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THE BIOMETER:

A HAND-HELD BIOMASS METER

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TABLE OF CONTENTS

Page

Title Page i

Table of Contents ii

Abstract iii

Introduction 1

Development of Hand-Held Biomass Meter (Biometer). 1
Tektronics J-16 Digital Radiometer 3
Hewlett-Packard Model 35 Pocket Calculator 6
Control and Interface Circuit 8

Field Verification of Hand-Held Biomass Meter 20

Conclusion 23

Literature Cited 24

ABSTRACT

A simple hand-held instrument has been designed and constructed to nondestuctively estimate above-ground grassland biomass using radiometric measurements. The instrument has been named a biometer, short for biomass meter. The prototype unit consists of a modified two-channel digital radiometer interfaced to a pocket calculator. A digital interface was constructed to electronically join and control the radiometer and calculator to enable the biometer to solve a linear conversion solution from radiometric units to estimated biomass. This report contains a detailed description of the elctronic construction of the biometer and the results of two validation experiments which demonstrate the utility of the biometer in estimating the biomass of certain grassland plants.

INTRODUCTION

This report covers a portion of the remote sensing of shortgrass prairie experiment funded by the National Science Foundation as a part of the U.S. International Biological Program (IBP) Grassland Biome. It describes the simple hand-held device (the biometer) which was constructed to estimate the standing crop biomass of selected shortgrass prairie species in a nondestructive manner. This report also contains the results of two validation experiments which were conducted to test the accuracy and predictability of the biometer estimates. A more extensive series of validation experiments which tested the biometer at various times throughout the growing season and over several species (shrubs and forbes as well as grass) has been conducted. The results of this experiment are currently being analyzed and are not included in this report. They will be reported at a later time when the analysis is complete.

DEVELOPMENT OF HAND-HELD BIOMASS METER (BIOMETER)

Biomass measurements of shortgrass prairie vegetation have traditionally been made by hand clipping plots of known area and weighing the vegetation removed to determine its wet or dry biomass per unit area. The use of this traditional method is tedious and inefficient and prevents remeasuring the same plot again at a later date to obtain an estimate of the change in biomass with time--the productivity of the vegetation. Several methods have been devised to nondestructively estimate standing crop biomass using various techniques such as capacitance measuring, beta attenuation, ocular estimation, etc. Analysis of field spectroreflectance measurements taken at the Pawnee National Grasslands, Colorado has yielded the new concept of taking the ratio between two radiance or reflectance measurements at two selected wavelength bands to measure this biomass nondestructively. The development of this radiance or reflectance ratio technique has previously been reported (Pearson and Miller, 1972 a, b) and will not be described again here.

A simple hand-held device has been constructed which estimates the green biomass of a plot using this radiance ratio method. The prototype device consists of a Tektronics J-16 digital radiometer, a Hewlett-Packard Model 35 pocket calculator and a control and interface circuit which joins these two instruments (Fig. 1).

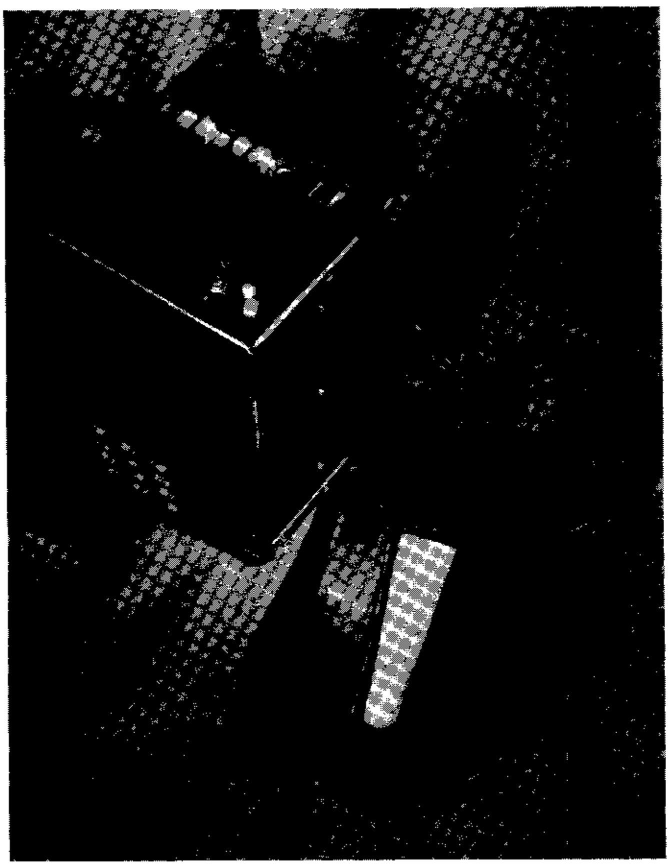

Fig. 1. Hand-held biomass meter. The instrument consists of a digital radiometer which measures the radiance from the vegetated plot with two filtered probes, a calculator which computes the radiance ratio and converts to units of biomass and a control and interface circuit which joins the radiometer to the calculator.

