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# RESULTS OF A REMOTE MULTIPLEXER/DIGITIZER UNIT ACCURACY AND ENVIRONMENTAL STUDY

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CONTENTS

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## INTRODUCTION

A highly flexible digital instrumentation system was developed at the NASA Dryden Flight Research Center through the airborne integrated flight test data system (AIFTDS).

The heart of the AIFTDS is the remote multiplexer/digitizer unit (RMDU) (figs. 1 and 2). An RMDU can be operated in conjunction with an airborne computer or data management unit or as an independent data acquisition system. When in independent operation, the RMDU is referred to as operating in the stand-alone configuration.

An accuracy and environmental study was undertaken to insure that the unit met the requirements under which it was procured as well as to determine the overall accuracy and reliability of the stand-alone system. Any discrepancies between

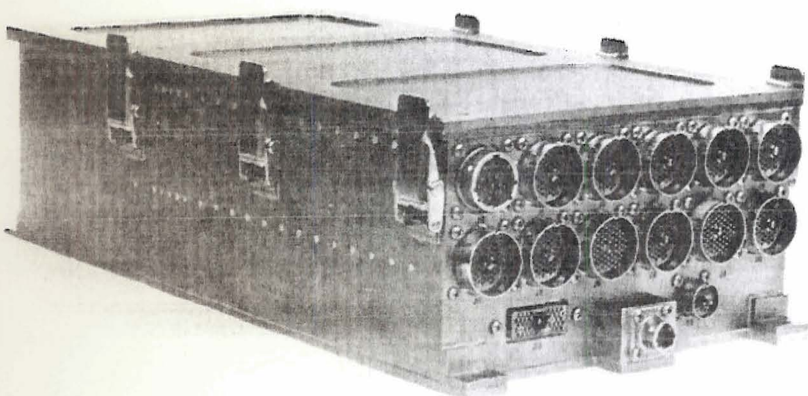


*Figure 1. RMDU front view.*

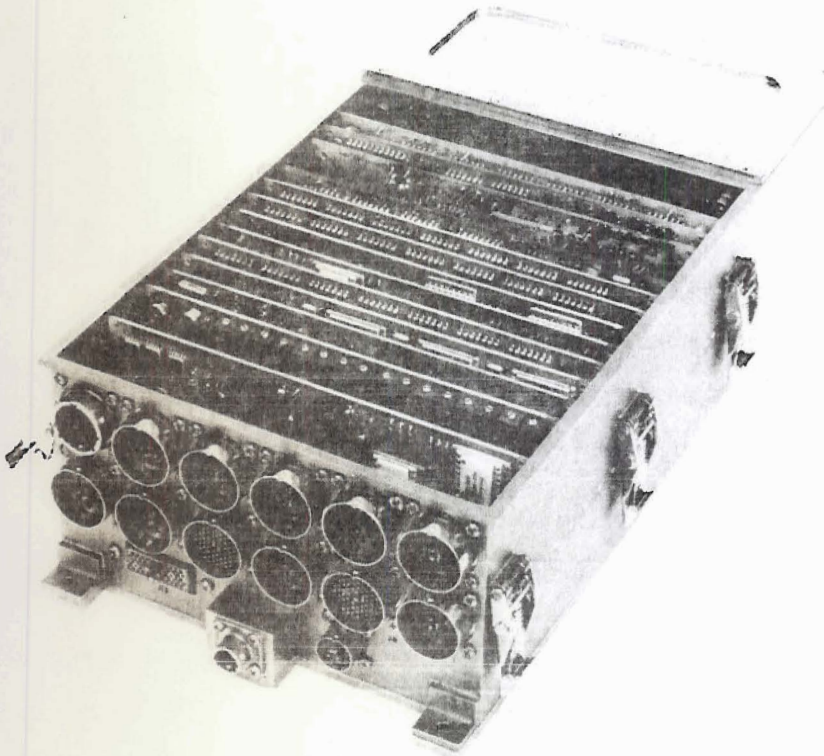


*Figure 2. RMDU with top cover removed.*

the actual output and the expected output were to be understood at the conclusion of the study.

This report documents the results of the accuracy study and reports the means used to obtain the best possible results from the RMDU. Much of the discussion on correcting the data is in general terms, since the ideas presented can be applied directly to other RMDU's.

## SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AIFTDS | airborne integrated flight test data system |
| Bi∅-L | biphase level form of PCM coding |
| Bi∅-M | biphase mark form of PCM coding |
| CORDATA | raw data corrected for gain and offset |
| c | zero offset |

| | |
|---|---|
| $Data_{raw}$ | uncorrected raw data obtained from RMDU |
| $Data_{zero}$ | uncorrected raw data response from RMDU with zero input voltage |
| $f_1(x)$ | theoretical transfer function without autoranging |
| $f_1^*(x)$ | theoretical transfer function with autoranging |
| $f_2(x)$ | actual transfer function without autoranging |
| $f_2^*(x)$ | actual transfer function with autoranging |
| $f_2'(x)$ | actual transfer function corrected for zero offset |
| $f_2^{*'}(x)$ | actual transfer function (autoranged portion) corrected for zero offset |
| $f_2''(x)$ | actual transfer function corrected for zero offset and slope change |
| $f_2^{*''}(x)$ | actual transfer function (autoranged portion) corrected for zero offset and slope change |
| $Gain_{theoretical}$ | desired gain used by the amplifier |
| GPA-Ø | response of gain programmable amplifier zero input |
| HLC | response of analog to digital converter with three-quarters of full scale voltage applied to input |
| LLC | low level calibration signal on analog multiplexer card |
| $LLC_{raw}$ | uncorrected response from LLC signal |
| $LLC_{zero}$ | zero offset measurement of LLC signal |
| $LLC_{xxx}$ | response from the LLC divider (in counts) at gain xxx |
| MOSFET | metal oxide semiconductor field effect transistor |
| MSB | most significant bit |
| m | magnitude of slope |
| $m_1$ | slope of theoretical transfer function without autoranging |

| | |
|---|---|
| $m_1^*$ | slope of theoretical transfer function with autoranging |
| $m_2$ | slope of actual transfer function without autoranging |
| $m_2^*$ | slope of actual transfer function with autoranging |
| NRZ-L | nonreturn to zero level form of PCM coding |
| NRZ-M | nonreturn to zero mark form of PCM coding |
| n | total number of points in a collection |
| PCM | pulse code modulation |
| PSB | power supply bite; a go/no-go signal indicating whether the sum of the secondary voltages in power supply is within 10 percent of the sum |
| RMDU | remote multiplexer/digitizer unit |
| T | temperature |
| $V_{in}$ | input voltage to analog multiplexer |
| $V_{LLC}$ | excitation voltage used for LLC signal |
| (x, y) | distance from ordinate axis and abscissa axis, respectively |
| $x_i$ | x value of the ith (x, y) pair |
| $y_i$ | y value of the ith (x, y) pair |
| $\gamma_x$ | ratio of theoretical slope to actual slope at gain x |

## RMDU DESCRIPTION

It is not the intent of this report to explain the entire AIFTDS; several documents and manuals do a superb job of this already (refs. 1 to 4). Instead, this report discusses the RMDU used throughout accuracy and environmental tests and considers where errors might be generated or introduced into the system.

The basic stand-alone RMDU configuration used in the tests can be divided into six major parts (fig. 3): the analog multiplexer, gain programmable amplifier, autoranging amplifier, analog to digital converter, stand-alone timing module, and power supply.

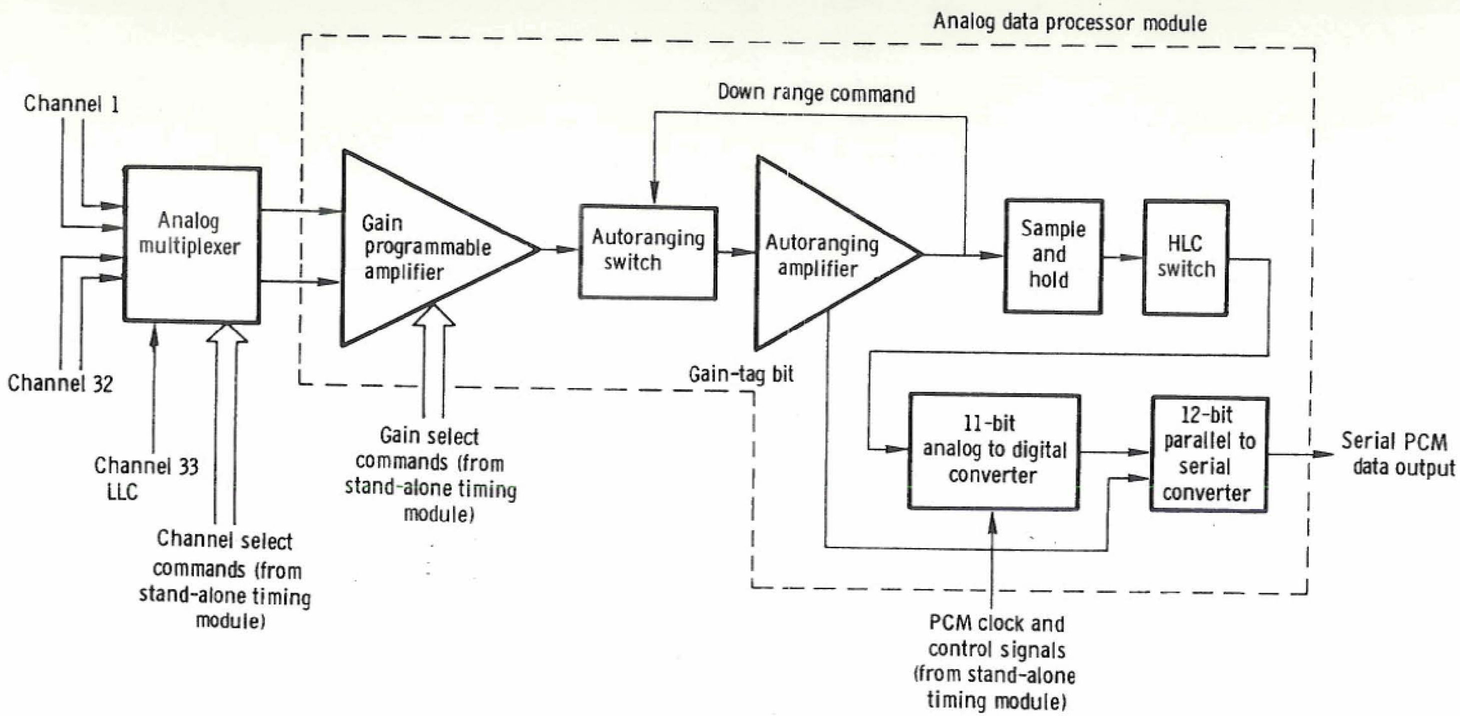



*Figure 3. Functional block diagram of RMDU used during tests.*

## Analog Multiplexer

The function of the analog multiplexer is to select one of 32 external channels or one internal channel per card to be amplified and digitized. The analog multiplexer consists of cards, or modules, with 33 accessible channels per card and a maximum of 11 cards per RMDU. This gives an RMDU the capability of accessing any of 352 external analog channels and 11 internal calibration channels.

The internal calibration channel on each card is treated as if it were any other analog signal. This channel is used as a low level calibration (LLC) channel in that it consists of a precision resistor divider network that generates a stable, precise voltage. The resistors used in this divider network are matched to within 0.05 percent, and the temperature coefficients are matched to within ±5 parts per million per degree Celsius (±9 parts per million per degree Fahrenheit) over a temperature range from -54° C (-65° F) to 85° C (185° F). The LLC divider network used in the Dryden RMDU unit consists of a 146.475-ohm resistor in series with a 199,854-ohm resistor. This network is driven from a doubly regulated 10-volt supply and generates a precise 7.3237-millivolt signal which is used for calibration and fault detection.

## Gain Programmable Amplifier

The sampled output of the analog multiplexer is input directly to the gain programmable amplifier, where the pulse amplitude modulated signal is amplified by the gain specified by the control signals emanating from the stand-alone timing module. The Dryden amplifier has eight selectable gains: 1000, 400, 100, 50, 10, 3, 2, and 1. Any gain programmable amplifier can be configured by the manufacturer at the time of manufacture to provide any eight selectable gains from 1 to 1024.

A provision is incorporated in the amplifier for automatically shorting the input before any word is sampled. This provision, designated GPA-Ø, can be sampled as an internal calibration point to indicate the offset of the amplifier.

## Autoranging Amplifier

The autoranging amplifier senses the level of the gain programmable amplifier output signal. When the signal reaches approximately 90 percent of full scale (for both negative and positive going signals) the autoranging amplifier switches to half the original gain. This feature prevents the accidental saturation of the amplifier.

Whenever the autoranging amplifier downranges to a gain of one half, a logic "1" is appended to the most significant bit (MSB) of the 12-bit word as a gain tag bit. This bit is decoded at the receiving end of the data acquisition system and indicates that the overall gain for that channel is half the original gain. When no autoranging occurs, a logic "0" is appended to the MSB as a gain tag bit. When decoded at the receiving end, it indicates no change in the original gain.

## Analog to Digital Converter

The actual conversion from a pulse amplitude modulated signal to a binary formatted signal is performed in this section. The pulse amplitude modulated signal is input to a dual sample and hold circuit which maintains the signal amplitude during the conversion process. The converter itself is a conventional 11-bit bipolar successive approximation converter capable of a conversion in less than 5 microseconds. The 11-bit binary word emanating from the converter is offset binary in format and has a resolution of 5 millivolts per bit. This gives a total input range of ±5.115 volts.

An internal calibration point was also incorporated in the design of the analog to digital converter. This provision, designated HLC, injects a precision three-quarter full scale voltage into the input of the analog to digital converter, giving an indication of the converter's offset and stability.

The last block in the analog to digital converter is the 12-bit parallel to serial shift register. The MSB of this serial word is the gain tag bit from the autoranging amplifier, and the other 11 bits consist of the offset binary word from the converter.

## Stand-Alone Timing Module

The stand-alone timing module generates all internal and external time base signals, contains the sampling format memory for the data cycle, and formats the 12-bit digital data for transmission, recording on an onboard tape recorder, or both. The available output formats are nonreturn to zero level (NRZ-L), nonreturn to zero mark (NRZ-M), biphase level (Bi∅-L), biphase mark (Bi∅-M), and delay modulation mark (Miller).

To summarize the whole system, the RMDU is a serial analog to digital converter with the capability of random channel sampling in accordance with a preprogramed format stored in memory. Such functions as word rate, data frame length, subframe depth, channel, and channel gain are stored in this preprogramed format.

The original approach taken toward the accuracy and environmental tests was to submit the RMDU to tests according to NASA Specification 21-2 (appendix A) while monitoring the pulse code modulation (PCM) output stream. The first two phases of the tests (altitude and vibration) revealed no problems that could not be either explained or rectified; however, the temperature tests revealed several problems in the system and, hence, an in-depth study was initiated.

The experimental setup for the temperature tests is shown in figure 4. Great care was taken (through the use of a precision divider network) to insure that the input excitation voltage was noise free and accurate within 1 microvolt. The input voltage source cabling shield was driven at the source to minimize any common mode voltages. For all the tests, the word rate was 31,200 words per second. The flight line tester monitors the PCM serial data stream and decommutates and displays the data in signed decimal values. Through the use of the flight line tester, the user can accurately and instantaneously monitor the response of the RMDU to any input stimulus and to any of the internal calibration signals.

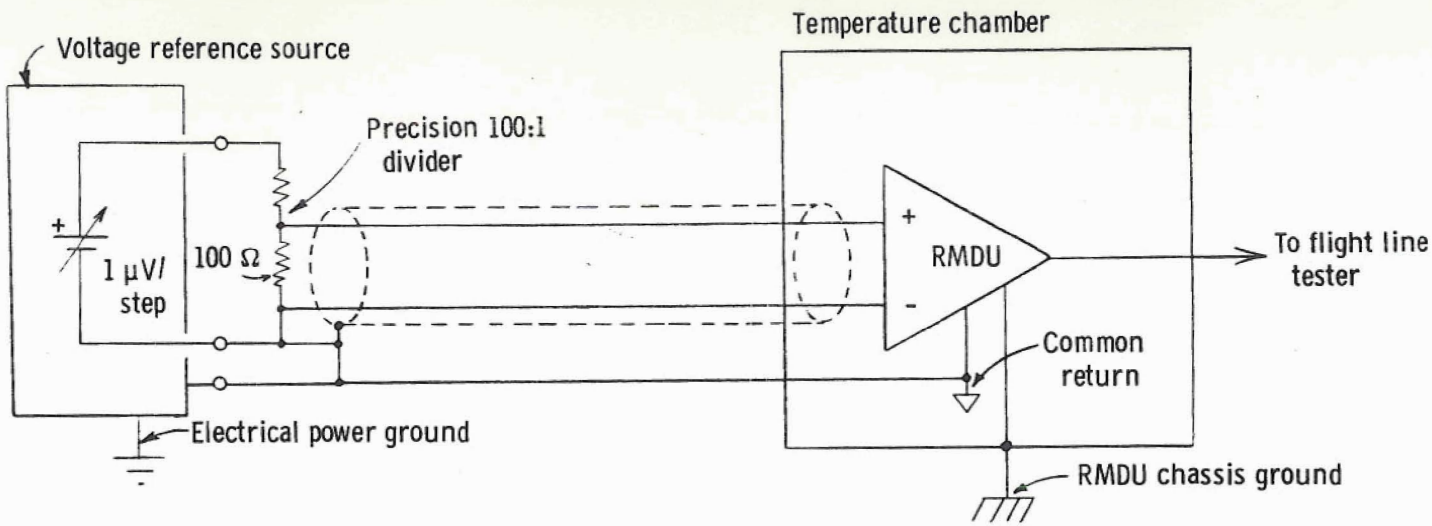



*Figure 4. Accuracy and environmental test setup.*

## TEMPERATURE TESTS

Nine temperature tests were performed on the RMDU between October 1975 and October 1976. The first temperature runs uncovered several problems, among which were the following:

- The analog data processor module failed at extreme temperatures. The failures were due primarily to the breaking of solder joints at low temperatures and the failure of components at high temperatures. It must be noted, however, that this RMDU was an early production unit.

