Artificial Electron Beams as Probes of the Magnetosphere

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During the past decade a series of large suborbital vehicles has carried high-powered electron guns into the ionosphere over the eastern United States, Canada, and Alaska to inject electron beams as probes of the distant plasma medium in the magnetosphere. The electron beams were reflected from the conjugate hemisphere and were detected and analyzed to study the origins of the Van Allen radiation belts and the aurora by measuring plasma perturbations in space during magnetic storms. This paper summarizes the technical details of the accelerators, the method of injecting and analyzing the beams using television techniques and particle counters in space, and how the beams in their behavior simulate the natural trapped electrons and give clues as to the acceleration processes.

Introduction

ONE of the earliest and most important results of the space era was the discovery of intense zones of trapped particles circulating in the outer regions of the Earth's magnetic field above the ionosphere.[1] The electrons and protons were found to have energies in the million electron volt range and to vary as a result of magnetic storm activity detected by magnetometer stations on the ground. Early experiments with identical counters measuring simultaneously in the radiation belts and in interplanetary space far from the Earth showed that the trapped particle intensity increased remarkably, even in the million electron volt range, without the presence of similar particles arriving with the solar plasma from the sun.[2,3] Thus the acceleration of particles to high energy was known to occur near the Earth in what is now called the Earth's magnetosphere.

These particles radiate radio waves of great intensity and it was by means of radio waves from the planet Jupiter that the existence of intense radiation belts around Jupiter was predicted. The prediction was verified by the Pioneer and Voyager spacecrafts, which in penetrating Jupiter's magnetosphere found energies and intensities far exceeding those present near the Earth. Again it was found that these particles were locally accelerated.

Many observations of the plasmas, magnetic fields, and high-energy particles of the planetary magnetospheres have now been made. The production of energetic particles has been frequently observed near the solar surface in solar flares and detected by indirect means elsewhere in the cosmos as well. Besides the basic scientific interest in these naturally accelerated particles, many practical applications of space both manned and unmanned must contend with the high radiation dosage encountered in various parts of the radiation belts. The deterioration of solar cells and other solid-state devices and disturbances in the operation of sensitive detectors are examples of radiation damage effects. There was great concern that the Pioneer and Voyager spacecrafts would suffer damage by Jupiter's radiation belts and in fact some effects were recorded.[4] Many near-Earth missions are subject to deterioration by the intense inner radiation belt protons and electrons, or to spacecraft charging or radiation damage in the important synchronous orbit region during magnetic storms. Beyond the Earth's magnetosphere there are solar flare accelerated low-energy cosmic rays which are particularly hazardous for extra-vehicular activities or exploration of the surface of the planets. Yet there is a surprising lack of direct measurements which identify exactly the accelerating processes.

More than a decade ago the author began a series of controlled experiments in which electron beams were used to probe the outer reaches of the Earth's magnetic field to establish the cause and effect relationship between the presence of electrodynamic processes during magnetic storms and the injection and changes in energy and other properties of the trapped electrons. A technique known as the "electron echo" has been developed for this purpose. The procedure is shown schematically in Fig. 1. The figure is drawn in perspective but more or less to scale and illustrates a very useful location on the Earth for carrying out the experiment, namely in central Alaska in the auroral zone. A large sounding rocket is launched into the ionosphere flying for periods up to 10 min above the atmosphere carrying a powerful electron accelerator. Pulses of electrons are injected and spiral outward in the Earth magnetic field in exactly the manner of the natural electrons which are present in the same region of space as part of the radiation belts. The electron pulses pass through the equatorial plane and reflect from the converging fields in the Southern Hemisphere, and like the natural particles, return near their point of origin over Alaska. These magnetic lines of force pass through the equatorial plane in a region where plasma clouds are often injected from the magnetospheric tail plasma sheet. Instabilities cause fluctuating fields which accelerate the trapped particles to higher energies, making this region of space particularly important.

