Programmable control unit for a balloon-borne quadrupole mass spectrometer

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For the measurement of the ionic composition of the atmosphere a reprogrammable control unit for a quadrupole mass filter has been constructed. The heart of this unit consists of two programmable read only memories which allows the choice of 16 different measuring jobs by six telecontrol channels. The underlying principles as well as the performance of the unit are described.

I. INTRODUCTION

The ionic composition of the atmosphere has always been one of the major interests of aeronomists. Thus far, however, identification of the atmospheric ions has been made only at altitudes greater than 64 km.[1–3] For lower altitudes only global ion densities are available.[4–6]

In order to determine the ion composition of the stratosphere at an altitude of about 40 km a balloon-borne mass spectrometer has been built at our institute. This instrument basically consists of a quadrupole mass filter built in a liquid helium cooled cryopump. On top of this a molecular leak[7–8] has been mounted through which the atmospheric ions emerge into the mass filter. The ion detector is a Spiraltron electron multiplier, the signals of which are treated by pulse counting techniques.

Since most of the global ion density measurements indicate an ion density of the order of 10^3 cm^{-3}, a very low pulse counting rate can be expected if the ions are filtered according to their mass-to-charge ratio. Therefore a procedure has been chosen which consists of measuring the ion counting rate in mass domains rather than at definite mass peaks. This measuring procedure, which will be discussed to a larger extent in the next section, requires a special quadrupole control unit. It is the aim of this paper to describe the technical details of this control unit. As will become clear from the text, the underlying principles of the unit can be applied to many other balloon-borne experiments where several parameters have to be changed by a limited number of telecontrol channels.

II. OUTLINE OF THE MEASURING PROCEDURE

As has been shown by Paul *et al.*[9] the equations of motion within the quadrupole field are Mathieu differential equations which can be solved in terms of the ion mass (m) and the dc (U) and rf voltage ($V \cos\omega t$) applied on the filter rods and the field radius (r_0). By setting

$$a = 8eU/(m\omega^2 r_0^2) \tag{2.1}$$

and

$$q = 4eV/(m\omega^2 r_0^2) \tag{2.2}$$

and solving the equations of motion, the well known stability diagram of Fig. 1 is obtained.

Under normal laboratory operation the ratio U/V is chosen to make the scanning line, the slope of which is determined by U/V, intersect the top of the stability region and to obtain a high resolution. However, by choosing the working line such as line 2 in Fig. 1, the quadrupole becomes a band-pass mass filter, and all ions lying in a mass domain m_1 and m_2 are passed. The limiting masses m_1 and m_2 are then given by

$$m_1 = 4eV/(q_2 r_0^2 \omega^2), \tag{2.3}$$

and

$$m_2 = 4eV/(q_1 r_0^2 \omega^2). \tag{2.4}$$

Theoretically the mass domain which is transmitted by the quadrupole is completely defined by two parameters U and V once the working frequency ω and the geometry are chosen. It must be mentioned however that the foregoing treatment is oversimplified. In reality many more factors, such as the radial velocity of the ions, the fringing fields, and the finite length of the filter must be taken into account.

The quadrupole mass filter used in our arrangement is the Finnigan model 750. Its characteristics are summarized in Table I. The last two parameters are determined by the quadrupole voltage supply, which is built in such a way that the dc and rf voltages U and $V \cos\omega t$ are determined by applying proportional control voltages U_c and V_c. A more detailed description of this unit, which has been especially built for this experiment, would be beyond the scope of this paper. Thus, by using the proper control voltage U_c and V_c, a mass domain can be filtered by the quadrupole.

Now in order to determine the ionic composition of the stratosphere, the ion counting rate will be measured in several mass domains. As a first step the regions 5–30, 30–55, 55–80, and 80–105 amu will be investigated. Subsequently these domains will be split up in smaller mass domains,

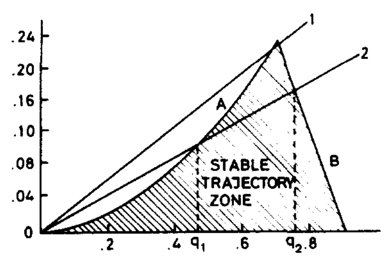

FIG. 1. Stability diagram of the Mathieu differential equations. $a = 8eU/(m\omega_2 r^0_2)$; $q = 4eV/(m\omega_2 r_0^2)$.