- Some of the components in the doubly regulated 10-volt power supply were temperature sensitive. This sensitivity to temperature was directly reflected in the LLC readings.

- The excitation voltages were improperly monitored during the first two temperature runs. The multiplexing action introduced voltage spikes onto the input voltage, and these spikes, in turn, were integrated by the digital voltmeter, causing erroneous readings of the input voltage.

- Excessive crosstalk arose from overscale or open circuiting of adjacent channels.

- Excessive capacitance was present at the excitation source.

- The temperature coefficients of components associated with the gain programmable amplifier at gains of 400 and 1000 were improper. This is discussed in greater detail in appendix B.

- One of the transformers shorted out at low temperatures.

- Nonconstant sensor impedance caused erroneous readings.

When these problems were rectified, a final temperature run was performed on the RMDU at temperatures of -54° C (-65° F), 27° C (80° F), and 71° C (160° F) for the highest three gains (1000, 400, and 100). The data obtained at these gains are discussed separately below. The RMDU was allowed to soak at each temperature, without a heat sink, for 2 hours to insure that the internal temperature was stable.

### Gain of 1000

The Dryden RMDU has a sensitivity of 5 microvolts per count (200 counts per millivolt) at a gain of 1000. At this gain the RMDU is susceptible to noise and improper operating techniques; however, the errors in the offset corrected data for this gain (table 1) are within 10 counts over the temperature range.

Figure 5 depicts the residual error in the offset corrected data (sixth column, table 1(a)) as a function of input voltage for a gain of 1000 and a temperature of 71° C (160° F). The figure shows that the errors change from predominantly negative to predominantly positive when autoranging occurs.

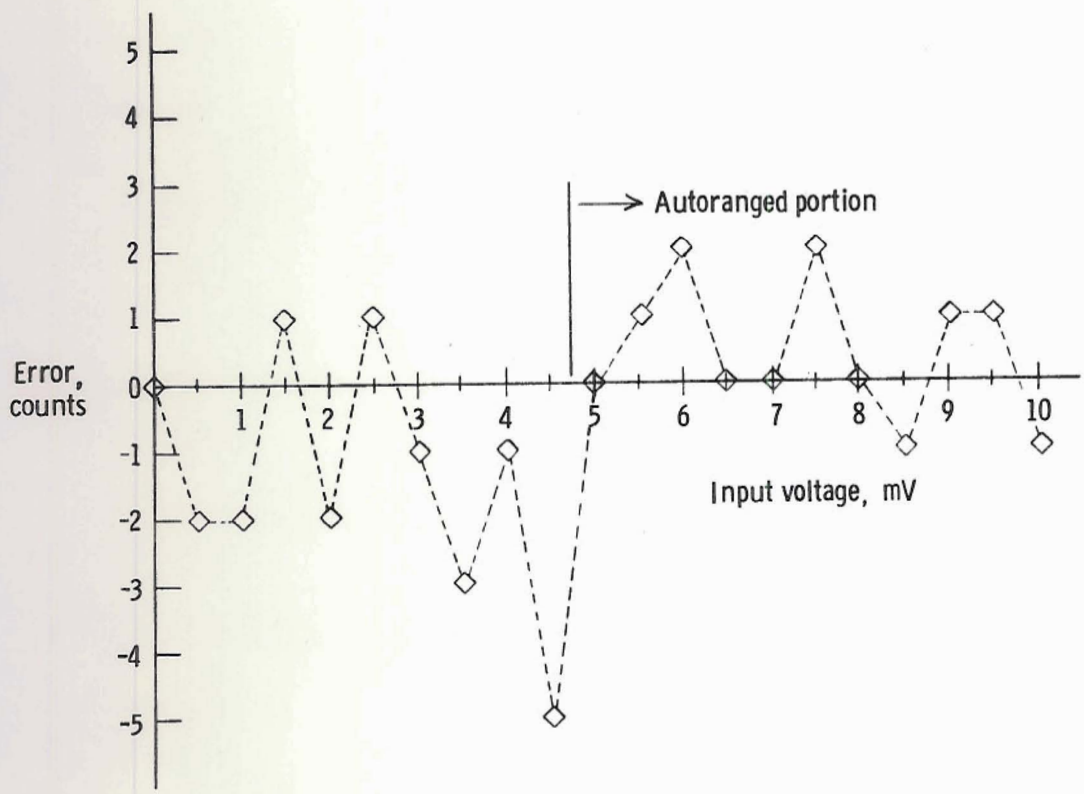



*Figure 5. Error counts for offset corrected data versus input voltage to RMDU. Gain = 1000, temperature = -54° C (-65° F).*

Figure 6 depicts the residual error in the offset corrected data (sixth column, table 1(c)) as a function of input voltage for a gain of 1000 and a temperature of -54° C (-65° F). It is fairly obvious from this graph that the errors at this temperature are proportional to input voltage; for example, the gain is somewhat larger than 200 counts per millivolt. Performing a least-squares linear fit to the data in the sixth column of table 1(c) reveals that the gain is 200.74 counts per millivolt rather than 200 counts per millivolt. This variation of gain with temperature is easily corrected, as is shown below.

## Gain of 400

At the second highest gain tested, 400, the Dryden RMDU has a sensitivity of 12.5 microvolts per count (80 counts per millivolt), and consequently it is less susceptible than at a gain of 1000 to noise and improper operating techniques.

The data corrected for zero offset at this gain (table 2) show that the errors are within 12 counts across the temperature range. This error, which is shown in greater detail in figures 7 and 8, represents a full scale error of 12 counts per 2048 counts (full scale), or 0.586 percent. As for a gain of 1000, the gain deviation is more pronounced at lower temperatures. Performing a least-squares linear fit for the data in the sixth column in table 1(c) yields a sensitivity of 80.79 counts per millivolt rather than the theoretical value of 80 counts per millivolt. This error, which is due to the sensitivity of gain to temperature, can easily be corrected, as is shown below.

## Gain of 100

The gain of 100 is slightly less interesting than the previous two in that both the zero offset error and the gain variations are greatly diminished. In fact, the gain variations are hardly discernible. The data for this gain (table 3) show that zero offset error and quantization errors are the most significant errors present.

## Effects of Temperature

The data obtained in these tests showed a general temperature trend. This trend consists of an increase in error in terms of zero offset and gain deviations with increasing temperature, especially at the higher gains. It should be noted, however, that even at a gain of 1000, an error of 5 counts represents an error of only 25 microvolts. Existing PCM systems in use at Dryden today do not have a resolution of even 25 microvolts per count. At gains of 100 and lower, gain deviations from the RMDU appear to be insignificant. At these lower gains, the data remaining after correcting for zero offset are well within the 0.3 percent full scale accuracy range. This is not to say, however, that other types of errors may not exist, even at the lower gains, in any given RMDU application.

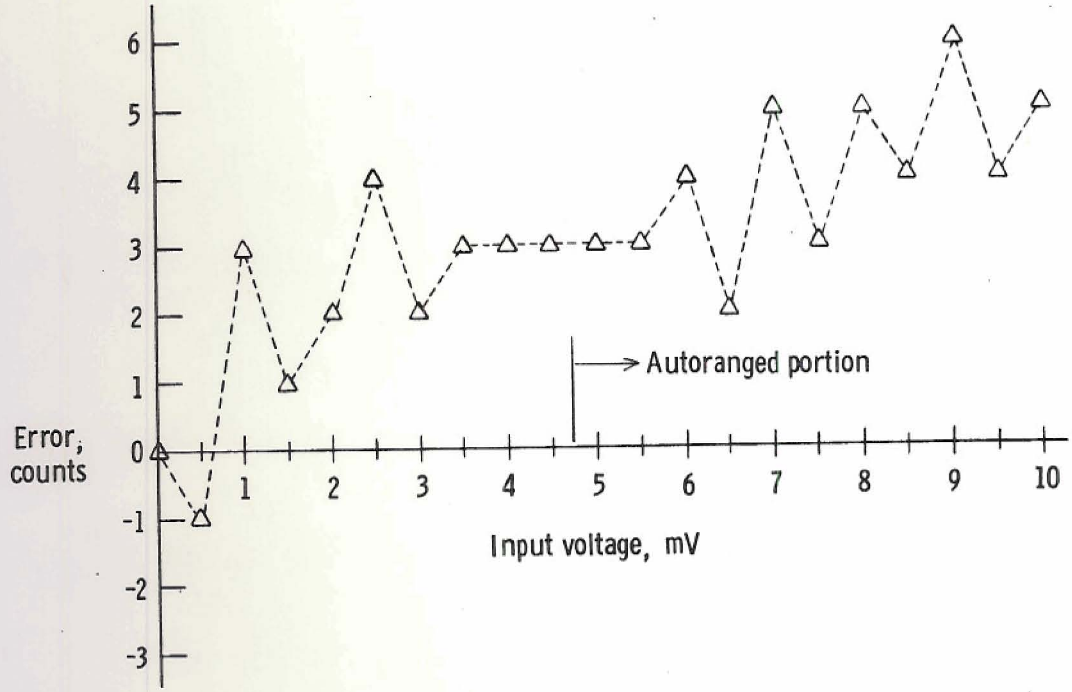



*Figure 6. Error counts for offset corrected data versus input voltage to RMDU. Gain = 1000, temperature = 71° C (160° F).*

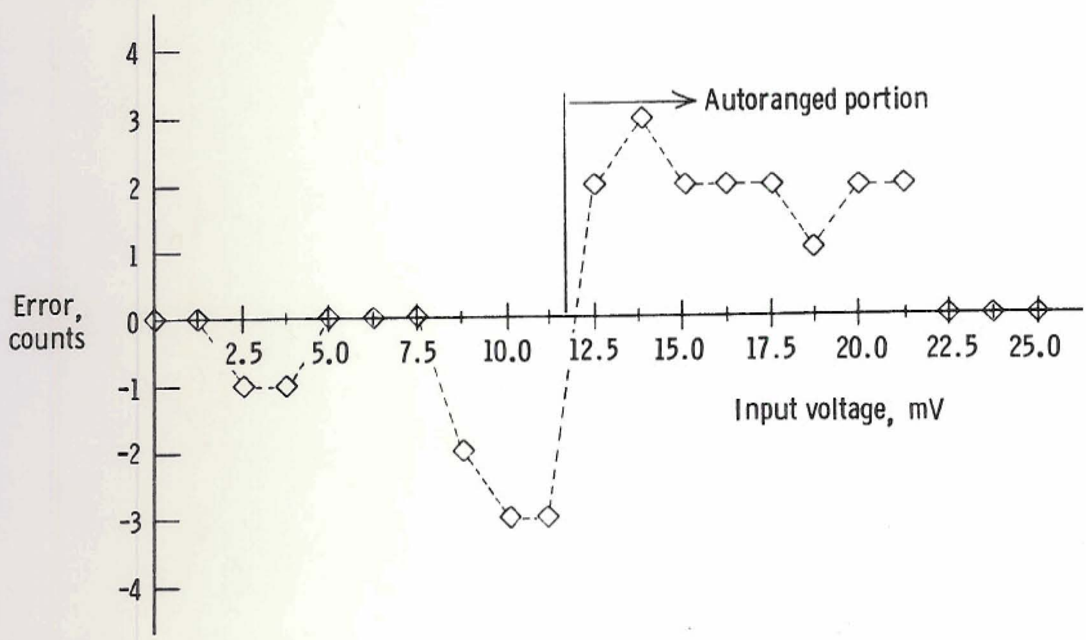



*Figure 7. Error counts for offset corrected data versus input voltage to RMDU. Gain = 400, temperature = 71° C (160° F).*

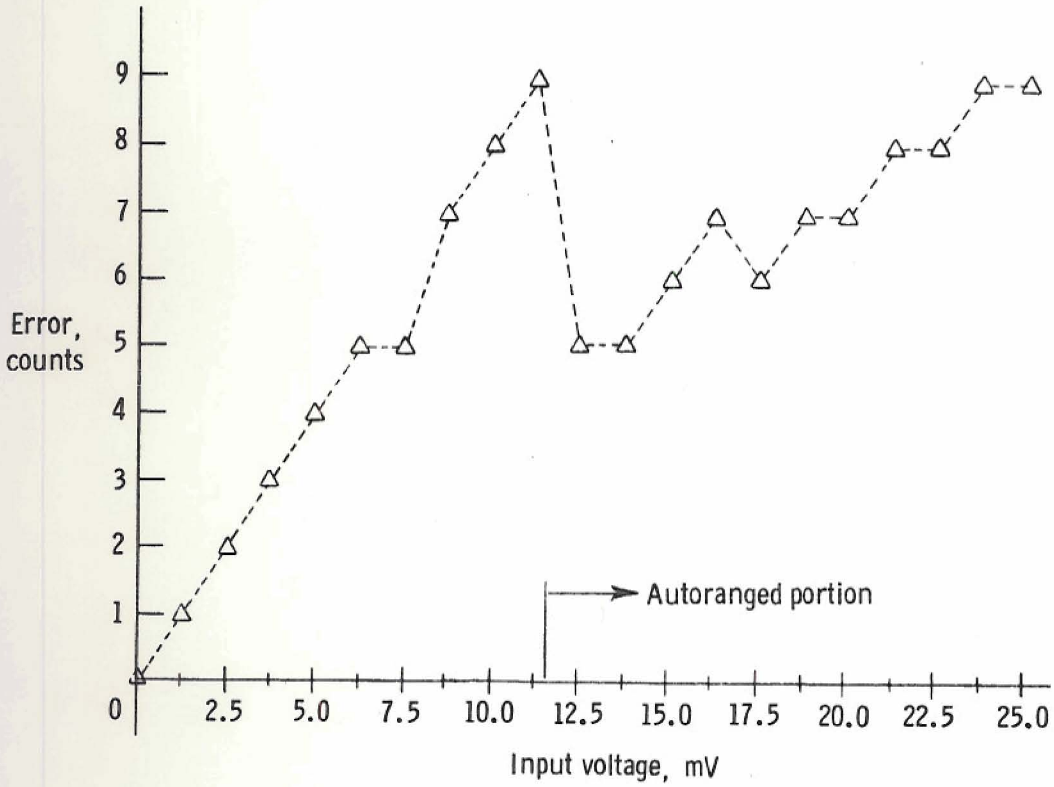



*Figure 8. Error counts for offset corrected data versus input voltage to RMDU. Gain = 400, temperature = -54° C (-65° F).*

DATA CORRECTION TECHNIQUES

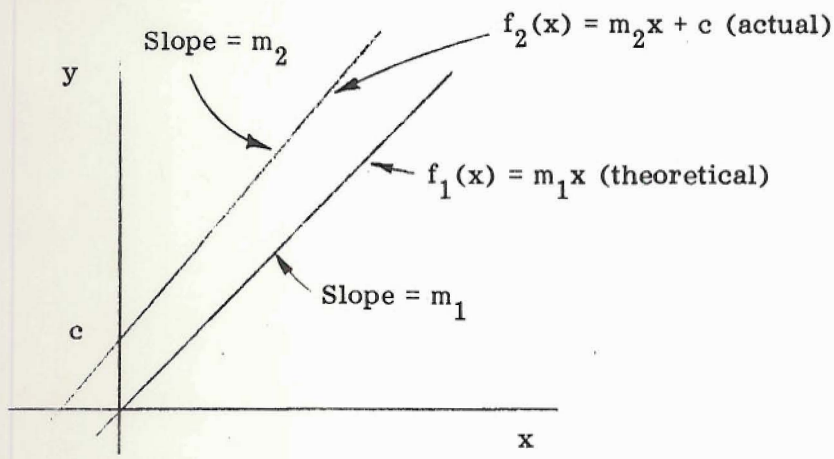
Although the magnitude of the errors may differ from one RMDU to another, the correction techniques discussed below are applicable to all RMDU's.

