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A Microcomputer-Modified Particle Size Spectrometer

Description and Program Listings

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A MICROCOMPUTER-MODIFIED PARTICLE SIZE SPECTROMETER

Description and Program Listings

by

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ABSTRACT

A fully automated aerosol particle size spectrometer system is described that consists of a light scattering particle sensor, an analog to digital converter, and a microcomputer with associated printout device. The system is capable of acquiring a differential particle size distribution, printing the resulting spectrum in one of three representations, and repeating the procedure at preselected intervals. An example of the application of the system for measuring an outdoor aerosol size distribution is presented.

The appendices contain documented microcomputer program listings and flow charts for Program Sizer (the program that operates the spectrometer system and the principal result of this study) and Program MCA (a program that converts part of the spectrometer system to a conventional 256-channel pulse height analyzer).

This report covers a period from September 1976 to December 1977, and work was completed as of December 22, 1977.

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ACKNOWLEDGEMENTS

The enthusiastic support and encouragement given to this project by Robert K. Stevens, Chief, Atmospheric Instrumentation Branch, is happily acknowledged. Paul J. Lamothe made important microcomputer programming contributions during the early stages of this project.

SECTION 1

INTRODUCTION

Recently a new device - the microprocessor - has become readily available. The impact of this device on future analytical instrumentation and control systems promises to be at least as great as that of the minicomputer in the past. For the experimental research scientist, a microcomputer is a particularly convenient form in which to use a microprocessor. A microcomputer usually consists of a central processor unit (the microprocessor), memory, and interface circuitry all present on a single printed circuit board. The resulting "computer on a board" has most of the desirable features of a minicomputer: (1) flexibility of a stored program in contrast to hard-wired circuitry, (2) high speed operation, (3) capability for interruption by peripheral devices requiring service, and (4) interface compatibility with a variety of peripheral devices. The important difference, however, is that the microcomputer is significantly smaller in size and lower in cost than a minicomputer by roughly an order of magnitude. Furthermore, the cost savings are magnified by the usage of comparatively inexpensive peripheral devices, for example, ordinary audio cassette recorders for the magnetic tape recording medium. Thus many possibilities now exist for the incorporation of microprocessors or microcomputers in stand-alone instruments that could not justify the cost of a minicomputer.

An aerosol particle size spectrometer system that uses a $245 microcomputer is described here. The system is able to (1) acquire a differential size distribution simultaneously over 19 intervals of equal logarithmic size between 0.3 and 11 μm diameter, for an arbitrary preset counting time, (2) print the size distribution directly in a number, surface or volume representation, and (3) repeat the cycle indefinitely for unattended operation. The system has obvious predecessors, for example, in the work of Whitby et al (1972a), but the present system seems to be particularly attractive in terms of cost, convenience, and flexibility.

A condensed version of the present report is available elsewhere (Lewis and Lamothe, 1978). The most significant part of the report is the appendices, which contain documented listings of the microcomputer programs developed in this study, and which have not been published previously.

SECTION 2

SYSTEM DESCRIPTION

HARDWARE

A photograph of the assembled system is shown in Figure 1; the block diagram form is shown in Figure 2. Each component of the system is described below.

Sensor

A Model 208 Particle Analyzer (Climet, Inc.) was used to generate an analog voltage pulse for each aerosol particle drawn into the analyzer from the ambient atmosphere. The height of each pulse (produced by light scattering from the particle as it passes through an internal light beam) is monotonically related to the size of the particle and is available at a standard coaxial connector at the rear of the unit. Additional circuitry within the analyzer, conventionally used to count all particles larger than several selectable size thresholds, was not used. The CALIBRATE ADJUST circuitry was retained however as it provided a convenient means to set the total gain of the Climet unit. Any one of several commercial particle sizing instruments based on light scattering could be used as a sensor for the system. The Climet unit was chosen because of its unique optical system, which not only produces the important monotonic character of the response function, but also causes the response to be nearly independent of refractive index (Cooke and Kerker, 1975).

Figure 1. Aerosol spectrometer system.

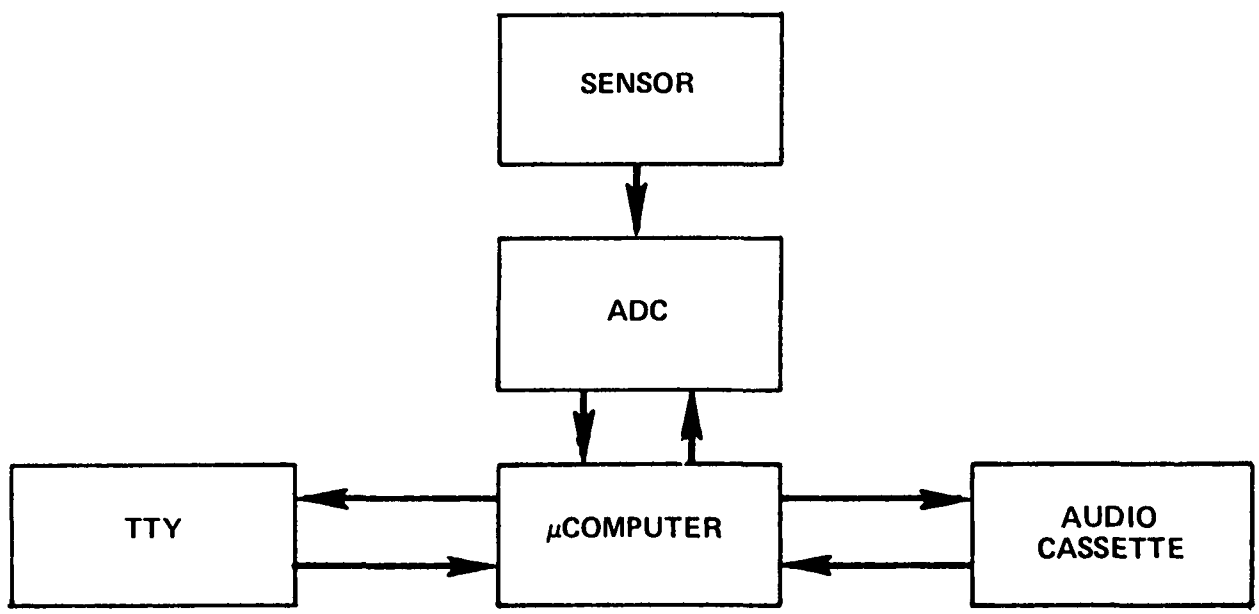

Figure 2. Aerosol spectrometer block diagram.

Analog to Digital Converter (ADC)

Each pulse (approximately Gaussian shape, several microsecond duration) from the sensor was fed directly to an 8192 channel 50-MHz Analog to Digital Converter (Tracor Northern, Model TN-1211). A simple resistor network voltage divider was added to the ADC input to attenuate the input pulse by about 20%. This change produced a better match between the nominal 10 volt maximum output of the Climet unit and the 8 volt maximum input of the ADC. The ADC converted each pulse to a 13 bit binary number proportional to the pulse height. At the end of conversion the ADC generated a positive TTL level which was used to signal the microcomputer that an event was ready to be transferred. After transfer, the ADC was cleared and made ready for the next conversion by receipt of a positive TTL pulse of about one μsec duration, generated by the microcomputer. The particular ADC used was only one of several alternatives which would have been suitable.

Microcomputer

A KIM-1 microcomputer (MOS Technology, Inc.) served as the interface between the system's input and output components and provided the intermediate data storage medium. The device is shown in Figure 3. The heart of this "computer on a board" is a 1-MHz 8-bit microprocessor (MOS 6502). The 26 by 21 cm board also includes (a) a keyboard and 6-digit light-emitting diode (LED) display, (b) interface and control circuitry for teletypewriter and audio magnetic tape cassette additions, (c) a program stored in read only memory (ROM), which constitutes a complete operating system for the LED/keyboard, teletypewriter, and audio cassette, (d) storage for user written programs and data, in the form of approximately 1100 8-bit words of random access memory (RAM), (e) 15 individually programmable input-output lines, in addition to others dedicated to teletypewriter and cassette use, and (f) a 1-MHz programmable clock for interval timing applications. All of these features were used in the system described here.

A 16-conductor connection is necessary between the ADC and microcomputer (13 data inputs, a "ready" input, a "clear" output, and, of course, a

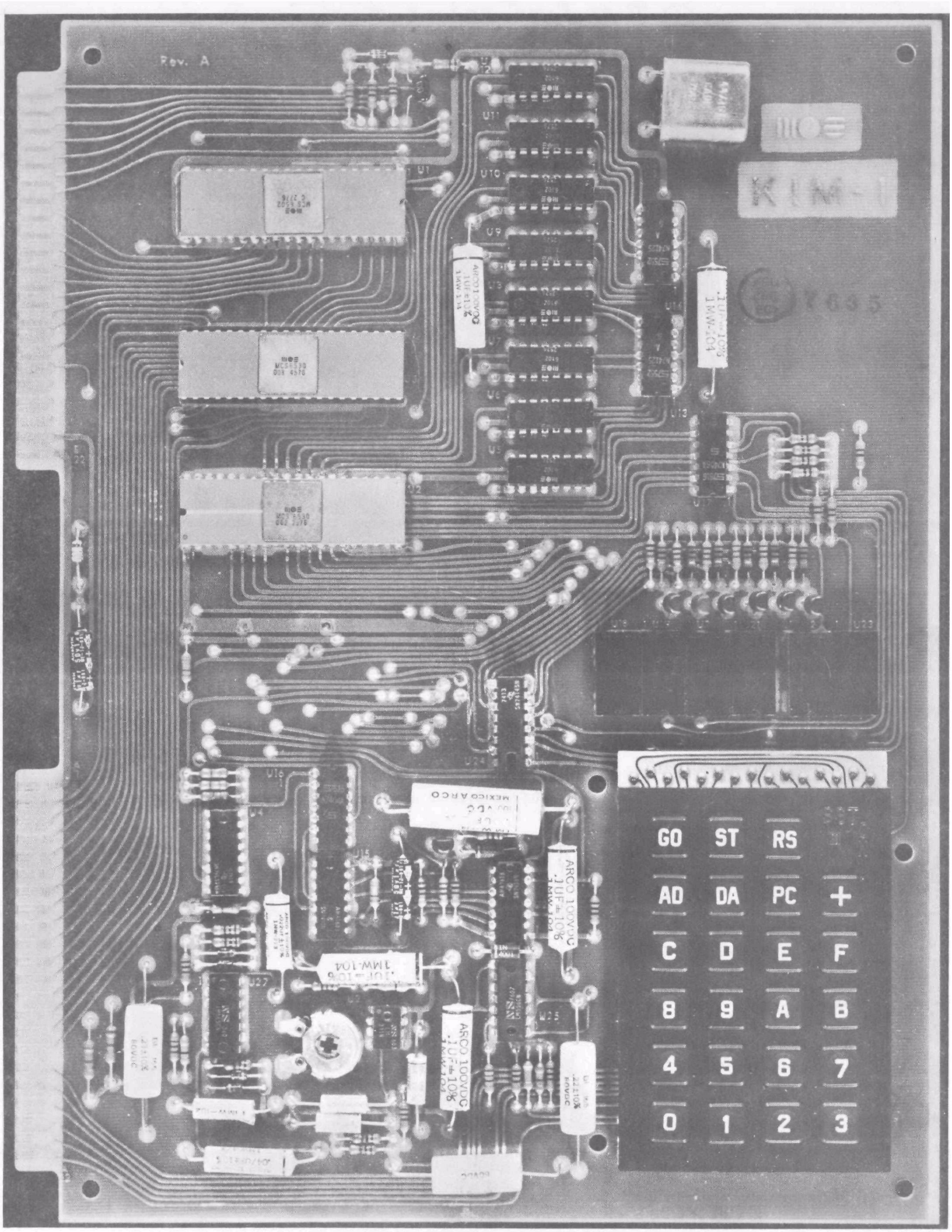

Figure 3. KIM-1 Microcomputer.

ground line). The teletypewriter involves a 4-line connection; the cassette recorder involves a 3-line connection. It is important to appreciate that the task of interfacing peripheral devices to the microcomputer is essentially trival since all active circuitry to drive these devices is an integral part of the microcomputer itself.

The microcomputer requires +5 and +12 VDC, the latter voltage being necessary only if an audio cassette recorder is used. An Econo/Mate II dual power supply (Power/Mate Corp.) furnished both voltages. All electrical connections between the microcomputer and the rest of the system components are given in Table 1.

The microcomputer is the least interchangeable system component, since the spectrometer system was designed around the special features of the KIM-1 unit. There are, however, several other microcomputer systems presently available with features similar to those of the KIM-1 unit. Most of these probably would be suitable as the basis of a spectrometer system like the one reported here.

Teletypewriter and Audio Cassette Recorder

The system used a Model ASR33 teletypewriter, so that keyboard, printer, and paper tape read and punch functions were all available. However, any 20-mA current loop serial teleprinter could be used, because the KIM microcomputer is capable of adjusting to the teleprinter's bit rate over a large range of rates. A similar flexibility exists with regard to choice of a magnetic tape recorder. A medium priced non professional recorder has been used with the system.

