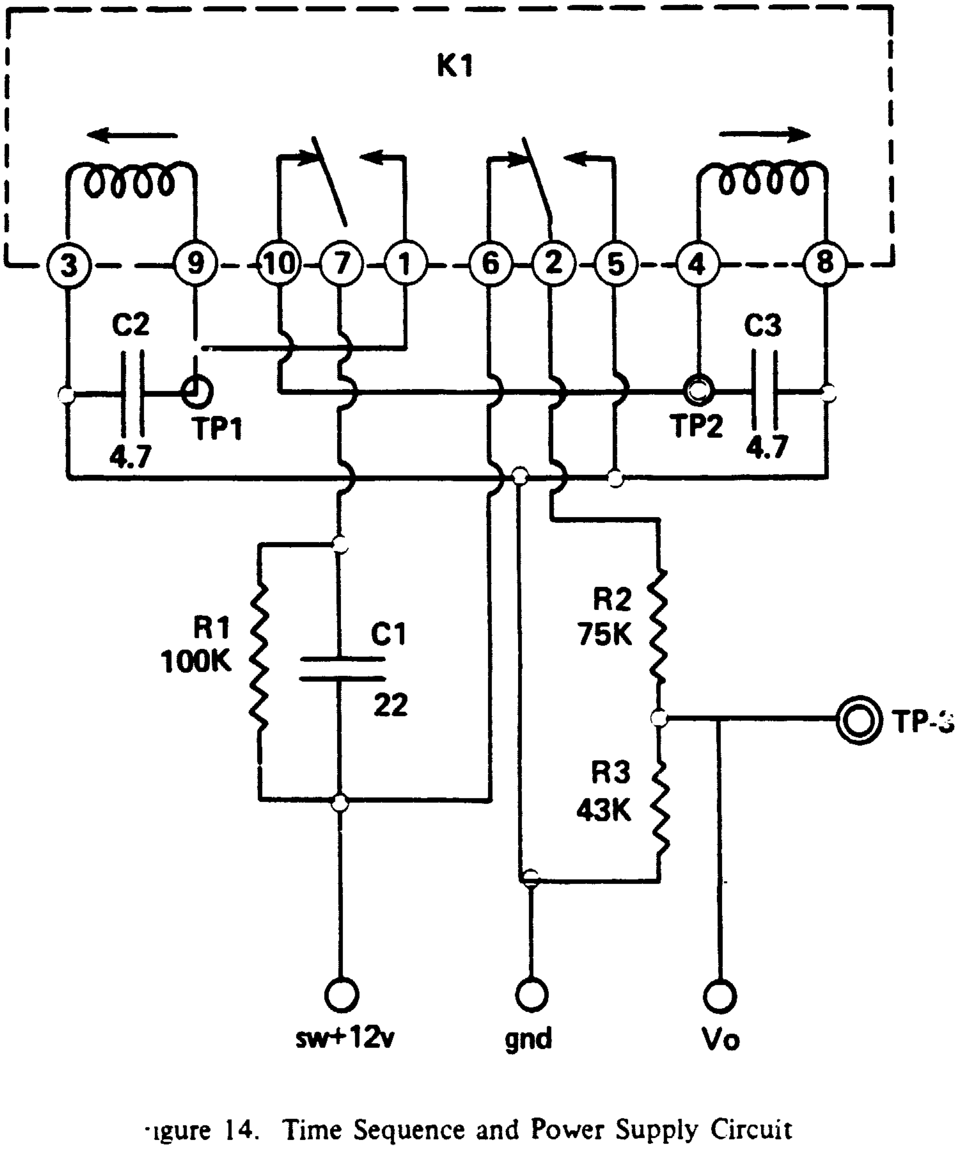
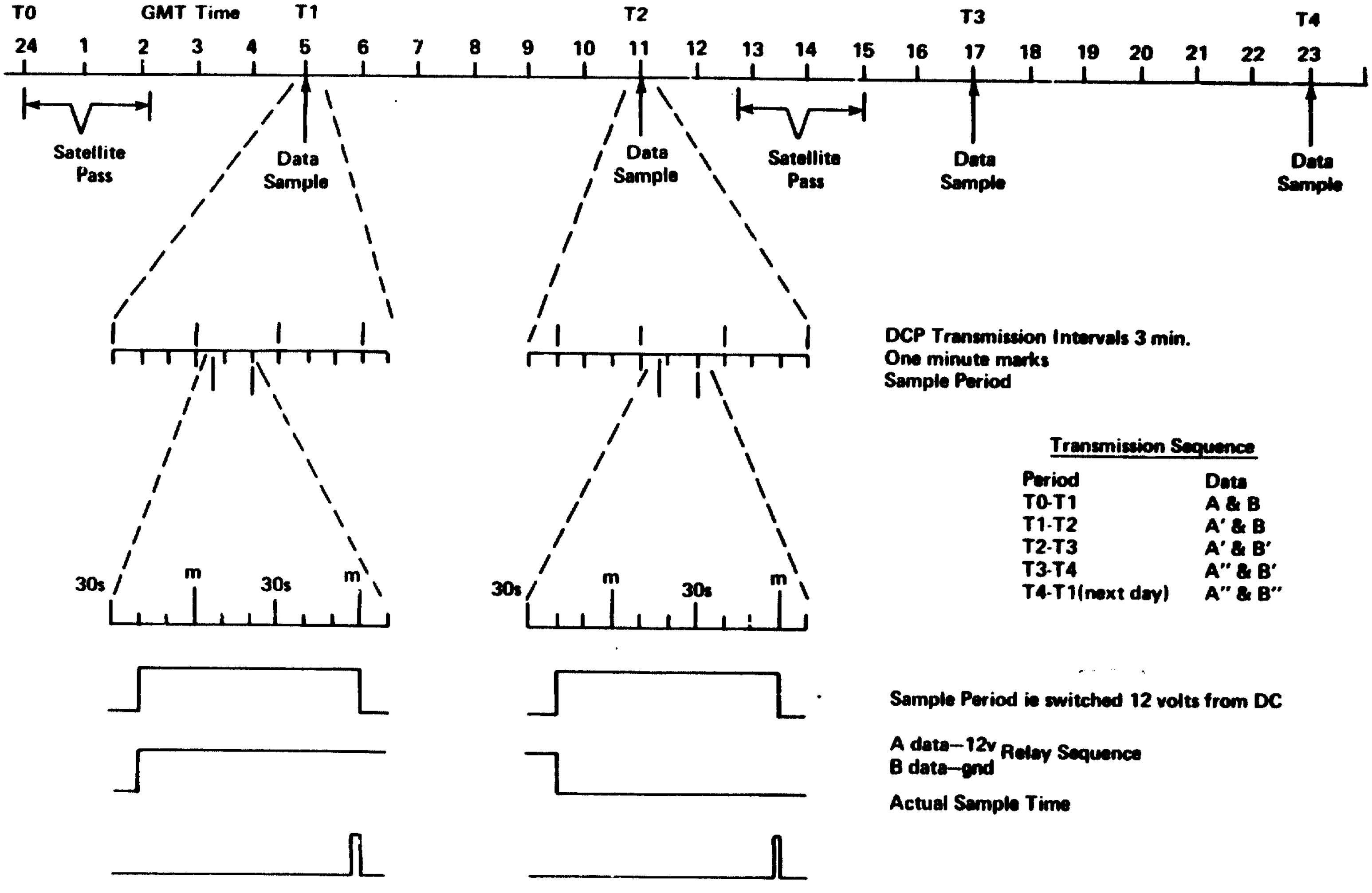


Figure 13. Time Sequence and Power Supply Interface Board



·igure 14. Time Sequence and Power Supply Circuit



Transmission Sequence

Period	Data
T0-T1	A & B
T1-T2	A' & B
T2-T3	A' & B'
T3-T4	A'' & B'
T4-T1(next day)	A'' & B''

Figure 15. DCP Data Timing Sequence

APPENDIX I

Set-Up and Operating Instructions

APPENDIX I

Set-Up and Operating Instructions

Field Set-Up for Tiltmeter

1. Carefully unpack all the equipment and inspect it for damage.
2. Install the antennas and connect them to the DCPs using the cables provided.
3. Place the batteries, as nearly as possible, in the location they will be used and activate them. Refer to Figure I.
4. With the exception of the 12 volt batteries, connect the wire harness assembly to the DCPs, the Interface Box, and the tiltmeter electronics as shown in Figure 1. Be sure that WG 1 is connected to DCP 1 and WG 2 is connected to DCP 2. Refer to Table III to connect WG 3. The number tags on WG 3 refer to J 1 pin numbers.
5. Disconnect antenna cable from DCP 1.
6. Remove dummy load from cover of test set and connect to DCP 1.
7. Connect WG 4 to one of the 12 volt battery packs.