For the correction techniques to be useful, the following two assumptions must be made:

(1) That the transfer function is linear over the temperature range of interest (no significant contribution from second order and higher coefficients).

(2) That the effect of the autoranging amplifier is not temperature dependent (gain is reduced only by one half).

These assumptions have been verified experimentally. If one observes a simple offset and slope deviation like that in the following sketch,




it can be shown that by subtracting the zero offset (translating the coordinate axes)

$$f_2'(x) = f_2(x) - c$$

$$f_2'(x) = m_2x$$

and that

$$f_2''(x) = f_2'(x)m_1/m_2$$

Therefore

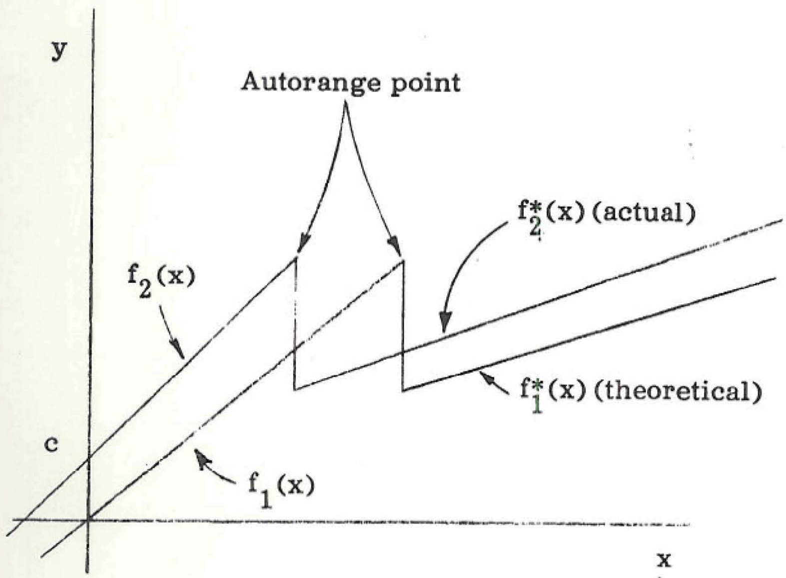
$$f_2''(x) = f_2'(x)m_1/m_2$$

$$f_2''(x) = m_2x(m_1/m_2)$$

$$f_2''(x) = m_1 x$$

$$f_2''(x) = f_1(x)$$

The case for the RMDU is the same as that just analyzed, with the exception of the autoranging function, as shown in the sketch below.




In this sketch, the slope $m_1^* = 0.5m_1$ and the slope $m_2^* = 0.5m_2$. Hence, for the portion of the curve without autoranging, one merely follows the formula below:

$$f_2''(x) = [f_2(x) - c]m_1/m_2$$

where $f_2''(x)$ represents the corrected response, and $f_2(x)$ represents the raw data.

For the autoranged portion of the curve, a slightly different case exists:

$$f_2^{*\prime}(x) = f_2^*(x) - 0.5c$$

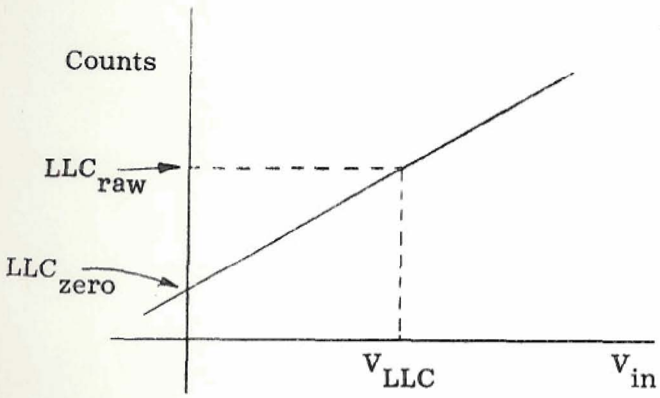
$$f_2^{*\prime\prime}(x) = (m_1^*/m_2^*)f_2^{*\prime}(x)$$

$$f_2^{*\prime\prime}(x) = [f_2^*(x) - 0.5c]m_1^*/m_2^*$$

where $f_2^{*\prime\prime}(x)$ represents the corrected response for the autoranged portion of the curve and $f_2^*(x)$ represents the raw data.

The theoretical method described above, in combination with the Dryden experience with its RMDU's, was used to derive a general data correction method for all RMDU's. From the theoretical cases presented, it was apparent that to correct a given transfer function it was only necessary to correct the slope of each function (the theoretical slope and the slope that was actually obtained) and the zero offset. These parameters are the only two needed to correct the data from an RMDU. The zero offset was easily obtained in most cases; however, the calculation of the slope of the transfer function was a little more involved since, as shown in the previous graphs, the slope varies with temperature. One way to obtain the correct slope for a given transfer function is to measure the temperature inside the RMDU and then to compute the gain (slope) from the composite equations determined from the least-squares fit of the gain versus temperature results, as was performed earlier. However, this approach may not be particularly advisable, since it has not been determined whether aging or other factors perturb these quantities. Therefore, it was found advisable to allow the RMDU to measure the slope of its own transfer function instantaneously during operation. This measurement was made through the use of the internal LLC signal. Since the voltage developed by the LLC divider is not temperature dependent, a good indication of the gain can be obtained by correcting the LLC signal for zero offset.

From the sketch below




it can be verified that

$$\text{Gain} = (LLC_{raw} - LLC_{zero})/V_{LLC}$$

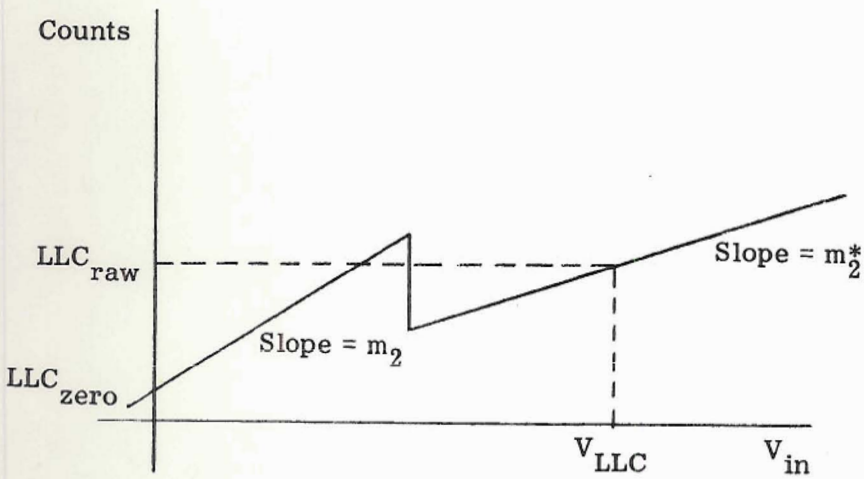
where gain is indicated in counts per millivolt, $LLC_{raw}$ is the reading of the LLC signal, $LLC_{zero}$ is the zero offset obtained by shorting a spare analog multiplexer channel directly at the RMDU input, and $V_{LLC}$ is the calculated voltage of the particular LLC divider network in millivolts.

When the procedures described above were followed with the Dryden RMDU with a gain of 400, a temperature of 71° C (160° F), and a $V_{LLC}$ of 7.3237 millivolts, $LLC_{raw}$ was observed to be 590 counts, and $LLC_{zero}$ was 10 counts. Therefore, in counts per millivolt, slope (gain), $m_2$, was as follows:

$$m_2 = (590 - 10)/7.3237 = 79.19$$

Theoretically, $m_2$ should have equaled 80.00 counts per millivolt ($m_1$). Hence, the gain factor used for correcting data at this temperature and gain, $m_1/m_2$, would equal 1.0102.

A case where the LLC signal causes autoranging for the desired gain is a minor variation, and can be plotted as in the following sketch.




In this case, the slope $m_2^*$ is given by the following equation:

$$m_2^* = (LLC_{raw} - 0.5LLC_{zero})/7.3237$$

and $m_2 = 2m_2^*$. Therefore, the factors involved in correcting the data for gain variation in this case would be as follows. For the portion with no autoranging,

$$m_1/m_2 = (200 \text{ counts/mV})/2(LLC_{raw} - 0.5LLC_{zero})/7.3237 \text{ mV}$$

$$m_1/m_2 = 732.37/(LLC_{raw} - 0.5LLC_{zero})$$

For the autoranged portion,

$$m_1^*/m_2^* = (100 \text{ counts/mV})/(LLC_{raw} - 0.5LLC_{zero})/7.3237 \text{ mV}$$

$$m_1^*/m_2^* = 732.37/(LLC_{raw} - 0.5LLC_{zero})$$

The gain factors $m_1/m_2$ and $m_1^*/m_2^*$ used for the two portions of the curve are identical. This is the result of assuming that the effect of the autoranging amplifier is not temperature dependent.

When these procedures were followed with the Dryden RMDU with a gain of 1000, a temperature of 71° C (160° F), and a $V_{LLC}$ of 7.3237 millivolts, $LLC_{raw}$ was observed to be 730 counts and $LLC_{zero}$ was 8 to 9 counts. The resulting ratio $m_1/m_2$ or $m_1^*/m_2^*$ was 732.37/(730 - 8.5/2), or 1.0084. (From this point on the ratio $m_1/m_2$ or $m_1^*/m_2^*$ is denoted by $\gamma_x$, where x denotes gain.) The value of $LLC_{zero}$ was obtained by shorting an analog multiplexer channel directly at the input plug to the RMDU. It should be emphasized that all three parameters ($LLC_{raw}$, $LLC_{zero}$, and the data to be corrected) must be obtained at the same gain.

The procedure for obtaining corrected data may be summarized as follows:

- For gains in which the LLC signal causes autoranging,

$$\gamma_x = 0.5(V_{LLC})(Gain_{theoretical})/(LLC_{raw} - 0.5LLC_{zero})$$

where $V_{LLC}$ is in millivolts, and $Gain_{theoretical}$ is the gain range of the RMDU in counts per millivolt.

  - For data without autoranging, corrected data (CORDATA) can be found as follows:

$$CORDATA = \gamma_x(Data_{raw} - Data_{zero})$$

  - For data with autoranging,

$$CORDATA = \gamma_x(Data_{raw} - 0.5Data_{zero})$$

- For gains in which the LLC signal does not cause autoranging,

$$\gamma_x = V_{LLC}(Gain_{theoretical})/(LLC_{raw} - LLC_{zero})$$

  - For data without autoranging,

$$CORDATA = \gamma_x(Data_{raw} - Data_{zero})$$

  - For data with autoranging,

$$CORDATA = \gamma_x(Data_{raw} - 0.5Data_{zero})$$

- For low gains, where the gain variation is negligible ($\leq$100):
  - For data without autoranging,

$$CORDATA = Data_{raw} - Data_{zero}$$

  - For data with autoranging,

$$CORDATA = Data_{raw} - 0.5Data_{zero}$$

The factor $Data_{zero}$ must not be confused with $LLC_{zero}$, although at first glance the terms seem synonymous. $Data_{zero}$ is the output data obtained when the sensor excitation is set equal to zero. In many cases—with strain gages, for example—disconnecting the excitation voltage is sufficient to obtain $Data_{zero}$. However, in other cases it is necessary to interchange the sensor with a resistor having a resistance equal to the source resistance of the sensor. This insures that the "zero" voltage received by the RMDU equals the Thevenin equivalent voltage of the sensor. The main difference between $LLC_{zero}$ and $Data_{zero}$ is that $Data_{zero}$ is usually larger because of the length of the cable going to the sensor and the common mode voltage developed through the unbalance of the cable/sensor combination. $LLC_{zero}$ is obtained by shorting out the excitation voltage to the LLC resistor network. Since this procedure is relatively difficult in practice, it is sufficient to short a spare analog multiplexer channel at the input plug to the RMDU. This minimizes the offset due to cable length and noise.

## INSURING CORRECTABLE DATA

The previous discussion concerning the correction of raw data assumed that the data were indeed correctable. Correctable is used here to mean that all error sources except gain variation and offset variations with variations in temperature can be eliminated. However, data can be hard or impossible to correct if they are affected by any or some of the following factors: noisy excitation signal, excessive sensor impedance, improper shielding technique (especially at gains in excess of 100), acquisition rate that is excessive for the type of sensor or data cycle map used, improper stand-alone timing module data cycle map layout, poor regulation of the 10-volt reference supply, improper temperature coefficient components in the gain programmable amplifier, nonconstant sensor impedance, and improper word rate (rate affects data validity).

There are doubtless other error sources in any given RMDU application; however, these appeared to be the most severe in this study. Most of these problems plague every sensitive data acquisition system; in fact, poor operating technique prevents the acquisition of good data from any data acquisition system—even sensitive digital voltmeters.

### Noisy Excitation Signal

At a gain of 1000, resolutions on the order of 5 microvolts per count are obtained, and millivolt-level noise can destroy data validity. When signals are noisy, the source of the noise should be determined. The noise is often of the type referred to as common mode noise, or noise due to that voltage that is common to both signal leads and ground. If the noise is common mode noise, better shielding techniques may be needed. Filtering the signal may prove effective; however, the filter must be designed to accommodate the impedance requirements of the RMDU.

## Excessive Sensor Impedance

Excessive sensor impedance is a result of the fact that the RMDU is a sampling type of data acquisition system. Two characteristics of the RMDU (and of most PCM systems) affect the maximum allowable sensor impedance. The first is input impedance. The input impedance to the RMDU, which is 50 megohms, is in parallel with undesirable capacity on the order of 200 picofarads. This capacitance (which is always shorted by the start of every sample by GPA-Ø) must become fully charged to the sensor voltage within the 8-microsecond sample and amplification period.

The second characteristic that affects the maximum allowable sensor impedance is the fact that when the sensor channel is sampled at a fixed frequency, the action of the 200-picofarad capacitance on the sensor capacitance is to deplete some of its stored charge. This depleted charge then must be replenished through the sensor resistance by the time the next sample is taken. If the depleted charge is not fully replenished by this time, the net effect is to depress the output reading for that channel.

If the first problem exists, the procedure recommended for correcting it is to extend the period of acquisition by selecting a lower crystal frequency. A lower crystal frequency, however, reduces the RMDU maximum word rate, which is normally 125,000 words per second. Another way to correct this problem is to insure that the product of the sensor resistance and the 200-picofarad capacitor is less than one-eighth of the sample and amplification period. This allows the 200-picofarad capacitor to become charged to within 0.03 percent of its intended voltage.

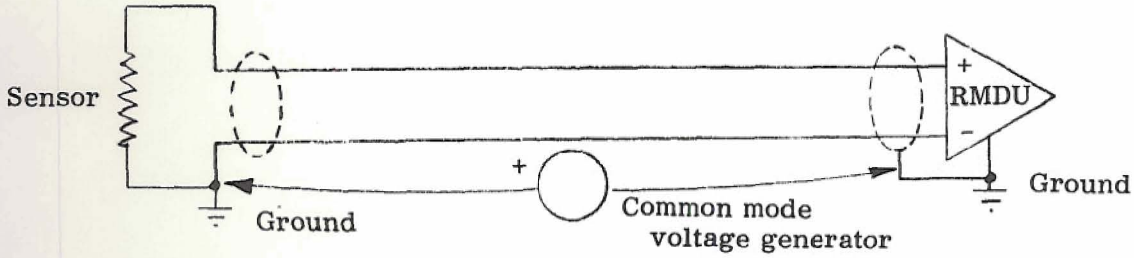
The method for correcting the second problem is to insure that the time constant of the sensor (the product of the sensor resistance and the cable/sensor capacitance) is much less than the reciprocal of the sample rate for that sensor. If the sensor impedance cannot readily be changed to accommodate this, the alternative is to sample that particular sensor at a slower rate.

The best solution to both problems is to use sensors with extremely low resistance. It should be reiterated that these problems exist in any sampling data acquisition system.

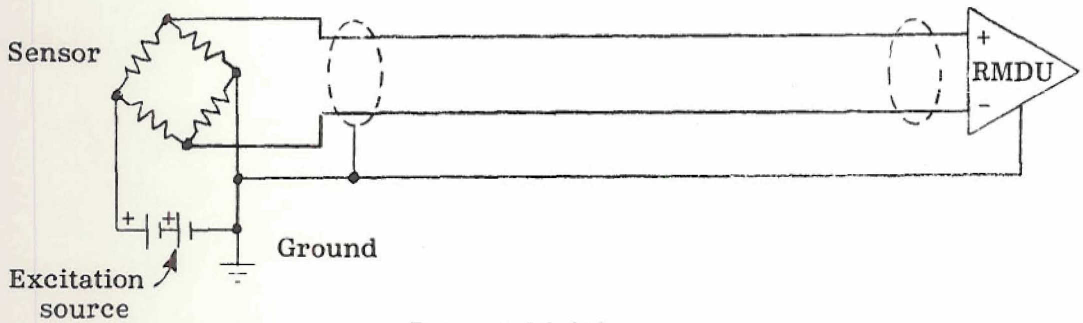
## Improper Shielding Technique

Shielding and grounding is a controversial subject, in that engineers seldom agree on the proper method for grounding and shielding a system. The techniques and configurations described below are those that proved most reliable at Dryden during these studies.