SOFTWARE

The program ("Sizer") written to control the operation of the spectrometer occupies nearly all of the user available RAM of the microcomputer. It consists of three segments -- acquisition, transformation, and output. A complete listing may be found in Appendix A. It is also available upon request in the form of punched paper tape.

TABLE 1. INPUT/OUTPUT CONNECTIONS

Microcomputer Connector Pin	I/O Port Designation	I/O Signal
A-A		+5 VDC
A-14	PA0	A0 (ADC LEAST SIGNIFICANT BIT)
A-4	PA1	A1
A-3	PA2	A2
A-2	PA3	A3
A-5	PA4	A4
A-6	PA5	A5
A-7	PA6	A6
A-8	PA7	A7
A-10	PB1	A8
A-11	PB2	A9
A-12	PB3	A10
A-13	PB4	A11
A-16	PB5	A12 (ADC MOST SIGNIFICANT BIT)
A-15	PB7	STORE (ADC READY SIGNAL)
A-9	PB0	CLEAR (ADC RESET SIGNAL)
A-R		TTY KEYBOARD RETURN
A-S		TTY PRINTER RETURN
A-T		TTY KEYBOARD
A-U		TTY PRINTER
A-1*		GROUND (FOR ADC, AUDIO RECORDER, +5 and +12 VDC)
	OPTIONAL:	
A-L		AUDIO IN (EARPHONE JACK)
A-M		AUDIO OUT (MICROPHONE JACK)
A-N		+12 VDC

*A jumper wire must connect pins A-1 and A-K. Also if the teletypewriter keyboard, instead of the microcomputer keyboard, is used as the input device a jumper wire must connect pins A-21 and A-V.

Acquisition

Upon receipt of a "ready" signal, the microcomputer accepts an ADC binary number, and a "clear" signal is generated that prepares the ADC to accept its next input. The ADC binary number is compared with successive pre stored values in a table with the values arranged in order of increasing size. Each value in the table corresponds to a boundary between the adjacent particle size bins. When the ADC number is found to exceed a table value, the content of a memory address corresponding to the appropriate size bin is incremented by one. The cycle repeats until either the number of counts in any size bin exceeds 99×10^6 or a variable preset time is exceeded, which can be any integral number of minutes between 1 and 99.

The primary consideration in designing the acquisition program segment was to make its execution time as fast as possible. The result was a program efficient in execution time, but inefficient in memory storage. Although the linear search procedure used to locate the proper bin size is generally considered to be very slow, it is time efficient in the present application because ambient aerosol size distributions are so strongly biased toward particles of small size. Similarly, it was important that the ADC be reset as quickly as possible so that ADC acquisition of the next event could occur simultaneously with microcomputer sorting of the previous one. Finally, because it was awkward to deal with 13-bit ADC numbers, no more than 8 of the most significant bits were used in the search procedure.

Transformation

The data are transformed by multiplying each bin content by either of two prestored numbers proportional to the average volume or surface area corresponding to a spherical particle in that bin size. This step is omitted if a raw number representation of the data is desired.

Output

The data are printed on the teletypewriter in a table giving 19 values of average particle diameter and the number, surface, or volume value (in 4-place floating point decimal form) corresponding to each diameter. The total numbers of particles of sizes greater and less than an arbitrarily chosen size are also printed, as well as the data acquisition time interval. A cassette recorder was not used in this automatic output system, but one could be used to store data through manual intervention by the operator.

SECTION 3

CALIBRATION

The table of pre stored values with which each ADC number is compared constitutes the calibration constants of the spectrometer system. These constants depend on the electro-optical properties of the sensor and ADC components, and on the user's choice of parameters for the size intervals into which the particles are to be classified. Intervals of equal logarithmic width were used, because of the resulting desirable features in ambient aerosol studies (Whitby et al., 1972b). In choosing the number of size intervals, the basic consideration was to realize the intrinsic resolution capability of the sensor, within the constraint imposed by the amount of microcomputer memory. Accordingly, each decade of particle size was divided into 12 intervals and centered such that the midpoint (logarithmic) of the last one occurred at exactly 10 μm. Thus a series of 19 midpoints $\bar{D}_i$ and 20 boundary values D_i were generated from the relations

$$\text{Log } D_{i+1} = \log D_i + 1/12$$

and

$$\log \bar{D}_i = (\log D_{i+1} + \log D_i)/2$$

with $\bar{D}_{19} = 10$ μm. The resulting values of $\bar{D}_i$ and D_i are listed in Table 2.

To convert the boundary values from their representation in terms of particle size to the corresponding ADC values, a calibration curve was required. A simple program was written for the microcomputer (The program

TABLE 2. SIZE INTERVAL CALIBRATION CONSTANTS

$\overline{D}_i$ (μm)	D_i (μm)	Ch. No. (Decimal)	Ch. No. (Hex)	Ch. No. (Binary)	Calib. Const.	Address
0.316	0.348	25	19	0000000011001	19	002F
0.383	0.422	34	22	0000000100010	22	0035
0.464	0.511	45	2D	0000000101101	2D	003B
0.562	0.619	58	3A	0000000111010	3A	0041
0.681	0.750	74	4A	0000001001010	4A	0047
0.825	0.909	94	5E	0000001011110	5E	004D
1.00	1.10	120	78	0000001111000	78	0053
1.21	1.33	156	9C	0000010011100	9C	0059
1.47	1.62	207	CF	0000011001111	CF	005F
1.78	1.96	288	120	0000100100000	09	00AB
2.15	2.37	416	1A0	0000110100000	0D	00B1
2.61	2.87	576	240	0001001000000	12	00B7
3.16	3.48	832	340	0001101000000	1A	00BD
3.83	4.22	1216	4C0	0010011000000	26	00C3
4.64	5.11	1760	6E0	0011011100000	37	00C9
5.62	6.19	2560	A00	0101000000000	50	00CF
6.81	7.50	3680	E60	0111001100000	73	00D5
8.25	9.09	5344	14E0	1010011100000	A7	00DB
10.0	11.0	7808	1E80	1111010000000	F4	00E1

listing is given in Appendix B) which converted it to a 256-channel pulse height analyzer, with which the frequency distribution, or spectrum, of pulse heights could be obtained for any series of pulses input to the ADC. (By means of the ADC's digital offset switches, the 256-channel "window" could be moved to any portion of the ADC's full 8192 channel range.) Individual spectra were then obtained by passing several monodisperse polystyrene latex aerosols through the sensor. All but one of the aerosols (4.96 μm) were generated with a Collison nebulizer from Dow stock solutions highly diluted with water, in accordance with the precautions of Fuchs (1973). The dilution factors ranged from 8000:1 to 150:1 for particle sizes between 0.357 and 2.02 μm. The stock solution for the 4.96 μm aerosol was obtained from Duke Scientific Corp. (Palo Alto, California) in very dilute form (about 10^6 particles/ml). For each aerosol the nebulizer output was diluted 10:1 with clean dry air, and passed through a Kr85 radioactive charge neutralizer and a 17-liter settling chamber before entering the particle sensor. A composite spectrum based on most of the individual monodisperse aerosol measurements is shown in Figure 4. The widths of the peaks are all dominated by the intrinsic resolution of the particle sensor. The center channel for each of the peaks is plotted in Figure 5. The curve shown in Figure 5 is the one supplied with the Climet sensor, but with the vertical axis linearly scaled to best fit the measured points.

Obtaining the calibration constants from the curve in Figure 5 is straightforward in principle, but somewhat complicated in practice due to the decision to deal with no more than 8 of the possible 13 bits constituting each ADC value. In Table 2 the numerical steps by which the constants were derived are explicitly indicated. Column 3 lists the ADC channel number, obtained from the curve in Figure 5, corresponding to each size interval boundary (column 2). Columns 4 and 5 convert the decimal numbers of column 3 to their hexadecimal and binary representations, respectively. For those ADC channel numbers whose binary representation involve eight bits or less, the corresponding calibration constant (column 6) is identical to the hexadecimal value from column 4. For those numbers requiring more than eight bits, the corresponding calibration constant is derived from the hexadecimal equivalent of the eight most significant bits of the binary

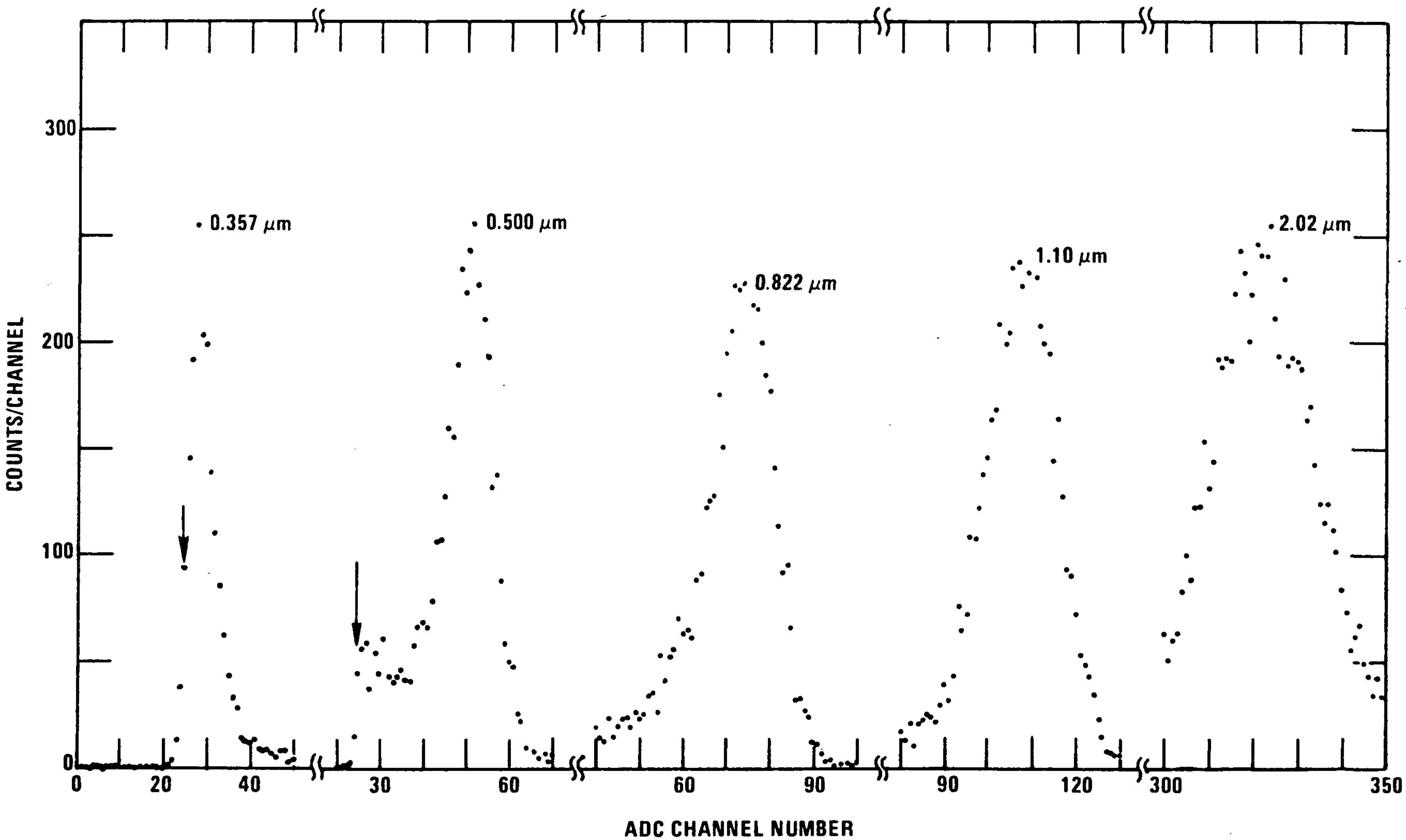

Figure 4. Polystyrene latex aerosol calibration spectra. Arrows indicate the ADC threshold.

