

SPACE PHYSICS

by Carl O. Bostrom
and George H. Ludwig

IN ATTEMPTING TO DESCRIBE the present status of instrumentation in "space physics" one is faced with the problem of defining terms. Space physics may be interpreted broadly to include (1) all experimental areas of physics in which the use of balloons, rockets, satellites, or space probes offer some advantage, and (2) ground based measurements of "space" phenomena. In category 1 are included all the in situ measurements of the environment (from the atmosphere to interplanetary space) as well as some areas of astronomy, astrophysics, lunar and planetary physics, geodesy, and meteorology. Examples of measurements in category 2 are solar and magnetic observatory measurements, ionospheric studies using radio propagation characteristics, auroral observations, etc. Clearly, a listing of the disciplines that might be considered part of space physics would be quite long and each of these areas uses a specialized and complex set of instrumentation that is worthy of detailed description.

Instead of trying to survey the instrumentation in all these areas, we concentrate here on the system aspects of experimental space physics and, further, limit most of the discussion to satellite systems. We begin by considering the common factors that influence design of all satellite experiments and proceed to a detailed discussion of data-handling systems. This is followed by descriptions of several examples of experiments and

an attempt to point out some of the approaches to system design that promise greatly to influence future capabilities.

Although we emphasize the data-handling problem as being of prime interest to all experimenters, it should be mentioned that the success of a satellite experiment depends heavily on the operation of the auxiliary subsystems that make up the spacecraft. Especially important are the power and thermal designs, attitude-control and measurement systems and tracking system.

It is probably fair to say that very few satellite-borne experiments incorporate sensor or measurement principles that are completely new. Often, the problem in space experiments is not so much how to make the measurement as how to make it within the constraints imposed by the spacecraft (power, weight, volume, data system) and the environment (launch vibration, temperature variations, background interference and other experiments). In general, experiment design requires a series of compromises forced on the experimenter by facts of satellite life. We do not mean to imply that the design of space-borne instruments is simply the repackaging of ground-based equipment. In fact, the design of experiments from both physics and engineering points of view is quite challenging and requires an equivalent or greater amount of ingenuity than comparable ground

To get experimental data from space vehicles to the ground, physical quantities (temperature, particle energy, etc.) must be converted to electrical quantities and then broadcast. Equipment for the purpose varies according to the nature of the experiment and the amount of on-board data processing desired. Early systems delivered fairly "raw" data to the ground, but as experiments grow more sophisticated, more on-board sorting and analysis are necessary.



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SPACE PHYSICS

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equipment. The major reason is the requirement for completely untended operation, and therefore, very high reliability. Reliability to the physicist means more than just the probabilities of parts failure computed in the classical manner. The results obtained from an instrument can depend critically on the stabilities of the component parts, and the experimenter must have high confidence in the instrument, particularly if an anomalous effect is observed. In other words, it is not sufficient to know that an instrument is working; we must know that it is working *correctly*. In that sense, perhaps credibility is a more appropriate word than reliability.

Various in-flight calibration techniques can be used to increase credibility. With certain particle-detector systems, radioactive sources can be used to good advantage. If, however, the experiment is complex and has several detectors, each having several discriminators operated in several combinations of coincidence, anticoincidence or both, in-flight calibration becomes equally complex, and one must worry about the credibility of the calibrator! Clearly this is another point where one must arrive at a suitable compromise. Basically, credibility is achieved through careful design, the best available components, proven fabrication and assembly techniques, attention to quality control practices, extensive pre-launch calibration, and rigorous (non-destructive) testing.

Types of spacecraft

Returning now to the system aspect and its effect on individual experiments, let us consider types of spacecraft currently available. There are several categories based on mission: earth orbiters; lunar probes, orbiters and landers; planetary probes, orbiters and landers; interplanetary probes; solar probes and galactic probes. We will not discuss the various probes at length because the experiment-spacecraft interfacing prob-

lems are in general similar to those for earth satellites. The major difference is in the telemetry link, which will have a much smaller information capacity than for near-earth missions.

Another categorization is by size. It is possible to go into the sometimes controversial question whether large or small spacecraft should be used in a given case; but we will confine ourselves to pointing out some of the advantages of each.¹

The small satellites (weighing less than about 150 kg) make the task of controlling all types of interference easier, simply because there are fewer experiments and smaller spacecraft subsystems. Program coordination, testing and scheduling are easier because of the smaller numbers of people involved. And it is possible to meet the orbital requirements more closely because of the larger range of launch-vehicle capabilities for the lighter payloads and because it is easy to assemble small payloads of experiments with closely matched orbital requirements.

The larger observatories, besides having the obvious advantage of being able to perform very large or heavy experiments can also carry large numbers of related experiments to perform studies of the correlative aspects of numerous space phenomena. (This advantage may be difficult to realize however, if the experiments come from many geographically separated institutions.) The large observatories, in addition, can carry higher-performance data-handling systems, which provide a larger information bandwidth for the experiments. Their active attitude-control systems can also provide accurate orientation control. Another important aspect is that the larger observatories make more efficient use of the ground receiving and tracking stations and data-processing facilities than a comparable number of small satellites.

Power per unit experiment weight and cost per experiment weight appear to be comparable for the two categories. There is a higher probability at present for successfully launching the small satellites because of their relative simplicity. But rather limited experience with the observatories thus far indicates that once a

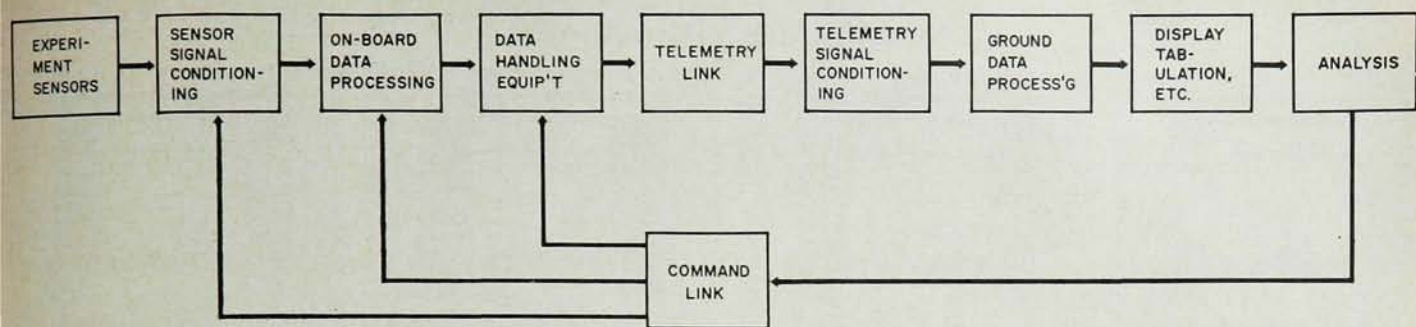
larger observatory is successfully placed in operation its probability for a long life is greater because of the large amount of redundancy of subsystems and repairability by use of the extensive command link. On the large observatories an attempt has been made to standardize spacecraft structure and subsystems. The advantage of this standardization is that, in principle, the only major changes from one flight to the next are in the scientific missions. The spacecraft and the ground data-handling systems require a minimum of modification, leading to lower cost per mission and higher reliability and dependability. The small spacecraft have not, in general, been able to adopt much standardization because of the need for more tightly integrated packages to take full advantage of the more limited weight. But with the recent advent of smaller electronics packaging techniques, efforts are now being made to provide a higher degree of standardization on the small satellites as well.²

SPACE INFORMATION SYSTEM

"Information system" refers to that portion of the electronic systems that collects outputs from experiment sensors on the spacecraft, processes these data on the spacecraft, transfers them to the ground receiving stations, and prepares the information in suitable form for the experimenters so that they may reach conclusions about the phenomena being measured.

