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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

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RESULTS OF AN ACCURACY TEST OF THE
MOD-II SITE DATA ACQUISITION SYSTEM

by

Donald R. Patterson
Electronics Division

prepared for

Energy and Environmental Systems Division

December 1980

work sponsored by

U.S. DEPARTMENT OF ENERGY
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RESULTS OF AN ACCURACY TEST
OF THE MOD-II SITE DATA
ACQUISITION SYSTEM

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Donald R. Patterson

ABSTRACT

The National Solar Data Network, established and operated by the U.S. Department of Energy, collects and analyzes data on the performance of active and passive solar-energy systems throughout the United States. The accuracy of the specially designed Site Data Acquisition System (SDAS) used in the network has not been adequately characterized. Uncertainty about the SDAS's accuracy has become one of the major limitations in evaluating the accuracy of the network. This report describes the results of SDAS testing for basic calibration accuracy and for errors caused by changes in ambient temperature, changes in a-c line voltage, drift with time, changes in loading on the excitation power supplies, channel-to-channel cross-talk, and maintenance. System accuracy was found to depend on the configuration of the SDAS channel. Over one year of operation and with the expected changes in temperature and ac line voltage, an accuracy of 0.6% of the input signal plus one count, with error-free initial calibrations assumed, was typical. For a full-scale signal, this error is seven counts. Most of the error is introduced through the power supplies used for sensor excitation; with improved power supplies, this seven-count error could be reduced to two counts. Most of the accuracy testing was conducted on only one SDAS, a Mod-II unit. Therefore, generalizations to other SDAS units are difficult. However, a Mod-II SDAS probably will not have errors less than half or more than twice as great as those measured and reported here.

1 BACKGROUND

A National Solar Data Network (NSDN) has been established and operated by the United States Department of Energy to collect and analyze data on active and passive solar-energy-system performance throughout the United States. The performance of individual sites and performance comparisons between different sites are documented and reported. Reference 1 lists reports available from the NSDN and the procedure for obtaining copies. A microcomputer-based Site Data Acquisition System (SDAS) collects data every 320 seconds from up to 95 sensors at each instrumented solar-energy site.

The SDAS temporarily stores these data on a digital cassette recorder. About once each day a communications computer, using standard telephone lines, calls each SDAS. The recorded data are transmitted to the communications computer and stored on magnetic tape. The data are then analyzed by a central computer to calculate the site performance. This process is illustrated in Fig. 1 and described in more detail in Ref. 2.

Clearly, the overall accuracy of the data collected can be no better than the accuracy of each component considered separately. After the data are digitized by the SDAS, they are immune from further accuracy degradation, since the digital error-checking codes being used will flag, and cause the rejection of, erroneous data. Therefore, the accuracy of the sensors used and the analog portions of the SDAS are critical to overall system accuracy. The SDAS is a specially designed system produced specifically for use in the NSDN and its accuracy has not been adequately characterized. Therefore, uncertainty about SDAS accuracy has become one of the major obstacles to evaluating the accuracy of the overall NSDN system for data collection.

This paper presents the results of a series of tests conducted on the Mod-II SDAS to determine the magnitude and type of errors the system is likely to introduce into the data. Other error sources, including those caused by the potential incompatibility of the SDAS with the sensors, are not considered here. A complete assessment of NSDN, which will consider all significant error sources, is being prepared.

Fig. 1 Overview of Data-Collection Procedures Used In National Solar Data Network

2 TEST LIMITATIONS

Because of external constraints, the accuracy tests described in this report could not be conducted on a large number of SDAS units, as would have been desirable. Most tests were conducted on only one SDAS. A subset of the drift tests was conducted on two SDAS units, as described in Secs. 3 and 5.5 of this paper.

In addition, two SDAS models are in use in the NSDN. There are about twice as many Mod-II units in use as there are Mod-I units. The analog circuitry of the two models is nearly identical, except that the Mod-II can handle up to 95 sensors, whereas the Mod-I can handle only 47 sensors.

In generalizing the test results presented here to all SDAS units, or even to all Mod-II SDAS units, one must be cautious and bear in mind the small sample tested. The SDAS tested may be significantly more or less accurate than the other SDAS units in the NSDN. However, given the test results and field observations, a Mod-II SDAS probably will not have errors of less than half or more than twice those measured and reported here.

The accuracy of the Mod-I SDAS will be identical in most respects with that of the Mod-II SDAS, since both units use the same circuits -- multiplexor, sample-and-hold, amplifier, and analog-to-digital conversion. However, the power supplies used in the two systems to generate the sensor-excitation voltages are different, so that errors related to these voltages may not be the same for the Mod-I and Mod-II SDASs.

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3 SUMMARY OF TEST RESULTS AND CONCLUSIONS

The SDAS was tested for basic calibration accuracy and errors caused by changes in ambient temperature, changes in a-c line voltage, drift with time, changes in loading on the excitation power supplies, cross-talk, and maintenance. All measured errors equal to or greater than 1/2 count (0.1% of a full-scale signal) are summarized in Table 1. For tests conducted on two SDAS units, the larger measured error is listed. In this table, it is assumed that error-free calibrations of all bridge channels, current-to-voltage terminating resistors, and excitation voltages are made. It is also assumed that the calibrations can be conducted anywhere within the range of temperatures and line voltages listed in the table, but no changes occur in the currents drawn from the excitation power supplies without a new error-free calibration being conducted.

The expected overall accuracy of the SDAS can be calculated by combining the individual errors recorded in Table 1. All of these errors that will affect any given channel are clearly independent of each other, because they arise from independent sources. Because these errors probably will cancel each other (at least partially), they should be combined using the square-root-of-the-sum-of-the-squares method. When errors are combined in this way, the expected error over one year for a channel using a bridge-type signal conditioner and 15-V excitation for the ranges 0-40°C and 105-130 V a-c, (and experiencing no maintenance) is 0.6% of the signal plus one count. For a full-scale signal, the resulting error is seven counts -- about ten times the expected error of 1/2 to one count for a high-quality data-acquisition system. The major contributors to this large error are the effects of time and temperature of the 15-V excitation power supply.

Other calculations of channel errors under specific conditions can be made from the data in Table 1. However, major error sources clearly are always introduced through the 15-, 5-, and 3.6-V excitation power supplies. A modification to the supplies to increase their stability could decrease the total error for the case calculated above from seven to two counts.

Improvements in the SDAS needed to increase its accuracy to that expected of a high-quality data-acquisition system are, in order of their effect on accuracy:

1. Sensitivity of 15-V excitation power supply (EPS) to temperature changes
2. Sensitivity of 3.6-V EPS to temperature changes
3. Drift of 15-V EPS with time
4. Drift of 5-V EPS with time
5. Drift of 3.6-V EPS with time
6. Drift of the analog-to-digital converter's gain
7. Absolute gain of the signal amplifier
8. Interchangeability of signal conditions or recalibration after replacement of signal conditioners

Table 1 Summary of All Measured Errors
Greater than $\pm 1/2$ Count

Test	Channels Affected	Error Magnitude	Error Type
Basic Accuracy	All using gain of 50	0.12% of signal	Gain
Temperature Changes, 0-40°C	All using 15-V excitation	0.5% of signal	Gain
	All using 5-V excitation	0.1% of signal	Gain
	All using 3.6-V excitation	0.4% of signal	Gain
	All using current-to-voltage-conversion resistor	0.1% of signal	Gain
Changes in a-c Line Voltages, 105 - 130 Vac	All using 15-V excitation	0.1% of signal	Gain
	All using 5-V excitation	0.1% of signal	Gain
Time (1 year)	All	0.15% of signal	Gain
	All	1/2 count	Offset
	All using 15-V excitation	0.3% of signal	Gain
	All using 5-V excitation	0.3% of signal	Gain
	All using 3.6-V excitation	0.3% of signal	Gain
	All using bridge-type signal conditioners	1 count	Offset/ Gain ^a
Maintenance	All using bridge-type signal conditioners	1.3 counts at mid-range	Offset/ Gain ^a

^aThe offset-and-gain error components could not be separated.