   NOTE: If 12 volt battery is removed from either DCP after preliminary programming, antenna must be replaced with dummy load and programming repeated.
8. Set the test set switches as follows:
   (a) Set power switch to off.
   (b) Set memory switch to secure.
9. Connect test set to DCP 1 with the cable provided.
10. Set test set switches as follows:
    (a) Set power switch to on.
    (b) Set memory switch to access.

11. Perform preliminary programming of DCP by entering constants into the DCP memory addresses as follows:
    (a) Set address thumb wheel switches to 01.
    (b) Set data thumb wheel switch to C.
    (c) Depress enter switch.
    (d) The data display lights should indicate a value of C hexadecimal.

12. Refer to Table I and complete the preliminary programming, using the procedure outlined in step 11.

13. Initiate DCP 1 by setting test set switches as follows:
    (a) Set data switch to 0.
    (b) Set address switch to 00.
    (c) Depress timer reset switch twice within one second.
    (d) Depress enter switch.

14. Set test set switches as follows:
    (a) Set memory switch to secure.
    (b) Set power switch to off.

15. Disconnect test set from DCP 1.

16. Disconnect dummy load from DCP 1.

17. Connect antenna cable to DCP 1.

18. Disconnect antenna cable from DCP 2.

19. Connect dummy load to DCP 2.

20. Connect WG 5 to the remaining 12 volt battery pack.

21. Repeat steps 8 through 17 to perform preliminary programming of DCP 2. At this point the following conditions should exist for both DCPs:

(a) A transmission should occur approximately every 180 seconds. The green RF power and modulation lights should go on momentarily when transmission occurs.

(b) Data update should occur every six minutes, indicated by flashing of the amber data data display lights.

(c) Before proceeding, at least 12 minutes should have passed since the DCPs were initiated, to ensure that the data memories contain a full data set.

22. Repeat sets 8 through 10.

23. Set address thumb wheel switches to 30 and record binary word indicated by data display lights.

24. Repeat set 23 for memory location 31 through 3F for first sample data and also 40 through 4F for second sample data.

25. Refer to Table I and enter final program constants for DCP 1. Check all address locations that are used to ensure that they contain the correct constants.

26. Set timer for proper update times by depressing the timer reset two times within one second. The second timer reset switch actuation must be executed at a desired update time, namely, 5:00, 11:00, 17:00 or 23:00 GMT.

27. Perform final initialization of DCP 1 by setting test set switches as follows:

    (a) Set data switch to 0.

    (b) Set address switch to 00.

    (c) Depress enter switch.

    Step 27 must be performed within 180 seconds of step 26 to ensure proper data management.

28. Set test set switches as follows:

    (a) Set memory switch to secure.

    (b) Set power switch to off.

29. Disconnect test set from DCP 1 and connect it to DCP 2.

30. Set test set switches as follows:

    (a) Set power switch to on.

    (b) Set memory switch to access.

31. Repeat set 23 and 24.

32. Refer to Table I and enter final program constants for DCP 2. Check all address locations that are used to ensure that they contain the correct constants.

33. Repeat step 26 through 28.

34. Disconnect test set from DCP 2.

Field Verification of Interface Calibration

NOTE: Step 1 through 7 must be performed for both DCPs.

1. Refer to Table II and convert the data, obtained in steps 23 and 24, to interface output voltages.

   Example:

   (a) Write the data from memory addresses 30 and 31 in binary form. Remember 30 contains the LSB and 31 to MSB.

31	30
MSB 1000	0011 LSB

   (b) Convert to decimal, 1 plus 2 plus 128 equals 131.

   (c) Multiply by 5/256 or 0.195 131 times 0.0195 equals 2.558 volts.

2. Figure II was compiled with the DCP battery voltage set at 12:00 volts. Any change in this voltage (as the battery discharges) will change the interface outputs, therefore, in the data conversion process it will be necessary to determine the DCP battery voltage at the time of data sampling and use Table IV to obtain the value to be added to or subtracted from the interface output signals stored in the data memory. This is accomplished as follows:

(a) Using the procedure outlined in step 1, convert data word 8, from binary to analog. The first sample is in 3E and 3F, the second sample is in 4E and 4F. One sample will be zero and the other will represent the 12 V DCP battery.

(b) Refer to Figure III and convert value obtained in (a) above to the battery voltages level.

(c) Refer to Table IV and determine the value to be added to or subtracted from interface value for data words 1 through 6.

3. Correct the value obtained in step 1 for data words 1 through 6 by adding or subtracting the value obtained in step 2.

4. Refer to Figure II and convert data words 1 through 6 to actual tiltmeter voltages.

5. Refer to Figure IV and convert data word 7 to a plus or minus 15 volts battery level depending on which DCP is being checked.

6. Measure the analog voltages listed in the Function column of Table II.

   NOTE: All tiltmeter x and y axis outputs as well as the plus and minus 15 volt battery voltages are available in the tiltmeter array junction box. The +12 V switched from DCP 1 and DCP 2 can be measured on the back side of card K1 and K2, respectively, (The points are labeled.)

7. Compare the value measured in step 6 with the value contained in step 1 for the +12 V DCP battery, step 3 for the tiltmeter outputs, and step 4 for the plus or minus 15 volt tiltmeter battery.

Table I

Program Constants for DCPs

Address	Initial DCP#1	Final	Initial DCP#2	Final
01	C	C	C	C
02	1	1	1	1
03	6	6	7	7
04	*	*	*	*
05	*	*	*	*
06	*	*	*	*
07	*	*	*	*
08	*	*	*	*
09	0	0	0	0
0A	1	1	1	1
0B	*	*	*	*
0C	*	*	*	*
0D	0	0	0	0
0E	8	8	8	8
0F	1	1	1	1
10	*	*	*	*
11	*	*	*	*
12	*	*	*	*
13	*	*	*	*
14	1	8	1	8
15	0	1	0	1
16	1	0	1	0
17	0	0	0	0
18	0	0	0	0
19	2	2	2	2

*Not used value does not matter

0	o	o	o	o
1	o	o	o	*
2	o	o	*	o
3	o	o	*	*
4	o	*	o	o
5	o	*	o	*
6	o	*	*	o
7	o	*	*	*
8	*	o	o	o
9	*	o	o	*
A	*	o	*	o
B	*	o	*	*
C	*	*	o	o
D	*	*	o	*
E	*	*	*	o
F	*	*	*	*

o - light is off
* - light ison

Table II

Data Addresses and Sample Reduction

Function	DCP	Address			
		1st Sample		2nd Sample	
		msb	lsb	msb	lsb
Tiltmeter #1					
X axis	1	31	30	41	40
Y axis	1	33	32	43	42
Tiltmeter #2					
X axis	1	35	34	45	44
Y axis	1	37	36	47	46
Tiltmeter #3					
X axis	1	39	38	49	48
Y axis	1	3B	3A	4B	4A
Tiltmeter #4					
X axis	2	31	30	41	40
Y axis	2	33	32	43	42
Tiltmeter #5					
X axis	2	35	34	45	44
Y axis	2	37	36	47	46
Tiltmeter #6					
X axis	2	39	38	49	48
Y axis	2	3B	3A	4B	4A
Tiltmeter power					
positive	1	3D	3C	4D	4C
negative	2	3D	3C	4D	4C
DCP #1 power	1	3F	3E	4F	4E
DCP #2 power	2	3F	3E	4F	4E

Data Address	msb				lsb			
Pannel Lights	8	4	2	1	8	4	2	1
Multiplier	128	64	32	16	8	4	2	1
Sample data	1	0	0	1	0	1	0	1