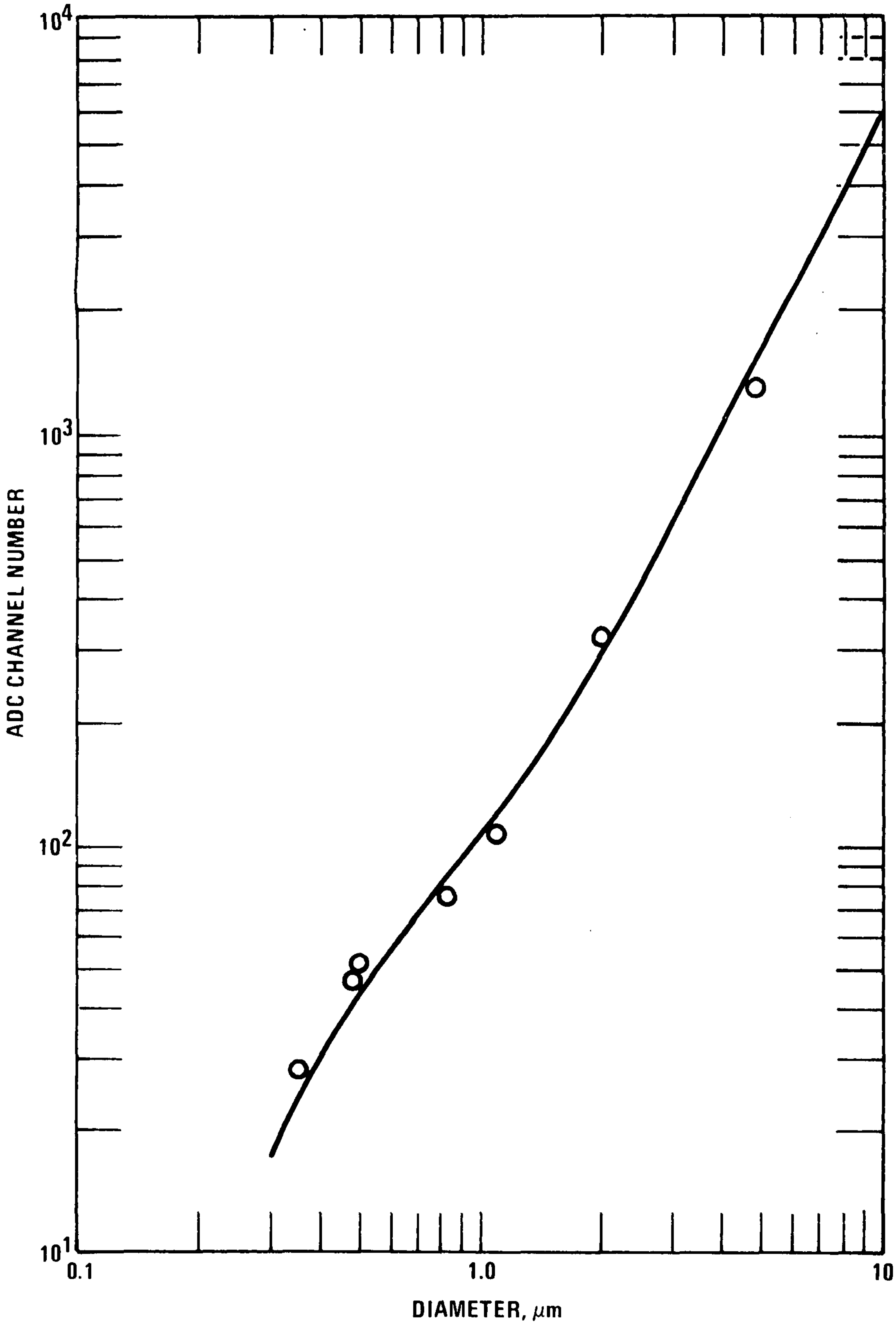

Figure 5. ADC channel vs. PSL particle diameter.

representation. In either case that portion of the binary representation being utilized is underlined in column 5. Finally, column 7 gives the address in the microcomputer program at which each calibration constant is stored.

A cautionary note should be added, relating to the calibration procedure. The set of numbers in column 3, being derived from an experimental curve, naturally have some degree of uncertainty. In arriving at a final best set of values, it is important that a candidate set be examined regarding the widths of the size intervals (i.e., the differences of successive pairs of entries in column 3) that result from that choice. If the widths are not a smooth function of particle size, the measured aerosol size distributions will exhibit "scatter," which is not actually present in the sample itself. The width vs. size relationship for the calibration constants in Table 2 is shown in Figure 6.

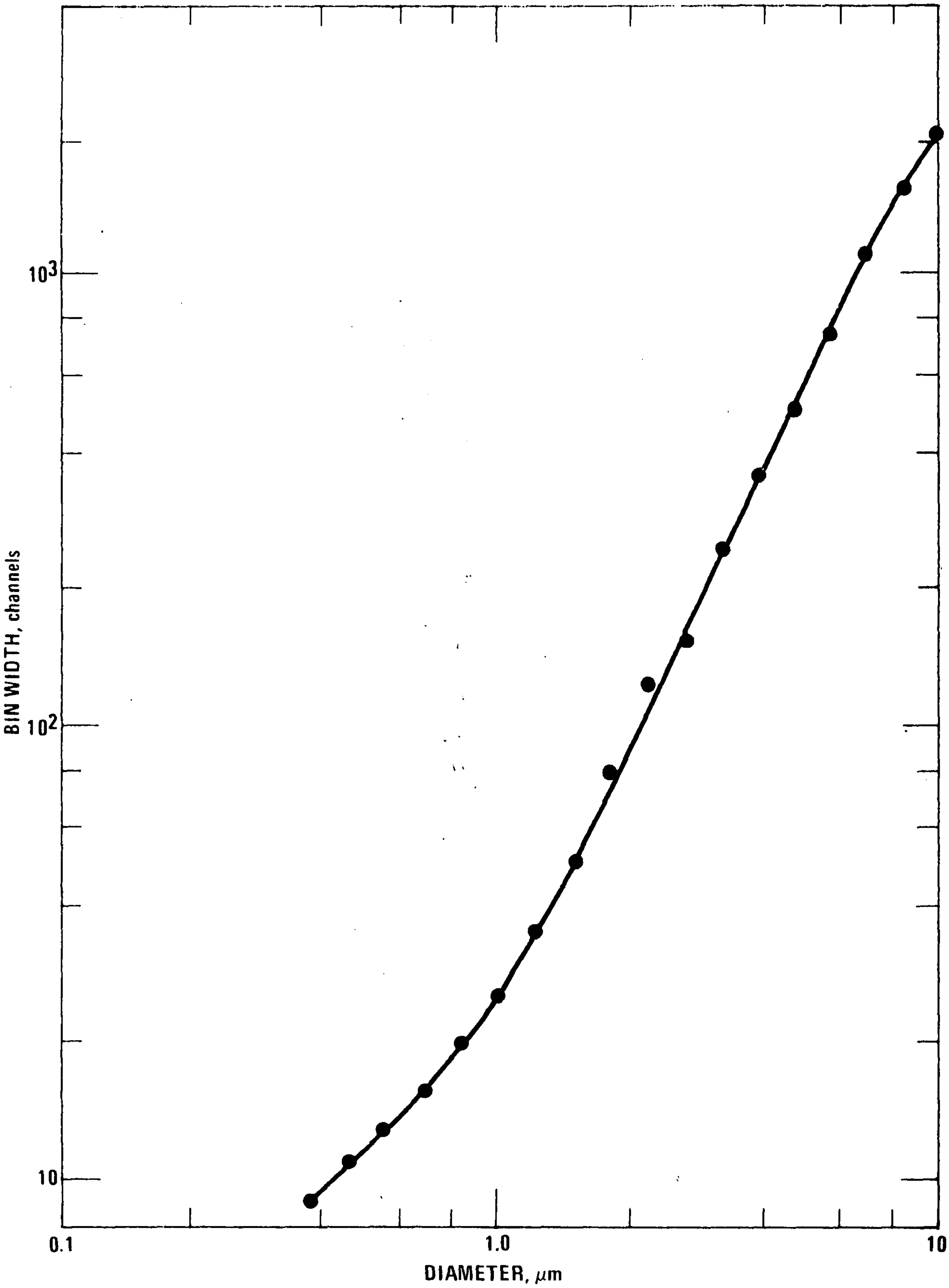

Figure 6. Size interval width vs. particle diameter.

SECTION 4

RESULTS

The spectrometer system has been used to make many measurements of ambient aerosol size distributions since its assembly. Figure 7 shows results from a representative measurement performed between 10 and 11 a.m. EDT on August 9, 1977, on the roof of a three-story building in Research Triangle Park, North Carolina. The figure presents the results in three forms: (1) the teletypewriter tabular output, (2) a plot of the tabular values, and (3) a histogram derived from the counting circuitry of the Climet Particle Analyzer, which is normally bypassed.

In the teletypewriter output shown in Figure 7, the average particle diameters (in μm) for each size interval constitute the left column, with the floating point decimal content (fraction plus power of 10 multiplier) of each on the right. The content of the smallest size interval (0.32 μm) is affected by an ADC threshold and should be neglected. It is retained in the output for diagnostic purposes, to aid in setting the ADC threshold. The first element of the automatic output is the number of minutes (hexadecimal) used during data acquisition. This is followed by a character that identifies the form of the output, in this case signifying the choice of a "volume" representation of the data. For convenience the last two lines of the output give the measured total number of particles below and above a threshold that may be arbitrarily set at any of the size interval boundaries. In the present case the threshold is such that the "above threshold" sum includes all 19 size intervals. The resulting "number" representation is independent of the representation chosen for the 19 size intervals. The tabular and plotted values differ by a constant factor

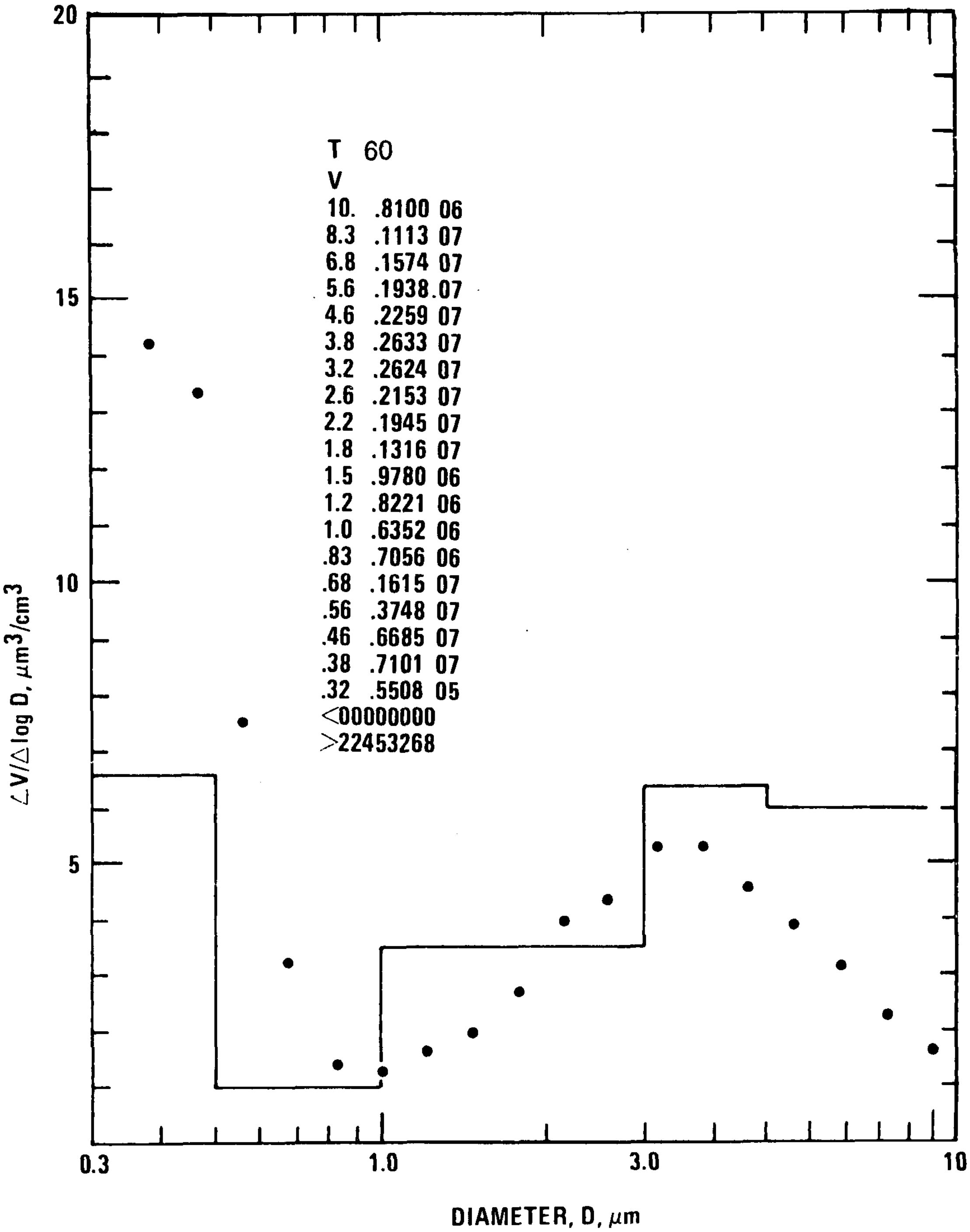

Figure 7. Outdoor ambient aerosol size distribution results. The histogram was derived from sequential readings recorded manually from the Climet, while during the same time interval the microcomputer automatically accumulated and printed out the tabular data shown. The plotted points are the same as the tabular data, to within a calculated proportionality constant.

which contains the aerosol flow rate through the sensor and the measuring time interval.