Generalized system

The basic generalized system is illustrated in figure 1. A sensor converts some physical quantity, such as temperature, charged-particle energy, or magnetic field intensity, into an electrical quantity. Signal conditioning circuits aboard the spacecraft, such as amplifiers, feedback networks, charge integrators, etc., are often associated directly with the sensors to make the electrical quantities more easily processed and telemetered. These are often followed by additional signal conditioning circuits that count pulses, measure amplitudes of pulses, measure amplitudes of more slowly varying analog quantities such as current, voltage, and resistance, and



GENERALIZED space information system. —FIG. 1

measure time intervals to simplify the task of telemetering the data to the ground.

After on-board signal conditioning, additional processing of two basic types can be done on the spacecraft. The first reduces the amount of raw data without reducing information content. This processing includes elimination of redundant information, elimination of meaningless zero readings and reformatting operations that involve simply rearrangement of data. The second type of on-board processing reduces the information content of the raw data and includes curve fitting, statistical analysis and mathematical manipulation.

Since one often wants to perform a number of experiments in the same spacecraft and obtain status and performance information about various spacecraft subsystems, it is common practice to multiplex a number of data channels onto a common telemetry link. This link includes necessary encoding and decoding equipment, transmitters, receivers, anten-

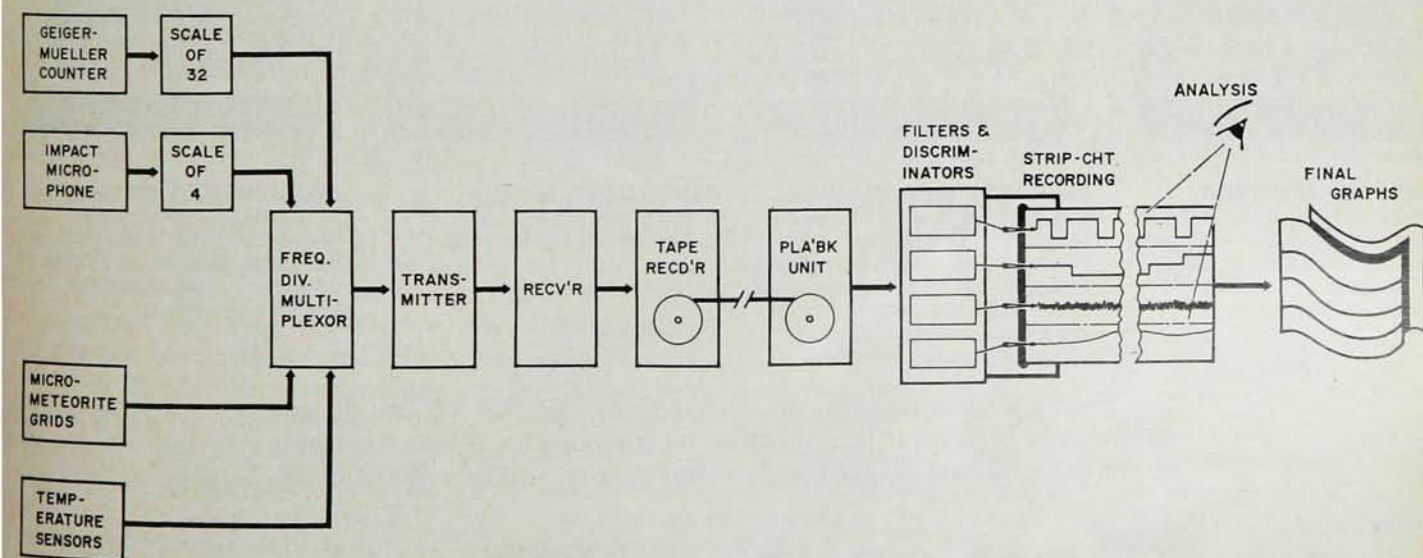
nas and the space path. This entire link can be represented in general by a transfer function in which noise is added to data. If one must manipulate space-borne equipment from the ground, a reverse or "up-telemetry" link, usually referred to as a "command link" is also included.

After data have reached the ground one must perform a number of additional operations before they can be used by experimenters in their analyses. These operations commonly include synchronization, noise removal, time decoding, quality determination, editing and documentation or sorting. These processes result in the provision to experimenters of data tapes containing the best estimation of the original data from each experiment's sensors, along with the necessary status, performance, time and validity information. It is also common practice to supply orbit and spacecraft attitude information necessary for use in the experimenter's analyses. Each experimenter then

passes this information through an additional processing operation in which he reformats, sorts, performs additional mathematical manipulations and ultimately obtains outputs that he can use directly in analyzing the phenomena being investigated.

A simple system

An example of an extremely simple space information system is shown in figure 2. This is the Explorer I system,³ which was successfully launched on 31 Jan. 1958 and led to discovery of the Van Allen radiation belts surrounding the earth. In this system, pulses from a single Geiger-Müller counter were accumulated in a five-stage binary register capable of 32 counts. The state of the output stage was continuously transmitted. In addition, a number of temperatures and the continuities of a number of micrometeoroid detection grids were also telemetered. Each signal source controlled a subcarrier oscillator so the oscillator frequencies were proportional to the voltages from the



EXPLORER I information system. —FIG. 2

Yes, our MR Recorder often seems like many instruments at work

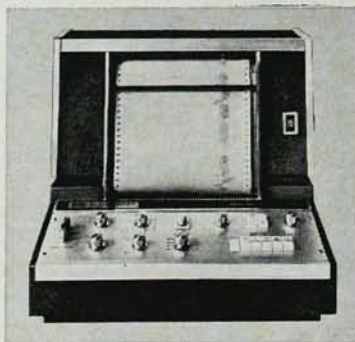
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DESCRIPTION: SARGENT MODEL MR RECORDER—automatic, self-balancing, 10-inch potentiometer recorder. Includes special high gain amplifier, and high stability solid state reference power supply requiring no standardization. Line operated.



QUANTITY RECORDED: mV, V, μ a and ma—selected by panel switch.



ELECTRICAL RANGE: twelve pre-calibrated ranges by switch selection — 0.5, 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000. Variable range expansion from 100% (off) to 40% of selected range with continuously adjustable dial.



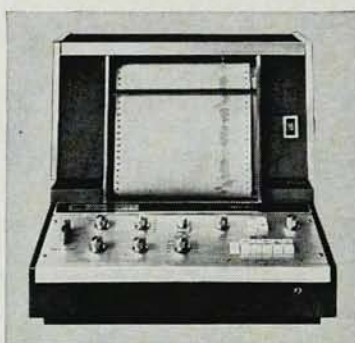
LIMIT OF ERROR: 0.1% or 5 μ v, whichever is greater.



ZERO DISPLACEMENT: calibrated ranges of 10, 100, 1000 and 5000 of the selected units, upscale or downscale. Continuously adjustable reading dial for 0 to 100% of selected range.



SOURCE RESISTANCE TOLERANCE: 50,000 ohms in most sensitive range, increasing with increasing range.



ELECTRICAL FILTERING: four position switch to reject transverse and common mode A.C. superimposed on the D.C. signal, without loss of sharp balancing characteristics.



PEN SPEED: 1 second for full scale transverse.



DAMPING GAIN ADJUSTMENT: automatic with range change; panel dial for fine adjustment—particularly for low resistance systems like thermocouples.

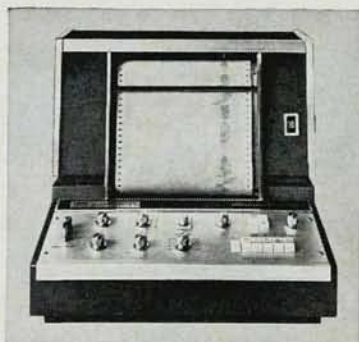


CHART DRIVE: twelve synchronous speeds—0.5, 1, 2, 4, 10, 20—by dial selection, inches per hour or per minute by panel switch. Magnetically braked in "off" position. Free clutch system scans chart with rapid drive; averages 50 feet per minute in forward or reverse directions.

