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By

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VELA-4 SATELLITE ENERGETIC PARTICLE EXPERIMENT

S. Singer, W. P. Aiello, J. P. Conner, and R. W. Klebesadel*

ABSTRACT

The Vela-4 satellite energetic-particle experiment consists of (a) a pair of diffused-junction semiconductor detectors for electrons in the energy range 30-600 keV, and (b) a guarded, four-element, solar particle telescope for detecting protons from 0.5-100 MeV and alpha particles from 3.6-380 MeV, in 13 differentially-counted channels. Separation of protons from alpha particles is accomplished by an in-flight particle identifier. Two additional simplified telescopes are used to extend the angular coverage of the primary telescope, and a wide angle, high sensitivity scintillation detector is employed to monitor low intensity solar particle events. The design and operation of these instruments will be described.

INTRODUCTION

Although the primary purpose of the Vela Satellite Program¹ is to detect atmospheric and deep-space nuclear detonations, it has become traditional to supplement the detection system with research instruments for studying solar x-rays, the interplanetary medium and the earth's magnetosphere. On Vela Launch 4, a solar energetic-particle experiment was included in the payload for the purposes of (a) providing information concerning the propagation of solar protons in the interplanetary medium; (b) providing information concerning the interaction of solar energetic particles with the earth's bow shock, magnetosphere, and magnetic tail, and (c) observing the fluxes of energetic solar and magnetospheric electrons. The primary instrument used to obtain these data is the ST detector, which contains a pair of electron detectors and a multi-element solar particle telescope. Two supplementary instruments are included in the experiment: the STE detector, consisting of a pair of simplified semiconductor telescopes, which serve to extend the angular coverage of the ST telescope; and the X-2 detector, a large-area, wide-angle, scintillation counter, used to extend the heavy particle flux sensitivity to lower values. In this paper, the design and operation of these instruments will be described.

SPACECRAFT AND ORBIT CONSIDERATIONS

The Vela 4 payload consists of two identical spacecraft, each of which contains the same complement of instruments. The spacecraft are injected into a circular orbit in such a way that they are separated azimuthally by $\sim 180^\circ$. The orbital radius is ~ 18 earth radii and the orbit plane is inclined to the ecliptic by $\sim 58^\circ$.

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These spacecraft are not spin-stabilized but instead are actively controlled so that their spin axes are always pointed at the earth. Although the spacecraft have zero angular momentum, they are made to spin (for thermal considerations) at one rotation per 64 seconds by the action of an internal reaction wheel. The ST detector is mounted near the spacecraft equator so that the center of its cone of acceptance is oriented perpendicular to the spacecraft spin axis. The STE telescopes, however, are oppositely mounted near the spacecraft spin axis. Over the 64 second rotation period of the spacecraft, this arrangement enables good angular coverage to be obtained over the entire celestial sphere. The X-2 detector is equatorially mounted, and its wide angular response enables it to be used as an omnidirectional monitor.

ST ELECTRON SENSORS

In order to adequately cover the range in counting rate encountered in the energy band 30-600 keV, the ST experiment uses two sensors: E1, a small-area, low-noise device for electrons of energy 30-150 keV, and E2, a larger area device for electrons of energy > 150 keV. An outline drawing of these two devices is shown together with their collimators in Figs. 1 and 2.

E1 is a 10 mm^2 silicon diffused-junction, guard-ring device which is 300μ deep and is operated at approximately 1.5 times its full depletion voltage. At 20°C , and with equal 0.5 μsec RC integrating and differentiating time constants, the RMS noise of the sensor itself was 5-7 keV FWHM. At the in-orbit operating temperature (typically -10°C) the sensor noise figure is substantially reduced, and the system noise is determined by that of the charge-sensitive preamplifier. The preamplifier noise figure is normally 10 keV FWHM and is nearly independent of temperature. The equivalent energy at which the integral noise counting rate falls below 1 cps is observed to be at ~ 2.5 times the system noise expressed in keV FWHM; if this point is also taken to be the lowest practical threshold for counting electrons, the low energy threshold is ~ 25 keV.