Tektronics J-16 Digital Radiometer

The Tektronics radiometer was modified by adding a plug and switch for a second uncorrected radiance probe. Each of the probes contains a custom built interference filter which sharply limits the wavelengths of the radiance entering the probe to that desired. The filter for probe 1 is designed to pass .800±.025 μm energy and the filter for probe 2 passes .675±.025 μm energy. The filter bandwidths were set as narrow as possible consistant with allowing enough radiant energy through to the silicon photo diode in each probe to give a sufficiently noise-free output (Fig. 2).

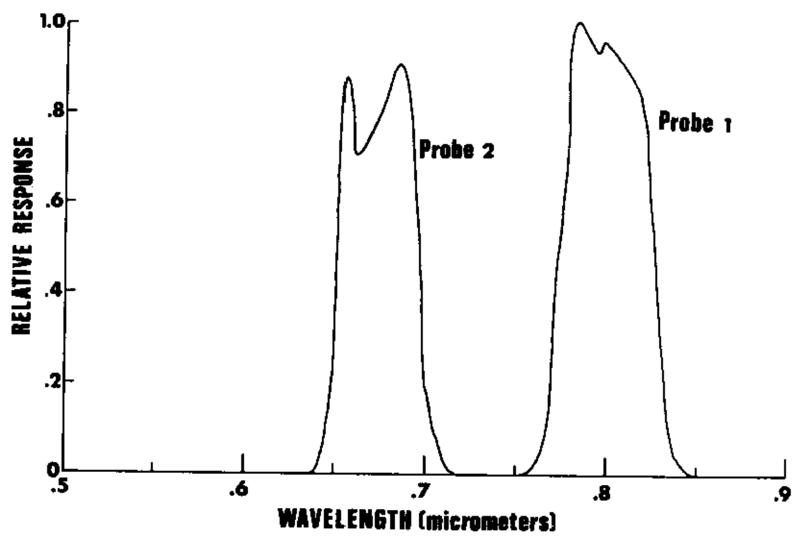

Fig. 2. Spectral acceptance of radiometer probes. Each probe consists of a silicon photo diode which views the vegetated plot through a custom made interference filter.

The probes have been internally modified to view approximately a 1/4 square meter plot from a distance of 1.25 meters (∿4 feet) instead of the entire hemisphere as originally configured. This was accomplished by moving the photo diode mount so that the diode is ∿4 cm behind the front viewing window in the probe. At this distance the probe has a 25° viewing angle or a solid angle viewed of ∿.15 steradians. Each probe contains a calibration potentiometer which allows the calibration of the probe in absolute radiometric units independent of the radiometer analog to digital conversion circuitry. Each probe also contains a READOUT HOLD switch which allows the user to store the last displayed reading as long as desired.

The photo diode in each probe generates a current proportional to the intensity of the radiance from the vegetated plot which enters the probe. This current is amplified and converted to a voltage output by the amplifier (Fig. 3). Also included in this circuit is the range selection switch which determines the radiance sensitivity of the radiometer. The output of the amplifier is connected to the integrator through the calibration potentiometer in the probe.

The remaining circuitry in the radiometer comprises a digital volt meter (DVM) and display. The integrator produces a ramp signal which varies in amplitude in response to the voltage output of the amplifier. This ramp is applied to the comparator where it is checked against a fixed reference voltage. When the ramp voltage equals the reference voltage, the comparator produces a pulse signal. The output pulse from the comparator triggers the display latches which update the display in the 2 1/2 digit readout.

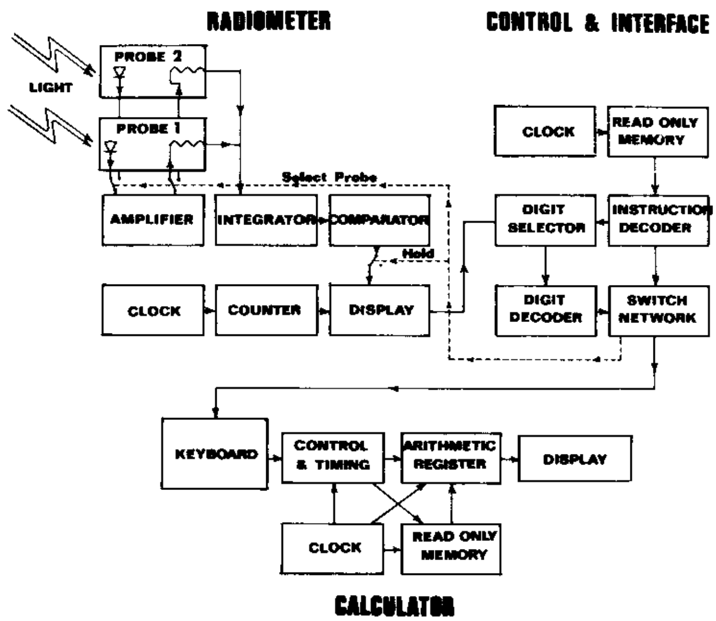

Fig. 3. Block diagram of the hand-held biomass meter. Each major function in the instrument is represented by a block. Note that the meter consists of a radiometer and a calculator which are functionally joined and controlled by the control and interface circuit.