1
4
16
+ 128
149

Magic Number (5 divided by 256)	times	0.019531
Input Voltage to DCP		2.910 volts

Table III

Wire Group	From			To			Signal
	Wire Group Connector		Module or Housing Pinmating Connector	Wire Group Connector		Module or Housing Pinmating Connector	
WG 1	J 1	2	Interface Box P1	J-101	j	DCP 1	TM 1 X Out
		4			m		TM 2 X Out
		6			AA		TM 3 X Out
		7			P		Grnd
		18			A		+12 V Switched
		34			z		TM 1 Y Out
		36			N		TM 2 Y Out
		38			T		TM 3 Y Out
		40			n		KY 1
WG 1	J 1	43	Interface Box P1	J-101	U	DCP 1	+15 V P.S. Out
WG 2	J 1	10	Interface Box P1	J-101	U	DCP 2	-15 V P.S. Out
		11			A		+12 V Switched
		13			j		TM 4 X Out
		15			m		TM 5 X Out
		17			AA		TM 6 X Out
		41			P		Grnd
		44			n		KY 2
		45			z		TM 4 Y Out
		47			N		TM 5 Y Out
WG 2	J 1	49	Interface Box P1	J-101	T	DCP 2	TM 6 Y Out
WG 3	J 1	1	Interface Box P1	(Terminals)		TM Junction	TM 1 X In
		3					TM 2 X In
		5					TM 3 X In

Table III (Continued)

	From			To			
Wire Group	Wire Group Connector		Module or Housing Pinmating Connector	Wire Group Connector		Module or Housing Pinmating Connector	Signal
W3	J 1	8	Interface Box P1	(Terminals)			Grnd
		9					-15 V P.S. In
		12					TM 4 X In
		14					TM 5 X In
		16					TM 6 X In
		35					TM 1 Y In
		37					TM 2 Y In
		39					TM 3 Y In
		42					+15 V P.S. In
		46					TM 4 Y In
		48					TM 5 Y In
WG 3	J 1	50	Interface Box	(Terminals)		TM Junction Box	TM 1 Y In
WG 4	J-101	C	DCP 1	(Terminals)		12 V Battery	+12 V P.S.
		Y				No. 1	+12 V P.S.
		E					Grnd
WG 4	J-101	F	DCP 1	(Terminals)		12 V Battery No. 1	Grnd
WG 5	J-101	C Y	DCP 2	(Terminals)		12 V Battery No. 2	+12 V P.S. +12 V P.S.
		E					Grnd
WG 5	J-101	F	DCP 2	(Terminals)		12 V Battery No. 2	Grnd

Table IV

Interface Output Voltage Corrections vs. DCP Battery Voltage

	Interface Output Ranges - Volts									
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
10.0**10.2	-.14	-.14	-.14	-.14	-.14	-.14	-.12	-.10	-.06	-.04
10.2**10.4	-.12	-.12	-.12	-.12	-.12	-.12	-.10	-.10	-.06	-.02
10.4**10.6	-.10	-.10	-.10	-.10	-.10	-.10	-.10	-.10	-0.6	-.02
10.6**10.8	-.08	-.08	-.08	-.08	-.08	-.08	-.08	-.08	-.04	-.02
10.8**11.0	-.06	-.06	-.06	-.06	-.06	-.06	-.06	-.06	-.04	-.02
11.0**11.2	-.06	-.06	-.06	-.06	-.06	-.06	-.06	-.06	-.04	-.02
11.2**11.4	-.04	-.04	-.04	-.04	-.04	-.04	-.04	-.04	-.02	-.02
11.4**11.6	-.02	-.02	-.02	-.02	-.02	-.02	-.02	-.02	-.00	-.00
11.6**11.8	-.02	-.02	-.02	-.02	-.02	-.02	-.02	-.02	-.00	-.00
11.8**12.0	.00	.00	.00	.00	.00	00	.00	.00	.00	.00
12.0**12.2	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
12.2**12.4	+.02	+.02	+.02	+.02	+.02	+.02	+.02	+.02	.00	.00
12.4**12.6	+.02	+.02	+.02	+.02	+.02	+.02	+.02	+.02	+.02	+.02
12.6**12.8	+.04	+.04	+.04	+.04	+.04	+.04	+.04	+.04	+.02	+.02
12.8**13.0	+.06	+.06	+.06	+.06	+.06	+.06	+.06	+.04	+.02	+.02
13.0**13.2	+.06	+.06	+.06	+.06	+.06	+.06	+.06	+.06	+.04	+.02
13.2**13.4	+.08	+.08	+.08	+.08	+.08	+.08	+.08	+.06	+.06	+.02
13.4**13.6	+.08	+.08	+.08	+.08	+.08	+.08	+.08	+.08	+.06	+.02
13.6**13.8	+.10	+.10	+.10	+.10	+.10	+.10	+.10	+.08	+.08	+.02
13.8**14.0	+.12	+.12	+.12	+.12	+.12	+.10	+.10	+.10	+.08	+.04