9. Drift of the bridge-type signal conditioners
10. Sensitivity of 5-V EPS to temperature changes
11. Sensitivity of the current-to-voltage conversion resistance to temperature
12. Sensitivity of the 15-V EPS to changes in a-c line voltage
13. Sensitivity of the 5-V EPS to changes in a-c line voltage
14. Drift of the analog-to-digital converter's output

The relative importance of these potential improvements will differ somewhat from that in the order given here, because of the differing frequency of use and accuracy requirements of each channel of data.

4 SDAS ORGANIZATION

To understand the detailed tests and test results, one needs a general understanding of the internal organization and functioning of the SDAS. Figure 2 is a functional block diagram for both the Mod-I and Mod-II SDASs. Each SDAS consists of from one to six signal-conditioner and multiplexor circuit cards. Each card can handle 15 or 16 sensor channels. Each channel makes use of a dedicated signal conditioner, typically a bridge circuit or a straight-through circuit, which effectively provides no conditioning. These signal conditioners consist entirely of passive components.

The multiplexed signals are amplified by a common signal amplifier with programmable gains of one and 50. Since the following 10-bit analog-to-digital converter accepts only a 5-V unipolar signal, the SDAS input-signal voltages must be either 0-100 mV or 0-5 V. Other signal types handled by the SDAS are converted to one of these ranges by the signal conditioners.

The SDAS is controlled by a microprocessor and the program stored in read-only memory. This microprocessor controls the multiplexor, amplifier, and analog-to-digital converter to collect sensor data. The data are temporarily stored in a random-access memory. When the memory is full, the data are transmitted to a digital cassette-tape recorder, with time information from the real-time clock added to the data stream by the microprocessor. (The clock is powered by batteries, but no other component of the SDAS, including the data memory, has battery back-up.) The microprocessor communicates through the modem and its interface to the remotely located data-collection computer via telephone lines. An optional On-Site Monitor (OSM) or Digital-Count Meter (DCM) can be attached to the SDAS to display data as they are being collected.

The SDAS collects and records single samples from most sensors once every 320 seconds. However, a few sensors can be sampled every 32 seconds. In these cases, ten samples are collected and accumulated in the data memory in 320 seconds, and at the end of that time their average is calculated and stored with the single scan of data collected from the other channels; the individual 32-second scans are discarded.

The SDAS supplies d-c voltages intended to excite external sensors and internal bridge circuits. A single power supply and voltage regulator provide 15 V to all bridge circuits used in the SDAS and to any external sensors requiring 15-V excitation. There are 5-V and 3.6-V sources also available to power external sensors, but they are not used inside the SDAS.

Table 2 lists the standard signal-conditioning types available and their nominal channel ranges. For most types of signal conditioners, the accuracy of the SDAS is measured from the signal input to the digital-counts output as displayed on a DCM or as recorded by the communications computer. However, all temperature channels receive an on-site calibration, which effectively determines correction factors to be applied to the counts output. Temperature is measured by a resistance-temperature device (RTD) whose resistance is related to temperature by a second-order equation. The SDAS measures RTD resistance by using a bridge-type signal conditioner to convert resistance to voltage.

Fig. 2 Site Data Acquisition System (Functional Block Diagram)

Table 2 Standard Signal-Conditioning Types and Channel Ranges Used in SDAS

Signal Conditioner	Channel Range	Amplifier Gain	Sensor
Bridge	-55 - 120°F	50	100-ohm nominal RTD
Bridge	-20 - 120°F	50	100-ohm nominal RTD
Bridge	30 - 160°F	50	100-ohm nominal RTD
Bridge	30 - 230°F	50	100-ohm nominal RTD
Bridge	30 - 330°F	50	100-ohm nominal RTD
Bridge	30 - 450°F	50	100-ohm nominal RTD
Straight-through (No conditioning)	0 - 5 V	1	Any with unipolar d-c voltage output
Straight-through (No conditioning)	0 - 100 mV	50	Any with unipolar d-c voltage output
3-to-1 Voltage Divider	0 - 15 V	1	Any with unipolar d-c voltage output
1000-ohm Terminator	0 - 0.1 mA	50	Any with unipolar current output

In on-site calibration, an RTD is simulated by a calibrated resistance-substitution box. Resistance values and the corresponding output of the SDAS as displayed on a DCM are recorded. Later, the temperature corresponding to each resistance value is calculated from the second-order equation. A curve-fitting equation is then calculated to relate the SDAS counts output directly to temperature.

By using this procedure, constant errors (those that do not vary with time) introduced into the digital output of the SDAS can be corrected by the counts-to-temperature curve-fitting equation. Therefore, the overall accuracy of the SDAS calibration data and curve-fitting equation must be considered in evaluating signal conditioners designed to handle temperature data.

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5 TEST DETAILS AND SAMPLE DATA

5.1 GENERAL TEST ENVIRONMENT

The SDAS testing was conducted in two parts. The first part consisted of conducting limited drift and accuracy testing on a Mod-II SDAS, which was installed, and collecting NSDN data from the solar-energy site at the Argonne National Laboratory (ANL) cafeteria. The second part was done on a Mod-II SDAS dedicated entirely to the testing program. Using this unit allowed more extensive testing without loss of valuable NSDN data.

The dedicated SDAS was installed as it would be in a typical NSDN site. Connections to the channel inputs were brought out to an external junction box, as is done for normal site installation. Except as noted in the following sections, the SDAS operated from normal, unconditioned a-c power and in a room with an ambient temperature of 68-78°F.

The channel-scan rates and signal conditioners were selected as shown in Table 3. These selections were intended to sample all sensor ranges, signal-conditioner types, and scan rates adequately. Channel 1 on this SDAS (and all SDAS units) is shorted by the signal conditioner and is a monitor of offset errors in the system; its input terminals are not available in the junction box. Channels 44, 45, 47, and 48 also contain shorted signal conditioners, but with input leads brought out to the junction box. These channels were reserved for maintenance tests and were not used in the accuracy testing.

Channel 25 was connected to the 15-V bridge excitation through a special voltage-dividing signal conditioner and served throughout the testing to monitor the bridge excitation voltage. Likewise, channel 26 was connected to the 5-V sensor excitation voltage through a special voltage divider. The 3.6-V sensor excitation was monitored by channel 27 using a standard straight-through signal conditioner. Except where otherwise stated, all temperature sensing channels were connected to a 105-ohm one-percent metal-film resistor, which simulated an RTD. Also, all other channel inputs were either shorted in the junction box or connected to external sensors of different types, unless otherwise stated.

5.2 BASIC CALIBRATION ACCURACY

This section deals with the absolute accuracy of the SDAS near the beginning of the testing and under nominal operating conditions. Later sections describe the effects on SDAS accuracy that resulted from altering individual operating conditions.

