A NOVEL PMCM SYSTEM FOR GEOPHYSICAL RESEARCH

P. A. Toney and J. M. Walter, Jr.
Dynatronics Inc.
Orlando, Florida

Summary The concepts leading to development of an inexpensive digital data acquisition system employing novel Pulse-Morse Code Modulation and providing accuracy comparable to that of PCM are discussed. The several system-level and circuit-level considerations permitting the complete elimination of separate signal conditioning equipment and receiving-site synchronization, recording and processing equipment are presented. Finally, there is a brief commentary on future applications of the device and suggestions for related work.

Introduction Although PCM telemetry is a relatively young field of endeavor, it has grown rapidly and become well-established, especially among aircraft and missile instrumentation users, for the well-known reasons of accuracy, performance in the presence of noise, and data handling ease. A great variety of sensing, signal conditioning, modulation, encoding, detection, and data processing equipment has been developed to handle the vast amount of data required. Because of his much more modest budget, the natural scientist, who has historically been a pacesetter as far as precision and quantity of data gathered was concerned, has paradoxically been placed at a disadvantage. It is hoped that this development effort will enable the geophysicist (who up to now could employ only direct measurement or analog telemetry techniques) to utilize digital techniques for scientific data collection.

The work described herein is a continuation of efforts by the Research Instrumentation Laboratory of the Air Force Cambridge Research Laboratories to adapt PCM telemetry technology to high-altitude geophysical research. The equipment developed for AFCRL is significant in that it can be used in much oceanographic and meteorological, as well as geophysical data gathering. Most important, it realizes the accuracy, reliability, and environmental capabilities of sophisticated missile-borne PCM systems at a cost of perhaps one-quarter that of PCM for the remote telemeter itself, and at an overall system cost of several-fold less.

The design resulting from Air Force Contract AF18(628)-4224 features the use of integrated circuitry in all logic functions, an overall accuracy (peak-to-peak, exclusive of quantizing error) of ±0.3% over a -30°C to +55°C temperature range, and an operating temperature range of -45°C to +85°C. Like PCM instrumentation, it also provides a high degree of accuracy under environmental stresses and noisy radio link conditions.

System Considerations The original data system concepts defined by AFCRL determined the overall PMCM system transfer characteristic: a linear resistance-to-binary (Morse) characteristic, which eliminates the need for signal conditioning equipment since all parameters are measured by means of resistive sensing elements. The output is in binary Morse code form so that transmitted data may be easily and accurately hand-copied by Morse code operators without use of the elaborate ground equipment required by PCM systems. The important feature is that this approach provides the accuracy potential of 9-bit PCM but at greatly reduced overall cost, owing to the signal conditioning and ground equipment savings. AFCRL established these concepts and has employed the technique successfully for several years. (A transistorized “encoder” was developed for AFCRL by Dynatronics, Inc. in 1960[1] and has been used steadily since that time.) The completely new development described herein, which represents substantial improvements in the areas of accuracy, environmental performance, and reliability over the previous device, attests to the soundness of the original data system approach.

A large amount of low-frequency data is available from resistive transducers – the following are examples:

Parameter	Transducer
Temperature	Calibrated thermistors; resistance thermometers
Displacement	Potentiometers; strain gages
Pressure (altitude or depth)	Bellows, bourdon tubes, and diaphragms with potentiometer pickoff; hypsometers with thermistor output
Attitude	Potentiometer-pickoff gyros
Humidity	Resistance-path sensing cells
Light level	Photo-resistive cells

Because of the variety of such transducers available, the system could be designed to accept these sensors directly, without the use of bridge or potentiometric techniques. An obvious advantage is the increase in possible accuracy, since the voltage or current excitation sources normally required introduce noise and drift of their own in other data systems. Also, the lack of remote signal conditioners reduces the per-channel cost.