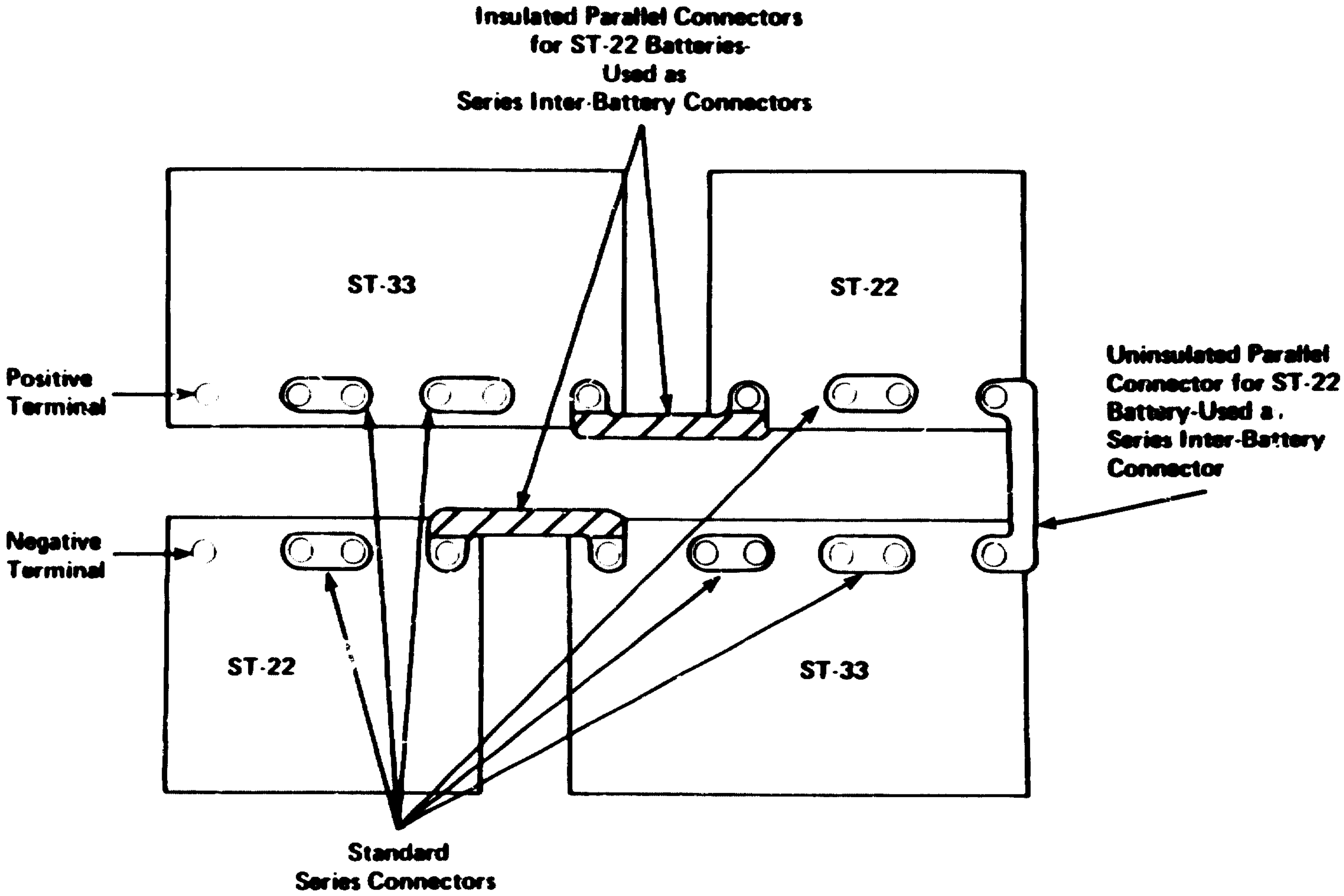


Figure I. Suggested Battery Configuration

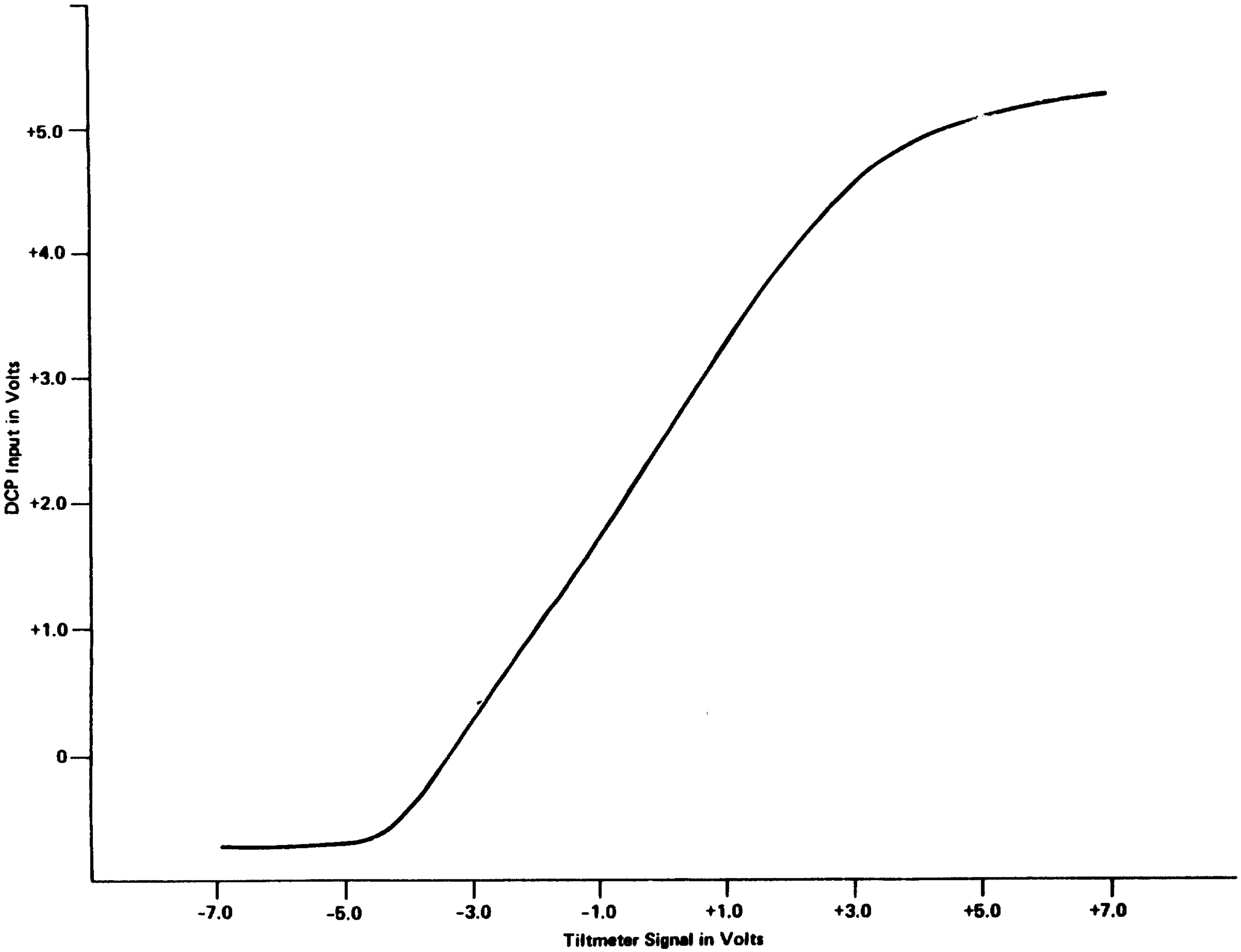


Figure II. Data Word #1

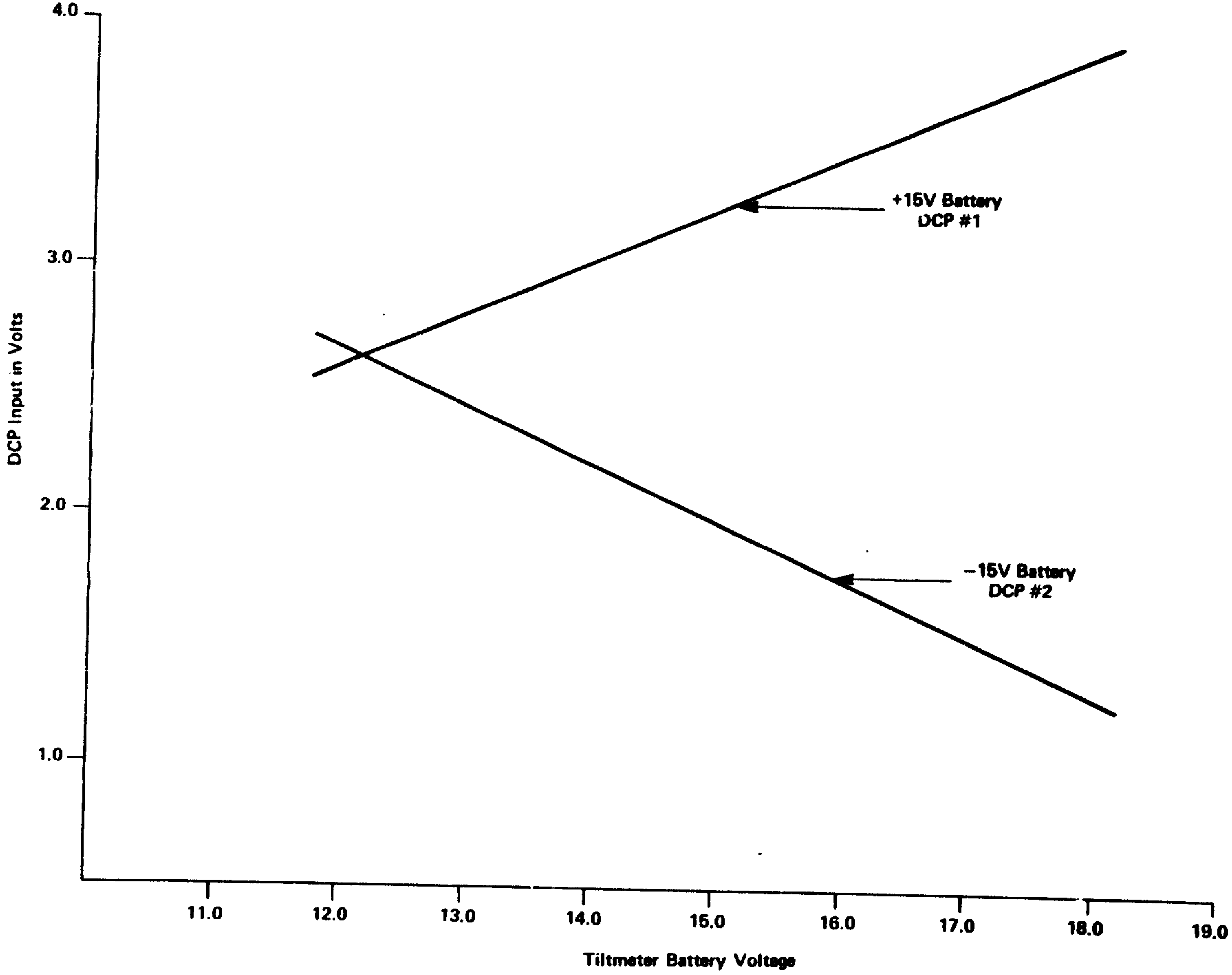


Figure III. Data Word #7

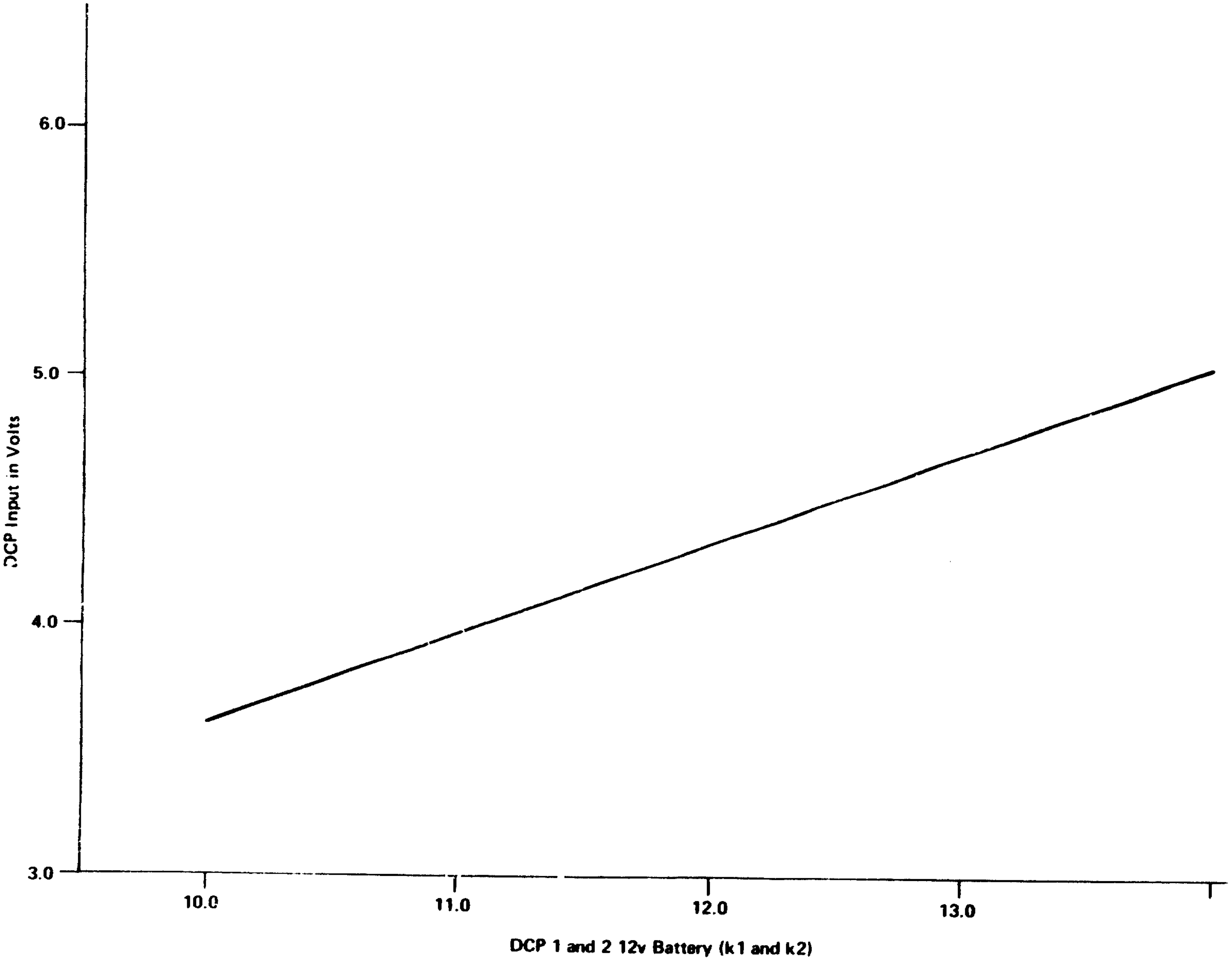


Figure IV. Data Word #8

APPENDIX II

Extract from Final Report on Grant NSG 5072

APPENDIX II

Extract from Final Report on Grant NSG 5072

TILT MEASUREMENTS ON A SMALL TROPICAL ISLAND

Roger Bilham and John Beavan

ABSTRACT

Tilt measurements have been made on the Caribbean Island of Anegada (18°44'N, 64°25'W) using precision levelling, sea-level measurements and an array of borehold tiltmeters. The tiltmeter measurements after two years of undisturbed operation indicate a tilt rate of approximately a microradian per month, whereas the precision levelling indicates that the island is stable to within a microradian per year (1976–1978). Variations in sea level appear to affect the tiltmeters coherently, although tidal tilts vary significantly over 400m distances.

INTRODUCTION

There has been much discussion concerning the fidelity of short-baseline tiltmeters installed near the Earth's surface because there are no published results that can be considered totally beyond suspicion. That is, redundancy and duplication of tiltmeters is rare and coherence of tilt signals is frequently poor even over distances of kilometers. Long-term measurements of tilt do not agree with absolute measurements using independent methods such as levelling. Tiltmeters respond to rainfall, changes in subsurface hydrology and surface temperature and it is usually difficult to exclude some or all of these noise sources as a possible source of observed signals.

Moreover, the generation of tilts can occur through the interaction of local elastic inhomogeneity and applied strainfields. Hence, tilt amplitudes and phases can be distorted even if instruments are of adequately good fidelity. These secondary problems cannot be studied systematically without first demonstrating tiltfield coherence.

It was decided, therefore, that six of the Kinemetrics borehole instruments would be installed sufficiently close to each other to examine the wavelengths of surface tilt and that additional different tiltmeters and measurements would be introduced to provide an independent evaluation of the real tilt of the area.

LOCATION OF THE EXPERIMENT

The experiment was set up on Anegada in the British Virgin Islands (Fig. 1). The Virgin Islands have not experienced a major earthquake in the last 500 years of recorded history but there is reason to believe that a major earthquake may be overdue because regions to the west and south have experienced earthquakes with magnitudes greater than 7. An alternative explanation of the gap in significant seismic energy release may be that strain energy is released in the form of creep or as "slow" or "silent" earthquakes with a large component of long-period energy (minutes to days) and relatively high little frequency energy. The installation of strainmeters or tiltmeters was considered to be a possible means to provide an insight into the two alternative tectonic mechanisms or others that might be involved. Anegada was chosen to site the array since it is essentially horizontal, low-lying, and surrounded by a shallow shelf. Approximately four micro-earthquakes a day are detected by the Lamont-Doherty Caribbean Seismic Network and there is about one magnitude 4 earthquake a month. The residents on Anegada feel one or two earthquakes a year, which appear to be centered about 20km to the NW of the island.