The 7.2 KHz oscillator free-runs continuously to provide a clock signal for the DVM. This clock signal is applied to the counter circuit where it is counted to provide a digital number to the read-out and to the control and interface circuitry described later.

The readout, when triggered by the comparator, transfers the present count from the counter to latches driving the light emitting diode display on the front of the radiometer. The display is updated in this manner approximately every 80 milliseconds unless either the READOUT HOLD switch on probe 1 is switched to HOLD or the Hold A/D converter flip flop in the control and interface is set. Under either of these conditions, the radiometer readout retains the display present when the HOLD command was received.

Several convenience features are provided by Tektronics in the radiometer readout to facilitate accurate measurement. If the light intensity being measured is too great for the measurement range which has been selected, the display blinks at a 6Hz rate to call the operator's attention. Another feature is the built-in battery check feature for determining the charge level remaining in the nickle-cadmium batteries of the radiometer. When the BATT CHK button on the front panel is pressed, the battery potential is measured by the DVM and displayed on the readout.

Rechargable nickel-cadmium batteries provide operating power for the instrument. A DC-DC converter with an electronic voltage regulator provides stable voltages for accurate operation of the DVM circuitry. A protection feature is included in the power supply circuit which interrupts instrument operation to prevent battery damage when the batteries become over discharged. The batteries can be fully recharged in about 16 hours with the external battery charger. A spare battery pack and charger were purchased so that the radiometer portion of the biometer can be operated longer than the two (2) hours of continuous use provided by one battery pack.

Hewlett-Packard Model 35 Pocket Calculator

The Hewlett-Packard Model 35 Calculator was chosen as the data processor for the hand-held biomass meter for several reasons. The primary reasons are that the calculator is very small and has the ability of storing two separate constants in its working and storage registers. Another important reason was its ability to perform non-linear functions such as logarithms or exponentiation should they be required to convert radiance readings to biomass.

The calculator as supplied by Hewlett-Packard is operated from the 35 key keyboard on the face of the instrument. The keyboard is arranged in a matrix with 5 columns and 8 rows (Table 1). The keyboard is scanned sequentially by the control and timing circuit which detects a shorted condition between a particular row and column indicating that a particular key has been depressed. The calculator was modified for external operation by attaching interface lines from the biometer control and interface circuit to the rows and columns of the calculator keyboard. This arrangement allows the operation of the calculator from either the keyboard or from the external switching network contained in the biometer control and interface circuit.

Table 1. Keyboard layout of H.P. 35 and interface connector pin numbers for each row and column and calculator common.

Interface Connector Pin Number					
16	x^y	log	ln	e^x	CLR
15	$\sqrt{x}$	arc	sin	cos	tan
14	1/x	$x \rightleftarrows y$	R↓	STO	RCL
13	ENTER↑		CHS	E EX	CLX
12	−	7	8	9	
11	+	4	5	6	
10	x	1	2	3	
9	÷	0	.	π	
8 (common)	5	4	3	2	1 Interface Connector Pin Number

The calculator display is utilized to output the results of the computation. In the field situation, the light emitting diode display is hard to read in the direct sunlight. This problem as well as the problem of hand recording all of the reduced field data can be solved by attaching either a printing type calculator to the biometer in place of the H.P. 35 or a magnetic tape recorder to the general binary coded decimal output line from the H.P. 35 calculator. Both of these solutions are being studied as solutions to these problems but neither has been implemented as yet.

Control and Interface Circuit

The two "off the shelf" components of the hand-held biomass meter described above were electronically joined together with the biometer control and interface circuit. As the name suggests, this circuit has two main functions: digital interface of the radiometer to the calculator and control of both instruments to allow the solution of the biomass estimation equation.

The entire circuit was constructed on two circuit boards using RCA Complementary symmetry metal-oxide-semiconductor (COS/MOS) integrated circuits (Table 2). This type of digital integrated circuit (IC) was chosen over other types (i.e., TTL or DTL) because of the very low amount of power required for operation and the wide voltage range (5 to 15 volts) under which the COS/MOS integrated circuits can be operated. Another consideration was the high degree of functional packing of some of the IC's which allowed a lower total package count and simplified the wiring of the entire control and interface circuit (Fig. 4). The control and interface circuit was hand wired using Wire Wrap techniques to further reduce the over all size of the control and interface circuits.

Table 2. Components list of control and interface circuit. Components numbered less than 100 occur on main circuit board, greater than 100 occur on ROM circuit board.