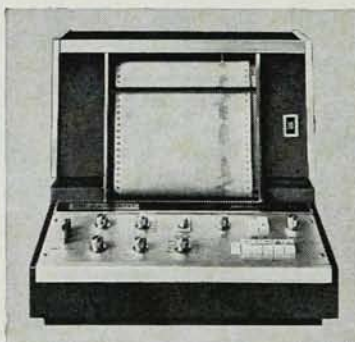


CHART TAKE-UP: automatic, by motor with preset torque—or by-pass for free end chart tear off.



SYNCHRONIZATION: chart drive may be synchronized with external systems connected to rear panel, and operated by the chart drive switch. Or chart drive may be operated from an external switch.

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sources. These various signal sources were frequency multiplexed by the addition of the outputs from the oscillators. The resulting single composite signal modulated the transmitters directly and the output of the receiver on the ground was, in turn, demultiplexed by passing the signals through a number of bandpass filters and frequency discriminators. At the output of the frequency discriminators on the ground, the signals (identical in form to the signals that modulated the subcarrier oscillators in the spacecraft) were used to produce strip chart recordings. These strip chart recordings were then manually reduced by a number of data readers to provide, ultimately, tabulations of the G-M counter pulse rates, temperatures, and the rates of breakage of the micrometeoroid grids. This system employed very little on-board data processing and very little machine processing on the ground. It provided an output containing a large fraction of the raw data produced on the spacecraft. This very simple system was used in the first satellites to give a high probability of success at a time when instrumentation on satellites was still an unknown art, and when large-volume data-processing techniques on the ground were relatively unknown.

Since that time, technology has advanced until one can make quite complex electronics systems on spacecraft and operate them reliably for a year or more. In addition, we now want to perform many more experiments that are much more complex than those on early Explorers. The reason is that as we investigate various phenomena in more and more detail in order to study their detailed characteristics, we must make more and more discriminating measurements, which involve a higher order of data processing. To illustrate, on Explorer I only the omnidirectional intensity of all particles above a threshold energy determined by the thickness of the G-M counter wall was measured. Now, in the continued in-

vestigation of cosmic rays and energetic trapped radiation, the directional characteristics, the types of particles, the intensity as a function of particle energy and type, and the temporal variations of these parameters must all be determined. Therefore, where one could once simply count the number of pulses, one must now perform a multiparametric pulse height analysis from rather complex detectors. These additional requirements impose a requirement of increased capability for the entire information system.

A more complex system

The information system for a recent large spacecraft is illustrated in figure 3. It is for the Orbiting Geophysical Observatory⁴ (OGO), a spacecraft in the 500-kg category, which was designed for a variety of orbits ranging from low, near-circular, polar orbits (Polar Orbiting Geophysical Observatory, POGO) to very highly eccentric orbits extending to approximately 24 earth radii at apogee (Eccentric Orbiting Geophysical Observatory, EGO). The first of these observatories, OGO-I, launched in September 1964 into the eccentric orbit, carried 22 experiments from 17 institutions.

Instrumentation for OGO experiments ranges from extremely simple generators of analog signals corresponding to, for example, currents in ion collectors, to extremely complex digital-data-processing subsystems involving digitization and manipulation of pulse heights from a number of detectors. Each of the two digital-data-handling subsystems on the spacecraft consists of a main time-division multiplexer (which can be imagined as a sampling switch) with 128 experiment inputs and three slower sub-multiplexers with 128 inputs each for an assortment of spacecraft and experiment inputs. In addition, each has a flexible-format time multiplexer that can be set at any one of 32 different input-data formats by ground command. The latter multiplexer is intended for use with extremely high information bandwidth experiments for relatively short periods. Two large-capacity tape recorders are included on the spacecraft. They can

record at 1000 bits/sec for 24 hours for EGO missions and 4000 bits/sec for 8 hours for POGO missions. These rates correspond to approximately one and four main multiplexer measurements per channel per second for the two cases. In addition, information can be telemetered directly without the tape recorder at bit rates up to 64 000 bits/sec corresponding to 55 measurements per input channel per second.

Central data processing on the ground involves four major steps. The recordings containing the raw output of the receiver decoders are first played through a set of equipment that estimates values of original data bits, establishes bit, word and frame synchronization and decodes the times recorded on the tapes at the ground receiving stations. The equipment produces a computer buffer tape. The second major step involves editing of this computer tape to ascertain that there were no errors in its production and to determine data quality. The third step involves establishment of the relationship between data as recorded on the spacecraft and Universal Time (GMT). The fourth step is decommutation (sorting) of buffer-tape data and generation of individual experimenter's data tapes and a status and performance data tape that is used for subsystem analysis.

On-board processing

Up to now, data processing on spacecraft has been kept relatively simple to obtain high equipment reliability and high confidence in our ability to interpret results after flight. Some steps have been made in the direction of increasing the amount of data processing on board the spacecraft, however. A very simple example is inclusion of floating-point counters on some OGO-I experiments that count pulses in a nonlinear manner. One such device is a part of the cosmic-ray experiment described later. This counter has a large dynamic range and fixed accuracy that are ideal for many intensity measurements in a wide variety of experiments.

There are a number of arguments at present for developing more extensive on-board processing tech-

SPACE PHYSICS

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niques. The major one is that the sheer volume of data being returned from satellites is becoming extremely large and the task of processing the data on the ground is expensive. As we have said earlier, two separate types of information processing on board the spacecraft are possible, one involving reduction of raw data while retaining information content, the second involving information-content reduction. The system should be designed so that any degree of on-board processing from essentially zero to a large amount of the second type can be performed by programming from the ground after the spacecraft is launched, at least in the early systems. Thus the spacecraft can be launched with a very simple data-processing format and, as the characteristics of the phenomena and the behavior of the instruments are ascertained in orbit, additional degrees of data processing can be used. On-board computers with stored (but replaceable) programs are now being developed by several groups. These computers may also be able to control calibrations of the experiments, computation of spacecraft attitude relative to the sun or magnetic field (with resulting control of experiment sampling times and programs) and to interface with the spacecraft attitude control, power and thermal-control subsystems.

SEVERAL EXPERIMENTS

We shall now describe several experiments that are currently scheduled for flight or well along in development. We do not claim that these are "typical"; rather they reflect the experience and environments of the authors. Nevertheless, they do serve as examples and indicate the capabilities of current systems. Only the experiments are described since the ground data processing follows the procedures discussed above.

Solar proton monitoring

An example of a relatively simple, straightforward instrument designed to make a specific kind of measure-

ment is the Solar Proton Monitoring Experiment⁵ (SPME). Since its function is to monitor the frequency of occurrence and intensity of energetic protons emitted from the sun and to provide a crude measure of their energy spectrum, emphasis is on simplicity, reliability and reproducibility. The experiment is intended for inclusion in a number of spacecraft so as to have, as nearly as possible, continuous coverage over at least half a solar cycle. The experiment is currently scheduled for a series of sounding rockets to be launched (from Fort Churchill, Canada) into a solar-proton event, if possible during the summer of 1966. It is also one of 12 experiments in the IMP (Interplanetary Monitoring Platform) F and G spacecraft, which will be placed into highly eccentric orbits in 1966 and 1967.

The experiment consists of an array of solid-state detectors designed to measure proton intensities in the following energy ranges: $E_p \geq 60$ MeV, $E_p \geq 30$ MeV, $E_p \geq 10$ MeV, and $1 \leq E_p \leq 10$ MeV. Separate detectors are used for each energy range, and a combination of discriminator levels and shielding thickness defines the energy response of each channel. This method permits accurate absolute flux determinations and accurate unit-to-unit comparisons when a series of packages monitors events over an extended time period. No attempt is made to discriminate between protons and other particles, but energetic-electron contamination can be ignored if we restrict the observations to locations outside the trapping region, that is, outside the magnetosphere or over the polar caps. Contributions from heavier nuclei will vary from one event to another but should not exceed 10%.