TABLE I. Characteristics of the Finnigan model 750 quadrupole mass filter.

Rod radius	6.35 mm
Field length	11.4 cm
Radio frequency	2.14 MHz
Maximum injection angle	60° (at reduced resolution)
Ion injection energy	0–150 eV
Peak rf voltage (ampl.)	300 V
Mass range	0–110 amu

each 5 amu wide, and depending upon the counting rates in these regions a scanning with a higher resolution will be made in several mass domains. To realize ion counting in a mass domain, the electronics must receive three information factors, namely U_c and V_c (which are proportional to U and V and thus determine the mass domain) and the measuring time t. (In reality, however, U_c/V_c is transmitted instead of U_c.) For scanning a mass domain, however, two additional parameters are necessary, namely ΔV_c and N. In the latter case counting will be realized in N mass domains during a time t, each domain characterized by the following dc and rf voltages:

$$U=U_c/\alpha[1+j(\Delta V_c/V_c)] \tag{2.5}$$

and

$$V=V_c/\beta[1+j(\Delta V_c/V_c)], \tag{2.6}$$

where $j=0, 1, 2, \cdots, N-1$, and α and β are the proportionality factors of $U_c=\alpha U$ and $V_c=\beta V$.

In view of the fact that only a limited number (eight) of telecontrol channels were available and that two were already used for general purposes (power on–off and squib activation) a unit has been devised which controls the mass domain measurements as well as the scannings by only six telecontrol channels (four address lines and two interrupt lines).

III. GENERAL DESCRIPTION OF THE UNIT

A block diagram of the controller's architecture is shown in Fig. 2. Essentially the controller consists of a central unit, called the "master controller and memory" (MCM) and several subunits, called "slaves," the number of which can be seven at maximum. In fact these slaves are counters, registers, and digital-to-analog converters controlling the mass domain and measuring time setting of the mass spectrometer, as will be explained later.

The slaves communicate with MCM through a one-directional serial data bus (T-bus), along which MCM transfers binary data stocked in its memory area of 256 words. This memory area is divided into stacks filled with parameters, each parameter dedicated to a particular slave. Every time one wants to switch over to a new mass domain measurement an interrupt circuit is activated by telecontrol, which forces MCM to search in its memory for a new parameter stack needed by the slaves.

In the absence of intervention T-bus remains dead unless a task (measurement) is fully accomplished. In that case one of the slaves responds with an end-of-task signal, starting MCMs automatic search mode. This means that MCM takes the parameters needed for the next measurement from the stack immediately following the last one in use. In other words, in this mode MCM sequentially runs the measurements programmed in its memory. Another interesting feature of MCM is that when it works in the automatic search mode, it is able to jump after task completion to a stack located anywhere in its memory. In this way looping of programmed tasks is made possible.

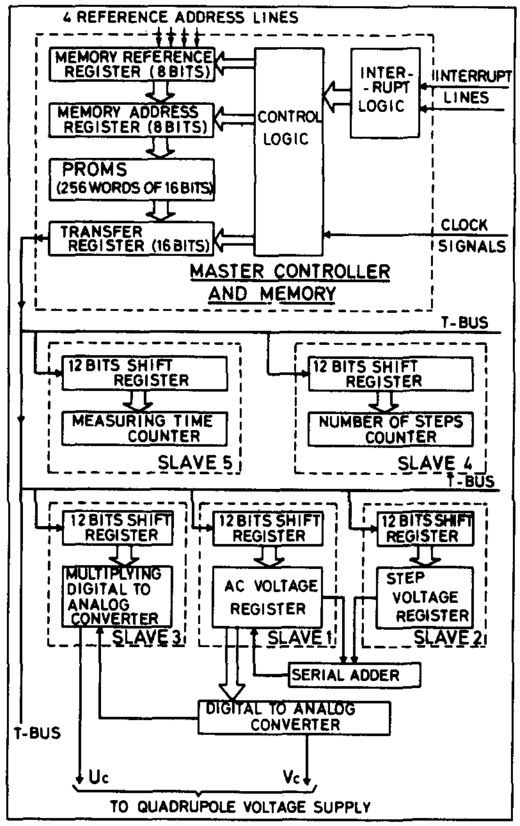

FIG. 2. General block diagram of the control unit.