In this simplified digital telemetry system the data acquisition system itself is the significant cost item. Therefore, one of the principal design considerations was that of cost, and value analysis was employed at every step of the development effort. The anticipated manufacturing cost was considered in every design decision, from circuit configuration and component choice to logic configuration and minimization. Although low cost was of great importance, it could not be obtained at the expense of reduced accuracy, reliability, or environmental capability. For this reason, circuit and system simplification was relied upon to minimize cost. The specific design approaches followed to achieve the maximum possible accuracy, reliability, and environmental capability the art would allow, while at the same time minimizing cost, are treated in the discussion on Design Approach.

"PMCM" has been coined (by the authors) as an abbreviation pseudonym similar to PCM because it also employs analog-to-digital conversion and transmitter keying techniques which establish a binary data train, and provides an overall data link similar to that of PCM. The technique imposes an obvious data bandwidth limitation on the system because the transmission rate is limited by the facility of the Morse operator. This limitation is of little consequence in much geophysical work, however, since temperature, pressure, displacement, and many other measurements are slowchanging physical phenomena.

The output data wave train contains DASHES which represent binary ONES and DOTS which represent binary ZEROS (see Figure 1) . A ONE (DASH) bit length is three times that of a ZERO (DOT) bit. Bits are separated by a space one DOT in length. Each word consists of three 3-bit characters (letters) , which are separated by three DOT lengths, and complete words are separated by nine DOT lengths. Finaly, end-of-frame (message) is identified by a space of 18 DOT lengths. Obviously PMCM word length is not constant due to the 3:1 timing relationship between ONES and ZEROS. For example, all ZEROS words are transmitted at 20 words per minute and all ONES words are sent at 12.5 wpm, while the average word rate is standard International Morse code - 15 wpm.

Design Goals A tabulation of the design goals established at the outset of the development effort is an appropriate introduction to this subject and will establish a frame of reference to which the reader may refer in the remainder of the paper.

<u>Inputs:</u>

Signal source	Floating resistive source, 0-128k ohms
Number of channels	11 to 33
Excitation applied to source	40 μamps constant current, .003% duty cycle
Peak sensor power dissipation	200μwatts

Average sensor power dissipation	.01 μwatts
Peak sensor energy level	0.2 μwatts-sec
External commands	Separate contact closures for read-out of a single frame, for continuous readout, and for system start
Power	12 ± 1.2v dc, 6 watts average

Outputs:

Format	9-bit serial Morse code words
Bit length	Dash (ONE): 300 ms; Dot (ZERO): 100 ms
Bit spacing	100 Ms
Character length	3 bits
Character spacing	300 ms
Word length	4 seconds, average
Word spacing	900 ms
Frame spacing	1.8 seconds

Operating Characteristics:

Accuracy	±0.3% ±1/2 bit (9 bits), -30°C to +55°C
Functional temperature range	-30°C to +55°C

The input was to accept floating resistive sources in the range of zero to 128k ohms because this range represented the best compromise between resolution and dynamic range for the group of sensors employed. The source excitation levels were established to minimize the self-heating tendency in tiny bead thermistors used for temperature measurement and to avoid damage to these or to other more sensitive sensors. A provision for three types of external commands was made: 1) one contact closure should cause the system to scan and readout all data channels continuously; 2) another closure would cause only one frame of channels to be read out after which the system would stop; and 3) still another would develop a start command to start the system following power turn-on or readout of a single frame. The single-frame and restart provisions were made so that system power could be conserved by sampling data channels only periodically and switching off power between samples. A system power requirement of only 6 watts would allow long periods of operation from the battery supply anticipated.

The output characteristics specified enable a Morse code operator with average ability to copy the three 3-letter code groups comprising each 9bit binary word with ease. The word spacing provided distinguishes in dividual words and frame spacing identifies the completion of a complete frame of data, both of which are analogous, roughly, to synchronization techniques as employed in PCM. The accuracy goal specified is that desired over the temperature environment encountered in AFCRL high altitude balloon flights. The figure of ± 0.3% (exclusive of quantizing) was thought to represent a reasonable but difficult goal in view of the high full scale source resistance (128k ohms). This was understood to be a peak accuracy specification (not rms) which would be a worst case combination of errors from all sources, such as noise, temperature drifts, and non-linearities. This is a specification which can be determined by actual measurement.