Accuracies of the basic analog-to-digital converter and the signal amplifier were measured by comparing the SDAS output voltages on selected channels of two SDAS units with the outputs expected from the accurately measured input voltages on those channels. Details about the reference-voltage source used are given in Sec. 5.5. Table 4 lists results of the comparison. Basic calibration accuracy with an amplifier gain of one is within the $\pm 1/2$ -count digitizing error for both SDAS units. However, channels using a gain of 50 in the test SDAS show a gain error of 0.12%,

Table 3 Channel Scan Rates and Signal Conditioners Used in SDAS Tested

Channel Numbers	Scan Rate, s	Signal Conditioning	Range	Amplifier Gain
24, 28, 29, 30	32	Straight-through	100 mV	50
16, 17, 18	32	Straight-through	5 V	1
2, 3	32	Bridge	-20 - 120°F	50
4, 5	32	Bridge	30 - 230°F	50
33, 37, 38, 39, 40, 41, 42, 46	320	Straight-through	100 mV	50
34, 35, 36, 43	320	Straight-through	5 V	1
6, 7	320	Bridge	-55 - 120°F	50
10, 11	320	Bridge	-20 - 120°F	50
12, 13, 14	320	Bridge	30 - 230°F	50
15, 19	320	Bridge	30 - 160°F	50
20, 21	320	Bridge	30 - 450°F	50
22, 23	320	Bridge	30 - 330°F	50
31, 32	320	3 to 1 divider	15 V	1
8, 9	320	Terminator	0.1 mA	50
25, 26	320	See text	See text	1
27	320	Straight-through	5 V	1
1, 47, 48	320	Short	--	50
44, 45	320	Short	--	1

Table 4 Initial SDAS Accuracy

System	Channel	Gain	Input Voltage	Output, Average Counts	
				Ideal	Measured
Test SDAS	16	1	4.0217 V	822.8	823.0
	17	1	0	0	0
	24	50	88.006 mV	900.3	901.4
	40	50	5.256 mV	53.8	53.8
	41	50	0	0	0
SDAS at ANL Cafeteria	A	1	4.4996 V	920.6	920.7
	B	50	90.024 mV	920.9	921.2
	C	50	4.986 m	51.0	51.1

enough to cause an error of 1.2 counts in the measurement of a full-scale signal. The corresponding error in the SDAS at the ANL cafeteria is 0.03%, which will cause an error of 0.3 counts in the measurement of a full-scale signal. (The fractional counts are significant for SDAS gains of 50 because of noise effects; see Appendix B.)

Signal-conditioning resistors are used internal to the SDAS to convert an input current signal from 0-0.1 mA to 0-100 mV. Any departure from the ideal 1000-ohm resistance will cause a gain error on these channels. The resistances of the two conversion resistors in the test SDAS were measured at 1000.10 and 997.62 ohms. The first discrepancy will cause negligible error, but the second will produce gain errors of 0.24%, or 2.4 counts in the measurement of a full-scale signal, if not measured and accounted for in calibration factors.

The measured initial values of the 15-, 5-, and 3.6-V sensor-excitation voltages were 14.989 V, 5.1458 V, and 3.6892 V, respectively. These values will cause gain errors in the channels with outputs that are linearly dependent on one of the excitation voltages (0.07%, 2.9%, and 2.5%, respectively). Clearly, the excitation voltages must be measured and included in calibration factors for the accuracy of these channels to approach the 0.005% quantization accuracy of the SDAS.

The absolute accuracy of the channels using bridge-type signal conditioners to accommodate RTD temperature sensors cannot be determined in these tests, because their accuracy depends more on the quality of the calibration data and procedures than on SDAS performance. The calibration procedure is described briefly in Sec. 4.

5.3 EFFECTS OF AMBIENT TEMPERATURE ON ACCURACY

To allow control of changes in the temperature of the air surrounding the SDAS, an environmental chamber was constructed around it. This chamber

was made of 4-in.-thick Styrofoam boards, the cracks between boards being taped to eliminate heat loss by air circulation. The SDAS was separated from the inner walls of the chamber at the top, right side, left side, bottom, and front by 6, 5, 9-1/4, 9, and 4 in., respectively. The SDAS was mounted on an uninsulated sheet-metal wall.

A fan and heater were placed in the lower left corner of the chamber. The fan was needed to eliminate temperature stratification within the chamber. Pre-test measurements showed that the operation of the fan did not noticeably alter internal SDAS temperatures. In the cooling tests, dry ice was placed in the bottom of the test chamber, and the fan was moved to the top of the chamber to prevent formation of ice on the fan blades. The DCM, adjustable voltage reference, junction box, and telephone coupler were all mounted outside the test chamber. The front of the chamber could be opened to allow both complete access to the SDAS and adequate air circulation to assure that between tests the chamber temperature was equal to the room temperature. A mercury thermometer with a resolution of 0.05°C was installed at mid-height in the right side of the chamber to give a reference measurement of air temperature. In addition, three thermocouples were inserted around the SDAS (inside the chamber) and three inside the SDAS. The first three thermocouples monitored the chamber air temperature on the right side of the SDAS (next to the reference mercury thermometer), beneath the SDAS, and on the left side of the SDAS. The second three thermocouples monitored the air temperature in the microprocessor, tape-recorder, and power-supply compartments inside the SDAS. Data from these thermocouples were collected and printed locally by a data logger. Tables 5 and 6 summarize the data collected during these temperature tests. In the course of these tests, all inputs to all channels remained constant, and no other parameters were intentionally changed. Since the four measurements of chamber temperatures when the fan was operating agreed very well, the chamber temperatures given in the tables are the readings of the mercury thermometer, which is more accurate than the thermo-

Table 5 Internal SDAS Temperatures and Excitation
Voltages as Functions of Chamber Temperature

Chamber Temperature, $^{\circ}\text{C}$	SDAS Internal Temperatures, $^{\circ}\text{C}$			Excitation Voltages, V		
	Microprocessor	Power Supply	Tape Recorder	15	5	3.6
1.0	13	9	1	14.963	5.1486	3.6969
7.0	19	11	8	14.964	5.1525	3.6951
12.5	22	20	13	14.981	5.1515	3.6940
24	39	31	29	15.004	5.1532	3.6910
35.3	48	42	37	15.018	5.1527	3.6860
38.5	51	45	41	15.020	5.1535	3.6843
40.5	54	48	43	15.031	5.1541	3.6823
43.5	56	51	46	15.035	5.1537	3.6799

Table 6 Data Recorded by Sample SDAS Channels as Functions of Chamber Temperature

Chamber Tempera- ture, °C	Channels (Input Range)								
	16	28	7	11	12	19	20	23	9
	(5 V)	(0.1 V)	(-55-120°F)	(-20-120°F)	(-30-230°F)	(30-160°F)	(30-450°F)	(30-330°F)	(0-0.1mA)
1.0	824.0	902.1	644.2	545.2	112.0	183.5	51.8	74.8	997.13
7.0	824.0	902.0	644.5	545.1	112.0	184.5	52.0	74.5	997.26
12.5	824.0	902.0	646.3	546.6	112.7	184.0	52.2	74.5	997.28
24	824.0	902.0	646.2	545.5	112.4	183.7	52.3	74.3	997.62
35.3	824.0	901.9	647.1	546.0	112.6	183.7	52.6	74.3	997.77
38.5	824.0	902.0	647.3	546.1	112.6	183.7	52.7	74.2	997.87
40.5	824.0	902.0	647.6	546.3	112.6	183.8	52.7	74.4	997.90
43.5	824.0	902.0	647.3	546.1	112.5	183.8	52.4	73.4	997.95

couples. The temperatures inside the SDAS are given for the reader's information and are not a part of the tests as such. The channel data given in Table 6, except for the last column, are averages of data collected over 1-12 hr. These averages eliminate most of the noise (± 2 - ± 3 counts) observed on all channels using an amplifier gain of 50.