GEOGRAPHY OF ANEGADA REGION

Anegada Island measures approximately 16km east-west by 3km north-south. The central and eastern parts of the island are surfaced by partly recrystallized coral reef, calcarenites and calcareous sand which nowhere attain a height of more than 9m above mean sea level. The western part of the island is a layer of sand which thickens westward to a maximum of 10m depth and which rarely exceeds 2m above sea level except in the form of wind-blown dunes. The western area has a series of salt ponds that drain poorly to the sea. The eastern part of the island consists of interleaved horizontal layers of calcarenite and coral with a vertical spacing of about 1 m between layers. Borehole information does not exist below 20m.

The island is fringed by coral reefs. To the north the shelf drops steeply toward the Puerto Rico trench and to the east to the Anegada trough. To the south and west the sea floor is uniformly shallow (about 10m) across to the islands of St. Thomas and Tortolla. Three or four submerged terraces with a vertical spacing of 3–4m have been identified to the south of Anegada and Howard (1970) argues that this signifies stages of geological uplift.

In 1797 Anegada was marked by Captain Waring (1797) on a map as the "drowned island" being "almost entirely covered at spring tide." This "drowning" may have referred to the western half of the island which is now at least 50cm above the highest tide. If we assume that no other process is operating, the difference between Captain Waring's map and the present implies an emergence of approxiamtely 1 to 3mm/year. A more probable mechanism is that the present surface is the product of sedimentation. The rapid erosion and rebuilding of the westerly tip of Anegada occurs presently during storm conditions although it is clearly restricted by the reef. According to admiralty charts made in 1890 and more recently, shallowing of the sea floor to the south by about 1m has occurred. This is interpreted as sediment influx and although it is clear that sediment transport from west to east occurs, it is uncertain where such quantities of sand come from.

Studies by Schomburgk (1832) and by developers more recently show large quantities of fresh water underlying the island. The general porosity of the island was revealed by two experiments we performed in 1976. A series of wells up to 90m from the beach at the west end encountered brackish water right up to the beach with a periodic modulation of height caused by the 30cm sea tide. The amplitude of the periodic effect fell off rapidly to about 30% of the tidal amplitude in the first 10m and then less than 5% for the next 100m. A well 1.5km from the coast shows a 5cm tide.

