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MARINER-JUPITER-SATURN LOW ENERGY CHARGED PARTICLE EXPERIMENT

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SUMMARY

The Low Energy Charged Particle Experiment shown in Figure 1 will be launched on the Mariner-Jupiter-Saturn spacecraft in August 1977. The experiment has been designed to perform particle measurements in the intense radiation belts of the Jovian and Saturnian environments, and to provide detailed spectral analysis of both solar and galactic particles in interplanetary space. These objectives are met by a single instrument which uses 23 solid-state detectors configured in two distinct detector subsystems. One subsystem is optimized for interplanetary and interstellar measurements. The second subsystem is optimized for specific particle species, energies, and intensities expected near the planets. Angular distributions in the ecliptic plane and pitch angle distributions are obtained using an 8-sector scanning motor.

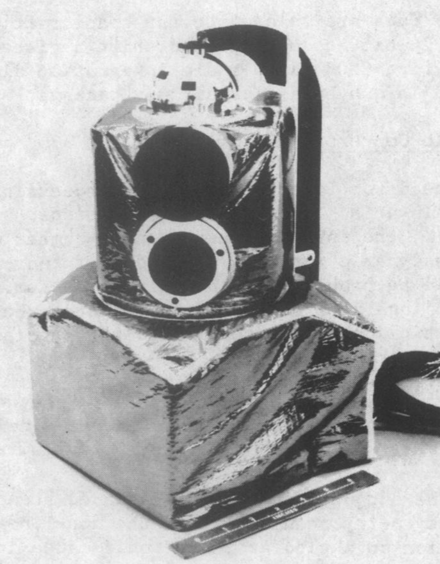


Figure 1 The Low Energy Charged Particle Experiment

Over 30,000 solder joints bond almost 6000 components within the instrument. Due to experiment complexity, the circuitry is based on the use of 261 custom-designed hybrids of 14 different types for amplification, discrimination, timing, pulse height analyzer and data functions. A discussion of the experiment pulse height analyzer and logarithmic amplifier design and performance is included.

Interplanetary/Interstellar Measurements

The interplanetary/interstellar particle measurements subsystem is based on a bi-directional telescope consisting of seven silicon surface barrier detectors. The "Low Energy Particle Telescope (LEPT)", as it is called, is shown in Figure 2. The telescope consists of two multi-dE/dx x E detector systems (D1 - D5) placed back-to-back and utilizing a common eight-element cylindrical lithium-drifted silicon detector shield (AC1 - AC8). Detectors in the LEPT telescope vary between 2.0 microns and 2.5 mm in thickness. The particle types and nominal energy passbands are listed below:

Particle	Enter D1 First MeV/Nucleon	Enter D5 First MeV/Nucleon
protons	0.35 - 20	3.0 - >170
alphas	0.07 - 21	3.0 - > 64
(Light, e.g., Be)	0.12 - 33	4.0 - 21
(Medium, e.g., N)	0.05 - 40	6.3 - 200
Z ≥ 19)	0.06 - 74	8.6 - >1000

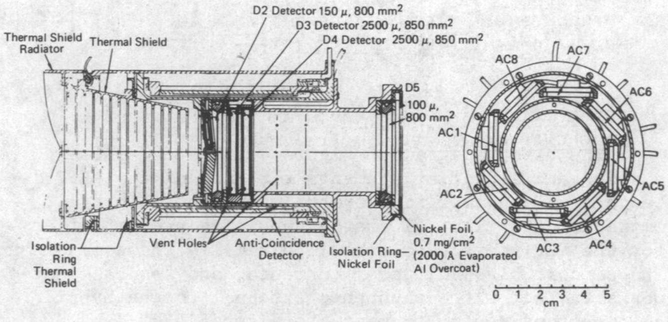


Figure 2 Low Energy Particle Telescope

The interplanetary/interstellar subsystem employs two basic particle identification and energy measurement techniques. The first method is the conventional range-energy technique. The second method of identification[1] relies on forming the product:

$$P = a\ \Delta E_1\ \Delta E_2^b\ ,$$

where ΔE_1 and ΔE_2 are the energies deposited in detectors 1 and 2 and a and b are constants. The product P is unique for each particle type and has a relatively constant slope on a log-log scale over a large range of particle energy. Appropriate "P" discriminator levels (which plot as P=constant) as well as energy discriminators are then used to distinguish particle types as illustrated in Figure 3.