In Figure 7 the Climet-derived histogram and the microcomputer result are at least in qualitative agreement, in that their magnitudes are generally consistent and both show the bimodal character anticipated for outdoor ambient aerosol volumetric size distributions. There are at least two reasons for the observed differences between the Climet and microcomputer results. The first is that each element of the Climet histogram had to be obtained by taking the difference of two successive integral measurements. As a result each integral measurement occupied on average only about 20% of the time during which the microcomputer spectrum was acquired. Thus changes in the actual aerosol size distribution during the full 1-hr measuring period could have contributed to measured differences between the two methods. Secondly, the relative coarseness of the Climet size intervals can cause substantial uncertainty when the volume transformation factors (D^3) are applied. While the total variation in the value of the transformation factor between the extremes of any microcomputer size interval is 78%, the corresponding maximum variation across a Climet size interval is about 33 times larger! Both considerations vividly illustrate the improved quality of data that can be obtained with the modified system.

It should be noted that the results shown in Figure 7 have not been corrected for the particle size dependent sampling efficiency of the Climet aerosol inlet. While this omission has, of course, no effect on the relative agreement between the results of the two methods shown in the figure, the general effect of its inclusion would be to shift the position of the mode above 1 μm to a larger size (Liu et al., 1974). In passing, it may be noted that the latter mode was conspicuously absent in measurements performed indoors, as anticipated.

SECTION 5

DISCUSSION

The spectrometer system described here has a number of desirable features: (1) a choice of different representations is possible in the data output, (2) the output data consists of "better" size intervals (a greater number and more thoughtfully chosen) than are usually available, (3) the calibration can be easily changed, if the system is used on particles having unusual index of refraction values, and (4) the system components have a high degree of substitutability.

The system can be improved in several ways. While teletypewriters enjoy the advantage of frequent availability in laboratories, their choice as the output medium is archaic and costly relative to newer and more compact printers that are well suited to microcomputer usage. Secondly, the system's data acquisition rate is limited by the speed of the microcomputer. For a Junge distribution of aerosol particle sizes ($dN/dD \propto D^{-4}$) the average ADC conversion time is about 7 μsec, whereas the average time taken by the microcomputer to process an event is about 65 μsec. At high aerosol concentrations the resulting dead time will allow a fraction of the particles to pass through the system without being counted. One method to correct for this loss is to introduce at the ADC input test pulses of fixed amplitude and repetition rate concurrently with the Climet-generated pulses. Then the correction factor, F, by which the measured size distribution should be multiplied is simply

$$F = RT/N$$

where R is the test pulse repetition rate, T is the data acquisition time, and N is the number of test pulses actually counted by the system. The problem of dead time loss can of course be made less severe by utilizing faster microcomputers, which are now available.

A system similar to the one described could certainly have been assembled before the advent of microcomputers, through use of a minicomputer, or by means of hard-wired custom electronic circuitry. With the former solution the computer cost would be about a factor of 10 greater, while the latter would involve a very formidable electronic design problem and a relatively inflexible final product. The approach taken with the system described was to tailor commercial modules of general utility to the specific application demanded of the system through the flexibility of an easily alterable stored program. The attractiveness of such an approach is nicely illustrated by recalling that the calibration constants required for the spectrometer's normal operation were obtained through merely using a different microcomputer program to convert the same system hardware components into a multichannel pulse height analyzer.

Finally, perhaps the most valuable aspect of our work is the example it provides of the application of a remarkable new technology to the aerosol instrumentation field.

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APPENDIX A

PROGRAM SIZER

GENERAL DESCRIPTION

This appendix provides a complete listing of Program Sizer, the microcomputer software described in general terms in Section 2, which operates the aerosol size spectrometer. The program is specific to the hardware configuration also described in Section 2, including the electrical interconnections listed in Table 1.

If the program is not present in the microcomputer memory (this will be the case if the microcomputer's power has been turned off) it must be loaded following the simple procedure given in the microcomputer manufacturer's documentation. The program may be loaded either from punched paper tape via the teletypewriter or from magnetic tape via the audio cassette recorder. Since the program is in two parts, the complete loading requires two successive load operations. The program is put into operation by entering the program's starting address (0100), and pressing the GO key. It can be stopped by pressing the ST key.

USER OPTIONS

Preset Time

Any integral number of minutes from 1 to 99 may be chosen for the data acquisition time interval. The choice is determined by entering the appropriate 2-digit decimal number at address 000B. The default value is 01. However, if the number of particles recorded in any size interval should exceed 99 x 10^6, the output cycle will immediately occur even through the preset time has not been reached. In either case the first element of the automatic teletypewriter output records the decimal number of actual data acquisition minutes, preceded by the letter "T."

Number, Surface, and Volume Representations

The content of address 0348 determines the output form of the size distribution:

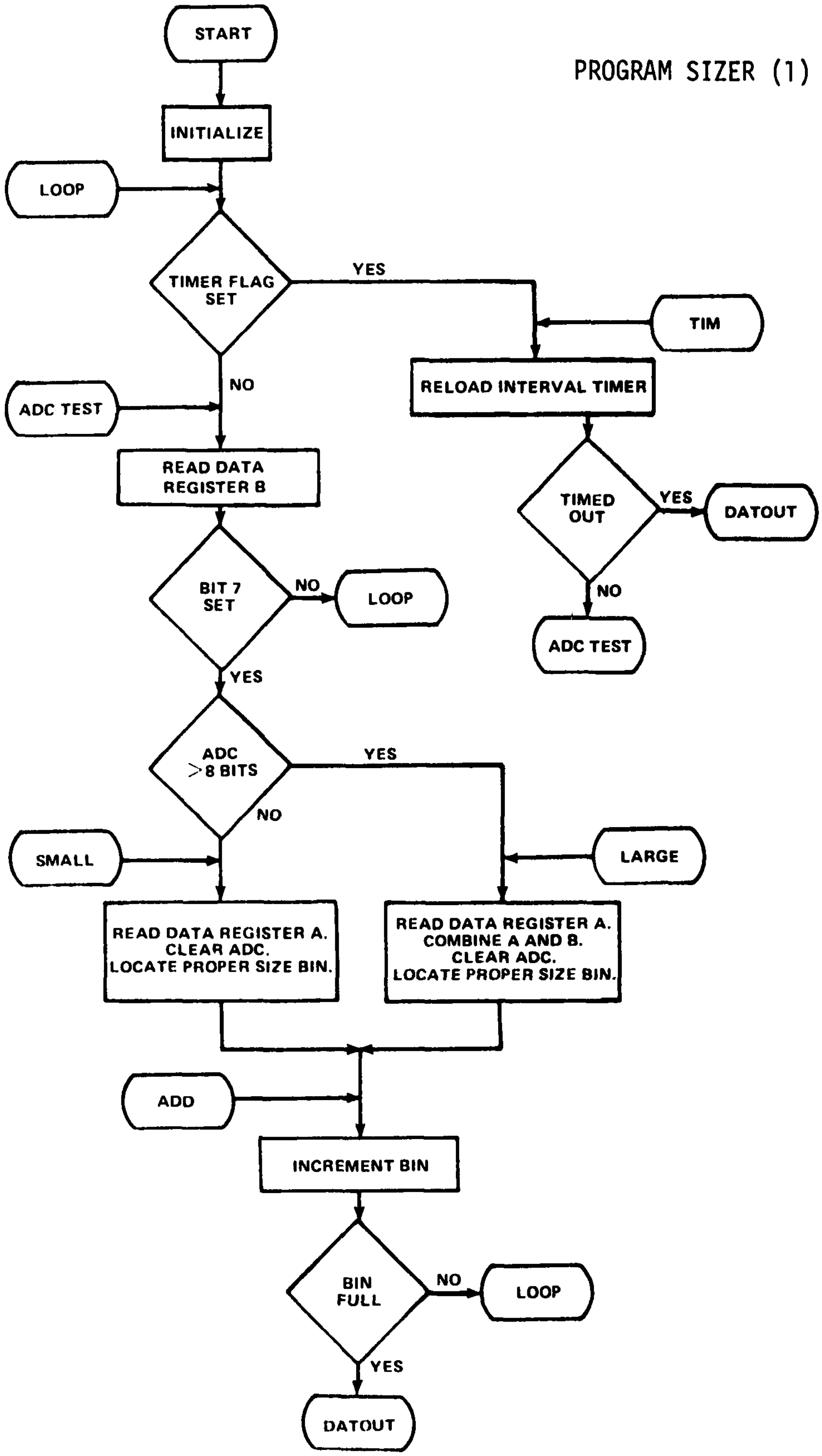
Address	Code	Output Choice	
0348	88	N	(number)
0348	56	$N * \overline{D}^2$	($\propto$ surface area)
0348	4E	$N * \overline{D}^3$	($\propto$ volume)

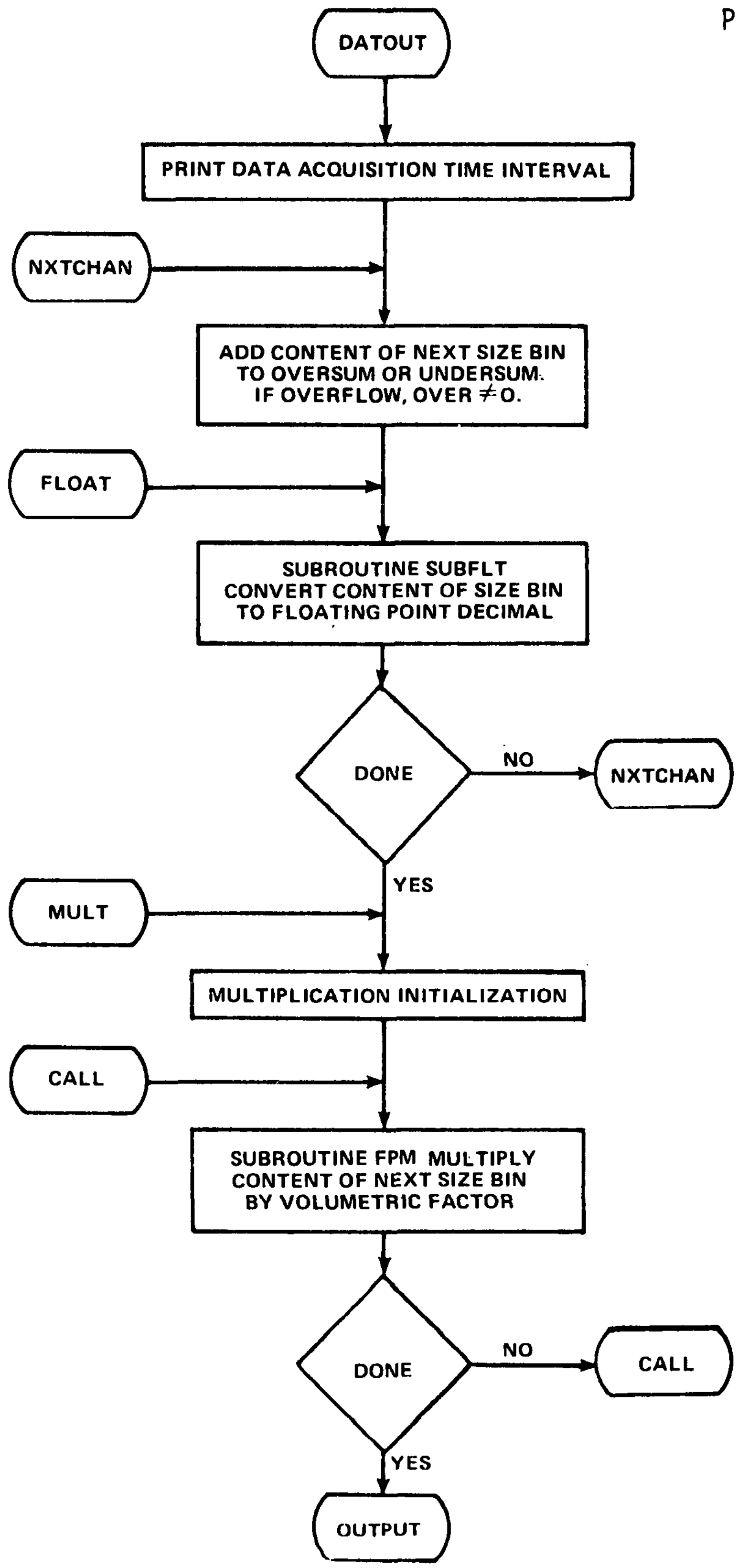
The default value is 4E. The output will be preceded by the letters "S" or "V" if either the surface or volume representations are chosen. Assuming dead time losses are negligible the output can be converted to more conventional units by a multiplicative factor. For example dV/dlogD ($\mu m^3/cm^3$) is obtained by multiplying the volume output numbers by 0.8881×10^{-3}/T (minutes).

