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Balloon-Flight Instrumentation for Solar Cell Measurements

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

BALLOON-FLIGHT INSTRUMENTATION FOR SOLAR-CELL MEASUREMENTS

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Group 63

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ABSTRACT

We have developed instrumentation which automatically measures the V-I characteristics of a number of solar cells, and transmits the resultant serialized data stream over an RF telemetry link. Our particular system was designed for 64 cells whose selection is accomplished entirely by semiconductor switching. Two-hundred-and-fifty-two points are taken on the V-I characteristic, giving detailed information on slopes as well as actual values. Measurement accuracies are 0.03 percent of full scale for voltage, and 0.1 percent for current; these do not represent attainable limits, but are simply reasonable limits for this specific application. The system described was built to calibrate solar cells on a high-altitude balloon flight, but the techniques can be used equally well for ground or satellite applications.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

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BALLOON-FLIGHT INSTRUMENTATION FOR SOLAR-CELL MEASUREMENTS

I. INTRODUCTION

We have built a system capable of measuring solar-cell V-I characteristics with high accuracy and resolution. The need for such detailed measurements has become increasingly apparent in recent experimental studies. For example, Waddel's experiment[1] on ATS-1 and, more recently, our results from an experiment aboard Lincoln Laboratory satellite LES-6 (Ref. 2) have shown that short-circuit current measurements do not adequately depict solar-cell degradation in space. In each of these cases, a number of points were taken on the V-I curve of each solar cell under test; degradations observed at maximum power varied substantially from those observed at short-circuit current.

The particular system described in this report was designed to measure characteristics of solar cells in a Lincoln Laboratory experiment carried aboard a high-altitude balloon flight conducted by Jet Propulsion Laboratory (JPL). This system is capable of measuring 64 cells; the cell being measured is selected entirely by semiconductor techniques. Accuracy of the voltage and current measurements is 0.2 mV and 0.16 mA, respectively. Data are digitized and serialized by the system, and telemetered to a ground station. After reconversion to a parallel digital format, the data are recorded by a paper printer and also recorded on an incremental tape recorder for later computer processing.

II. BACKGROUND

A solar-cell calibration and degradation experiment was carried aboard LES-6 which was injected into synchronous orbit on 26 September 1968. A detailed description of the experiment, which consisted of 30 experimental cells, has been published.[3]

The solar cells for the flight experiment, plus a duplicate backup set, were calibrated in sunlight at Kitt Peak Observatory in Arizona at an altitude of ~6000 feet above sea level. Irradiance levels during the calibration tests were ~122 mW/cm^2, and a plot of these levels during a typical day is shown in Fig. 1.

The calibration values of short-circuit current I_{sc} were extrapolated to air mass zero (AM0) on the basis of the standard cell which had been employed as a calibration standard. Table I compares these values with those observed immediately following orbital injection. All cells labeled A through F are silicon cells, those labeled G are CdS cells, while those labeled H are CdTe cells. It is apparent that the post-launch values for the silicon cells are all below those anticipated; a plot of the distribution of the I_{sc} discrepancies for those cells is shown in Fig. 2. The CdS cell values show too much scatter to observe a systematic error; in addition, one would not expect the same error as that observed in the silicon cells because of spectral

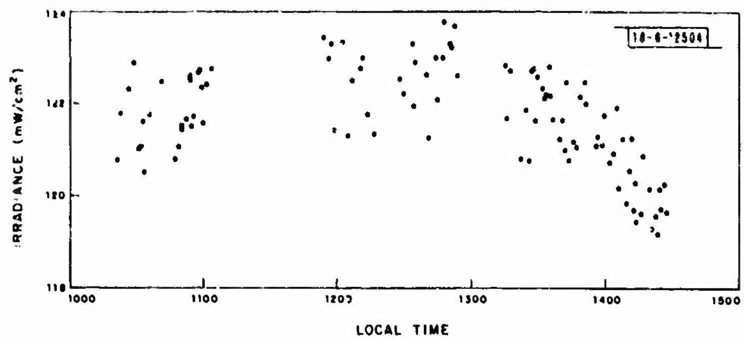

Fig. 1. Typical test period irradiance level measurements at Kitt Peak Observatory.

TABLE I

CALIBRATION AND FLIGHT SHORT-CIRCUIT CURRENT COMPARISON
(Currents in milliamperes)

Cell	Calibration	Flight	Percent Change	Cell	Calibration	Flight	Percent Change
A1	63.5	62.5	−1.5	E1	42.6	41.6	−2.3
A2	64.1	61.6	−3.9	E2	39.0	37.5	−3.9
A3	49.5	48.3	−2.5	E3	56.9	54.3	−4.7
A4	49.0	47.0	−4.1	E4	41.9	40.3	−3.7
B1	60.9	60.3	−1.0	F1	58.6	56.2	−4.1
B2	60.0	58.4	−2.6	F2	41.9	40.6	−3.1
B3	50.2	48.6	−3.2	F3	52.3	50.8	−2.9
B4	48.3	47.0	−2.8	F4	64.7	63.5	−1.8
C1	61.5	60.6	−1.4	G1	26.4	26.7	+1.0
C2	47.1	44.8	−4.9	G2	28.1	26.7	−5.2
C3	44.3	43.2	−2.6	G3	27.4	25.4	−7.5
C4	60.4	58.4	−3.2	G4	29.5	28.6	−3.2
D1	62.4	61.0	−2.[illegible]	H1	11.3	5.7	−49.5
D2	46.9	45.7	−2.[illegible]	H2	9.3	4.8	−43.7
D3	40.7	40.3	−1.1				
D4	54.9	54.0	−1.8				

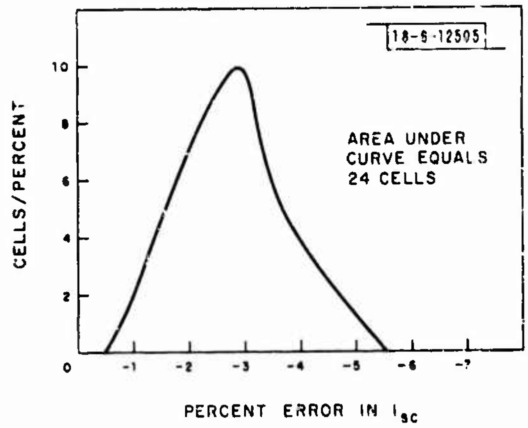

Fig. 2. LES-6 post-launch I_{sc} error distribution based on predicted values from pre-launch calibration.

differences between AM1 and AM0 sunlight. The CdTe cells had very poor contacts, and we surmise that these lifted or became resistive during launch causing the excessive degradation observed.

We suspected that the few-percent discrepancy in the silicon cell values arose from the calibration standard cell used. This was a tertiary standard, and transfer errors plus possible spectral differences between it and the original cell could easily account for the differences observed.