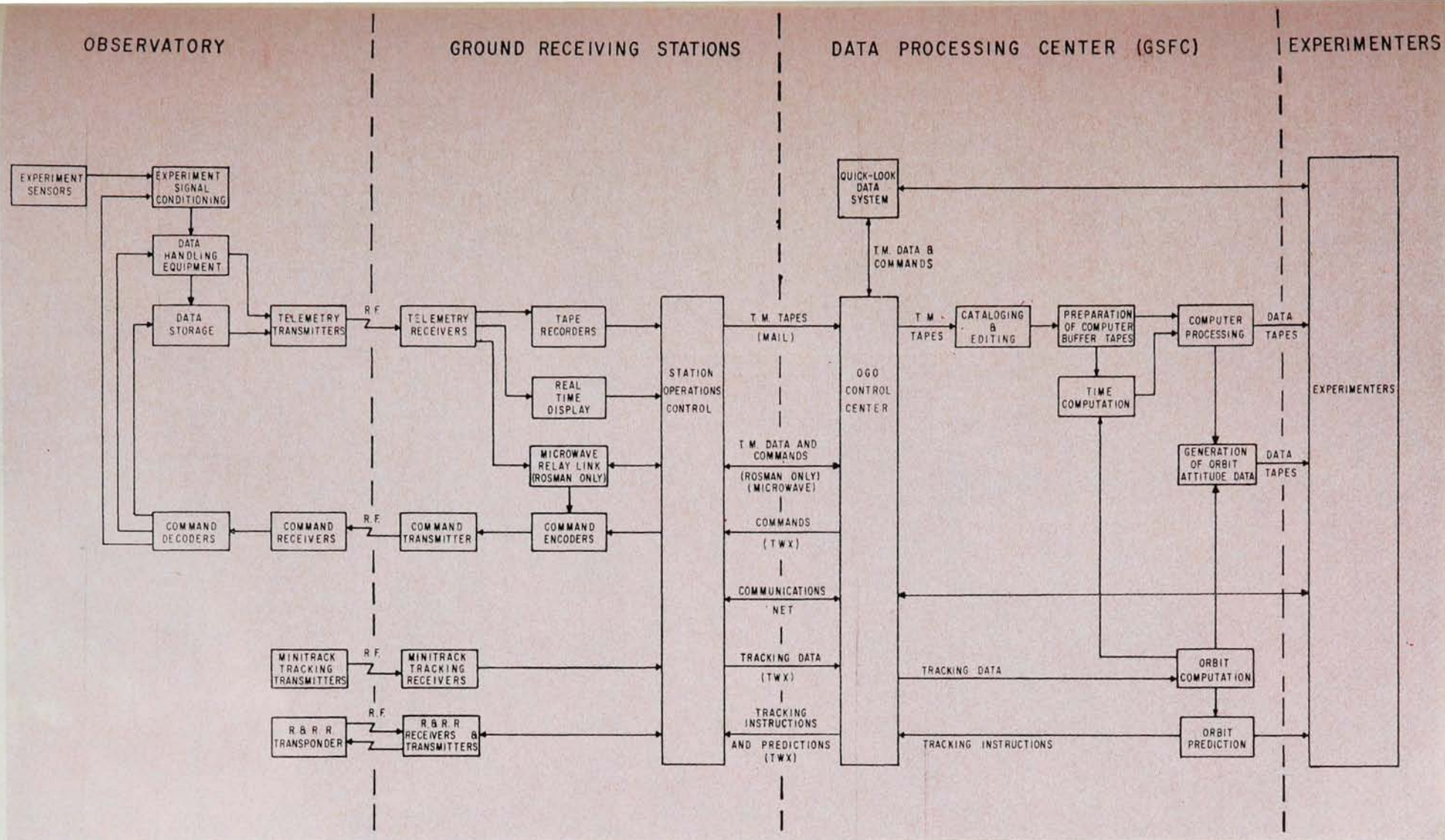
The two high-energy detectors (60 and 30 MeV) are identical except for absorber thickness. Each consists of three surface-barrier detectors (700 microns thick by 0.8 cm²) mounted on adjacent faces of a cube and connected in parallel. The three detectors, therefore, form a unit that provides a large area and fairly uniform omnidirectional characteristics over 2π steradians. Typical three-detector arrays have noise widths of 25–35

keV fwhm (full width at half maximum) at a bias voltage of 200 V, which is about 25% above that required for full depletion. A single discriminator level at 150 keV ensures detection of minimum ionizing particles, which deposit a nominal 280 keV at normal incidence. The energy threshold is set primarily by the hemispherical copper absorbers, 5.6 mm thick for the 60-MeV unit and 1.6 mm thick for the 30-MeV unit.

Similarly the 10-MeV channel has omnidirectional sensitivity over 2π steradians and a hemispherical absorber to set the energy threshold. The detector itself, however, is a lithium-drifted silicon cube, 3 mm on a side. At 200 V bias the detector noise is less than 50 keV fwhm and the discriminator level is set between 250 and 300 keV.

The 1–10-MeV detector is also a straightforward device. It employs a 100-micron-thick solid-state detector of 2 cm² active area, fully depleted, and operated at 50 V ($\sim 25\%$ overbias). The 1–10-MeV (approximate) interval is obtained with a single discriminator level at about 900 keV. Detector response is linear up to the point where proton range equals detector thickness (about 3.2 MeV for normal incidence). For higher energies the pulse height ΔE decreases as dE/dx decreases. Thus the energy interval for protons is 0.9–9.4 MeV. The effective lower threshold is increased to about 1 MeV by an aluminized mylar light shield. As angle of incidence is increased, effective path length and upper energy limit are increased. At 30 deg, however, the upper limit goes only to 10.5 MeV and all angles greater than 30 deg are shielded with at least 1.6 mm of copper, equivalent to about 30 MeV for protons. To eliminate contributions to the counting rate from high-energy protons that penetrate the shielding and traverse a long path length in the detector, an upper discriminator is set at about 3.6 MeV, a level greater than the largest pulse height from protons incident within the 30 deg (half-angle) acceptance cone.

Some will argue that the use of solid-state detectors, surface-barrier and



ORBITING GEOPHYSICAL OBSERVATORIES information system. Each of two digital-data systems has a main time-division multiplexer with 128 experiment inputs and three slower submultiplexers with 128 inputs each. In addition each system has a flexible-format time multiplexer that can be set at any of 32 different input-data formats by ground command. Two large-capacity tape recorders can record at 1000 bits/sec for 24 hours for EGO missions and 4000 bits/sec for 8 hours for POGO missions. Data can be telemetered directly at up to 64 000 bits/sec.—FIG. 3

SPACE PHYSICS

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lithium-drifted types in particular, is questionable in a high-reliability application. It is worth mentioning, therefore, that the Applied Physics Laboratory group has been using solid-state detectors in satellite experiments for over five years (on five satellites) and that all types of detectors have performed satisfactorily.

A block diagram of the IMP version of the experiment is shown in figure 4. Since only one spacecraft encoder register is available for the experiment, the five outputs are commutated, and voltage amplifiers and discriminator for channels 1 and 2 are time-shared. Counts are accumulated for 19.2 sec out of the 20.48 sec encoder-sequence time. A complete readout requires eight sequences, but channels 3, 4A and 4B are each read twice during this time. In the sounding-rocket version, the encoder was made a part of the experiment package. The basic detector channels are essentially the same as in IMP, except that time sharing is unnecessary.