By various techniques the returning beams are detected and analyzed to give information about the changes which they

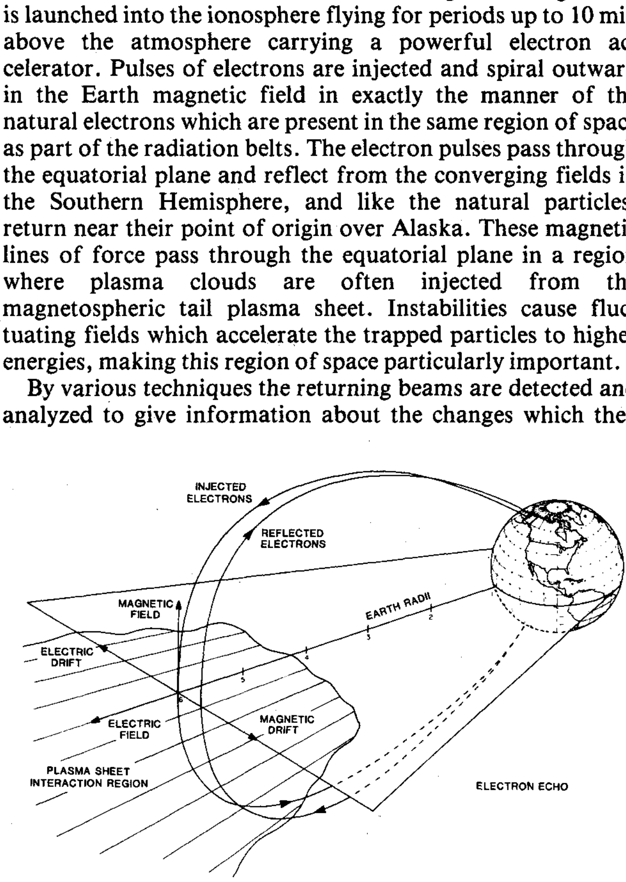

Fig. 1 Electron beam paths in space.

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have undergone while traversing the distant regions, effects which also act on the natural particles. This experiment carries out on a cosmic scale a procedure well known in laboratory plasma physics in which particle beams are used as probes for investigating the structure of fluctuating fields and for observing accelerating processes. In fact, the observation of the acceleration of electrons by plasma instabilities was one of the earliest observations by Langmuir in 1929 in his investigations of gaseous arcs. It was Langmuir who gave the name "plasma" to highly ionized gases showing collective effects and began the entire field of plasma physics.[5]

In the last decade many groups have begun programs using electron beams for plasma research in space. Nearly 30 large sounding rockets have been launched and experiments are being planned for the Space Shuttle. This work has recently been summarized in a review article.[6] Recent "electron echo" results have been summarized in an advanced study conference proceedings, which also constitutes a good summary of the field.[7]

The Basic Elements of the Experimental System

The Beam Injecting Rocket System

The utilization of electron beams as a plasma probe in the magnetosphere requires that electron pulses of a well-determined nature be sent out into the distant magnetic field from the ionosphere where the beams may be injected by sounding rockets or eventually by orbiting vehicles. The beams must be injected from heights above 150 km where collisions between the beam electrons and the residual atmosphere are unimportant. The beam injecting system may be separated into that portion lying within the rocket skin which includes the accelerator, its drive system and programmer, and auxiliary monitoring devices, and that portion exterior to the rocket which includes the partially ionized ionospheric plasma with its magnetic field and the exterior beam which passes through this region on its way outward toward the equatorial plane. The problems within the rocket skin involve the construction of a battery-operated high-powered electron gun together with the rocket support systems of attitude control, telemetry, and environmental monitoring devices. The problems external to the rocket are much more difficult. First, the ionosphere must provide a return current to the rocket skin to balance the charge carried away by the beam, otherwise the potential of the rocket would rise and in a few tens of microseconds would trap the beam and prevent its escape to infinity. In addition, the beam interacts with the ionosphere as a beam-plasma system and is, in most cases, unstable against the production of plasma and electromagnetic waves which partially degrade the energy of the beam and may seriously perturb that part of the magnetosphere which is under investigation.