Design Approach Now that the specific requirements imposed by the particular application have been considered, the various means drawn upon to achieve these design goals can be discussed.

Figure 2 illustrates the PMCM system divided into five principal sections. A commutator is required in any time-division sampled-data system and a double-ended commutator is shown. The classic approach to the problem of measuring a resistive sensor is constant voltage or current excitation followed by a voltage-operated system “front-end”. A disadvantage of constant-voltage excitation applied to the unknown resistive sensor in a voltage-divider connection (as is usual) is the non-linear resistance-tovoltage transfer characteristic that is obtained. Constant-current excitation overcomes this problem and a modified form of constant-current excitation has been employed here (represented by the “amplifier” shown in Figure 2) .

A simple but accurate analog-to-digital converter had already been developed by Dynatronics for satellite applications and this voltage-input device became the second element on the signal flow diagram. Finally, the parallel binary output of the a-d converter must be converted to serial International Morse code; this was to be accomplished by a variety of logic elements in a binary-to-Morse converter section of the equipment.

Commutator Cost and technical data on numerous gating devices which could form the basic commutator building block was collected and considered (field-effect transistors, junction transistor “Bright” circuit configurations, opto-electronic devices, reed relays, stepping switches, etc.). The device chosen must have an extremely high OFF impedance (because of full-scale source resistance of 128k ohms), an ON impedance of less than approximately 100 ohms, and must be well isolated from its driving source. It must also be inexpensive. Field-effect transistors having an rds of less than 100 ohms are quite expensive, and their necessarily large-chip geometry produces relatively large leakages which would give rise to some channel crosstalk. The well-known “Bright” switches are marginal in “ON” resistance, have leakage currents only two orders of magnitude below the excitation current, and are expensive compared to some of the other devices considered.

Still another solid-state device appeared attractive-a photo-resistive chopper having a nominal “ON” resistance of 100 ohms and driven by an isolated miniature incandescent bulb. However, when several of these devices were evaluated, they were found to have “OFF” resistances of as low as 200 megohms. This is intolerable since a ganged 11-channel commutator places 10 other gates in parallel with the one being sampled. (For example, 10 parallel channels having an “OFF” resistance of 200 megohms each results in a 20 megohm load across the sampled source, and this produces a loading error of more than 0.5% on a 128k ohm source.) Also, since each such gate would require a separate power driver, the per-channel cost using opto-electronic devices was unattractive.

Operating speed is not a limitation of electromechanical switches in this application, although at first -their operating life appeared to be unacceptable. Switch contact (ON) resistance is very low, and their “OFF” resistance is initially higher and does not worsen with temperature when compared to opto-electronic devices or field-effect transistors. Reed relays, having no moving parts, would appear to have a reliability advantage over stepping switches. However, such is not the case - primarily because contact failure is defined by an abrupt increase in contact resistance, and reed relays do not benefit as do stepping switches from a contact cleaning effect (due to the “ wiping” action of stepping switch contacts) . The enormous commercial usage of stepping switches has refined the mechanism so that standard oil-filled units have an operating life of over 2×10^8 steps. On the other hand, among the best reed relays considered were newly-developed high-reliability units attaining only about 5×10^6 operations and which were not well suited to “dry” service because they depended on contact arcing current for self-cleaning. Another advantage of stepping switches was that only one power driver was required, whereas one for each channel would be needed for separate reed relays (a reed-relay magnetic-scanner requiring only one driver could be used, however).

Operating at the average word rate, the commutating stepping switch would have an operating life of roughly 25 years in continuous, uninterrupted service! Detailed cost comparisons indicated a clear-cut advantage for the stepping switch. This consideration completed the elimination of the other commutating approaches considered. The stepping switches’ disadvantages were size and weight, and these were not of great significance considering the preponderance of advantages over the solid-state devices.