The E2 sensor is a 100 mm^2 silicon P-I-N diffused junction device with a thickness of 1000 μ , and is also operated at ~ 1.5 times its full depletion voltage. As shown in Fig. 2, it is composed of two stacked 500 μ diodes connected parallel electrically. At 20°C and with equal 0.5 μsec RC time constants, the sensor noise is typically 30 keV, and the lowest practical electron energy threshold is about 60 keV. Both the E2 and E1 sensors are made light-tight by a double layer of aluminized 0.1 mil mylar placed over the sensor entrance aperture.

A block diagram of the electronics is shown in Fig. 3. Pulses produced in the sensor by charged particles are amplified and sent to a group of 6 level discriminators for E1 and 3 for E2. Normally, a count will be stored in the telemetry data accumulators for each channel whose level discriminator is triggered. However, if the pulse amplitude is so large that the "upper edge" discriminator is triggered (discriminator 10 in E1 and discriminator 11 in E2), the inhibit logics are activated and no count is stored in any channel. The use of a counting window is very helpful in discriminating against the large fluxes of energetic protons produced in some solar flares in that the ability of the detectors to observe electrons in the presence of a heavy particle background flux is improved.

ENERGETIC PARTICLE TELESCOPES

The ST telescope, which is the principal solar energetic particle detector used to monitor protons and alpha particles, is composed of 6 semiconductor diodes arranged in a group of 4 sensors. Except at the particle entrance window, the array of sensors is completely surrounded by a guard scintillator which is used to inhibit the counting of particles arriving from other than the desired direction. An outline drawing of the telescope is shown in Fig. 4.

Sensor D1 is a single 75 μ surface barrier detector of area 0.75 cm^2 , having thin entrance and exit dead layers. Because of its thickness, the maximum (non-scattered) electron energy deposition in D1 is ~ 50 keV and the sensor counts only those few (energetic) electrons which scatter nearly 90° inside the silicon wafer, or those which produce pile-up pulses in the electronics during high electron flux conditions. Sensor D2 is a single 500 μ diffused junction P-I-N diode; sensor D3 is a stack of 3 such 500 μ diodes, and sensor D4 is a single 500 μ diode. The areas and spacings of these sensors are so arranged that any straight line path inside the normal acceptance angle of the telescope intersects all sensors; hence the solid angle factor (0.2 cm^2 -ster) is essentially independent of energy. The gold "stopper" is used to set the upper energy edge of the ST telescope. Without the stopper, the upper energy would be determined by the thickness of the detector stack, since particles penetrating the stack would produce a scintillation in the guard counter and inhibit the counting of these events. Use of the stopper enables the upper edge to be set at 100 MeV (protons), inasmuch as only > 100 MeV protons can penetrate both the detector stack and the stopper.

The STE telescopes each consist of three semiconductor diodes and a gold absorber which are mounted inside a gold shield as shown in Fig. 5. No guard sensor is used, and the acceptance angle is determined by the sensor spacings and by coincidence requirements imposed on the sensor signals. The sensors are diffused-junction guarding P-I-N diodes with room temperature noise figures of about 30 keV. The diodes are operated at

about twice nominal full-depletion voltage to insure that they remain fully depleted under the high leakage condition produced by in-orbit operating temperatures up to 45° C. Sensor D1 is 200 μ thick and has an active area of 50 mm^2 ; sensors D2 and D3 are each 300 μ thick with an active area of 100 mm^2 . The 0.76 g/cm^2 gold absorber is used in the identification of particles of different charge and mass, and to provide proper separation of the instrument's energy levels. The gold shield is used to avoid saturation of the sensors by intense fluxes of plasma sheet and magnetosheath electrons frequently encountered in or near the earth's magnetotail.

X-2 DETECTOR

In studying the correlation between the occurrence of a solar flare and the detection of solar energetic particles near the earth, it is important that the results not be adversely affected by the use of a particle detector with a high threshold sensitivity. While the telescopes can yield detailed information about particle events of moderate intensity, their geometrical factors are too small to enable them to serve as low particle-intensity monitors. Therefore, the telescopes were supplemented by an omnidirectional scintillation detector with a large geometrical factor called X-2, which is shown in Fig. 6.