A number of groups have developed high-powered, high-current electron guns for basic particle beam research in space. Triode planar geometries have been used in several experiments.[6] Space charge grid control in these systems permits easy programming and high-frequency modulation capability. Sellen[8] has discussed high-powered gun systems for space use, considering how to achieve maximum perveance. These systems have used oxide cathodes, which must be vacuum sealed until exposed in space, and are accordingly difficult to test. In the Norwegian "Polar" series[7] and the ECHO series, diode guns with relatively indestructible tungsten or tantalum cathodes were used, but at the cost of lower perveance per gun. The gun current and voltage programming for diode guns must be applied to the primary power drive, which complicates the modulation problem and limits the frequency range of modulation. Figure 2 shows schematically the ECHO diode gun which was adopted from an electron beam welding accelerator and is similar to the Pierce design.[9] The anode of the gun is, in effect, part of the outer conducting skin of the rocket. The cathode is operated at negative high potential inside the rocket body. Voltages up to 40 kV have been used and are provided by a high-powered dc-dc converter also shown schematically in Fig. 2. The present system utilizes power transistor switching and a bridge rectifier using high-voltage solid-state diodes. The primary power is provided by silver zinc batteries furnishing 100 A at 100 V under load. The batteries store approximately 5 MJ of energy and power transformation is accomplished in one step from 100 V to 40 kV using a transformer designed to withstand the high potentials and sizable current and retain a compact form. The voltage-current characteristics of one of the ECHO 5 diode guns is shown in Fig. 3. This gun operated near the upper range of the $V^{3/2}$ space charge region as shown in the figure and furnished 250 mA at 40 kV. The perveance for a single gun defined as $A = I/V^{3/2}$ was 4×10^{-8} with I in amperes and V in volts. The defocusing of the beam by Coulomb repulsion is compensated by an axial magnetic focusing coil so that most of the beam is confined within 2 deg. The beam angular profile is displayed in Fig. 4, which was obtained by melting a hole in a stainless steel target plate with a 1-s pulse at 1 m from the gun anode. The beam was normally injected perpendicular to the rocket axis, but could be deflected by a small electromagnet to control the beam direction with respect to the local Earth magnetic vector.

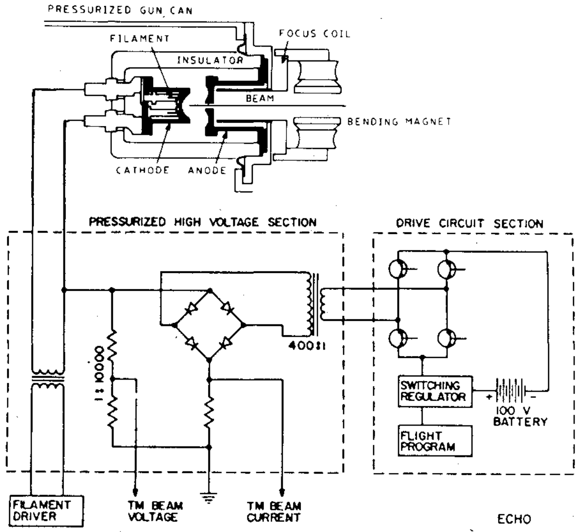


Fig. 2 Diode gun structure and power drive.

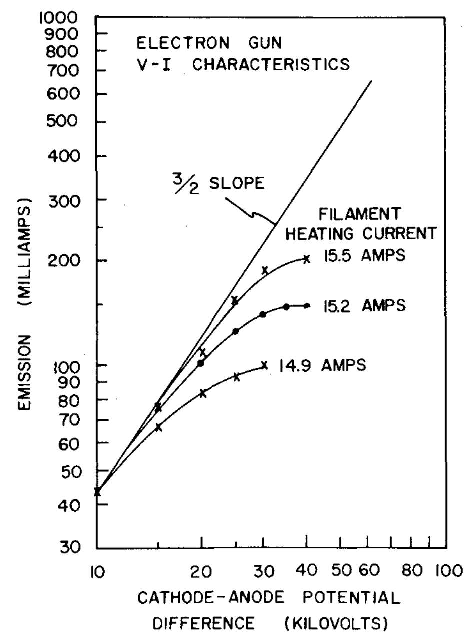
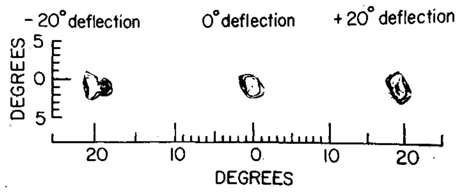


Fig. 3 Electron gun voltage current characteristics.