Cosmic rays

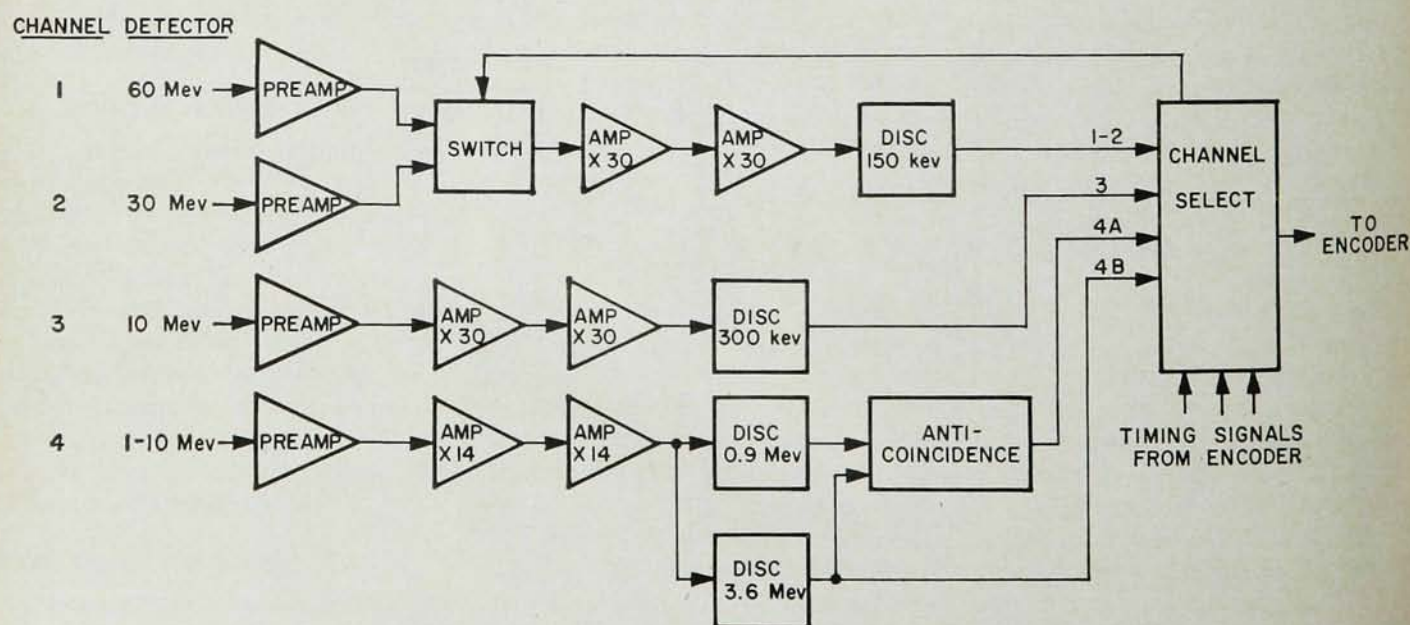
In galactic and solar cosmic-ray studies, one of the basic needs is for de-

tailed charge and energy spectra over a wide dynamic range extending from the MeV to the GeV region from hydrogen through the very heavy nuclei group. We now discuss an experiment⁶ that provides these spectra through an integrated set of three detectors. Simultaneous observations resulting from these three detectors are expected to lead to a better understanding of the production, acceleration, and modulation of the galactic and solar cosmic rays. The major measurements are: (1) absolute proton flux and differential energy spectra over the range 0.4–1000 MeV and integral flux greater than 1000 MeV; (2) absolute helium flux and differential energy spectra over the range between 2 and 1000 MeV per nucleon and integral flux greater than 1000 MeV per nucleon; (3) charge and differential energy spectra of individual nuclear constituents between proton numbers 3 and 18 in the range between 20 and 1000 MeV per nucleon and the integral flux greater than 1000 MeV per nucleon; (4) flux and differential energy spectra of 1–10-MeV solar and galactic electrons in the region beyond the magnetosphere; (5) isotopic abundance of H, D, T, ³He, and ⁴He in the interval between 20 and 80 MeV per nucleon.

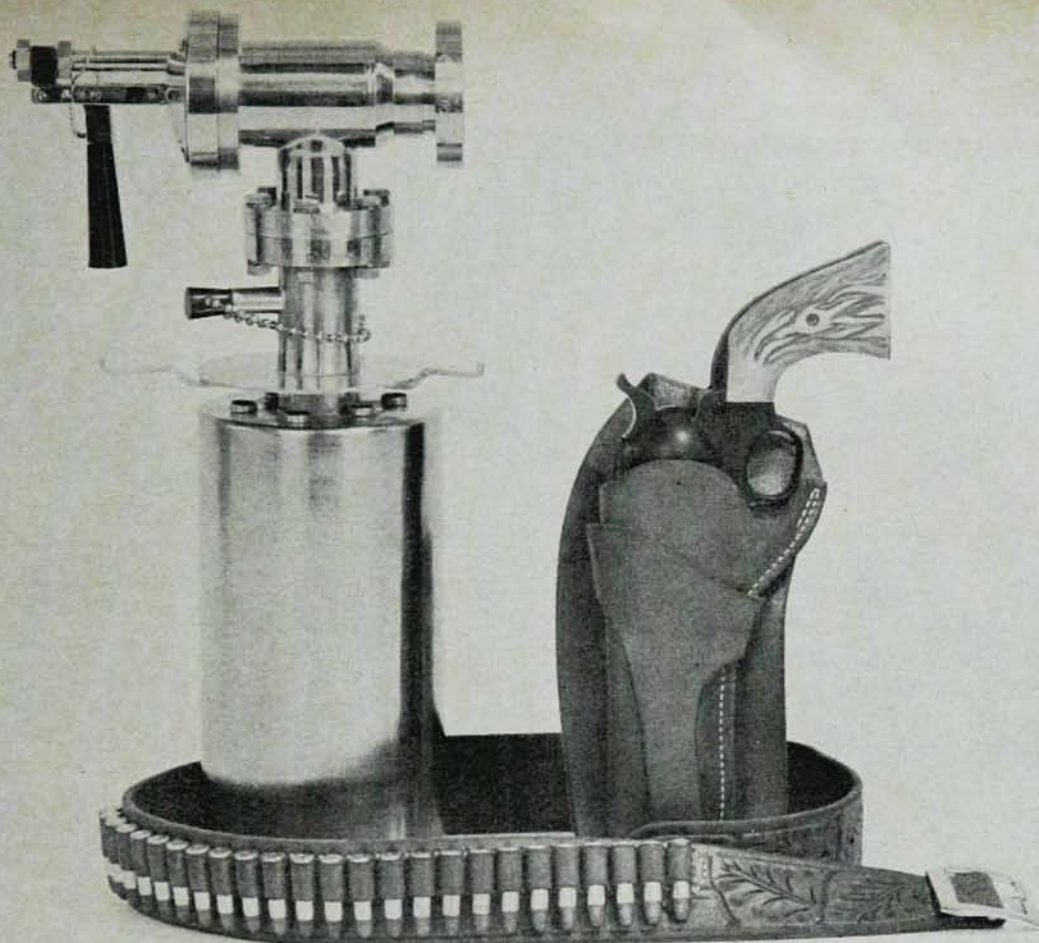
The experiment is shown in block-diagram form in figure 5. The ex-

periment instrumentation is split into four major areas, one corresponding to each of the three detectors, and an accumulator and readout system. They are described separately in that order.

High-energy detector. A double scintillator-Cerenkov telescope provides charge and differential energy spectra over the range between 220 and 1000 MeV per nucleon, and integral particle flux above 1000 MeV per nucleon. Two thin thallium-activated cesium iodide scintillation counters provide two separate measurements of the rate of ionization loss (dE/dx), and a Cerenkov counter measures the Cerenkov radiation above the 200-MeV-per-nucleon threshold. Coincidences between the two scintillators define the geometrical acceptance aperture of the telescope. Measurements of scintillation and Cerenkov-detector pulse heights identify charge and energy of the incident particle (over the indicated energy range), regardless of its velocity. Approximate equality is demanded between the two scintillator pulses to help in discriminating against multiple-particle events in the background, such as those due to showers, local nuclear interactions, etc. For particles having velocities below the Cerenkov threshold, the detector is used as a simple two-element scintillator telescope, thereby extending its energy



SOLAR PROTON monitoring experiment for IMP F.—FIG. 4



Model 50-135 Sorption Pump with new 1½" quick-acting lever valve.