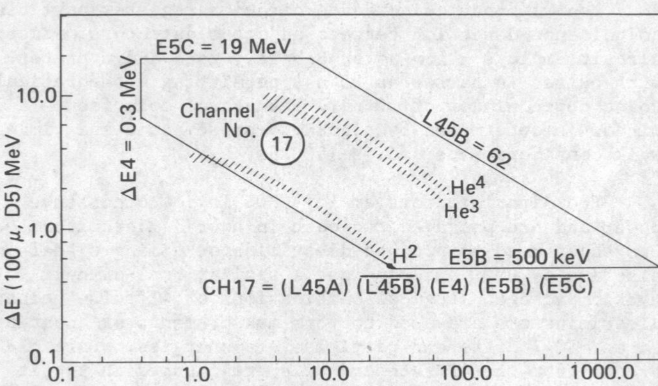


Figure 3 Energy Loss in LEPT 100μ-2500μ Detectors

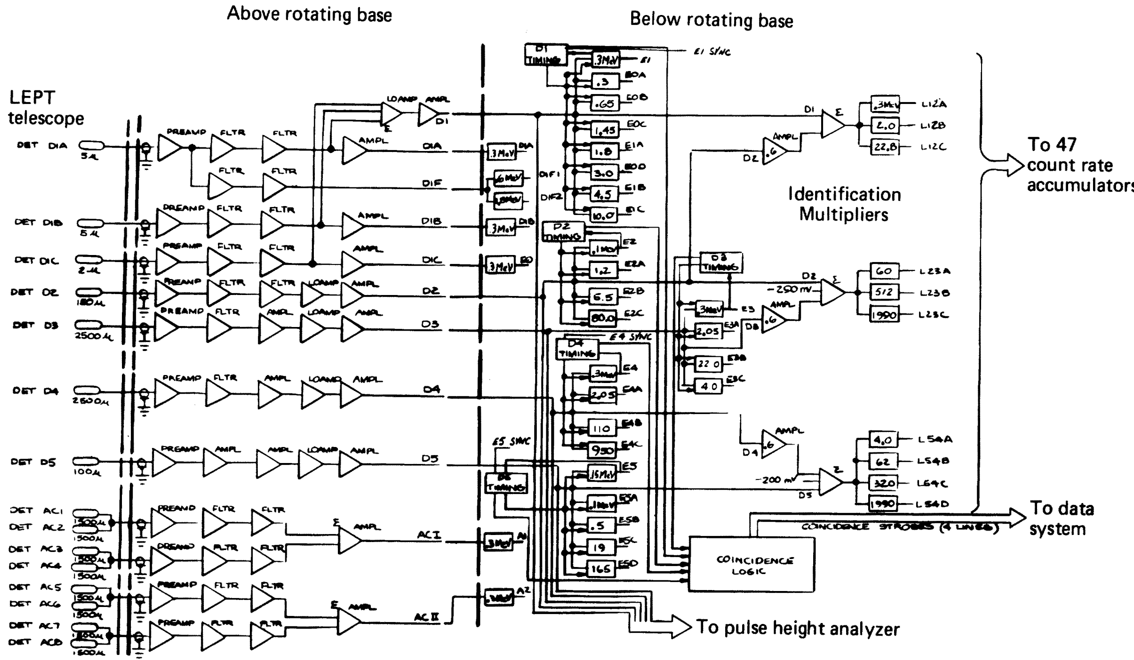


Figure 4 LEPT Pulse Electronics

The block diagram of Figure 4 shows the pulse shaping and amplifier elements for each of the LEPT detectors. Each amplifier symbol represents a hybrid microcircuit. The FET charge sensitive pre-amplifiers for the LEPT detectors are all basically the same design. The circuit bias voltages, currents, and feedback networks are set with components external to the hybrid allowing one design to meet the diverse LEPT dynamic range and detector capacitance requirements.