Spectrum Integrals

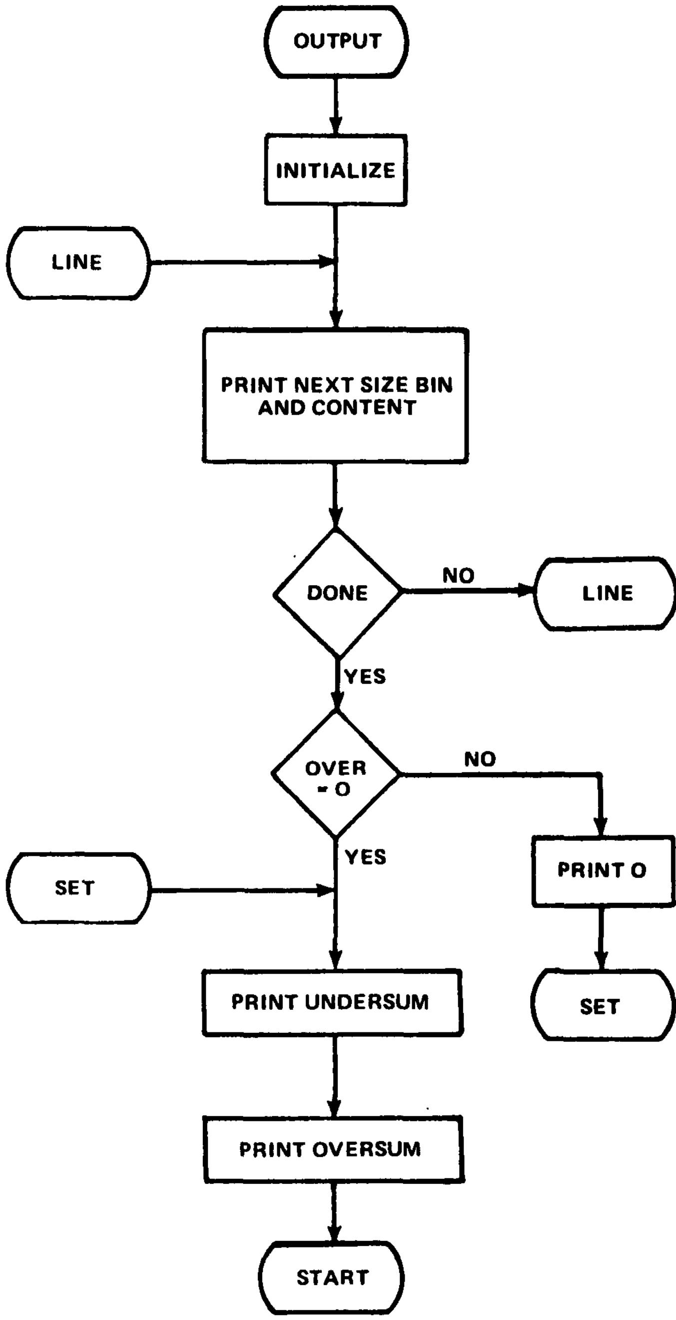
In the output the number of particles recorded in all 19 size intervals are summed into two groups, yielding the total number below (<) and above (>) an adjustable size threshold. The threshold is determined by the content of address 0014, whose allowed range is 00 (default value) to 13_{16}, inclusively: 00 corresponds to the entire spectrum summed into the (>) group, and 13_{16} corresponds to all summed into the (<) group. The summations are always in a "number" representation, independent of the representation chosen for the individual size intervals. If either of the two summations exceed $10^9 - 1$, the summation value will be in error. In this case the letter "O" signifying "overflow" will be printed immediately before the two summations.

PROGRAM SIZER (1)




DATOUT
PRINT DATA ACQUISITION TIME INTERVAL
NXTCHAN
ADD CONTENT OF NEXT SIZE BIN TO OVERSUM OR UNDERSUM. IF OVERFLOW, OVER ≠ O.
FLOAT
SUBROUTINE SUBFLT CONVERT CONTENT OF SIZE BIN TO FLOATING POINT DECIMAL
DONE
NO
NXTCHAN
YES
MULT
MULTIPLICATION INITIALIZATION
CALL
SUBROUTINE FPM MULTIPLY CONTENT OF NEXT SIZE BIN BY VOLUMETRIC FACTOR
DONE
NO
CALL
YES
OUTPUT

PROGRAM SIZER (3)



ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0000	A9 E4	TIM	LDA #E4	TIMER SERVICING ROUTINE
0002	8D 07 17		STA 1707	RELOAD INTERVAL TIMER
0005	C8		INY	INCREMENT 0.2345 SEC. COUNTER
0006	D0 12		BNE ADCTEST	IF NOT FULL, GO TO ADCTEST
0008	4C BC 17		JMP INCTIM	GO TO INCREMENT 1 MIN. COUNTER
000B	01	PRESET		01 =PRESET TIME (MIN.)
000C	XX XX XX			UNUSED
000F	XX XX XX			UNUSED
0012	XX			UNUSED
0013	XX	TCOUNT		
0014	00	THRESH		NUMBER OF PARTICLE SIZE INTERVALS INCLUDED IN UNDERSUM (MAX. = 13_{16})

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0015	AD 05 17	LOOP	LDA 1705	DATA ACQUISITION ROUTINE
0018	D0 E6		BNE TIM	IF TIMER FLAG SET, GO TO TIMER SERVICING ROUTINE
001A	AD 02 17	ADCTEST	LDA 1702	TEST PB7 (ADC READY)
001D	10 F6		BPL LOOP	IF NOT SET, GO TO LOOP
001F	29 3E		AND #3E	IF SET, MASK PB1-5
0021	D0 71		BNE LARGE	IF NON-ZERO, JUMP TO LARGE
0023	AD 00 17	SMALL	LDA 1700	LOAD LO ORDER ADC WORD
0026	EE 02 17		INC 1702	CLEAR ADC
0029	CE 02 17		DEC 1702	
002C	A2 00		LDX #00	IF ADC WORD IS LESS THAN
002E	C9 19		CMP #19	1ST (LOWEST) THRESHOLD
0030	90 33		BCC ADD	GO TO ADD
0032	A2 04		LDX #04	
0034	C9 22		CMP #22	2ND
0036	90 2D		BCC ADD	
0038	A2 08		LDX #08	
003A	C9 2D		CMP #2D	3RD
003C	90 27		BCC ADD	
003E	A2 0C		LDX #0C	
0040	C9 3A		CMP #3A	4TH
0042	90 21		BCC ADD	
0044	A2 10		LDX #10	
0046	C9 4A		CMP #4A	5TH
0048	90 1B		BCC ADD	
004A	A2 14		LDX #14	
004C	C9 5E		CMP #5E	6TH
004E	90 15		BCC ADD	
0050	A2 18		LDX #18	
0052	C9 78		CMP #78	7TH
0054	90 0F		BCC ADD	
0056	A2 1C		LDX #1C	
0058	C9 9C		CMP #9C	8TH

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
005A	90 09		BCC ADD	
005C	A2 20		LDX #20	
005E	C9 CF		CMP #CF	9TH
0060	90 03		BCC ADD	
0062	A2 24		LDX #24	10TH
0064	EA		NOP	
0065	18	ADD	CLC	DECIMAL INCREMENT ROUTINE
0066	BD 00 02		LDA 0200,X	
0069	69 01		ADC #01	ADD 1 TO LEAST SIGNIFICANT
006B	9D 00 02		STA 0200,X	BYTE OF SELECTED CHANNEL
006E	90 A5		BCC LOOP	
0070	BD 01 02		LDA 0201,X	
0073	69 00		ADC #00	PROPAGATE CARRY BIT, IF
0075	9D 01 02		STA 0201,X	NON-ZERO
0078	90 9B		BCC LOOP	
007A	BD 02 02		LDA 0202,X	
007D	69 00		ADC #00	PROPAGATE CARRY BIT, IF
007F	9D 02 02		STA 0202,X	NON-ZERO
0082	90 91		BCC LOOP	
0084	BD 03 02		LDA 0203,X	
0087	69 00		ADC #00	PROPAGATE CARRY BIT, IF
0089	9D 03 02		STA 0203,X	NON-ZERO
008C	C9 99		CMP #99	CHANNEL CONTENT=$99x10^6$?
008E	D0 85		BNE LOOP	NO, GET NEXT EVENT
0090	D8		CLD	YES, CLEAR DECIMAL MODE, AND
0091	4C 00 03		JMP DATOUT	GO TO DATOUT
0094	0A	LARGE	ASL	TRANSFER PB1-5 INTO
0095	0A		ASL	A3-7 AND FILL A0-2 WITH 0'S
0096	85 E8		STA TEMPB	
0098	AD 00 17		LDA 1700	LOAD LO ORDER ADC WORD
009B	EE 02 17		INC 1702	
009E	CE 02 17		DEC 1702	CLEAR ADC

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
00A1	4A		LSR	
00A2	4A		LSR	TRANSFER PA5-7 INTO
00A3	4A		LSR	A0-2 AND FILL A3-7
00A4	4A		LSR	WITH 0'S
00A5	4A		LSR	
00A6	05 E8		ORA TEMPB	8 MSB'S OF ADC WORD IN A.
00A8	A2 24		LDX #24	IF ADC WORD IS LESS THAN
00AA	C9 09		CMP #09	10TH THRESHOLD,
00AC	90 B7		BCC ADD	GO TO ADD
00AE	A2 28		LDX #28	
00B0	C9 0D		CMP #0D	11TH
00B2	90 B1		BCC ADD	
00B4	A2 2C		LDX #2C	
00B6	C9 12		CMP #12	12TH
00B8	90 AB		BCC ADD	
00BA	A2 30		LDX #30	
00BC	C9 1A		CMP #1A	13TH
00BE	90 A5		BCC ADD	
00C0	A2 34		LDX #34	
00C2	C9 26		CMP #26	14TH
00C4	90 9F		BCC ADD	
00C6	A2 38		LDX #38	
00C8	C9 37		CMP #37	15TH
00CA	90 99		BCC ADD	
00CC	A2 3C		LDX #3C	
00CE	C9 50		CMP #50	16TH
00D0	90 93		BCC ADD	
00D2	A2 40		LDX #40	
00D4	C9 73		CMP #73	17TH
00D6	90 8D		BCC ADD	
00D8	A2 44		LDX #44	
00DA	C9 A7		CMP #A7	18TH
00DC	90 87		BCC ADD	

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
00DE	A2 48		LDX #48	IF ADC WORD IS LESS THAN
00E0	C9 F4		CMP #F4	19TH THRESHOLD
00E2	90 81		BCC ADD	GO TO ADD
00E4	4C 15 00		JMP LOOP	DISCARD OTHERWISE
00E7	XX	TEMPA		TEMPORARY STORAGE
00E8	XX	TEMP B/ EXP		ADDRESSES
00E9	XX	SUMPNTL/ PLIERPNTL		THREE POINTER ADDRESSES
00EA	02	SUMPNTH/ PLIERPNTH		
00EB	XX	FLTPNTL/ CANDPNTL		
00EC	02	FLTPNTH/ CANDPNTH		
00ED	XX	DATPNTL/ PRODPNTL		
00EE	02	DATPNTH/ PRODPNTH		
00EF	XX XX XX			ADDRESSES 00EF -
00F2	XX XX XX			00FF NOT AVAILABLE
00F5	XX XX XX			FOR USER PROGRAMS
00F8	XX XX XX			
00FB	XX XX XX			
00FE	XX XX			

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0100	D8	START	CLD	STARTING ADDRESS, CLEAR DECIMAL
0101	A2 FF		LDX #FF	MODE
0103	9A		TXS	INITIALIZE STACK
0104	20 2F 1E		JSR CRLF	
0107	20 2F 1E		JSR CRLF	CARRIAGE RETURN, LINE FEED
010A	A9 01		LDA #01	PB0=OUTPUT (ADC CLEAR)
010C	8D 03 17		STA 1703	PB1-5 = INPUTS (ADC MSB'S)
010F	A9 00		LDA #00	PB7 = INPUT (ADC READY)
0111	8D 01 17		STA 1701	PA0-7 = INPUTS (ADC LSB's)
0114	A0 54		LDY #54	SET TO ZERO:
0116	99 00 02	AGAIN	STA 0200,Y	SPECTRUM (19X4 BYTES),
0119	88		DEY	OVERSUM (4 BYTES),
011A	10 FA		BPL AGAIN	UNDERSUM (4 BYTES),
011C	85 13		STA TCOUNT	OVER, TCOUNT,
011E	A8		TAY	Y
011F	8D 02 17		STA 1702	
0122	EE 02 17		INC 1702	CLEAR ADC
0125	CE 02 17		DEC 1702	
0128	A9 E4		LDA #E4	SET TIMER FOR
012A	8D 07 17		STA 1707	0.2345 SEC.
012D	F8		SED	SET DECIMAL MODE
012E	A9 00		LDA #00	SET UP INTERRUPT VECTOR
0130	8D FA 17		STA 17FA	FOR NMI
0133	A9 1C		LDA #1C	
0135	8D FB 17		STA 17FB	
0138	4C 15 00		JMP LOOP	BEGIN DATA ACQUISITION