One major advantage of the design of the RMDU is the number of independent "grounds," or returns, provided. There are separate returns for 5-volt power, analog signals, digital communication signals, 28-volt power, and 400-hertz power. These returns are connected at one point in the power supply module, eliminating digital current flow in, for example, the analog ground leads. This feature also allows for more flexible shielding schemes. When cables more than a few meters (yards) long are used, especially at gains of 1000 and 400, it has proven more effective to connect the shield of the cable at the source instead of at the RMDU. This minimizes common mode voltages, which can be on the order of several volts for cable lengths of approximately 15 meters (50 feet). Since a shield is only effective if it is maintained at a fixed potential with respect to the circuit being protected, this method of shielding is preferred over grounding the shield at the RMDU. Keeping the shield at a potential other than chassis ground is desirable in cases where the sensor output floats above ground.

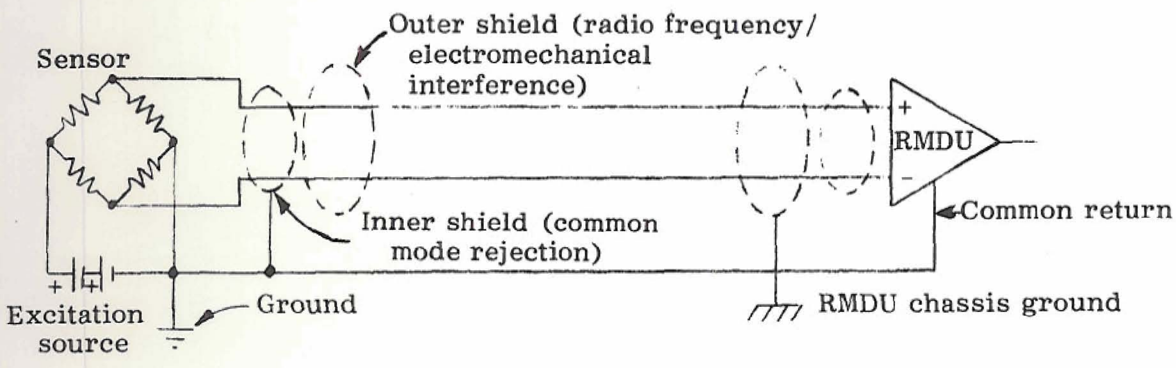



Improper shielding




Proper shielding

Another method of shielding, which is now being investigated in flight tests, is the use of double shielding. Double shielding is intended to reduce radio frequency and electromechanical interference in the low level signal lines (see sketch). It is hoped that data from sensors shielded in this manner will be uncontaminated by these types of interference as well as by common mode voltages.



## Excessive Acquisition Rate

Excessive acquisition rate is not usually a problem in RMDU applications; however, in combination with an improper data cycle map it can sometimes make a difference of a few counts in the output.

Excessive acquisition rate is caused by the fact that the sampling and amplification period is determined by the timing crystal in the stand-alone timing module. In cases where drastic changes in gain occur in adjacent word samples or high impedance sensors are used, the sample period may not be long enough for the 200-picofarad amplifier capacitance to charge up fully. This usually results in a slight depression in the output data.

The crystal in the Dryden RMDU was changed from 10.000 megahertz to 6.666 megahertz to increase the acquisition period. It has yet to be determined whether this change affects the output data obtained from high impedance sources.

## Improper Data Cycle Map

The information that directs the RMDU channel sampling sequence, gain, and sampling rate is stored in semiconductor memory integrated circuits in what is called a data cycle map.

The user has a great deal of flexibility in designing this map. He should, however, be sure to program a sufficient number of calibration words, avoid topographical errors, and stay within basic map limits and constraints.

The user may forget to program enough calibration words into the data cycle map to obtain corrected data. The necessary calibration words are as follows:

- Power supply bite (PSB), which is a go/no-go signal indicating whether the sum of all the secondary voltages in the power supply are within the 10 percent tolerance

- HLC, which indicates the accuracy of the analog to digital converter

- GPA-∅, which indicates the zero offset of the amplifier and analog to digital converter

- LLC (one LLC word should be programed for each gain used)

- $LLC_{zero}$ (one $LLC_{zero}$ word should be programed for each gain used)

This number of calibration channels may appear excessive (11 calibration words are used in the Dryden map at this time); however, it is most discouraging to realize after data have been obtained that there are not enough calibration points for correction.

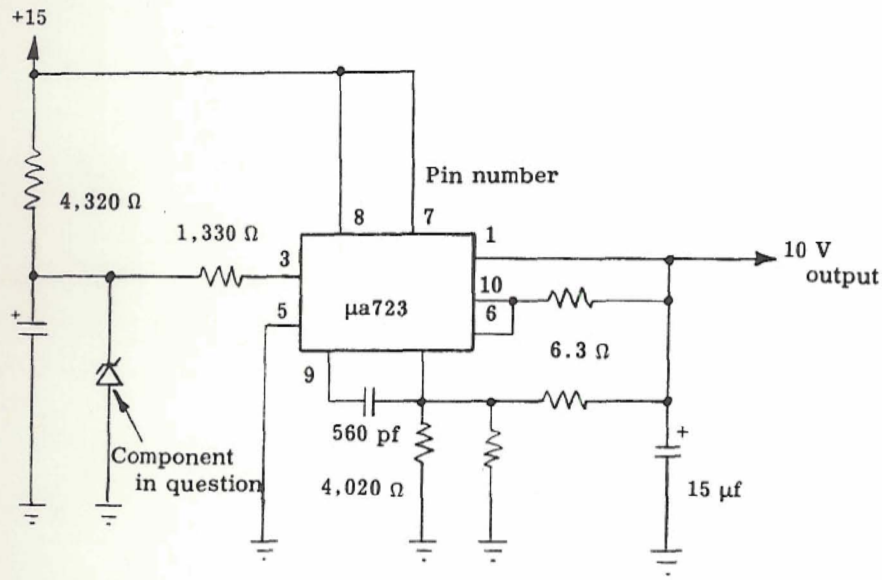
Topographical errors are not so obvious and hence can easily be overlooked. Basic topographical procedures insure that all words, especially the calibration words, are preceded by a word that never saturates. Saturation causes a slight amount of crosstalk and gives slightly erroneous data for the calibration channels.

Map limits and constraints concern primarily the overall size limitations of the semiconductor memory circuits. It is up to the user to configure this map (to set the number of mainframe words and subframe words, for example) to achieve the aforementioned goals. Any number of mainframe channels can be specified up to and including 128, including the synchronization and subframe counter words. Similarly, any number of subframe words can be specified, as long as the product of the number of subframe columns and the depth of the deepest subframe column does not exceed 256.

## Poor Regulation of 10-Volt Reference Supply

Much of the accuracy of the data obtained from the RMDU is directly related to the accuracy and stability of the 10-volt reference supply. The LLC signals and the HLC signal reflect any change in this supply, and the conversion gain of the analog to digital converter is related to this supply.

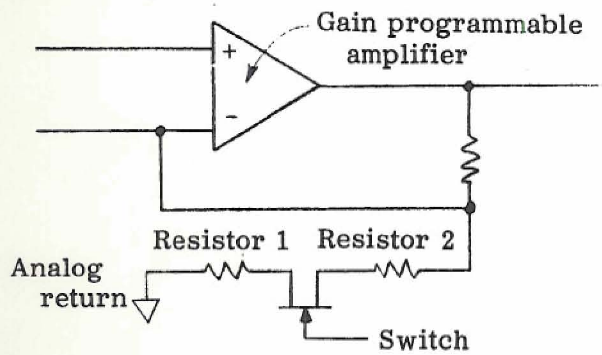
The Dryden RMDU had a temperature-sensitive component in both power supplies (see circuit diagram). This caused a deviation from 9.813 volts to 10.167 volts over the temperature range in this reference supply. Because of either the fatigue of this component due to the environmental testing of the RMDU or the manufacture of the power supply module, the temperature coefficient of this component (a 1N4573A zener diode) deteriorated. If a change of more than 1 count occurs in the HLC signal, or if the LLC signals change over the temperature range, this diode should be checked.




Power supply module

Improper Temperature Coefficients

The gain programmable amplifier utilizes switched precision resistors in the feedback loop to achieve the desired gain. If this gain is to be nontemperature dependent, the feedback loop must be nontemperature dependent. As can be seen in the following diagram,




the combination of the resistance of the field-effect switch and the sum of resistor 1 and resistor 2 must remain constant over the temperature range. Therefore, the negative temperature coefficients of resistor 1 and resistor 2 must cancel out the positive temperature coefficient of the switch.

In the unit delivered to Dryden, positive temperature coefficient resistors were introduced into the feedback network by mistake, so the sensitivity of the gain to temperature variations was compounded. (The problem has since been rectified by the manufacturer.) Appendix B describes the effect of this assembly error in detail. Despite this error, however, the RMDU had sufficient capability and enough information was available from the RMDU to achieve corrected data.

Nonconstant Sensor Impedance

Nonconstant sensor impedance, which is difficult to ascertain, is caused primarily by the leakage current from the metal oxide semiconductor field effect transistor (MOSFET) multiplexers flowing back through the sensor impedance. The maximum leakage current from a single MOSFET gate is approximately 1 nanoampere (maximum) at room temperature; however, since the RMDU is a multiplexed system, a worst case analysis shows that as many as 11 gates may leak current through the source impedance at any one time. This gives a worst case value of 11 nanoamperes (maximum) leakage current at room temperature. However, the leakage current doubles for every increase of 10° C (18° F), giving a worst case leakage of about 0.33 microampere at 70° C (158° F).

For a gain of 1000, the voltage offset produced by this leakage current at 70° C (158° F) for a source impedance varying from 1000 ohms to 2000 ohms is about 0.33 millivolt. This problem of leakage current, which occurs when gains are high, is not new to instrumentation amplifiers.

## Word Rate Effects

In the stand-alone configuration, the use of the maximum word rate (62,500 words per second for the Dryden RMDU) causes a slight offset in the raw data (8 or 9 counts for a gain of 1000). This offset appears to be caused by the fact that the stand-alone timing module radiates noise into the gain programmable amplifier. The manufacturer is addressing this problem at the present time; better shielding between the stand-alone timing module and the analog data processor module may be in order.

# CONCLUDING REMARKS

Because the remote multiplexer/digitizer unit (RMDU) is an advanced data acquisition system, certain guidelines must be followed to insure the acquisition of good data. Ground loops must be eliminated and shielding techniques should be used that minimize common mode noise as well as radio frequency and electromechanical interference.

The elimination of ground loops is a bit easier with the RMDU because of its independent ground and return signal lines; however, common mode noise must be minimized through the proper shielding of sensor cables.

As expected, the sensitivity of the RMDU results in undesirable temperature effects. However, even with temperature variations, the data can be corrected within about 0.5 percent of full scale at high gains and even better than that at low gains. By comparison, a worst case error of 5 counts at a gain of 1000 represents an error of 25 microvolts, which is less than the resolution of a single count of the existing pulse code modulation (PCM) systems in use at the NASA Dryden Flight Research Center. The existing PCM systems are also susceptible to the same noise and errors as the RMDU.

The errors obtained in the Dryden RMDU study are believed to be greater than those obtained with other RMDU's. This is probably because the Dryden RMDU has been subject to repeated repairs and modifications and because the RMDU has been subject to extensive environmental testing. Furthermore, even though external noise was minimized as much as possible (and to the limitations of the monitoring equipment), a certain amount of noise undoubtedly entered the system. In light of these factors, the accuracy of the raw data at gains of 100 and less, and that of the corrected data at higher gains, is certainly acceptable.

*Dryden Flight Research Center*
*National Aeronautics and Space Administration*
*Edwards, Calif., November 9, 1976*

## APPENDIX A

## NASA SPECIFICATION 21-2

Equipment to be mounted in or on Category II aircraft (lifting body vehicles and all jet aircraft), must meet the following standards.

### Altitude

Components are to withstand pressure altitudes from ground level to 22,860 meters (75,000 feet) if unit is to be installed in a pressurized compartment; from ground level to 30,480 meters (100,000 feet) otherwise.

### Temperature

Temperature tests for units not mounted in temperature controlled environments should be no less severe than a cold soak at -54° C (-65° F) and a hot soak at 71° C (160° F).

### Vibration

The most severe vibration requirements at Dryden are set for components to be installed in jet aircraft. These tests follow the following format:

- Sinusoidal excitation of ±1g for vibration frequencies from 14 hertz to 23 hertz

- Excitation of ±0.09144 centimeter (±0.036 inch) at frequencies from 23 hertz to 74 hertz

- Sinusoidal excitation of ±10g at frequencies from 74 hertz to 2000 hertz

All three orthogonal axes are to be tested at these levels.

# APPENDIX B

## EARLY ACCURACY/TEMPERATURE DATA

As mentioned in the text, early accuracy studies were hampered for a variety of reasons. One of the most difficult problems to overcome was gain deviation with temperature. The major causes of this problem are discussed in the text; however, gain instability with changes in temperature and improper gain can be a problem in other forms of instrumentation amplifiers besides RMDU's, and, hence, this appendix is devoted to this problem. From figure 9 and table 4, which show data obtained at a gain of 1000 and at temperatures from -54° C (-65° F) to 71° C (160° F), it is obvious that zero offset decreases as temperature increases and that gain decreases as temperature increases. The graph in figure 9 represents the transfer function for this gain for positive values of input only. The RMDU is also capable of amplifying negative voltages and of representing these voltages as negative counts (-1024 counts full scale); however, for the sake of simplicity, only positive voltages are considered herein. The large discontinuity in the curves at approximately 4.5 millivolts represents the autoranging function of the amplifier. For the output data corresponding to input voltages greater than 4.5 millivolts, the gain tag bit (MSB) is set to a logical "1".

Table 4 shows the anomalies in much greater detail. Each part of the table shows a test at a specific temperature. The method used for correcting the data for zero offsets and gain variations is explained in the text.

From the graph of the transfer function (fig. 9, which was obtained from the data presented in table 4), errors in the raw data output at the two temperature extremes were in the neighborhood of sixty-seven counts (±33.5 counts). Correcting the data for zero offset still left a total peak to peak error of 46 counts (±23 counts) out of a full scale of 1023 counts.

Figures 10 and 11 indicate error as a function of excitation voltage for three cases: raw data, raw data corrected for zero offset only, and raw data corrected for zero offset and gain variation. These figures and figure 9 show that the gain of the amplifier deviated from the expected value of 5 microvolts per count (200 counts per millivolt) to a higher gain at low temperatures and to a lower gain at high temperatures. A least-squares curve fit of the raw data clearly illustrates this effect.