The sensitive volume of the detectors is a 0.006 inch CsI(Tl) scintillator bonded to five of the six surfaces of a hollow lucite cube. Light produced by the deposition of energy in the scintillator can be detected by the photomultiplier tube mounted at the sixth face of the cube. The detector is made light tight by a cube-shaped multi-layer beryllium window.

Only protons with energy > 3 MeV can penetrate the window and deposit sufficient energy in the scintillator to trigger the detector counting logics. Above 100 MeV, the energy deposited by penetrating protons drops below counting threshold, so that oblique incidence of the particle is required for its detection. As a result, the detector efficiency is essentially 100% from 3-100 MeV, and somewhat less above 100 MeV. Each of the five faces has an area of 20 cm^2 , so that the (omnidirectional) geometrical factor approaches 160, a factor of 800 larger than that of the ST telescope. The detection of proton events for which the (omnidirectional) flux intensity is ≥ 0.01 particles/ cm^2 sr-sec for energies > 3 MeV is thus much more likely with the X-2 detector.

ST TELESCOPE LOGICS SYSTEM

A. Signal Processing

Within the limits set by the electronics dead time, every charged particle entering the ST telescope aperture is processed in some fashion by the telescope logics system. For each particle above the experiment energy threshold, the processing sequence proceeds as follows: (a) determine the coincidence order (i.e., D1 singles, D1-D2

coincidence, D2-D3 coincidence, D2-D3-D4 coincidence, or guard counter-any sensor coincidence); (b) depending on coincidence order, select the sensor whose pulse will be analyzed (always the deepest in the telescope stack); (c) block all other sensor channels; (d) terminate processing and wait for next event if this pulse is in coincidence with a guard counter signal; (e) determine if the pulse is due to a proton or α -particle and steer the pulse to the appropriate set of energy level discriminators; and (f) add a count to the highest energy-level accumulator whose threshold is exceeded (and to that accumulator only).

Each sensor channel consists of a series of pulse amplifiers, a 0.3 μ sec delay line, and one or more analog switches. By the time an analog sensor pulse has traversed the delay line, the logics system has had time to complete most of the processing described above, and the proper set of switches can be opened and/or closed so that the pulse will be correctly analyzed. In the following discussion, the switching that occurs at each coincidence level is summarized.

D1 Singles. Since no coincidence is involved, the D1 channel contains only one normally-closed analog switch which is opened if a guard counter or D2 pulse occurs. Pulses smaller than the maximum energy deposition for protons are presumed to be protons and are counted differentially in 5 energy channels. Pulses above this level are presumed to be α particles and are counted in a separate set of differential scalars.

D1-D2 Coincidence. The operation of this portion of the system is exemplary and its block diagram is shown in Fig. 7. Pulses from the first amplifier drive the α channel switches and those from the second drive the proton channel; the operation of both is similar. Pulses delivered to the input of the proton channel delay line also drive two gate generators: an inhibit gate generator, whose output blocks the D1 sensor channel, and a coincidence gate generator, whose output is fed to the D1-D2 "AND" gate. If the "AND" condition with D1 is satisfied, the first (normally open) switch in the proton channel is closed. The second (normally closed) is opened if either a D3 sensor pulse or a guard counter signal occurs. The third switch is used to prevent counting of the wrong type of particle, and it is normally configured so that the α gate is open (i.e., blocked) and the proton gate is closed. If the on-board particle identifier (to be described below) senses that the event is produced by a proton, no change is made in this configuration, and the pulse is analyzed by the proton discriminators. If the event is produced by an α particle, the gate configuration is inverted and the pulse from the α channel is analyzed by the α discriminators. Separate sets of scalars are used to store the counts and only one set at a time is connected to the telemetry system.