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
013B	48	FPM	PHA	DECIMAL FLOATING POINT
013C	08		PHP	MULTIPLY SUBROUTINE
013D	86 E7		STX TEMPA	(DECIMAL MODE
013F	84 E8		STY TEMPB	PREVIOUSLY SET)
0141	A9 03		LDA #03	
0143	8D E4 01		STA CNTSHIFT	INITIALIZE SHIFT COUNTER.
0146	A0 06		LDY #06	SET TO ZERO:
0148	A9 00		LDA #00	CANDSRH, CANDSRL,
014A	99 E7 01		STA CNTEXP,Y	PROD1, PROD2,
014D	88		DEY	PROD3, PROD4,
014E	10 FA		BPL	CNTEXP.
0150	A0 02		LDY #02	LOAD PLIERH
0152	B1 E9	LDP	LDA (PLIERPNTL),Y	AND PLIERL
0154	88		DEY	INTO RESIDENT
0155	99 E5 01		STA PLIERL,Y	STORAGE
0158	D0 F8		BNE LDP	
015A	A0 01		LDY #01	LOAD CANDL
015C	B1 EB		LDA (CANDPNTL),Y	AND CANDH
015E	8D EF 01		STA CANDL	INTO RESIDENT
0161	C8		INY	STORAGE
0162	B1 EB		LDA (CANDPNTL),Y	
0164	8D EE 01		STA CANDH	
0167	AD E5 01	CKPLIER	LDA PLIERL	CHECK 4 LSB'S
016A	29 0F		AND #0F	OF PLIERL
016C	F0 13		BEQ DECCNTSHIFT	
016E	A8		TAY	Y = ADDITION COUNTER
016F	18	SETX	CLC	ADD ALL 4 BYTES
0170	A2 03		LDX #03	OF CAND TO PROD
0172	BD EC 01	SUM	LDA CANDSRH,X	
0175	7D E8 01		ADC PROD1,X	
0178	9D E8 01		STA PROD1,X	
017B	CA		DEX	

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
017C	10 F4		BPL SUM	
017E	88		DEY	REPEAT ADDITIONS
017F	D0 EE		BNE SETX	FOR Y TIMES.
0181	CE E4 01	DECCNTSHIFT	DEC CNTSHIFT	BRANCH IF ALL 4 DIGITS
0184	30 16		BMI LJD	OF PLIER HAVE BEEN USED
0186	A0 04		LDY #04	Y = 4 BIT COUNTER
0188	A2 03	NEXTDIG	LDX #03	X = 4 BYTE COUNTER
018A	18		CLC	SHIFT CAND
018B	3E EC 01	ROCAND	ROL CANDSRH,X	LEFT 1 BIT
018E	CA		DEX	REPEAT FOR ALL 4
018F	10 FA		BPL ROCAND	BYTES
0191	4E E6 01		LSR PLIERH	SHIFT PLIER
0194	6E E5 01		ROR PLIERL	RIGHT 1 BIT
0197	88		DEY	REPEAT FOR 4
0198	D0 EE		BNE NEXTDIG	BITS.
019A	F0 CB		BEQ CKPLIER	
019C	A0 00	LJD	LDY #00	
019E	B1 E9	ADDEXP	LDA (PLIERPNTL),Y	ADD EXPONENTS
01A0	18		CLC	OF PLIER AND
01A1	71 EB		ADC (CANDPNTL),Y	CAND
01A3	8D E7 01		STA CNTEXP	
01A6	A9 F0	CKMSD	LDA #F0	CHECK 4 MSB'S
01A8	2C E8 01		BIT PROD1	OF PROD
01AB	D0 1E		BNE STOREXP	BRANCH IF ≠ 0
01AD	A0 04		LDY #04	4 BITS FOR EACH BCD
01AF	18	DIGSHIFT	CLC	DIGIT
01B0	A2 03		LDX #03	PROD CONTAINS 4 BYTES
01B2	3E E8 01	BITSHIFT	ROL PROD1,X	SHIFT PROD LEFT
01B5	CA		DEX	1 BIT. REPEAT FOR
01B6	10 FA		BPL BITSHIFT	ALL 4 BYTES
01B8	88		DEY	REPEAT FOR 4 BITS
01B9	D0 F4		BNE DIGSHIFT	
01BB	38	DECEXP	SEC	DECREMENT EXPONENT

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENTS
01BC	AD E7 01		LDA CNTEXP	FOR EACH DIGIT
01BF	E9 01		SBC #01	SHIFTED
01C1	8D E7 01		STA CNTEXP	
01C4	D0 E0		BNE CKMSD	
01C6	F0 03		BEQ STOREXP	
01C8	XX XX XX			UNUSED
01CB	AD E7 01	STOREXP	LDA CNTEXP	(Y = 0)
01CE	91 ED		STA (PRODPNTL),Y	EXPONENT STORED AT LOWEST
01D0	A0 02		LDY #02	ADDRESS
01D2	AD E8 01		LDA PROD1	
01D5	91 ED		STA (PRODPNTL),Y	HI STORED AT HIGHEST ADDRESS
01D7	88		DEY	
01D8	AD E9 01		LDA PROD2	
01DB	91 ED		STA (PRODPNTL),Y	LO STORED AT MIDDLE ADDRESS
01DD	A6 E7		LDX TEMPA	
01DF	A4 E8		LDY TEMPB	
01E1	28		PLP	
01E2	68		PLA	
01E3	60		RTS	RETURN FROM SUBROUTINE
01E4	XX	CNTSHIFT		TWELVE TEMPORARY
01E5	XX	PLIERL		STORAGE ADDRESSES
01E6	XX	PLIERH		USED BY MULTIPLY
01E7	XX	CNTEXP		SUBROUTINE
01E8	XX	PROD1		
01E9	XX	PROD2		
01EA	XX	PROD3		
01EB	XX	PROD4		
01EC	XX	CANDSRH		
01ED	XX	CANDSRL		
01EE	XX	CANDH		
01EF	XX	CANDL		
01F0	XX XX XX			UNUSED
01F3	XX XX XX			UNUSED

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENTS
01F6	XX XX XX			UNUSED
01F9	XX XX XX			UNUSED
01FC	XX XX			UNUSED
01FE	XX			RESERVED FOR
01FF	XX	STACK		STACK OPERATION

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0200	XX XX XX	SPECTRUM		ADDRESSES 0200 - 024B COMPRISE THE ACCUMULATED PARTICLE SIZE SPECTRUM, ORGANIZED AS 19_{10} FOUR BYTE BCD INTEGERS
|	|			
024B	XX			
024C	XX XX XX	OVERSUM		FOUR BYTE SUM
024F	XX			ABOVE THRESHOLD
0250	XX XX XX	UNDERSUM		FOUR BYTE SUM
0253	XX			BELOW THRESHOLD
0254	XX	OVER		IF ≠ 0, OVERFLOW OCCURRED

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0255	00 16 03	DCUBE		TABLE OF VOLUME
0258	00 62 05			TRANSFORMATION
025B	00 00 10			FACTORS FOR EACH
025E	00 78 17			SIZE BIN,
0261	00 62 31			STORED IN
0264	00 23 56			REVERSE DECIMAL
0267	01 00 10			FLOATING POINT
026A	01 78 17			FORMAT.
026D	01 62 31			FOR EXAMPLE
0270	01 23 56			THE FIRST
0273	02 00 10			FACTOR IS
0276	02 78 17			0.0316×10^0
0279	02 62 31			$= (0.3162)^3$
027C	02 23 56			
027F	03 00 10			
0282	03 78 17			
0285	03 62 31			
0288	03 23 56			
028B	04 00 10			

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
028E	32 33 2E	TABLE		TABLE OF
0291	38 33 2E			AVE. PARTICLE
0294	36 34 2E			DIA. (IN
0297	36 35 2E			MICROMETERS)
029A	38 36 2E			FOR EACH
029D	33 38 2E			SIZE BIN,
02A0	30 2E 31			STORED IN
02A3	32 2E 31			REVERSE
02A6	35 2E 31			ASCII
02A9	38 2E 31			FORMAT.
02AC	32 2E 32			FOR EXAMPLE
02AF	36 2E 32			THE FIRST
02B2	32 2E 33			ENTRY
02B5	38 2E 33			CORRESPONDS
02B8	36 2E 34			TO 0.32
02BB	36 2E 35			SINCE
02BE	38 2E 36			32 = 2
02C1	33 2E 38			33 = 3
02C4	2E 30 31			2E = .

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
02C7	00 00 10	DSQUARE		TABLE OF
02CA	00 68 14			SURFACE
02CD	00 54 21			TRANSFORMATION
02D0	00 62 31			FACTORS FOR
02D3	00 42 46			EACH SIZE BIN,
02D6	00 13 68			STORED IN
02D9	01 00 10			REVERSE DECIMAL
02DC	01 68 14			FLOATING POINT
02DF	01 54 21			FORMAT
02E2	01 62 31			FOR EXAMPLE
02E5	01 42 46			THE FIRST
02E8	01 13 68			FACTOR IS
02EB	02 00 10			0.1000×10^0
02EE	02 68 14			$= (0.3162)^2$
02F1	02 54 21			
02F4	02 62 31			
02F7	02 42 46			
02FA	02 13 68			
02FD	03 00 10			

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
				SUMMING ROUTINE
0300	D8	DATOUT	CLD	CLEAR DECIMAL MODE
0301	A9 54		LDA #54	
0303	20 A0 1E		JSR OUTCH	PRINT "T"
0306	20 9E 1E		JSR OUTSP	
0309	A5 13		LDA TCOUNT	
030B	20 3B 1E		JSR PRTBYT	PRINT TCOUNT
030E	20 2F 1E		JSR CRLF	CARRIAGE RETURN, LINE FEED
0311	F8		SED	SET DECIMAL MODE
0312	A9 00		LDA #00	INITIALIZE:
0314	85 ED		STA DATPNTL	DATPNTL
0316	85 EB		STA FLTPNTL	AND FLTPNTL
0318	A2 00		LDX #00	SET SIZE BIN COUNTER
031A	A9 4C	NXTCHAN	LDA #4C	SET SUMPNT TO
031C	E4 14		CPX THRESH	ADDRESS OF
031E	B0 02		BCS STR	OVERSUM (024C)
0320	A9 50		LDA #50	OR ADDRESS OF
0322	85 E9	STR	STA SUMPNTL	UNDERSUM (0250)
0324	A0 00	SUM	LDY #00	SET INDEX REGISTER
0326	A9 04		LDA #04	
0328	85 E8		STA TEMPB	4 BYTE COUNTER
032A	18		CLC	
032B	B1 ED	AGAIN	LDA (DATPNTL),Y	
032D	99 4A 03		STA SCRATCHL,Y	ADD NO. OF COUNTS IN NEXT
0330	71 E9		ADC (SUMPNTL),Y	SIZE BIN (4 BYTES)
0332	91 E9		STA (SUMPNTL),Y	TO OVERSUM OR UNDERSUM
0334	C8		INY	
0335	C6 E8		DEC TEMPB	
0337	D0 F2		BNE AGAIN	
0339	90 03		BCC FLOAT	IF EITHER SUM > 4 BYTES,

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
033B	EE 54 02		INC OVER	INCREMENT OVER
033E	20 80 17	FLOAT	JSR SUBFLT	GO TO FLOATING POINT CONVERSION SUBROUTINE
0341	E8		INX	
0342	E0 13		CPX #13	$13_{16} = 19_{10}$ SIZE BINS
0344	D0 D4		BNE NXTCHAN	
0346	D8		CLD	CLEAR DECIMAL MODE
0347	4C 4E 03		JMP MULT	GO TO MULTIPLY ROUTINE
034A	XX	SCRATCHL		FOUR BYTE
034B	XX	SCRATCHL+1		STORAGE REGISTER
034C	XX	SCRATCHL+2		REFERENCED BY
034D	XX	SCRATCHL+3		SUBROUTINE SUBFLT

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
				MULTIPLY ROUTINE
034E	A9 55	MULT	LDA #55	LOAD PLIERPNTL WITH
0350	85 E9		STA E9	ADDRESS OF DCUBE
0352	A9 56		LDA #56	ASCII "V"
0354	D0 06		BNE CHAR	
0356	A9 C7	ENTR2	LDA #C7	LOAD PLIERPNTL WITH
0358	85 E9		STA E9	ADDRESS OF DSQUARE
035A	A9 53		LDA #53	ASCII "S"
035C	20 A0 1E	CHAR	JSR OUTCH	PRINT "V" OR "S"
035F	20 2F 1E		JSR CRLF	
0362	A9 00		LDA #00	INITIALIZE:
0364	85 EB		STA EB	CANDPNTL AND
0366	85 ED		STA ED	PRODPNTL
0368	A0 13		LDY #13	19_{10} SIZE BINS
036A	F8	CALL	SED	SET DECIMAL MODE
036B	20 3B 01		JSR FPM	MULTIPLY
036E	D8		CLD	CLEAR DECIMAL MODE
036F	88		DEY	
0370	D0 03		BNE #03	IF ALL BINS DONE
0372	4C 88 03		JMP OUTPUT	GO TO OUTPUT
0375	A2 04		LDX #04	IF NOT DONE,
0377	F6 E9	INCP	INC E9,X	INCREMENT
0379	F6 E9		INC E9,X	PLIERPNTL,
037B	F6 E9		INC E9,X	CANDPNTL, AND
037D	CA		DEX	PRODPNTL
037E	CA		DEX	THREE TIMES
037F	10 F6		BPL INCP	
0381	30 E7		BMI CALL	DO NEXT MULTIPLICATION
0383	XX XX			UNUSED
0385	XX XX			UNUSED
0387	XX			UNUSED