Through JPL, we were offered an opportunity to fly the backup panel on one of their 1969 solar-cell calibration balloon flights at 120,000 feet. Since their instrumentation measured only short-circuit current and did not have sufficient sampling channels for our cells plus those JPL wished to calibrate, we decided to build a system which would measure the V-I characteristics and telemeter the data in a digital fashion to the ground over an unused subcarrier in the JPL telemetry link. We also decided to make the system sufficiently accurate and versatile so that we could use it for prototype studies for the solar-cell experiment contemplated for our next satellite, as well as for other possible future experiments.

III. SYSTEM SPECIFICATION

The following paragraphs describe the system characteristics.

Number of Cells:— The experiment can handle any number of samples up to 64. By means of switches, the system can be made to reset to cell 1 after any given cell has been scanned; consequently, unoccupied sample inputs need not be scanned, provided they are all grouped at the end of the 64-sample sequence.

Voltage Scan:— 252 voltage steps starting from zero volts are applied to the sample. The step increment can be set to either 2.5 or 3.125 mV. Accuracy of the voltage applied to the cell is about 0.2 mV over the entire range, and over a temperature range of −25° to +75°C.

Current Measurement:— Cell currents can be measured up to 163 mA, with a measurement quantization of 0.16 mA. The current-measurement range can be scaled by changing one resistor in the system. Measurement accuracy is such that the quantization error is the only accuracy limit which need be considered over the temperature range of −25° to +75°C.

Data Format:— The serial data stream is divided into frames as shown in Fig. 3. Each frame begins with an 8-bit frame identification (ident) which is either a specific 8-bit sequence

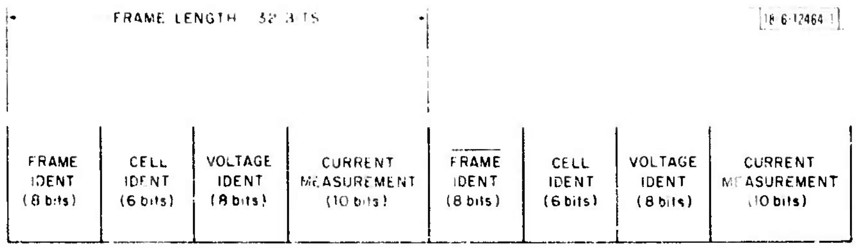

Fig. 3. Serialized data stream.

or its complement. The frame ident is followed by the ident of the cell being measured, the ident of the step of the measurement sequence, and, finally, the output of the analog-to-digital converter (A/D) for that particular measurement. The measurement sequence for a cell is comprised of 256 steps; the first 252 are voltage steps applied to the cell, and the A/D reading represents the current at those steps. During the last four steps, thermistor circuits behind the solar cells are measured by the A/D.

Operating Speed:– The system operates at about ten measurements per second, so a given solar-cell V-I characteristic is measured in about 26 seconds.

Telemetry Link:– The digital output of the system is inserted on an 18.1-kHz output with a biphase modulation technique in which the phase of the 18.1-kHz signal undergoes a 180° phase reversal each time a data zero occurs. The 18.1-kHz signal is then modulated as a subcarrier on a 230-MHz telemetry down-link.

Data Presentation:– Received data are demodulated with a phase-locked loop system and reconverted to a parallel format. The data are recorded on a Kennedy incremental tape recorder for later computer processing, and also on a paper-tape printer for experimental monitoring. A Nixie display is also provided for quick monitoring and troubleshooting.

Weight and Power:– No particular efforts were made to minimize weight and power. The flight portion of the system weighed about 3 lb and consumed about 5 W from the 26-V bus supplied by the JPL system. These weight and power numbers included the weight and efficiency of the power converter which we built for the experiment.

IV. BASIC V-I MEASUREMENT TECHNIQUE

The basic technique for measuring the cell's V-I characteristic is illustrated in Fig. 4. The cell under test is connected between two operational amplifiers, both of which are assumed to have high open-loop voltage gain and low input current. OA1 is connected as a voltage follower, while OA2 is connected in an inverting configuration as a transimpedance amplifier. Because

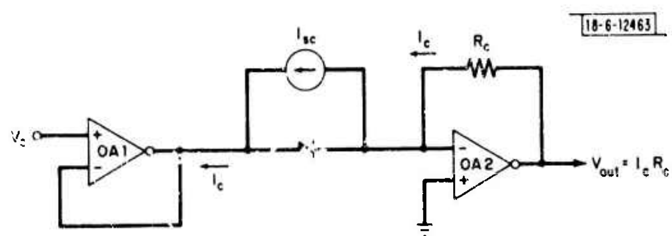

Fig. 4. Basic V-I measurement circuit.

of the high gain, the negative input terminal of OA2 is virtually at ground potential; the actual voltage is

$$V_{in} = V_{offset} - \frac{V_{out}}{G}$$

where V_{offset} is the amplifier input offset error, and G is the amplifier open-loop gain. With the high-performance IC operational amplifiers available today, V_{offset} can be reduced to under 0.1 mV; thus, with voltage gains of 25,000 and up, V_{in} can be made negligible with respect to the voltage of the cell being tested. If the input current to OA2 is also negligible, then all external cell current I_c flows through the resistor R_c and the output voltage of OA2 is $I_c R_c$. The voltage V_c appears at the output of OA1 because of its voltage-follower connection; hence, it also appears across the solar cell. Therefore, by stepping or sweeping the input voltage to OA1, we can scan the V-I characteristic of the cell.

Modification of this basic circuit to allow selection of one of a number of cells by semiconductor switching is shown in Fig. 5. To select cell 1 for measurement, devices Q_1 through Q_4 are turned ON. Q_1 and Q_2 are bipolar transistors which sink the necessary current from the solar cell. Q_3 and Q_4 are field effect transistors (FET's) which complete the voltage-follower feedback path to the cell under test. So long as the input current to OA1 is negligible, the voltage drop across Q_3 and Q_4 can be neglected and the voltage applied to cell 1 is equal to the input voltage V_c. The voltage across Q_1 and Q_2 divided by the gain of OA1 appears as an error voltage at the input of OA1, but so long as the gain is sufficiently high, this error can be neglected.

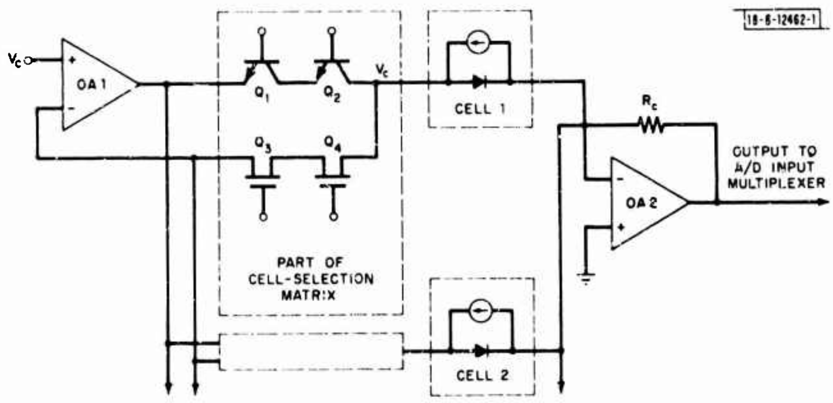

Fig. 5. Solar-cell feedback loop with selected cell.