IV. MASTER CONTROLLER AND MEMORY

As explained in Sec. III the MCM is the heart of the reprogrammable controller. In the first place MCM stores all the binary information needed by the rest of the system. Its memory consists of two electrically programmable read only memories (PROMS) of 2048 bits each. These circuits (National Semiconductor MM 4203 Q) have nonvolatile memories and are programmed by charge storage in floating silicon gates. Erasure of information is accomplished by irradiation with uv light, which results in discharging the gates to their initial uncharged condition.

The PROMS are organized as 256 words of 16 bits. Words 0–15 are reference words (see Fig. 3, format a) which allow access to words 16–255 through only four telecontrol address lines. The latter part of memory is divided into stacks of data words, the configuration conforming to format b of Fig. 3. The lower 12 bits of each word represent a parameter value, and bits 16, 15, and 14 form the address of the slave which should accept that particular parameter. Furthermore, the last data word of a stack has an end-of-stack (EOS) bit equal to 1, telling the MCM logic that it is the last word to be transmitted along T-bus.

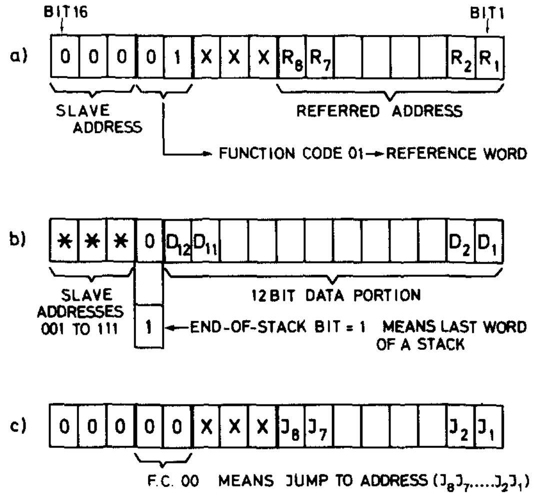

FIG. 3. Formats of the different memory words. (a)—reference words; (b)—data words; c—jump.

Two ways of interrupting the system exist: "absolute priority interrupt," which interrupts on the next 1 sec pulse and "search after task interrupt," which waits with interrupting until the actual task is finished. In both cases MCM reacts on the interrupt command by entering the reference word address of 4 bits, transferred by telecontrol, into its memory reference register. The output of the PROMS now holds the selected reference word. It is then moved along T-bus to the memory reference register (slave 0) which retains only the 8-bit address portion of it and shifts it into the memory address register. Now all words from this address up to the word with the EOS bit set to 1 are pushed on T-bus by MCMs transfer register, shown in Fig. 4. Finally MCM stops with its memory address register content equal to the address of the first word of the succeeding stack. When not receiving any interrupt command MCM waits in a standby mode until an EOS signal occurs. As soon as this pulse appears MCM responds by putting the next stack on T-bus.

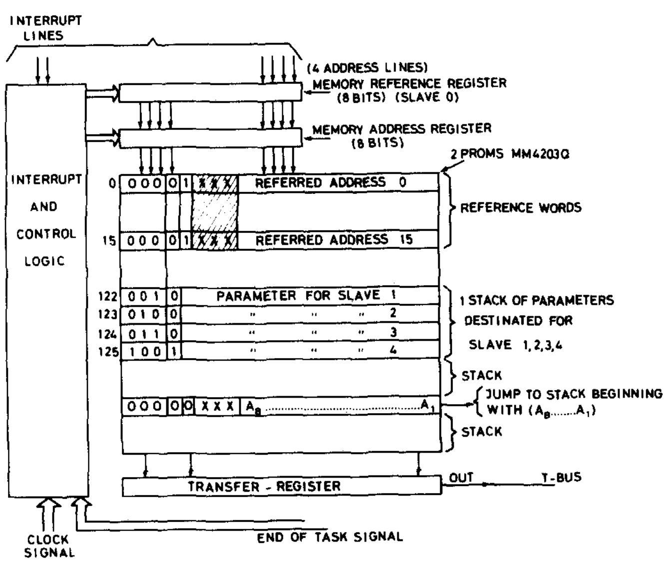

FIG. 4. Interaction scheme of the memory and the different registers of the Master Controller and Memory.