TILTMETERS

In 1976 we installed six Kinemterics tiltmeters in boreholes in a 2km array along the island. Our intention was to examine the nature of island tilt noise and the suitability of using borehole tiltmeters in island-arc deformation studies. Operating problems in the first two years of installation encouraged us to reduce the array dimensions to a more modest array of three instruments (numbered 2, 3, and 4 on Fig. 4). The details of our initial installation are to be found in the Final Report to USGS contract 14-08-0001-G371. An important feature of the tiltmeter installation is that the tiltmeters were encased in sand-filled 7.5cm diameter, 3m long aluminum tubes before being lowered into 15cm diameter, 3m auger holes in the coral. The tiltmeter electronics are augmented by a servo-system for maintaining the tiltmeters close to zero output, by a local recording system, and by a centrally located satellite transmitter (DCP). Each installation is covered by a 1m high mound of white sand canopied by an elevated sheet roof to minimize the direct effects of sun and rain. The installation method successfully reduces thermal contamination of the tilt data to an acceptable level (see Fig. 2).

The local chart recorder at each tiltmeter is multiplexed to monitor the x and y tilt channels and the output from a thermistor thermometer positioned within the electronics unit. The chart is advanced at a rate of approximately 5cm per day. The tilt data are dominated at high frequencies (3-6s) by microseismic tilt that has its origin in surf action on the surrounding reefs. The microseismic noise varies in amplitude from 0.1 to 0.3 microradians according to surf conditions. The telemetered data are smoothed with a 20s filter to attenuate the microseismic energy, sampled every six hours on six channels and transmitted twice daily.

During the first two years of operation the signals from the six tiltmeters were greater than 10^{-5} radians per month in random directions. By 1978 the drift rate had reduced to approximately 10^{-6} radians in a month. The observed decay in the drift rate is presumably due to settling of the instrument and may be an elastic adjustment of the borehole tiltmeter casing in response to installation stresses (Stauder and Morrissey 1978).

We present two figures illustrating recent data. In Figure 2, synchronous data from tiltmeters 2 and 3 are shown. The x and y channels of tiltmeter 2 show a clear semidiurnal tide with a peak-to-peak amplitude of 1–2 microradians. The y channel of tiltmeter 3 shows a diurnal thermal signal with an amplitude of 4 microradians and the x channel suggests a semidiurnal tide with an amplitude of less than 0.5 microradians. The microseismic tilt amplitude is approximately the same amplitude on 2x, 2y, and 3y but is about half that on channel 2x. Three teleseismic earthquakes confirm that the calibration of 2y and 3y are within 20% of each other in that surface wave magnitudes recorded by each are similar. We view the tiltmeter 2 data with suspicion since the tidal amplitudes are larger than we might expect from tidal loading and may be the result of direct influence of semidiurnal variations of hydraulic pressure (Van der Kamp 1973). Tiltmeter 2 is the deepest operating tiltmeter and is less than 1 m above mean sea level. Curiously, 1976 data from this instrument showed a dominant diurnal thermal variation although its absence in recent data may be the result of an improved surface cover. On the other 5 tiltmeters the maximum semidiurnal tide peak-to-peak amplitude has not exceeded 0.5 microradians. The thermal signal apparent on the tilt data varies in amplitude from 1 to 5 microradians. Much of this signal is the direct effect of temperature on the electronics unit.

In Figure 3 we plot data obtained via satellite between March and July 1978 together with rainfall and sea-level data. Tiltmeter 2 behaves erratically and eventually fails when its negative power line is severed by a goat. Tiltmeters 3 and 4 show an interesting correspondence with sea level. Inflections in tilt and sea level occur at similar times. The sea-level data follow each other for the period plotted but the tiltmeter data have different trends on all channels.

PRECISION SURVEYING

A 2.5 km levelling line was laid out in 1976 consisting of 38 benchmarks in an approximately E-W line along the tiltmeter array. In 1977 the line was extended to the north. Brass levelling pins were cemented into the coral surface at intervals of 40–100 m, although the majority were spaced at 70m intervals. Cairns were constructed to locate the mid-points of every measurement pair to within 50cm. We used matched invar rods and a Zeiss Ni2 level with optical micrometer for the measurements. A reading precision of 0.1mm can be obtained with this equipment.

The levelling line has been measured five times in two years (Fig. 4). We adopted standard first-order levelling procedures for the measurements with one addition; where the outgoing and return levelling measurements for an adjacent pair of bench-marks differed by more than 0.3mm they were repeated the following day. Normally such errors were attributable to a dust particle on one or another of the benchmarks during a previous measurement. The closure errors for the five outward and return levelling runs vary between 0.3mm and 1.4mm, that is, within the 1.6mm error defined as "first order levelling" (e.g., Bomford 1971). In most cases the errors were less than the ±0.6mm we estimated as the cumulative reading error for the line.

The island tilt tide may be a significant source of systematic error since it has a measured daily peak-to-peak amplitude of up to 2×10^{-6} radians. Surveying was usually done over a period of six hours in the morning and two in the early evening. The whole line was usually surveyed over a period of two days. Consider two extreme possibilities. In a period of six hours the tilt tide could tilt the surface from $+1\,\mu$rad to $-1\,\mu$rad or it could tilt from zero, $\pm 1\,\mu$rad to zero. In the first instance, a cumulative tilt of $2\,\mu$rad would be measured; in the second instance, no tilt would be measured. Note that none of our measurements result in more than a $1\,\mu$rad tilt for the whole line but that there are slopes within the line that may be the result of tidal changes of tilt during the measurements. We plan to try to correct the levelling data for the island tilt tide using the borehole tiltmeter measurements.

SEA-LEVEL MEASUREMENTS

A number of measurements of mean sea level are being made on the island and other nearby islands (Fig. 1 and Bilham 1977). On Anegada we are currently operating three sea-level monitors: at the west end, on the NE coast, and in a water well near the center of the island. The latter instrument shows a 5cm tide and longer period oscillations that closely follow sea-level variations monitored by the other gauges. The two coastal sea-level monitors are installed on the beach and monitor the water table rather than sea level. This experimental arrangement was adopted in order to avoid a direct connection to the sea that we have found vulnerable to vandalism and erosion. The arrangement appears to be effective an Anegada since all three gauges track each other (Fig. 3). Long-period changes of sea level are detected by the tiltmeters and can account for some of the inflections in tilt rate observed by the array. Rainfall does not have any obvious effect on either the sea level or tiltmeter data.

DISCUSSION

The tidal tilt of Anegada observed by borehole tiltmeters appears to vary over a relatively short distance (400m) by a factor of four. The maximum measured value for daily tilt (2μrad) is sufficiently large to disturb precise geodetic levelling surveys of the island, although the data we present do not appear to be seriously disturbed. This may be due to fortuitous timing of the outward and return surveys used to derive a mean value for the line or it may be due to a systematic error in the tiltmeter measurements. We intend to process the levelling data more carefully to remove the known tilt tide.

An error analysis on the numerical values obtained for each adjacent pair of levelling pins provides a surprisingly low cumulative error estimate: ±0.6mm in 2.5km. This is approximately three times smaller than the maximum permissible error required in normal precision levelling although it has been attained by other investigators (e.g., Schellens 1965). An earthquake ($M_s = 5$) occurred on 15 Oct. 1976, 20km to the NW of Anegada. The tiltmeter array was inoperative at the time but the levelling line showed no change ($\pm 2 \times 10^{-7}$) when it was resurveyed nine days later. Over a period of two years there appears to be a suggestion of a tilt up to the NE amounting to 0.5 microradians. Since this value is barely above the estimated measurement precision and we are not yet certain of the influence of tilt tides on the island, we do not place much confidence on its significance.

The long-term tilt rate (~ 10^{-6} rad/month) seen by the tiltmeters even after two years from installation is approximately an order of magnitude larger than that established by precision levelling. Some inflections in the tilt rate can be accounted for by sea-level variations around and under the island. The levelling data indicate that it may be possible to install a long baseline tiltmeter on the surface between two selected levelling pins to obtain a stability of at least 10^{-6} radians per year. This would represent a significant improvement in the continuous monitoring of surface tilt on the island.

We have observed nothing suggestive of a "slow" earthquake on the data though this may have occurred during the numerous occasions when the tiltmeters were inoperative. The seismograph network operated by this observatory has revealed a complex pattern of earthquakes with magnitudes from -1 to 5 in the Anegada region (Murphy, et al., 1978). Our measurements do not clarify the mechanism of plate collision in this corner of the Caribbean. A longer span of data may help and so would continuous tilt measurements of improved fidelity.