Obviously, only one bipolar transistor and one FET are fundamentally necessary to accomplish the cell selection. The double-device realization shown in Fig. 5, however, allows a matrix design of the selection circuits, greatly reducing the decoding necessary to select cells.

It is worth noting that a remote-sense capability can be realized by employing a two-wire system on each end of the solar cell.

V. SOLAR-CELL SELECTION MATRIX

The complete solar-cell selection matrix is shown in Fig. 6. To simplify the drivers for 64 cells, an 8 × 8 matrix realization was used. One output line of each decoder/driver (D/D)

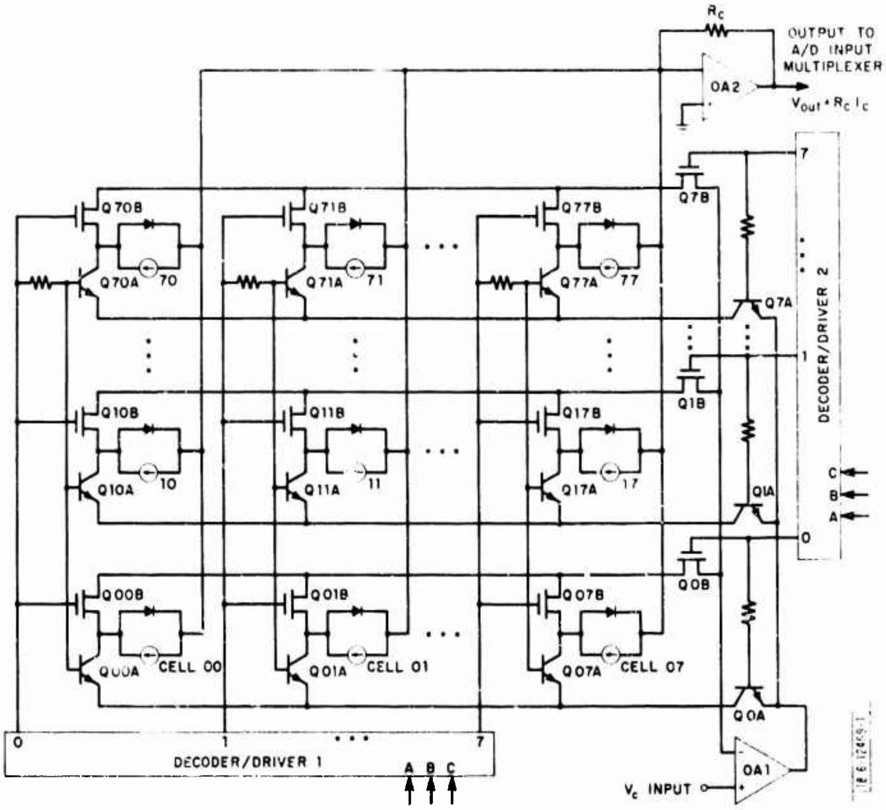

Fig. 6. Solar-cell selection matrix.

is at +15 V; all others are at −3 V. If the 0 output of D/D 2 is +15 V, Q_{0A} and Q_{0B} are ON (FET's are n-channel devices); all other devices in the vertical column ($Q_{1A}, Q_{1B}, \ldots, Q_{7A}, Q_{7B}$) are OFF. If the 0 output of D/D 1 is +15 V, $Q_{00B}, Q_{10B}, \ldots, Q_{70B}$ are ON; also, base drive is available to $Q_{00A}, Q_{10A}, \ldots, Q_{70A}$. Since Q_{0A} is ON, Q_{00A} is ON. All other devices in the matrix are OFF. The only path of ON bipolar devices from OA1 output to a cell is the $Q_{0A} - Q_{00A}$ path to cell 00. Similarly, the only MOSFET path from the negative input terminal of OA1 to a cell is the $Q_{0B} - Q_{00B}$ path to cell 00. Hence, cell 00 is the selected cell as shown in Fig. 3.

In Fig. 4, all solar-cell cathodes are connected to the virtual ground at the negative input of OA2. Since the only external current pulled from any cell is that of the selected cell, the current through R_c is the current of the selected cell.

Thus, by providing an analog voltage input V_c and digital inputs to the D/D's, an analog output voltage $R_c I_c$ is produced, where R_c is a constant, and I_c is the cell current at voltage V_c of the particular selected cell.

As described above, MOSFET's are used as the main switch in the feedback path due to the simplicity of the required drive circuitry. If the system were to be redesigned for an environment precluding the use of MOS devices, a matrix of junction FET's could be constructed, with a slight increase in the complexity of the drive circuits.

VI. SYSTEM BLOCK DIAGRAM

Figure 7 is a block diagram of the Balloon-Flight Solar-Cell-Calibration Experiment.

An 18.1-kHz Wien-Bridge oscillator provides the timing signals for the equipment and also serves as the source of a high-spectral-purity sine wave that is biphase modulated and injected directly into the down-link transmitter as a telemetry subcarrier. The biphase modulation scheme was chosen because of its narrow bandwidth and the relatively simple way to demodulate the signal on the ground.