Pattern melted into target plate by Echo V electron beam during vacuum test.

Fig. 4 Electron beam pattern.

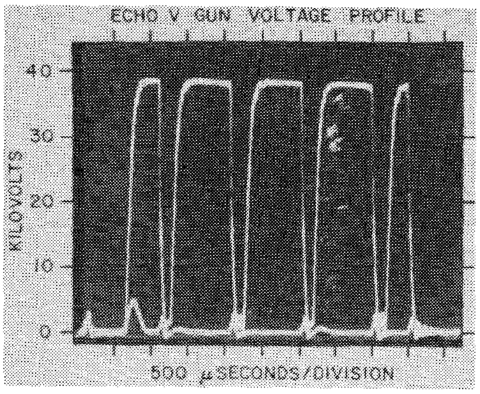


Fig. 5 Electron gun profile.

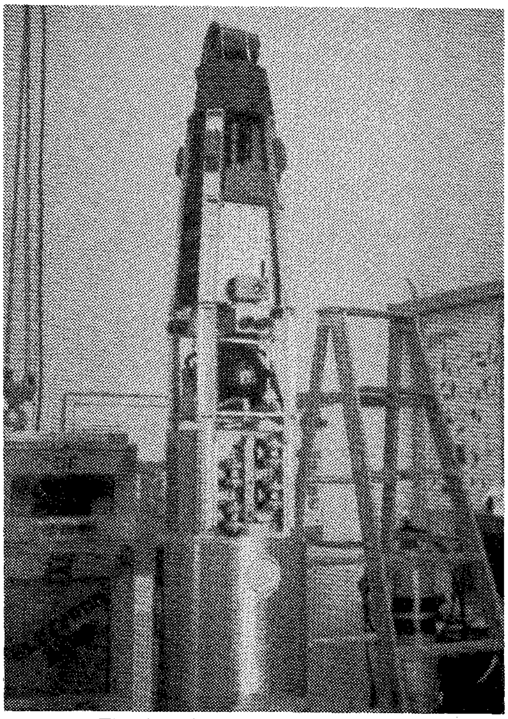


Fig. 6 ECHO 5 scientific section.

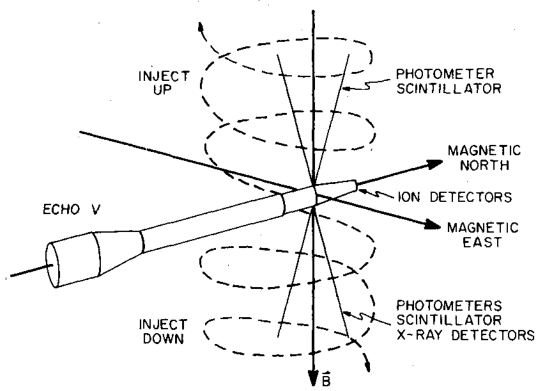


Fig. 7 Payload aspect in space.