ACKNOWLEDGMENTS

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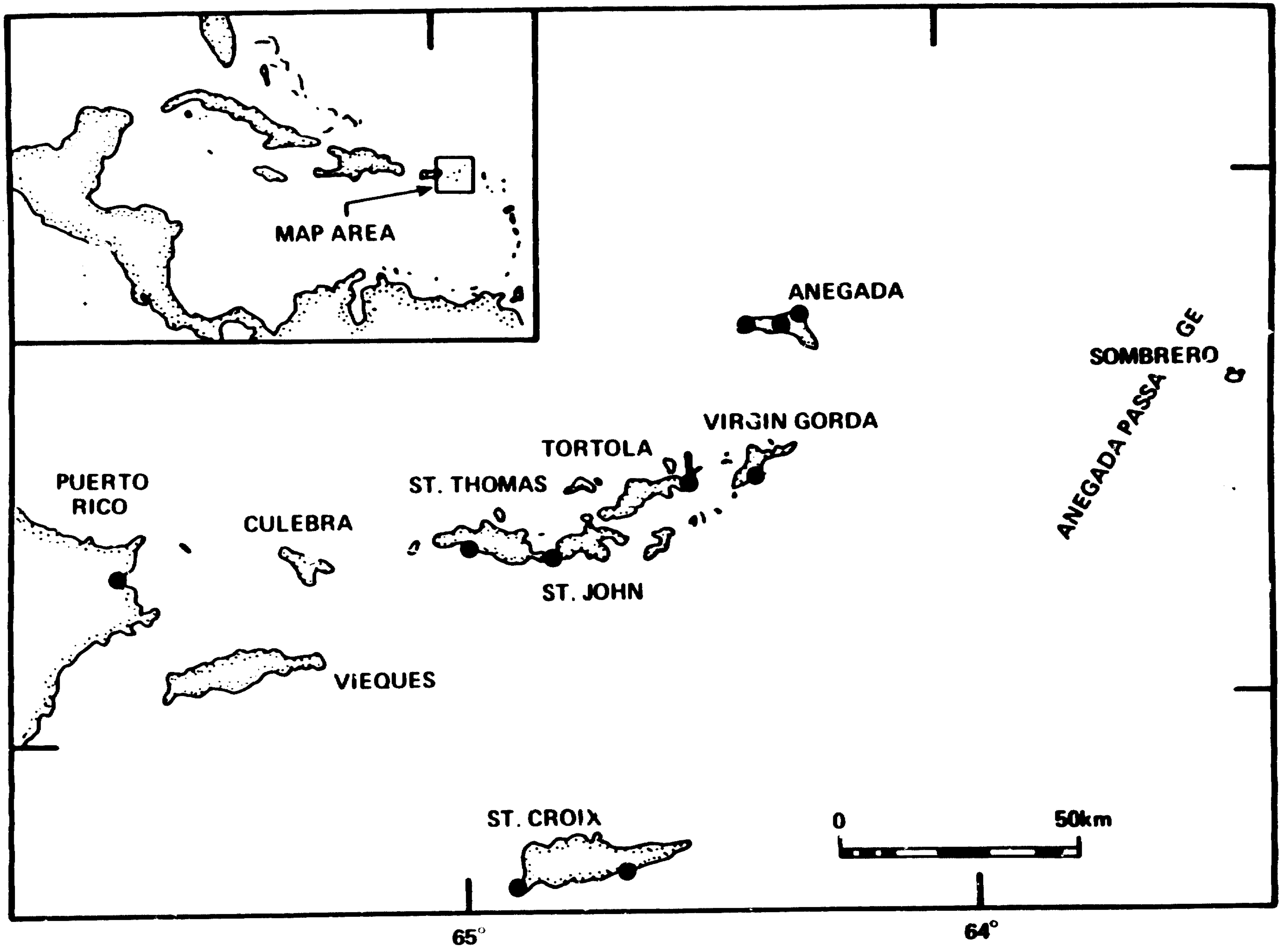

Figure 1. Anegada is the most northerly of the Virgin Islands group. The location of tide gauges and mean sea-level monitors is indicated by a dot.

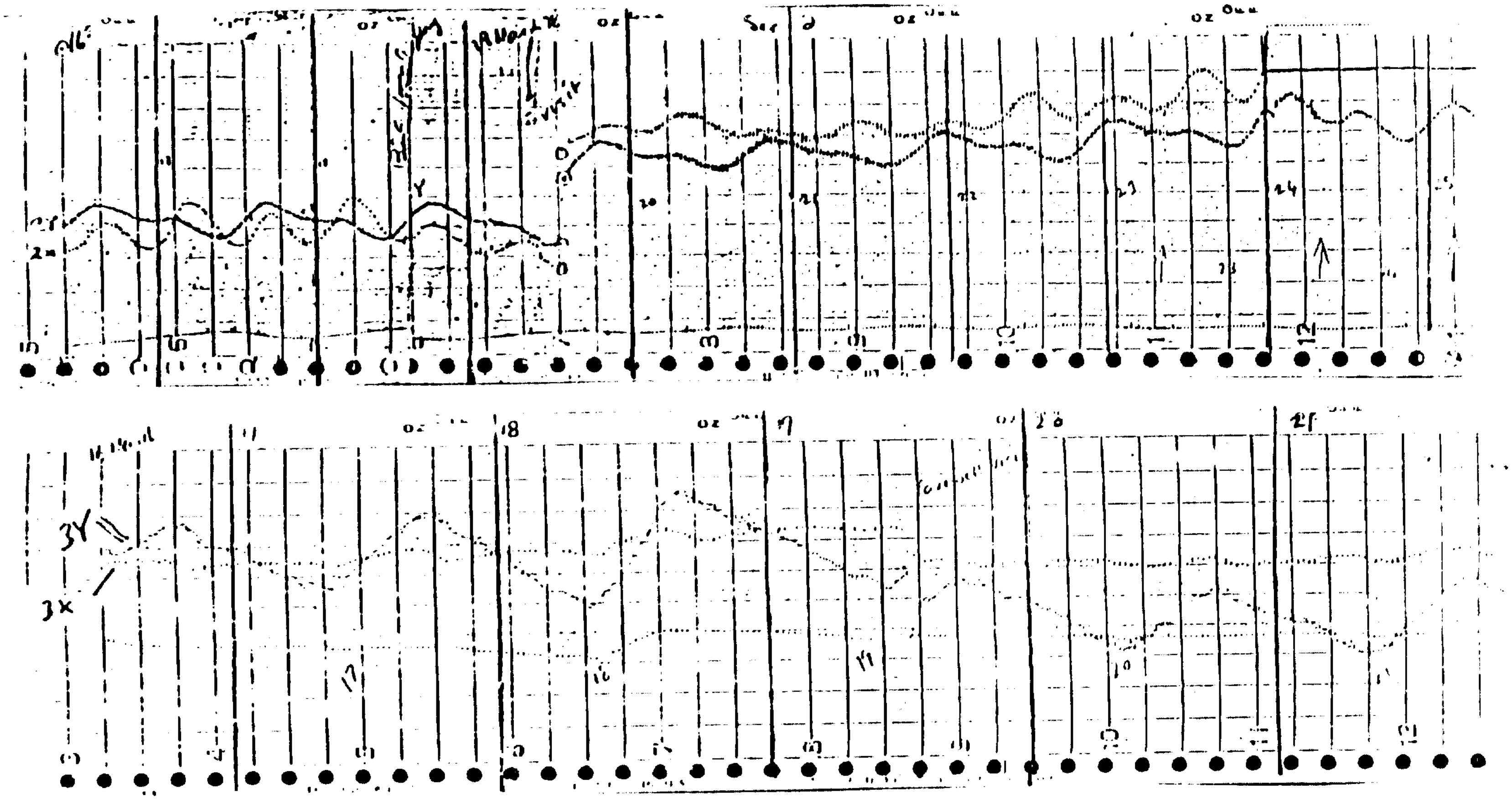

Figure 2. Copy of typical tiltmeter records from instruments 2 and 3. The tiltmeters were visited on 16 and 19 March 1978 between which times they were minimally insulated from surface temperature variations. The lowest trace on each record is the temperature record. An intermittent fault develops on 2x on 24 March. Teleseismic arrivals are indicated by arrows. A semi-diurnal tide is recorded by tiltmeter 2. Tiltmeter 3 shows a large diurnal thermal signal on the y channel and a small semi-diurnal signal after insulation 19 March on the x channel. The calibration on each record is the same (14 microradians full-scale, 20°C full-scale).