If one has a collection of (x, y) values and assumes that the expected error is within the y values, the best straight line through this collection of points (via the least squares method) is given as follows:

$$y = mx + c$$

$$m = \frac{n\Sigma x_i y_i - \Sigma x_i \Sigma y_i}{n\Sigma x_i^2 - (\Sigma x_i)^2}$$

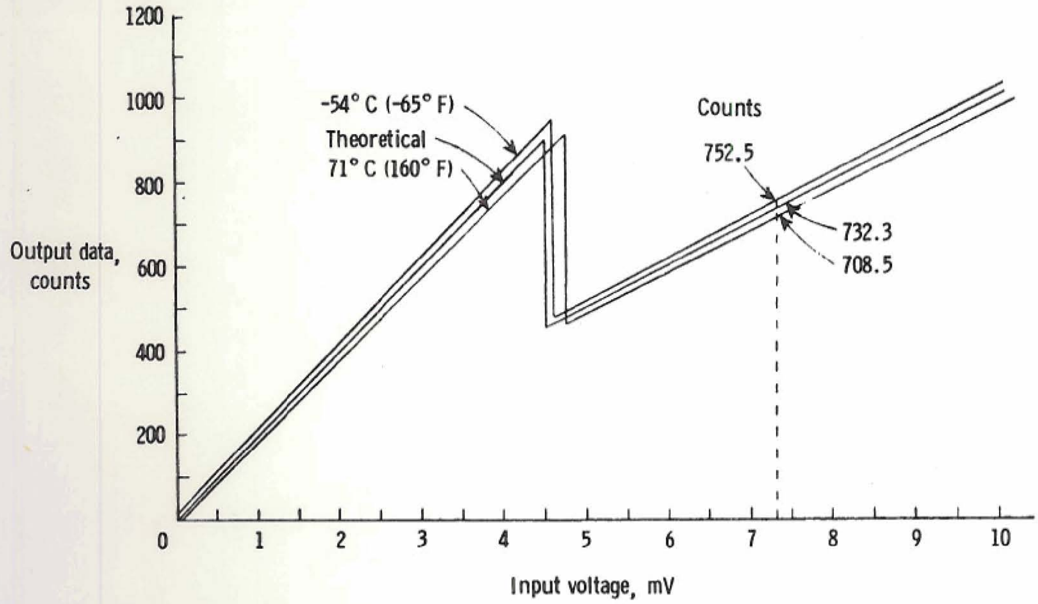



*Figure 9. Uncorrected raw data versus input voltage for temperatures of -54° C (-65° F), 71° C (160° F), and theoretical ambient temperature. Gain = 1000.*

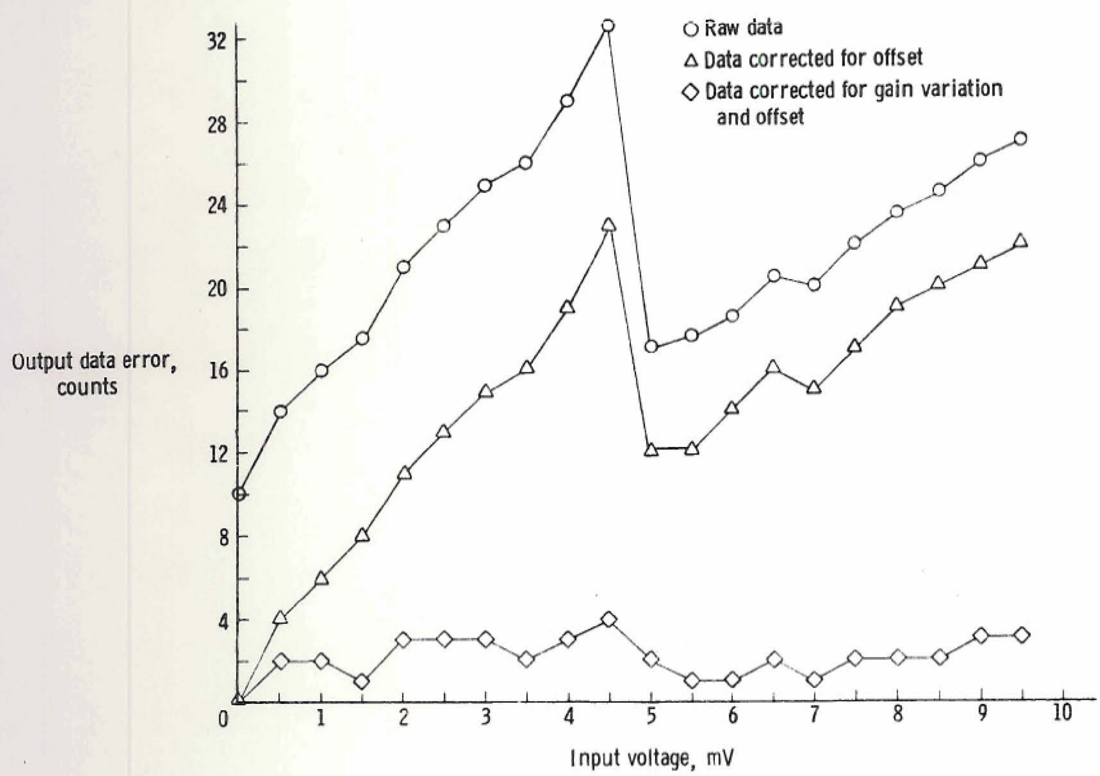



*Figure 10. Output data error for a temperature of -54° C (-65° F). Gain = 1000.*

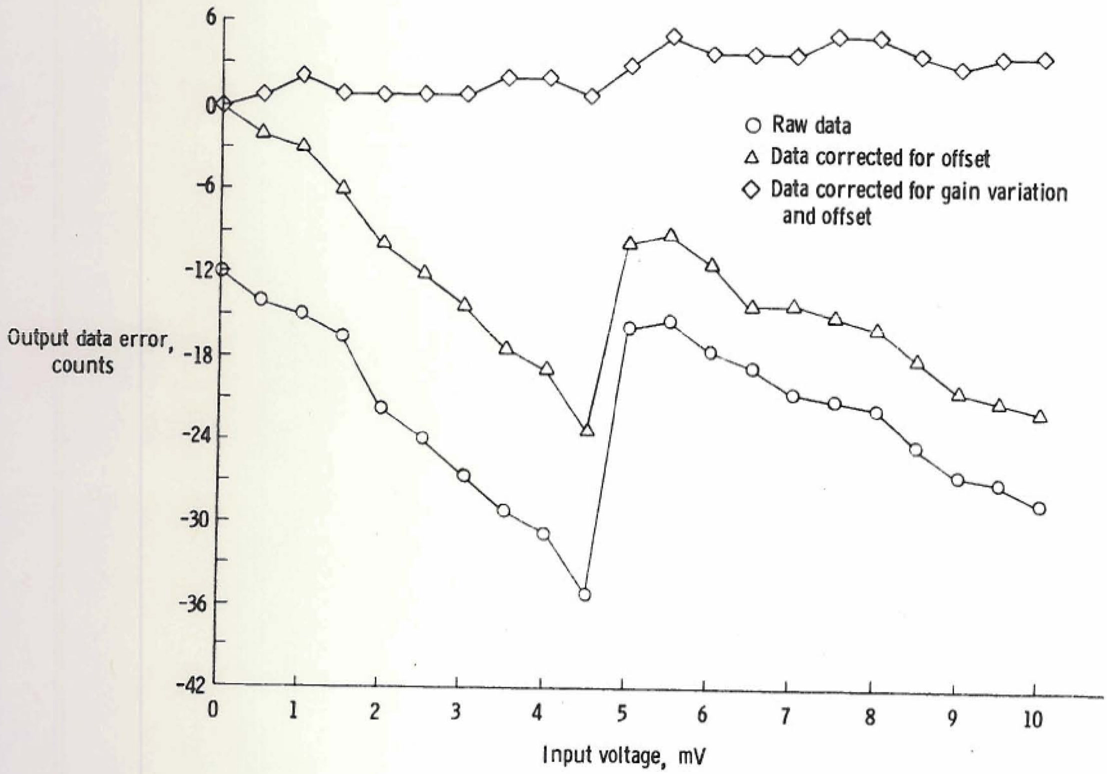



*Figure 11. Output data error for a temperature of 71° C (160° F). Gain = 1000.*

$$c = \frac{\Sigma x_i^2 \Sigma y_i - \Sigma x_i \Sigma x_i y_i}{n\Sigma x_i^2 - (\Sigma x_i)^2}$$

where m is the slope of the least-squares straight line, c is the y intercept, and n is the total number of (x, y) values in the collection. These formulas were applied to the raw data, with the results shown in figures 12 and 13. A polynomial fit computer program was also used on the data to determine the presence of higher order coefficients, with the result that second order and higher order coefficients were found to be less by three orders of magnitude than first order coefficients. This supports the hypothesis that the gain function remains linear over the temperature range.

Figure 12 shows a plot of the gain values obtained from the least-squares method as a function of temperature. It can be seen from this plot that there was a strong linear relationship between gain and temperature. The best fit equation for this plot is as follows:

$$\text{Gain} = -0.043462T + 201.84$$

where Gain is indicated in counts per millivolt and T is temperature in degrees Fahrenheit, or

$$\text{Gain} = 0.078232T + 200.45$$

for T in degrees Celsius. According to these equations, an actual gain of 200 counts per millivolt (5 microvolts per count) occurred at a temperature of 6° C (43° F). At a temperature of -54° C (-65° F) there was a 2.3 percent change in the gain, while at 71° C (160° F) there was a -2.6 percent change in gain.

Fortunately, this gain variation with temperature is linear and can therefore easily be corrected for. The techniques for performing this correction are discussed in the text. The characteristics of the zero offset were similar to those of the gain; however, the functional dependence on temperature was not quite as linear (fig. 13). Performing a best straight line fit to the zero offset points (using $LLC_{zero}$, a spare channel shorted at the RMDU plug) yielded the following equation:

$$\text{Offset} = -0.078463T + 3.68$$

where Offset is indicated in counts and T is temperature in degrees Fahrenheit, or

$$\text{Offset} = -0.14123T + 1.17$$

for T in degrees Celsius. This indicates an offset of approximately 0.22 microvolt per degree Celsius (0.39 microvolt per degree Fahrenheit) referred to the input of the RMDU, which represents a peak to peak error of approximately 18 counts over the temperature range.

The data obtained from the accuracy tests for a gain of 400 were similar to those obtained for a gain of 1000 except that the deviations from the expected values

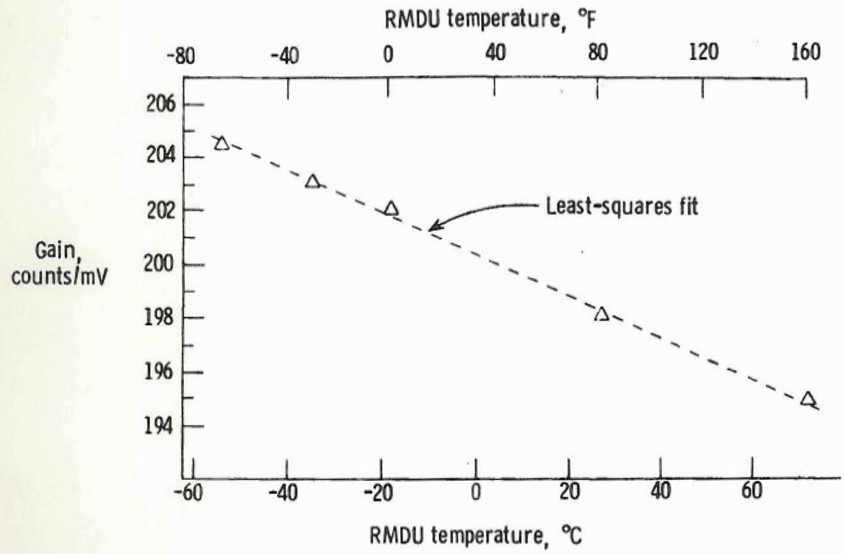



*Figure 12. Gain as a function of RMDU temperature. Gain = 1000; no autoranging.*

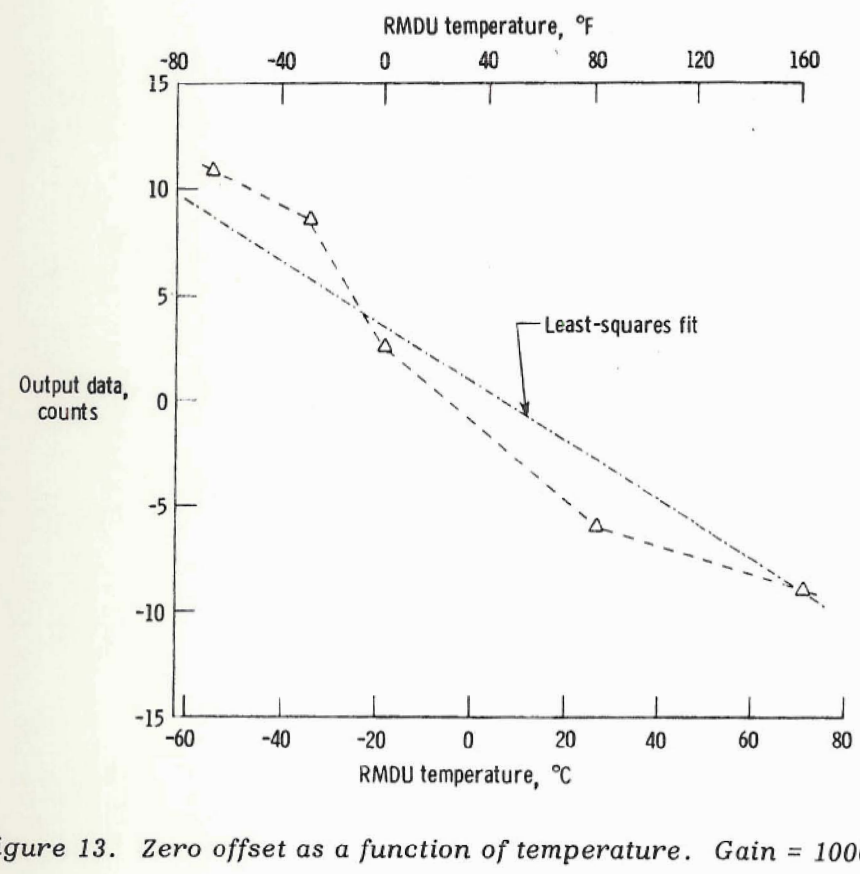



*Figure 13. Zero offset as a function of temperature. Gain = 1000.*

were smaller. From figure 14, which is a graph of output data versus input voltage, and figures 15 and 16, and the tabulated results (table 5) it can be assumed that errors in the neighborhood of 30 counts (approximately ±15 counts) can be obtained from the raw data.

Correcting the data for zero offset still yielded about 26 counts of error over the temperature range.

Performing an analysis similar to that performed on the data for a gain of 1000 revealed similar temperature effects (fig. 17). For instance, a gain of 400 represents a resolution of 12.5 microvolts per count (80 counts per millivolt); however, this sensitivity ranges from 81.25 counts per millivolt at -54° C (-65° F) to 78.95 counts per millivolt at 71° C (160° F). The fundamental relationship between gain and temperature from this plot is as follows:

$$\text{Gain} = -0.01023T + 80.62$$

where Gain is indicated in counts per millivolt and T is temperature in degrees Fahrenheit, or

$$\text{Gain} = -0.01841T + 80.29$$

for T in degrees Celsius. This indicates a total deviation of slightly less than 3 percent over the temperature range from -54° C (-65° F) to 71° C (160° F).

Zero offset variations were not as well behaved for a gain of 400 as for a gain of 1000. Performing a best straight line fit to the zero offset yielded a solution of

$$\text{Offset} = -0.03308T + 2.66$$

where Offset is in counts per millivolt and T is temperature in degrees Fahrenheit, or

$$\text{Offset} = -0.05944T + 1.60$$

where T is temperature in degrees Celsius. However, a reasonable fit could be achieved with a straight line (fig. 18). From this fit it can be concluded that zero offsets on the order of 8 counts could be expected for a gain of 400 over the temperature span from -54° C (-65° F) to 71° C (160° F).

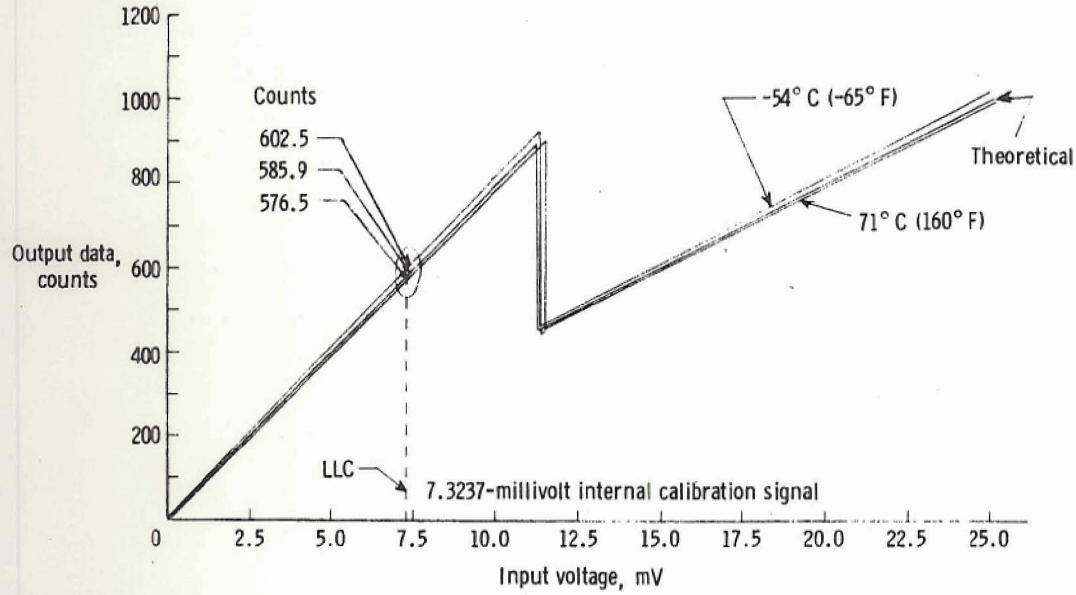



*Figure 14. Uncorrected raw data versus input voltage for temperatures of -54° C (165° F), 71° C (160° F), and theoretical ambient temperature. Gain = 400.*