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0388	A9 00	OUTPUT	LDA #00	OUTPUT ROUTINE
038A	85 ED		STA ED	INITIALIZE DATPNTL
038C	A9 38		LDA #38	$38_{16} = 56_{10} =$
038E	85 E7		STA TEMPA	3 x NO. OF BINS - 1
0390	85 E8		STA TEMPB	
0392	A9 03	LINE	LDA #03	
0394	85 E9		STA COUNTER	3 CHARACTER COUNTER
0396	A6 E7	ASCII	LDX TEMPA	
0398	BD 8E 02		LDA TABLE,X	ASCII TABLE ADDRESS = 028E
039B	20 A0 1E		JSR OUTCH	PRINT NEXT ASCII CHARACTER
039E	C6 E7		DEC TEMPA	
03A0	C6 E9		DEC COUNTER	
03A2	D0 F2		BNE ASCII	PROCEED AFTER 3 CHARACTERS
03A4	20 9E 1E		JSR OUTSP	
03A7	20 9E 1E		JSR OUTSP	PRINT 2 SPACES
03AA	A9 2E		LDA #2E	ASCII "."
03AC	20 A0 1E		JSR OUTCH	PRINT "."
03AF	20 F6 03		JSR OUTBYT	PRINT HI ORDER BYTE
03B2	20 F6 03		JSR OUTBYT	PRINT LO ORDER BYTE
03B5	20 9E 1E		JSR OUTSP	PRINT SPACE
03B8	20 F6 03		JSR OUTBYT	PRINT EXPONENT
03BB	20 2F 1E		JSR CRLF	
03BE	A5 E8		LDA TEMPB	
03C0	10 D0		BPL LINE	PROCEED AFTER 19_{10} LINES
03C2	AD 54 02		LDA OVER	CHECK FOR OVERFLOW
03C5	F0 08		BEQ SET	
03C7	A9 4F		LDA #4F	ASCII "O"
03C9	20 A0 1E		JSR OUTCH	PRINT "O" IF OVERFLOW
03CC	20 2F 1E		JSR CRLF	
03CF	A9 53	SET	LDA #53	END ADDRESS OF
03D1	85 E8		STA TEMPB	UNDERSUM = 0253
03D3	A9 02		LDA #02	
03D5	85 E9		STA COUNTER	2 SUM COUNTER

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
03D7	A9 3C		LDA #3C	ASCII " < "
03D9	A2 04	SUMPRT	LDX #04	
03DB	86 E7		STX TEMPA	4 BYTES PER SUM
03DD	20 A0 1E		JSR OUTCH	PRINT " < " OR " > "
03E0	20 9E 1E		JSR OUTSP	PRINT 1 SPACE
03E3	20 F6 03	RPT	JSR OUTBYT	PRINT NEXT BYTE
03E6	C6 E7		DEC TEMPA	
03E8	D0 F9		BNE RPT	PROCEED AFTER 4 BYTES
03EA	20 2F 1E		JSR CRLF	
03ED	A9 3E		LDA #3E	ASCII " > "
03EF	C6 E9		DEC COUNTER	AFTER PRINTING OF
03F1	D0 E6		BNE SUMPRT	UNDERSUM AND OVERSUM,
03F3	4C 00 01		JMP START	RESTART ACQUISITION
03F6	A4 E8	OUTBYT	LDY TEMPB	SUBROUTINE TO
03F8	B1 ED		LDA (ED),Y	PRINT ONE BYTE
03FA	20 3B 1E		JSR PRTBYT	
03FD	C6 E8		DEC TEMPB	
03FF	60		RTS	RETURN FROM SUBROUTINE

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
				DECIMAL FLOATING POINT
				CONVERSION ROUTINE
1780	A9 08	SUBFLT	LDA #08	08 = INITIAL BIAS
1782	85 E8		STA EXP	FOR EXPONENT
1784	A9 F0	MASK	LDA #F0	IF ANY OF 4 MSB'S
1786	2C 4D 03		BIT SCRATCHL+3	OF SCRATCH ≠ 0,
1789	D0 15		BNE STORE	GO TO STORE
178B	A0 04		LDY #04	OTHERWISE,
178D	0E 4A 03	SHIFT	ASL SCRATCHL	SHIFT 4 BYTE CONTENT
1790	2E 4B 03		ROL SCRATCHL+1	OF SCRATCH LEFT
1793	2E 4C 03		ROL SCRATCHL+2	BY 4 BITS
1796	2E 4D 03		ROL SCRATCHL+3	
1799	88		DEY	
179A	D0 F1		BNE SHIFT	
179C	C6 E8		DEC EXP	DECREMENT EXPONENT
179E	D0 E4		BNE MASK	GO TO MASK IF EXPONENT ≠ 0
17A0	A0 00	STORE	LDY #00	STORE AT 3 SEQUENTIAL
17A2	A5 E8		LDA EXP	ADDRESSES IN ORDER:
17A4	91 EB		STA (FLTPNTL),Y	EXPONENT AT LOWEST ADDRESS
17A6	C8	BACK	INY	LO ORDER AT MIDDLE ADDRESS
17A7	B9 4B 03		LDA SCRATCHL+1,Y	HI ORDER AT HIGHEST ADDRESS
17AA	91 EB		STA (FLTPNTL),Y	
17AC	C0 02		CPY #02	
17AE	D0 F6		BNE BACK	
17B0	A0 03		LDY #03	
17B2	E6 EB	MORE	INC FLTPNTL	INCREMENT:
17B4	E6 ED		INC DATPNTL	FLTPNTL 3 TIMES
17B6	88		DEY	DATPNTL 4 TIMES
17B7	D0 F9		BNE MORE	
17B9	E6 ED		INC DATPNTL	
17BB	60		RTS	RETURN FROM SUBROUTINE

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
17BC	18	INCTIM	CLC	
17BD	A5 13		LDA TCOUNT	
17BF	69 01		ADC #01	INCREMENT 1 MIN. COUNTER
17C1	85 13		STA TCOUNT	
17C3	C5 0B		CMP PRESET	
17C5	D0 03		BNE CONTIN	PRESET TIME REACHED?
17C7	4C 00 03		JMP DATOUT	YES
17CA	4C 1A 00	CONTIN	JMP ADCTEST	NO
17CD	XX XX XX			UNUSED
|				|
17EB	XX			UNUSED

APPENDIX B

PROGRAM MCA

GENERAL DESCRIPTION

The following program listing is specific to the microcomputer-ADC-teletypewriter system configuration described in Section 2, including the electrical interconnections listed in Table 1. Program MCA converts this system to a conventional 256-channel pulse height analyzer (MultiChannel Analyzer) with spectrum print-out capability. The program consists of two segments, data acquisition and spectrum printout. Their starting addresses are 0000 and 00A0, respectively.

USER OPTIONS

Maximum Channel Count

In the present program data acquisition is terminated when the number of counts in any one of the 256 channels reaches 9900. The channel number (a hexadecimal number between 00 and FF) for which the condition occurred is then automatically printed. The maximum count may be changed to any decimal integral multiple (between 01 and 99) of 100 by appropriately changing the content of the two addresses 006D and 0088.

Output Spectrum Range

In the present program the output segment prints the entire spectrum from channel number 0 to FF (255_{10}), in the form of 10 channels per line with the hexadecimal channel number of the following channel content beginning each line. Any smaller subset of the full spectrum may be chosen for output by changing the initial and final channel numbers, contained at addresses 0161 and 0162, respectively. If these channel numbers are mistakenly entered in reverse order an error message ("E") will be printed and the program will halt at address 0161 for operator inspection of its contents. The sample output reproduced below corresponds to initial and final channel numbers 30 (48_{10}) and 3E (62_{10}), resulting from the input of an electronic pulser centered at channel number 3B (59_{10}).

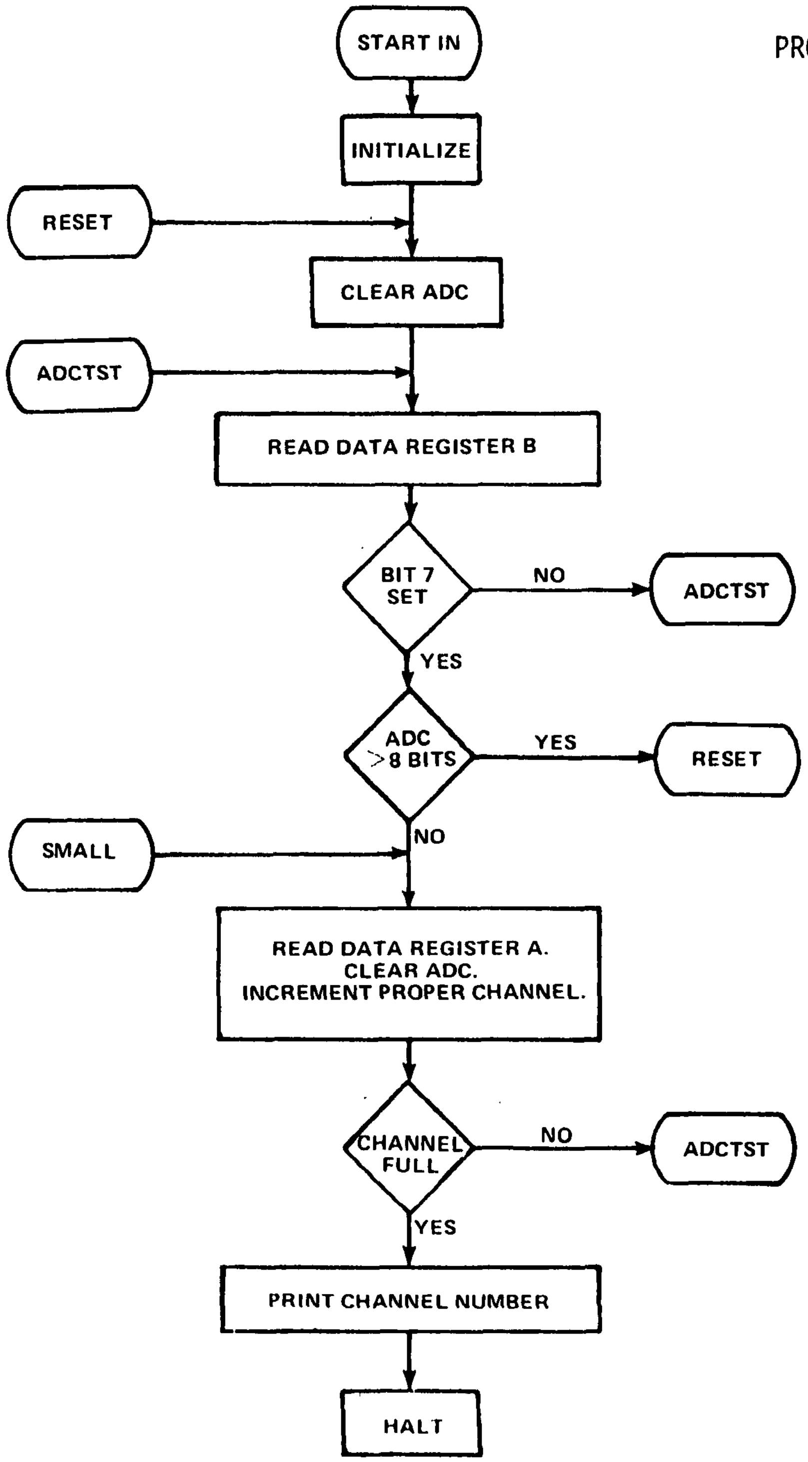
```
3B

30   0000  0000  0000  0000  0000  0000  0000  0000  0000  0000
3A   0000  9900  0000  0000  0000
```