D2-D3 and D2-D3-D4 Coincidences. When a particle penetrates into D3, the operation of the

circuit is very similar to D1-D2 coincidence operation. The major difference lies in the necessity for determining whether the particle stops in D3 or whether it penetrates. The D3 pulse height alone cannot be used to infer this condition, since the energy deposition is not uniquely related to the incident energy, and it is necessary to use the D4 pulse to signal D3 penetration. Protons which do not penetrate D3 (D2-D3 coincidence) must be analyzed in a "low" incident energy discriminator set, whereas those which do penetrate (D2-D3-D4 coincidence) must be separately analyzed and accumulated in a "high" incident energy discriminator set. This is accomplished by adding a fourth analog switch to the D3 sensor channel; this switch steers the proton pulse to the "high" or "low" energy discriminators depending on whether or not a coincident D4 signal is present. Since each set corresponds to a different range in particle energy, the accumulated data from both sets of accumulators must be telemetered. The D3 α channel operation is identical to that of the proton channel.

The ST telescope analyzes protons from 0.5-100 MeV in 13 differential energy channels, and α particles in the range 3.6 to 380 MeV. The 13 heavy particle and the 9 electron level energies are listed in Table 1.

B. ST Telescope Particle Identifier

The ST telescope logics system uses a simple scheme for determining if an incident particle is a proton; if not, it is assumed to be an α particle. The operation of the identifier can be perceived by examining Fig. 8, the particle loci in energy deposition space for sensors D1 and D2. The abscissa is the energy deposition in D1, the ordinate is that in D2, and the locus is constructed by plotting points for a manifold of values of incident particle energy. As the proton energy increases from zero, the entire energy of the proton is deposited in D1, so the locus moves along the ΔE_1 axis to the right. At $E_p \sim 2.8$ MeV, the proton penetrates D1, significant amounts of energy begin to be deposited in D2, and the locus moves upwards and to the left. As the proton energy increases, less energy is deposited in D1 and more in D2. At $\Delta E_2 \sim 1$ MeV, the event is identified as a D1-D2 coincidence. At a proton incident energy of ~ 9 MeV, penetration of D2 occurs, ΔE_2 starts to decrease, and the locus rapidly retreats towards the origin. A similar analysis yields the shape of the α locus; the two curves are similar except for a scaling factor of ~ 4 .

The principle of particle identification rests on the observation that as long as the system is considering only D1-D2 coincidences, the proton locus remains within the rectangle defined by $\Delta E_1 \leq 2.8$ MeV and $\Delta E_2 \leq 8$ MeV, and for no energy does the α locus enter this region. If one places threshold discriminators on D1 and D2 and sets them at $\Delta E_1 \sim 3.5$ MeV and $\Delta E_2 \sim 10$ MeV, respectively, a pulse which triggers neither discriminator must be a proton; if either discriminator is triggered, the particle cannot be a proton (and, hence, must be an

α particle). The discriminator outputs are combined in an "OR" gate whose output is used to determine the configuration of the alpha-proton analog gates in the various sensor channels. The extension of this principle to include D2-D3 and D2-D3-D4 coincidences is straightforward.

C. STE Signal Processing

After amplification in their respective pulse amplifiers, signals from the three STE sensors are fed to a group of discriminators whose outputs in turn are intercompared in a set of coincidence circuits. The functions of the digital circuitry are (a) to establish the energy channels of the detector; and (b) to distinguish between protons and alpha-particles and accumulate them separately. The method of particle identification relies on the proper choice of the gold absorber, and on the comparison of the energy depositions in the several sensors; it is practical in this application primarily because of the limited number of energy channels. The STE telescopes count protons from 5-160 MeV in three bands, alpha-particles from 20-440 MeV in two bands, and electrons from 0.3-0.9 MeV in two bands (see Table 1). Because of electron scattering, the electron channel band edges are not well defined, and their counting efficiency is substantially less than one.