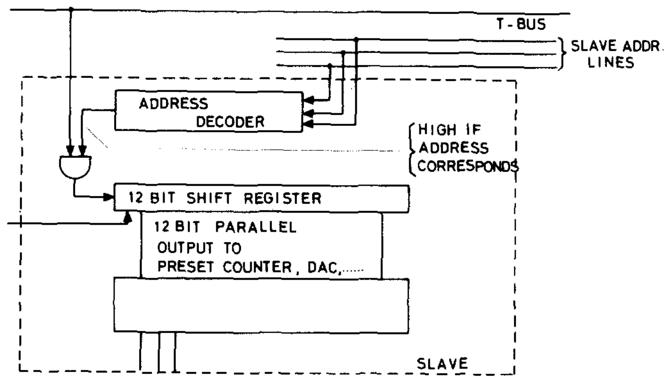

FIG. 5. Schematic representation of the interaction between MCM and the slaves.

Jumping or looping in memory works almost the same way as interrupting. If the first word MCM starts transmitting along T-bus corresponds to format c of Fig. 3, it is moved towards the memory reference register (slave address 0), which retains only the eight address bits J8–J1. From this point on MCM follows the same procedure as in the case of interrupt: The address is loaded into the memory address register and so on.

V. SLAVE UNITS

The foregoing sections contained a description of how the MCM reacts on the intervention of telecontrol. We will now explain how the subunits or slaves accept data from MCM.

All slaves are connected to T-bus and to three slave address lines carrying the slave address portion of the actual addressed memory location. Every time MCM pushes a word on T-bus, this address helps the slave to decide if the word was destined to it. If so, the slave address decoder enables input to a 12-bit shift register, retaining only the lower 12 bits of the accepted word (Fig. 5).

The bits received in this way become available to other circuits. Two slaves are driving two 12-bit digital-to-analog converters, which control the rf and dc voltages on the quadrupole rods. Another one produces a gating signal for the ion counter and thus determines how many seconds a counting in a certain mass domain will last.

In fact, with a total of three slaves a system can be built capable of measuring the number of ions counted in a predetermined mass domain during a predetermined time. However, two other slaves have been added offering the possibility to perform measurements in small succeeding domains by adding a fixed amount to the ac voltage and keeping the dc/rf voltage ratio constant. The two parameters concerned with this feature are the rf step size ΔV_c and the number of steps N.

VI. PERFORMANCE OF THE SYSTEM

To test the performance of the system, the experimental setup as pictured in Fig. 6 has been used. Actually this arrangement is the balloon-borne mass spectrometer package itself, with some slight modification, such as

(i) Installation of an electron impact ion source above the molecular leak.