Integrated Components

IC Socket Number	Type	Manufac-turer	Description
1 - 9	2N5458	Motorola	Fet switches soldered to 16 pin plug
10 - 13	CD4028AE	RCA	BCD to Decimal Decoder
14	CD4019AE	RCA	Quad AND/OR Select Gate
15	CD4028AE	RCA	BCD to Decimal Decoder
16	CD4049AE	RCA	Hex Inverter (replaced CD4009AE)
17	CD4028AE	RCA	BCD to Decimal Decoder
18	CD4011AE	RCA	Quad 2 input NAND Gate
19	CD4027AE	RCA	Dual J-K Master Slave Flip Flop
20	CD4001AE	RCA	Quad 2 input NOR Gate
21	CD4011AE	RCA	Quad 2 input NAND Gate
22,23	MRR1CDL	Dunco	5 volt SPDT Relay
24,25	SN5407	Texas Inst.	Hex Buffer with Open Collectors
101	CD4020AE	RCA	14 Stage Ripple-Carry Binary Counter/Divider
10102	CD4049AE	RCA	Hex Inverter (replaced CD4009AE)
103-107	CD4028AE	RCA	BCD to Decimal Decoder
108	CD4028AE	RCA	Hex Buffer (replaced CD4010AE)
109-124	16 pin sockets wired as diode programmable READ ONLY MEMORY BOARD		

Discrete Components

Component	Type
C1	.015 μf capacitor
C2	.001 μf capacitor

Table 2. Continued.

Component	Type
C3-C5	.015 μf capacitor
C6	100 pf capacitor
C7	.015 μf capacitor
D1-D5	1N118 diode
D100-D200	1N118 diode (as required for a particular ROM program)
R1	80 KΩ resistor
R2	1.0 mΩ resistor
R3	50 KΩ resistor
R4-R5	100 KΩ resistor
R6-R7	10 KΩ resistor
R8	20 KΩ resistor
R9	100 KΩ resistor
R10	100 Ω, 1 watt resistor
R11	10 KΩ variable trimmer potentiometer
R12-R20	15 KΩ resistor
R100-R104	100 KΩ resistor
Ti-T2	2N3643 silicon transistor
T3	2N2904 silicon transistor