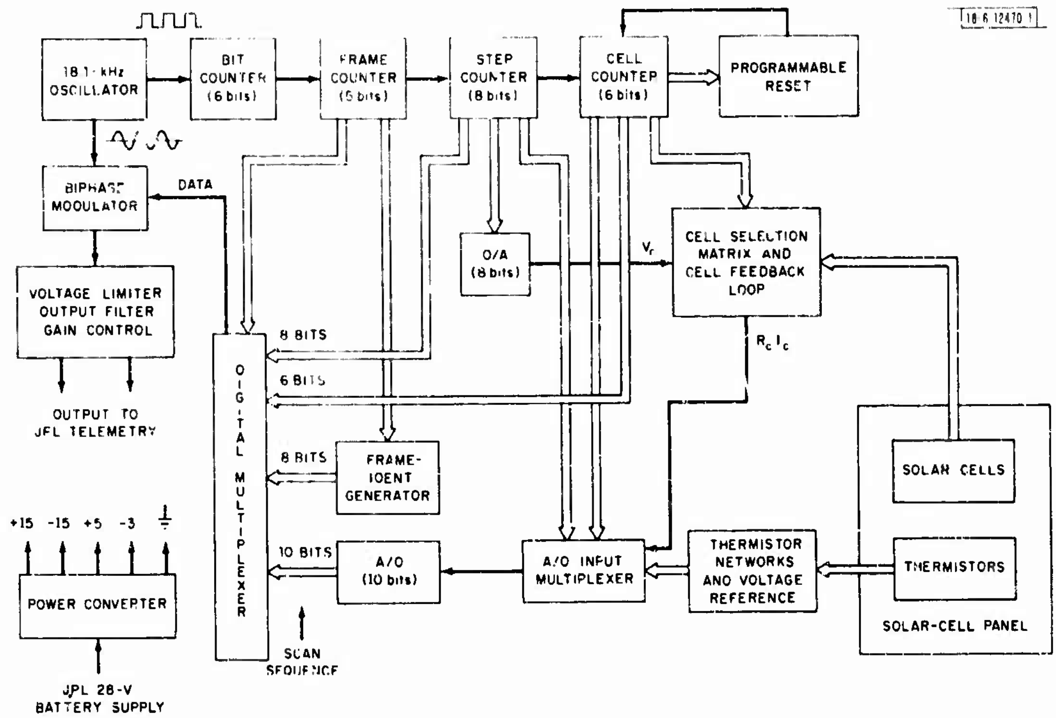

Fig. 7. Block diagram of Balloon-Flight Solar-Cell-Calibration Experiment.

In Fig. 7, the oscillator sine wave is converted to TTL logic levels and drives the Bit Counter, which divides the 18.1-kHz frequency by a factor of 64. The time for one complete cycle of the Bit Counter constitutes one output data bit. The Bit Counter advances the Frame Counter which drives the Digital Multiplexer which, in turn, presents the next data bit to the Biphase Modulator. If the data bit is a logical ZERO, the Biphase Modulator changes the phase of the output carrier by 180°; if the data bit is a logical ONE, no phase reversal occurs. Thus, a phase reversal can occur every 64 cycles of the oscillator output.

After modulation, the subcarrier proceeds through a passive voltage limiter to prevent excessive voltages from being injected into the Telemetry Link subcarrier mixer. A passive low-Q output filter suppresses signals outside the assigned pass band. The filter output is transformer-coupled to avoid DC ground loops. The signal finally goes through a passive gain control (potentiometer) to allow amplitude adjustment. All components after the Biphase Modulator are passive to prevent excessive or out-of-band signals from entering the JPL telemetry link even if a catastrophic failure occurs in the Lincoln instrumentation.

The Frame Counter controls, by means of the Digital Multiplexer, the 32-bit telemetry frame which consists of an 8-bit frame-ident word, a 6-bit solar-cell word, an 8-bit solar-cell-voltage word, and a 10-bit solar-cell-current word. The frame-ident word allows frame synchronization

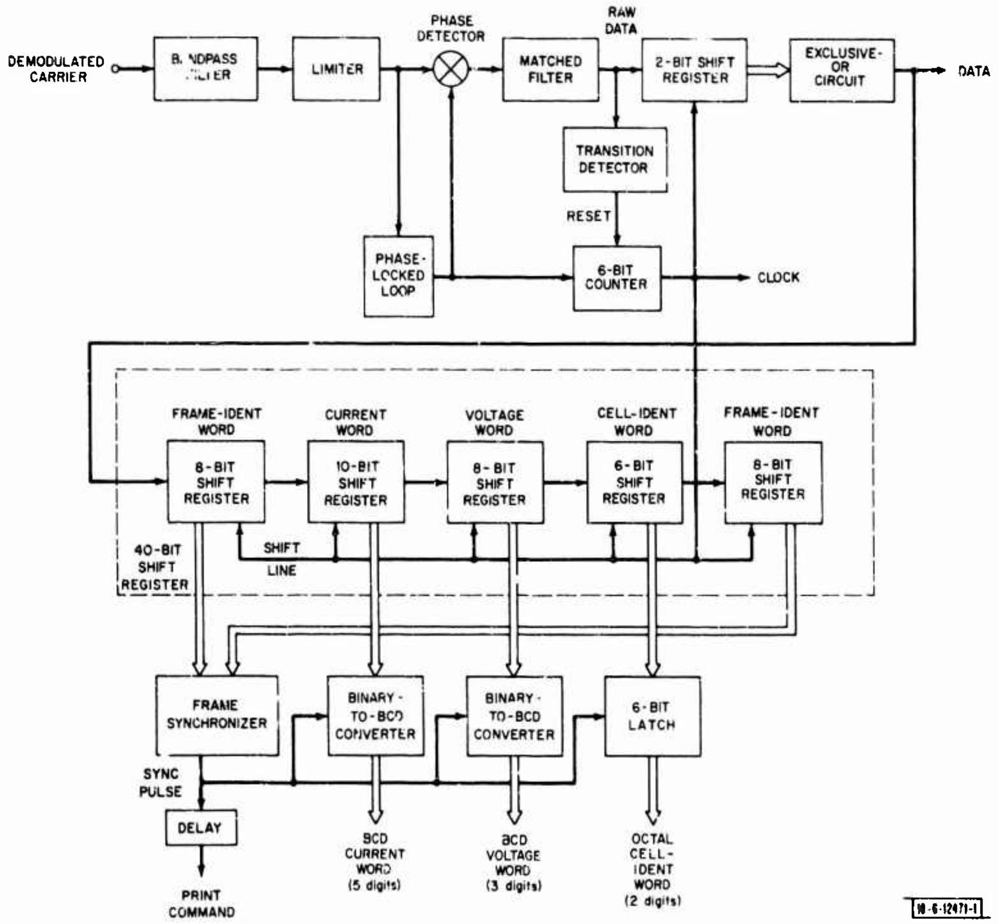

Fig. 8. Balloon experiment ground station.

of the data stream after ground-station demodulation. The particular frame-ident code was chosen to minimize the probability that the same sequence would appear anywhere else in the data stream. The frame-ident code in all even-numbered frames is the logical complement of the ident code in all odd-numbered frames. All data words are transmitted Most-Significant-Bit first.

The Frame Counter drives the 8-bit Step Counter. This Step Counter controls the voltage output of a D/A which, in turn, establishes the voltage across the particular solar cell being sampled. The output of the D/A is either 2.5 or 3.125 mV/step, depending on a switch setting.

The Cell Counter is a 6-bit counter that determines which of the 63 solar cells is being scanned. After one complete cycle of the Step Counter, which corresponds to a complete scan of the V-I characteristic of one solar cell, the Cell Counter is automatically incremented, initiating the scanning of the next solar cell. Since the system was designed to accommodate any number of cells from 1 to 63, internal manual programming switches force the sequencing to automatically recycle to cell 00 (the first cell) after any predetermined number of cells have been scanned.