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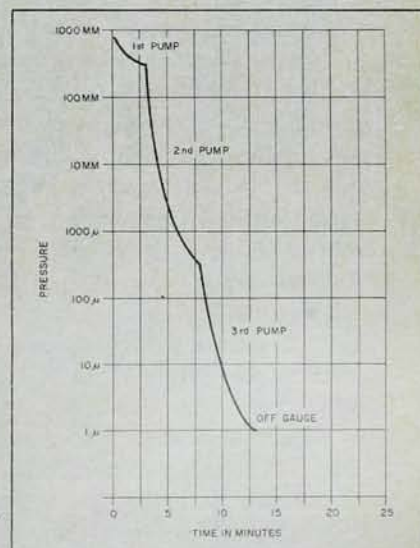
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SPACE PHYSICS

(Continued)

range down to about 50 MeV per nucleon. The two scintillation crystals are 1.0 g/cm² thick and 5 cm in diameter. The Cerenkov radiator is the 1-cm-thick sapphire window of the photomultiplier tube. Its top surface is blackened to discriminate against upward moving particles.

Medium-energy detector. An E against dE/dx scintillator telescope measures charge and differential energy spectra in the range between 20 and 80 MeV per nucleon, the integral flux above 80 MeV per nucleon, and the electron spectrum from 1 to 10 MeV. It employs a thin (0.45 g/cm²) dE/dx CsI(Tl) scintillator followed by a thick (9 g/cm²) total-energy CsI(Tl) scintillator. Surrounding the total-energy detector is a combination of a plastic guard scintillator and another 0.45-g/cm² CsI(Tl) scintillator. A phoswich circuit separates the pulses electronically from the plastic guard scintillator and the lower slow scintillator.

Low-energy detector. The low-energy detector employs two large-area, fully depleted solid-state detectors and a guard scintillator. The outer dE/dx solid-state detector is a surface-barrier device used to insure a minimum dead layer. Its area is approximately 3 cm², and it has an active thickness of 120 microns. The inner total-energy detector consists of two stacked 1-mm-thick by 3 cm² fully depleted surface-barrier detectors with their outputs summed. The plastic guard scintillator reduces the background flux arising from scattering and nuclear interactions in the spacecraft and detects particles that enter the aperture but penetrate the total energy detector. Charge-sensitive preamplifiers are used with the two solid-state detectors to minimize bias-voltage effects and detector capacitance changes. All events in the thin dE/dx detector are analyzed in a five-step, fast, integral pulse-height analyzer that provides flux and energy information for particles having more energy than 0.4 MeV. In this mode of operation the guard scintillator is not

used to provide active collimation, but it does provide a measure of mechanical collimation. This mode is intended primarily for use during periods of very high counting rate that follow solar flares.

Readout and control circuits. All differential pulse-height digitizers provide inputs to separate scalars in the binary accumulator system. The integral pulse height analyzers and other rate sources from the three detectors provide inputs through a commutator to a floating-point accumulator system. This floating-point accumulator provides an output that is approximately a binary floating-point equivalent of the number of input pulses. It provides a very large dynamic range (count capacity greater than 2 000 000) and a fixed accuracy of 3%. The readout system transfers the contents of all scalars and the floating-point accumulator to the spacecraft data-handling system.

Digitized spark chamber

A digitized spark chamber for detection of high-energy gamma rays of celestial origin has been under development by a group at the Goddard Space Flight Center.⁷ The spark chamber was chosen over more conventional Cerenkov and scintillation-counter arrays, because gamma-ray intensities are very small compared to the several sources of background. The detector, therefore, must satisfy the criteria of relatively large collection area, high efficiency, unambiguous identification of gamma rays and adequate angular resolution for identifying point sources. A digitized chamber offers several advantages for satellite use. Primarily it eliminates the requirement for recovery of pictures, but it also presents the information directly in electrical digitized form for computer analysis, permits the discharge energy to be reduced below that in optically-viewed chambers, has inherent fiducial marks and reduces the information rate by allowing logical operations in chamber readout.

The detector system is shown in figure 6. It consists of a thick plastic scintillator dome used as an anti-coincidence mantle, a pair of spark chambers to provide detailed infor-

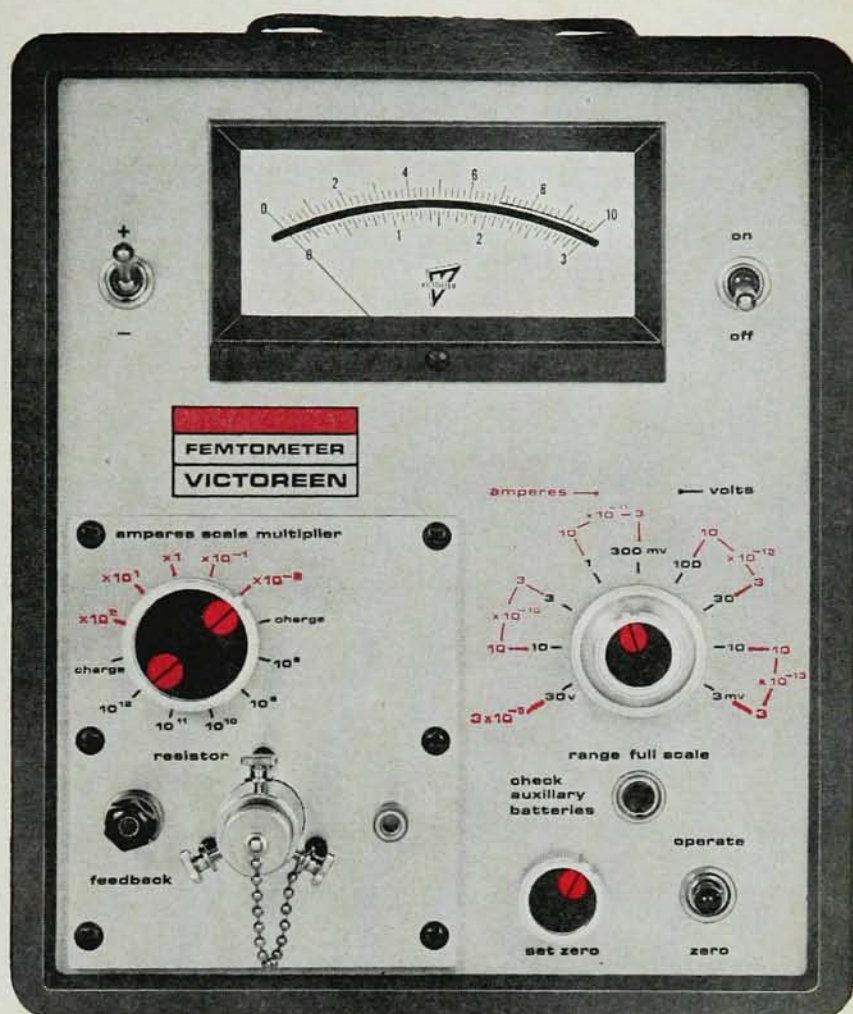
mation about each event, and a central plastic scintillator and a Cerenkov counter, which are used as triggering devices. Each of the two spark chambers consists of 16 plate-and-wire-grid modules. Each frame-wire module has a high-voltage plate and two orthogonal sets of 128 wires. All modules are identical except for the bottom one in each chamber in which the wires run at 45 deg to all the others to eliminate the ambiguity in relating the x and y readings of multiple tracks. The wires in each set are spaced 1.2 mm apart, and the sets are separated so that when a plate is inserted between them, the plate-wire spacing is 2.46 mm. The wires are 0.15-mm-diameter beryllium copper held under tension and ultrasonically welded to pins in the terminal strip. The wire plane is flat within 0.025 mm. The plate consists of a structural layer of aluminum, 0.178 mm thick, chemically milled and coated on both sides with a total thickness of gold of 0.0685 mm. This thickness is equal to about 1/50 of a radiation length for relativistic electrons and yields a system thickness (32 plates) of less than one radiation length.