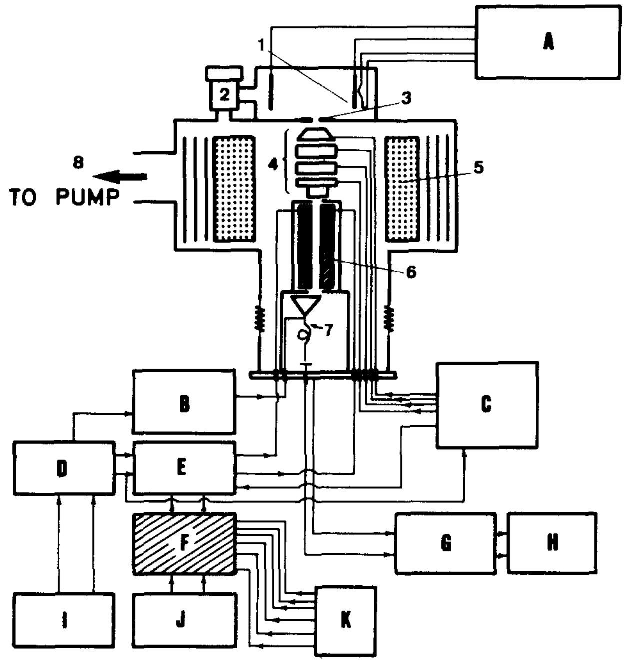

FIG. 6. Experimental setup used during the tests. 1—Electron impact ion source; 2—bypass valve; 3—molecular leak; 4—ion lens; 5—cryopump; 6—quadrupole mass filter; 7—Channeltron electron multiplier; 8—to Vacion pump (50 liters/sec); A—ion source control unit; B—high voltage supply (2700 V); C—ion lens control unit, also produces some voltages for the quadrupole voltage supply; D—booster; E—quadrupole voltage control unit; F—programmable control unit; G—electrometer (Keithley model 417A); H—strip chart recorder (Texas Instrum.); I and J—power supplies (Hewlett-Packard) delivering 28 and 20 V, respectively (each replacing one set of batteries); K—switch box simulating the telecontrol channels.

(ii) Replacement of the batteries by a set of laboratory power supplies.

(iii) Pumping by an external Vacion pump (50 liters/sec) instead of the cryopumping system.

(iv) Simulation of the telecontrol channels by a switch box, which allowed us to simulate all the telecontrol commands which can be given in flight conditions.

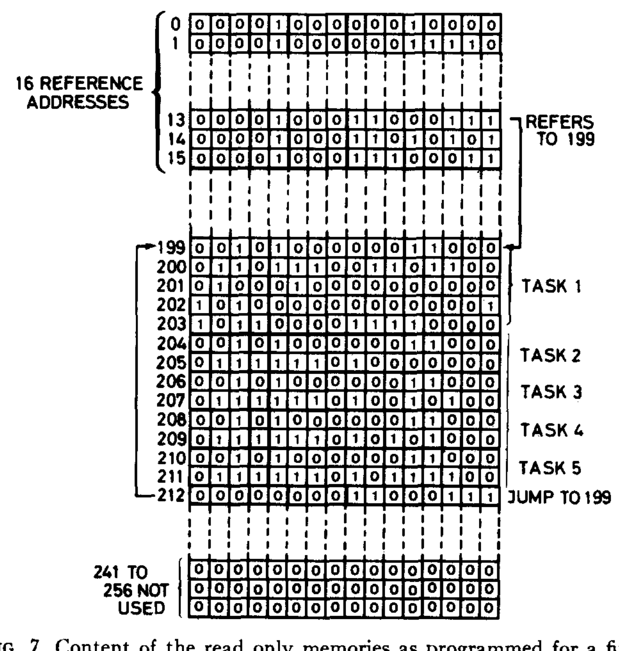

FIG. 7. Content of the read only memories as programmed for a first test experiment.

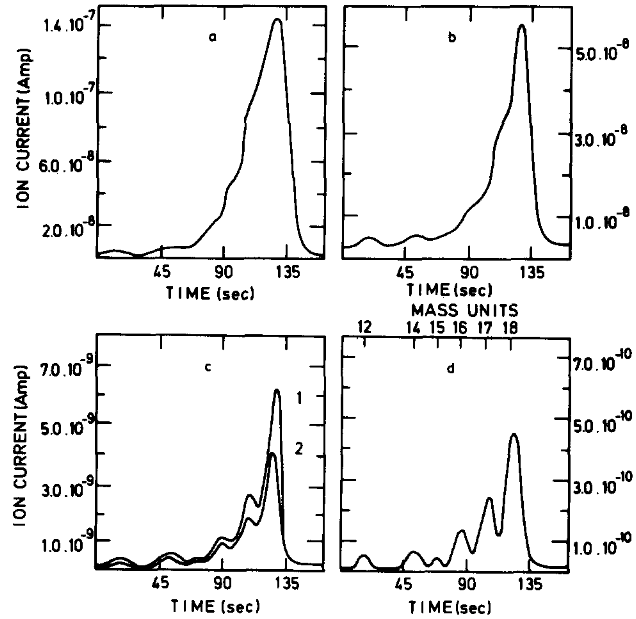

FIG. 8. Mass spectra obtained with PROMS as indicated in Fig. 7.

(v) Replacement of the ion counting system by an electrometer and a strip chart recorder.