The Cell Selection Matrix and Cell Feedback Loop, which have been discussed previously, select the appropriate solar cell, force the voltage across the cell to be equal to the voltage output of the D/A converter, and produce an output voltage proportional to the solar-cell current. Output voltage is transmitted to the A/D by the A/D Input Multiplexer where it is converted to digital form.

During the last four steps of each solar-cell scan, the A/D Input Multiplexer selects thermistor voltages and a reference voltage instead of the solar-cell current by means of junction-FET devices.

The A/D is a dual-slope design accurate to better than 0.05 percent; conversion time is 35 msec. The input-integration time is 16.7 msec, which greatly reduces the effects of 60-Hz pickup and facilitates ground testing of the system.

VII. POWER CONVERTER

The power converter shown in Fig. 1 is a high-efficiency DC/DC converter that incorporates a transformer flyback technique. The converter accepts all input voltage from 12 to 35 V and delivers +15, −15, +5, and −3 V from a multiple-tapped transformer. The +5-V output is regulated to better than 0.1 percent for all output-load and input-voltage variations. A total of 4.2 W is delivered at an overall efficiency of 85 percent.

The complete system employs regular-power commercial-grade TTL for logic elements. All operational amplifiers are either LM201 or LM201A (commercial grade). No attempt was made to minimize power consumption. Taking the 85-percent efficiency of the power converter into account, the complete system consumes 5 W.

VIII. TEMPERATURE EFFECTS

Although all components in the package were commercial grade (0° to 70°C), satisfactory operation was observed over a −50° to +75°C temperature range. Both the A/D and D/A have a maximum variation of 0.05 percent over a −25° to +75°C temperature range. The power converter has a linear variation of 0.015 percent over a −20° to +60°C range.

IX. GROUND STATION

After receiving the demodulated carrier from the telemetry receiver, the ground station (Fig. 8) first filters the signal to obtain the desired subcarrier and then converts to TTL levels with a hard limiter. The signal is then passed to a phase-locked loop (PLL) which is described

BALLOON FLIGHT SOLAR CELL EXPERIMENT

-8-12500

ID	VOLT	CURR	ID	VOLT	CURR	ID	VOLT	CURR	ID	VOLT	CURR	ID	VOLT	CURR	ID	VOLT	CURR	ID	VOLT	CURR	ID	VOLT	CURR
35	0.0	134.56	35	2.5	134.56	35	5.0	134.55	35	7.5	134.56	35	10.0	134.56	35	12.5	134.56	35	15.0	134.56	35	17.5	134.56
35	20.0	134.56	35	22.5	134.56	35	25.0	134.56	35	27.5	134.56	35	30.0	134.56	35	32.5	134.56	35	35.0	134.56	35	37.5	134.56
35	40.0	134.56	35	42.5	134.56	35	45.0	134.56	35	47.5	134.56	35	50.0	134.56	35	52.5	134.56	35	55.0	134.56	35	57.5	134.56
35	60.0	134.56	35	62.5	134.56	35	65.0	134.56	35	67.5	134.56	35	70.0	134.56	35	72.5	134.40	35	75.0	134.40	35	77.5	134.40
35	80.0	134.40	35	82.5	134.40	35	85.0	134.40	35	87.5	134.40	35	90.0	134.40	35	92.5	134.40	35	95.0	134.40	35	97.5	134.40
35	100.0	134.40	35	102.5	134.40	35	105.0	134.40	35	107.5	134.40	35	110.0	134.40	35	112.5	134.40	35	115.0	134.40	35	117.5	134.40
35	120.0	134.40	35	122.5	134.40	35	125.0	134.40	35	127.5	134.24	35	130.0	134.24	35	132.5	134.24	35	135.0	134.24	35	137.5	134.24
35	140.0	134.24	35	142.5	134.24	35	145.0	134.24	35	147.5	134.24	35	150.0	134.08	35	152.5	134.08	35	155.0	134.08	35	157.5	134.08
35	160.0	134.08	35	162.5	133.92	35	165.0	133.92	35	167.5	133.92	35	170.0	133.92	35	172.5	133.76	35	175.0	133.76	35	177.5	133.76
35	180.0	133.60	35	182.5	133.60	35	185.0	13[illegible].60	35	187.5	133.44	35	190.0	133.44	35	192.5	133.28	35	195.0	133.28	35	197.5	133.12
35	200.0	133.12	35	202.5	132.96	35	205.0	132.80	35	207.5	132.64	35	210.0	132.64	35	212.5	132.43	35	215.0	132.32	35	217.5	132.16
35	220.0	132.00	35	222.5	131.84	35	225.0	131.68	35	227.5	131.36	35	230.0	131.20	35	232.5	131.04	35	235.0	130.72	35	237.5	130.56
35	240.0	130.24	35	242.5	129.92	35	245.0	129.60	35	247.5	129.28	35	250.0	128.96	35	252.5	128.64	35	255.0	128.32	35	257.5	127.84
35	260.0	127.36	35	262.5	126.88	35	265.0	126.40	35	267.5	125.92	35	270.0	125.44	35	272.5	124.80	35	275.0	124.32	35	277.5	123.68
35	280.0	123.04	35	282.5	122.24	35	285.0	121.60	35	287.5	120.80	35	290.0	120.00	35	292.5	119.20	35	295.0	118.24	35	297.5	117.28
35	300.0	116.48	35	302.5	115.36	35	305.0	114.40	35	307.5	113.28	35	310.0	112.16	35	312.5	111.04	35	315.0	109.76	35	317.5	108.48
35	320.0	107.20	35	322.5	105.76	35	325.0	104.48	35	327.5	103.04	35	330.0	101.44	35	332.5	100.00	35	335.0	98.40	35	337.5	95.64
35	340.0	95.04	35	342.5	93.28	35	345.0	91.52	35	347.5	89.60	35	350.0	87.68	35	352.5	85.76	35	355.0	83.84	35	357.5	81.76
35	360.0	79.68	35	362.5	77.60	35	365.0	75.36	35	367.5	73.12	35	370.0	70.88	35	372.5	68.48	35	375.0	66.24	35	377.5	63.68
35	380.0	61.28	35	382.5	58.72	35	385.0	56.16	35	387.5	53.60	35	390.0	50.88	35	392.5	48.16	35	395.0	45.44	35	397.5	42.72
35	400.0	40.00	35	402.5	37.12	35	405.0	34.24	35	407.5	31.36	35	410.0	28.32	35	412.5	25.28	35	415.0	22.24	35	417.5	19.04
35	420.0	16.00	35	422.5	12.80	35	425.0	9.60	35	427.5	6.24	35	430.0	2.88	35	432.5	0.0	35	435.0	0.0	35	437.5	0.0
35	440.0	0.0	35	442.5	0.0	35	445.0	0.0	35	447.5	0.0	35	450.0	0.0	35	452.5	0.0	35	455.0	0.0	35	457.5	0.0
35	460.0	0.0	35	462.5	0.0	35	465.0	0.0	35	467.5	0.0	35	470.0	0.0	35	472.5	0.0	35	475.0	0.0	35	477.5	0.0
35	480.0	0.0	35	482.5	0.0	35	485.0	0.0	35	487.5	0.0	35	490.0	0.0	35	492.5	0.0	35	495.0	0.0	35	497.5	0.0
35	500.0	0.0	35	502.5	0.0	35	505.0	0.0	35	507.5	0.0	35	510.0	0.0	35	512.5	0.0	35	515.0	0.0	35	517.5	0.0
35	520.0	0.0	35	522.5	0.0	35	525.0	0.0	35	527.5	0.0	35	530.0	0.0	35	532.5	0.0	35	535.0	0.0	35	537.5	0.0
35	540.0	0.0	35	542.5	0.0	35	545.0	0.0	35	547.5	0.0	35	550.0	0.0	35	552.5	0.0	35	555.0	0.0	35	557.5	0.0
35	560.0	0.0	35	562.5	0.0	35	565.0	0.0	35	567.5	0.0	35	570.0	0.0	35	572.5	0.0	35	575.0	0.0	35	577.5	0.0
35	580.0	0.0	35	582.5	0.0	35	585.0	0.0	35	587.5	0.0	35	590.0	0.0	35	592.5	0.0	35	595.0	0.0	35	597.5	0.0
35	600.0	0.0	35	602.5	0.0	35	605.0	0.0	35	607.5	0.0	35	610.0	0.0	35	612.5	0.0	35	615.0	0.0	35	617.5	0.0
35	620.0	0.0	35	622.5	0.0	35	625.0	0.0	35	627.5	0.0												