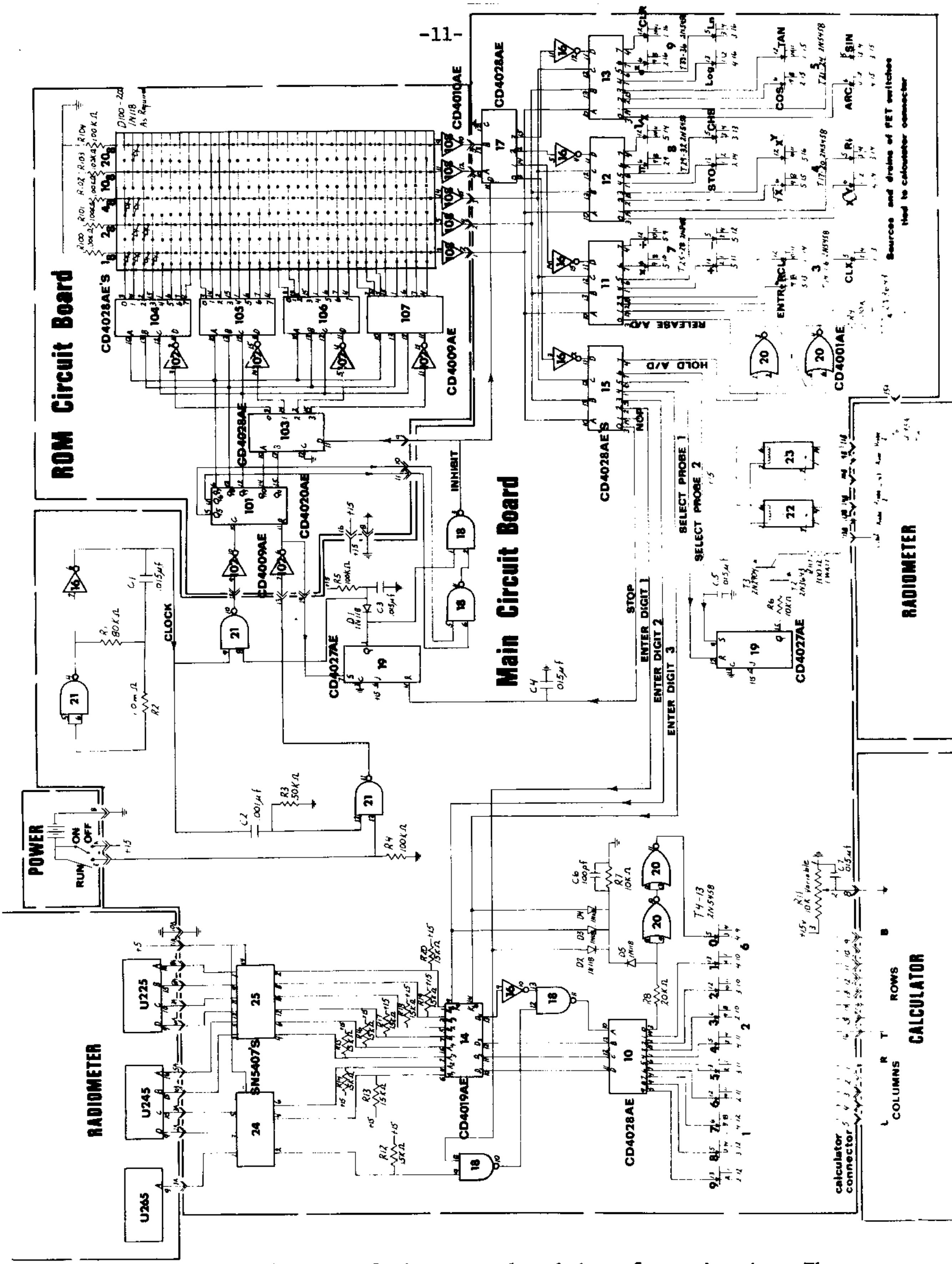

Fig. 4. Schematic diagram of the control and interface circuit. The components labled in this diagram are listed in Table 2. Locations of the components on the circuit boards are annotated on Figs. 5 and 6.

The portion of the circuit which allows the execution of a predetermined program is the read only memory (ROM). The memory is arranged in 32 addressable instructions of 5 binary bits each which allows a program of 32 steps with 2^5 or 32 possible instructions for each step.(Table 3). To retain flexibility, a diode program board was built from 16 pin IC sockets to act as the ROM rather than purchasing a preprogrammed ROM from an integrated circuit manufacturing house (Fig. 5). The diode board is programmed by plugging diodes into the board at specific addresses and in the proper pattern codes to become an operating program (Table 4).

Each instruction in the ROM is addressed sequentially from Address 1 by a counter and address decoder which is incremented by a 360 Hz clock oscillator (IC 21-2 and IC 16-3). The momentarily closed run switch which is depressed by the operator is gated through a NAND gate (IC 21-4) with a pulse generated from the clock which sets the run flip flop (IC 19-1). The clock signal is then gated through another NAND gate (IC 21-3) with the delayed Q output from the run flip flop (IC 19-1) to the clock input of the 14 stage binary counter (IC 101). The binary output from the counter is decoded in the ROM address decoder (IC's 103-107) to one selected ROM address line.

The diode pattern on the selected address line determines the coded instruction which is output from the ROM. If a diode is connected from the horizontal address line to the vertical instruction line in the ROM, the instruction line will be pulled up to a high or "1" condition. If no diode is connected, the instruction line will be held low or "0" condition by the appropriate pull down resistor (R 100-104). The binary instruction from the ROM is buffered through

Table 3. Instruction codes for control and interface circuit which can be stored in the ROM. The octal code corresponding to a particular instruction causes that instruction to be executed when the address containing the instruction code is accessed in the ROM. Codes 05-10 refer to control of the radiometer and codes 11-37 refer to control of the calculator.

Octal Code	Instruction
00	Stop execution (STOP)
01	No operation (NOP)
02	Enter digit 1
03	Enter digit 2
04	Enter digit 3
05	Select probe 1
06	Select probe 2
07	Hold A/D conversion
10	Release A/D conversion
11	Clear X register
12	Enter number into Y register
13	Recall constant from storage register
14	Add X and Y
15	Subtract X from Y
16	Multiply X and Y
17	Divide Y by X
20	Exchange X and Y
21	Rotate operating register stack down one place
22	Calculate square root of X
23	Raise X to Y power
24	Store X in constant storage register
25	Change sign of X
26	Enter π
27	Calculate reciprocal of X

Table 3. Continued.

Octal Code	Instruction
30	Compute ARC trigonometric function
31	Compute sine of X
32	Compute cosine of X
33	Compute tangent of X
34	Compute common logarithm of X
35	Compute natural logarithm of X
36	Raise e to X power
37	Clear calculator