ST CLOCK

It is well established² that the flux intensities of solar energetic particles or magnetosphere electrons can reach levels of at least 10^8 particles/cm²-sec-sr. Any experiment which is bit-rate limited must therefore employ some compression scheme for achieving a suitable dynamic range without undue loss of accuracy. The energetic particle experiment uses a time-compression clock technique in which the particle counting rate is determined. This procedure requires only a 2048 pps source available from the spacecraft clock circuitry) and a single, switchable 12 bit scaler, and is common to all counting channels.

The operation of the ST clock is depicted in Fig. 9. At $T = 0$, the data accumulator A (from a typical telescope or electron energy channel) and the working scaler WS are cleared, and the pre-scale index N is set to 0. Switch "S" is normally connected to the digital logics, so that A accumulates counts due to particles. If the low order 9 bits of A spill (binary configuration 1000000000), the input to A is switched to the "clock" mode, and A accumulates clock pulses from the output of the pre-scaler. In the clock mode, the contents of A will indicate the time from spill to the end of the 4 second accumulation period.

Initially, the pre-scale factor for the working scaler WS is $2^0 = 1$, and WS begins to accumulate counts at 2048 pps for any position of S. Each time WS spills (except for the first time), the prescale factor is increased by a factor of two, and the time between pulses doubles. Should accumulator A switch into the clock mode, it counts the number of prescale output pulses from A-spill

time (T_0) to the end of the 4 second period. Since the time ΔT from A-spill to the end of the 4 second period is uniquely related to the number of prescale pulses counted during T_0 , ΔT can be determined and the counting rate (in the clock mode) is given by

$$CR = 512.0/\Delta T$$

$$= \frac{8192.0 * 2^{NI}}{128 - (IA + 0.5) * \Delta(NI)}$$

$$\text{where } NI = \{ (A-512.0)/64.0 / 64.0 + 1 \}$$

A = Contents of accumulator A
(decimal integer)

$$IA = \{ A - 64.0 * (NI - 1) - 512.0 \}$$

$$\Delta(NI) = \{ 1 + NI/8 \}$$

The brackets { } indicate a truncation of the argument to the largest integer less than or equal to the argument.

Since A-spill can occur at an arbitrary time, the number of prescale output pulses can be uncertain by as much as one count. The error in counting rate produced by this digitization is less than $\pm 0.78\%$ for any counting rate $< 15 \times 10^3$ /sec; above this level the error increases because the period between prescale counts becomes comparable to the time-to-spill. At 50×10^3 cps, the error is $\pm 1\%$ and at 100×10^3 (a practical upper limit set by the 5 μ sec logics pulses the error is $\pm 5\%$. Thus, over nearly all of the useful range the statistical error exceeds the digitization error.

DATA GATHERING CYCLE

The data handling system of the Vela 4 spacecraft can operate in either of two modes, Real Time or Memory. In the real time (RT) mode, the spacecraft is actively tracked by a ground station, and payload data are transferred directly to the telemetry system for transmission to earth at a rate of 256 bits/sec. In the memory mode, the spacecraft is not actively tracked, and payload data are stored in a 30,000 bit magnetic core memory. The contents of the memory can be telemetered during any real time tracking pass. The Vela 4 spacecraft are usually tracked in real time 25% of the time (1 out of every 4 hours).

In the RT mode the basic accumulation period of the experiment is 4 seconds. During this period data from 13 ST telescope, 4 STE telescope (2 from each unit), and 9 electron detector levels are gathered. At the end of the accumulation period the contents of these 26 channels are transferred to a 260 bit temporary storage unit, the data accumulators are cleared, and another 4 sec accumulation period is begun. During the first two seconds of the second accumulation period, the contents of the temporary storage unit are telemetered to earth at the rate of 130 bits per sec.

As indicated earlier, the ST telescope uses a particle identifier to avoid storing α counts in the proton scalars, and vice versa. In order to study both the proton and helium components of solar particle events, the data-gathering cycle is arranged so that the particle type being accumulated and telemetered changes at the beginning of each new 4 second accumulation period. The first 4-second period is devoted to accumulating proton data only, the second to α -particle data only, the third to protons, etc. During the 64-second spin period of the spacecraft, 8 sets of proton energy spectra and 8 sets of α -particle energy spectra are obtained about a plane parallel to the equatorial plane of the spacecraft.