Amplifier One can employ a constant-current source to excite an unknown resistance and thereby develop a linear resistance-to-voltage transfer characteristic across the terminals of the unknown. Since in this case the source resistance could be as high as 128k ohms, an amplifier would be required to reduce the impedance level at the a-d converter input, and this would be an additional error source. Also, both the constant-current source and the amplifier would have to be commutated.

Another simpler scheme was devised by a colleague of the authors - namely, use of an ordinary inverting operational amplifier as both a precision constant-current source and an impedance-buffering device. Figure 3 shows such an amplifier. It is easy to develop the transfer function for this amplifier, making the following assumptions: V_i and R_i are constant; (-A) is very large; $i_e = 0$. Then the regulating action of the amplifier makes $V_e = 0$ volts (“virtual ground”) .

Since i_e and $V_e = 0$, $i_f = i_i = \frac{V_i}{R_i}$ and $i_f R_f = \frac{V_i}{R_i} \times R_f$

so

$$V_o = \frac{V_i}{R_i} \times R_f$$

From this and the knowledge that V_i and R_i are constant, one readily sees that V_o and R_f are linearly related. Also, since i_e and $V_e = 0$, and i_i and V_i are constant, if must be constant, and this is the source of constant current excitation applied to R_f, the sensor.

It should be noted also that V_o is taken between the operational amplifier output terminal and ground (<u>not</u> across R_f) , which because of the load regulating action of the amplifier presents an effective output impedance of only a few ohms. Thus a single amplifier provides the constant-current excitation and impedance buffering required, and it was largely these findings that lead to the equipment development approach.

Analog-to-Digital Converter The a-d converter employed in the PMCM system is a subsystem (Model DMC-17) developed recently by Dynatronics, Inc. for satellite and missile PCM systems. It features extreme simplicity (therefore, low cost), excellent accuracy, and low power consumption, all of whichwere important reasons for its choice. As in any analog-digital data system, the a-d converter is an important element. Because the design itself is not new, however, it will be discussed only in terms of its capabilities.

The a-d converter is a relatively high speed unit capable of completing 9-bit conversions in 530 μsecs. This is only an instant in time compared to the commutator dwell time in each channel (3 to 4.8 seconds, depending on the value of the PMCM word generated) . Therefore, sensor excitation and dissipation may be limited to a very short time compared to commutator dwell time. An additional .5 ms delay is provided for amplifier and sensor settling prior to the .5 ms encoding interval, and these together require an excitation interval of I ms. It follows that the excitation interval can be reduced from a minimum of 3 seconds, the commutator dwell time to I ms, or a 3,000: 1 reduction in sensor dissipation. The removal of sensor excitation is achieved by adding a clamping transistor to the operational amplifier in such a way as to reduce the sensor current to zero except during encoding. The very low average dissipation levels needed were achieved largely by this method, and this justifies use of high speed a-d converters.

Binary-to-Morse Converter The two main functions the binary-to-Morse converter must accomplish are serialization and conversion of the parallel binary code produced by the a-d converter into a properly-spaced serial PMCM wavetrain. Serialization may be accomplished by use of a shift register or by means of sequential bit-by-bit readout from a parallel storage register. The latter, more reliable method has been employed here.

The several timing pulses needed (bit, character, word, frame spacing, dot-dash generation, and system timing) and accommodation of several external commands required a broad array of logic building blocks (NAND, NOR, counter, flip-flop, one-shot, inverter). Because of the emphasis on low system manufactured cost, recently introduced, low cost, computer-type integrated circuitry demanded consideration. It was found the system could be configured around these integrated devices for about $500 less than by use of discrete-component logic elements, with no sacrifice in performance and with an unquestioned improvement in reliability. One question remained unanswered: "Since the input serializing commutator could be most inexpensively implemented by means of a stepping switch, should not the same be true of the serializing function of the binary-to-Morse converter?" A complete system design and cost comparison both ways answered this question affirmatively, in spite of the low cost of the integrated logic elements the stepping switch would replace.