TEMPERATURE (5) = 80.1 FOR SOLAR CELL 35
TEMPERATURE (6) = 78.6 FOR SOLAR CELL 35
TEMPERATURE (7) = 79.5 FOR SOLAR CELL 35

Fig. 9. Tabulated data from Balloon-Flight Solar-Cell-Calibration Experiment.

further in a Lincoln Laboratory internal memorandum. The PLL produces a signal of the same frequency as the original subcarrier, but without any phase reversals.

The output of the limiter is mixed with the output of the PLL and passes through a matched filter which optimizes the signal-to-noise ratio. The output of the matched filter is the "raw-data" signal that changes level every time a phase reversal in the subcarrier occurs. Every transition of the raw-data signal resets a 6-bit counter that divides the PLL output by 63. The counter output is a clock signal that is fed to the rest of the ground station. One cycle of the clock corresponds to 1 bit in the original data in the balloon package.

Since the original data were encoded as phase transitions rather than absolute phase, a comparison of the phase of the subcarrier during two successive bit times is necessary to recover the data. This comparison is accomplished by means of a 2-bit shift register and exclusive-OR circuit.

The data and clock signals are buffered for magnetic-tape recording and are also fed to a 40-bit shift register. The first 8 and last 8 bits of the register are fed to a frame synchronizer. If the frame-ident code and its complement appear in these 16 bits, the remaining 24 bits are treated as legitimate data. For random data, the probability of a false frame synchronization is approximately 1 part in 2^{15}, or 1 part in 32,000. Because of constraints on data changes between successive frames and because of the nature of the frame-ident code, the probability of a false frame synchronization is considerably less when data are being received.

The frame synchronizer controls the two Binary/BCD converters that produce the BCD-current and BCD-voltage words; these converters have storage capability. The decimal outputs are appropriately scaled to read in millivolts and milliamperes. The cell-ident word is not converted to decimal but is treated as a 2-digit octal word. The frame synchronizer also strobes the 6-bit latch that stores the cell-ident word.

The sync pulse is delayed and fed to a digital printer and an incremental tape recorder as a print/record command. The printer allows monitoring of the system during data-taking in addition to a backup data record, while the incremental tape recorder stores raw data in a form suitable for dumping into a computer for data processing.

A Nixie-Tube display was also constructed to allow visual monitoring of the experiment.

X. DATA PROCESSING

Recorded data from the incremental magnetic-tape recorder are fed into an IBM 360/67 for processing. To date, we have only carried the programming to the point of printing out tabulated data as in Fig. 9, and plotting the data as shown in Fig. 10. It is immediately apparent from the data that quite-accurate values for currents, voltages, and slopes of the V-I characteristic can be obtained with this system. With proper calibration of individual cells, the measurement of open-circuit voltage should allow temperature determination of the cell to within 0.2°C. Programming will be continued to determine the extent to which reasonable internal modeling parameters for the various cells can be derived from these data.

XI. FLIGHT RESULTS

The balloon instrumentation and launch operations are carried out for JPL by the Applied Science Division of Litton Systems, Inc., at Minneapolis. Our instrumentation was delivered to them on 2 September 1969, and because of the excellent advance cooperation of JPL and Litton personnel, integration with the JPL sun tracking and telemetry systems was quite easy (electrical check-outs were completed in less than 3 hours, and mechanical details completed in a day-and-a-half).