Each wire is connected to a series resistor and then to a wire that passes through a ferrite memory core to ground on one side, and is terminated but not grounded on the other. Each core is also threaded by a separate readout wire and a common sense wire. The chambers are triggered whenever the appropriate combination of signals is received from the three-element charged-particle detector array. The dome scintillation guard, A, the central scintillator, B, and the Cerenkov counter C, produce a trigger pulse in the modes $\overline{CA}$ or $\overline{BCA}$ and this in turn fires a high voltage circuit which energizes the spark chamber. $\overline{BC}$ is a 10^{-7} second coincidence and $\overline{A}$ is a 3×10^{-6} second anticoincidence. The high-voltage circuit provides a 2.5 kV pulse with a rise time of 10^{-8} seconds and a delay time of 4×10^{-8} seconds.

The gas used in the chamber is 89% Ne, 10% He, 1% A, and a trace of alcohol, and the chamber is operated at a pressure of one atmosphere. Plastics have been avoided in

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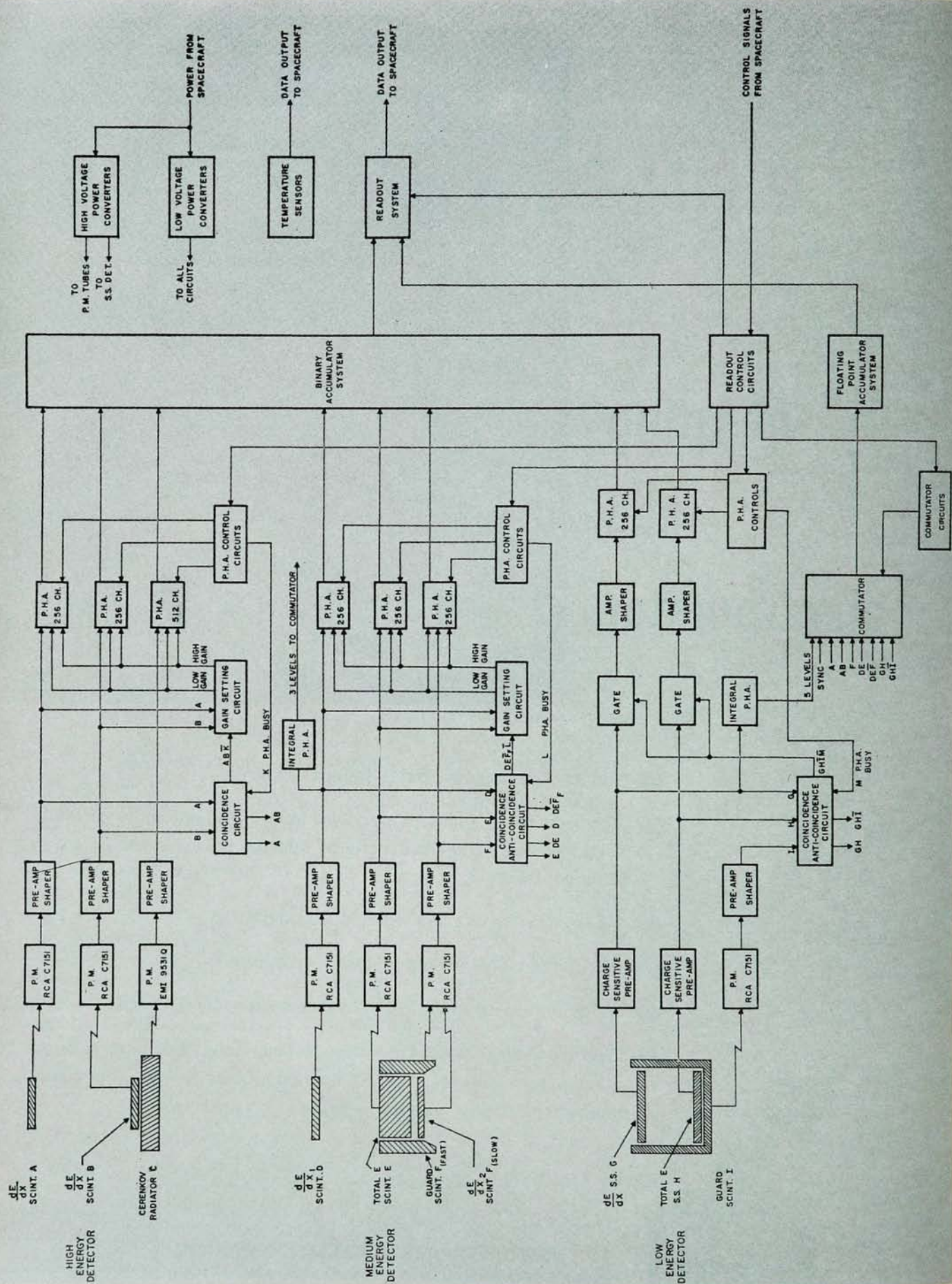


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COSMIC-RAY experiment for OGO E. Equipment is divided into four parts, including three detectors (high, medium and low energy) and an accumulator and readout system. Charge and energy spectra over a wide range are measured.

—FIG. 5

SPACE PHYSICS

(Continued)

the chamber construction to minimize the possibility of poisoning the gas.

The magnetic cores are normally in the "reset" state. Spark current in a wire "sets" a core and the readout cycle resets it. In this system (two chambers) there are 32 modules of 256 cores each, or a total of 2^{13} (8192) cores. Rather than transmit 8192 bits of information per event, only the addresses of "set" cores are transmitted. If a pair of tracks originates at the top of the chamber and no further multiplication occurs, the total number of sparks is 64. Since a core address can be specified by 13 bits the total number of bits required for the event is 64×13 (832). Of course, multiplication or multiple sparks (that is, to adjacent wires) would increase this number, but the method is still more efficient than the 8192-bit readout. The scheme for obtaining the addresses of "set" cores is fairly straightforward. The contents of a column of cores (that is, corresponding cores in each of the 32 modules) are transferred to a 32-bit shift register and shifted out. Each time a set bit is detected, the state of the 13-bit address register, which counts the shift pulses, is transmitted. All 256 columns are read out in this manner and all set addresses are telemetered or stored on tape. With a very modest bit rate, say 50 per second, up to 3 events per minute could be read out. Considering anticipated count rates from gamma rays and spurious events, this is a wide margin of safety.

The efficiency for detection of gamma rays through pair production is as high as 38% for very-high-energy photons (about 1 GeV) considering the volume of the entire chamber as sensitive. Efficiency decreases with decreasing energy and near 70 MeV efficiency should be about 20%. The product of approximate area times solid angle for the system is $225 \text{ cm}^2 \times 0.8 \text{ ster}$ ($180 \text{ cm}^2 \text{ ster}$). Direction of flight of an incoming gamma ray is determined by analyzing the vec-