Since the output-serializing stepping switch must operate 10 times as rapidly as the commutator (9-position stepping switches are not available) , it becomes the new limiting factor on system operating life, reducing the overall operating life to roughtly 2-1/2 years of continuous operation. This is more than an order of magnitude greater than the mission life defined by AFCRL, however. Stepping switch failure would be a "wear-out" type failure that is strictly cumulative, and the <u>electronic</u> portions of the system would likely be "worn out" from <u>handling</u> long before stepping switch failure occurred under normal intermittent operation. For this reason, the two stepping switches are hard-wired directly into the system wiring harness and should never require replacement.

The serializing stepping switch is used to develop a serial binary data train, to program each word for bit, character, and word spacing, and to originate most system timing pulses, essentially the same functions a more expensive electronic sequencer would perform. It operates in conjunction with integrated logic elements supplying various delay, storage, and gating functions to develop the PMCM data train.

Another area of cost reduction and standardization was accomplished after it was determined that only two of the many types of integrated circuits evaluated would be required to implement all logic functions. This degree of standardization was made possible through utilization of a limited number of external passive components in conjunction with a dual, 2-input gate. This basic building block furnishes NAND, NOR, and inverter functions without change. Addition of the very few external components allowed one-shot multivibrators and set-reset flip-flbps (both with transistor-buffered inputs) , to be designed. Only the counter-register needed by the a-d converter could not be economically fabricated from this device, and an integrated J-K flip-flop element was utilized here.

Special Considerations Two additional areas of endeavor contributing significantly to overall system accuracy should be briefly discussed. Figure 4 illustrates that the PMCM system has been fully isolated from the extensive primary power ground by use of a high-reliability reed relay and a dc-dc converter transformer. The advantage in this arrangement is that an essentially single-ended system can achieve a large degree of noise rejection of which it would otherwise be incapable. This is easily understood by assuming the generalized noise generator e_n has a low internal impedance and injects a noise voltage into the system at its input terminals. Knowing that the impedance level at low frequencies between the point of injection and system ground is low (in this case a few ohms) and assuming the isolating mechanisms provide a very high isolating impedance (100 megohms, say), it follows that practically all of e_n is developed across this isolating impedance. The effect of en on system accuracy is therefore not seen, or is minute. Excellent behavior of the system in a high-noise environment has been observed, and this performance is due in large measure to the isolation employed. (Many precision laboratory instruments using single-ended amplification employ this technique to obtain the effect of common mode rejection which is normally provided by a differential instrument.)

A significant problem encountered during the development was that of operational amplifier input error current drift. Referring again to Figure 3, but neglecting none of the error currents or voltages, one can derive an expression exactly describing the problem as follows:

By inspection,
$$i_f = i_i + i_e \qquad (1)$$

and
$$V_o = -AV_e \qquad (2)$$

From (1)
$$\frac{V_o - V_e}{R_f} = \frac{V_e - V_i}{R_i} + i_e$$

From (2)
$$V_e = -V_o/A$$

Combining these,
$$\frac{V_o + V_o/A}{R_f} = -\frac{V_i + V_o/A}{R_i} + i_e$$

Simplifying and solving for V_o gives
$$V_o = \frac{(i_e R_i - V_i)\, AR_f}{AR_i + R_i + R_f}$$

or
$$V_o = \frac{(i_e R_i - V_i)\, R_f}{R_i + \dfrac{R_i + R_f}{A}}$$

In our case, A is extremely large, so $$\lim_{A \to \infty} (V_o) = \frac{(i_e R_i - V_i) R_f}{R_i}$$

or
$$V_o = i_e R_f - V_i \frac{R_f}{R_i} \qquad (3)$$

In expression (3) the second term is the normal expression for the output voltage of the amplifier. The first term is an error term which may be "adjusted out" at any given temperature, but which is temperature dependent because of the temperature drift of i_e, the amplifier input bias current. Now, if i_e changes only 0.1 μa over the temperature range, an output error of 12.8 mv (~ 0.25%) is developed for 128k sources! An i_e drift as small as 0.1 μa is difficult to achieve, but an effect of this magnitude cannot be tolerated when an overall system analog accuracy of ± 0. 3% must be met.