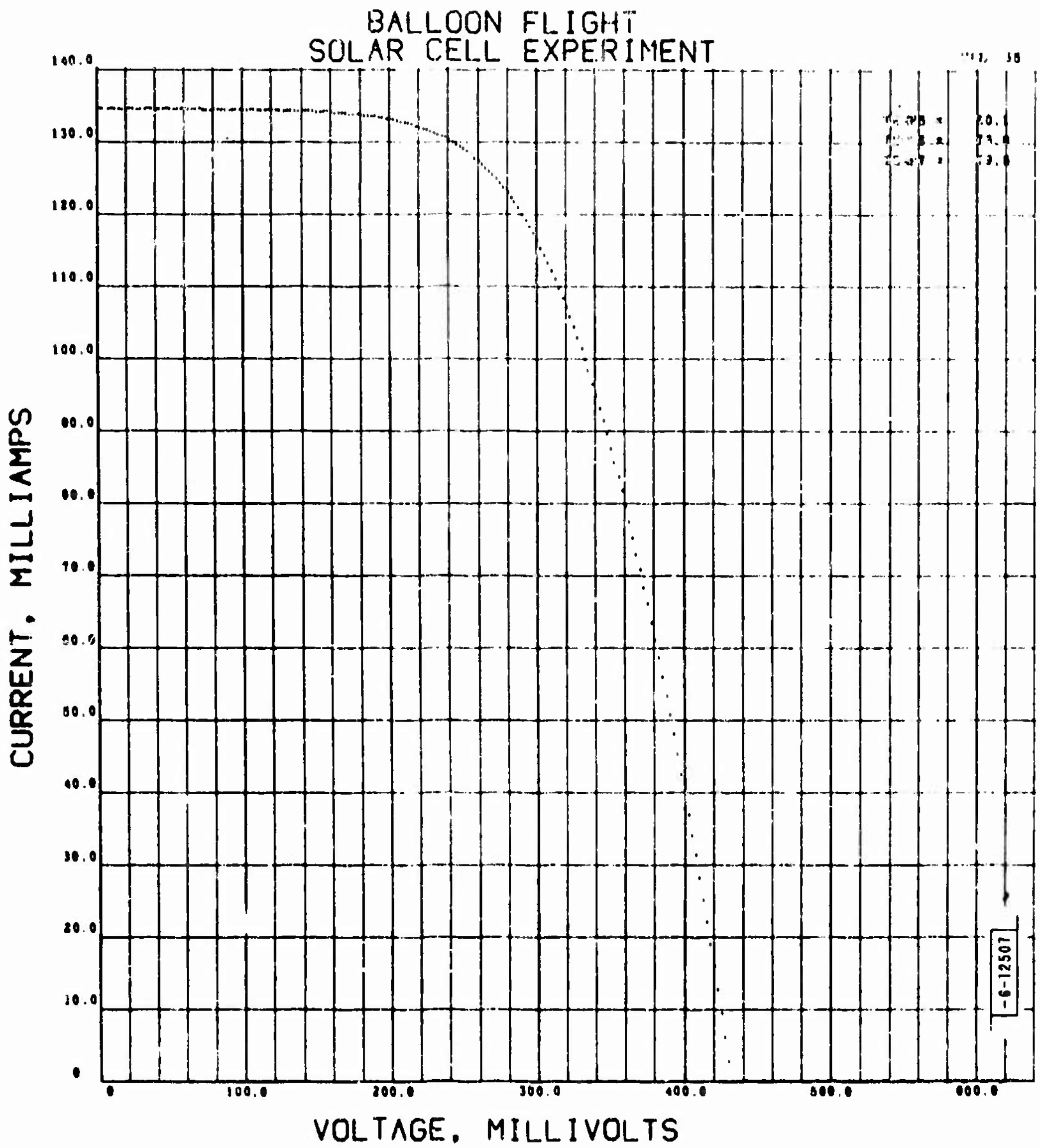

Fig. 10. Typical solar-cell characteristic for a 2- × 2-cm silicon cell.

Launch occurred at 8:30 a.m. on 8 September 1969 from an abandoned airfield at the northern edge of Minneapolis. The balloon reached its float altitude of 120,000 feet at 10:56 a.m. where it remained until 3:00 p.m., at which time descent was initiated. The experiment was recovered undamaged when the balloon landed at 7:30 p.m. in the middle of the airfield at Durand, Wisconsin, about 70 miles from the launch site.

At an altitude of 60,000 feet on the ascent, the control circuits of the JPL sun tracker were turned on. From that time until the balloon descended to 55,000 feet, the cells were maintained within 1° of normal incidence to the incident sunlight.

Because of lack of adequate heat sinking, the temperature of the Lincoln cells had risen to 60°C by the time the balloon reached its float altitude. This rise continued during float, reaching a maximum of 86°C prior to descent. However, we believe that temperature data obtained on the ascent, coupled with the high resolution of the A/D, will allow satisfactory extrapolation to lower temperatures for comparison with the LES-6 post-launch data.

XII. POTENTIAL INSTRUMENTATION MODIFICATIONS

Two areas which would require modifications of the present instrumentation are (a) use of the system in a space experiment, and (b) use of the system for ground testing of solar arrays.

In space applications, power consumption and reliability are prime considerations. Obviously, low-power circuits should be used throughout such circumstances. The use of Darlington circuits as shown in Fig. 11 can significantly reduce the power required by the cell-selection matrix. A recent design for a 32-cell experiment in a near-earth orbit resulted in a power consumption slightly in excess of 1 W (including power converter losses); about half this power resulted from the cell short-circuit current which must be drawn from voltages supplied by the power converter.

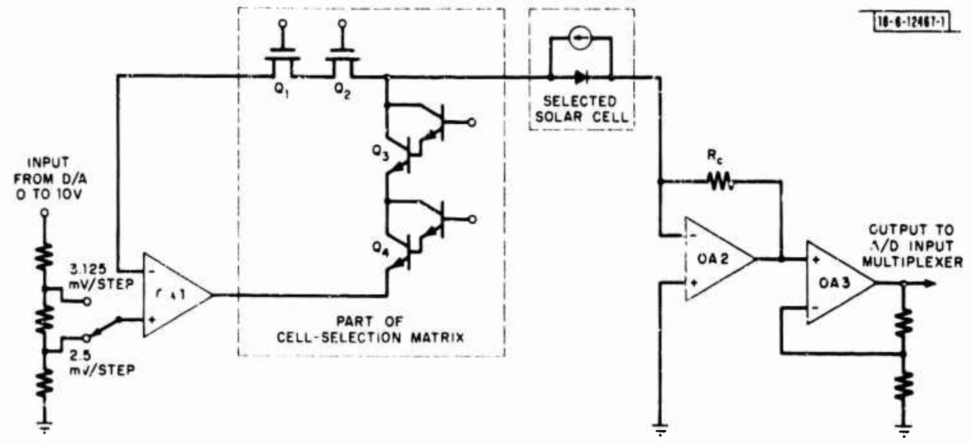

Fig. 11. Modification of solar-cell feedback loop to reduce power consumption.

At present, the degradation of MOS devices in a space environment would preclude their use in a space experiment. Modification of the cell matrix switches to use junction FET's is shown in Fig. 12.

For experiments involving large numbers of solar cells (i.e., several hundred), failure of a single device in the cell matrix or the development of leakage currents in large numbers of the matrix devices can ruin all subsequent measurements. This vulnerability can be avoided

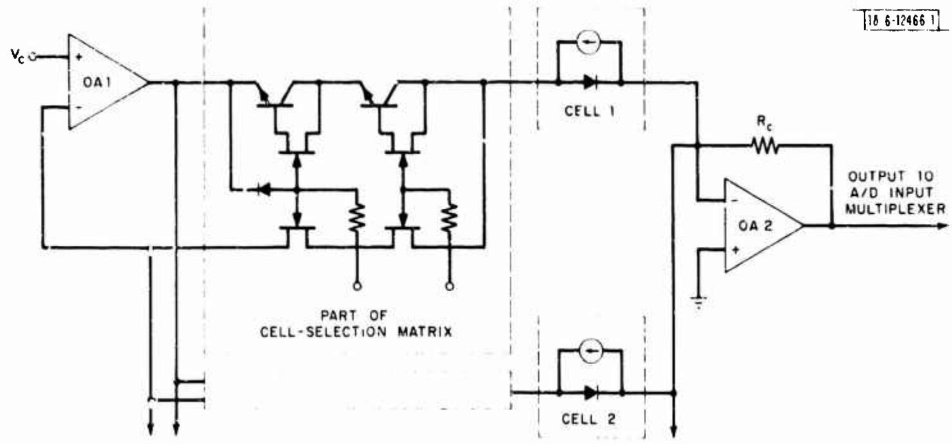

Fig. 12. Modification of solor-cell feedback loop to use junction FET's.