The linear amplifiers in the LEPT are also one type of microcircuit, and external bias and filter components are added to produce the desired pulse shaping and dynamic range. Double-integration, double-differentiation bipolar pulse shaping with pole-zero cancellation is used in all channels. The pulse width from the beginning of the pulse to its zero-crossing is approximately 3 microseconds, and particle counting rates in excess of 100 KPPS can be handled. The discriminator settings are shown in Figure 4.

The large range of particles and energies measured by this subsystem require the use of logarithmic pulse amplifiers. These amplifiers combined with pulse summing amplifiers perform the product "P" in a straightforward manner as shown in Figure 4 (Identification Multipliers).

Four 2-input coincidence circuits register particle coincidence detection between adjacent detectors. Each circuit employs a low-power Schottky gate and operates with pulses as narrow as 25 ns, permitting a theoretical coincidence window of 50 ns. The actual coincidence window is determined by signal-to-noise ratio and timing walk considerations and is ±800 ns.

The discriminators employ CMOS logic to conserve power and are packaged two-each in hybrid microcircuits. One-shots used to produce discriminator timing signals also employ CMOS dice and use a similar dual-circuit hybrid package. Logical combinations of 41 pulse height discriminators are used to form measurements of counting rates of 47 different particles and energies. Particle events from the 47 rate channels are counted in 24-bit accumulation registers. The data are transferred and stored in 24-bit parallel-in serial-out registers until a "read" command is received. The data are then shifted into a 24- to 10-bit log compression circuit, and the compressed data are relayed to the spacecraft data system. The 24-bit accumulator and shift register are made from five CMOS large-scale integration dice which are housed in a hybrid microcircuit package.

Logarithmic Converter

The need for logarithmic analog processing of the LEPT signals arises from two considerations. In the first place, the intended energy and Z-number coverage requires a dynamic range on the order of four decades, which would be prohibitive in a linear system. Secondly, the use of logarithmic signals facilitates the task of analog multiplication, essential to the species identification system.

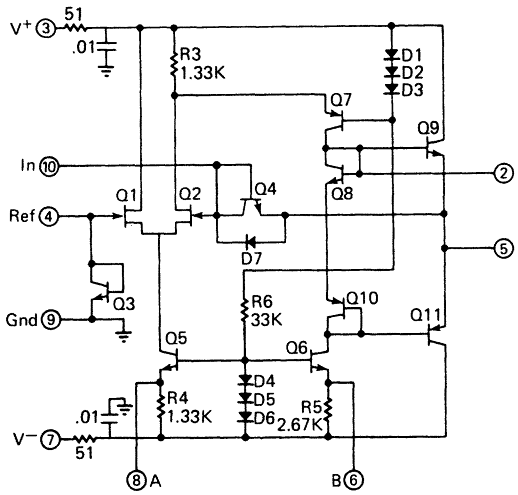
Among the special problems faced in the design of the logarithmic circuitry, other than the dynamic range requirement alluded to above, were the following:

a) The output must be D.C. balanced because the asymmetry resulting from the non-linear operation on a bipolar pulse would cause intensity dependent offsets in subsequent A.C. coupled circuits.

b) The circuit must be packaged in hybrid form, with external provisions for setting mid-range points and nulling the offset.

c) Allowance must be made for at least a first-order temperature compensation.