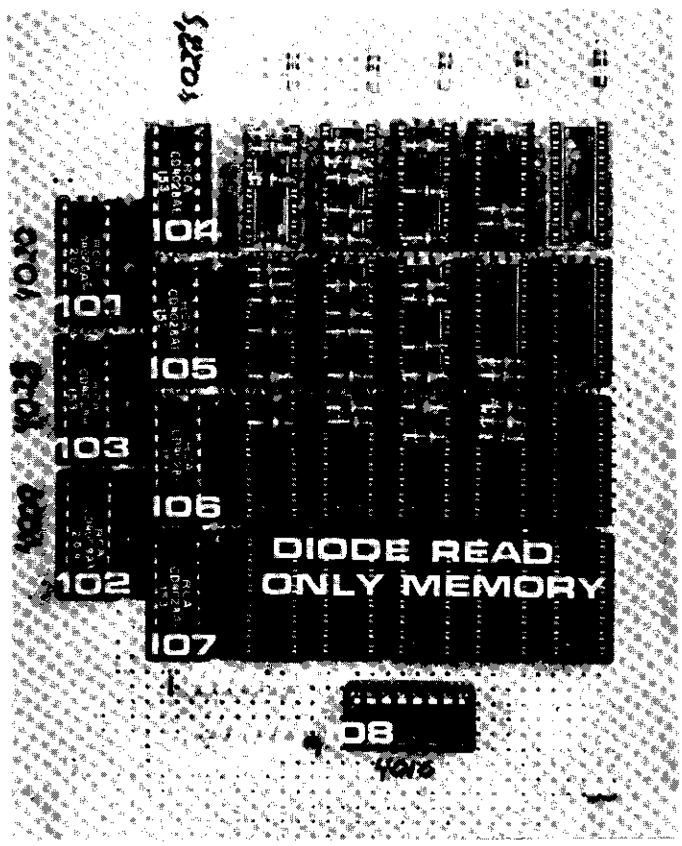

Fig. 5. Diode programmed read only memory board. The component annotations refer to the desinations listed in Table 2 and schematically diagrammed in Fig. 4.

Table 4. A typical ROM program used to read the radiances sampled by the two radiometer probes, ratio them, and convert to units of biomass in the calculator.

ROM Address	Instruction	Octal Code
1	Clear X	11
2	Hold radiometer A/D	07
3	Enter Digit 1	02
4	Enter Digit 2	03
5	Enter Digit 3	04
6	Enter number into Y register	12
7	Release radiometer A/D	10
8	Select radiometer Probe 2	06
9	No Operation (to allow time for radiometer A/D to settle)	01
10	Hold radiometer A/D	07
11	Select radiometer Probe 1 (to stop large current drain by probe select relays)	05
12	Enter Digit 1	02
13	Enter Digit 2	03
14	Enter Digit 3	04
15	Release radiometer A/D	10
16	Divide	17
17	Multiply*	16
18	Recall**	13
19	Add	14
20-32	Stop	00

* Slope of least squares linear conversion from radiance ratio to biomass is stored in the operating stack of the calculator.

** Y intercept of least squares conversion from radiance ratio to biomass is stored in the constant storage register of the calculator.

the hex buffer (IC 108) and onto the main circuit board where it is decoded in the instruction decoding network (Fig. 6).

An inhibit instruction is generated for 18 milliseconds of the 72 millisecond ROM address incrementing period to allow for circuit settling before the next instruction is addressed and executed. The inhibit instruction is generated by gating the Q5 and Q6 outputs from the address counter (IC 101) through a NAND gate IC 18-2) and gating this output with the Q output from the run flip flop (IC 19-1) through a second NAND gate (IC 18-1). The inhibit instruction is applied to the D inputs of the primary BCD to decimal decoders in the address decoding network (IC 103) and instruction decoding network (IC 17).

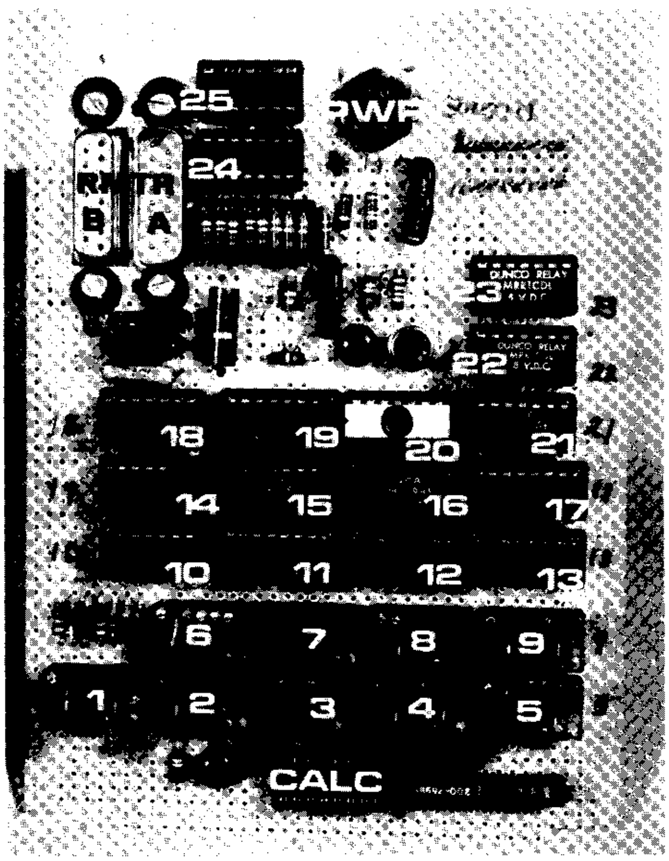

Fig. 6. Main circuit board of control and interface circuit. The component annotations refer to the designations listed in Table 2 and schematically diagrammed in Fig. 4.