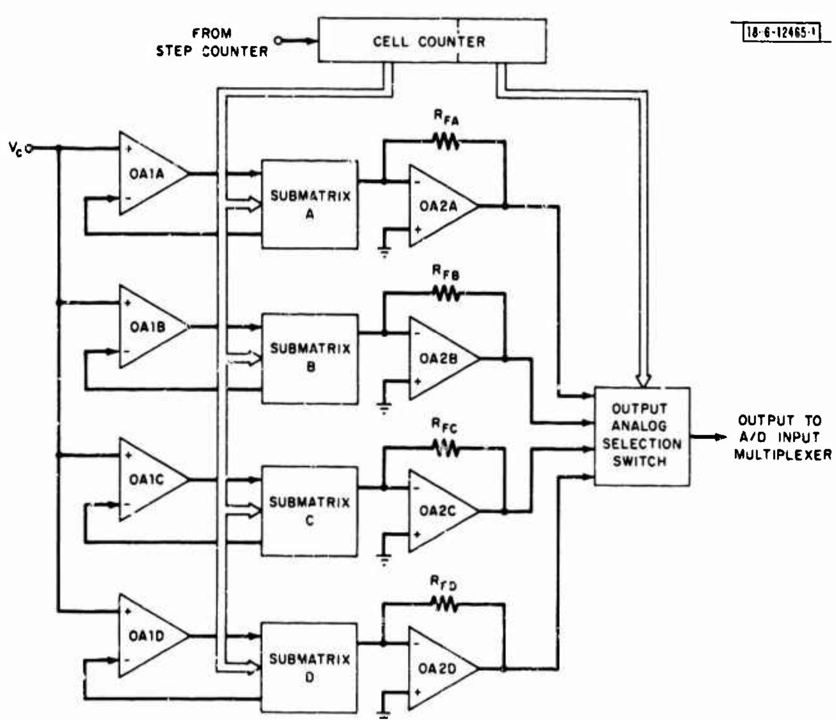

Fig. 13. Subdivided cell-selection motrix.

by dividing the matrix into submatrices, each with its own set of operational amplifiers. An example of a subdivision of four is shown in Fig. 13 where the two most-significant bits of the cell counter select the operational amplifier to be read out by the A/D; the remaining bits drive the submatrices in parallel. Although not illustrated in the figure, power drain can be kept down by turning off the OA2's which are not being read out.

It may be desirable to increase the rate of measurements for some ground or space applications. For measurements on single cells, the LES-6 system is the fastest we have accomplished to date. In this system, a given voltage is switched across 16 different cells in succession; this is far worse than switching voltage across a single cell. However, the LES-6 circuit settles out in 160 μsec; for switching voltages on a single cell, the settling time should be substantially less. Successive approximation A/D's can accomplish 12-bit conversions in less than 100 μsec. and 8-bit conversions in the 1- to 5-μsec range (the price paid is power consumption). With these numbers, a conservative rate of data-taking would be every 120 μsec for a 12-bit system and every 25 μsec for an 8-bit system, with an additional 50 to 150 μsec required for switching from one cell to the next.

The accuracies of this system, 0.1 percent of full scale for current and 0.2 mV for voltage, represent accuracy limits which are adequate for most applications. Using chopper-stabilized amplifiers with high-accuracy D/A resistive networks and suitable calibration techniques, it would be quite possible to develop a system which could maintain an accuracy (even over several years in orbit) of 0.01 percent of full scale for current and 0.01 mV for the applied voltage. Applications of such systems in orbit might be (a) measuring temperature coefficients with very limited swings in temperature, (b) measuring the effects of differing earth-sun distance throughout the year, (c) measuring the effects of short-term solar variation, and (d) determining very slow rates of cell degradation in the space environment.

It is quite possible to scale up the instrumentation to measure solar arrays or portions of solar arrays. Using high-power operational amplifiers and scaling the stepped voltage appropriately would yield a system capable of measuring most solar panels built to date.

XIII. CONCLUSIONS

Instrumentation which basically operates as a specialized incremental x-y plotter has been developed for measuring solar-cell V-I characteristics. The circuit technique was originally flown on LES-6. An improved system capable of taking V-I characteristics with substantial detail and accuracy has been constructed and recently flown on a high-altitude balloon. Accuracies of this system do not represent attainable limits, but were simply reasonable limits for this particular application. The techniques described are eminently suited for space applications as well as for many nonspace measurement situations.

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Although the authors developed the instrumentation desc . ' in this report, many other individuals obviously contributed to the ...perimént described. We wish to acknowledge particularly Dr. A G. Stanley of Lincoln Laboratory who assumed major responsibility in selecting cells for the LES-6 experiment and in interpreting results from the reduced data. Through the efforts of R. Greenwood, who manages the JPL balloon-flown cell standardizing program, we were able to have our experiment flight tested. R. D. Conlon of Litton Systems, Inc., was in charge of the balloon-flying operation itself. We also wish to acknowledge the contributions of other Lincoln personnel, namely: E. Landsman, who designed the power converter; A. Howitt and D. Bold, who were responsible for the mechanical design; and H. Holmes, P. Johnson, J. Grady and B. Case, who constructed the flight instrumentation and ground equipment.

REFERENCES

1. ..C. Waddel, "Radiation Damage Shielding of Solar Cells on a Synchronous Spacecraft," IECEC Record (1968), pp. 128-137.
2. F.W. Sarles and A.G. Stanley, "Preliminary Results from the LES-6 Solar Cell Experiment" (to be published in the Proceedings of the AIAA 3rd Communications Satellite Systems Conference, Los Angeles, 6-8 April 1970).
3. F.W. Sarles, A.G. Stanley and C. Burrowes, "The Solar Cell Calibration Experiment of the Lincoln Laboratory LES-6 Satellite," Proceedings of the 7th Annual Photovoltaic Specialists Conference, November 1968, pp. 262-268.

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13. ABSTRACT

We have developed instrumentation which automatically measures the V-I characteristics of a number of solar cells, and transmits the resultant serialized data stream over an RF telemetry link. Our particular system was designed for 64 cells whose selection is accomplished entirely by semiconductor switching. Two-hundred-and-fifty-two points are taken on the V-I characteristic, giving detailed information on slopes as well as actual values. Measurement accuracies are 0.03 percent of full scale for voltage, and 0.1 percent for current; these do not represent attainable limits, but are simply reasonable limits for this specific application. The system described was built to calibrate solar cells on a high-altitude balloon flight, but the techniques can be used equally well for ground or satellite applications.

14. KEY WORDS

solar cells	analog-to-digital conversion	field effect devices
LES-6	RF telemetry link	balloons
satellite power systems		

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