Table 5 clearly shows that the 15-V sensor excitation has a positive temperature coefficient of about $1.7 \text{ mV}/^\circ\text{C}$ over the range tested. Most sensors powered by this voltage, and in particular the temperature bridge circuits, produce an output directly proportional to the excitation voltage. If the readings for bridge calibration are taken at 40°C and later the temperature drops to 0°C (extremes of the specified SDAS temperature range), this temperature change alone will cause an error of about 0.5% of the reading, or 5 counts for a nominally full-scale reading. This error is much larger than the expected SDAS accuracy of $\pm 1/2$ - ± 1 count. Even if the calibration readings are taken at 20°C , an error of about 2.5 counts will be introduced at the temperature extremes for any full-scale signal linearly dependent on the 15-V excitation. The 5-V and 3.6-V excitation supplies show temperature coefficients of about $+0.12 \text{ mV}/^\circ\text{C}$ and $-0.40 \text{ mV}/^\circ\text{C}$, respectively. For a temperature variation of 20°C , these temperature coefficients will cause errors in all full-scale signals that are linearly dependent on the 5-V and 3.6-V excitation voltages of 0.5 counts and 2.2 counts, respectively.

Table 6 lists sample data recorded by the SDAS as the temperature varied. There is no measurable effect on the accuracy of the 5-V and 0.1-V channels, which use a straight-through signal conditioner. This indicates that the stability of both the analog-to-digital converter and the amplifier is adequate for expected temperature changes. Those channels using a bridge signal conditioner show changes, with temperature generally consistent with those caused by the changing excitation voltages. Some channels show somewhat greater, and other somewhat lesser, changes than would be expected because of the measured changes in excitation voltage alone. These differences may indicate that additional errors of random sign are being introduced by the resistances making up the bridge signal conditioners. However, these additional errors could be caused, at least in part, by noise components preserved in the data by the relatively short averaging intervals used.

The last column of Table 6 shows how the measured value of the (nominally) 1000-ohm resistor, which is used to convert a current input of 0-0.1 mA to a 0-100-mV signal, changes with temperature. The values were recorded by using a digital ohmmeter and so represent single readings rather than averages. These data indicate a temperature coefficient of resistance of about $0.02 \text{ ohm}/^\circ\text{C}$. If this channel is calibrated at one temperature extreme, its error at the other extreme will be about 0.8 counts for a full-scale input signal. If the channel is calibrated at 20°C , the maximum error will be only 0.4 counts under similar conditions.

The input resistance of a second current-input channel (channel 8) was also measured. This channel showed no shift of resistance with temperature larger than the random repeatability error introduced by the digital ohmmeter and the variable contact resistance between the ohmmeter and the contacts in the junction box.

5.4 EFFECTS OF LINE VOLTAGE ON ACCURACY

The a-c line voltage to the SDAS was controlled by connecting a variable autotransformer between the a-c power line and the SDAS power input. The DCM and the telephone coupler were not connected to the autotransformer and so received power directly from the a-c line. During these tests, the channel inputs remained constant.

Tables 7 and 8 present some sample data collected during these tests. Table 7 shows that the 15-, 5-, and 3.6-V excitation supplies change by about 0.4 mV, 0.17 mV, and -0.02 mV, respectively, per volt. The break in the overall pattern between 115 and 120 V in Table 7 is unexplained. At 95-115 Vac input, the supply sensitivities are 0.5 mV, 0.2 mV, and -0.03 mV, respectively, per volt. At 120 - 130 Vac, the supply sensitivities are 1.3 mV, 0.4 mV, and -0.08 mV, respectively, per volt. At 93 Vac, the excitation supplies drifted rapidly, indicating lack of voltage regulation.

A signal conditioner with a full-scale output that depends linearly on the 15-V excitation voltage, such as bridge circuits used to measure temperature, will have an error at one a-c voltage extreme of about one count due to this source alone if it is calibrated at the other a-c voltage extreme. Under similar conditions, sensors using the 5- and 3.6-V excitations will have errors of 1.3 counts and 0.25 counts, respectively; total errors of 1/2-1 counts are expected from a high-quality data-acquisition system. Because of the rapid changes in the excitation voltages that occur between 115 and 120 Vac, the overall error due to changes in line voltage will be only slightly less if the SDAS channels are calibrated with the a-c voltage at 115 - 120 Vac.

Table 7 SDAS Excitation Voltages as Functions of a-c Power Input Voltage

a-c Power Input Voltage, V	Excitation Voltages, V		
	+15	+5	+3.6
93	Excessive, fast drift over wide range		
95	14.989	5.1430	3.6958
98	14.992	5.1436	3.6955
100	14.994	5.1441	3.6954
102	14.995	5.1447	3.6954
105	14.996	5.1453	3.6952
107	14.997	5.1459	3.6949
110	14.999	5.1468	3.6947
115	14.999	5.1470	3.6952
120	14.990	5.1452	3.6957
125	14.992	5.1477	3.6952
130	15.003	5.1492	3.6949

Table 8 Data Recorded by Sample SDAS Channels as Functions of a-c Power Input Voltage

a-c Power Input Voltage ,V	SDAS Channels							
	16	40	7	11	12	19	20	23
	(5 V)	(0.1 V)	(-55-120°F)	(-20-120°F)	(-30-230°F)	(30-160°F)	(30-450°F)	(30-330°F)
95	823.9	52.8	645.9	545.4	112.4	183.1	52.2	74.3
97	823.6	52.6	646.1	545.7	112.2	183.4	52.2	74.4
100	823.5	52.7	646.0	545.3	112.2	183.2	52.1	74.2
103	823.4	52.7	646.0	545.3	112.0	183.1	52.1	74.1
115	823.3	52.7	646.6	545.9	112.3	183.4	52.2	74.4
[Note: The following data, taken at a different time than the above data, are not directly comparable because of uncontrollable changes with time.]								
105	823.0	52.7	645.6	544.2	112.0	183.0	52.4	74.5
108	823.0	52.9	645.8	544.4	112.0	182.9	52.5	74.4
110	823.0	52.7	646.0	544.3	112.0	182.8	52.4	74.5
115	823.0	52.8	646.1	544.5	112.0	183.1	52.5	74.6
125	823.0	52.7	646.5	544.7	112.0	182.9	52.5	74.6
130	823.0	52.8	646.4	544.9	112.1	183.0	52.7	74.6

Table 8 shows averaged data collected from selected channels during the a-c line-voltage testing. Unfortunately, the data in the two halves of this table were collected several months apart. Because of uncontrollable changes with time, the data in one half of the table are not directly comparable with the data in the other portion. In Table 9, this difficulty has been partially corrected by reproducing the data from Table 8 with correction factors applied to the data from the upper half of that table. The correction factor for each channel (either added or subtracted, as appropriate) was selected to force the two sets of data to match at the 115-Vac data points common to both.

Table 9 shows that the output recorded by a 0-5-V channel using a straight-through signal conditioner appears to have dropped steadily with increasing a-c line voltage up to 105 V and then remained constant. However, data not shown here indicate that, after the a-c line voltage was increased from 95 V to 115 V, channel 16 continued to read the same value as that read at 95 V. Apparently, channel 16 showed no measurable shift with line voltage. Rather, the changes shown in the second column of Table 9 are the result of a slow accuracy drift with time, which caused the quantization threshold from 823-824 counts to drift past the input signal. This drift, in turn, produced an apparently rapid change with time that the correction factors could not accommodate.