The circuit that evolved was based on the familiar theme of using a transistor as a feedback element around an operational amplifier. The amplifier has a differential, high-impedance input, effected by a matched dual JFET. This is followed by a common-base stage driving a complementary follower. Bias currents and primary D.C. balance are achieved by matched current sources, with the overall hybrid design making use of the tight matching properties of monolithic transistor and diode arrays. The hybrid circuit is shown in Figure 5a, and the overall log converter with its external connections in Figure 5b. The feedback transistor Q4 is diode connected and serves as the logarithmic element. The matching transistor Q3 raises



D1 – D6	CA 3039
Q1, Q2	2N5564
Q3, Q4	LM114
Q5, Q6	LM114
Q8, Q9	LM114
Q7	2N4209
Q10	2N4209
Q11	2N4209

All resistors ± 20%

$\frac{R4}{R3} = 1.00 \pm 0.02$

$\frac{R5}{R3} = 2.00 \pm 0.04$

Figure 5a Logarithmic Amplifier Hybrid Circuit

the reference input to the same D.C. level as the signal input, forcing the output terminal quiescent point to ground potential. The bias-current sources are adjustable externally through the balance terminals A and B. In practice, offset levels at the output point have typically run 5 mv or less, and these are easily nulled by means of a single resistor tied to one or the other of the balance terminals.

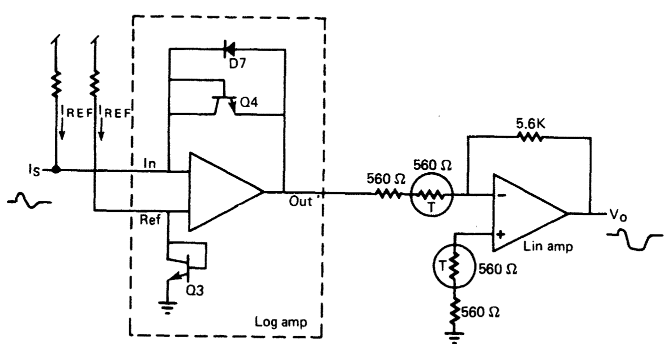


Figure 5b Logarithmic Converter

The logarithmic characteristic is generated by supplying equal D. C. currents, I_{ref}, to the reference and feedback transistors and coupling the signal in a current mode as I_s. The resulting voltage swing at the output, V_o, is given by the equation:

$$\frac{I_s+I_{ref}}{I_{ref}} = e^{\frac{qV_o}{kT}}$$

$$V_o = \frac{kT}{q} \log \frac{I_s+I_{ref}}{I_{ref}}$$

$$\approx \frac{kT}{q} \log \frac{I_s}{I_{ref}} \text{ for } I_s \gg I_{ref}$$

At T = 300°K, this relation yields a slope of 26 mV/octave or 59 mV/decade. In the LECP, the output from the log amp is D.C. coupled into a linear inverting amplifier, sensistor-compensated to cancel the inherent temperature dependence of the log amp to first order. Since the input signal is a bipolar pulse, an additional diode (D7) around the log amp is necessary, opposite to the logging element, in order to limit the response in this direction.

Response curves for the log circuit are given in Figure 6. These curves include the X5 gain due to the inverting amplifier, resulting in a slope of ~ 300 mV/decade.