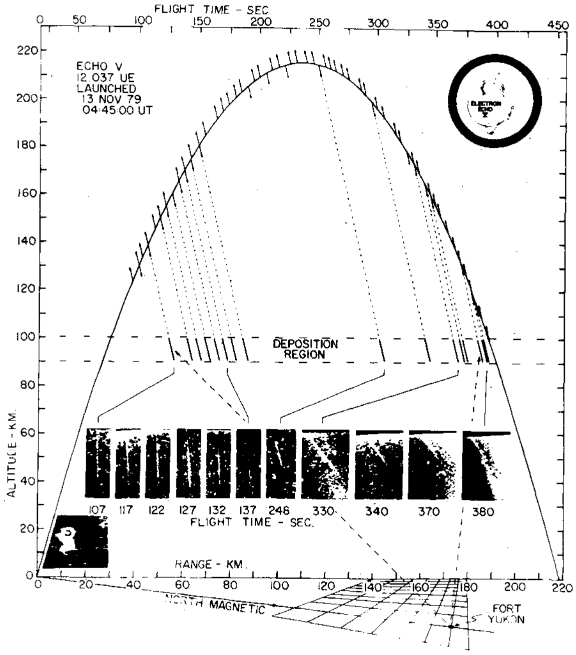


Fig. 8 Geometry of artificial auroral streaks.

Typical deflections of 20 deg each side of the perpendicular were used and are also shown in Fig. 4. An example of the voltage time profile commonly used is shown in Fig. 5, derived from the 500 Hz power converter with full wave rectification but no filtering. The profile starts with a 0.5-ms turn-on pulse, followed by 1.0-ms rectified cycles to give the desired injection length, and terminated with a 0.5-ms turn-off pulse to re-establish a low final residual flux level in the transformer iron. The gun is capable of continuous operation, but the pulses are normally not longer than 1 s in duration. Four such diode guns were built into the ECHO 5 rocket payload, resulting in a power of more than 30 kW. The guns and other components, such as the high-voltage transformers and the diode filament drive isolation transformers, were enclosed in a pressurized section filled with Freon 22. The power system for ECHO 5 is described in a technical memo.[10]

The scientific portion of the ECHO 5 payload is shown in Fig. 6. The top instrument is an ionospheric ion and auroral particle detector. Below this are photometers for measuring the beam fluorescence or the aurora, and below this is a battery of 5-40 keV x-ray detectors. To the left of the step ladder is shown a spherical gas tank for a gas injection experiment and below this the four electron guns with the deflection magnets in place. The lowest section (enclosed) contains the power drive and batteries. The payload weight was about 682 kg.

The Injected Beam in Space

In the ideal case, the beam produced by the accelerator would leave the rocket skin and spiral in the geomagnetic field freely in accordance with the well-known Lorentz force on the electrons. This is shown schematically in Fig. 7 in which the rocket payload has been oriented in flight with its axis magnetically horizontal and pointing toward magnetic north. By the control of the magnetic deflection the beam can be caused to spiral upward or downward. The downward injections intercept the atmosphere far below the rocket where they produce artificial auroral streaks that can be detected by sensitive television techniques. These streaks for 40 keV energy beams extend from about 90-100 km. The injections which spiral upward move out away from the Earth and in the decreasing magnetic field the pitch of the spiral increases, until near the equatorial plane (about six Earth radii from Earth center for auroral zone injection over Alaska) the beam is moving parallel to the magnetic field within a few degrees. The spiral becomes flat as the beam again approaches the Earth in the Southern Hemisphere, and the beam mirrors at the southern conjugate altitude and eventually returns northward arriving near the point of origin. If sufficient beam intensity were still present, an "echo" artificial auroral streak would appear near the original downward marker but displaced horizontally by the drift distance of the beam in one bounce to and from the conjugate region. In the ECHO 5 experiment the downward pulses were used as position markers to enable a search for conjugate echo streaks which could then be measured and analyzed. Very many marker pulses were observed, and some samples are shown in Fig. 8. This figure shows actual photos of the streaks taken from television video frames placed in relative position on a diagram of the rocket trajectory over Alaska. Despite the considerable power used in the pulses in the ECHO 5 experiment, which was specially designed for optical detection, no echo streaks were detected. It is surmised that scattering of the beam by plasma turbulence near the equatorial plane deflected the trajectories so that most of the beam electrons mirrored above the rocket. The return beam reaching the atmosphere thus did not have sufficient intensity to produce an observable optical image. Nevertheless, on most of the previous flights conjugate echoes have been detected by particle counters carried on the same rocket which injected the beam. Particle counters have a much greater sensitivity than optical detection, but, in this case, it is necessary that during at least part of the trajectory the rocket move exactly in the ionosphere along the drift shell followed by the electron beams returning from great distance. This seemingly impossible requirement, to have the rocket intercept its own echoes even in the presence of both electric and magnetic drifts, is made feasible because for a wide variety of conditions it is possible for the rocket trajectory to become parallel to a drift shell at one or more parts of its flight. At that time the conditions for echo detection can be met for certain combinations of electron energy, magnetospheric electric fields, and magnetospheric magnetic field configurations. During the ECHO 4 experiment, a 0.5-s duration pulse of 90 mA current at 40 keV, which was initially directed downward and subsequently backscattered, was observed during at least four bounces between hemispheres, as shown pictorially in the upper panels in Fig. 9 (not to scale!). The intensity of the detected electrons decreased regularly each bounce by nearly a factor of 10 (see lower part of graph, Fig. 9) until the signal merged with the natural trapped radiation