No measurable shift with line voltage for channel 40, a 0.01-V, straight-through channel using an amplification of 50, is indicated in Table 9. This information, combined with the lack of drift on a channel with a gain of one, indicates that both the analog-to-digital converter and the amplifier introduce negligible error for changes in a-c line voltages of 95-130 V.

Channels 7 and 11 show increases in readings with increasing a-c voltage that are about what would be expected if the only error source were the increase in the 15-V excitation. Channels 12, 19, 20, and 23 do not show any obvious change with line voltage. However, if such errors were caused by changes in the 15-V excitation exclusively, I would expect to see errors of 0.1% of the reading over the entire range of a-c line voltage. For these four channels, this expected error ranges from 0.05 to 0.18 counts. Additional calculations (not presented here) indicate that the averages for channels 12, 19, 20, and 23 still contain about 0.15 counts (two standard deviations from the mean) out of the original 2-3 counts generated by noise. The leftover noise would easily obscure the expected drifts resulting from changes in the 15-V excitation alone.

The only SDAS errors of significance produced by changes in a-c line voltage are those caused indirectly by changes in the 15-V and 5-V supplies and, to a much lesser extent, by the 3.6-V supply.

5.5 EFFECTS OF TIME ON ACCURACY

Tests designed to measure the drift with time of SDAS accuracy were conducted on two different Mod-II SDAS units. One SDAS is installed at the ANL cafeteria, where it collects data from a set of instruments on a solar water heater. To test the SDAS for long-term drift, ANL designed, tested, and installed a highly stable adjustable voltage reference (AVR). This reference produces three stable output voltages; one output is adjustable

Table 9 Data from Table 8, after Applying Correction Factors

a-c Power Input Voltage, V	SDAS Channels							
	16	40	7	11	12	19	20	23
	(5 V)	(0.1 V)	(-55-120°F)	(-20-120°F)	(-30-230°F)	(30-160°F)	(30-450°F)	(30-330°F)
95	823.9	52.7	645.4	544.0	112.1	182.8	52.5	74.5
97	823.3	52.5	645.6	544.3	111.9	183.1	52.5	74.6
100	823.2	52.6	645.5	543.9	111.9	182.9	52.4	74.4
103	823.1	52.6	645.5	543.9	111.7	182.8	52.4	74.3
105	823.0	52.7	645.6	544.2	112.0	183.0	52.5	74.6
108	823.0	52.9	645.8	544.4	112.0	182.9	52.5	74.4
110	823.0	52.7	646.0	544.3	112.0	182.8	52.4	74.5
115	823.0	52.8	646.1	544.5	112.0	183.1	52.5	74.6
125	823.0	52.7	646.5	544.7	112.0	182.9	52.5	74.6
130	823.0	52.8	646.4	544.9	112.1	183.0	52.7	74.6

from 0 to 5 V and the other two are adjustable from 0 to 0.1 V. These ranges match the voltage ranges of the SDAS input. Table 10 gives the accuracy of the voltage reference as determined by design calculations and verified by measurement. The three outputs of the AVR were connected to three spare channels on the cafeteria SDAS. Data from these channels were recorded by the SDAS, averaged over one-month intervals by the central data-collection-and-processing computer, and reported to ANL. ANL periodically measured the AVR outputs independently with a calibrated digital voltmeter.

The results of this test are summarized in Table 11. The data in the columns labeled "Reference Input" are averages of the ANL measurements of the AVR outputs if one or more measurements were taken during the month; a dash indicates that no measurement was taken that month. The output voltages of the reference were changed on August 20, 1979, as indicated in the table. The Channel-A data recorded by the SDAS were available to only three significant figures during 1979.

Table 11 shows no visible drift with time in the 5-V channel. However, owing to quantizing errors and low noise on this channel (see Appendix B for details), drift of up to one count could have gone undetected. The 0.1-V channels show an SDAS drift of 0.05 mV (1/2 count), well above the residual noise of about 0.005 mV. Since this drift is of the same sign and magnitude in both 0.1-V channels, even though the reading of one is four times the reading of the other, the drift is clearly caused by an additive, or offset, type of drift rather than by a multiplicative, or gain, type.

Table 10 Accuracy Specifications for the Adjustable Voltage Reference (Model VR-58)

	Channel	
	A	B and C
Output voltage	0-5 V	0-0.1 V
Max. output current	5 mA	5 mA
Output temperature coefficient	± 12.5 ppm/ $^{\circ}$ C ± 2.3 μ V/C	± 12.5 ppm/ $^{\circ}$ C ± 1.5 μ V/C
Output drift with time	± 210 ppm/6 mo ± 5 μ V/6 mo	± 210 ppm/6 mo ± 5 μ V/6 mo
Output drift with a-c line voltage (105-125 V)	± 0.03 ppm ± 0.15 μ V	± 0.03 ppm ± 0.15 μ V
Total output change for 20 $^{\circ}$ C change and 6 mo	± 326 ppm ± 46 μ V	± 326 ppm ± 30 μ V
Total output change for 20 $^{\circ}$ C change, 6 mo and full-scale output	± 0.002 V ($\pm 0.04\%$ of full scale)	± 63 μ V ($\pm 0.06\%$ of full scale)

Table 11 Summary of Data from Voltage
Reference at ANL Cafeteria

Month	Channel A (0 - 5 V)		Channel B (0-0.1 V)		Channel C (0 -0.1 V)	
	Reference Input, V	SDAS Output, V	Reference Input, mV	SDAS Output, mV	Reference Input, mV	SDAS Output, mV
June 1979	4.4996	4.50	90.024	90.05	4.986	5.00
July	4.4987	4.49	-	90.05	-	4.96
August 1-20	4.4995	4.49	90.035	89.96	4.983	4.95
August 20-30	2.5000	2.50	19.993	19.93	80.003	79.94
September	-	2.49	-	19.93	-	79.94
October	2.5004	2.50	19.992	19.93	80.007	79.96
November	2.4998	2.50	19.987	19.94	79.997	79.96
December	-	2.49	-	19.94	-	79.95
January 1980	2.5001	2.495	-	19.96	-	79.98
February	-	2.495	-	19.96	-	80.00
March	-	2.495	-	-	-	-
April	-	2.495	-	19.96	-	79.99
May	-	2.495	-	19.95	-	79.98
June	2.5002	2.495	19.990	19.95	79.988	79.98
July	-	2.495	-	19.95	-	79.98
August	-	2.495	-	19.94	-	79.97
September	-	2.495	-	19.96	-	79.95

A similar test was conducted on the test SDAS, using a duplicate voltage reference. The results of the test are shown in Table 12. This table is similar to Table 11, except that the SDAS outputs were obtained directly in counts and converted to voltages for comparison with the ANL measured values and with data in Table 11. The SDAS data for channel 28 for October and November, 1979, were not available. The SDAS averages in this table are averages over a period of four days or more within the listed month and may not be true monthly averages like those in Table 11. These averages were used to exclude data taken during specific tests that might have obscured the drift information (because conditions were not constant).