In a first test the PROMS of MCM have been programmed as indicated in Fig. 7. The first 16 words of the PROMS refer to 16 different reference jobs, each of them consisting of five tasks (stacks) and a jump. As can be seen from Fig. 7 the last tasks of one reference job differ from the first task only by their value of U_c/V_c. Actually task 1 of reference job 13, which is completely shown in Fig. 7, consists of measuring successively 1 sec in small mass intervals, each of them characterized by formulas (2.5) and (2.6) with $N=240$, $V_c=940$ mV, $\Delta V_c=4.88$ mV, and $U_c/V_c=0.1803$. The proportionality factors between U_c and U and V_c and V have been measured separately and are given by $U=27.4U_c$ and $V=29.8V_c$. The measurement of task 1 in job 13 thus corresponds to a scanning from mass 11.3 to mass 25.3 amu, with a resolution defined by $U/V=0.166$ (the step size ΔV_c is so small here that we can really speak of a scanning). As a matter of fact the resolution in terms of U/V can be varied from 0.108 to 0.180 in steps of approximately 9×10^{-4} through the 80 different tasks of the 16 reference jobs. Each job can be separately accessed by an interrupt. Some typical spectra obtained in this way are shown in Fig. 8. The masses 12, 14, 15, 16, 17, and 18, which originate mainly from hydrocarbons and water vapor, are clearly recognized. The corresponding resolutions of Fig. 8 are given in Table II.

TABLE II. Calculated and measured resolutions for the different measurements of Figs. 7 and 8.

Ref. job	Task no.	Fig.	$(U/V)_{calc}$	$(U/V)_{meas}$
11	1	8(a)	0.1568	0.1550
12	1	8(b)	0.1613	0.1605
13	1	8(c) (1)	0.1657	0.1649
13	2	8(c) (2)	0.1665	···
14	1	8(d)	0.1702	0.1693

The value $(U/V)_{\text{calc}}$ has been computed by means of the memory content of the PROMS, and the $(U/V)_{\text{meas}}$ values have been obtained by measuring the control voltages at the output of the control unit. As can be seen, the agreement is excellent, taking into account the possible measuring errors.

Furthermore, it is noticed that the separation between the different mass peaks becomes more clear when U/V is increased, which is in agreement with the quadrupole theory. It might be surprising that at values of $U/V>0.167$ the transmittance of the mass filter is not yet reduced to zero. The accuracy of the U/V values, however, depends entirely on the accuracy with which the proportionality factors α and β have been obtained. Since the measurement of these factors is extremely difficult a slight fault can easily be introduced here. The fact that no better mass resolution could be obtained than the one in Fig. 8(d) is due to high frequency spikes which have been observed at the output of the mass filter control unit. For our purposes, however, the resolution obtained is quite satisfactory.

As a second test the PROMS have been reprogrammed as is partly tabulated in Table III. Instead of the control voltages, the actual dc and rf voltages are tabulated, taking into account the measured proportionality factors. The control voltages have been calculated by setting forward the corresponding mass domain and by approximating the curves A and B of Fig. 1 by[10]

$$a=q^2/2-(7/128)q^4 \tag{6.1}$$

and

$$a=1-q-q^2/8+q^3/64-(1/1536)q^4.$$

Again 16 reference jobs have been programmed, of which only five are shown in the table. The other jobs are those described in Sec. 2.

The mass spectra recorded with the newly programmed PROMS are shown in Figs. 9 and 10. Figure 10 represents the ion current measured in succeeding small intervals,

TABLE III. Contents of the PROMS for a second test, the corresponding mass spectra of which are shown in Figs. 9 and 10.