This effect was eliminated by careful redesign of the operational amplifier front end to reduce i_e to on the order of 10 na, while maintaining an equivalent input drift of about 10 μ v per degree C, -30°C to +55°C. This was perhaps one of the more important technical "breakthroughs" since, so far as could be determined, no amplifier having these characteristics was available in the desired size and cost range.

Equipment Description The resulting PMCM system meets or exceeds all of the design goals outlined earlier. In addition to accepting up to. 11 channels, provision has been made to accommodate a 33-channel commutator with only minor mechanical changes. Temperature tests on the engineering model have yielded accuracy data considerably betterthan required (± .2%). The functional temperature range of the unit was expanded 45°C (-45°C to +85°C) , principally to assure that production units would function reliably over the required range of -30°C to +55°C. Pre-production units were also individually tested -45°C to +85°C, however, in order to further verify the design.

The system has been designed to meet other environmental parameters not specifically adopted as design goals:

Altitude	Sea level to 1 millibar (this was a design goal)
Shock	MIL-STD-810, Method 516, procedure I I
Vibration	MIL-STD-810, Method 514, Figure 514-1, Curve A
Humidity	95 ± 5% relative humidity

The system's physical characteristics are as follows:

Case	12-1/2" x 10-1/2" x 4" drawn aluminum alloy
Weight	16 pounds nominal
Construction	Silicon and integrated circuitry mounted on ten 1.9" x 3.2: printed circuit cards

Considering the PMCM system's capabilities outlined above, perhaps the most gratifying result of the development effort is that an adequately low production cost figure has been achieved.

Conclusions and Recommendations AFCRL utilizes the PMCM system with Class Al (CW emission), an acronym for which might be " PMCM/AM." Other forms of modulation such as PMCM/FM are conceivable, and an interesting subject for future study might involve a comparison of PMCM/AM or /PM with PCM/FM as to efficiency and accuracy under equivalent s/n ratios. An interesting difference one immediately notices between PMCM/ AM and PCM/FM, although the former is also relatively insensitive to amplitude disturbances, is that PMCM/AM information is primarily in the time domain while PCM/FM information is primarily in the frequency domain.

These questions may remain unanswered because power conservation and low s/n ratio performance are likely less important to the geophysicist than to the missile or satellite instrumentation engineer. On the other hand, a theoretical justification of PMCM/AM or /FM is really not needed since the practical features of the approach, elimination of signal conditioning and ground processing equipment while providing the accuracy potential of a coded-binary output, are sufficient justification for its use. For this reason alone, the approach should be given serious consideration by those gathering data on natural phenomena or from other slow-changing data sources, especially those having limited equipment budgets.

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REFERENCES 1. W. H. Starling and R. J. Cowie, "A Transistorized Direct Digital Encoder for High Altitude Balloon Research," Proceedings of the National Telemetering Conference, pp 683-690, May 23-25, 1960