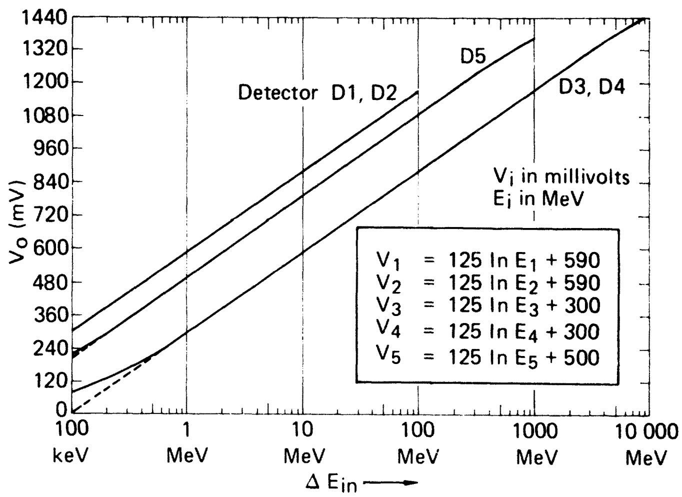


Figure 6 Response Curves for Logarithmic Pulse Amplifiers

Priority Selection

The rate channels discussed above provide sufficient time resolution to obtain complete and detailed particle intensity distributions. They are limited in energy resolution, however, because a prohibitive number of discriminators and accumulators would be necessary to obtain fine energy measurements. Consequently, the rate channel measurements are supplemented with a 256 channel pulse height analyzer (PHA) which analyzes four detector outputs per event and about two events per second.

In order to observe rare events with consistency, a priority scheme is established. Heavy particles, such as ${}_{26}Fe^{56}$, are given priority I; intermediate particles, such as ${}_{7}N^{14}$, are given priority II; and protons and alphas are given priority III. One expects heavy particles to be rare and therefore should receive the highest priority. But this might restrict measurements of other particles which are almost as rare, depending on time, solar activity, and location in space. Consequently, a rotating priority system is used.

If an abundant particle such as a proton has top priority and is analyzed, the priority assignment will rotate such that, after the analysis, the proton will have the lowest priority and intermediate particles will have the highest priority. Subsequently, when an intermediate particle is analyzed, the priorities will again rotate so that a heavy particle has top priority. In this manner, even though the relative abundances of the various groups may change, the priorities will always rotate so that the least abundant group will retain the top priority for the longest time.

Once a priority event has been identified by the LECP data system, the pulse height analysis is done. Since the analysis is done after the logical determination, peak detectors are necessary to hold the signal amplitudes until an "analyze" decision is made. Of course, the first particle to arrive is analyzed regardless of priority, preventing data loss.

Pulse Height Analyzer

The Pulse Height Analyzer consists of redundant digital voltmeters with input multiplexers and five independent peak detector circuits. Figure 7 shows the basic block diagram for a pulse height measurement. The bipolar (log compressed) input signal drives the peak detector hybrid which charges a capacitor positive to the peak input value. The output at the capacitor remains positive until S2 closes. The actual decay of the capacitor is less than 6mV in 1 millisecond at 50°C which is less than 1/2% error. The input pulse crosses zero going negative, at which time the discriminator initiates a 2 microsecond "wait" period. If no signal occurs from the experiment data system requesting a readout within the "wait" interval, the reset cycle initiates with the "hold" relay opening and the "Reset" relay closing for about 6 microseconds. The circuit uses a junction FET for reset and unbalance the peak detector amplifier to achieve a "hold" (no possible positive output) condition. The "hold" overlaps the "reset" signal to prevent high transient current during reset. The peak detector will again track positive signals after the reset cycle.