Since only two channels from each STE telescope are telemetered for each 4-second accumulation period, a total of 16 seconds are required to cycle through all seven STE channels (one channel is repeated). The angular separation between like samples of data, however, is not excessive because of the STE detector axis orientation with respect to the spacecraft spin axis.

In the memory mode of operation, only a small fraction of the data available from the experiment can be stored. These consist of three proton, one alpha, and two electron levels from the ST instrument, and one proton level from the STE telescope which points away from the earth (see Table 1). This set of data is collected every 16 seconds (i.e., every 90° of spacecraft rotation) for the duration of one rotation, and is repeated every 512 seconds.

In the RT mode, the results of a one-second accumulation of counts from the X-2 detector are telemetered to earth every 32 seconds. No data are available from this detector when the data system is in the memory mode.

CONCLUSION

From the foregoing descriptions, it is evident that the Vela-4 Solar Energetic Particle Experiment provides an abundance of information concerning the spatial environment at $\sim 10^5$ km from the earth. Measurements of proton, alpha-particle, and electron angular distributions and energy spectra are made with good resolution in the spacecraft equatorial plane; lower resolution measurements are made in the spacecraft polar directions so as to fill out most of the 4π solid angle around the spacecraft. By combining the known spacecraft orientation and the use of a sun sensor to define the spacecraft the absolute orientation in space of the particle angular distributions are determined. In addition, a broad-band wide-range detector is used to monitor very low fluxes of heavy particles.

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Table 1. Energy Levels in the ST Experiment.

Those levels from which data are taken in the memory mode are indicated by (M)

ST Telescope			
Protons		Alphas	
P1	0.55 - 0.68 Mev	A1	3.6 - 4.8 Mev
P2(M)	0.68 - 0.95	A2	4.8 - 6.4
P3	0.95 - 1.4	A3	6.4 - 9.0
P4	1.4 - 2.05	A4	9.0 - 12.7
P5	2.05 - 3.05	A5	12.7 - 18
P6	3.05 - 4.5	A6	18 - 26.5
P7(M)	4.5 - 6.3	A7	26.5 - 38
P8	6.3 - 10	A8	38 - 52.5
P9	10 - 13.6	A9	52.5 - 78
P10	13.6 - 19	A10(M)	78 - 114
P11	19 - 29	A11	114 - 163
P12	29 - 58	A12	163 - 240
P13(M)	58 - 100	A13	240 - 380

Electrons

E-1	> 28 keV
E-2	> 42.4
E-3	> 58.5
E-4	> 80.5
E-5(M)	> 111
E-6	> 153.5
E-7	> 150
E-8	> 260
E-9(M)	> 450

STE Telescope

Protons		Alphas	
P1	5 - 20 MeV	A1	20 - 75 MeV
P2	20 - 80	A2	75 - 440
P3(M)	80 - 160		

Electrons

E-1	0.3 - 0.5 MeV
E-2	0.5 - 0.9

Figure Captions

- Fig. 1 E1 electron sensor
- Fig. 2 E2 electron sensor
- Fig. 3 Block diagram of E1 and E2 signal processing system
- Fig. 4 ST semiconductor detector telescope for monitoring solar energetic particles
- Fig. 5 STE telescope
- Fig. 6 X-2 detector
- Fig. 7 Block diagram for D1-D2 coincidence signal processing electronics
- Fig. 8 Plot of proton and alpha-particle loci in energy deposition space for D1-D2 coincidences. The arrowheads indicate direction of increasing incident energy.
- Fig. 9 Block diagram of the ST clock used for wide range, accurate recording of detector counting rates.

Fig. 1

Fig. 2

Fig. 3

VELA LAUNCH IV
SOLAR PARTICLE TELESCOPE

BERYLLIUM WINDOW

GOLD
SHIELD

SILICON
DIODES

GOLD
ABSORBER

1 CM

Fig. 5

Fig. 6

Fig. 7

Fig. 9