Table 12 shows that, during the one-year test, channel 16 has drifted upward 1-2 counts; channel 28 has drifted upward about 1.4 counts, and channel 40 has drifted upward about 0.1-0.2 counts. (Fractional counts are less significant on the 5-V channel than on the 0.1-V channels, as explained in Appendix B.) The residual noise in these count data is 0.1 counts or less. These data clearly imply that a drift in gain of 0.15% occurred simultaneously on all three channels, but no noticeable drift in offset occurred in any channel. The gain shift most likely occurred in the analog-to-digital converter, because it is the major gain-determining element common to these three channels.

Table 12 Summary of Data from Voltage Reference at
Test SDAS Dedicated to Accuracy Testing

Month	Channel 16 (0-5 V)			Channel 28 (0-0.1 V)			Channel 40 (0-0.1 V)		
	ANL Input, V	SDAS Output		ANL Input, mV	SDAS Output		ANL Input mV	SDAS Output	
		Volts	Counts		mV	Counts		mV	Counts
October 1979	4.0217	4.022	823.0	88.008	-	-	5.256	5.15	52.7
November	4.0214	4.022	823.0	88.006	-	-	5.255	5.16	52.8
December	-	4.022	823.0	-	88.11	901.4	-	5.16	52.8
January 1980	4.0217	4.022	823.0	88.009	88.11	901.4	5.248	5.16	52.8
February	-	4.022	823.0	-	88.12	901.5	-	5.15	52.7
March	-	4.022	823.0	-	88.12	901.5	-	5.15	52.7
April	-	4.023	823.1	-	88.14	901.7	-	5.15	52.7
May	-	4.024	823.3	-	88.14	901.7	-	5.15	52.7
June	4.0216	4.027	824.0	87.993	88.17	902.0	5.257	5.17	52.9
July	-	4.027	824.0	-	88.17	902.0	-	5.17	52.9
August	-	4.027	824.0	-	88.19	902.2	-	5.17	52.9
September	-	4.028	824.2	-	88.23	902.6	-	5.17	52.9
October	4.0206	4.032	824.9	87.989	88.25	902.8	5.256	5.17	52.9

Table 13 shows the drifts of excitation voltage with time in the test SDAS. Over the year of monitoring, the 15-, 5-, and 3.6-V outputs drifted over a range of 51, 17, and 12 mV, respectively. If these voltages were measured and incorporated into a calibration when they were at one extreme of the drift range, drift alone would cause errors of 3.5, 3.5, and 3.3 counts, respectively, over a year for a signal that was near full-scale and linearly dependent on the 15-, 5-, and 3.6-V sources.

These three excitation voltages were continually monitored, although at a lower accuracy, by the SDAS itself. These data (not listed here) show similar results when corrections are made for the SDAS gain drift described above.

Table 14 gives the drift data collected by bridge and current-input channels of the test SDAS. The last column shows that the current-to-voltage-conversion resistor drifted about 0.1 ohms during the year of testing. This drift would cause a gain error on that channel of about 0.1 counts, which is negligible.

The other columns in Table 14 contain errors caused by the previously quantified drift in the analog-to-digital converter and in the 15-V excitation supply. The output data also show a change of 1/2-1 count due to small changes in the input resistance. (The ratios of input resistance to output counts listed in the footnote to Table 14 are approximations obtained from data not shown here.) After taking these three effects into account, the data for channels 11 and 19 still show unaccounted-for drifts, which probably represent changes in the resistors or potentiometer used in the bridge circuit. The amplitude of these drifts with time is difficult to quantify,

Table 13 Summary of Excitation-Voltage Drifts (in volts)

Month	Excitation Voltages		
	+15 V	+5 V	+3.6 V
October 1979	14.989	5.1458	3.6802
November	14.993	5.1441	3.6980
December	-	-	-
January 1980	14.994	5.1420	3.7012
February	15.000	5.1422	3.7016
March	-	-	-
April	-	-	-
May	-	-	-
June	15.004	5.1532	3.6910
July	-	-	-
August	-	-	-
September	-	-	-
October	15.040	5.1592	3.6912

Table 14 Summary of Drift Data from Resistance and Current-Input Channels

Month	Channel 7 ^a (-55 to 120°F)		Channel 11 (-20 to 120°F)		Channel 19 (30 to 160°F)		Channel 20 (30 to 450°F)		Channel 9 (0-0.1 mA)
	ANL Input, ohms	SDAS Output, counts	ANL Input, ohms	SDAS Output, counts	ANL Input, ohms	SDAS Output, counts	ANL Input, ohms	SDAS Output, counts	Input Resistance, ohms
October 1979	-	645.2	-	543.7	-	182.6	-	52.3	-
November	104.685	646.1	104.929	544.5	104.920	183.1	104.638	52.5	997.62
December	-	645.9	-	544.5	-	183.1	-	52.3	-
January 1980	104.694	646.0	104.941	544.4	104.942	183.1	104.662	52.2	997.53
February	104.706	646.0	104.948	544.4	104.932	183.3	104.660	52.2	997.54
March	-	645.9	-	544.3	-	183.3	-	52.2	-
April	-	646.3	-	545.7	-	183.4	-	52.2	-
May	-	646.6	-	545.9	-	183.4	-	52.2	-
June	104.687	646.2	104.926	545.6	104.912	183.6	104.633	52.3	997.62
July	-	646.5	-	545.9	-	184.1	-	52.2	-
August	-	647.8	-	547.3	-	185.0	-	52.5	-
September	-	647.8	-	547.3	-	184.9	-	52.5	-
October	104.672	648.1	104.919	547.5	104.898	185.0	104.616	52.4	997.58

^a Approximate sensitivity, in counts/ohm, is as follows: Channel 7, 27; Channel 11, 33; Channel 19, 37; and Channel 20, 12.

because of the masking drifts, but appears to be about one count in channels 11 and 19 and even less (or nonexistent) in channels 7 and 20. Depending on which resistor values in the bridge circuit are changing, the drifts could be offsets or a combination of offset and gain types. The data are inadequate to determine the drift type.

5.6 EFFECTS OF EXTERNAL LOADING ON ACCURACY

All testing, except for that described in this subsection, was conducted with no load current being drawn from the excitation supplies for the 3.6- and 5-V sensors. A current of about 89 mA is drawn from the 15-V supply internal to the test SDAS to supply the bridge signal conditioners. The current ratings of 15-, 5-, and 3.6-V supplies are, respectively, 1.5 A, 1 A, and 50 mA.

Table 15 lists the supply voltages as measured in the junction box for different total current loads, including the load imposed by the bridge

Table 15 Variations in Supply Voltage
with Load Current

Excitation Supply, V	Total Current Draw, A	Voltage at Junction Box, V
15	0.089	15.040
15	0.19	15.012
15	0.23	14.999
15	0.39	14.955
15	0.58	14.898
15	0.80	14.833
15	1.03	14.762
15	1.47	14.620
5	0	5.1589
5	0.10	5.1143
5	0.16	5.0882
5	0.25	5.0489
5	0.47	4.9483
5	0.88	4.7890
3.6	0	3.6912
3.6	5.1×10^{-3}	3.6828
3.6	9.0×10^{-3}	3.6764
3.6	20×10^{-3}	3.6584
3.6	35×10^{-3}	3.6339
3.6	43×10^{-3}	3.6205

circuits. From the table, we can calculate that the effective output impedances of the 15-, 5-, and 3.6-V supplies, when measured at the junction box, are 0.30, 0.42, and 1.64 ohms, respectively. A one-count error will be introduced in any external sensor that is linearly dependent on its respective excitation voltage if the current load changes by 50 mA from the 15-V supply, by 12 mA from the 5-V supply, or by 2 mA from the 3.6-V supply. Errors in the bridge outputs caused by supply loading will be somewhat less than these errors, because the bridge circuits do not "see" the cable resistance from the SDAS to the junction box. Errors in the outputs from external sensors may be somewhat greater because of the extra cabling resistance from the junction box to the sensor.