The instruction decoding network converts the five bit binary instruction from the ROM to one of the 32 possible instruction commands (Table 3). The STOP command which is coded as 0_8 in the ROM enables the STOP line which resets the run flip flop and prevents the address counter from being further incremented. The NOP or "no operation" command which is coded as 1_8 allows the programming of dummy commands in the ROM to allow extra settling time in slow settling circuits (such as the analog front end of the radiometer or the calculator when it is executing an exponential or logarithmic command). Instructions 2_8, 3_8, and 4_8 instruct the digit selector to transmit one digit from the radiometer to the digit decoder (IC 10) for entry into the calculator. Instructions 5_8 and 6_8 set and reset the probe select flip flop (IC 19-2) which switch the probe select relays (IC's 22,23) from one radiometer probe to the other. Probe 2 should be selected as little as possible due to the very high current pulled by the relays when they are set. Instruction 7_8 and 10_8 set and reset the A/D flip flop (IC 20-1, 20-2) which holds and releases the A/D converter in the radiometer. Instructions 11_8 - 37_8 cause the closing of one field effect transistor (FET) switch (IC's 3, 4, 5, 7, 8, 9) which enters the appropriate command into the calculator.

The digital information from the radiometer in binary coded decimal (BCD) format is taken from the display latches in the radiometer at 5 volts, is buffered up to 15 volt COS/MOS logic levels with the open collector buffers (IC's 24 and 25), and is applied to the digit selector. The most significant digit (digit 1) from the radiometer is either a one or zero and is applied to NAND gate (IC 18-3). The remaining digits 2 and 3 are applied to the AND-OR SELECTOR (IC 14).

The enter digit commands from the instruction decoder are used to select in order the digits from the radiometer and apply them to the digit decoder (IC 10) which selects the proper FET switch (IC's 1, 2, and 6) to enter the proper digit into the calculator.

The digit decoder (IC 10) supplied by RCA as a BCD to decimal decoder does not have an inhibit feature which would disable the 0 output line even when the BCD input was 0. Therefore a zero inhibit circuit was built using a diode OR-AND gate and 2 NOR gate buffers (IC 20-3, and 20-4) to close the 0 FET switch only when one of the enter digit lines is high and the 0 line from the decoder line is high.

The power to operate the control and interface circuit is derived from an external 15 v battery pack carried on the shoulder of the operator. The 15 v operating voltage was found to be necessary to properly drive the FET switches due to the unexpectedly large switching voltages found in the Hewlett-Packard calculator (+5 to -11 volts relative to the calculator common). The calculator common was biased 11 volts above the control and interface common with a potentiometer (R 11) so that neither the source or drain voltage on the FETS when attached to the calculator would be below the "off" gate voltage causing the FET switch to close by itself. When the gate voltage is equal to the lower of either the source or drain voltage the FET switch is open. When the gate voltage is significantly above the source or drain voltage (when the instruction decoder brings the gate line high) the FET switch closes entering the appropriate command to the calculator.

FIELD VERIFICATION OF HAND-HELD BIOMASS METER

The hand-held biomass estimation device has been field tested for a portion of a growing season to verify the accuracy of the device in estimating biomass. An experiment utilizing a series of 40, 1/4 square meter grass plots was performed to test the biomass prediction capability of the reflectance ratio method used in the biometer. The 40 plots were subsampled into 2 sets of 20 plots each. The data from the first subset was input into a linear regression routine to establish the linear relationship between the reflectance ratio and the green fraction of the air dry biomass (Fig. 7). The data demonstrated a very good linear trend with a correlation coefficient of .98 between the estimated and actual amounts of green biomass on the first 20 plots. Next the linear relationship equation and the biomass values

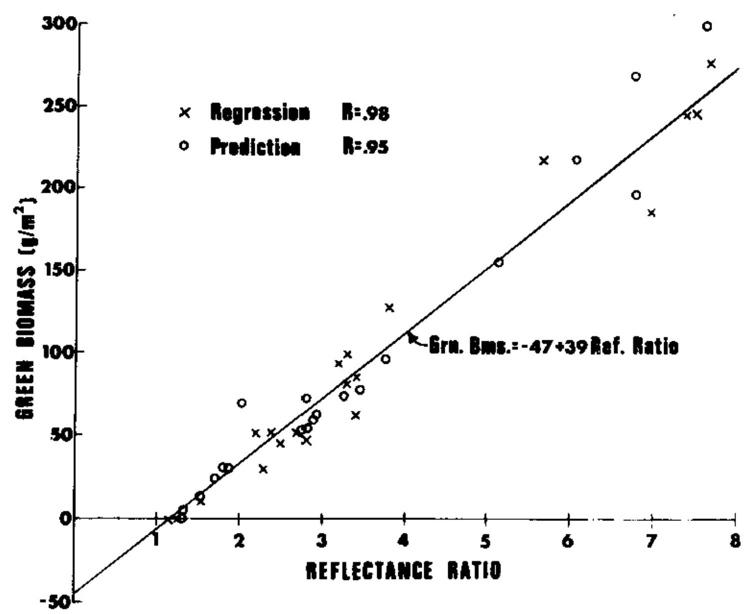

Fig. 7. Channel ratio used to predict biomass in unknown plots. The linear relationship between the channel ratio and green biomass was established on 20 plots using a least squares linear regression routine. Next the linear relationship was input into a prediction routine to predict the biomass on 20 new plots.