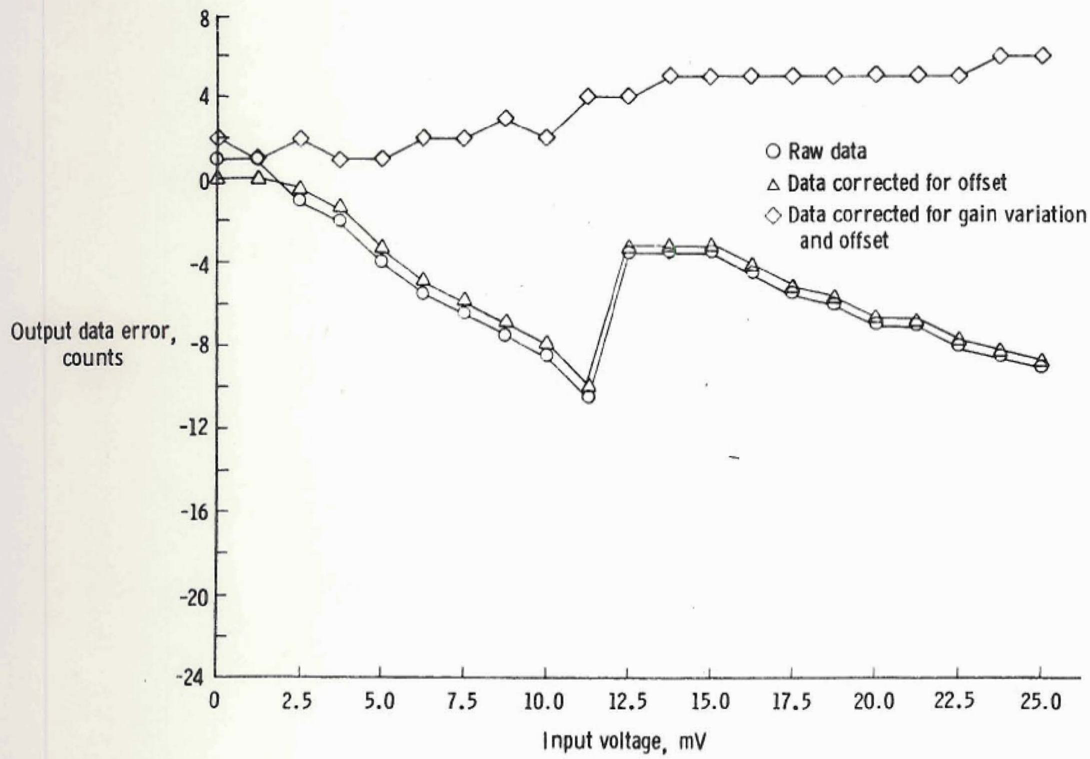



*Figure 15. Output data error for temperature of 71° C (160° F). Gain = 400.*

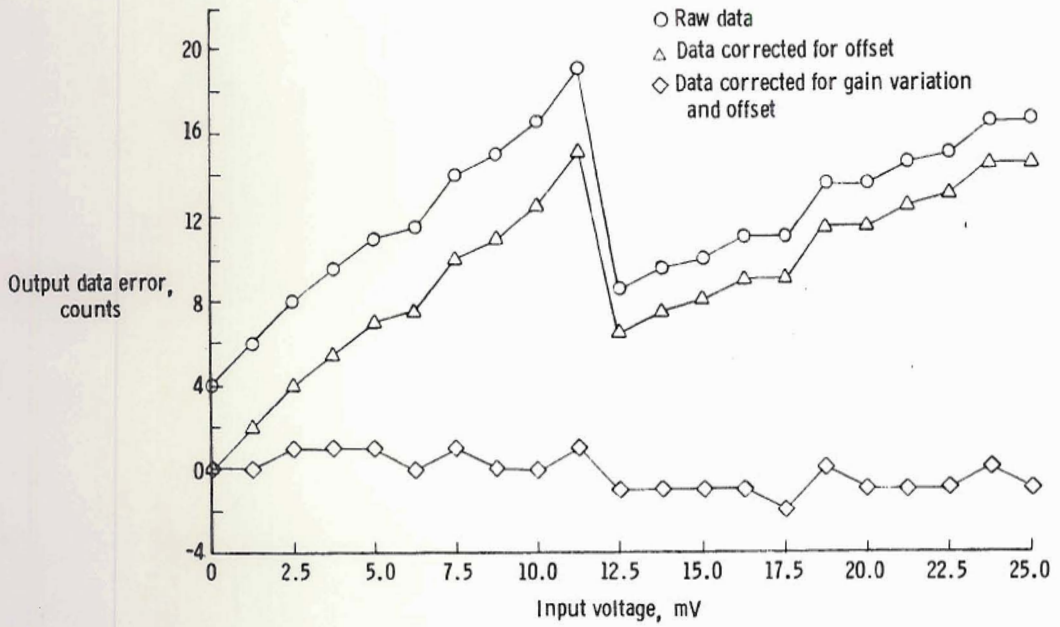



*Figure 16. Output data error for temperature of -54° C (-65° F). Gain = 400.*

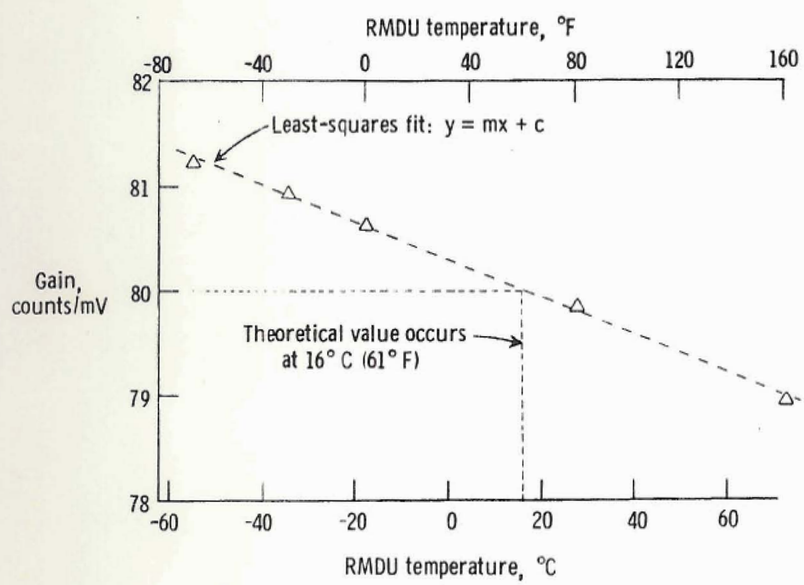



*Figure 17. Gain as a function of temperature. Gain = 400; no autoranging.*

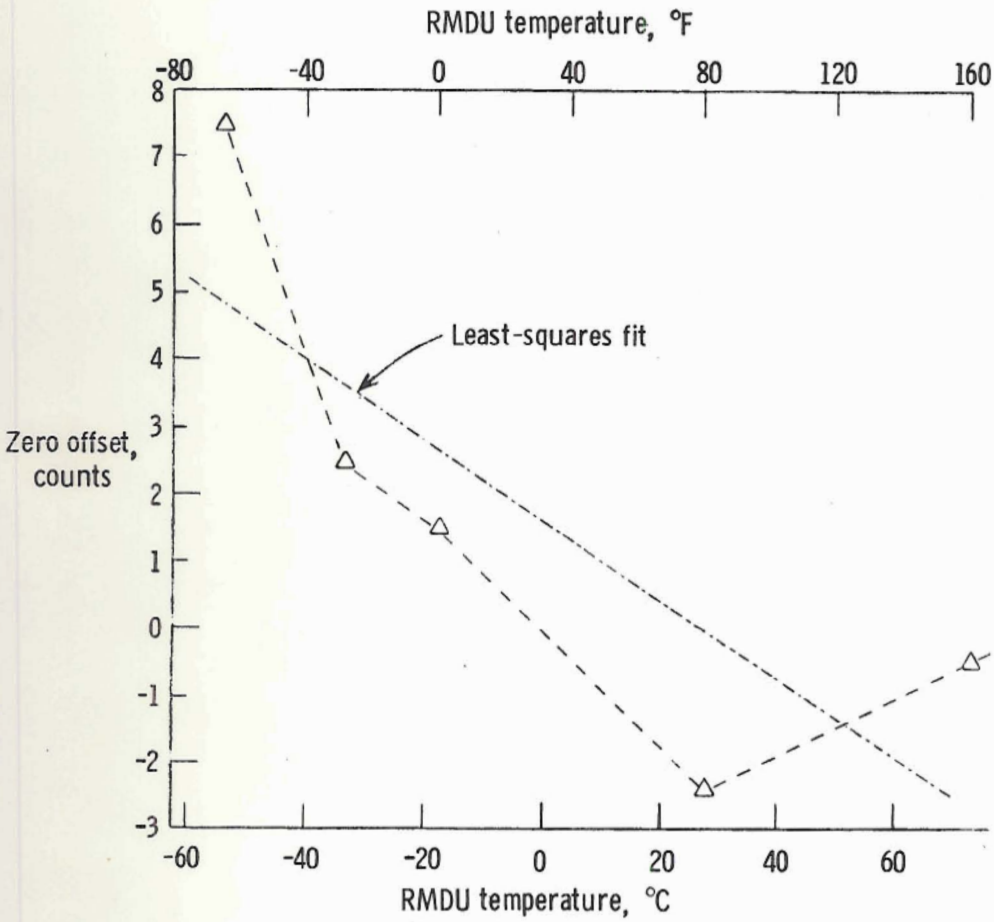



*Figure 18. Zero offset as a function of temperature. Gain = 400.*

## REFERENCES

1. Bartoli, Febo: An Advanced Airborne Data Acquisition System. NASA paper presented at AGARD Flight Mechanics Panel Symposium on Flight Test Techniques, Porz Wahn, Germany, Oct. 1976.

2. Borek, Robert W.: Development of AIFTDS-4000, a Flight-Qualified, Flexible, High-Speed Data Acquisition System. NASA TM X-56018, 1973.

3. Trover, William F.: A High Speed Airborne Data Acquisition and Control System With an Integrated Digital Computer. ITC Proceedings, Volume IX, c.1973, pp. 88-105.

4. Sanderson, K. C.: A New Flight Test Data System for NASA Aeronautical Flight Research. Proceedings of the 8th International Aerospace Instrumentation Symposium, 1975.

TABLE 1.—RMDU ACCURACY DATA FOR A GAIN OF 1000
[5 microvolts per count]

(a) Temperature = 71° C (160° F), $LLC_{1000}$ = 730 to 731*, $LLC_{zero}$ = 8 to 9, HLC = 750

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Averaged raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|---|
| 0 | 0 | 3 to 6 | 4.5 | 5 | 0 | 0 |
| 0.50 | 100 | 101 to 104 | 102.5 | 3 | 98.0 | -2 |
| 1.00 | 200 | 202 to 203 | 202.5 | 3 | 198.0 | -2 |
| 1.50 | 300 | 305 to 306 | 305.5 | 6 | 301.0 | 1 |
| 2.00 | 400 | 401 to 403 | 402.0 | 2 | 397.5 | -2 |
| 2.50 | 500 | 504 to 506 | 505.0 | 5 | 500.5 | 1 |
| 3.00 | 600 | 602 to 605 | 603.5 | 4 | 599.0 | -1 |
| 3.50 | 700 | 700 to 702 | 701.0 | 1 | 696.5 | -3 |
| 4.00 | 800 | 803 to 804 | 803.5 | 4 | 799.0 | -1 |
| 4.50 | 900 | 898 to 901 | 899.5 | 0 | 895.0 | -5 |
| 5.00 | 500* | 502 to 503* | 502.5* | 3 | 500.25* | 0 |
| 5.50 | 550* | 552 to 554* | 553.0* | 3 | 550.75* | 1 |
| 6.00 | 600* | 604 to 605* | 604.5* | 5 | 602.25* | 2 |
| 6.50 | 650* | 651 to 653* | 652.0* | 2 | 649.75* | 0 |
| 7.00 | 700* | 702 to 703* | 702.5* | 3 | 700.25* | 0 |
| 7.50 | 750* | 754 to 755* | 754.5* | 5 | 752.25* | 2 |
| 8.00 | 800* | 802 to 803* | 802.5* | 3 | 800.25* | 0 |
| 8.50 | 850* | 851 to 852* | 851.5* | 2 | 849.25* | -1 |
| 9.00 | 900* | 903 to 904* | 903.5* | 4 | 901.25* | 1 |
| 9.50 | 950* | 953* | 953.0* | 3 | 950.75* | 1 |
| 10.00 | 1000* | 1003* | 1003.0* | 3 | 1000.75* | 1 |

*Autoranging occurred.

TABLE 1.—Continued

(b) Temperature = 27° C (80° F), $LLC_{1000}$ = 730 to 731*, $LLC_{zero}$ = 9 to 11, HLC = 751

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Averaged raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|---|
| 0 | 0 | 7 to 9 | 8 | 8 | 0 | 0 |
| 0.50 | 100 | 104 to 106 | 105.0 | 5 | 97.0 | -3 |
| 1.00 | 200 | 204 to 206 | 205.0 | 5 | 197.0 | -3 |
| 1.50 | 300 | 304 to 305 | 304.5 | 5 | 296.5 | -3 |
| 2.00 | 400 | 406 to 408 | 407.0 | 7 | 399.0 | -1 |
| 2.50 | 500 | 503 to 504 | 503.5 | 4 | 445.5 | -4 |
| 3.00 | 600 | 606 to 607 | 606.5 | 7 | 598.5 | -1 |
| 3.50 | 700 | 703 to 705 | 704.0 | 4 | 696.0 | -4 |
| 4.00 | 800 | 806 to 808 | 807.0 | 7 | 799.0 | -1 |
| 4.50 | 900 | 906 to 908 | 907.0 | 7 | 899.0 | -1 |
| 5.00 | 500* | 503 to 504* | 503.5* | 4 | 499.5* | 0 |
| 5.50 | 550* | 553 to 555* | 554.0* | 4 | 550.0* | 0 |
| 6.00 | 600* | 603 to 604* | 603.5* | 4 | 599.5* | 0 |
| 6.50 | 650* | 655 to 656* | 655.5* | 6 | 651.5* | 2 |
| 7.00 | 700* | 703 to 704* | 703.5* | 4 | 699.5* | 0 |
| 7.50 | 750* | 755 to 756* | 755.5* | 6 | 751.5* | 2 |
| 8.00 | 800* | 803 to 804* | 803.5* | 4 | 799.5* | 0 |
| 8.50 | 850* | 855 to 856* | 855.5* | 6 | 851.5* | 2 |
| 9.00 | 900* | 904 to 906* | 905.0* | 5 | 901.0* | 1 |
| 9.50 | 950* | 954 to 956* | 955.0* | 5 | 951.0* | 1 |
| 10.00 | 1000* | 1004 to 1005* | 1004.5* | 5 | 1000.5* | 1 |

TABLE 1.—Concluded

(c) Temperature = -54° C (-65° F), $LLC_{1000}$ = 739* to 740*, $LLC_{zero}$ = 18 to 20, HLC = 752

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Averaged raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|---|
| 0 | 0 | 2 to 4 | 3 | 3 | 0 | 0 |
| 0.50 | 100 | 101 to 102 | 101.5 | 2 | 98.5 | -1 |
| 1.00 | 200 | 203 to 208 | 205.5 | 6 | 202.5 | 3 |
| 1.50 | 300 | 303 to 305 | 304.0 | 4 | 301.0 | 1 |
| 2.00 | 400 | 402 to 408 | 405.0 | 5 | 402.0 | 2 |
| 2.50 | 500 | 505 to 508 | 506.5 | 1 | 503.5 | 4 |
| 3.00 | 600 | 604 to 606 | 605.0 | 5 | 602.0 | 2 |
| 3.50 | 700 | 705 to 707 | 706.0 | 6 | 703.0 | 3 |
| 4.00 | 800 | 805 to 807 | 806.0 | 6 | 803.0 | 3 |
| 4.50 | 900 | 904 to 907 | 905.5 | 6 | 902.5 | 3 |
| 5.00 | 500* | 503 to 505* | 504.0* | 4 | 502.5* | 3 |
| 5.50 | 550* | 553 to 556* | 554.5* | 5 | 553.0* | 3 |
| 6.00 | 600* | 604 to 606* | 605.0* | 5 | 603.5* | 4 |
| 6.50 | 650* | 652 to 655* | 653.5* | 4 | 652.0* | 2 |
| 7.00 | 700* | 704 to 708* | 706.0* | 6 | 704.5* | 5 |
| 7.50 | 750* | 753 to 756* | 754.5* | 5 | 753.0* | 3 |
| 8.00 | 800* | 805 to 808* | 806.5* | 7 | 805.0* | 5 |
| 8.50 | 850* | 854 to 856* | 855.0* | 5 | 853.5* | 4 |
| 9.00 | 900* | 906 to 908* | 907.0* | 7 | 905.5* | 6 |
| 9.50 | 950* | 955 to 956* | 955.5* | 6 | 954.0* | 4 |
| 10.00 | 1000* | 1006 to 1007* | 1006.5* | 7 | 1005.0* | 5 |

TABLE 2.—RMDU ACCURACY DATA FOR A GAIN OF 400
[12.5 microvolts per count]

(a) Temperature = 71° C (160° F), $LLC_{400}$ = 590, $LLC_{zero}$ = 10, HLC = 750

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Averaged raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|---|
| 0 | 0 | 10 to 11 | 10.5 | 11 | 0 | 0 |
| 1.25 | 100 | 110 to 111 | 110.5 | 11 | 100.00 | 0 |
| 2.50 | 200 | 209 to 210 | 209.5 | 10 | 199.00 | -1 |
| 3.75 | 300 | 309 | 309.0 | 9 | 298.50 | -1 |
| 5.00 | 400 | 410 | 410.0 | 10 | 399.50 | 0 |
| 6.25 | 500 | 510 | 510.0 | 10 | 499.50 | 0 |
| 7.50 | 600 | 610 | 610.0 | 10 | 599.50 | 0 |
| 8.75 | 700 | 708 | 708.0 | 8 | 697.50 | -2 |
| 10.00 | 800 | 807 to 808 | 807.5 | 8 | 797.00 | -3 |
| 11.25 | 900 | 907 to 908 | 907.5 | 8 | 397.00 | -3 |
| 12.50 | 500* | 507 to 508* | 507.5* | 8 | 502.25* | 2 |
| 13.75 | 550* | 558* | 558.0* | 8 | 552.75* | 3 |
| 15.00 | 600* | 607* | 607.0* | 7 | 601.75* | 2 |
| 16.25 | 650* | 657* | 657.0* | 7 | 651.75* | 2 |
| 17.50 | 700* | 707* | 707.0* | 7 | 701.75* | 2 |
| 18.75 | 750* | 756* | 756.0* | 6 | 750.75* | 1 |
| 20.00 | 800* | 807* | 807.0* | 7 | 801.75* | 2 |
| 21.25 | 850* | 857* | 857.0* | 7 | 851.75* | 2 |
| 22.50 | 900* | 905 to 906* | 905.5* | 6 | 900.25* | 0 |
| 23.75 | 950* | 956 to 957* | 956.5* | 7 | 950.25* | 0 |
| 25.00 | 1000* | 1006 to 1007* | 1006.5* | 7 | 1000.25* | 0 |

*Autoranging occurred.