I have no way of determining the expected changes in current loading, so I cannot calculate the errors anticipated to be caused by such a change in loadings. However, it is clear that to maintain overall accuracy, the supply voltages must be recorded and included in a set of calibration factors. A recalibration will be needed whenever sensor changes that alter the load currents significantly are made.

5.7 EFFECTS OF CROSS-TALK ON ACCURACY

Cross-talk tests were conducted by supplying rapidly varying signals to one or more input channels while other input channels were held constant. The standard deviations for the population of samples collected from each channel, which are a measure of the noise in that channel, were calculated and compared with standard deviations calculated when all inputs were held constant. All rapidly changing input signals were selected to be entirely within the normal operating ranges of the channels to which they were applied, but with peak-to-peak changes of about 80% of the full-scale input ranges for those channels. Frequencies of 1000 Hz and 60 Hz and sinusoidal and square waveforms were used. Channels using bridge-type signal conditioners were monitored for cross-talk but not driven, both because of the increased difficulty of driving them and because there was no reason to believe that doing so would supply any additional information.

Table 16 summarizes data taken from a final cross-talk test. During this test, channels 18, 31, 32, and 43 were simultaneously driven by a 1.37-V RMS, 1000-Hz sine wave offset by 2.57 V dc. This drive signal was also attenuated to a 28-mV RMS signal with 54-mV dc offset and connected to channels 24, 29, 30, 33, 42, and 46. Table 16 lists the standard deviations for the sample population, collected with the drive signal just described, and, for reference, the standard deviations for a sample population that were collected with the drive signal set to zero.

As is explained in Appendix B, changes between the reference and test standard deviations of less than 1/2 count (the maximum standard deviation due to quantization uncertainty alone) in those channels with gains of one are not significant. Changes of less than 1/2 count in channels with gains of 50 may be significant, owing to the greater amount of noise in data from such channels.

Table 16 Sample Results of Cross-Talk Tests

Channel	Gain	Standard Deviation, Counts	
		Reference	Test
2	50	0.45	0.43
3	50	0.49	0.46
4	50	0.42	0.33
5	50	0.49	0.45
6	50	0.98	1.19
7	50	0.81	0.80
9	50	0.19	0
10	50	0.89	0.88
11	50	0.98	0.92
12	50	0.94	0.95
13	50	0.94	0.93
14	50	1.01	1.04
15	50	0.95	1.00
16	1	0.45	0.21
19	50	0.79	0.79
20	50	1.00	0.94
21	50	0.99	0.99
22	50	1.02	1.00
23	50	0.94	0.95
25	1	0	0.04
26	1	0.49	0.34
27	1	0.25	0.40
28	50	0.46	0.36
40	50	1.13	1.10

No changes in standard deviation shown in Table 16 appear to be significant. Approximately equal numbers of channels showed decreased and increased standard deviations during the test. Any standard-deviation increases due to cross-talk are too small to be seen in this table and must be well below the standard deviation caused by quantization alone. Therefore, cross-talk can be ignored as an error source in the test SDAS.

5.8 EFFECTS OF MAINTENANCE ON ACCURACY

The effects of maintenance on the accuracy of the SDAS could be studied only in an uncontrolled way, because maintenance was performed as needed by the NSDN contractor and was effectively outside the control of the

experimenter. During the testing, several maintenance visits were made to both the test SDAS and the SDAS located at the ANL cafeteria. Only one visit had a noticeable effect on SDAS accuracy.

During testing, channel 10 began displaying intermittent full-scale readings. The NSDN contractor determined that the channel-10 signal conditioner had failed and replaced it. While signal conditioners were being tested, the conditioner used in channel 11, which was good, was also replaced. The contractor did not recalibrate channels 10 and 11 and said that no recalibration was needed.

Table 17 lists averages of the readings collected by a representative set of the SDAS channels two weeks before and two weeks after maintenance. The residual noise in these data is less than 0.1 counts. The only channel for which the average changed by more than 0.2 counts is channel 11; this channel's average changed by 1.3 counts. Such a large change can only be explained by the change in signal conditioners for that channel.

Table 17 Sample Data Showing Error Introduced to
Channel 11 by Replacement of Signal
Conditioner

Channel	Average Reading, Counts	
	Before Maintenance	After Maintenance
2	573.6	573.7
4	112.9	112.9
7	646.1	646.3
9	0	0
11	544.4	545.7
12	112.3	112.3
15	171.2	172.1
16	823.0	823.1
19	183.4	183.4
20	52.3	52.2
22	72.8	72.7
23	74.4	74.3
24	0	0
28	901.6	901.7
30	0	0
32	0	0
33	0.1	0.2
40	52.7	52.7
46	0	0

Maintenance in which a bridge-type conditioner is replaced, then, can result in an error as large as 1.3 counts at about mid-range. This error could be entirely an offset type, or it could be some combination of offset and gain types. It could, of course, be compensated for by recalibration of the affected SDAS channel.

REFERENCES

1. *Availability of Solar-Energy Reports from the National Solar Data Program*, SOLAR/0020-80/44 (July 1980).
2. *National Solar Data Network*, prepared by Vitro Laboratories, SOLAR/0003-80/17 (Jan. 1980).

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APPENDIX A: OBSERVATIONS NOT RELATED TO ACCURACY

A.1 SDAS RELIABILITY

Because the SDAS is required to collect data continuously without manual intervention to support the NSDN data analysis, and because of the high cost of sending repair teams to remote sites, the reliability of the SDAS is critical. During the year of testing, five failures occurred at the two SDAS units being monitored. Of these five failures, one resulted from incorrect setup of the SDAS, one from a failure in a signal conditioner, and one from changes in mechanical alignment of the tape recorder occurring shortly after the temperature cycling of the SDAS. One total SDAS failure lasted for about a week, after which the SDAS resumed normal operation without any repairs being made. Additional failures occurred at the ANL cafeteria SDAS before accuracy testing began.

A sixth, intermittent, SDAS failure was noted but was never isolated or repaired: Occasionally, the test SDAS would transmit data for one to three consecutive scans that contained obviously invalid data in five channels, even though the other channels continued to carry valid data. This intermittent failure appeared to be related to the unexplained appearance of abnormal intervals between scans (other than the nominal 320 seconds).

The observed failure rate appears excessive. High temperatures inside the SDAS may partly account for this rate. Table 5 shows that the air temperature in the microprocessor section of the SDAS is always about 13°C above that of the air around the SDAS: This temperature difference meant an internal air temperature of 54°C (130°F) versus an external air temperature of 40°C (104°F). The case temperature of the active components would be well above 54°C. Also, note that these measurements were made for a 48-channel SDAS. Any SDAS containing more than 48 channels has more heat-producing circuits in the microprocessor chamber, so that the internal air temperature would be even higher. These high temperatures can greatly increase SDAS failure rates.

A.2 SDAS RECOVERY FROM AC POWER INTERRUPTIONS

Occasionally, short-term power interruptions occur, and the SDAS must recover from such occurrences with minimal loss of data. I tested the SDAS response to power loss by removing the a-c plug from its socket during all phases of SDAS operation (except during communication with the central data-collection computer, when it was not practical). In each case, the SDAS recovered adequately, losing only those data not yet recorded on tape.