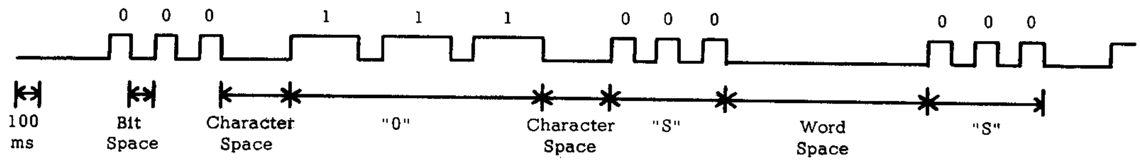


Fig. 1 - PMCM (Pulse -Morse Code Modulation) Wavetrain

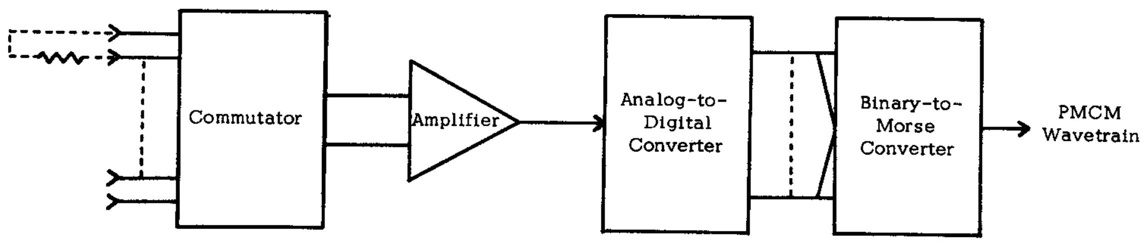
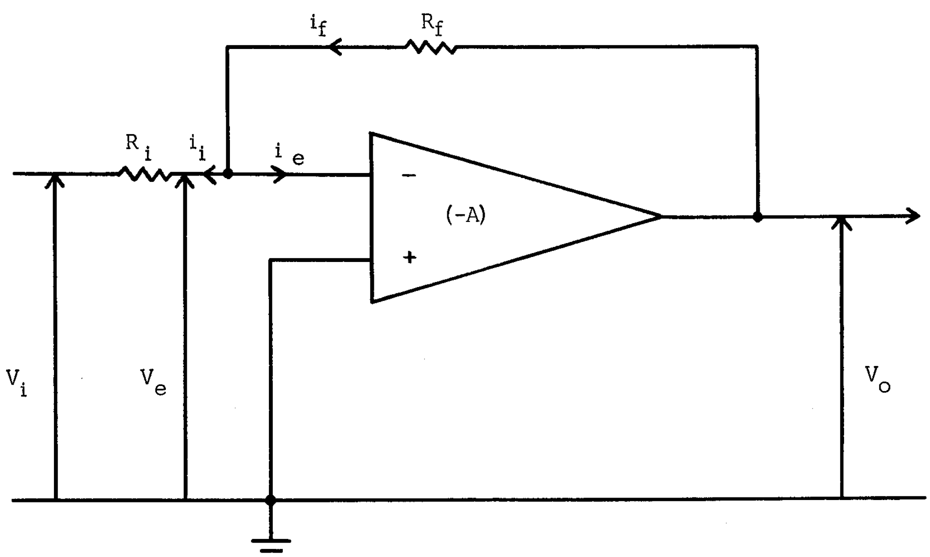