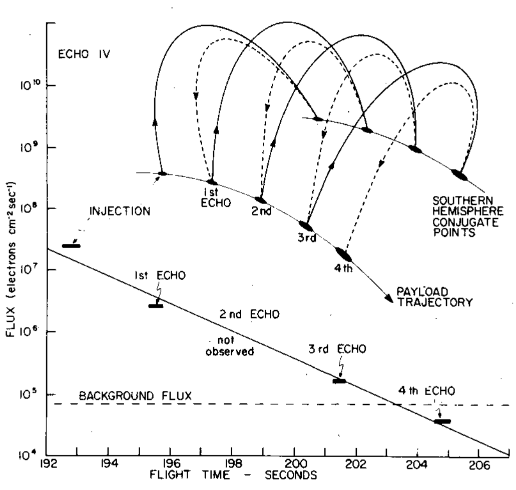


Fig. 9 Observed echo intensity.

background present at rocket altitudes. This set of echoes was produced by electrons of about 15 keV energy which resulted from the 40 keV beam after the initial scattering and can be shown to be caused by the effects of eastward magnetic drifts of 570 m/s average value and electric drifts with a northward component of 195 m/s and a westward component of 205 m/s. These drifts added vectorially to match the rocket velocity with components north 195 m/s and east 365 m/s. The result further shows that the electric field drifts acting on the beam in the distant magnetosphere can be predicted from those observed in the ionosphere near the rocket as if magnetic field lines connecting the equatorial plane with the auroral zone were equipotentials. The magnetic and electric field drifts combined to cause the echoes to displace successively in a northeasterly direction, which lay exactly along the rocket trajectory during a period of 10-15 s.

Discussion

One of the major problems in injecting powerful beams in space is the charge neutralization of the space vehicle during beam injection. This problem has been widely discussed (see Ref. 6 and review article by Linson in Ref. 7). In summary, it appears that when an electron beam is injected from a sounding rocket in the ionosphere that the rocket potential rises to a positive value and collects a current of ionospheric plasma electrons. This current flows partly from a nearby cylindrical region in the ionospheric magnetic field. The electrons must be transferred across the magnetic lines by a diffusion process which is part of a plasma discharge enveloping the rocket in a manner similar to a Penning discharge in the laboratory,[11] in which a current is drawn through an ionized gas contained between a cylindrical anode and a surrounding cylindrical outer electrode with the magnetic field along the axis of the cylinder. It has also been observed that an enhanced current flows back to the rocket body and provides additional beam neutralization coming from the region around the beam as it spirals away from the rocket. It is thought that the beam plasma interaction produces a discharge in which there is a greatly enhanced plasma density which permits the extraction of a large additional current flowing back to the positively charged rocket. Prior to the first electron beam experiment in the ionosphere carried out by Hess,[12] it was felt that the rocket would charge to a high positive potential and prevent the escape of the beam. It has been found that rocket potentials rise to values of 10 V or at most a few hundred volts in the ionosphere. Positive potentials can be effectively neutralized by the very mobile electrons in space. *Negative* potentials on the other hand are difficult to compensate because the relatively large mass of the positive ions means that the current which they can contribute is small. High *negative* potentials may be encountered when positive particle beams are injected and may be very difficult to neutralize. Negative charging of spacecraft in the distant magnetosphere, for example in synchronous orbit, has frequently been observed up to 10 kV as a result of the bombardment of the spacecraft by high-energy electrons in the outer radiation belts during magnetic storms.[6]