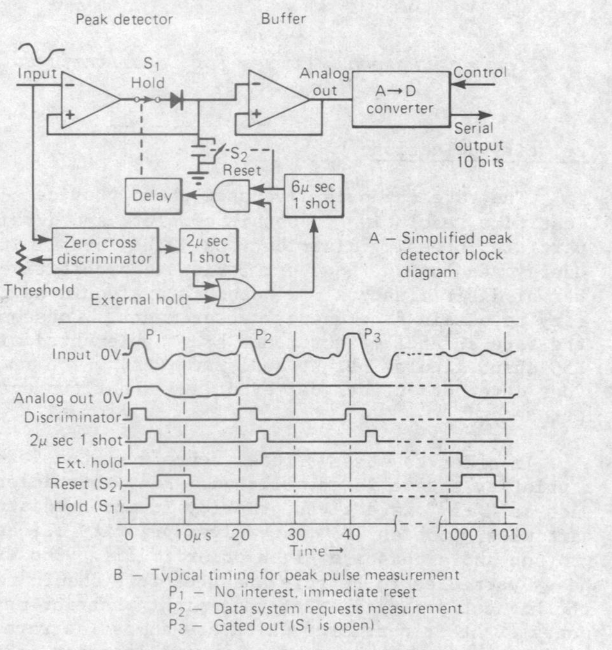


Figure 7 PHA Block Diagram and Timing

If the data system determines that a higher priority event has occurred, it generates a "Go" signal during the 2 microsecond "wait" period, and a measurement cycle begins. The pulse inputs from D2 through D4 and either D1 or D5 are selected for analysis by the experiment data system. About 1000 microseconds are required for the complete conversion.

The "Go" signal from the experiment logic sets the readout binary within the DVM and the peak detector hold logic. The hold signal provides two functions within the peak detector. It prevents any new, larger pulses from contaminating the reading during the cycle and it minimizes reset currents. A buffer FET input amplifier is required after the peak detector to minimize the current load on the storage capacitor. The peak measuring circuit is fast enough to provide less than 1% error on a 1.5 microsecond half-pulse, and maintains its accuracy for pulse amplitudes up to 2 volts. The peak detectors require approximately 300 mW and are turned OFF during planetary encounter to conserve power.

The digital voltmeter is a redundant 10-bit instrument. It uses an internal voltage regulator and maintains 0.1% accuracy with ± 10% changes in input power. Much of the electronics is off until the measurement cycle. This both minimizes power consumption and radiation sensitivity. Only one of the redundant systems will be powered during planetary encounter, further minimizing radiation damage.

The pulse height analyzer is a 256 channel device. The α and β detector current measurements which are used to extend the counting range of those channels, however, use the full 10-bit resolution of the DVM.

The reproducibility has proved excellent with less than 0.1% calibration difference observed between the two units tested thus far. The inputs to the digital voltmeter are multiplexed through CMOS gates which produce a small channel-to-channel calibration error. Also the isolation resistors used in each channel contribute uncertainty. For this reason a calibration should be used on each individual channel if higher absolute accuracy is desired.

A self-calibration function is included in the PHA which is exercised as commanded by the experiment data system. This uses the internal voltage reference with precision resistor dividers to establish two points on the calibration. The calibration can verify operation of the system but will not show changes in the internal reference voltage since it will self-compensate. However, the two redundant voltmeters may be switched in and out for comparative checks if the data appear in error.

Near-Planet Measurements

The near planet subsystem is primarily a magnetospheric instrument designed to investigate a large range of particle types in medium and high abundances. The detector arrangement is shown in Figure 8 and is called the Low Energy Magnetospheric Particle Analyzer (LEMPA). LEMPA uses two primary identification methods. In the first method, low and medium energy electrons

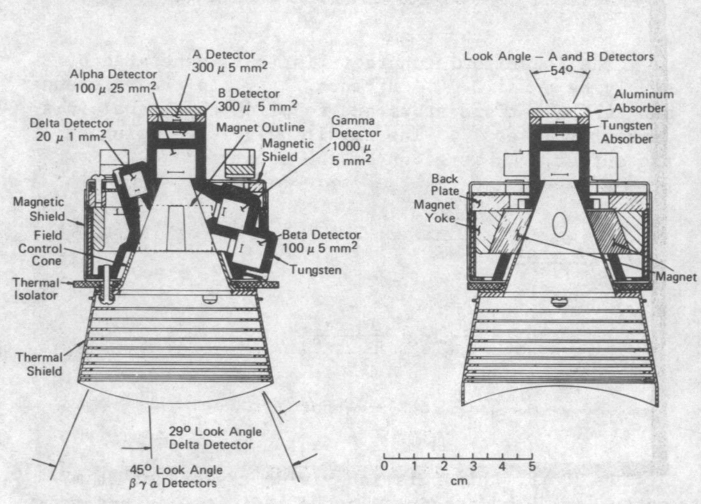


Figure 8 Low Energy Magnetospheric Particle Analyzer

are deflected into total energy detectors (beta and gamma) via a sintered Cobalt-Samarium rare earth magnet. The more massive protons and ions pass through the magnet's field and strike the total energy detector alpha.