Fig. 2 - Simplified PMCM System



Where V_i = input voltage wrt amplifier ground

V_e = input error voltage wrt amplifier ground

V_o = output voltage wrt amplifier ground

R_i = input resistance

R_f = feedback resistance

i_i = input current

i_e = input error current

i_f = feedback current

(-A) = amplifier open-loop voltage gain

Fig. 3 - Operational Amplifier

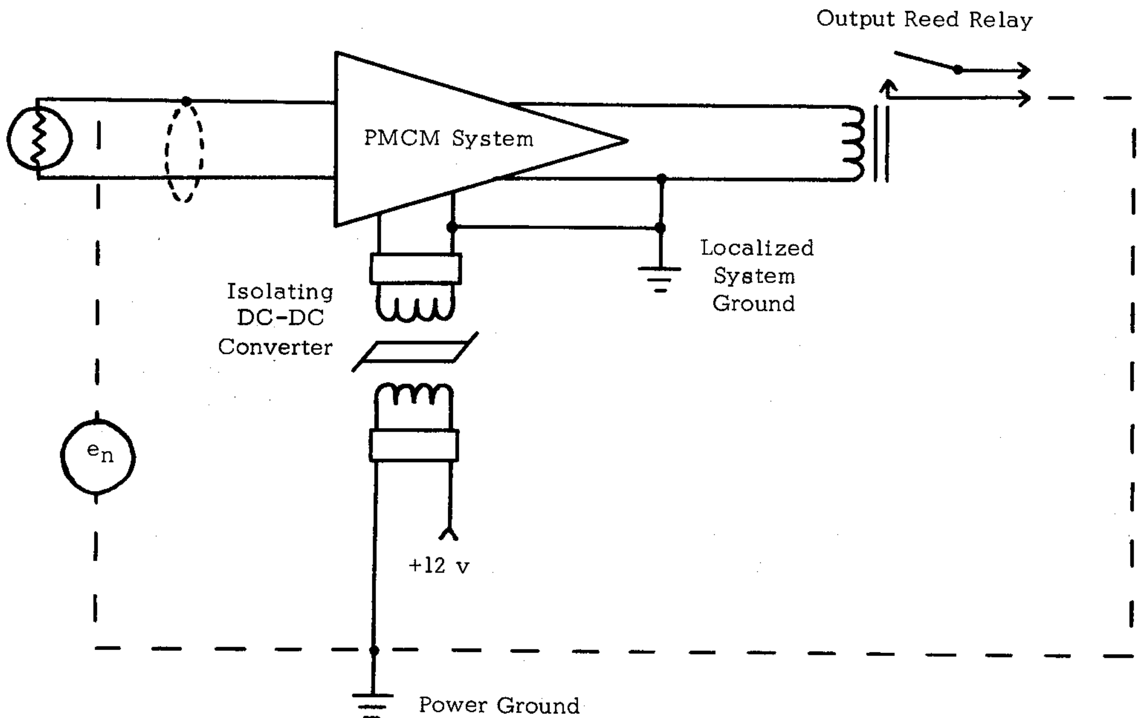


Fig. 4 - System Isolation

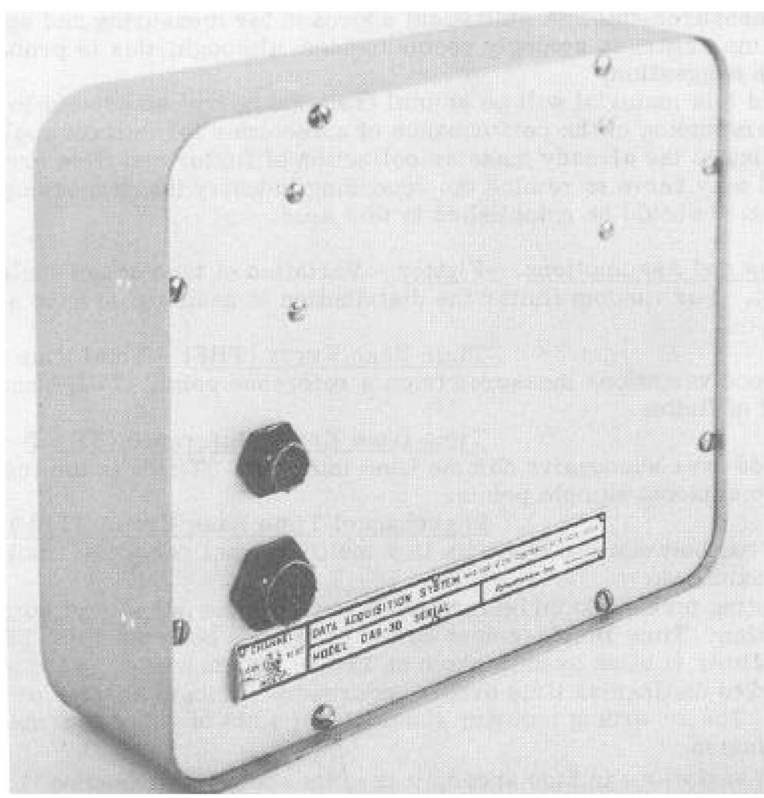


Fig. 5 - Model DAS-30 PMCM Data Acquisition System