Another potential problem which arises if electron beams are to be used as probes, as discussed in this paper, is that the beam in passing through the ionospheric or magnetospheric plasma may become unstable and produce strong electrostatic waves which tend to destroy the beam. Such instabilities are well known in laboratory plasmas but in almost all cases the finite dimensions of the beam damp the growth of waves so that the beam thermalization is only partially effective. In the case of the ECHO experiments described herein, a fraction of the beam at least survived this instability and was observable on its return even after very large travel distances up to several hundred Earth radii as discussed earlier for the ECHO 4 experiment. It should be noted that the magnetospheric plasma itself is unstable; in fact, these instabilities can accelerate particles to high energies as well as the reverse process

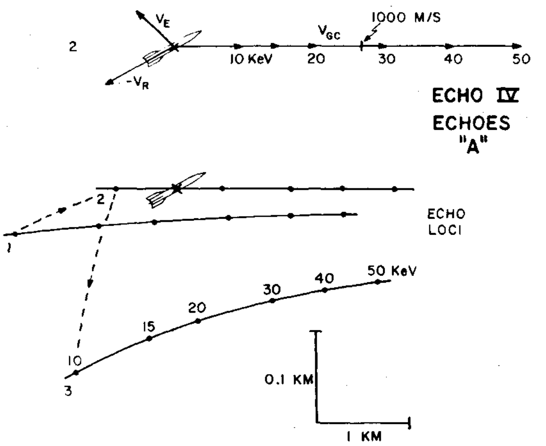


Fig. 10 Theoretical echo positions.

of thermalization. Such processes are of great scientific interest and constitute one of the subjects for investigation by the electron beams as probes. This kind of process was mentioned above in connection with the ECHO 5 experiment in which the scattering was so severe that even powerful beams did not produce optically observable echo streaks.

The program has been successful, however, in observing echoes on numerous occasions with particle counters and in reducing the data to give information about the distant electric fields in the magnetosphere. A scheme devised for this purpose is graphically laid out in Fig. 10. This figure represents the intersection of the ECHO beam with a plane drawn perpendicular to the local magnetic field and containing the rocket instantaneously in its trajectory. The ECHO beams come back along curves or "loci" with the electrons of various energies spread out, as shown in the lower diagram of Fig. 10. This entire locus moves about in response to the electric and magnetic drifts and also to the rocket motion if we take a reference system fixed in the rocket. The unusual multibounce echo shown in Fig. 9 must have represented a turning of the electric field vector in the distant magnetosphere so that the locus moved from position 1 (Fig. 10) to position 2 when it encountered the rocket and remained in that vicinity for more than 10 s and then moved away to position 3. At position 2 the various vector drifts cancel, as shown in the upper diagram of Fig. 10 so that the echo directly encountered the moving rocket at a return energy of about 15 keV.

The motivation for attempting echo detection by optical means came from the requirement just outlined that rather special circumstances must occur if the rocket is to intercept the electron beams returning as echoes from the conjugate hemisphere. Although all five of the ECHO flights have been technically successful, and three have given detected echoes, it is clear that the quantity of data is small and does not justify the technical difficulty and expense of the flights if echoes must be detected onboard the beam emitting rocket. If echoes could be optically registered essentially every injected pulse could be studied as an echo and a relatively extensive analysis could be made of plasma effects and particle acceleration. In the case of the ECHO 5 experiment shown in Fig. 8 and discussed extensively above, the highest possible beam power was used to increase the probability of the formation of artificial auroral streaks in the atmosphere not only by the direct downward pulses as shown in Fig. 8 but also by electrons returning as conjugate echoes. The ECHO 5 experiment gave a predicted echo intensity a factor of 5-10 above the ECHO 4 experiment, which also used low light level television techniques to measure the marker pulses. The nonobservation of optical echoes with ECHO 5 is attributable to some deterioration in the atmospheric seeing due to the background light from the aurora, but mostly due to particle scattering in the distant magnetosphere, probably caused by electric field