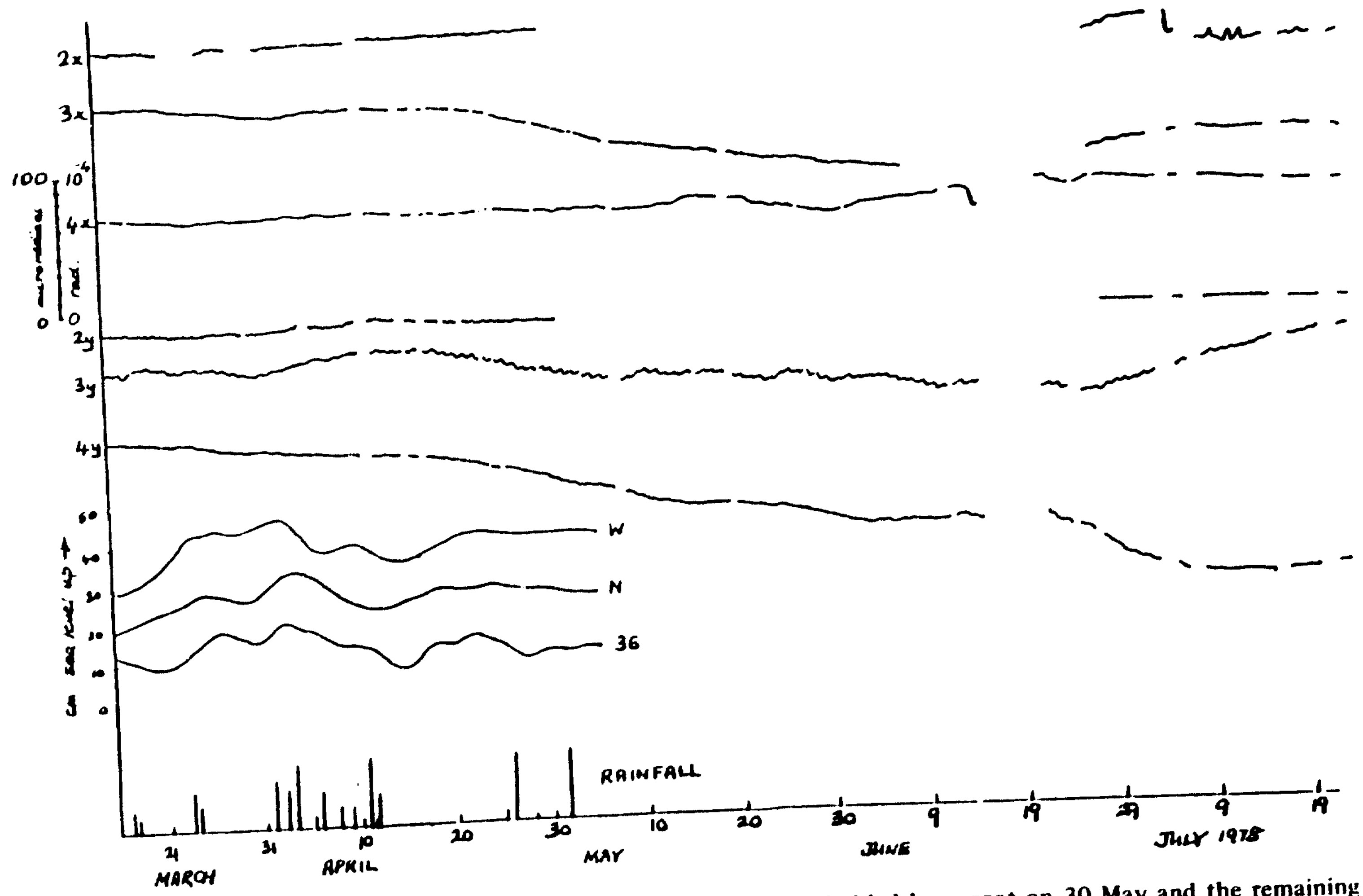

Figure 3. Satellite telemetered data from three tiltmeters. 2x and 2y are disabled by a goat on 30 May and the remaining records are interrupted by the launch of Landsat 4 in late June. The instruments were visited on June 26. The rainfall and daily mean values of sea level are plotted to the beginning of May. Note that inflections of sea level recorded by the three Anegada sea level monitors can be identified on the tiltmeter data. The lowest sea-level trace is obtained from an inland well near the tiltmeters (see Fig. 4).

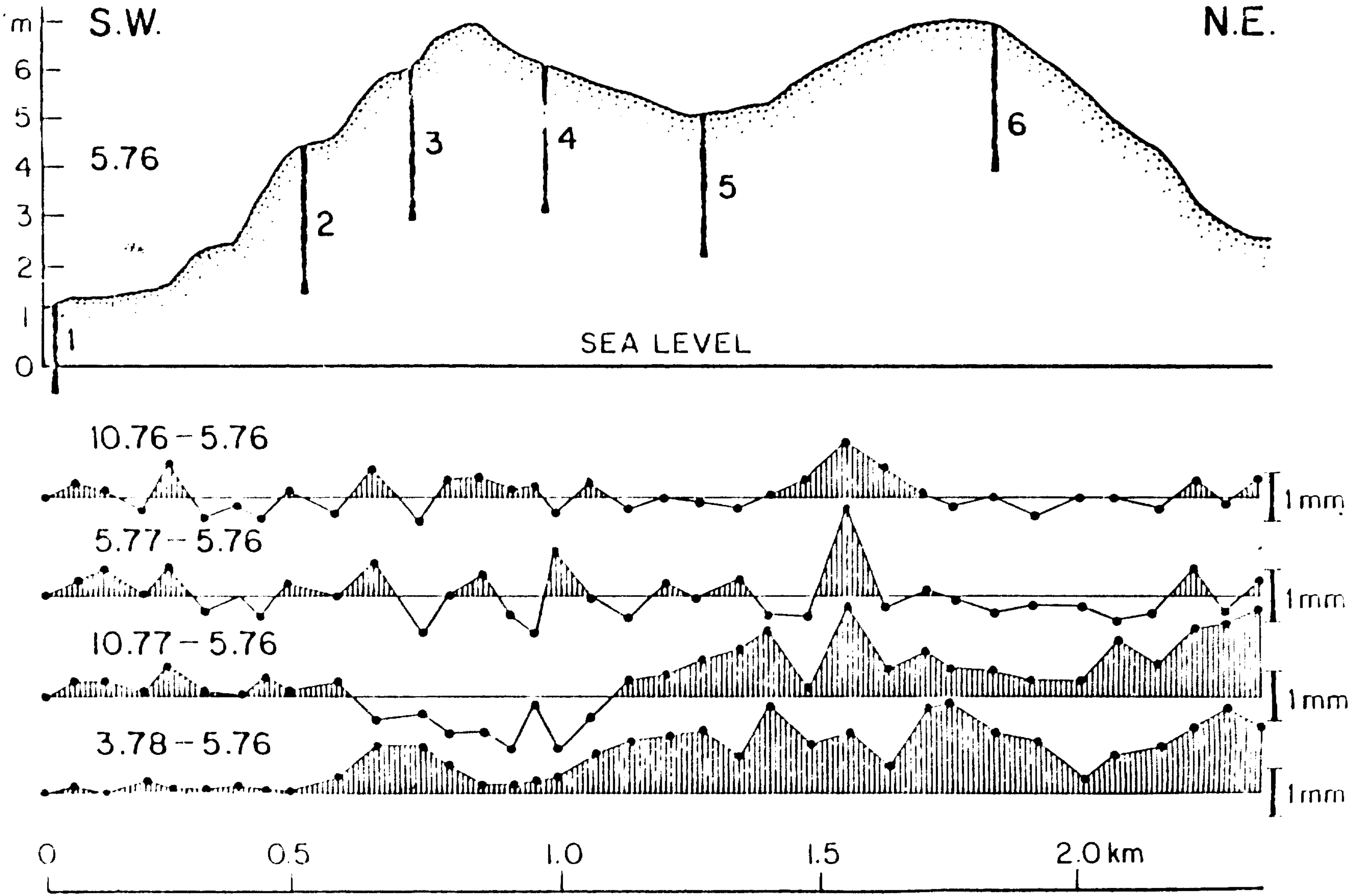

Figure 4. Profile along the Anegada levelling line. The top figure is the topography (vertical exaggeration x 100) with the locations (2-6) of borehole tiltmeters. Data (trace 36 in Fig. 3) from a water-level monitor located at position 1 follow mean sea-level data monitored on the coast. The lower figures show the cumulative differences between subsequent levellings and the original (May 1976) levelling.