TABLE 2.—Continued

(b) Temperature = 27° C (80° F), $LLC_{400}$ = 592, $LLC_{zero}$ = 7 to 8, HLC = 751

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Averaged raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|---|
| 0 | 0 | 8 | 8.0 | 8 | 0 | 0 |
| 1.25 | 100 | 109 | 109.0 | 9 | 101.0 | 1 |
| 2.50 | 200 | 209 to 210 | 209.5 | 10 | 201.5 | 2 |
| 3.75 | 300 | 309 | 309.0 | 9 | 301.0 | 1 |
| 5.00 | 400 | 404 | 409.0 | 9 | 401.0 | 1 |
| 6.25 | 500 | 509 to 510 | 509.5 | 10 | 501.5 | 2 |
| 7.50 | 600 | 610 to 611 | 610.5 | 11 | 602.5 | 3 |
| 8.75 | 700 | 710 to 711 | 710.5 | 11 | 702.5 | 3 |
| 10.00 | 800 | 811 | 811.0 | 11 | 803.0 | 3 |
| 11.25 | 900 | 911 to 912 | 911.5 | 12 | 903.5 | 4 |
| 12.50 | 500* | 508* | 508.0* | 8 | 504.0* | 4 |
| 13.75 | 550* | 558 to 559* | 558.5* | 9 | 554.5* | 5 |
| 15.00 | 600* | 608* | 608.0* | 8 | 604.0* | 4 |
| 16.25 | 650* | 658* | 658.0* | 8 | 654.0* | 4 |
| 17.50 | 700* | 708* | 708.0* | 8 | 704.0* | 4 |
| 18.75 | 750* | 759* | 759.0* | 9 | 755.0* | 5 |
| 20.00 | 800* | 808* | 808.0* | 8 | 804.0* | 4 |
| 21.25 | 850* | 859* | 859.0* | 9 | 855.0* | 5 |
| 22.50 | 900* | 908* | 908.0* | 8 | 904.0* | 4 |
| 23.75 | 950* | 959* | 959.0* | 9 | 955.0* | 5 |
| 25.00 | 1000* | 1004* | 1009.0* | 9 | 1005.0* | 5 |

TABLE 2.—Concluded

(c) Temperature = -54° C (-65° F), $LLC_{400}$ = 603, $LLC_{zero}$ = 13 to 14, HLC = 752

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Averaged raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|---|
| 0 | 0 | 10 | 10 | 10 | 0 | 0 |
| 1.25 | 100 | 110 to 111 | 110.5 | 11 | 100.5 | 1 |
| 2.50 | 200 | 211 to 212 | 211.5 | 12 | 201.5 | 2 |
| 3.75 | 300 | 312 to 314 | 313.0 | 13 | 303.0 | 3 |
| 5.00 | 400 | 413 to 414 | 413.5 | 14 | 403.5 | 4 |
| 6.25 | 500 | 514 to 516 | 515.0 | 15 | 505.0 | 5 |
| 7.50 | 600 | 614 to 616 | 615.0 | 15 | 605.0 | 5 |
| 8.75 | 700 | 716 to 717 | 716.5 | 17 | 706.5 | 7 |
| 10.00 | 800 | 817 to 818 | 817.5 | 18 | 807.5 | 8 |
| 11.75 | 900 | 918 to 920 | 919.0 | 19 | 909.0 | 9 |
| 12.50 | 500* | 509 to 510* | 509.5* | 10 | 504.5* | 5 |
| 13.75 | 550* | 560* | 560.0* | 10 | 555.0* | 5 |
| 15.00 | 600* | 610 to 611* | 610.5* | 11 | 605.5* | 6 |
| 16.25 | 650* | 661 to 662* | 661.5* | 12 | 656.5* | 7 |
| 17.50 | 700* | 711* | 711.0* | 11 | 706.0* | 6 |
| 18.75 | 750* | 761 to 763* | 762.0* | 12 | 757.0* | 7 |
| 20.00 | 800* | 812* | 812.0* | 12 | 807.0* | 7 |
| 21.25 | 850* | 863* | 863.0* | 13 | 858.0* | 8 |
| 22.50 | 900* | 912 to 913* | 912.5* | 13 | 907.5* | 8 |
| 23.75 | 950* | 964* | 964.0* | 14 | 959.0* | 9 |
| 25.00 | 1000* | 1014* | 1014.0* | 14 | 1009.0* | 9 |

TABLE 3.—RMDU ACCURACY DATA FOR A GAIN OF 100
[50 microvolts per count]

(a) Temperature = 71° C (160° F), $LLC_{100}$ = 150 to 151, $LLC_{zero}$ = 4 to 5, HLC = 750

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|
| 0 | 0 | 4 to 6 | 5 | 0 | 0 |
| 5.00 | 100 | 104 to 106 | 5 | 100 | 0 |
| 10.00 | 200 | 204 to 206 | 5 | 200 | 0 |
| 15.00 | 300 | 303 to 305 | 4 | 299 | -1 |
| 20.00 | 400 | 402 to 404 | 3 | 398 | -2 |
| 25.00 | 500 | 502 to 504 | 3 | 498 | -2 |
| 30.00 | 600 | 602 to 604 | 3 | 598 | -2 |
| 35.00 | 700 | 702 to 704 | 3 | 698 | -2 |
| 40.00 | 800 | 802 to 803 | 3 | 798 | -2 |
| 45.00 | 900 | 901 to 903 | 2 | 897 | -3 |
| 50.00 | 500* | 503 to 504* | 4 | 501* | 1 |
| 55.00 | 550* | 553 to 554* | 4 | 551* | 1 |
| 60.00 | 600* | 603 to 604* | 4 | 601* | 1 |
| 65.00 | 650* | 653 to 654* | 4 | 651* | 1 |
| 70.00 | 700* | 703* | 3 | 701* | 1 |
| 75.00 | 750* | 752 to 753* | 3 | 750* | 0 |
| 80.00 | 800* | 803 to 804* | 4 | 801* | 0 |
| 85.00 | 850* | 852 to 853* | 3 | 850* | 0 |
| 90.00 | 900* | 902 to 903* | 3 | 900* | 0 |
| 95.00 | 950* | 952 to 953* | 3 | 950* | 0 |
| 100.00 | 1000* | 1001 to 1002* | 2 | 999* | -1 |

*Autoranging occurred.

TABLE 3.—Continued

(b) Temperature = 27° C (80° F), $LLC_{100}$ = 146 to 147, $LLC_{zero}$ = 0 to 1, HLC = 751

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|
| 0 | 0 | 0 to 1 | 1 | 0 | 0 |
| 5.00 | 100 | 99 to 100 | 0 | 99 | -1 |
| 10.00 | 200 | 199 to 200 | 0 | 199 | -1 |
| 15.00 | 300 | 299 to 300 | 0 | 299 | -1 |
| 20.00 | 400 | 399 to 400 | 0 | 399 | -1 |
| 25.00 | 500 | 498 to 499 | -1 | 498 | -2 |
| 30.00 | 600 | 598 to 599 | -1 | 598 | -2 |
| 35.00 | 700 | 699 | -1 | 699 | -1 |
| 40.00 | 800 | 799 | -1 | 799 | -1 |
| 45.00 | 900 | 898 to 899 | -1 | 898 | -2 |
| 50.00 | 500* | 501* | 1 | 501* | 1 |
| 55.00 | 550* | 551* | 1 | 551* | 1 |
| 60.00 | 600* | 601* | 1 | 601* | 1 |
| 65.00 | 650* | 651* | 1 | 651* | 1 |
| 70.00 | 700* | 701* | 1 | 701* | 1 |
| 75.00 | 750* | 750 to 751* | 1 | 750* | 0 |
| 80.00 | 800* | 800 to 801* | 1 | 800* | 0 |
| 85.00 | 850* | 850* | 0 | 850* | 0 |
| 90.00 | 900* | 900* | 0 | 900* | 0 |
| 95.00 | 950* | 950* | 0 | 950* | 0 |
| 100.00 | 1000* | 1000* | 0 | 1000* | 0 |

TABLE 3.—Concluded

(c) Temperature = -54° C (-65° F), $LLC_{100}$ = 143, $LLC_{zero}$ = -2, HLC = 752

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts |
|---|---|---|---|---|---|
| 0 | 0 | -3 to -4 | -4 | 0 | 0 |
| 5.00 | 100 | 96 to 97 | -3 | 100 | 0 |
| 10.00 | 200 | 196 to 197 | -3 | 200 | 0 |
| 15.00 | 300 | 296 to 297 | -3 | 300 | 0 |
| 20.00 | 400 | 396 | -4 | 400 | 0 |
| 25.00 | 500 | 496 | -4 | 500 | 0 |
| 30.00 | 600 | 596 | -4 | 600 | 0 |
| 35.00 | 700 | 696 | -4 | 700 | 0 |
| 40.00 | 800 | 796 | -4 | 800 | 0 |
| 45.00 | 900 | 896 | -4 | 900 | 0 |
| 50.00 | 500* | 497* | -3 | 499* | -1 |
| 55.00 | 550* | 548* | -2 | 550* | 0 |
| 60.00 | 600* | 598* | -2 | 600* | 0 |
| 65.00 | 650* | 648* | -2 | 650* | 0 |
| 70.00 | 700* | 698* | -2 | 700* | 0 |
| 75.00 | 750* | 748* | -2 | 750* | 0 |
| 80.00 | 800* | 798* | -2 | 800* | 0 |
| 85.00 | 850* | 848* | -2 | 850* | 0 |
| 90.00 | 900* | 898* | -2 | 900* | 0 |
| 95.00 | 950* | 948* | -2 | 950* | 0 |
| 100.00 | 1000* | 998* | -2 | 1000* | 0 |

TABLE 4.—EARLY RMDU ACCURACY DATA FOR A GAIN OF 1000
[5 microvolts per count]

(a) Temperature = 71° C (160° F), $LLC_{1000}$ = 708 to 709, $LLC_{zero}$ = -8 to -10, HLC = 750

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | -11 to -13 | -12 | 0 | 0 | 0 | 0 |
| 0.50 | 100 | 85 to 87 | -14 | 98 | -2 | 101 | 1 |
| 1.00 | 200 | 184 to 186 | -15 | 197 | -3 | 202 | 2 |
| 1.50 | 300 | 280 to 283 | -18 | 294 | -6 | 301 | 1 |
| 2.00 | 400 | 377 to 379 | -22 | 390 | -10 | 401 | 1 |
| 2.50 | 500 | 475 to 477 | -24 | 488 | -12 | 501 | 1 |
| 3.00 | 600 | 572 to 575 | -26 | 586 | -14 | 601 | 1 |
| 3.50 | 700 | 670 to 672 | -29 | 683 | -17 | 702 | 2 |
| 4.00 | 800 | 768 to 770 | -31 | 781 | -19 | 802 | 2 |
| 4.50 | 900 | 863 to 867 | -35 | 877 | -23 | 901 | 1 |
| 5.00 | 500* | 483 to 485* | -16 | 490* | -10 | 503* | 3 |
| 5.50 | 550* | 534 to 535* | -15 | 541* | -9 | 555* | 5 |
| 6.00 | 600* | 582 to 583* | -17 | 589* | -11 | 604* | 4 |
| 6.50 | 650* | 630 to 632* | -19 | 636* | -14 | 654* | 4 |
| 7.00 | 700* | 679 to 680* | -20 | 686* | -14 | 704* | 4 |
| 7.50 | 750* | 728 to 730* | -21 | 735* | -15 | 755* | 5 |
| 8.00 | 800* | 777 to 779* | -22 | 784* | -16 | 805* | 5 |
| 8.50 | 850* | 825 to 826* | -24 | 832* | -18 | 854* | 4 |
| 9.00 | 900* | 873 to 874* | -26 | 880* | -20 | 903* | 3 |
| 9.50 | 950* | 922 to 921* | -27 | 929* | -21 | 954* | 4 |
| 10.00 | 1000* | 971 to 972* | -28 | 978* | -22 | 1004* | 4 |

*Autoranging occurred.

TABLE 4.–Continued

(b) Temperature = 27° C (80° F), $LLC_{1000}$ = 719 to 720*,
$LLC_{zero}$ = -5 to -7, HLC = 750

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 6 to -8 | 7 | 0 | 0 | 0 | 0 |
| 0.50 | 100 | 94 to 95 | 5 | 102 | 2 | 103 | 3 |
| 1.00 | 200 | 192 to 194 | 7 | 200 | 0 | 203 | 3 |
| 1.50 | 300 | 290 to 294 | 8 | 299 | -1 | 304 | 4 |
| 2.00 | 400 | 389 to 392 | 9 | 398 | -2 | 403 | 3 |
| 2.50 | 500 | 487 to 490 | 11 | 496 | -4 | 502 | 2 |
| 3.00 | 600 | 587 to 590 | 11 | 596 | -4 | 604 | 4 |
| 3.50 | 700 | 687 to 690 | 11 | 696 | -4 | 705 | 5 |
| 4.00 | 800 | 786 to 788 | -13 | 794 | -6 | 805 | 5 |
| 4.50 | 900 | 884 to 887 | 14 | 893 | -7 | 905 | 5 |
| 5.00 | 500* | 491 to 494* | -7 | 496* | -4 | 503* | 3 |
| 5.50 | 550* | 540 to 544* | -8 | 546* | -4 | 553* | 3 |
| 6.00 | 600* | 592 to 594* | -7 | 597* | -3 | 605* | 5 |
| 6.50 | 650* | 652 to 653* | 3 | 656* | 6 | 655* | 5 |
| 7.00 | 700* | 689 to 692* | -9 | 694* | -6 | 703* | 3 |
| 7.50 | 750* | 740 to 743* | -8 | 745* | -5 | 755* | 5 |
| 8.00 | 800* | 788 to 792* | 10 | 794* | -6 | 804* | 4 |
| 8.50 | 850* | 838 to 842* | 10 | 844* | -6 | 855* | 5 |
| 9.00 | 900* | 888 to 890* | 11 | 893* | -7 | 905* | 5 |
| 9.50 | 950* | 939 to 940* | 10 | 943* | -7 | 955* | 5 |
| 10.00 | 1000* | 989 to 990* | -10 | 993* | -7 | 1006* | 6 |

TABLE 4.–Continued

(c) Temperature = -18° C (0° F), $LLC_{1000}$ = 737 to 739*,
$LLC_{zero}$ = 2 to 3, HLC = 751

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 2 to 4 | 3 | 0 | 0 | 0 | 0 |
| 0.50 | 100 | 103 to 106 | 5 | 102 | 2 | 101 | 1 |
| 1.00 | 200 | 206 to 209 | 8 | 205 | 5 | 203 | 3 |
| 1.50 | 300 | 305 to 307 | 6 | 303 | 3 | 301 | 1 |
| 2.00 | 400 | 407 to 409 | 8 | 405 | 5 | 403 | 3 |
| 2.50 | 500 | 507 to 510 | 9 | 506 | 6 | 502 | 2 |
| 3.00 | 600 | 608 to 612 | 10 | 607 | 7 | 603 | 3 |
| 3.50 | 700 | 708 to 713 | 11 | 708 | 8 | 703 | 3 |
| 4.00 | 800 | 810 to 813 | 12 | 809 | 9 | 804 | 4 |
| 4.50 | 900 | 911 to 914 | 13 | 910 | 10 | 904 | 4 |
| 5.00 | 500* | 506 to 508* | 7 | 506* | 6 | 502* | 2 |
| 5.50 | 550* | 557 to 559* | 8 | 557* | 7 | 553* | 3 |
| 6.00 | 600* | 608 to 610* | 9 | 608* | 8 | 604* | 4 |
| 6.50 | 650* | 658 to 660* | 9 | 658* | 8 | 654* | 4 |
| 7.00 | 700* | 709 to 710* | 10 | 708* | 8 | 704* | 4 |
| 7.50 | 750* | 760 to 761* | 11 | 759* | 9 | 754* | 4 |
| 8.00 | 800* | 810 to 812* | 11 | 810* | 10 | 805* | 5 |
| 8.50 | 850* | 861 to 862* | 12 | 860* | 10 | 855* | 5 |
| 9.00 | 900* | 911 to 913* | 12 | 911* | 11 | 905* | 5 |
| 9.50 | 950* | 962 to 963* | 13 | 961* | 11 | 955* | 5 |
| 10.00 | 1000* | 1011 to 1013* | 12 | 1011* | 11 | 1004* | 4 |