Ref. job	Task no.	V (volts)	U/V	ΔV (volts)	Time (sec)	No. of steps	Mass domain
0	1	10	0.180	1	120	1	0–0
	2	12.5852	8.44×10^{-3}	1	300	1	4–106
1	1	12.189	0.02794	1	300	1	4–31
	2	79.2417	0.09889	1	300	1	29–56
	3	142.728	0.12192	1	300	1	54–81
	4	205.475	0.13333	1	300	1	79–106
2	1	12.5684	0.08408	1	300	1	4.5–10.5
	2	25.4018	0.11383	1	300	1	9.5–15.5
	3	38.0031	0.12788	1	300	1	14.5–20.5
	4	50.5239	0.13607	1	300	1	19.5–25.5
	5	63.0073	0.14143	1	300	1	24.5–30.5
3	1	75.4706	0.14521	1	300	1	29.5–35.5
	2	87.9207	0.14801	1	300	1	34.5–40.5
	3	100.364	0.15018	1	300	1	39.5–45.5
	4	112.801	0.15191	1	300	1	44.5–50.5
	5	125.235	0.15331	1	300	1	49.5–55.5
...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
6	1	0.00	0.166	2.48	6	100	0–100
...	...	...	...	...	...	...	...

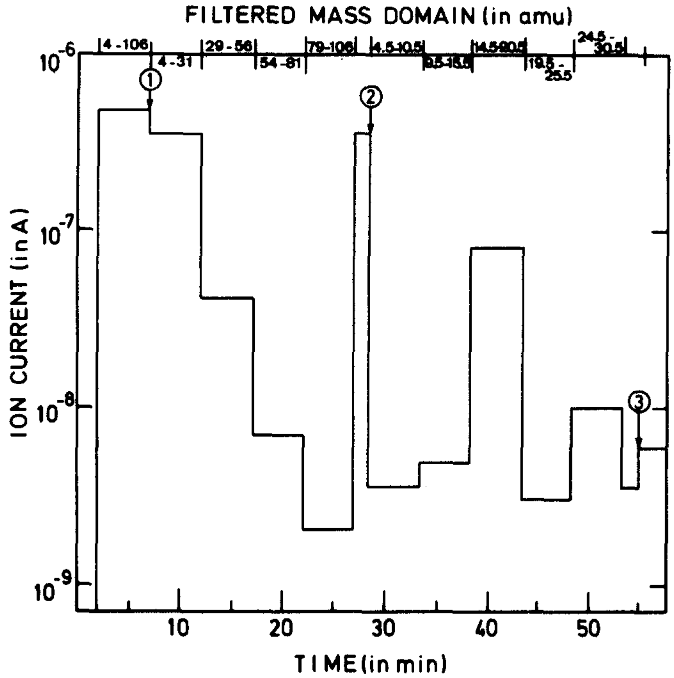

FIG. 9. Mass spectra as obtained with the ref. jobs 0, 1, 2, and 3 of Table III. The meaning of the encircled numbers is 1—absolute priority interrupt to ref. job no. 1; 2—absolute priority interrupt to ref. job no. 2; 3—absolute priority interrupt to ref. job no. 3.

which can be calculated by applying formulas (2.3) and (2.4). In this case q_1 and q_2 are intersecting points of the curves A and B of Fig. 1, the equations of which are given by formulas (6.1) and (6.2), and the straight line

$$a=2U_j/V_j\cdot q,$$

where U_j and V_j are given by

$$U_j=U/V\cdot(V+j\Delta V),$$
$$V_j=V+j\Delta V,$$

j being the number of the mass domain as indicated in Fig. 10. Again the mass peaks of water (mass 18) and its satellites can be clearly recognized. From the foregoing tests it can be concluded that the designed control unit is quite suitable for the measurements described in Secs. I and II.

The complete unit can be mounted on two 10×13.5 cm printed circuit boards. Furthermore, it must be noticed that since all the electronics except the PROMS are executed

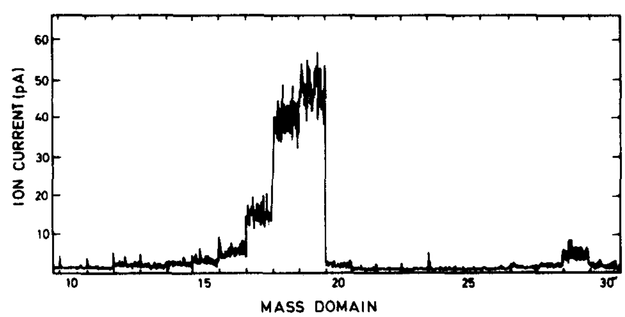

FIG. 10. Mass spectrum obtained with ref. job no. 6 of Table III.

in COSMOS components, the power consumption is very low, which makes it very attractive for balloon-borne measurements.

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