The low-noise alpha and beta channels allow measurement of electron and proton energies as low as 12 keV. As particle intensities increase and simple pulse counting becomes difficult, the alpha and beta detector currents are monitored, thus extending the useful range of intensity measurements. The pulse widths of the alpha and beta amplifiers are approximately 1.5 microseconds from beginning of pulse to zero-cross.

The second identification method employs a combination of shielding and energy loss to restrict the response of detectors A and B to high energy particles. The A-B detector system is also arranged as a telescope. The particles detected by the LEMPA telescope are:

Detector	Particle Type	Medium Intensity	High Intensity
$\beta,\beta'\gamma$,(A,B)	electron	0.01-1.5MeV	($\geq$1,$\geq$10MeV)
α,(A,B)	proton	0.015-4.0MeV	(20-180MeV)
α	alpha	1.0-4.0MeV/nuc	--
δ,δ'	Z$\geq$1,Z$\geq$2, Z$\geq$3		0.3-~5MeV/nuc

High energy electrons will be abundant near the planets and heavy shielding is necessary to prevent high-energy electron contamination of the low-energy detectors. About one pound of tungsten is used for this purpose. The high intensities of radiation trapped in the Jovian and (probably in the) Saturian magnetic fields necessitate the use of extremely fast-pulse circuitry in several channels to prevent pulse pile-up effects and saturation. Special hybrid amplifiers and discriminators were developed to handle counting rates in excess of 25 MPPS (see Figure 9). Schottky, TTL is used to divide the very high counting rates down to a rate which can be transmitted through the experiment without introducing cross-talk and noise problems.

Pitch Angle Distribution

The MJS-77 spacecraft attitude is very nearly fixed in inertial space except during occasional maneuvers. Measurements of particle angular distributions, therefore, require a rotating platform. The platform is driven by a stepper motor through eight 45^o sectors. The sector rate is once every 24 seconds during planetary encounter, once every 6 seconds during Io (a Jupiter moon) encounter, and once every 6 minutes in the interplanetary medium. Pitch angle distributions are obtained by two additional detectors placed in a cone/dome combination in which the cone sets the azimuth view angle and holes cut in the dome set the elevation view angles (see Figure 10). Thus a single mechanism is used to obtain pitch angle distributions in two planes.