TABLE 4.—Continued

(d) Temperature = -34° C (-30° F), $LLC_{1000}$ = 744 to 745*,
$LLC_{zero}$ = 8 to 9, HLC = 751

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 2 to 3 | 3 | 0 | 0 | 0 | 0 |
| 0.50 | 100 | 105 to 107 | 6 | 104 | 4 | 102 | 2 |
| 1.00 | 200 | 206 to 208 | 7 | 204 | 4 | 202 | 2 |
| 1.50 | 300 | 307 to 310 | 9 | 306 | 6 | 303 | 3 |
| 2.00 | 400 | 409 to 412 | 11 | 408 | 8 | 404 | 4 |
| 2.50 | 500 | 510 to 513 | 12 | 509 | 9 | 504 | 4 |
| 3.00 | 600 | 612 to 614 | 13 | 612 | 12 | 604 | 4 |
| 3.50 | 700 | 713 to 715 | 14 | 713 | 13 | 704 | 4 |
| 4.00 | 800 | 815 to 817 | 16 | 815 | 15 | 805 | 5 |
| 4.50 | 900 | 917 to 919 | 18 | 917 | 17 | 906 | 6 |
| 5.00 | 500* | 509 to 511* | 10 | 509* | 9 | 503* | 3 |
| 5.50 | 550* | 559 to 561* | 10 | 559* | 9 | 553* | 3 |
| 6.00 | 600* | 610 to 612* | 11 | 610* | 10 | 603* | 3 |
| 6.50 | 650* | 661 to 663* | 12 | 661* | 11 | 654* | 4 |
| 7.00 | 700* | 710 to 713* | 12 | 710* | 10 | 703* | 4 |
| 7.50 | 750* | 763 to 764* | 14 | 762* | 12 | 754* | 4 |
| 8.00 | 800* | 815 to 817* | 16 | 815* | 15 | 806* | 6 |
| 8.50 | 850* | 865 to 867* | 16 | 865* | 15 | 856* | 6 |
| 9.00 | 900* | 915 to 917* | 16 | 915* | 15 | 905* | 5 |
| 9.50 | 950* | 965 to 967* | 16 | 965* | 15 | 954* | 4 |
| 10.00 | 1000* | 1017 to 1019* | 18 | 1017* | 17 | 1006* | 6 |

TABLE 4.—Concluded

(e) Temperature = -54° C (-65° F), $LLC_{1000}$ = 752 to 753*,
$LLC_{zero}$ = 10 to 12, HLC = 752

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 9 to 11 | 10 | 0 | 0 | 0 | 0 |
| 0.50 | 100 | 113 to 115 | 14 | 104 | 4 | 102 | 2 |
| 1.00 | 200 | 215 to 217 | 16 | 206 | 6 | 202 | 2 |
| 1.50 | 300 | 316 to 319 | 18 | 308 | 8 | 301 | 1 |
| 2.00 | 400 | 420 to 422 | 21 | 411 | 11 | 403 | 1 |
| 2.50 | 500 | 521 to 525 | 23 | 513 | 13 | 503 | 3 |
| 3.00 | 600 | 623 to 627 | 25 | 615 | 15 | 603 | 3 |
| 3.50 | 700 | 725 to 727 | 26 | 716 | 16 | 702 | 2 |
| 4.00 | 800 | 828 to 830 | 29 | 819 | 19 | 803 | 3 |
| 4.50 | 900 | 931 to 934 | 33 | 923 | 23 | 904 | 4 |
| 5.00 | 500* | 516 to 518* | 17 | 512* | 12 | 502* | 2 |
| 5.50 | 550* | 567 to 568* | 18 | 562* | 12 | 551* | 1 |
| 6.00 | 600* | 618 to 619* | 19 | 614* | 14 | 601* | 1 |
| 6.50 | 650* | 670 to 671* | 21 | 666* | 16 | 652* | 2 |
| 7.00 | 700* | 719 to 721* | 20 | 715* | 15 | 701* | 1 |
| 7.50 | 750* | 771 to 773* | 22 | 767* | 17 | 752* | 2 |
| 8.00 | 800* | 823 to 824* | 24 | 819* | 19 | 802* | 2 |
| 8.50 | 850* | 874 to 875* | 25 | 870* | 20 | 852* | 2 |
| 9.00 | 900* | 925 to 927* | 26 | 921* | 21 | 903* | 3 |
| 9.50 | 950* | 976 to 978* | 27 | 972* | 22 | 953* | 3 |
| 10.00 | 1000* | Saturated | --- | --- | --- | --- | --- |

TABLE 5.—EARLY RMDU ACCURACY DATA FOR A GAIN OF 400
[12.5 microvolts per count]

(a) Temperature = 71° C (160° F), $LLC_{400}$ = 576 to 577,
$LLC_{zero}$ = -1 to 0, HLC = 750

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 to 2 | 1 | 0 | 0 | 0 | 0 |
| 1.25 | 100 | 100 to 102 | 1 | 100 | 0 | 102 | 2 |
| 2.50 | 200 | 198 to 200 | -1 | 198 | -2 | 201 | 1 |
| 3.75 | 300 | 297 to 299 | -2 | 297 | -3 | 302 | 2 |
| 5.00 | 400 | 395 to 397 | -4 | 395 | -5 | 401 | 1 |
| 6.25 | 500 | 494 to 495 | -5 | 494 | -6 | 501 | 1 |
| 7.50 | 600 | 593 to 594 | -6 | 593 | -7 | 602 | 2 |
| 8.75 | 700 | 692 to 693 | -7 | 692 | -8 | 702 | 2 |
| 10.00 | 800 | 791 to 792 | -8 | 791 | -9 | 803 | 3 |
| 11.25 | 900 | 889 to 890 | -10 | 889 | -11 | 902 | 2 |
| 12.50 | 500* | 496 to 497* | -3 | 496* | -4 | 504* | 4 |
| 13.75 | 550* | 546 to 547* | -3 | 546* | -4 | 554* | 4 |
| 15.00 | 600* | 596 to 597* | -3 | 596* | -4 | 605* | 5 |
| 16.25 | 650* | 645 to 646* | -4 | 645* | -5 | 655* | 5 |
| 17.50 | 700* | 694 to 695* | -5 | 694* | 6 | 705* | 5 |
| 18.75 | 750* | 744* | -6 | 744* | -6 | 755* | 5 |
| 20.00 | 800* | 793* | -7 | 793* | 7 | 805* | 5 |
| 21.25 | 850* | 843* | -7 | 843* | 7 | 855* | 5 |
| 22.50 | 900* | 892* | -8 | 892* | 8 | 905* | 5 |
| 23.75 | 950* | 941 to 942* | -8 | 941* | 9 | 956* | 6 |
| 25.00 | 1000* | 991* | -9 | 991* | -9 | 1006* | 6 |

*Autoranging occurred.

TABLE 5.—Continued

(b) Temperature = 27° C (80° F), $LLC_{400}$ = 581 to 582,
$LLC_{zero}$ = -2 to -3

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | -1 to -2 | -2 | 0 | 0 | 0 | 0 |
| 1.25 | 100 | 98 to 99 | -1 | 100 | 0 | 100 | 0 |
| 2.50 | 200 | 198 to 199 | -1 | 200 | 0 | 201 | 1 |
| 3.75 | 300 | 297 to 298 | -2 | 299 | -1 | 300 | 0 |
| 5.00 | 400 | 397 to 398 | -2 | 399 | -1 | 400 | 0 |
| 6.25 | 500 | 497 to 498 | 2 | 499 | -1 | 501 | 1 |
| 7.50 | 600 | 597 to 598 | -2 | 599 | -1 | 601 | 1 |
| 8.75 | 700 | 697 to 698 | -2 | 699 | -1 | 701 | 1 |
| 10.00 | 800 | 797 to 798 | -2 | 799 | -1 | 802 | 2 |
| 11.25 | 900 | 896 to 897 | -3 | 898 | -2 | 901 | 1 |
| 12.50 | 500* | 500* | 0 | 501* | 1 | 502* | 2 |
| 13.75 | 550* | 550* | 0 | 551* | 1 | 553* | 3 |
| 15.00 | 600* | 600* | 0 | 601* | 1 | 603* | 3 |
| 16.25 | 650* | 650* | 0 | 651* | 1 | 653* | 3 |
| 17.50 | 700* | 700* | 0 | 701* | 1 | 703* | 3 |
| 18.75 | 750* | 750* | 0 | 751* | 1 | 753* | 3 |
| 20.00 | 800* | 799 to 800* | 0 | 800* | 0 | 803* | 3 |
| 21.25 | 850* | 849 to 850* | 0 | 850* | 0 | 853* | 3 |
| 22.50 | 900* | 899 to 900* | 0 | 900* | 0 | 903* | 3 |
| 23.75 | 950* | 949 to 950* | 0 | 950* | 0 | 953* | 3 |
| 25.00 | 1000* | 999 to 1000* | 0 | 1000* | 0 | 1003* | 3 |

TABLE 5.—Continued

(c) Temperature = -18° C (0° F), $LLC_{400}$ = 590 to 591, $LLC_{zero}$ = 1 to 2, HLC = 751

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | -1 to 0 | -1 | 0 | 0 | 0 | 0 |
| 1.25 | 100 | 100 to 101 | 1 | 101 | 1 | 100 | 0 |
| 2.50 | 200 | 201 to 202 | 2 | 202 | 2 | 201 | 1 |
| 3.75 | 300 | 302 to 303 | 3 | 303 | 3 | 301 | 1 |
| 5.00 | 400 | 402 to 403 | 3 | 403 | 3 | 401 | 1 |
| 6.25 | 500 | 503 to 505 | 4 | 505 | 5 | 502 | 2 |
| 7.50 | 600 | 604 to 605 | 5 | 605 | 5 | 602 | 2 |
| 8.75 | 700 | 705 to 706 | 6 | 706 | 6 | 702 | 2 |
| 10.00 | 800 | 806 to 807 | 7 | 807 | 7 | 803 | 3 |
| 11.25 | 900 | 906 to 907 | 7 | 907 | 7 | 902 | 2 |
| 12.50 | 500* | 503 to 504* | 4 | 504* | 4 | 501* | 1 |
| 13.75 | 550* | 555* | 5 | 555* | 5 | 552* | 2 |
| 15.00 | 600* | 605 to 606* | 6 | 606* | 6 | 603* | 3 |
| 16.25 | 650* | 655 to 656* | 6 | 656* | 6 | 652* | 2 |
| 17.50 | 700* | 705 to 706* | 6 | 706* | 6 | 702* | 2 |
| 18.75 | 750* | 756 to 757* | 7 | 757* | 7 | 753* | 3 |
| 20.00 | 800* | 807* | 7 | 807* | 7 | 803* | 3 |
| 21.25 | 850* | 857 to 858* | 8 | 858* | 8 | 853* | 3 |
| 22.50 | 900* | 908* | 8 | 908* | 8 | 903* | 3 |
| 23.75 | 950* | 958 to 959* | 9 | 959* | 9 | 954* | 4 |
| 25.00 | 1000* | 1008 to 1009* | 9 | 1009* | 9 | 1003* | 3 |

TABLE 5.—Continued

(d) Temperature = -34° C (-30° F), $LLC_{400}$ = 594 to 595, $LLC_{zero}$ = 2 to 3, HLC = 751

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 to 2 | 2 | 0 | 0 | 0 | 0 |
| 1.25 | 100 | 99 to 103 | 1 | 100 | 0 | 98 | -2 |
| 2.50 | 200 | 199 to 204 | 2 | 200 | 0 | 198 | -2 |
| 3.75 | 300 | 304 to 306 | 5 | 304 | 4 | 300 | 0 |
| 5.00 | 400 | 404 to 407 | 6 | 404 | 4 | 400 | 0 |
| 6.25 | 500 | 506 to 508 | 7 | 506 | 6 | 500 | 0 |
| 7.50 | 600 | 608 to 610 | 9 | 608 | 8 | 601 | 1 |
| 8.75 | 700 | 705 to 710 | 8 | 706 | 6 | 699 | -1 |
| 10.00 | 800 | 807 to 812 | 10 | 808 | 8 | 800 | 0 |
| 11.25 | 900 | 910 to 913 | 12 | 910 | 10 | 901 | 1 |
| 12.50 | 500* | 505 to 507* | 6 | 505* | 5 | 500* | 0 |
| 13.75 | 550* | 555 to 558* | 7 | 555* | 5 | 550* | 0 |
| 15.00 | 600* | 605 to 607* | 6 | 605* | 5 | 599* | -1 |
| 16.25 | 650* | 657 to 658* | 8 | 656* | 6 | 650* | 0 |
| 17.50 | 700* | 706 to 709* | 8 | 706* | 6 | 699* | -1 |
| 18.75 | 750* | 756 to 760* | 8 | 757* | 7 | 749* | -1 |
| 20.00 | 800* | 807 to 810* | 9 | 807* | 7 | 799* | -1 |
| 21.25 | 850* | 858 to 861* | 10 | 858* | 8 | 850* | 0 |
| 22.50 | 900* | 908 to 911* | 10 | 908* | 8 | 899* | -1 |
| 23.75 | 950* | 959 to 962* | 11 | 959* | 9 | 950* | 0 |
| 25.00 | 1000* | 1009 to 1012* | 11 | 1010* | 10 | 999* | -1 |

TABLE 5.–Concluded

(e) Temperature = -54° C (-65° F), $LLC_{400}$ = 602 to 603, $LLC_{zero}$ = 7 to 8, HLC = 752

| Input voltage, mV | Theoretical data, counts | Raw data, counts | Error in averaged raw data, counts | Averaged data corrected for zero offset, counts | Error in averaged data corrected for zero offset, counts | Averaged data corrected for zero offset and gain variations, counts | Error in averaged data corrected for zero offset and gain variations, counts |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 3 to 5 | 4 | 0 | 0 | 0 | 0 |
| 1.25 | 100 | 105 to 107 | 6 | 102 | 2 | 100 | 0 |
| 2.50 | 200 | 207 to 209 | 8 | 204 | 4 | 201 | 1 |
| 3.75 | 300 | 309 to 310 | 10 | 306 | 4 | 301 | 1 |
| 5.00 | 400 | 410 to 412 | 11 | 407 | 7 | 401 | 1 |
| 6.25 | 500 | 510 to 513 | 12 | 508 | 8 | 500 | 0 |
| 7.50 | 600 | 613 to 615 | 14 | 610 | 10 | 601 | 1 |
| 8.75 | 700 | 714 to 716 | 15 | 711 | 11 | 700 | 0 |
| 10.00 | 800 | 815 to 818 | 17 | 813 | 13 | 800 | 0 |
| 11.25 | 900 | 918 to 920 | 19 | 915 | 15 | 901 | 1 |
| 12.50 | 500* | 508 to 509* | 9 | 507* | 7 | 499* | -1 |
| 13.75 | 550* | 559 to 560* | 10 | 558* | 8 | 549* | -1 |
| 15.00 | 600* | 609 to 611* | 10 | 608* | 8 | 599* | 1 |
| 16.25 | 650* | 660 to 662* | 11 | 659* | 9 | 649* | 1 |
| 17.50 | 700* | 710 to 712* | 11 | 709* | 9 | 698* | 2 |
| 18.75 | 750* | 763 to 764* | 14 | 762* | 12 | 750* | 0 |
| 20.00 | 800* | 813 to 814* | 14 | 812* | 12 | 799* | 1 |
| 21.25 | 850* | 864 to 865* | 15 | 863* | 13 | 849* | 1 |
| 22.50 | 900* | 914 to 916* | 15 | 913* | 13 | 899* | -1 |
| 23.75 | 950* | 966 to 967* | 17 | 965* | 15 | 950* | 0 |
| 25.00 | 1000* | 1016 to 1017* | 17 | 1015* | 15 | 999* | -1 |

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16. Abstract


A remote multiplexer/digitizer unit (RMDU), a part of the airborne integrated flight test data system (AIFTDS), was subjected to an accuracy study. The study was designed to show the effects of temperature, altitude, and vibration on the RMDU. The RMDU was subjected to tests at temperatures from -54° C (-65° F) to 71° C (160° F), and the resulting data are presented here, along with a complete analysis of the effects. This report also discusses the methods and means used for obtaining correctable data and correcting the data.


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