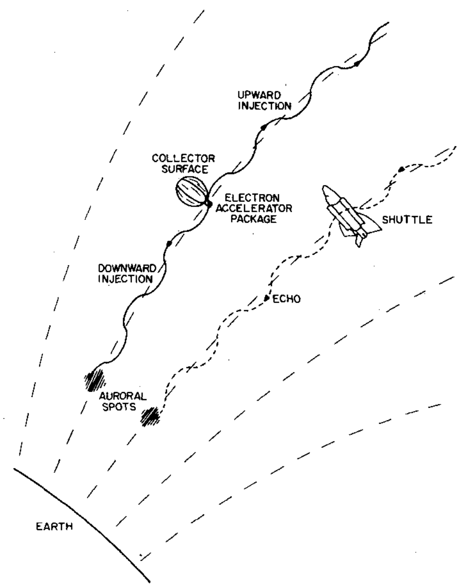


Fig. 11 Adaptation of ECHO to Space Shuttle.

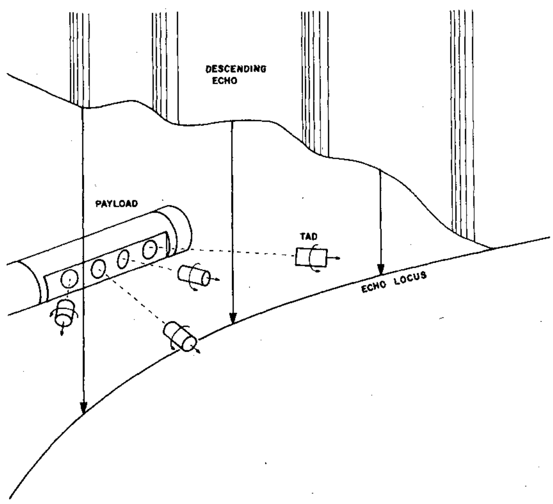


Fig. 12 Detection of echoes by TADS.

turbulence in the inner plasma sheet region. Such scattering can be very effective near the equatorial plane where the electron beams are moving nearly parallel to the terrestrial magnetic field. A small transverse deflection can move the echo beams out of the loss cone and cause them to mirror above the atmosphere on their return. Thus the very phenomena which it is desired to study may reduce the intensity and make optical detection ineffective.

It has been proposed to use optical methods on the Space Shuttle to analyze electron beams injected in orbit perhaps as shown in Fig. 11. In view of the results of the ECHO 5 experiment such optical techniques may prove ineffective because of background luminosity from the ground and other sensitivity limitations in addition to the loss of particles by natural scattering. The group is presently engaged in the design of a new sounding rocket mission to detect and analyze echoes more effectively with a series of deployable free-flying detectors called "TADS" (Throw Away Detectors). Figure 12 shows schematically how the TADS will be released from the main payload and propelled by small rocket motors outward into the echo region with velocities of approximately 15 m/s relative to the main payload. Each TAD contains a detector system, aspect magnetometer, is spin-stabilized, and includes a data encoder and telemetry system. The TADS are approximately 6 kg and will be deployed in pairs from the aspect-stabilized main payload at appropriate times during the parabolic trajectory of the rocket.

It is hoped that as the ECHO pulses descend, as shown qualitatively in Fig. 12, there will be repeated encounters between the pulses and the TADS at various energy positions along the locus and at various times. The TADS will intercept not only first echoes but second, third, and so on, for repeated bounces. This system is a crude approximation to a continuous distribution of detectors in space. The ECHO 6 experiment includes a separate plasma diagnostic package for measuring the local electric fields, auroral luminosity, and particle and plasma distribution functions. Besides measurements on the distant magnetosphere research on vehicle charge neutralization and beam plasma interaction will be accomplished. The TAD approach may lead to similar concepts for use on the Space Shuttle.

Acknowledgments

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