for the second subset of 20 plots were input into a prediction routine which computed the accuracy of prediction of the linear equation on the second subset of data (Fig. 7). The results showed that correlation coefficient of prediction for the second set of 20 plots was .95.

These results indicate that a double sampling technique of biomass estimation can be used in a field situation. The channel ratio of a few plots are measured and then the plots are clipped to determine their biomass. The linear relationship between the channel ratio and biomass is determined. Then the slope of the least squares fit for the clipped plots is entered into the operating stack of the calculator and the intercept of the least squares fit is stored in the constant storage register. The hand-held meter can then be used to nondestructively estimate the biomass of numerous other similar plots in the area.

A second simple experiment was devised to test the hand-held unit in actual field conditions. A series of 25, 1/4 square meter grass plots were chosen with a wide range of biomass. The radiance from each of the plots in each of the two spectral bands for natural solar illumination was measured by the hand-held radiometer and ratioed. Every plot was immediately clipped and the total dry biomass of each was determined. A multiple regression routine was used to determine the relationship between the ratio of the two spectral radiances measured by the hand-held radiometer and the biomass from the clipped plot (Fig. 8). The results showed a linear correlation between the spectral ratio and dry biomass of .98 for all 25 plots measured. The linear trend of the data indicated that a simple slope and intercept method of biomass estimation from spectroradiance data is adequate for the

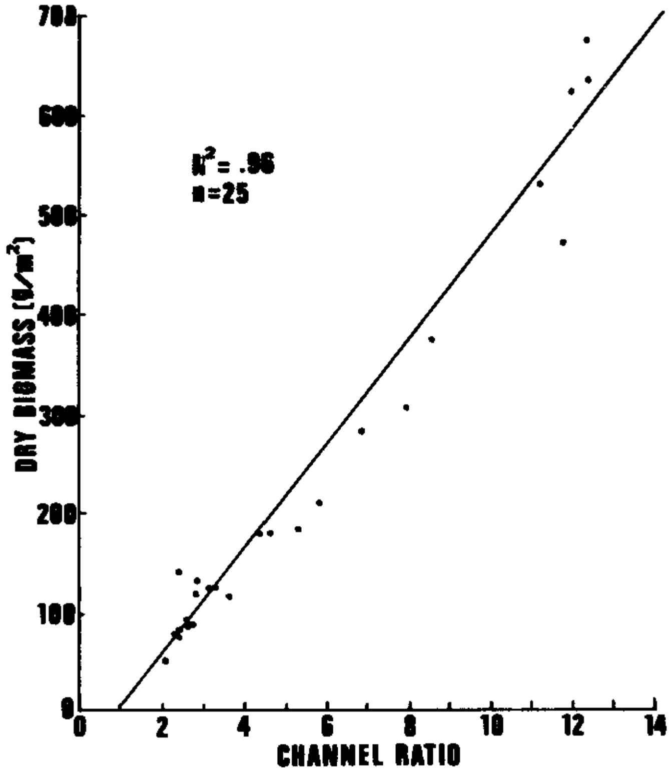

Fig. 8. Dry biomass for 1/4 square meter grass plots a function of the ratio of the radiances in 2 spectral channels. Natural solar illumination. R=.98 for 25 plots. The higher biomass plots were located in an area subjected to irrigation and fertilization.

shortgrass prairie vegetation. Other grassland vegetation types with higher amounts of biomass (greater than 500 g/m^2 for this example) may require the use of a nonlinear estimation due to the inability of the radiometer to equally sample radiances from lower leaf layers in a multiple leaf layer vegetation canopy. There is every reason to presume, however, that the device will work for heavier biomass ranges and for forbs and shrubs. Data to test these expanded applications has been collected and is currently being reduced.

CONCLUSION

The nondestructive biomass estimation device (biometer) described in this report has been shown to be accurate in the estimation of the above ground biomass of small area grass plots. Additional data which has been collected and is currently being evaluated indicates that the biometer is accurate for some forbes and shrubs as well as grasses occurring at the Pawnee National Grasslands, Colorado.

The prototype biometer was constructed using off-the-shelf components wherever possible to reduce construction time and increase flexibility. Now that the feasibility of such a unit has been proven, a second generation device can be designed and constructed which will omit the unnecessary features in the components of the first prototype unit thus reducing cost and providing a unit designed for simple field use.

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