A.3 EFFECTS OF OPEN-CIRCUITING AN INPUT CHANNEL

Various channels using different types of signal conditioners were open-circuited to determine whether doing so would introduce errors in other channels or not. Whenever a channel using a bridge-type signal conditioner was open-circuited and the following channel also used a bridge, both the open-circuited channel and the following channel indicated zero counts. If

any other signal-conditioner type was used by either the open-circuited channel or the following channel, only the open-circuited channel was affected.

This result appears to be caused by the relatively large negative overload signal applied to the amplifier and analog-to-digital converter when an open-circuited bridge is sampled. When the following channel is also a bridge, its relatively high signal/source impedance cannot correct the overload condition in one sampling interval, so that a second reading of zero counts results. In my test setup, all non-bridge-type signal conditioners and sensor simulators produced low signal impedances. These low impedances apparently could correct the overload in one sampling interval and so produced normal results. When a channel that did not use a bridge-type signal conditioner was open-circuited, no overload occurred and no other channels were affected.

This explanation implies that invalid data may be recorded whenever a sensor, wiring, or SDAS problem causes a negative overload signal on one channel and the next channel to be sampled has a relatively large signal/source impedance. The consequences of a positive overload signal were not studied.

APPENDIX B: SIGNIFICANCE OF FRACTIONAL COUNTS IN THE TEST DATA

In some places in this report, I have indicated that the calculated means and standard deviations are significant only to 1/2 count; elsewhere, I have indicated that the results are significant to 0.1 counts. This appendix resolves the seeming contradiction between these statements.

Figure B.1 shows the ideal transfer function of an analog-to-digital converter. The scale markings show output counts and the input voltages that correspond exactly to the respective output counts. A step (from one count to the next count) occurs when the input voltage falls midway between the voltages exactly represented by the two counts. Figure B.2 illustrates the situation in which the input signal contains an additive noise signal with a Gaussian probability distribution. In the low-noise case, the input voltage can take on average values such that the analog-to-digital converter can always output a single count, despite the additive noise. In the high-noise case, the output of the converter will vary by several counts, even with a constant average input, because the probability of finding the input in the range necessary to produce any one of several count outputs at the moment of sampling is high.

Figure B.3 reproduces the transfer function of the analog-to-digital converter but plots the average output as a function of the average input for the no-noise and low-noise cases. In the low-noise case, the steps from one output count to the next are no longer vertical, because when the average input voltage is near a transition point, the probability-density curve of Fig. B.2 encloses an appreciable area on both sides of the transition. This indicates that the converter will output both counts, and the count-output average will be related to the areas under the probability-density function on each side of the transition.

As the noise increases, both the length of each horizontal section of the plot of the low-noise case and the slope of the diagonal sections decrease. When the noise amplitude exceeds several steps of the converter, the transfer function of the averages becomes a straight line. The horizontal sections of Fig. B.3 indicate that in the low-noise case, variations in average input voltage can exist that cannot be seen in the output counts. The high-noise case results in a straight-line transfer function with no such undetectable input variations. Therefore, we can effectively increase the resolution (but not the accuracy) of the analog-to-digital converter by adding to the input voltage noise a Gaussian distribution, having a mean of zero and a standard deviation of 1 - 2 counts, and then averaging the output of the converter.

These conditions are approximated in the SDAS when a gain of 50 is used; thus, shifts of 0.1 counts in the mean output can be significant. However, the collected data show that when an SDAS gain of one is used, the noise pickup is significantly less than one count. Under these low-noise conditions, the calculated average output can deviate by as much as 1/2 count from the value implied by the average of the input voltage, if that were known.

A related argument may be offered in connection with calculations of the standard deviation for the output of an analog-to-digital converter. For the low-noise case, the standard deviation of the converter output will usually be zero, because the output is constant. However, if the average of the input is at one of the transition points shown in Fig. B.2, the output will be one count half the time and the other count the rest of the time. When the average input is near, but not on, a transition point, the standard deviation of the output will clearly be smaller. A simple calculation of the standard deviation for the low-noise cases shows that it reaches a maximum value of $1/2$ and that this maximum is independent of the average output. The standard deviation of a set of readings X_i is given by

$$\sigma = \sqrt{\overline{(X_i^2)} - (\overline{X_i})^2} \quad (\text{B.1})$$

where the first term under the radical is the average of the squares of the readings and the second term is the square of the average of the readings.

Fig. B.1 Transfer Function of an Ideal Analog-to-Digital Converter

Fig. B.2 Probability-Density Function for Low- and High-Noise Input Signals

When the readings are any integers K and $K + 1$, with equal rates of occurrence, then the standard deviation is as follows:

$$\sigma = \sqrt{\frac{K^2 + (K + 1)^2}{2} - (K + \frac{1}{2})^2}$$

$$= 1/2 \quad (\text{B.2})$$

For the low-noise case, an uncontrollable shift of the average input voltage or an uncontrollable shift of the transition points by an amount approximately equal to the noise amplitude can cause the standard deviation to change by up to $1/2$ count if the average input lies near a transition point. Therefore, only changes in the output standard deviation greater than $1/2$ count are significant in the low-noise case.

In the high-noise case, small uncontrolled changes in the average of the input voltage or the transition points will not significantly affect the standard deviation of the output. Therefore, changes of less than $1/2$ count in the output standard deviation can be significant.

Fig. B.3 Transfer Function of an Analog-to-Digital Converter for Averaged Inputs and Outputs (Low-Noise Case)

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APPENDIX C: ACCURACY OF THE CALIBRATION STANDARD

The SDAS could be tested for accuracy only by comparing its output data with information taken by a reference standard having a known accuracy greater than the potential accuracy of the SDAS. In my testing, I used a Data Precision Model 3500 digital multimeter (DMM) as the standard. All readings that were directly compared to the SDAS output were taken with this meter. Other, less critical, readings, such as a-c line voltages and output currents from the excitation power supplies, were occasionally taken using a less accurate DMM.

The Data Precision 3500 DMM is a part of ANL's CS-4 calibration system. It is itself repeatedly calibrated at six-month intervals. Documents describing the calibration and its results are maintained as part of the CS-4 calibration system.

Table C.1 lists the maximum uncertainty in the readings taken by the Data Precision 3500 for all normally encountered conditions of temperature, humidity, and line voltage.

Table C.1 Accuracy of Data Precision 3500 DMM
Used as Calibration Standard

Parameter	Range, V	Uncertainty, ppm
<u>Voltage level, % of range</u>		
100	1000, 100, 10, or 1	90
50	1000, 100, 10, or 1	110
20	1000, 100, 10, or 1	170
10	1000, 100, 10, or 1	270
<u>Voltage level, V</u>		
0.1	0.1	120
0.05	0.1	160
0.02	0.1	280
0.01	0.1	480
0.005	0.1	880
0.002	0.1	2080
0.001	0.1	4080
<hr/>		
	Range, ohms	Uncertainty, ppm
<u>Resistance, 10⁶ ohms</u>		
10	10 ⁷	2110
5	10 ⁷	2220
2	10 ⁷	2550
1	10 ⁶	230
0.5	10 ⁶	260
0.2	10 ⁶	350
<u>Resistance, % of range</u>		
100	10 ⁵ , 10 ⁴ , or 10 ³	90
50	10 ⁵ , 10 ⁴ , or 10 ³	110
20	10 ⁵ , 10 ⁴ , or 10 ³	170
<u>Resistance, ohms</u>		
100	100	120
50	100	160
20	100	280
10	100	480
5	100	880
2	100	2080
1	100	4080