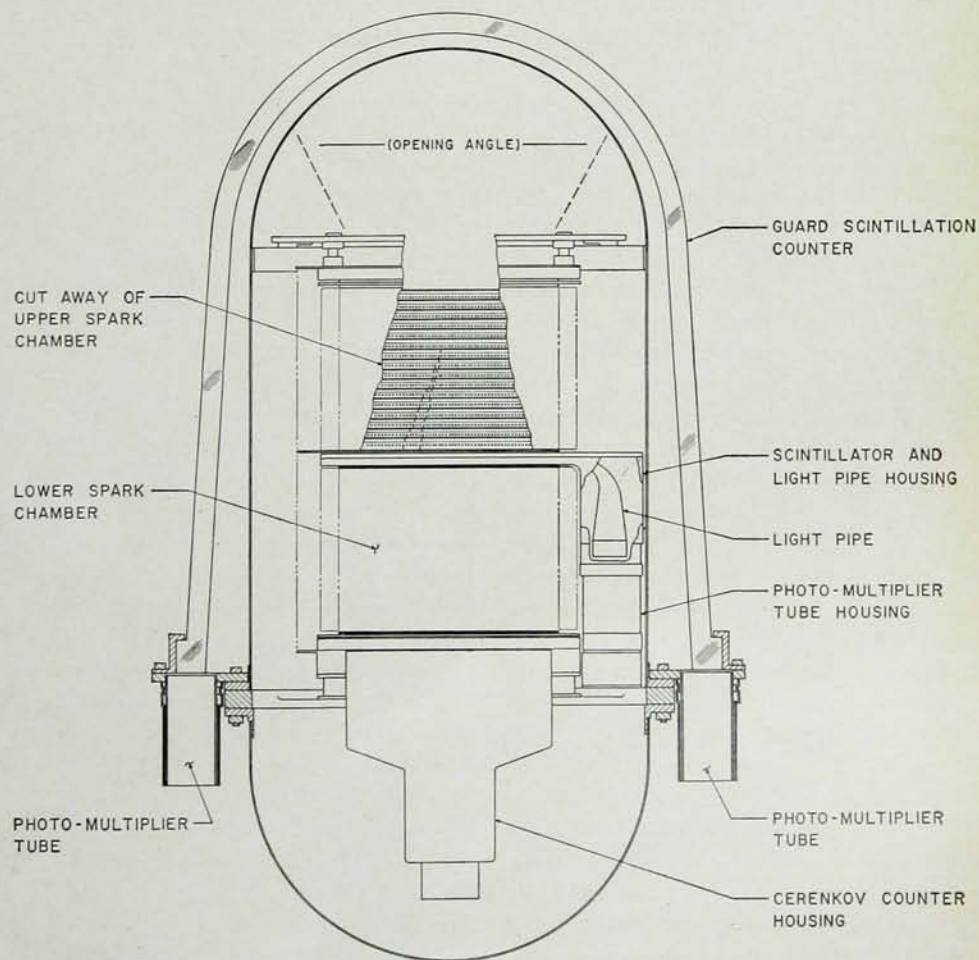
tor momentum of the electron pair. This requires knowledge of the opening angle of the pair as a function of photon energy, the relative sharing of energy and momentum by the two electrons and their scattering in the plates as a function of energy. It is anticipated that an angular resolution of about 2 deg can be attained at GeV energies and a few degrees at 100 MeV. The multiple-scattering properties of the electrons will provide the best measure of their energies and that of the original gamma ray, and the opening angle between the pair can be used for verification. With these techniques, energy resolution approaching 30% is possible. Other pertinent parameters are weight of the experiment (about 45 kg), volume (about 0.23 m^3) and power required (about 2.5 watts).

Package for OAO

The OAO Goddard Experiment Package (GEP) is basically a 97-cm-diam-

eter telescope feeding a photoelectric spectrometer and is designed to gather high-resolution spectral data from both point and extended sources in the ultraviolet region of the spectrum.⁸ The system is capable of observing stars as faint as tenth magnitude and will cover the spectral range from approximately 100 nanometers to 400 with a selectable spectral resolution of 0.2, 0.8 or 6.4 nm.

It will observe normal stars for energy distribution in the continuum, blanketing effects and identification, and intensities of strong emission lines. It will undertake time-dependent photometry of peculiar stars, such as Beta Canis Majoris, T Tauri, and the Wolf-Rayet stars. Its observations of nebular and interstellar media will investigate the law of reddening, the ultraviolet radiation field and spectra of emission and reflection nebulae. Galaxies and intergalactic media will be observed for spectral-energy distribution and magnitude



DIGITIZED SPARK CHAMBER. —FIG. 6

SPACE PHYSICS

(Continued)

and intensity of Lyman alpha red-shift.

The telescope has a Cassegrain configuration and is a modified Ritchey-Chrétien design; that is, the secondary mirror is a convex true hyperboloid and the primary mirror is a concave quasihyperboloid. With a primary-secondary spacing of 107 cm, the telescope has an effective focal length of 4.83 meters. Except for the secondary mirror, which is quartz, all optics (primary mirror, spectrometer mirror and diffraction grating) are of beryllium. For good uv reflection efficiency, the mirrors are coated with aluminum and then overcoated with magnesium fluoride.

The Goddard package contains seven detectors, six for uv and one for visible light detection. The six uv detectors measure spectral-energy distribution in specific bands in the range 105.0–426.7 nm. The seventh detector channel acquires data in the visible range of the spectrum so that uv intensity and star magnitude can be correlated.

The six uv detectors are mounted in the focal plane of a diffraction grating which is blazed at 120 nm in the first order and, in this spectrometer, gives a linear dispersion of 0.81 nm per millimeter. The output from each phototube feeds a data-accumulator channel. Each channel contains two counters, one to count photon-generated pulses with a maximum capacity of 4096 counts, the other to count clock pulses with a total capacity of 65 536 counts equivalent to 42 seconds of time. In normal operation the counters are both turned on together and count until either one or the other of the two counters fills, at which time both counters are turned off. Thus, for relatively high counting rates, the system provides a measure of the time required to fill the photon counter channel, and for very low counting rates the system measures the number of photons in a 42-sec time interval. In all cases division of the photon count by the clock count provides the photon rate, which is propor-

tional to the spectral intensity in the observed wavelength band. A focus detector provides information to the observer on the ground to permit him to command focus changes.

Since this detector requires a pointing accuracy greater than that provided by the observatory guidance system alone, the detector supplies a fine guidance signal to the observatory guidance system. This provides an over-all capability for guidance to within 1 sec of arc for stars brighter than third magnitude, 4 sec of arc for stars between third and eighth magnitude and 10 sec of arc for stars between eighth and tenth magnitude.

FUTURE DEVELOPMENT

In the near future a number of advances in instrumentation are certain to occur. Some will occur because rapidly developing technology will make them possible, others because we cannot proceed without them. Experiments themselves will become more complex. In some areas (for example, trapped radiation), the day of the survey experiment is past (although monitoring devices will still be valuable). To provide answers to today's questions more detailed measurements are necessary. Simultaneous measurements of related phenomena at the same point in space are required and, equally important, simultaneous measurements of the same phenomenon at different points in space. By the same token, more and better ground-based measurements of related phenomena will be required to complement and perhaps control spacecraft experiments. In-flight calibration techniques will be further developed and some experiments may require manned control.

Both large and small spacecraft will be used. Even in small satellites increased reliability and convenience to experimenters achieved through standardization is recognized.² In both cases, however, the information rate and probably the data rate will increase. On-board processing will be used to a greater extent, but the reduction afforded in data rate will probably be offset by the inclusion of more measurements.

The facility at the Goddard Space Flight Center is processing data from

current satellites at the rate of 60 million measurements per day. As this rate increases and as experiments become more complicated, a serious problem over use of these data can be expected. This problem cannot be solved simply by reducing data acquisition because a complete understanding of the various space-science phenomena requires measurements that are very broad in both spatial and temporal coverage. This requirement results in part from our present inability to extrapolate from one region to another and to predict detailed time behavior of natural phenomena. These requirements indicate the need for new techniques for data processing, reduction and presentation on the ground. □

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6. The cosmic-ray experiment is being developed by F. B. McDonald, V. K. Balasubrahmanyam, D. E. Teegarden, and G. H. Ludwig at the Goddard Space Flight Center.
7. The information on the spark chamber was kindly supplied to us by C. E. Fichtel and T. L. Cline who developed the instrument in collaboration with D. A. Kniffen, R. Ross, C. Ehrman, J. O'Conner, and E. Zugby.
8. The OAO Goddard Experiment Package is being developed by J. E. Kupperian, J. J. Boggess, E. S. Chin, and J. E. Milligan of the Goddard Space Flight Center and is being built by the Kollsman Instrument Corporation, Elmshurst, N. Y. For a more complete description see J. B. Rogerson Jr, *Space Science Reviews*, **2**, 621 (1963).