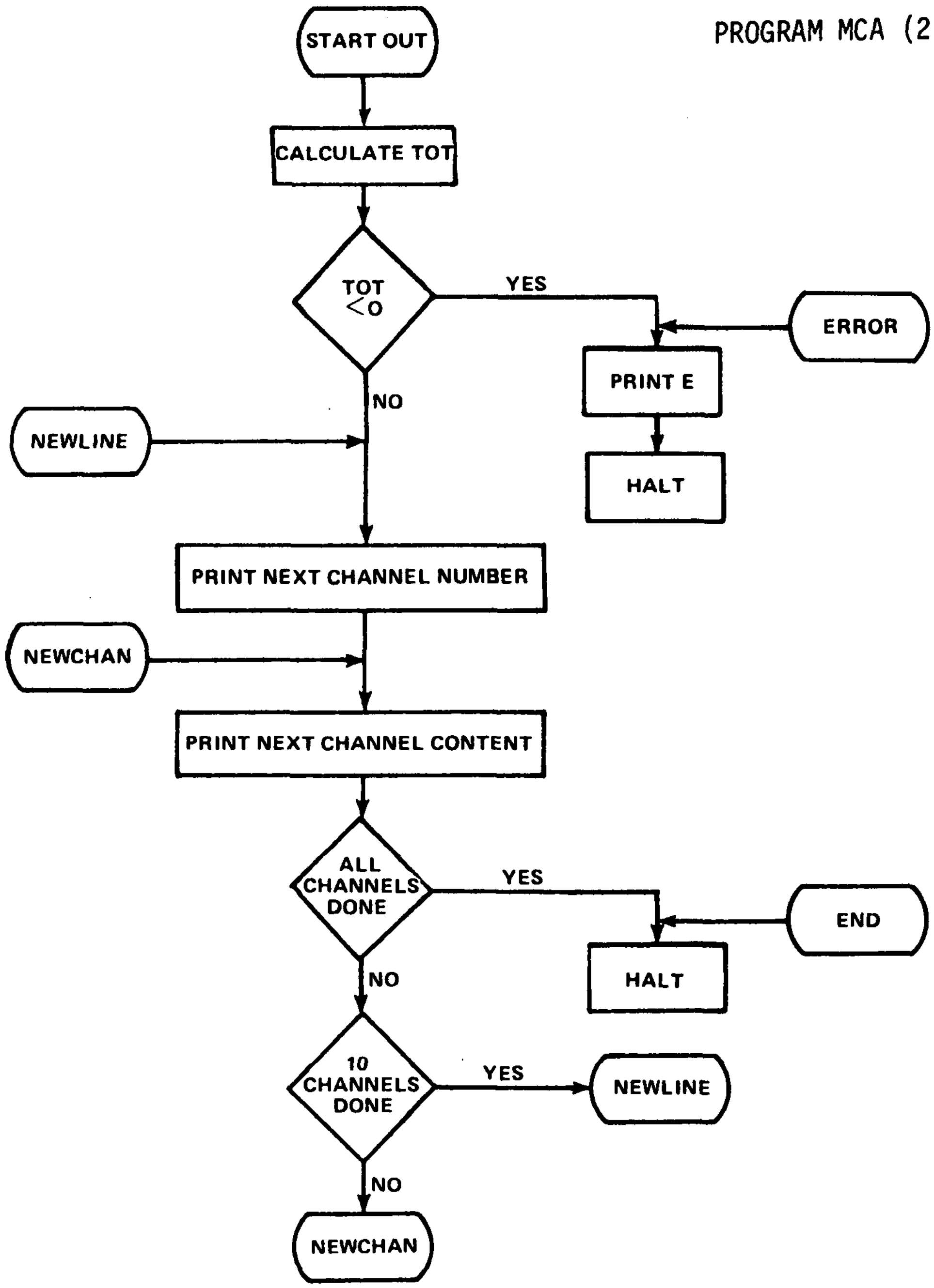
Restarting

The execution of Program MCA halts after completion of each acquisition or output cycle. So long as the operator is content to alternate the two cycles only the GO key need be pressed to start execution of the other cycle. If it is desired however to immediately repeat the same cycle, or to exercise one of the previous options, then the proper starting address for the cycle must be entered before GO.

PROGRAM MCA (1)



PROGRAM MCA (2)



ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0000	A9 1C	STARTIN	LDA #1C	STARTING ADDRESS FOR
0002	8D FB 17		STA NMIH	DATA ACQUISITION
0005	8D FD 17		STA RSTH	
0008	8D FF 17		STA IRQH	INITIALIZE INTERRUPT
000B	A9 00		LDA #00	VECTORS
000D	8D FA 17		STA NMIL	
0010	8D FC 17		STA RSTL	
0013	8D FE 17		STA IRQL	
0016	D8		CLD	CLEAR DECIMAL MODE
0017	20 2F 1E		JSR CRLF	CARRIAGE RETURN, LINE FEED
001A	20 2F 1E		JSR CRLF	DEFINE I/O:
001D	A9 01		LDA #01	PB0 = OUTPUT (ADC CLEAR)
001F	8D 03 17		STA 1703	PB1-5 = INPUTS (ADC MSB'S)
0022	A9 00		LDA #00	PB7 = INPUT (ADC READY)
0024	8D 01 17		STA 1701	PA0-7 = INPUTS (ADC LSB'S)
0027	A0 00		LDY #00	
0029	99 00 02	ZERO2	STA 0200,Y	CLEAR MEMORY ADDRESSES
002C	88		DEY	0200-03FF
002D	D0 FA		BNE ZERO2	
002F	A0 00		LDY #00	
0031	99 00 03	ZERO3	STA 0300,Y	
0034	88		DEY	
0035	D0 FA		BNE ZERO3	
0037	8D 02 17		STA 1702	
003A	EE 02 17	RESET	INC 1702	CLEAR ADC
003D	CE 02 17		DEC 1702	
0040	F8		SED	SET DECIMAL MODE
0041	AD 02 17	ADCTST	LDA 1702	TEST PB7 (ADC READY)
0044	10 FB		BPL ADCTST	IF NOT SET, TEST AGAIN
0046	29 3E		AND #3E	IF SET, MASK PB1-5
0048	D0 F0		BNE RESET	RESET IF ADC > 8 BITS

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
004A	AD 00 17	SMALL	LDA 1700	LOAD LO ORDER ADC WORD
004D	EE 02 17		INC 1702	CLEAR ADC
0050	CE 02 17		DEC 1702	
0053	85 EE		STA TEMP	
0055	0A		ASL	MULTIPLY ADC WORD X2
0056	B0 1B		BCS CRYSET	BRANCH IF CARRY SET
0058	AA		TAX	
0059	18		CLC	IF CARRY NOT SET,
005A	BD 00 02		LDA 0200,X	ADD 1 TO LEAST
005D	69 01		ADC #01	SIGNIFICANT BYTE
005F	9D 00 02		STA 0200,X	OF SELECTED CHANNEL
0062	90 DD		BCC ADCTST	ON PAGE TWO
0064	BD 01 02		LDA 0201,X	PROPAGATE CARRY
0067	69 00		ADC #00	BIT IF NON-ZERO
0069	9D 01 02		STA 0201,X	
006C	C9 99		CMP #99	CHANNEL CONTENT = 9900?
006E	D0 D1		BNE ADCTST	NO, GET NEXT EVENT
0070	4C 8B 00		JMP CHAN	YES, GO TO CHAN
0073	AA	CRYSET	TAX	
0074	18		CLC	IF CARRY SET,
0075	BD 00 03		LDA 0300,X	ADD 1 TO LEAST
0078	69 01		ADC #01	SIGNIFICANT BYTE
007A	9D 00 03		STA 0300,X	OF SELECTED CHANNEL
007D	90 C2		BCC ADCTST	ON PAGE THREE
007F	BD 01 03		LDA 0301,X	PROPAGATE CARRY
0082	69 00		ADC #00	BIT IF NON-ZERO
0084	9D 01 03		STA 0301,X	
0087	C9 99		CMP #99	CHANNEL CONTENT = 9900?
0089	D0 B6		BNE ADCTST	NO, GET NEXT EVENT
008B	D8	CHAN	CLD	CLEAR DECIMAL MODE
008C	A5 EE		LDA TEMP	PRINT CHANNEL WITH
008E	20 3B 1E		JSR PRTBYT	MAXIMUM COUNT
0091	00 00		BRK 00	HALT

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0093	4C A0 00		JMP STARTOUT	OUTPUT SPECTRUM
0096	XX XX XX			UNUSED
0099	XX XX XX			UNUSED
009C	XX XX XX			UNUSED
009F	XX			UNUSED

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
00A0	D8	STARTOUT	CLD	STARTING ADDRESS
00A1	38		SEC	FOR DATA OUTPUT
00A2	AD 62 01		LDA FIN	
00A5	ED 61 01		SBC INIT	CALCULATE TOT
00A8	B0 03		BCS 03	= NO. OF CHANNELS
00AA	4C 57 01		JMP ERROR	TO BE OUTPUT
00AD	18		CLC	ERROR MESSAGE
00AE	69 01		ADC #01	IF TOT < 0
00B0	8D 65 01		STA TOT	
00B3	A9 01		LDA #01	
00B5	85 ED		STA MEMH	
00B7	AD 61 01		LDA INIT	CALCULATE MEML, MEMH
00BA	8D 63 01		STA CURRENT	MEML = LO ORDER
00BD	85 EC		STA MEML	ADDRESS OF
00BF	06 EC		ASL MEML	INITIAL CHANNEL
00C1	B0 04		BCS 04	TO BE OUTPUT
00C3	A9 00		LDA #00	MEMH = HI ORDER
00C5	85 ED		STA MEMH	ADDRESS
00C7	18		CLC	
00C8	A5 EC		LDA MEML	
00CA	69 01		ADC #01	
00CC	85 EC		STA MEML	
00CE	A5 ED		LDA MEMH	
00D0	69 02		ADC #02	
00D2	85 ED		STA MEMH	
00D4	20 2F 1E		JSR CRLF	REMAINDER OF
00D7	4C 00 01		JMP NEWLINE	PROGRAM IN PAGE 1

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
00DA	XX XX XX			UNUSED
00DD	XX XX XX			UNUSED
00E0	XX XX XX			UNUSED
00E3	XX XX XX			UNUSED
00E6	XX XX XX			UNUSED
00E9	XX XX XX			UNUSED
00EC	XX	MEML		TEMPORARY STRORAGE
00ED	XX	MEMH		ADDRESSES
00EE	XX	TEMP		
00EF	XX XX XX			ADDRESSES 00EF -
00F2	XX XX XX			00FF NOT AVAILABLE
00F5	XX XX XX			FOR USER PROGRAMS
00F8	XX XX XX			
00FB	XX XX XX			
00FE	XX XX			

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0100	20 2F 1E	NEWLINE	JSR CRLF	
0103	A9 0A		LDA #0A	$0A_{16}$ = TEN
0105	8D 64 01		STA COUNT	CHANNELS PER LINE
0108	AD 63 01		LDA CURRENT	PRINT CHANNEL NO.
010B	20 3B 1E		JSR PRTBYT	OF NEXT OUTPUT
010E	20 9E 1E		JSR OUTSP	PRINT 1 SPACE
0111	20 9E 1E	NEWCHAN	JSR OUTSP	PRINT 1 SPACE
0114	A0 00		LDY #00	
0116	B1 EC		LDA (MEML),Y	PRINT 2 MSD'S
0118	20 3B 1E		JSR PRTBYT	OF CHANNEL CONTENT
011B	38		SEC	
011C	A5 EC		LDA MEML	
011E	E9 01		SBC #01	
0120	85 EC		STA MEML	DECREMENT
0122	A5 ED		LDA MEMH	MEML, MEMH
0124	E9 00		SBC #00	
0126	85 ED		STA MEMH	
0128	A0 00		LDY #00	
012A	B1 EC		LDA (MEML),Y	PRINT 2 LSD'S
012C	20 3B 1E		JSR PRTBYT	OF CHANNEL CONTENT
012F	CE 65 01		DEC TOT	
0132	F0 1B		BEQ END	GO TO END IF
0134	18		CLC	ALL CHANNELS PRINTED
0135	A5 EC		LDA MEML	
0137	69 03		ADC #03	INCREMENT
0139	85 EC		STA MEML	MEML, MEMH
013B	A5 ED		LDA MEMH	X3
013D	69 00		ADC #00	
013F	85 ED		STA MEMH	
0141	EE 63 01		INC CURRENT	
0144	CE 64 01		DEC COUNT	GO TO NEWLINE IF
0147	F0 03		BEQ 03	LINE CONTAINS

ADDRESS	CODE	LABEL	ASSEMBLY	COMMENT
0149	4C 11 01		JMP NEWCHAN	TEN CHANNELS
014C	4C 00 01		JMP NEWLINE	IF NOT, GO TO NEWCHAN
014F	20 2F 1E	END	JSR CRLF	
0152	00 00		BRK 00	HALT
0154	4C 00 00		JMP STARTIN	
0157	20 2F 1E	ERROR	JSR CRLF	
015A	A9 45		LDA #45	PRINT "E"
015C	20 A0 1E		JSR OUTCH	
015F	00 00		BRK 00	HALT
0161	00	INIT		
0162	FF	FIN		
0163	XX	CURRENT		
0164	XX	COUNT		
0165	XX	TOT		

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA 600/2-78-099	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE A MICROCOMPUTER-MODIFIED PARTICLE SIZE SPECTROMETER Description and Program Listings		5. REPORT DATE May 1978 6. PERFORMING ORGANIZATION CODE
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16. ABSTRACT

A fully automated aerosol particle size spectrometer system is described that consists of a light scattering particle sensor, an analog to digital converter, and a microcomputer with associated printout device. The system is capable of acquiring a differential particle size distribution, printing the resulting spectrum in one of three representations, and repeating the procedure at preselected intervals. An example of the application of the system for measuring an outdoor aerosol size distribution is presented.

The appendices contain documented microcomputer program listings and flow charts for Program Sizer (the program that operates the spectrometer system and the principal result of this study) and Program MCA (a program that converts part of the spectrometer system to a conventional 256-channel pulse height analyzer).

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Air pollution *Aerosols *Particle size distribution *Spectrometers *Computers *Computer systems programs		13B 07D 14B 09B

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