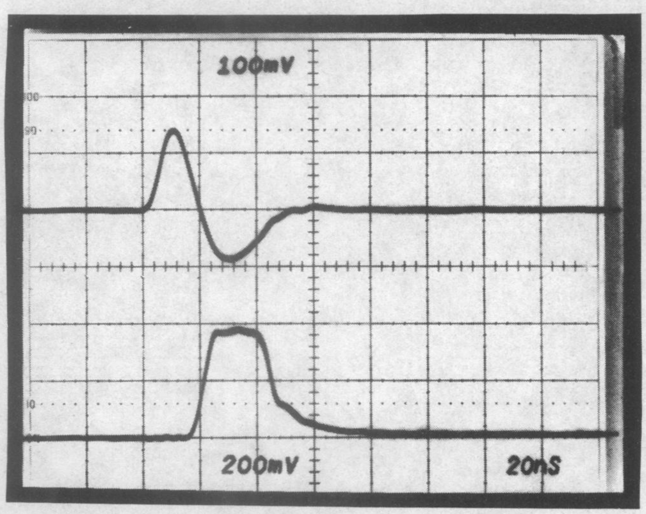


Figure 9 High Speed Amplifier and Discriminator Response

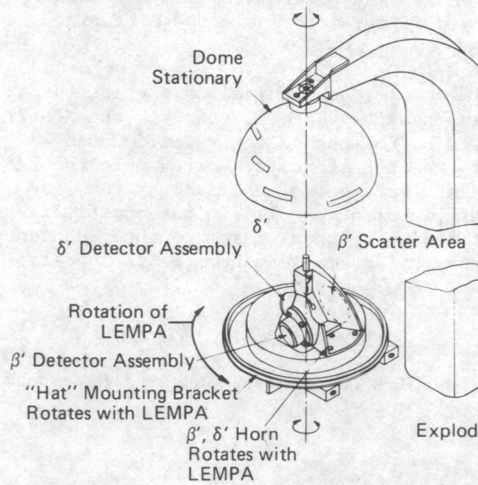


Figure 10 Low Energy Angular Distribution Detectors

Thermal Considerations

The experiment is mounted on a boom with thermal isolation mounts. From a thermal point of view, therefore, the experiment is sitting in space by itself. The motor housing which separates the main LECP structure from the rotating platform is made from titanium and is therefore a poor thermal conductor. Consequently, the telescopes and electronics on the rotating platform are thermally isolated from the main LECP structure. Further thermal constraints include passive cooling the alpha and beta detectors to obtain the 12 keV discriminator level. Finally, in order to obtain optimum performance from the logarithmic amplifiers, their temperature must remain relatively stable and perferably known. Consequently, the thermal design of the instrument is quite complex and employs various thermal finishes, a tight thermal blanket and three proportional temperature control circuits which set the LEMPA telescope, logarithmic amplifiers, and lower electronics at -15^{o}C, +25^{o}C, and -10^{o}C, respectively.

Other Experiment Systems

The large number of LECP discriminators and logic windows led to the development of a new calibration system[2] for amplifier gains and discriminator settings, as well as detector noise and PHA linearity. The calibrator pulse drives the preamplifiers with a continuous pulse train. Discriminator pulses are selectively fed back to set the pulse amplitude such that the discriminator triggers at 12 and 88% rates. Both the detector noise and discriminator setting may then be deduced. In addition, radioactive sources provide a background count rate for calibration.

Voltages for the detectors range from less than one volt for the thin detectors to 450 volts for the thickest detectors. The power supply for the detectors is a sinewave oscillator-Cockroft-Walton multiplier combination which is capable of producing bias voltages of many kilovolts.[3]

The experiment command receiver accepts 32-bit serial command words from the spacecraft and utilizes 12 of these bits in the form of four 10-bit command words and 2 address bits. Thus, 40-bits are available as commands to put the experiment into various operating modes. They are used primarily for switching power via hybrid power switches. For example, each of the detector amplifier channels can be individually shut off in case of failure. Also, the detector bias may be decreased by 25% upon command. In addition, there are several motor speed commands, as well as a sector-select command and a high-power motor drive commands which are employed if the motor develops a bearing wear problem.

The experiment will be required to operate for at lease 6 years and possibly 8 to 10 years as the MFS-77 spacecraft passes out of the solar system. Consequently many of the LECP circuits, for example the PHA and the serial data sections of the data system, are redundant. There is also over-lap in the capabilities of the detector channels, thus adding to the redundancy which is necessary to ensure long-term reliable data return.

Acknowledgment

The basic LECP instrument was conceived by a team of physicists, headed by S.M. Krimigis of the Applied Physics Laboratory. The team will have the monumental task of reducing the data as they arrive. The design and implementation of this complex instrument was also a team effort involving not only the authors of this paper, but also members of the University of Maryland Department of Physics and Astronomy and many members of the Applied Physics Laboratory staff. Sincere thanks are also given to the Jet Propulsion Laboratory for their support during the instrument development and the NASA Planetary Programs Office who sponsored this project.

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